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Monika Kuffer
Stefanos Georganos *Editors*

Urban Inequalities from Space

Earth Observation Applications in the Majority World

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Editors
Monika Kuffer
Faculty of Geo-Information Science
and Earth Observation (ITC)
University of Twente
Enschede, The Netherlands

Stefanos Georganos
Geomatics, Department of Environmental
and Life Sciences
Karlstad University
Karlstad, Sweden

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Abstract

Rapid transformation processes occur in the Majority World, where more than three-fourth of the world's population is living. This number is expected to increase in the following years, with Sub-Saharan Africa anticipated to account for over half of the global population growth by 2050. Presently, most of this growth is concentrated in areas deprived of access to infrastructure and services, and areas exposed to hazards and degrading environmental conditions. The continuous urbanization in many African, Asian, and Latin American cities is coupled with rapid socio-economic and demographic changes, impacting urban, peri-urban, and rural areas. These changes often increase socio-economic fragmentation and existing disparities. According to the United Nations, among the 36 fastest-growing cities (with an average annual growth rate of more than 6%), 7 are located in Africa, while 28 are found in Asia. On top of the socio-economic transformations, the increasing impacts of climate change are aggravating local vulnerabilities.

However, data to understand these transformation processes and relationships are either unavailable, scarce, or come with high degrees of uncertainty. While Earth Observation data and methods have a great potential to fill data gaps, they are not exploited to their full potential. Most urban remote sensing studies in the Majority World focus on primary cities, while little is known about secondary cities, urbanizing zones, or peri-urban areas. Attempting to measure and map environmental and socio-economic phenomena through remote sensing fundamentally differs from extracting bio-physical parameters. In general, studies done by researchers of the Minority World do not sufficiently grasp the information needs and capacity demands of the Majority World, especially those related to user requirements and ethical perspectives. In this book, we provide an outlook on how Remote Sensing can provide tailored solutions to information needs in urban and urbanizing areas of the Majority World, e.g., in terms of socioeconomic, environmental, and demographic transformation processes. We chart methodological and application routes aligning with local and national information needs and bolstering sustainable development, supporting the monitoring of the 17 Sustainable Development Goals. The book combines an overview of innovations in applications, methodologies, and data use, showing the capacity of Earth Observation to fill global knowledge gaps.

Preface

Our hopes to bring this book to fruition started when we took over as the EARSeL Chairs for the Special Interest Group on Developing Countries, with a first workshop on "Earth Observation and the Global South" in September 2022 in Cyprus. The rationale for preparing this book stems mainly from two factors. First, there is a clear lack of scientific books that investigate urban inequalities from an Earth Observation and spatial perspective. Second, we looked for a starting point to bring an extensive community together and tackle the topic of urban inequalities from multiple angles.

As mentioned in the title, we investigate urban topics in the *Majority World*. The Majority World is an alternative to terms such as the "Global South" and "Low-and Middle-Income Countries", which are also commonly used. We find the term more informative, accurate and with less ideological connotations. The interpretation of the term is clear – the Majority World houses the majority of the world's population and faces the biggest economic, social and environmental challenges. For instance, while anthropogenic climate change is mainly caused by the Minority World, the Majority World carries most of the burden – consequences, with limited resources to adapt. This was also one of the major outcomes of the COP27 (United Nations Climate Conference, 2022), where finally, an agreement on a loss and damage fund, particularly for nations most vulnerable to the climate crisis, was established.

In the context of the rapid urbanization, which is expected in many regions of the Majority World, e.g. Sub-Saharan Africa with presently low urbanization rates but, according to the UN, the fastest population growth, urban challenges are massive. For example, there is a massive divide between primary and secondary cities, e.g. in terms of services and infrastructure. However, a similar massive divide is found within cities between well-serviced and planned areas and unplanned (informal) areas. For instance, many inhabitants of cities like Lagos (Nigeria) do not have access to stable electricity or need to rely on self-helped connections (e.g. Nairobi, Kenya). Other challenges are environmental, housing, and socio-economic conditions. In this context, one of the biggest bottlenecks to evidence-based sustainability practices in the Majority World is the lack of up-to-date spatial information. Geospatial data such as censuses, settlement types and health measurements are often not available, outdated or inaccessible, but urgently needed to deal with the massive challenges in an effective way. Despite two decades of intensive research, there is no global dataset available that describes the location of the slums and informal settlements. The available data used by the United Nations (e.g. for the reporting of the Sustainable Development Goal 11.1.1 indicator) are country-level data reported by national governments, which are likely extremely underestimated. Therefore, there is an urgent need to develop alternative approaches to data collection, analysis, and integration. Earth observation data analysis combined with community engagement presents an excellent opportunity to fill such gaps.

As such, this book is an effort from multiple scientists to shed more light on the potential, limitations and future opportunities of using Earth observation and geospatial data to unravel and better understand urban inequalities. Novel modelling approaches, data integration, applications or meta-analyses of existing datasets are presented with an overarching goal – to see the urban areas of the Majority World through a new lens. We hope that this book will be an awareness call for more research and collaboration with researchers and communities of the Majority World.

Enschede, The Netherlands Monika Kuffer

Karlstad, Sweden Stefanos Georganos

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About the Editors

Monika Kuffer is an Associate Professor at the Faculty ITC (University of Twente, NL). Her research focuses on SDGs, poverty (deprivation), environment using Earth Observation, GIS, and AI. She (co)leads research projects on deprivation, e.g., IDEAtlas, SLUMAP, ONEKANA, ACCOUNT, and IDEAMAPS. She is the Dutch representative of EARSeL (chair Developing Countries), EO Toolkit, and JURSE Steering Committee.

Stefanos Georganos is an Associate Professor at Karlstad University. He does research in remote sensing, spatial epidemiology, and machine learning. He is interested in the use of geo-information to help address the UN Sustainable Development Goals. He is the Secretary-General of the European Association of Remote Sensing Laboratories (EARSeL) and chairperson of its Group on Developing Countries.

Chapter 1
Introduction

Stefanos Georganos and Monika Kuffer

Abstract This chapter discusses the challenges faced by low-and middle-income countries (LMICs) in dealing with rapid transformation processes, including increasing inequalities, overconsumption of natural resources, high urbanisation rates, massive environmental degradation, and the growing impacts of climate change. The Majority World, where most of the world's population resides, is the epicentre of the ongoing urban transformation, but it lacks accurate, high-resolution, and timely data to support mitigation and adaptation processes. The article highlights the potential of Earth Observation (EO) data to address data gaps and tackle urban and environmental challenges in LMICs. The article discusses the advances in using AI and EO-based algorithms to measure and characterize urban and environmental inequalities, including climate change and environmental challenges, infrastructure inequalities, and mapping the morphology and dynamics of cities, sub-urban and peri-urban areas with EO. We emphasize the innovative use of existing datasets to provide locally relevant information to users and how EO can create societal impacts.

Keywords Urban inequalities · Earth Observation · Urbanization · Environmental degradation

S. Georganos (✉)
Geomatics, Department of Environmental and Life Sciences, Karlstad University, Karlstad, Sweden
e-mail: stefanos.georganos@kau.se

M. Kuffer
Faculty of Geo-Information Science and Earth Observation (ITC), University of Twente, Enschede, The Netherlands

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1.1 Urban Inequalities from Space: Earth Observation Applications in Support of the Most Vulnerable in the Majority World

We are living in a rapidly changing world with increasing inequalities, overconsumption of natural resources, high urbanization rates, massive environmental degradation, increasing impacts of climate change and growing violent conflicts (United Nations 2019). These rapid transformation processes are often complex and connected. For example, climate change is reducing agricultural productivity and destroying traditional agricultural or nomadic lifestyles (e.g. of Maasais in Kenya) (Wafula et al. 2022). This, in return, leads to rural–urban migration, causing the rapid growth of cities (infill and outwards growth), massive pressures on low-income housing markets and often the growth of informal settlements that lack basic services and infrastructure. Climate change dramatically impacts the frequency and severity of hazards, such as floods, storms and heat waves. These massive impacts have a global scale but show considerable regional differences. Low- and middle-income countries (LMICs) are expected to have around 90% of the global urban growth. For instance, Sub-Saharan Africa will account for more than half of the global population increase by 2050 (doubling its population between 2022 and 2050) (UN DESA 2022). Thus, most of the global population is already living in LMICs (Fig. 1.1), and this expected growth will lead to a massive increase in population, particularly the urban population. However, the *Majority World*, where most of the world's population resides and is the epicentre of urban growth, has an extraordinary lack of data that can support understanding complex relationships and consequences to support evidence-based policies and knowledge-based adaptation measurements.

Rapid transformation processes and growing urbanization rates are leading to increased land consumption (Sustainable Development Goal 11.3.1 indicator). Cities are densifying and transforming green spaces into built-up areas. The consequences of lost recreational spaces directly impact cities' living qualities. In particular, cities in LMICs strongly rely on motorized transport, causing massive air pollution (Fig. 1.2). Another major environmental challenge of cities is waste management. Sometimes, even before the silhouette of a city is visible at the horizon, the traces of the city can be already seen in terms of waste accumulation (Fig. 1.3), while within LMIC cities, the scale of the waste problem is massive (Fig. 1.4). Such environmental challenges (e.g. air pollution, waste, land consumption) are global. However, the severity is more considerable in LMICs, while the capacity to work on effective mitigation and adaptation measurements is lower, primarily due to resource constraints.

The Majority World is the epicentre of the ongoing urban transformation but has limited accurate, high-resolution and timely data to support mitigation and adaptation processes. A recurring issue when talking with local stakeholders in LMICs is data gaps and access to spatial data (Kuffer et al. 2021). Data are often unavailable, e.g. many countries did not have a census in the last 10 years, and available data are

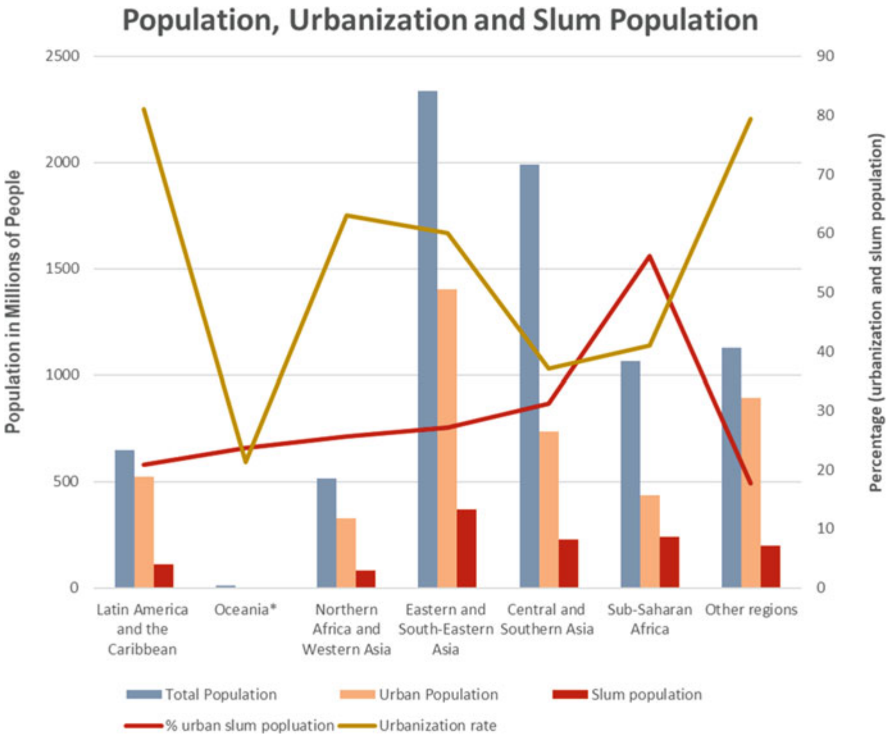

Fig. 1.1 Global population, urban population and population of slums/informal settlements. (Adapted from United Nations Statistics Division 2019) (*Oceania: excluding Australia/New Zealand)

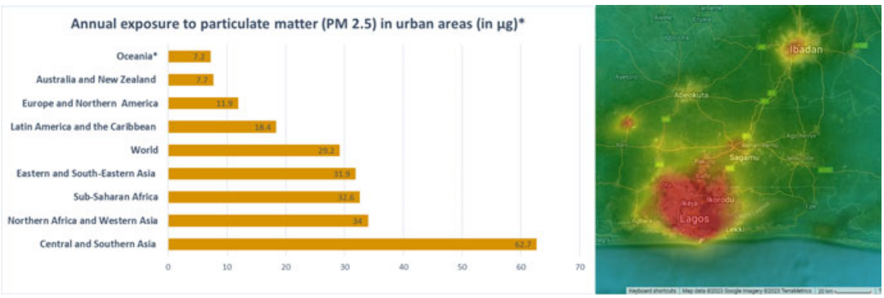

Fig. 1.2 Annual exposure to particulate matter (PM2.5) in urban areas, three-year average from 2017 to 2019 (micrograms per cubic metre). (Adapted from United Nations Statistics Division 2022) (left) and NO_2 air pollution (hotspots in red colour) showing the agglomeration of Lagos, Nigeria (using Sentinel-5, the first quarter of 2023) (right)

not consistently collected, documented and openly shared. With the increasing availability of Earth Observation (EO) data, such data gaps can be addressed or mitigated (Fig. 1.5: example of growing EO-based data but also lack of data in

Fig. 1.3 First traces of urbanization: traces of plastic waste in the outskirts of Khartoum, Sudan

Fig. 1.4 Municipal solid waste collection and management in controlled facilities, 2022 (percentage). (Adapted from United Nations Statistics Division 2022) (left), lack of waste collection in a residential neighbourhood in Lagos, Nigeria (right)

conflict areas). In particular, free-cost EO data and EO data products have the capacity to provide large-scale, consistent and reliable information regarding the urban processes of the Majority World (Merodio Gómez et al. 2021). However, there are major challenges to fully realize the potential of EO data analysis in these regions. These challenges can be summarized as the following:

(a) In situ data availability – e.g. training data repositories are biased towards the Minority World.
(b) Knowledge divide – most EO studies on the Majority World are done by researchers working for academic institutes located in the Minority World. There is an urgent need to foster research partnerships.

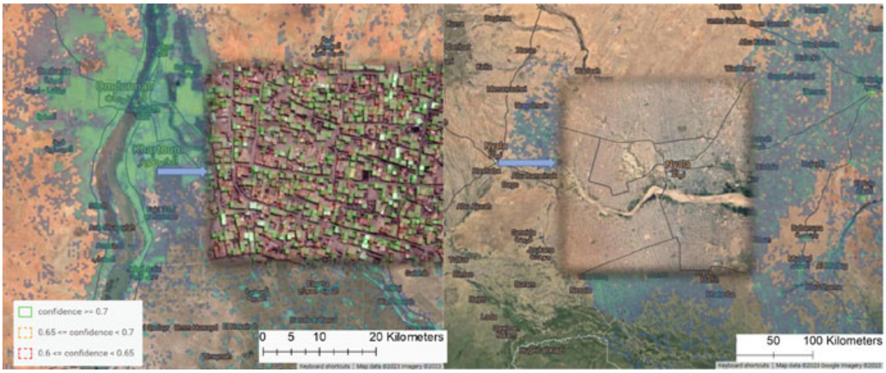

Fig. 1.5 Google Open Buildings of a deprived area of Khartoum, Sudan (right), and missing coverage of Google Open Buildings in conflict-impacted areas such as Nyala, Darfur, Sudan (right). (Google Building Source Sirko et al. 2021)

(c) Access to computational power and high-speed internet connection limits access to the advancements in cloud computations and generally AI-based models in the Majority World.

(d) Limited inclusion of local stakeholders in the development of mapping applications (limiting the relevance of the information). Much of the EO-based mapping is done without the inclusion and partnership with stakeholders living in mapped areas.

Therefore, the book focuses on EO-based innovation, with a focus on applications. It highlights advances in the current state of the art of using AI and EO-based algorithms to measure and characterize urban and environmental inequalities from various angles (environmental, demographic, socio-economic, technological, hazards, climate change). It emphasizes the novel use of existing datasets to contribute to this task as well as innovative applications. These applied studies tackle urban and environmental inequalities using EO that link methodological innovations to provide locally relevant information to users and show how EO can create societal impacts. The presented contributions focus on the applications of EO for filling data gaps in the Majority World:

- Mapping multiple deprivations (including slums, informal areas) (e.g. infrastructure inequalities) from space.
- Climate change and environmental challenges.
- The use of large-scale free and open data to better understand urban inequalities (i.e. Copernicus data, building footprints, built-up and population information).
- Mapping the morphology and dynamics of cities, sub-urban and peri-urban areas with EO.
- Mapping the missing population in data-scarce areas.

1.2 Overview of Contributions

In this book, we aim to provide an outlook on how EO data can provide tailored solutions to information needs in urban and urbanizing areas of the Majority World. The selected contributions provide methodological and applicational pathways in support of sustainable development, specifically, supporting the monitoring of the 17 Sustainable Development Goals. The book captures a variety of innovative methods, novel datasets and application areas to unravel different dimensions of urban inequalities using EO and geospatial data. We include contributions that operate in different analysis levels and from local to national and global scales.

At the *global level*, Melchiori et al. (Chap. 2) present a novel approach to integrate EO datasets derived from Copernicus and Landsat programs with social sensing information (broadband quality) to unravel digitization and urbanization in a joint manner. Their work sheds light on the emerging form of deprivation, particularly in the Majority World, that of uneven access to digital infrastructure. Ehrlich et al. (Chap. 3) investigate societal inequalities through the use of satellite-measured night-time lights, population density and information. Notably, they demonstrate in an exemplary way how inequalities are reflected in LMICs through the lack of access to electricity. Lamson-Hall and Angel (Chap. 4) tackle the topic of urban spatial connectivity of streets and roads using an EO-derived dataset – the Atlas of Urban Expansion. Their work documents the evolution and changes in road capacity and connectivity over a large sample of 200 cities, which is globally representative. Their results highlight the uneven development of arterial road connectivity in developing countries compared to the global average. A better understanding of the structure and form of informal settlements is crucial to foster a sustainable urban future and evidence-based policymaking. Samper et al. (Chap. 5) utilize data from over 30 cities from the Atlas of Informality, along with EO-based settlement layers, to map the spatial distribution of informal settlements worldwide. Their findings reveal that 60% of the inhabitants of informal settlements reside in peri-urban zones beyond municipal administrative boundaries, which has critical implications for urban planning and policy actions.

A significant part of the contributions focuses on unravelling dimensions of *urban deprivation* using geospatial approaches. The Integrated Deprived Area Mapping System (IDEAMAPS) was established as a global network in 2020 and aims at integrating and overcoming the limitations of four "slum" mapping traditions: citizen field mapping, census and survey data aggregation, manual digitization of satellite imagery and computer modelling. To allow for routine and accurate mapping of deprived areas, IDEAMAPS developed the Domain of Deprivation Framework, identifying relevant geospatial and EO data for urban deprivation mapping and analysis. Zamora et al. (Chap. 6) deploy the IDEAMAPS' deprivation framework in a pilot case study and discuss the current and future integration with satellite and satellite-derived datasets to better understand spatial inequalities. Vanhuysse et al. (Chap. 7) provide an operational, low-cost EO-based framework to model and map deprivation at city-wide scales. They deploy their framework on three case studies and two scales, the city-wide one (mapping deprivation) and the intra-urban one (characterizing deprivation). Pratomo et al. (Chap. 8) demonstrate the impact of expert background knowledge in the conceptualization of slum mapping through a novel object-based image analysis application in Jakarta, Indonesia. Their work emphasizes that different sources of uncertainties are rooted in the different conceptualizations of what a slum is, and simplistic rule-based approaches are unable to capture these systematic uncertainties for the task of slum detection. The potential of EO and its coupling with *computer vision* to contribute to a better understanding of deprivation is far from saturated. For instance, Debray et al. (Chap. 9) present an innovative application for mapping informal settlement graveyards using very high-resolution imagery and deep learning algorithms, in Lima, Peru. Their rationale is informed by the ever-changing informal urban transformation processes, such as housing invasions on burial grounds, as well as potential health risks that can emerge.

Pedrassoli et al. (Chap. 10) focus on the *temporal aspect* of deprivation mapping, which is often neglected in the literature. Using a vast time period of 36 years, they depict the pace and space of poverty expansion in Brazilian cities, using the cloud computing functions of Google Earth Engine. Their findings are striking as in some cities: The expansion of slums corresponded to more than 50% of its total urban growth. The massive urbanization has further deteriorated food security, particularly in LMICs, and one of the attributable factors is the conversion of agricultural land to built-up areas. Kebede and Rienow (Chap. 11) employ an EO-based analysis over a 15-year period in Addis Ababa and demonstrate that both grassland and croplands showed negative trends, while built-up land increased by extremely high rates. Their work has strong implications for urban development strategies and the integration of urban agriculture to support sustainable practices.

Salazar et al. (Chap. 12) demonstrate how satellite and open geospatial data can be used to retrieve socio-economic information such as gross domestic product estimates at intra-urban scales using innovative statistical approaches in the city of Medellin, Colombia, as a case study. Haas (Chap. 13) discusses the use of ecosystem services and landscape metrics to measure socio-ecological well-being in deprived urban areas in the Majority World. The study highlights the challenges in obtaining reliable data and recommends using freely available EO products. It emphasizes the importance of differentiating between ecosystem functions and services, incorporating spatial and temporal aspects and considering beneficiaries for accurate assessment. Abascal et al. (Chap. 14) demonstrate the urgent need for a reliable estimate of the number of citizens living in slums, in order to implement evidence-based decision-making and allocate resources adequately. The authors propose an approach that combines satellite imagery with in situ data collected through citizen science to produce gridded estimates of slum populations, highlighting the diversity of population distribution patterns within and between slums of the same city.

1.3 Outlook and Reflections

While the contributions of this book to better understand urban inequalities in the Majority World employed a wide variety of data, methods and case studies, the field is far from saturated. The potential of EO and geospatial data to act as data creation and modelling tools is only now realized by researchers, practitioners and stakeholders alike. While this book was the first effort to compile the breadth and width of recent and diverse developments, it also acts as a call to the community to devote more efforts to the field.

One of the largest challenges that often lead to bottlenecks when using EO data in the Majority World is the lack of good quality, curated datasets. This data scarcity can be discouraging when modelled EO outputs have large uncertainties as they are often trained with unreliable labels. While this is important to acknowledge, it should not be seen as a dead end. Engaging with local communities and stakeholders can lead to a data richness of unprecedented quality. Citizen science is a great pathway to fill these initial data gaps. Moreover, by collecting data through community engagement, we ensure that the most vulnerable urban residents have a direct say in the various research development stages – they are not numbers to be modelled, but the very essence of why such research takes place. They can directly impact what and how the research is performed, and how its results should be disseminated.

Moreover, in general, studies done by researchers of the Minority World do not sufficiently understand the information needs and capacity demands of the Majority World, especially related to user requirements and ethical perspectives. Attempting to measure and map socio-economic phenomena through remote sensing is fundamentally different from extracting bio-physical parameters. Here, the value of pixels does not necessarily or primarily reflect physical attributes (i.e. land cover) but phenomena difficult to define and disentangle, such as deprivation. This shift towards social sensing is far from well-defined in the field; concepts are blurred, frameworks are only now developing, and results can be challenging to interpret, come with uncertainties and can support or stigmatize communities depending on the way they are presented. This is an issue the remote sensing community suffers in a broader sense, the strong disconnection of research outcomes with applicable practices and connections to relevant stakeholders. While this is disappointing to see in the physical domain, it is disheartening to observe when it comes to the socio-economic territory. The urge to link, develop and disseminate our research in a joint effort with other disciplines, local communities and authorities is more important than ever as it is devoid of purpose otherwise.

Another aspect that is largely untouched is the geographic focus of the field. Most urban remote sensing studies in the Majority World focus on the primary cities. The primary reason is that the availability of data (e.g. training data) is overwhelmingly higher in large urban centers. It is then tempting to use primary cities as case studies, as training and validating models become easier. However, at the same time, very little is known about secondary cities, other than that they are rapidly expanding, and that some of them will be megacities of tomorrow. It is then imperative that we allocate more resources to investigate them, which will, in effect, make the use of EO-based approaches ideal to use as they have wide coverage and temporal resolution. Moreover, models can be transferred with reasonable success thanks to the advent of well-generalizable deep learning techniques.

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Part I
Global Analysis of Geospatial Datasets with a Focus on the Majority World

Chapter 2
Integration of Remote and Social Sensing Data Reveals Uneven Quality of Broadband Connectivity Across World Cities

Michele Melchiorri, Patrizia Sulis, Paola Proietti, Marcello Schiavina, and Alice Siragusa

Abstract Urbanisation and digitalisation are two of the megatrends characterising contemporary human society. Digital broadband access is an essential enabler, and despite its large growth potential, it can differ across territories. Taking a comparative approach from a global perspective, this chapter studies the relationship between urbanisation and digitalisation by looking at the quality of broadband access in urban centres using geospatial data processing. It is based on a combination of open and free data sourced from earth observation (Copernicus and Landsat programmes) to map and classify human settlements, with social sensing data to assess broadband quality with open data released by Ookla® at the grid level. We analyse the database in a stratified way to identify whether urban centres in high-income countries are better in terms of broadband connectivity compared to those in developing economies; whether urban centre population size is an advantage in the regions of the world where connectivity is low; and whether urban centres that have experienced stronger population growth in recent years display an advantage in terms of digitalisation. This work sheds light on the nature and type of deprivation related to uneven access to infrastructure, especially digital ones. The results indicate significant geographical and income disparities in terms of internet download speeds across the world. The performance of mobile and fixed broadband connectivity is different, and mobile connectivity offers a higher performance alternative to fixed networks in less affluent countries.

Keywords Inequality · Broadband · Urban · Population · Access · Development · SDGs

M. Melchiorri (✉) · P. Sulis · P. Proietti · M. Schiavina · A. Siragusa
European Commission, Joint Research Centre, Ispra, Italy
e-mail: michele.melchiorri@ec.europa.eu

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2.1 Introduction

Inequality is a relational concept concerning the difference in opportunities and outcomes between and within groups and territories. The Agenda 2030 set several ambitious goals to reduce inequalities and disparities across the world. In particular, Sustainable Development Goal 10 (SDG10) calls for a reduction in inequality to achieve sustainable development from the economic, social, environmental, and institutional points of view (European Commission. Directorate General for International Partnerships 2021). Together with climate change and other major anthropogenic and natural conditions, digitalisation contributes to the creation of a new generation of inequalities not previously considered. In this respect, the SDG17 aims, among other aspirations, to enhance the use of enabling technologies and to contribute to the reduction of inequality of opportunity (UN Department of Economic and Social Affairs 2015).

A growing literature has found that digital technologies reduce information friction, trade costs, and access to services (Broadbent and Papadopoulos 2013; Freund and Weinhold 2004; Zhou et al. 2022) and contribute to increasing the number of workplaces (Stenfeldt and Andersson 2016; Katz et al. 2010). Instead, there is less consensus on the relationship between broadband and economic growth, as well as broadband and population growth, especially when the endogeneity of the broadband process is taken into consideration (Mahasuweerachai et al. 2009). The availability, quality, and accessibility of digital technologies and the opportunities they offer for access to services and to work in a knowledge economy are two intertwined elements (European Commission. Directorate General for International Partnerships 2021). Therefore, these key conditions should be met for digital technologies to have a positive impact: the supply of adequate infrastructure (i.e. the hardware of single households and firms) and the digital literacy that permits widespread use of digital technology at both basic and highly advanced levels (Steyaert 2002).

From the infrastructural point of view, the expansion of broadband technology is significantly driven by private-sector firms focused on developing infrastructure and selling subscription services where the number of potential customers is higher, potentially strengthening pre-existing inequalities across territories and population groups. On the other hand, according to the political priorities of the administrations, recent years have witnessed the deployment of international, national, and local programmes and funds which might either exacerbate inequalities (Soja 2009) or reduce the digital divide (Graham 2005; Valenzuela-Levi 2021; Graham and Mann 2013), and favour agglomeration economies or convergence (Picot and Wernick 2007; van Winden and Woets 2004).

Since the net effect is very heterogeneous across countries, this work centres on deepening evidence on the geographic distribution of broadband availability and quality, together with an improved understanding of the relationship between broadband quality and income, population, and population growth. This chapter, therefore, aims to answer the following three research questions: (1) Are the urban centres

(UCs) located in higher-income countries also performing better both in mobile and fixed broadband quality? (2) Do UCs with a higher population today perform better in broadband quality? (3) What is the relationship between population dynamics and broadband speed in UCs?

Previous studies analysed broadband connectivity from an infrastructure standpoint using official data with a low disaggregation scale (e.g. at the country level), also focusing on the rural–urban divide in certain specific countries (Mahasuweerachai et al. 2009; Arribas-Bel 2014; Otioma et al. 2019) or regions of the world (Perpiña Castillo et al. 2021). In many cases, remote sensing technology was used to directly proxy inequality (McCallum et al. 2022).

This study focuses on a spatial feature that is not directly observable by satellite sensors and presents several innovations compared with most of the previous work on the geographic distribution of digital infrastructure.

First, it combines three different data sets sourced from both traditional and emerging data: (a) remote sensing data combined with official population statistics to delineate the urban centres of the planet along with their population dynamics (Global Human Settlement Layer – GHSL – data); (b) traditional data on countries and territories borders (Global Administrative layer, GADM) and income by country (World Bank, WB); and (c) social sensing global data on broadband speed collected through the Speedtest® by Ookla® application.

Second, this work analyses broadband accessibility and performance in a specific geographical realm: the urban centres. Urban centres are often identified as cities in common terminology and are part of the degree of urbanisation global definition of cities as settlements (European Commission, Statistical Office of the European Union 2021). Contemporary human society is remarkably urban, and urban centres are the most densely populated places on Earth. Urban centres occupy just 1% of the world's land area but account for more than 60% of its population (Dijkstra et al. 2020) and are responsible for 50% of anthropogenic air pollution (Crippa et al. 2021). Therefore, our investigation of broadband inequality targets the most innovative, economically vibrant, and service-endowed places on Earth, where the best conditions for broadband connectivity should be present. Previous work in the European Union showed how urban areas are generally well covered by spatial information on broadband quality (Proietti et al. 2022). This work also applies the GHSL approach of data integration to produce new comparable urban indicators with global coverage (Melchiorri 2022).

Third, this work analyses continuous values of average speed and also broadband classified in different speed classes, avoiding the common binary approach of the literature looking at the digital divide ('available', 'not available'). It, thus, broadens the focus on digital differentiation, which includes more information on the quality of broadband provision (Riddlesden and Singleton 2014). This aspect is particularly informative given that, according to Alvin and Heidi Toffler, economies of speed are a very important dimension and can replace economies of scale (Riddlesden and Singleton 2014; Toffler and Toffler 1994).

2.2 Data and Methods

2.2.1 Global Human Settlement Layer Urban Centres

The United Nations Statistical Commission designated urban centres (UCs) as one of the classes of the definition of urban areas adopted for international statistical comparison (UN. Statistical Commission 2020). UCs are defined according to a set of population-based rules, as described in the degree of urbanisation methodology (European Commission, Statistical Office of the European Union 2021). This methodology identifies UCs as contiguous cells (i.e. sharing a pixel side) of 1 square kilometre having a population density of at least 1500 inhabitants per km^2 of land or at least 50% of land surface covered by built-up areas, which altogether add up to 50,000 inhabitants or more (Dijkstra et al. 2020). At the basis of UCs' delineation, there is an extensive use of optical and radar earth observation data from Copernicus Sentinel satellites to map built-up surfaces at a global scale. Extraction of built-up surfaces from satellite data leverages a global Sentinel-2 mosaic and a combination of multiple training datasets (mainly building footprints datasets). The resulting Global Human Settlement Layer Built-up surface grid (GHS-BUILT-S) layer is used as input to produce a population grid Global Human Settlement Layer Built-up population grid (GHS-POP) by means of a dasymetric disaggregation of population counts from census data targeting a built-up surface density distribution. The dataset built to conduct this study consists of circa 9000 UCs, extracted from the Global Human Settlement Layer (GHSL) classification in 2020 Global Human Settlement Layer Built-up settlement classification grid (GHS-SMOD R2022 (Schiavina et al. 2022a)), the implementation of the degree of urbanisation method (European Commission. Joint Research Centre 2022) is based on the GHS-POP R2022 (Schiavina et al. 2022b) for 2020. The UCs' boundaries obtained are characterised by measuring their surface and population size in different years (2000–2020, in 5-year intervals), and by assigning the country or territory and the income group they belong to through zonal statistics processing in the Geospatial Information System (GIS) environment. Country data are assigned according to the Global Administrative layer (GADM 3.6 https://gadm.org/index.html), and population count is calculated using the GHS-POP R2022 layers for the respective year. According to figures and thresholds for gross national income (GNI, World Bank, NY.GNP.ATLS.CD), each country and territory is assigned to an income group, ranging from the low income (i.e. lower GNI) to the high income (i.e. higher GNI), with two intermediate groups: lower middle and upper middle.

We defined six UC population size classes for UCs, ranging from the extra small class (XS, 50–100 K people) to megacities (more than 10 M people) with the following intermediate classes: small (S, 100–250 K people), medium (M, 250 K–1 M people), large (L, 1–5 M people), extra large (XL, 5–10 M people).

2.2.2 *Ookla® Global Fixed and Mobile Network Performance Maps*

Data on broadband access and performance are provided by Ookla®. The data contain spatial information regarding global fixed broadband and mobile (cellular) network performance metrics at the grid level (with a grid size of 18 arc-seconds). Information on network performances is collected through the Speedtest® by Ookla® application, as a voluntary social sensing procedure, and aggregated into each square of the grid. Download speed, upload speed, and latency are averaged for each tile. For this work, the data employed refer to the last quarter of the year 2021 (October–December) and include information on (1) the average download speed of all tests performed in the tile, in kilobits per second, and (2) the number of tests taken by users in the tile. For each tile, data are available on (1) the fixed network performance for tests taken from a non-cellular connection type (e.g., Wi-Fi and Ethernet) and (2) the mobile network performance for tests taken from a cellular connection type (e.g., 4G LTE and 5G NR). To support this study, we prepared a dataset combining the GHSL UC with Ookla® data (Fig. 2.1). Tiles are spatially linked to the geographical boundaries of each urban centre to extract the corresponding data associated with population and income. Following the spatial link, we observed that of the 9119 UCs in the GHS-SMOD 2020 dataset, 988 UCs (~10%) have no associated information on fixed networks, and 684 UCs (~8%) have no associated information on mobile networks.

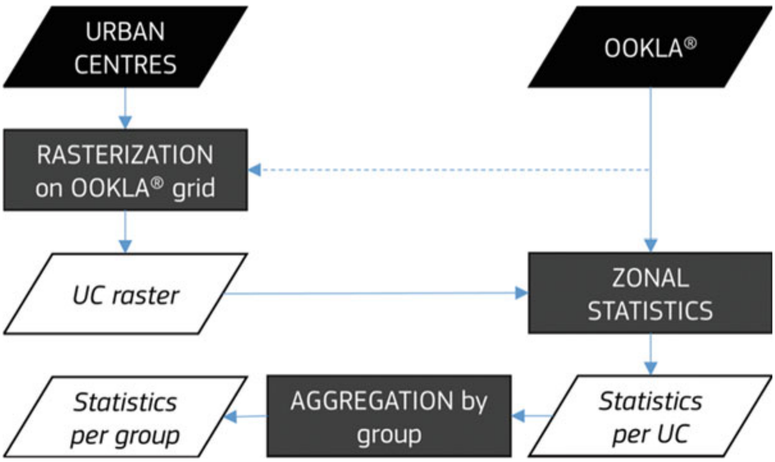

Fig. 2.1 Processing flowchart: the boundaries of urban centres (UCs) are rasterised on a grid co-registered to the Ookla® network performance raster. The two rasters are then combined in a zonal statistic geo-processing to obtain the average performance per urban centre. Results are finally aggregated at different scales (groups: countries, SDG regions, and income group), weighting UCs by the number of Ookla® data

A visual inspection of the geographic distribution of the data showed that missing data relate to small UCs in Southeast Asia and Africa. Furthermore, some UCs are associated with few tiles within their geographic boundary, only partially covering the UCs' entire surface and concentrated in a specific area (no isolated tiles). The lack of data for some areas in the UCs may be related to different aspects, for example, the location of urban functions in the UC (i.e. residential or services areas), the difference in income and affluence across areas in the city, etc. For fixed broadband and mobile networks, the following attributes have been calculated for each UC: (1) the average download speed (Mbps); (2) the number of tests (sum); (3) the speed class. Average speed is weighted by the number of tests performed in each UC to consider the uneven geographic distribution of measurements available in some UCs (therefore balancing out high-speed measurements with a low number of tests). Speed has been classified into three groups according to the standard approaches to average download speed (Spadafora 2022; Feijóo et al. 2018), as follows: from 0 to 30 Mbps (web surfing, e-mail, social networking, and moderate video for one or two devices); from 30 to 100 Mbps (multiple devices and online multiplayer gaming and 4 K streaming); and over 100 Mbps (more devices and sharing large files and live streaming video). The same indicators have been computed by aggregating UCs by country, country-income group, and UC size class.

2.3 Results

This section presents the results of the broadband indicators compiled for urban centres and aggregated per GADM entity, by geographical region of the world, by income group, and by population. With these results, we propose a multi-scale analysis of broadband connectivity for fixed and mobile networks. The first part of this section presents the results aggregated per country, followed by a more disaggregated analysis of urban centres.

2.3.1 Cities in 125 Countries Fall Below the Global Median Download Speed

The global median download speed from fixed lines in urban centres for 2021 is 86.45 Mbps. This value has been calculated by aggregating the 9119 urban centres for which data are available by GADM entity. Figure 2.1 displays the geographic distribution of the 125 GADM entities that fall below the median speed (in shades of red). The map clearly shows that the entire African continent is below the global median speed, with countries like the Central African Republic and Eritrea accounting for a median speed below 3 Mbps and seven other countries not achieving a median of 7 Mbps (i.e. South Sudan, Sudan, Comoros, Niger, Equatorial Guinea,

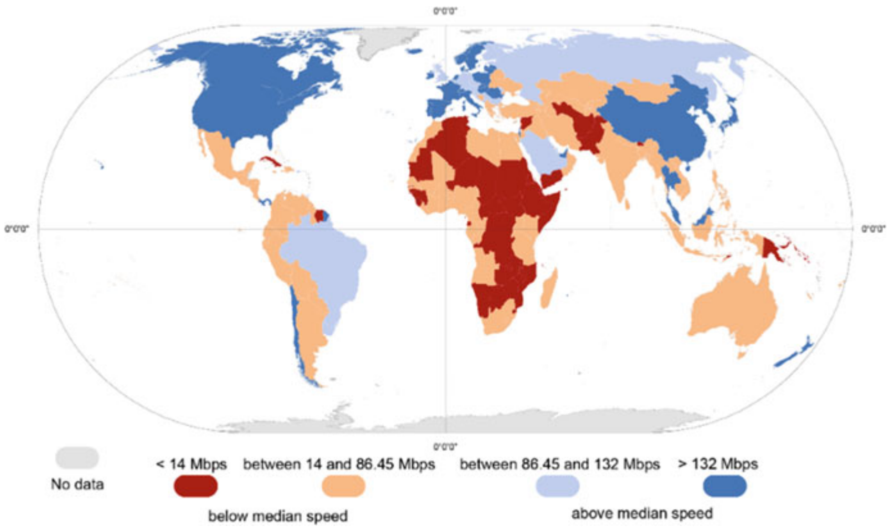

Fig. 2.2 Map of GADM entities above (shades of blue) and below (shades of red) the global median fixed line download speed of 86.45 Mbps in 2021. Dark colours highlight the tails of the distribution showing the lowest and highest quintiles

Guinea-Bissau, and Chad). Overall, 50 African countries have a median speed below 30 Mbps. On the contrary, the highest median speed is reached in Reunion (> 100 Mbps), South Africa (51 Mbps), Côte d'Ivoire (43 Mbps), and Ghana (38 Mbps). Another geographical zone where median fixed broadband connectivity falls below the global median value ranges across the Middle East, Central Asia, and South East Asia. Places such as Turkmenistan (2.8 Mbps) and Afghanistan (5 Mbps) have the lowest median speed in the region. Despite falling below the global median, UCs in other developing economies in this region are well positioned in terms of download speed, i.e. Philippines (67 Mbps), India (70 Mbps), and Vietnam (77 Mbps). In the remaining regions of the world, several countries fall below the global median speed (i.e. those in Latin America and the Caribbean, Eastern Europe), yet broadband download speed is mainly above 10 Mbps (excluding Cuba <5 Mbps) (Fig. 2.2).

2.3.2 Download Speed Varies by Region of the World and Income Group

About 40% of urban centres have Internet connectivity exceeding 100 Mbps, whereas the remaining 60% are equally split between the slowest connectivity class (0–30 Mbps) and the intermediate (30–100 Mbps). However, the geographical distribution of these classes shows a strong regional diversification. More than 70%

of the urban centres with connection speeds below 30 Mbps are between Africa (42%) and Central and Southern Asia. In Sub-Saharan Africa, 88% of the urban centres fall in the 0–30 Mbps class. This percentage reduces to 76% in Northern Africa and Western Asia and goes down further to 41% in Central and Southern Asia. In Latin America and the Caribbean, about 23% of the urban centres belong to the 0–30 Mbps class, whereas only 13% of the urban centres in Eastern and Southern Asia are in this class. None of the urban centres in Europe or North America has an average speed between 0 and 30 Mbps. The class of intermediate download speed includes 77% of the urban centres in Australia and New Zealand, 58% of the urban centres in Central and Southern Asia, 43% of the centres in Latin America and the Caribbean, and about one-third of the urban centres in Europe. Moreover, 11% of the urban centres in Eastern and Southern Asia, Oceania, and Sub-Saharan Africa have an average download speed between 30 and 100 Mbps. Most urban centres in Eastern and Southern Asia (76%), Europe (63%), and North America (100%) are in the highest speed class (> 100 Mbps). One-fifth of the urban centres in Australia and New Zealand and over one-third of the urban centres in Latin America and the Caribbean belong to this class. The three cities in Sub-Saharan Africa that achieve a speed above 100 Mbps are all located in Reunion (Table 2.1).

Analysis by income classes clearly shows a high correlation between connectivity and affluence (Table 2.2). Urban centres in high-income countries (HICs) have significantly better connectivity than all other classes. More than 88% of urban centres in HICs belong to the >100 Mbps class, and another 12% of the class 30–100 Mbps. Conversely, more than 92% of the UCs in low-income countries (LICs) belong to the 0–30 Mbps class. Eighty-four per cent of the UCs in

Table 2.1 Share of urban centres per region of the world and per speed class

Region\speed class	0–30 Mbps (%)	30–100 Mbps (%)	> 100 Mbps (%)
Central and Southern Asia	34	47	1
Eastern and Southern Asia	14	12	57
Europe	0	16	19
Latin America and the Caribbean	9	17	9
Northern Africa and Western Asia	22	5	1
Sub-Saharan Africa	20	2	0
Northern America	0	0	12

*Australia and New Zealand, and Oceania <1% per class

Table 2.2 Share of urban centres per income group and per speed class

Income class/speed	0–30 Mbps (%)	30–100 Mbps (%)	> 100 Mbps
High-income countries (HICs)	0.2	11.6	88.2
Upper-middle-income countries (UMICs)	17	23	61
Lower-middle-income countries (LMICs)	51	48	1
Low-income countries (LICs)	92.4	7.3	0.4