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DLR

Census versus morphological slums derived from EO data - A spatial comparison of locations and structures for two megacities in Brazil

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Abstract

Today more than half of the global population lives in cities and until 2050 this proportion is expected to rise to 66%. This rapid urbanisation puts pressure on the cities and policy makers to ensure the provision with basic services and infrastructure. Furthermore, a growing native population and the migration into the cities leads for example to urban sprawl or the emergence as well as expansion of slums. It is estimated that around one billion people live in slums. In order to understand the inherent dynamics of these settlements as well as to monitor and evaluate policies, there exists an utter necessity of up-to date data with an areawide coverage. In contrast to this need, consistent spatial or statistical data are often lacking or obsolete. The present thesis classifies slums in the metropolitan region of São Paulo (Brazil) based on morphological characteristics. The applied parameters are summarized and presented in a slum ontology which facilitates the comparability as well as transferability of the data. Furthermore, the average building density as well as building height are determined for every slum.
In general, slums can be described as heterogeneous, complex and context-specific urban phenomenons. In order to examine the influence of different definitions, parameters and methods on the classification of slums and their spatial distribution, the created dataset together with a similar dataset for Rio de Janeiro are compared to the spatial data of the demographic census of Brazil. The analyses are executed on three dimensions: area, time and location. The results show that the geography and structures of the slums differ depending on the applied criteria and classification method. Moreover, the present thesis displays differences between the two cities and concludes that they are mainly resulting from historic development and due to topographical characteristics. In essence, the slums classified by the different methods should not be seen as the complete mapping of the existing slums in São Paulo and Rio de Janeiro rather do they represent a snapshot of the cities and their settlements showing predefined criteria in the moment of classification.

Zusammenfassung

Aktuelle Schätzungen zeigen, dass die Hälfte aller Menschen in Städten lebt, wobei die Zahl bis zum Jahr 2050 bei 66% liegen soll. Die schnelle Urbanisierung löst Druck auf die Städte sowie politische EntscheidungsträgerInnen aus, um eine Versorgung der urbanen Bevölkerung mit grundlegender Infrastruktur zu gewährleisten. Sowohl das natürliche Wachstum der Stadtbevölkerung als auch Migration haben mitunter eine Ausdehnung der urbanen Fläche sowie die Entstehung und Ausbreitung von Slums zur Folge. Die Zahl der Menschen, die in Slums leben, wird auf etwa eine Milliarde geschätzt. Trotz gebotener Notwendigkeit sind aktuelle, vollständige räumliche oder statistische Daten zur Ausbreitung oder Größe dieser Siedlungen oft nicht vorhanden. Diese Daten sind wichtig, um ihre Dynamik besser verstehen sowie die Wirkung von Programmen einschätzen zu können. In der vorliegenden Arbeit werden Slums in der Metropolregion São Paulo (Brasilien) anhand morphologischer Merkmale durch die Anwendung visueller Interpretation von Sa-

tellitenbildern klassifiziert. Zur Erleichterung der Vergleichbarkeit sowie Übertragbarkeit der Methode werden die verwendeten Parameter in einer Slum-Ontologie zusammengefasst und präsentiert. Außerdem werden die durchschnittliche Bebauungsdichte sowie Gebäudehöhe für die einzelnen Slums bestimmt.
Insgesamt gelten Slums als heterogene, komplexe und kontextspezifische urbane Phänomene. Daraus lässt sich ableiten, dass Slum-Klassifikationen, die auf unterschiedlichen Definitionen und Parametern beruhen, unterschiedliche Ergebnisse generieren. Um dies zu prüfen, vergleicht die vorliegende Thesis die generierte Klassifikation für São Paulo sowie einen Datensatz für Rio de Janeiro, der auf einer ähnlichen Methode beruht, mit den räumlichen Daten zu Slums des brasilianischen demographischen Zensus aus dem Jahr 2010. Die Klassifikationen werden auf den drei Ebenen Fläche, Zeit und Lage verglichen. Die Ergebnisse zeigen, dass sich die Geographie und Struktur der Slums je nach angewandter Definition, Methode und Parametern unterscheiden. Außerdem werden Unterschiede zwischen den beiden Megastädten aufgezeigt, die teilweise auf die historische Entwicklung der Stadt sowie die Topographie zurückzuführen sind. Zusammenfassend lässt sich konstatieren, dass die jeweiligen Klassifikationen keine komplette Abbildung der Slums in São Paulo und Rio de Janeiro darstellen, sondern eine Momentaufnahme der Siedlungen, die den vordefinierten Parametern zur Zeit der Klassifikation entsprechen.

Resumo

Dados atuais mostram que mais da metade da população global mora nas zonas urbanas e, até o ano de 2050, a expectativa é que essa proporção cresça para 66%. Essa urbanisação acelerada acaba por exercer pressão sobre as cidades e as gestões políticas para garantir o abastecimento da população urbana com serviços básicos, inclusive de infraestrutura. Além do crescimento natural da população nas cidades, a migração para os grandes centros contribui por exemplo na expansão da área urbana, como também no surgimento e crescimento das favelas. Estima-se que cerca de um bilhão de pessoas no mundo morem em favelas. De modo a compreender as dinâmicas inerentes a esses assentamentos, bem como monitorar e avaliar a efetivação de políticas na área, faz-se necessário o levantamento de dados espaciais ou estatísticos atualizados sobre a extensão desses locais. Porém, apesar da necessidade, esse levantamento muitas vezes é obsoleto ou inexistente. Neste trabalho, as favelas da região metropolitana de São Paulo (Brasil) são classificadas com base em características morfológicas através da metodologia de interpretação visual de imagens de satélite. Os parâmetros aplicados estão resumidos e apresentados numa ontologia sobre favelas, que facilita a comparabilidade e a transferibilidade de dados. Além disso, a densidade média da construção e a altura média dos prédios são determinados para cada favela.
No geral, favelas são heterogêneas, complexas e cada uma se insere em um contexto específico. Decorrente disso, classificações de favelas que usam variadas difinições e parâmetros podem gerar resultados diferentes. Com o intuito de examinar os efeitos de se usar diferentes metodologias de classificação, essa pesquisa de bacharelado compara a base de

dados desenvolvida para São Paulo juntamente com a desenvolvida de forma similar para o Rio de Janeiro com os dados espaciais do censo demográfico do Brasil. As análises são executadas a partir de três dimensões: àrea, tempo e localização. Os resultados mostram que a geografia e as estruturas das favelas diferem de acordo com os critérios aplicados e métodos de classificação. Além disso, o presente trabalho apresenta diferenças entre as duas cidades, as quais podem ser atribuídas ao processo de desenvolvimento histórico e às características topográficas específicas. Em suma, pode-se constatar que as classificações respectivas não representam um mapeamento completo das favelas de São Paulo e Rio de Janeiro, mas um instantâneo dos assentamentos que correspodem aos critérios pré-definidos no momento da classificação.

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List of abbreviations

CBD	Central Business District
DLR	German Aerospace Center
EO	Earth Observation
GIS	Geographic Information System
GSO	Generic Slum Ontology
GUF	Global Urban Footprint
IBGE	Instituto Brasileiro de Geografia e Estatística
NASA	United States National Aeronautics and Space Administration
OBIA	Object-Based Image Analysis
SDGs	Sustainable Development Goals
SAR	Synthetic Aperture Radar
RS	Remote Sensing
USGS	U.S. Geological Survey
VHR	Very High Resolution
VI	Visual Interpretation

1 Introduction

Currently, more people live in cities than 1960 lived in the entire world (Davis & Kurz-Scherf, 2011). In other words, in 2015 more than four billion people, which is over half of the global population, lived in urban agglomerations (United Nations Economic and Social Council, 2017). This proportion is expected to rise in the next decades to a global urban population level of 66% by 2050 (United Nations, Department of Economic and Social Affairs (UN DESA), Population Division, 2014).
Various factors such as more employment opportunities in cities, crop loss due to infertile soils and weather dependency, the agricultural industrialisation (Taubenböck & Kraff, 2015) as well as land grabbing (Zoomers, van Noorloos, Otsuki, Steel & van Westen, 2017) are drivers of this accelerated urban growth.
This rapid urbanisation puts pressure on the global cities and policy makers to ensure the provision with adequate shelter, basic services such as water and energy supply, infrastructure, sanitation system as well as waste management (Cohen, 2006). Furthermore, the combination of a growing native population, an increasing urban migration and a lack of sufficient housing leads to urban sprawl, the emergence as well as the expansion of slums (Cohen, 2006; United Nations Economic and Social Council, 2017). Today, around one billion people are living in slums. The absolute numbers are not expected to decline - at the contrary, annually six million people add to the number of slum dwellers which is almost 50% of the total urban growth (UN-HABITAT, 2010, 2012).

1.1 Motivation to this study

In contrast to the increasing numbers of slum dwellers, consistent data such as statistics and maps are often obsolete, fragmentary, in a low temporal resolution or even inexistent (Herold, Goldstein & Clarke, 2003; Hofmann, 2001). This data is important to understand the complexity as well as the dynamics of urban processes (Esch et al., 2012) and to achieve the recognition of the slum settlements as an integral part of the formal city (Kohli, Warwadekar, Kerle, Sliuzas & Stein, 2013). Furthermore, this data as well as the correct understanding are necessary for the application and monitoring of convenient policies, such as goal 11 from the 17 Sustainable Development Goals (SDGs) by the UN to "[...] ensure access for all to adequate, safe and affordable housing and basic services and upgrade slums" by 2030 (United Nations Economic and Social Council, 2017).
Besides statistical data, consistent geographic information on the location, the expansion as well as the structure of urban areas and their slums are vital. This can be achieved with different approaches, such as a head-count method (e.g. demographic census) or by using Remote Sensing (RS) techniques.

The lack of good-quality, up-to-date spatial data together with the gap in research comparing different methods of slum mapping, were the primary motivation for this study. The provision of a consistent spatial dataset created via RS techniques by the German Aerospace Center (DLR) for Rio de Janeiro (Fricke, 2015) as well as the available census data for Brazil, including spatial information, favoured this decision.
In order to extend this comparison as well as to generate a further consistent dataset, using the methodology by Fricke (2015), the city of São Paulo was chosen as a second megacity in the Global South. Further details about the decision process are given in chapter 4 and 5.

1.2 Research questions and structure of this study

There does not exist a universal definition for the term slum neither based on qualitative nor on quantitative measures. This is partly due to the complexity and heterogeneity of this urban phenomenon (e.g., Kuffer, Pfeffer, Baud & Sliuzas, 2013; Taubenböck & Kraff, 2015). Furthermore, slums are relative and context-specific (Gilbert, 2007). Consequently, it can be reasoned that classifications based on different definitions of the term as well as different parameters lead to different results concerning the geography and structure (Wurm & Taubenböck, 2017). The two main contexts applied in this study are on the one hand the mapping of slums based on physical characteristics solely by using Earth Observation (EO) data. On the other hand, demographic census information, that include qualitative factors such as illegality of the settlements or adequate supply with basic services, which are not measurable via RS, are analysed. In essence, the present thesis is focusing on the following two questions:

1. How do the applied definitions and parameters on slum mapping influence the results concerning the geography and structure?
2. What are the differences between the census and morphological slums of Rio de Janeiro and São Paulo and what could be possible reasons?

These two main questions will be examined on the three dimensions: area, time and location in combination with the structural parameters building density and height.
The study at hand is structured into seven chapters with the aim to give a comprehensive understanding of the complex phenomenon of slums as well as the applied data and methodologies, to finally analyse and discuss the results of the comparison. In chapter 2, the term slum and its morphology will be defined and brief information about slums in Brazil, especially Rio de Janeiro and São Paulo will be given. Additionally, the state of the art of research on RS and slums will be presented. In chapter 3, the utilized EO data and details about the Brazilian demographic census are described. Moreover, the applied methodologies on the selection of the study sites, the processing of the data for further analysis, the classification of the slums via Visual Interpretation (VI) of EO imagery and the following analyses are explained. Chapter 5 will present the results of the study and

its data comparison. In chapter 6, the results of the study will be discussed. Finally, in chapter 7, a conclusion will be drawn and an outlook of questions that should be addressed by future research will be given.
Besides creating a consistent dataset of the slums in São Paulo, this study examines the spatial as well as structural differences and similarities of the slums in Rio de Janeiro and São Paulo and how these depend on historical factors and topographic characteristics as well as on the applied method and definition. This study combines the mapping of slums derived from EO data via VI for two megacities in Brazil and a systematic comparison of these datasets with the demographic census of Brazil from 2010.

2 Background

This chapter will give an overview of existing definitions of the term slum as well as its physical characteristics. Furthermore, information on slums in Brazil, especially in Rio de Janeiro and São Paulo are given. Moreover, existing research and methods of slum mapping via RS are presented.

2.1 Definition of the term slum

There does not exist a general or universal definition of the term slum. Furthermore, most of the existing definitions are of a qualitative nature and there is a lack of quantitative approaches. The UN-HABITAT (2003) states that several key factors make it difficult to establish a more universal, objective and quantitative definition. Firstly, slums are a relative concept which means that a definition and criteria for slums in one city may not be appropriate in another city (Gilbert, 2007). Besides this, a definition cannot rely on one parameter only due to the complexity of slums (UN-HABITAT, 2003). This intricate character can be observed on a spatial and temporal scale. Slums show different characteristics in different locations, even in one city. They change over time so that the defined parameters may not be valid any more (United Nations Human Settlements Progamme, 2003).

The first proven definition of the term slum was published 1812 in "the Vocabulary of the Flash Language" by James Hardy Vaux meaning "racket" (Davis & Kurz-Scherf, 2011). Since then different definitions emerged.

The definition of slums by the UN-HABITAT (2003) is widely used in international studies, providing several clear criteria on the phenomenon. It describes on the one hand once respectable residential areas that suffered from a process of deterioration by the migration of the original dwellers to new and better housing areas. Consequently, the units were subdivided and rented to lower-income groups.

On the other hand, the definition includes informal settlements which are unplanned housing areas, characterized by a lack of one of the following conditions: access to improved water, access to improved sanitation facilities, sufficient living area, structural quality/durability of dwellings or security of tenure. Additional characteristics are high population density, insecure residential status and inadequate housing. It is stated that these informal settlements become the visual expression of urban poverty (UN-HABITAT, 2003).

Bähr and Mertins (2000) describe slums as settlements without legal ownership or an official rental contract that are often located in the cities' peripheries, lacking sufficient infrastructure. Gilbert (2007) condenses the term slum in the meaning of its popular usage as ”bad shelter“, including both single buildings as well as large settlements which are of a substandard quality and inhabited by the poor. Though, he points out that the criteria ”inadequate“ or ”substandard“ are relative measures, as housing standards are different worldwide (Gilbert, 2007). In addition, the appraisal of slums depends on the respective perspective, thus the inhabitants may evaluate their situation differently in comparison to public, political or academic stakeholders (Nuissl & Heinrichs, 2013). Beside referring to physical characteristics, Nuissl and Heinrichs (2013) state that the definitions of the term slum also include a social component which is prone to the implicit or explicit articulation of prejudices and stigmatisation of the slum dwellers (Gilbert, 2007; Nuissl & Heinrichs, 2013).

The complexity of slums becomes apparent in the variety of the existing terms and synonyms. Examples for the latter are: "informal settlement" or "shanty town". Depending on the location of the slum, different terms are used such as "gecekondus" in Turkey, "aashawa" in Egypt, "bidonvilles" in francophone countries or "favela" in Brazil (Taubenböck & Kraff, 2014). To avoid conceptual confusion, the term slum is applied consistently in this study.

There also exist "federal slums" which are housing areas constructed by the government as a reaction to housing shortage. They are mostly located at inappropriate sites (Schneider-Sliwa & Meusburger, 2002). This type of slum is neglected in the classification of this study as these areas show different physical characteristics.

The lack of a universal definition of the term slum is an indication for the complexity and heterogeneity of this urban phenomenon. Not only the physical characteristics and housing conditions vary between locations but also the inhabitants of the slums show a wide diversity of origin, religion, culture, income etc. (Gilbert, 2007; Kuffer et al., 2013; Nuissl & Heinrichs, 2013).

Finally, most of the existing definitions are qualitative and can be rather ambiguous, making it difficult to differentiate slums from surrounding urban patterns (Kohli et al., 2012; Taubenböck & Kraff, 2014).

2.2 Morphology of slums

Most of the existing definitions of slums refer to qualitative factors such as the legality of the settlements. A different approach is to identify slums by means of their physical characteristics, their morphology. RS and especially Very High Resolution (VHR) imagery are suitable for this approach as many of the physical particularities of slums can be observed (Kohli et al., 2012). For the visual delineation via EO data, a compilation of the morphology is crucial (Graesser et al., 2012). The term morphology describes the examination of the formation, structure and pattern of a built environment (Graesser et al., 2012).

For the visual classification of slums, the understanding of their morphology and the physical differences between formal and informal settlements is necessary (Kuffer, Barros & Sliuzas, 2014). Taubenböck and Kraff (2015) state that a slum represents a snap-shot of the current phase in its development. This emphazises the context-specific and relative

character of the morphology of a slum as it is influenced by different factors such as the location, culture, history and the age or state of its development (Taubenböck & Kraff, 2015; Kuffer et al., 2013).
There exist various studies about the morphological particularities of slums. Taubenböck and Kraff (2014) show that a physical differentiation of formal and informal settlements is possible. In their study, they use both physical parameters such as building size or height as well as structural parameters such as density or structural heterogeneity within the area (Taubenböck & Kraff, 2014). They conclude that on the one hand, slums feature similar characteristics on a global scale and on the other hand, are distinguished by a heterogeneity between different locations as well as within one slum (Taubenböck & Kraff, 2015). Morphological slum characteristics were delineated by Kuffer and Barros (2011). As the main attributes of slums, they refer to high building density, organic layout structure meaning a heterogeneous, non geometric orientation of the buildings, lack of public green as well as open spaces and small building size (Kuffer & Barros, 2011). Further characteristics are narrow streets and alleyways, a variety of building materials and hazardeous constructions (Graesser et al., 2012). High building density can be stated as one of the main characteristics that slums show on a global scale. This can be explained as a result of unplanned growth and a high land use intensity (Taubenböck & Kraff, 2015). Though, the parameter building density should not be applied as the sole indicator due to its dependency on the age and state of the development of the respective settlement (Kohli et al., 2012; Pasternak & D'Ottaviano, 2016).
Finally, it can be stated that due to the diversity and heterogeneity of the physical characteristics of slums on a global, regional and local scale, a morphological approach is not capable of a holistic delineation and the compilation of a universal slum morphology is impossible (Taubenböck & Kraff, 2015).

2.3 Slums in Brazil

According to the Instituto Brasileiro de Geografia e Estatística (IBGE), 11.430.000 people in Brazil live in slums (Instituto Brasileiro de Geografia e Estatística, 2011, p. 83) which is about one quarter of the total population (UN-HABITAT, 2010). The local term for slum is favela, which is originally a spiky plant common to the area. Later, the term was used as a description for the precarious hillside shacks in Rio de Janeiro. Neuwirth (2016) states that favelas develop over time through successive land invasion.
The following chapter gives information on the historical background as well as some particularities about the development of slums in Rio de Janeiro and São Paulo. As the reasons for the development of slums are complex, they will not be discussed in detail in this study. Though, some of the main causes will be mentioned for both cities (O'Hare & Barke, 2003). These facts are important to understand possible differences in locations and structures of the slums in both metropolitan regions. In the present study, the utilized names of the cities Rio de Janeiro and São Paulo always embrace the entire metropolitan regions.

2.3.1 Slums in Rio de Janeiro

The metropolitan region of Rio de Janeiro, currently consists of 21 municipalities, covering an area of 5.292 km^2. However, in this study the former composition with 19 municipalities is applied as the data refers to a time before the new composition of 2014 (CEPERJ, 2014). In Rio de Janeiro, the first three slums developed in 1881 on steep slopes close to the city center and in the year 1898 the largest early slum “Morro da Providência” was built by military veterans (O’Hare & Barke, 2003). Though, the first slums emerged in the early 20th century, most of the megaslums developed after 1960 (Davis & Kurz-Scherf, 2011). While some areas showed a decline in population, the slums continued to grow through the processes of densification and verticalisation (Pamuk & Cavallieri, 1998). The slums have also been undergoing diverse urban development processes such as decentralisation of the population in the 1990s, marginalisation in some extent due to increased violence in more central slums as well as gentrification (O’Hare & Barke, 2003; Oliveira, 1996). All in all, the slums of Rio de Janeiro are characterized by a diversity of inhabitants with different socio-economic backgrounds (O’Hare & Barke, 2003).
In Rio de Janeiro, urban population growth, rural-urban migration together with the scarcity of standard housing with affordable prices for the lower and middle income classes are primary factors for the occupation of vacant land (O’Hare & Barke, 2003). In general, it can be stated that the location of the slums is strongly connected to employment opportunities (O’Hare & Barke, 2003). Further favourite locations in Rio de Janeiro are the steep hillsides as they are located close to the city center and thereby close to employment opportunities and are not considered for commercial or industrial development (O’Hare & Barke, 2003). The location of Rio de Janeiro‘s slums cannot be described as particularly marginal. O’Hare and Barke (2003) state that they are a relatively permanent feature in the urban landscape.

2.3.2 Slums in São Paulo

As for Rio de Janeiro, the metropolitan region of São Paulo was chosen to be examined consisting of 39 municipalities (Governo do Estado São Paulo, 2017), spreading over 7.946,96 km^2 (Fundação Sistema Estadual de Análise de Dados, 2017).
The development of slums in São Paulo started later than in Rio de Janeiro (De Sampaio, 1994; United Nations Human Settlements Progamme, 2003). Lloyd-Sherlock (1997) collected data on the history of São Paulo’s slums. According to him, the first registration was made in 1964 which does not automatically mean that prior to that date slums were inexistent (Lloyd-Sherlock, 1997). Hence, it can be assumed that the first slums developed less than 65 years ago (United Nations Human Settlements Progamme, 2003). In this time “about 60% of population growth was absorbed by São Paulo’s favelas”(United Nations Human Settlements Progamme, 2003, p. 4).
As mentioned for the case of Rio de Janeiro, the reasons for the emergence of slums are diverse and complex. The end of the uninterrupted economic growth in 1950 can be seen as one of the inicial factors (United Nations Human Settlements Progamme, 2003). Furthermore, the migration of economic activities inland lead to an increased impover-

ishment of the urban population. Moreover, several federal policies, which lead to a rise in prices of rental properties, a lack of affordable accomodation for low income groups as well as restrictions for the access of savings were hitting the low and middle income classes, forcing them to occupy or buy land in the city's peripheries in order to avoid inflated prices in the center (Pasternak & D'Ottaviano, 2016; Taschner & Bógus, 1999). This indicates a process that is particular for the development of São Paulo and its slums - the process of marginalisation. In the 1990s, the growth of the city mainly happened through the expansion of the periphery and its slums (Taschner & Bógus, 2001, 1999). The growth of the slums occured as in Rio de Janeiro through densification and verticalisation (Pasternak & D'Ottaviano, 2016). A further similarity with Rio de Janeiro is the deslocation of the city center through the shift of modern activities to other areas combined with gentrification (Taschner & Bógus, 2001).
Concerning the size and the location of the slums, the local physical characteristics as well as the type of available land play important roles. In São Paulo, the main occupation can be observed on areas of common use, allotments, small plots or even areas of environmental protection, wich are lacking governmental legislations (Gutberlet & Hunter, 2008; Taschner, 2001). Taschner (2001) states that due to this particularity, the size and number of slums in São Paulo are more likely to be subestimated.
As a result of the peri-urban development of a polycentrical conglomerate, there are no clearly identifiable borders between urban and rural areas (Davis & Kurz-Scherf, 2011; Hernández, Allen & Kellett, 2010). Finally, the city "São Paulo became more complex and more socially complicated and so did its physical form" (Hernández et al., 2010, p. 40).

2.4 Remote Sensing and in its application in slum research

As slum population and areas are continuously increasing, there is a growing need of information about their geography, spatial dynamics, scales and population (Kuffer et al., 2016; Sliuzas & Kuffer, 2008). These information are important for policy makers, urban planners and aid-organisation in order to e.g. ensure an efficient post-disaster management (Graesser et al., 2012). Furthermore, spatial information are essential for the assessment of policies as well as the monitoring of poverty targeting programs such as the UN SDGs (Kohli et al., 2013; Sliuzas & Kuffer, 2008). In contrast to this need, there is a lack of consistent, accurate and complete data such as maps, statistics and spatial data on the distribution of slums (Hofmann, Blaschke, Kux & Strobl, 2008; Herold et al., 2003). Owen and Wong (2013) state that "in many parts of the developing world, census and socio-economic data is severely lacking, outdated, or not collected at neighbourhood scales" (Owen & Wong, 2013, p.116). This deficit can be compensated by slum mapping with RS techniques.
In the last 15 year, there was an increase of scientific literature and research on slum mapping with RS which was promoted by the growing availability of VHR satellite images (Kuffer et al., 2016). RS is capable of analysing space and time dynamics of slums

worldwide and monitor their expansion as well as densification (Kuffer et al., 2016). Additionally, RS is able to link these information with socio-economic factors (Kuffer et al., 2016). RS techniques show various advantages compared to surveying which is mostly time- and cost-intensive. Furthermore, census data are characterized by a low temporal resolution, with time gaps from five to ten years which impede the analysis of spatial dynamics in slums (Ebert, Kerle & Stein, 2009). On the contrary, satellite images are taken in constant time intervals which are available in almost real-time, providing independent, area-wide and up-to-date images (Hofmann et al., 2008; Taubenböck & Kraff, 2014). Therefore, RS techniques can be applied as an alternative cost-effective tool for slum mapping (Owen & Wong, 2013). Moreover, RS is capable of mapping slums even in hazardous areas where conventional surveying is difficult (Kuffer et al., 2016).
One obstacle for the availability of RS images is the cloud cover, especially in tropical areas. This problem is tackled by the ongoing development of VHR sensors that are able to penetrate clouds such as the TerraSAR-X (Kuffer et al., 2016) and studies utilizing these imageries for the mapping of slums (Wurm, Taubenböck, Weigand & Schmitt, 2017). Further disadvantages of RS are the complexity of methods which are necessary for the extraction of the desired spatial information and the required experts. The aim should be to develop methods that can be applied independently without experts (Hofmann et al., 2008).
In the range of RS techniques, three main approaches for the extraction of spatial data from imagery can be distinguished: the VI, Object-Based Image Analysis (OBIA) and texture-based methods (TBM) as well as auxiliary methods such as machine learning, statistical methods and image texture (Baud, Kuffer, Pfeffer, Sliuzas & Karuppannan, 2010; Kuffer et al., 2016). Kuffer et al. (2016) executed a literature review in order to compare the frequency of methods applied for slum mapping (see figure 2.1). The most frequently applied method is the OBIA with 32.2% followed by the VI with 17.2%. Most of the studies (55.2%) aim at the mapping of the entire slum areas and fewer at the identification of objects such as roads and houses. Moreover, only a small number of studies aim at examining the link between image-based and socio-economic factors (Kuffer et al., 2016).
Despite the increase of research in the field of slum mapping with the help of RS, a generally applicable automatic classification method does not exist. This is mainly hampered by the inner-structural heterogeneity of slums as well as their structural and spatial homogeneity (Hofmann et al., 2008; Kuffer & Barros, 2011; Taubenböck & Kraff, 2014). Additionally, the direct application to local conditions and the microstructure of slums impede to develop general indicators and algorithms (Taubenböck & Kraff, 2014). An inherent problem for all these methods is the lack of ground truth data for the accuracy assessment. Again, the deficiency of a general definition hampers the comparability of different data sources (Kuffer et al., 2016).
The aforementioned OBIA approach is able to extract information on both, the area and the objects. One critical issue of this method is its low robustness and transferability (Kuffer et al., 2016). It should be considered that low accuracies can be caused by a high heterogeneity, which means that accuracy results do not only depend on the applied

		Methods							Total Number (Percentage)
		Contour Model	Machine Learning	Object-Based Approach	Pixel-Based Approach	Statistical Model	Texture/ Morphology	Visual Image Interpretation	
FOCI	Analysis of types of informal/slum areas	0	1	1	0	1	1	2	**6 (6.9%)**
	Correlation with socioeconomic indicators	0	0	1	3	0	0	1	**5 (5.7%)**
	Identification of slum areas	0	**8**	**15**	3	2	**9**	**11**	**48 (55.2%)**
	Extractions of roofs/roads (objects)	4	0	7	0	0	1	1	**13 (14.9%)**
	Land use/cover mapping	0	2	4	5	1	3	0	**15 (17.2%)**
Total Number (Percentage)		**4 (4.6%)**	**11 (12.6%)**	**28 (32.2%)**	**11 (12.6%)**	**4 (4.6%)**	**14 (16.1%)**	**15 (17.2%)**	**87 (100%)**

Table 2.1: Frequency of methods versus main focus for slum mapping using VHR imagery (Kuffer et al., 2016, S. 14)

method but also on the existing morphology (Kuffer et al., 2016).
Hofmann et al. (2008) applied an OBIA using QuickBird data in order to detect slums in Rio de Janeiro. First, an ontology was created to describe the reality of the slums, followed by a multi resolution segmentation with eCognition. Further, a classification of the generated objects, an iterative process of knowledge-based object enhancement and (re-) classification were executed (Hofmann et al., 2008). At the end, results derived in a manual classification were used to assess the accuracy of the applied OBIA method, achieving an overall accuracy of 50% (Hofmann et al., 2008).
In this study, the applied method is a VI with the primary aim to identify the entire slum areas. It is executed by trained interpreters combining spectral and contextual information. For instance, Gruebner et al. (2014) delineated slums in Dhaka, Bangladesh via VI using primarily QuickBird images from the years 2006 and 2010 in order to obtain a temporal comparison. In addition to the QuickBird imagery, ancillary data such as the 2005 census and slum mapping data as well as Google Earth and geolocated photographs were included (Gruebner et al., 2014).
This process can be very time consuming and requires effective quality control to ensure consistent results (Sliuzas, 2004). Despite this, VI is often preferred to mostly less reliable semi-automatic approaches (Barnsley & Barr, 1996). For repetitive surveys and to cover large areas, the VI method shows some disadvantages, particularly in terms of quality control over time and between interpreters (Sliuzas & Kuffer, 2008).
The basic hypothesis for VI is that slums show significant physical differences to formal settlements so that a visual differentiation is possible. But it has to be considered that not only physical parameters characterize a slum and by applying VI important other indicators are missed out (Taubenböck & Kraff, 2014). Moreover, the physical characteristics may indicate a slum area but the living conditions may have changed due to e.g. upgrading of housing conditions.

3 Data

The following chapter gives information on the utilized data. On the one hand, the applied raw EO data is listed. On the other hand, the Brazilian demographic census, specifically its data acquisition and the included information are described.

3.1 Earth Observation (EO) data

For the slum mapping via VI the Esri World Imagery Basemap was used as the primary data source. This map includes 15 m TerraColor imagery at small and mid-scales, 2.5 m SPOT imagery and data from DigitalGlobe as well as from the Geographic Information System (GIS) user community with a spatial resolution of up to 0.5 m. If the resolution of the Esri World Imagery Basemap was not sufficient, GoogleTM Street View and GoogleTM Earth were utilized as ancillary sources.
In order to examine the temporal dimension of the slums as well as to compare the slum development with the total urban settlement sprawl, the Global Urban Footprint (GUF) (Esch et al., 2012; Taubenböck et al., 2012) was utilized which is based on Landsat and TerraSAR-X imagery. A detailed description of the GUF is given in chapter 4.
The Landsat mission is a joint initiative of the U.S. Geological Survey (USGS) and United States National Aeronautics and Space Administration (NASA) (U.S. Department of the Interior & U.S. Geological Survey, 2017). The mission started with the Multi Spectral Scanner (MSS), with a spatial resolution of 59 m and four spectral bands (green, red, two NIR). Since 1982 the satellites are equipped with a Thematic Mapper (TM) with an advanced spatial resolution of 30 m and six spectral bands and one thermal band (U.S. Department of the Interior & U.S. Geological Survey, 2017). Landsat 7 which was launched in 1999 has an Enhanced Thematic Mapper (ETM) with an additional panchromatic band with a spatial resolution of 15 m. In the GUF, Landsat imageries from around the time steps 1975, 1990 and 2000 were used, depending on the availability of cloud-free images (Taubenböck et al., 2012).
Furthermore, TerraSAR-X data is utilized. The TerraSAR-X satellite is one of the two spacecrafts of the German TanDEM-X satellite mission which started in June 2010 (Esch et al., 2012; Zink et al., 2006). The goal was to acquire two VHR Synthetic Aperture Radar (SAR) datasets with a global coverage for 2011 and 2012, thus a homogenuous, consistent dataset (Esch et al., 2012; Zink et al., 2006). The TerraSAR-X satellite has a spatial resolution of about 3 m and a swath width of 30 km with the length of one strip of several hundreds of km (Esch et al., 2012; Taubenböck et al., 2012). This data has the advantages of being weather independent and consistently available for the global landmasses (Esch et al., 2012; Taubenböck et al., 2012).

3.2 Census in Brazil

With an interval of ten years, the Brazilian governmental IBGE conducts a comprehensive census, covering the whole country. The most recent census has been executed in 2010, including a special feature, the "Levantamento de Informações Territoriais -LIT" (engl. Enquiry of territorial information). This comprehends the collecting of data and information on identification and characterisation of slums, including morphological particularities. Beside the demographic information as well as the structural characteristics, the Census 2010 provides georeferenced data of the location of the slums (Pasternak & D'Ottaviano, 2016). The latter should be pointed out specifically as in most of the countries in the Global South, census are mostly restricted to the head-counted method without providing any detailed spatial information (Kohli et al., 2012).
The term for slums used in the census is "aglomerados subnormais" which corresponds in English to "abnormal agglomerations" and includes favelas, invasions, stilt settlements as well as illegal allotments that have been regularized recently, etc. (Instituto Brasileiro de Geografia e Estatística, 2011). During data acquisition, the focus has been on the identification of characteristics and location of the area, existing urban patterns such as access network and the settlement's degree of density as well as verticalisation (Instituto Brasileiro de Geografia e Estatística, 2011).
For the execution of the census, the country was divided into sectors, which is the smallest territorial unit. In total, 317.000 census sectors were defined from which 15.686 thus 5% were classified as slums (Instituto Brasileiro de Geografia e Estatística, 2011). In the process of identification and localisation, the number of dwellings was counted. A dwelling is defined as structurally seperated and independent, fulfilling the function of habitation for one or more people (Instituto Brasileiro de Geografia e Estatística, 2011).
The sectors are classified by their prevalent characteristics which does not mean that every single dwelling shows these characteristics. Therefore, the exact number of slum dwellings cannot be determined (Instituto Brasileiro de Geografia e Estatística, 2011). Moreover, it is important to note that one slum can consist of more than one sector. The applied criteria for the delineation of slums in the census are: a minimum of 51 dwellings and the illegal occupation of public or private property. Moreover, at least one of the following characteristics must be true: a) urbanisation against the prevailing patterns such as irregular orientation of the buildings, different sizes and forms of building lots, b) constructions not regularized by public authorities and/or c) precarious supply with public services such as energy, water, waste and sewage management (Instituto Brasileiro de Geografia e Estatística, 2011).
The density of the slums is not only determined by the lack of spaces between the buildings but also through verticalisation which is mentioned as typical for the metropolitan regions of Rio de Janeiro and São Paulo.
Furthermore, the census provides further demographic information of the single sectors such as number of inhabitants, number of male and female inhabitants, the age and number of children of the dwellers as well as economic variables such as income.

4 Methodology

Firstly, this chapter gives details about the selection of the study sites as well as information on the two selected cities Rio de Janeiro and São Paulo. Further, it briefly describes the methodology applied for the mapping of the slums in Rio de Janeiro by Fricke (2015). This method was partly used as the conceptual framework for the VI of the slums from EO data in São Paulo.

4.1 Selection of the study sites

The two main requirements for the selection of the two cities were comparability and availability of data. Concerning the former, the cities should show similar size and number of inhabitants. With the provision of the spatial and structural data derived from EO data for Rio de Janeiro (Fricke, 2015) as well as the availability of census data for the entire country of Brazil including spatial data, the first city was certain.

The second city should also be a megacity with more than ten million inhabitants, (United Nations, Department of Economic and Social Affairs (UN DESA), Population Division, 2014) which is located in the Global South and has available census data including spatial information on slums. In order to request information about existing spatial information on slums, several non-governmental organisations and institutions were contacted with no or negative responses.

Consequently, as there exist census data including geo-spatial data for the entire Brazil and a comparison of the slums of two cities in one country is particularly interesting, the city of São Paulo was chosen. Further criteria on the selection of the study site will be mentioned in chapter 5.

4.2 Global Urban Footprint

As mentioned before, with the rapid urban growth emerges the necessity of monitoring and observing urban development in order to handle potential problems, risks as well as to apply suitable policies. Addressing this demand, Esch et al. (2012) introduced an approach to automatically differentiate built-up area - meaning settlement area - from non-built-up area using VHR TerraSAR-X imagery from the TanDEM-X mission from 2011 and 2012. Furthermore, using the resulting GUF (Esch et al., 2012), Taubenböck et al. (2012) created a multi-temporal and multi-sensoral dataset, mapping the urban sprawl of 27 mega cities over a time period of 40 years by applying a change detection, utilizing Landsat imageries (see chapter 3).

The time steps were chosen in an interval of around ten years: 1975, 1990, 2000 and 2010. For the first three time steps, different Landsat imageries were used and for 2010 radar datasets from the TerraSAR-X were utilized.
The study by Taubenböck et al. (2012) includes several accuracy tests which all resulted in an overall accuracy of 80%, giving an "objective basis [...] for monitoring, assessing and evaluating the process of urbanization“ (Taubenböck et al., 2012, p.174). The resulting dataset enables the assessment of horizontal urban sprawl on a spatial and temporal dimension. In this study, the GUF is applied for the evaluation of the urban growth of Rio de Janeiro and São Paulo and the comparison of the slum areas in relation to the total settlement area. Moreover, the four time steps of the GUF are used to analyse the temporal dimension of the slums.

4.3 Data acquisition

In the following, the applied methodologies for the slum mapping for Rio de Janeiro (Fricke, 2015) and São Paulo will be presented.

4.3.1 Rio de Janeiro

The spatial and structural data for the slums in Rio de Janeiro were derived from the bachelor thesis "Slums in Rio de Janeiro: spatial and morphological analyses of slums derived from remote sensing data based on visual interpretation" by Fricke (2015). The VI of EO data and hence the classification of the slums in Rio de Janeiro are based on the definition by Kuffer et al. (2013) (see chapter 2.2). The mapping of the slums was executed on block level, except if the size of the blocks was too small, they were summarized. An individual slum was identified when the slum blocks were divided by a road or open space exceeding ten meters (Fricke, 2015). Fricke (2015) distinguishes between two categories of slums, based on the categorization by UN-HABITAT (2003). The first category is a combination of the UN-classes favelas and invasions which show similar characteristics such as a heterogeneous morphology and being located on steep slopes. A clear differentiation between these two classes is impossible via VI of EO data, therefore they were summarized. The second category are slums of the type loteamentons that are characterized by a more regular arrangement as well as a visible access network (Fricke, 2015). In summary, 2.022 slum polygons were drawn.
In addition to the slum mapping, the average building density and building height of the slums blocks were determined. The building density is defined as the ratio of the built-up area to the associated block area (Fricke, 2015). In total, five density classes with a range of 20% were defined. In order to simplify the VI, five slum blocks with probably different densities were chosen of which all the included buildings were digitized. With this data, the actual built-up area was calculated. These sample slum blocks were used as a visual support for the assignment of the density classes for all slum blocks (Fricke, 2015). The second quantitative variable is the average building height of the slum blocks. Fricke (2015) divided five building height classes depending on the number of storeys.

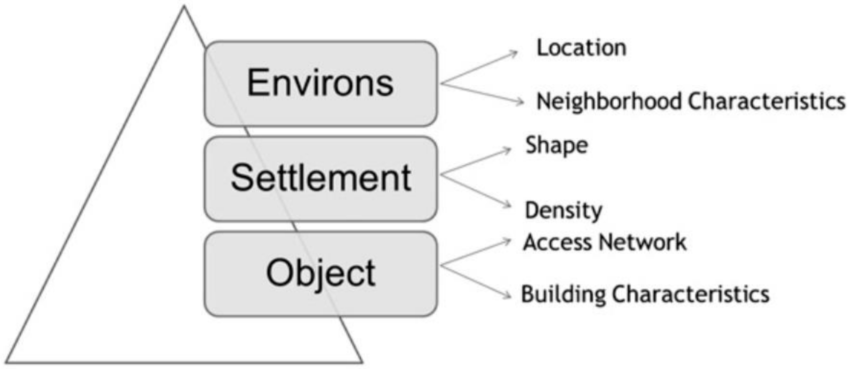

Figure 4.1: The six general indicators categorized to form a hierarchy to represent concepts at three spatial levels (Kohli et al., 2012, S. 158)

4.3.2 São Paulo

As the basis for the VI and classification of the slums in São Paulo, the applied methodology by Fricke (2015) was used. Additionally, an ontology was created, according to the Generic Slum Ontology (GSO) by Kohli et al. (2012). The following section defines the term ontology in general and describes the created slum ontology for the metropolitan region of São Paulo in detail, explaining the chosen indicators. Furthermore, the entire process of VI and categorisation is explained and differences compared to the methodology of Fricke (2015) to Rio de Janeiro are indicated.

Ontology

There is a growing interest in applying ontologies as a tool for representing knowledge in research, in which one of the shared ideas is the facilitation of information exchange (Kohli et al., 2012, S. 155). There exist different interpretations of the term ontology depending on the respective discipline. Swartout et al. (1997) define the term as the following: "An ontology is a hierarchically structured set of terms for describing a domain that can be used as a skeletal foundation for a knowledge base"(Swartout et al., 1997, S. 138). Furthermore, an ontology can be described as a systematic approach for the creation of a concept representing reality (Agarwal, 2005). Although, a growing interest in applying ontologies in GIScience can be observed, a comprehensive method for the generation of ontologies in the geo-spatial field does not exist (Timpf, 2002).
Ontologies facilitate and increase interoperability as well as data exchange between different users and systems by creating a structured conceptualisation and a common terminology (Agarwal, 2005). This is essential as different users can have different interpretations of one issue, leading to misunderstandings or inconsistency (Timpf, 2002).

Ontology São Paulo

The lack of a generic definition of slums and their heterogeneity hinder the creation of a universal method for detecting slums, using RS techniques. This results in the need of a definite and clear conceptualisation and definition of the object of interest (Kohli et al., 2012). For this reason, Kohli et al. (2012) developed a GSO, defining relevant indicators for the identification and classification of slums (Kohli et al., 2012). With the help of these indicators, the actual characteristics of slums can be related to the image. As slums show different characteristics in different locations, the GSO depends on the spatial context and should be adjusted according to the local slum morphology (Kohli et al., 2013).
In this study, the GSO by Kohli et al. (2012) is used as a conceptual framework for the visual slum classification. The different indicators and attributes were adapted for the metropolitan region of São Paulo. The categorisation into favelas/invasions and loteamentons was not applied for São Paulo because a clear determination via VI was not possible. Therefore, the categories are not considered in the analyses (see chapter 5).
Kohli et al. (2012) compiled slum characteristics on three spatial levels: the object level, the settlement level and the environment (see figure 4.1)(Kohli et al., 2012, S. 156) similar to the division by Taubenböck and Kraff (2014) into building level, block level and district level (Taubenböck & Kraff, 2014).
Kohli et al. (2012) suggest three phases for the creation of the slum ontology: specification, conceptualisation and implementation (Kohli et al., 2012). The first phase, the specification, includes a literature review in order to collect information on concepts and characteristics of slums. In this study a literature review was done collecting information on slum characteristics in general (see chapter 2.2) as well as for São Paulo specifically (see section 2.3.2).
The second step is the conceptualisation, which is the process of structuring and organizing the previously collected information, representing the first results in a semi-formal way (Kohli et al., 2012). As the structural framework of the slum ontology for São Paulo, the six general indicators at the three spatial levels (see figure 4.1) proposed by Kohli et al. (2012) were adapted and visible interpretation elements as well as spatially specific observations were acquired (see table 4.1).
At the environs level, the location and the neighbourhood are indicators for slums. For the location, it can be stated that slums often develop on hazardous sites as they are unsuitable for formal settlements. Examples for such locations are hillsides, along rivers and flood areas or along highways (Kohli et al., 2012; Hernández et al., 2010). Another factor of the location of slums is the distance to the city center. In the case of São Paulo it can be observed that the concentration of slums is higher in the periphery of the city (see section 2.3.2).
The location of slums is also interrelated with neighbourhood characteristics. An important factor is the availability of job opportunities mostly for unskilled or low-skilled workers (Davis & Kurz-Scherf, 2011).
On the settlement level, shape and density of the settlements are important indicators. The shape is characterized by an irregularity of the settlement blocks. Moreover, slums tend to imitate shapes of features of their surrounding such as highways, railways or rivers

(Davis & Kurz-Scherf, 2011; Neuwirth, 2016). Slums often show a higher building density compared to formal settlements. However, this factor is not suitable as a sole indicator for slums as the process of densification is typical over time resulting in a dependency of the density on the age of the settlement (Kohli et al., 2012; Pasternak & D'Ottaviano, 2016). Moreover, building density or roofcoverage can be a misleading indicator as there also exist both dense formal settlements and low density slums (Kohli et al., 2012). Furthermore, a lack of open spaces and vegetation is characteristic on the settlement level (Kohli et al., 2012).
The last level is the object level, giving information on the two indicators building and access network. A building is defined as a construction which consists of a roof and walls (Kohli et al., 2012). Buildings in slums show differences to buildings in formal settlements in the following attributes: shape, size, orientation, colour and material. Slums mostly show a rectangular or polyangular shape of the buildings. Concerning the size of the buildings in slums, it can be stated that the average size is smaller than in formal settlements (Kuffer & Barros, 2011). Their orientation is characterized by a haphazard arrangement and an organic layout pattern (Kohli et al., 2012; Kuffer & Barros, 2011). The last two attributes are interrelated as the colour of the roof depends on its material. The most common roof materials for buildings in slums are corrugated metal, tin or asbetos, resulting in a roof colour of different shades of grey or white (Kohli et al., 2012).
Furthermore, the access network plays an important role for the visual classification of slums. It is in general a heterogeneous indicator for slums as the roads differ in width, type and surfaces (Kohli et al., 2012). The shape of the street network is irregular and single roads are mostly not clearly identifiable. Both paved and unpaved roads are typical as well as stairways and narrow alleyways. The average width of the roads within the slum is less than three meters (Sliuzas & Kuffer, 2008). In general, it can be stated that access roads and streets within slums are smaller than ten meters, which is defined as the average width of a major road by Gruebner et al. (2014). Finally, it can be resumed that slums are a heterogeneous phenomenon concerning all of the mentioned characteristics.
The last phase is the implementation thus the application of the indicators on the slum classification in the image (Kohli et al., 2012).

Visual interpretation (VI)

At the beginning of the process of VI - the implementation phase of the ontology - a grid was created with cells of a size of 25-30 ha to facilitate the orientation. Areas with characteristics according with the slum ontology of São Paulo were digitized with polygons on block level. In order to minimize subjectivity, ambiguous settlements were primarily marked as "unsure" and were re-assessed. In total, 3577 polygons were digitized and classified as slums for the city of São Paulo.

Building density

The categorisation of the building density for São Paulo was executed as for Rio de Janeiro by Fricke (2015). The density classes are set in an interval of 20%. Five sample slum

Table 4.1: Slum Ontology São Paulo

Level	Indicators	Interpretation element	Observation
Environs	Location	Slope (DEM), pattern	Along highways Along rivers/flood areas Close to football grounds Slopes/hillsides
		Distance to city center	More in periphery
	Neighbourhood	Pattern	Close to industries or employment opportunities Surrounding planned areas
Settlement	Shape	Pattern	Imitation of shapes of surrounding Irregular shape of blocks
	Density	Texture	Mostly denser than formal settlements Lack of open spaces and vegetation
Object	Building	Shape	Rectangular and polyangular
		Size	Heterogeneous In general smaller than formal settlements
		Orientation	Haphazard arrangement
		Colour	Different shades of grey/white
		Material	Corrugated metal, asbestos, tin
	Access Network	Shape	Irregular Roads not clearly identifiable
		Type	Paved and unpaved Stairways Narrow alleys
		Width	Narrow, less than 3 m

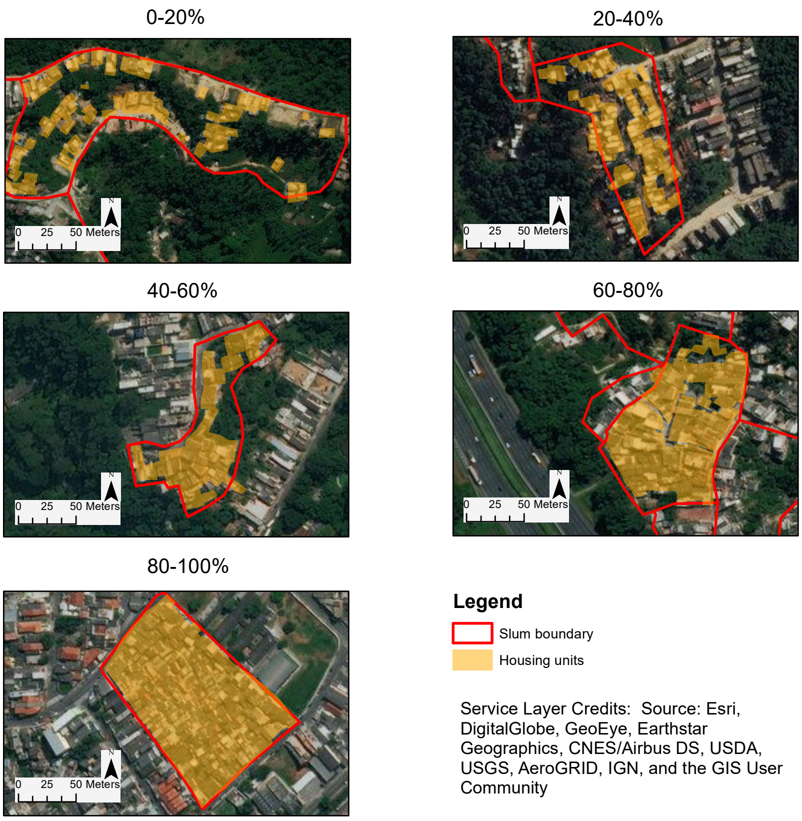

Figure 4.2: Reference polygons for the five building density classes

blocks were chosen with apparently different density classes of which all the buildings were digitized (see figure 4.2). Thereupon, the ratio of built-up to not built-up area was calculated. These sample slum blocks were used as references and visual support for the categorisation of the building density for all of the slums.
The building density classes were also assigned to the census slums in Rio de Janeiro and São Paulo.

Building height

As the clear differentiation of the number of storeys is difficult, only two categories were distinguished for São Paulo, one-storeyed and multi-storeyed (see figure 4.3). As mentioned before, verticalisation is a common process in the slum development so that the two categories can give indications for the age of the respective slum (Pasternak & D'Ottaviano, 2016).
The building height was also estimated for the census slums for both cities. Furthermore, the building height classes for the morphological slums in Rio de Janeiro were re-categorized as the determined classes by Fricke (2015) did not combine with the differ-

Figure 4.3: Reference polygons for the two building height classes

entiation into one- and multi-storeyed.

4.4 Comparison

In the following, the processing of the created dataset in order to compare and analyse it on the three dimensions area, time and location will be described. The spatial analyses as well as the creation of maps were executed in ArcGIS and the visual as well as statistical analyses in 'R'. The area was calculated in all cases by using the Esri tool "Calculate Geometry".

4.4.1 Area

Firstly, in order to compare the area of slums, the area of intersection of census and morphological slums was identified for both cities. This was achieved by the Esri tool "Select by location". As a result, all morphological slums that intersect with census slums were selected. In order to extract only the area that was classified by both approaches, these selected areas were clipped by the shape of the census slums.

On the basis of the assigned density classes, the built-up and not built-up area of the slums can be calculated approximately. For this calculation, the mean values of the density classes were used to estimate the built-up area, e.g. for the density class 0-20% the mean value 10% was used for calculation (d_i). In order to get the total built up area of the slums, the following calculation was applied (see 4.1). A_i is the sum of the area for every single density class d_i.

$$\sum (A_i * d_i/100) \tag{4.1}$$

4.4.2 Time

For the dimension of time, the temporal information of the GUF was utilized. It is important to bear in mind that one slum polygon could be split into different years in the GUF, therefore, two different processing approaches were possible. On the one hand, the slum polygons could be dissected along the temporal boundaries. The result would represent the absolute area of slums in the different time steps. Though, the assigned density values would not be valid any more, as they are an average for the original slum polygon.

On the other hand, the year with the highest proportion inside the slum polygon could be assigned by applying the Esri tool "spatial join"and choosing the "merge rule" "modus" for the information "year". This method was applied as the density class values are preserved allowing the temporal dimension to be complemented by the factor building density.

4.4.3 Location

Based on a monocentric city model and the theory that there is a concentration of job opportunities in the central part of the city (Alonso, 1964), the Central Business District (CBD) was chosen as the city center in Rio de Janeiro and São Paulo. In Rio de Janeiro, the CBD was set in the Avenida Rio Branco (Fricke, 2015) and in São Paulo in the Avenida Boa Vista as proposed by the Prefeitura São Paulo (Prefeitura de São Paulo Desenvolvimento Urbano, n.d.). In order to evaluate the distribution of the slums in reference to the city center, a ring buffer was created with a distance of 5 km (see appendix figures A.5 and A.6). Afterwards, the slum polygons were divided along the buffer zones utilizing the Esri tool "Identity", so that in some cases, the slum polygons were split as they stretched over different buffer zones.

5 Results

The following chapter presents the results of the spatial comparison of the two slum classification methods for the cities Rio de Janeiro and São Paulo. First, the selection of the study sites will be explicated. Subsequently, they will be presented briefly, above all in terms of their urban area and spatial extent. These information are important in order to understand the following analyses in the three dimensions area, time and location in the respective urban context of the two cities.

5.1 Study sites

As mentioned in chapter 4, the two main requirements for the selection of the study sites are comparability in terms of size as well as number of inhabitants and availability of data. After a literature review, São Paulo was chosen as the second study site. Beside the status of a megacity, Rio de Janeiro and São Paulo are classified as a mega-region (e.g., Florida, Gulden & Mellander, 2008; UN-HABITAT, 2010). The UN-HABITAT (2010) defines mega-regions as polycentric urban clusters, surrounded by a low-density periphery which resulted from growth, convergence and spatial spread of geographically linked metropolitan areas and other agglomerations (UN-HABITAT, 2010). They are characterized by a considerably larger population as well as spatial growth (Florida et al., 2008; Taubenböck et al., 2014). Taubenböck and Kraff (2015) conclude that the two megacities are not yet connected by examining the spatial connectivity based on the density of the settlements. Considering the continuing urbanisation, it is possible that Rio de Janeiro and São Paulo will be connected in the future as settlement density will increase.

Furthermore, the comparability of the two cities as well as the relevance is strengthened by the fact that they are located in the "economic heart" of Brazil where about 90% of the population is urban (Gutberlet & Hunter, 2008, p. 4).

5.1.1 Rio de Janeiro

The total urbanized area of Rio de Janeiro (see figure 5.1) has an extent of around 1190 km^2 according to the GUF (Taubenböck et al., 2012). The city shows an irregular urban sprawl which results from its topography that is characterized by hillsides and the Guanabara Bay. The city center is located on the southwest side of the bay and urban patterns can be observed in an irregular arrangement around the bay.

In 1975, 22% of the total urban area detected in 2010 already existed and almost the same proportion added up until 1990. The highest ratio of urban sprawl can be seen in

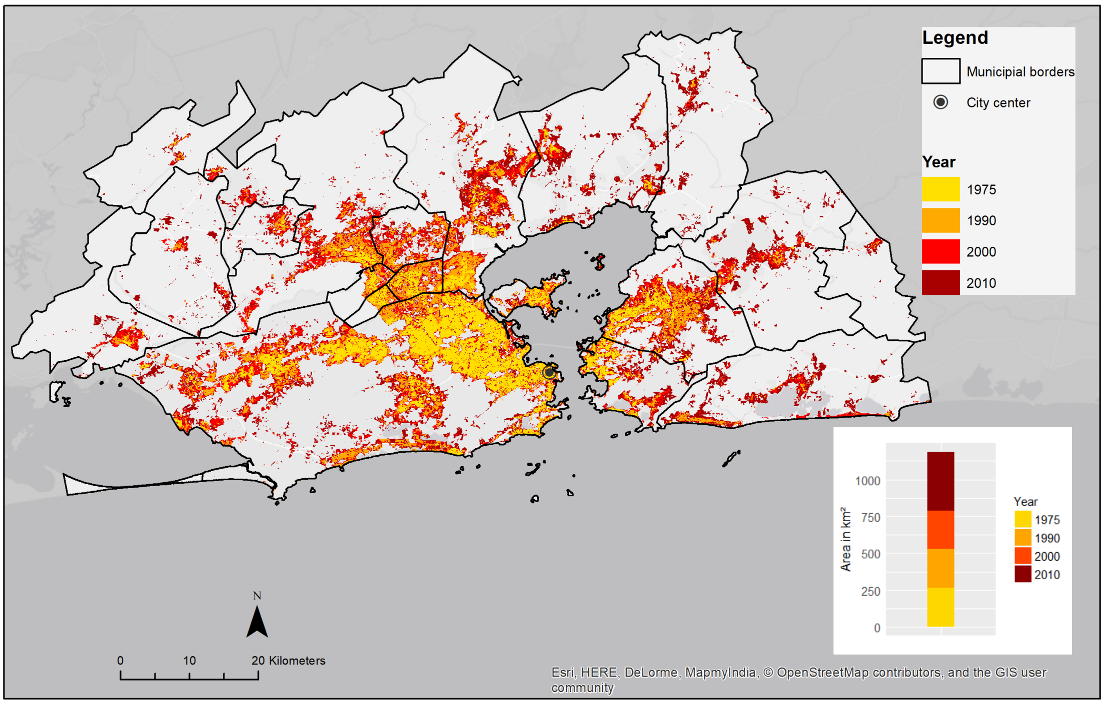

Figure 5.1: GUF Rio de Janeiro (Data source: Taubenböck et al. (2012). Own illustration)

the time period between 2000 and 2010 when around 400 km^2 of new settlement area were classified, primarily in the north and southeast of the metropolitan region.

5.1.2 São Paulo

In São Paulo, around 1710 km^2 are urbanized area of which over one third already existed in 1975 (see figure 5.2). For the decade between 2000 and 2010, a growth rate of the urbanized area almost as high as the area existent in 1975 was detected. According to the GUF, the lowest urban expansion happened between 1990 and 2000 (Taubenböck et al., 2012).
In contrast to Rio de Janeiro, for São Paulo a circular expansion of the city is visible. Most of the younger settlement areas can be located in a longer distance to the city center, in the peripheries. The highest urbanisation of the metropolitan region of São Paulo can be observed in the central municipality São Paulo. In contrast to this, the peripheral municipalities show a lower density and in total less urbanized area.

5.2 Area

Figure 5.3 and 5.4 show the spatial distribution of the slums in Rio de Janeiro and São Paulo. In both maps an extent of the metropolitan regions was chosen, where most of

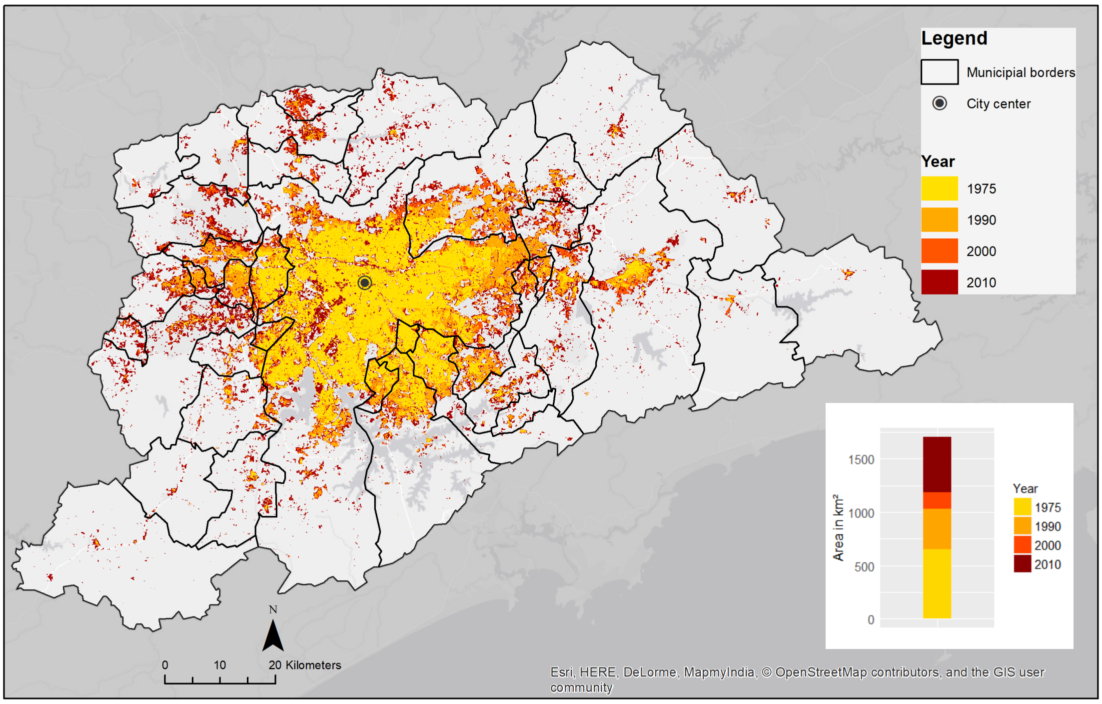

Figure 5.2: GUF São Paulo (Data source: Taubenböck et al. (2012). Own illustration)

the slums are located. The yellow colour shows the slum areas, which were classified by both, the census and morphological classification. The red colour represents slums that were only mapped by the latter and the salmon coloured areas by the former. The spatial distribution of the slum area of the single methods is shown in appendix figures A.1-A.4. The following analysis dimension compares the slum classification results by their area, building density and building height.

Slum area

Figure 5.5 shows the areas of census and morphological slums and their area of intersection for both cities. In Rio de Janeiro, 123,01 km^2 of slum area were classified by the demographic census, 30 km^2 by Fricke (2015) and 26 km^2 are overlapping. Expressed in percentage, around 87% of the morphologically classified slums overlap with the census slums, which adds up to one fifth of the total census area.

For São Paulo, the census classified 88,33 km^2 as slums, the morphological approach 59,83 km^2 whereof 58%, thus 34,15 km^2 are overlapping. In other words, one third of the census area was also classified as slum by the morphological approach. It can be observed that in both cities, more area was classified as slum by the census.

In figure 5.3 of Rio de Janeiro, it is visible that large areas were only classified by the census. Some of these areas do not show settlement patterns neither in the GUF nor on the Ersi basemap so that in matters of physical characteristics, the classification of these

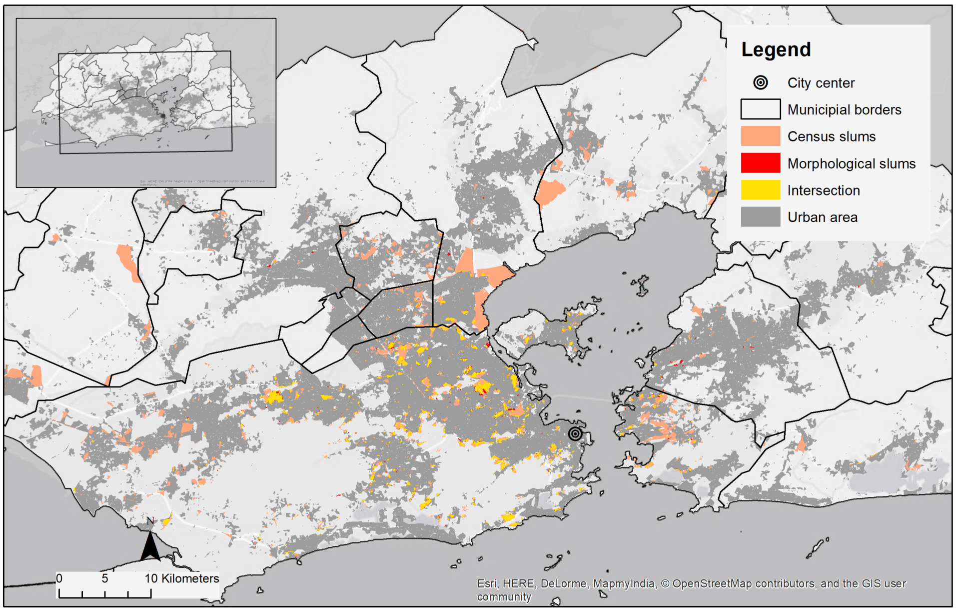

Figure 5.3: Spatial distribution of slums in Rio de Janeiro (Data sources: Fricke (2015); Instituto Brasileiro de Geografia e Estatística (2010); Taubenböck et al. (2012). Own illustration)

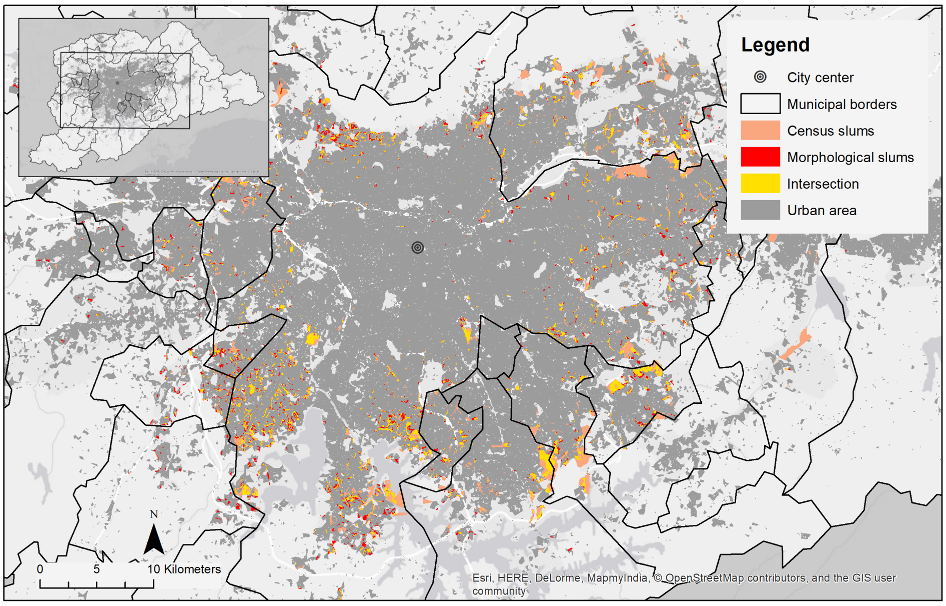

Figure 5.4: Spatial distribution of slums in São Paulo (Data sources: Instituto Brasileiro de Geografia e Estatística (2010), own dataset, Taubenböck et al. (2012). Own illustration)

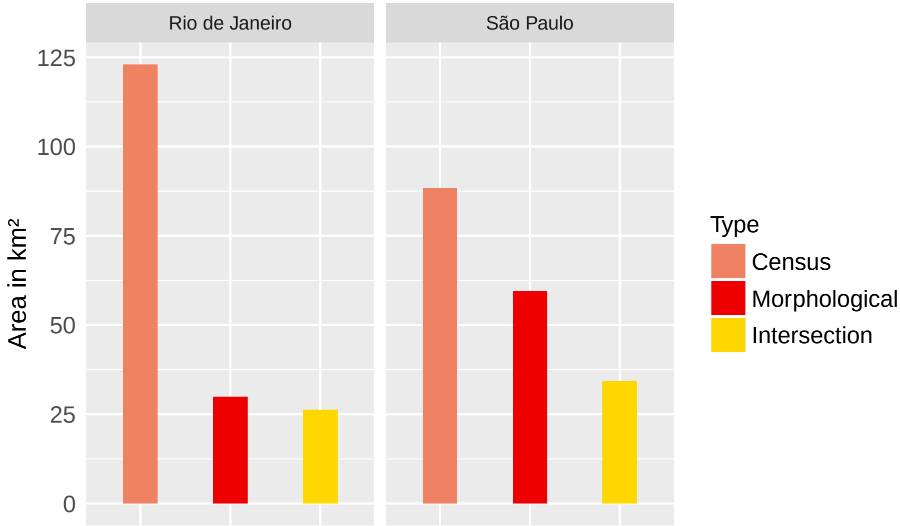

Figure 5.5: Comparison of census and morphological slum area as well as their area of intersection (Data sources: Fricke (2015); Instituto Brasileiro de Geografia e Estatística (2010), own dataset. Own illustration)

areas is not comprehensible.

Building density

Figure 5.6 displays the area of census and morphological slums in the five building density classes. The results show that around 61 km^2 of the census slums in Rio de Janeiro were categorized with a building density of 0-20% which is about half of the total census slum area. In contrast, only 2% of the morphological slum area were assigned to this density class. Whereas half of the morphological slum area and 22% of the census slum area show a building density of 40-60%. The least frequent category is the highest building density class of 80-100%, where the census and morphological slums in Rio de Janeiro show a similar area of around 0.7 km^2.
In São Paulo, one quarter of the census slum area and 1% of the morphological slum area were categorized to density class one. Also one quarter of the census slum area was assigned to density class three and four. The morphological slums show their highest shares in the density classes 40-60% and 60-80%. Over half of the total morphological slum area shows an average building density of 40-60%.
It can be observed that the distribution of the proportion of morphological slum area is similar for both cities. They show a small share in the lowest density class and an increasing proportion in higher density classes with their maximum in class three (Rio de Janeiro) and four (São Paulo). Peculiar are the differences between census and morphological slums in the first density class, especially for Rio de Janeiro.

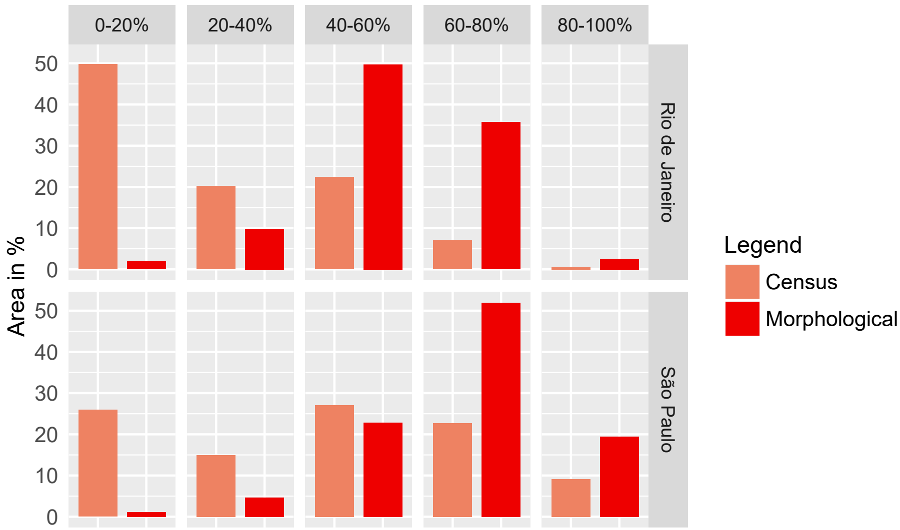

Figure 5.6: Comparison of distribution of slum area in % along the five density classes (Data sources: Fricke (2015); Instituto Brasileiro de Geografia e Estatística (2010), own dataset. Own illustration)

With the information of the estimated building density, the built-up and not built-up area were calculated, which is shown in figure 5.7. According to the results of this calculation, around 17 km², thus 55% of the morphological slums in Rio de Janeiro are built-up area. In contrast, 34 km², which is 28% of the in total census slum area, are covered with buildings. In São Paulo, the built-up area for both, census and morphological slums, is almost equal with around 40 km², expressed in percentage, 67% of the morphological and 45% of the census slums are built-up area. It can be perceived that in both cities, the percentage of built-up area is smaller for the census slums.

Height

Figure 5.8 shows the area of one-storeyed and multi-storeyed census and morphological slums in Rio de Janeiro and São Paulo. For all cases it is apparent that there exist more multi-storeyed than one-storeyed slums. In Rio de Janeiro 4.6% (5.6 km²) of the census slum area and 3.1% (0.9 km²) of the morphological slum area were categorized as one-storeyed. Whereas in São Paulo, the difference is smaller, 4.6% (4.1 km²) of the census slum area and 4.1% (2.4 km²) of the morphological slum area are one-storeyed. It can be summarized that the census slums show slightly more one-storeyed area in proportion to the total slum area.

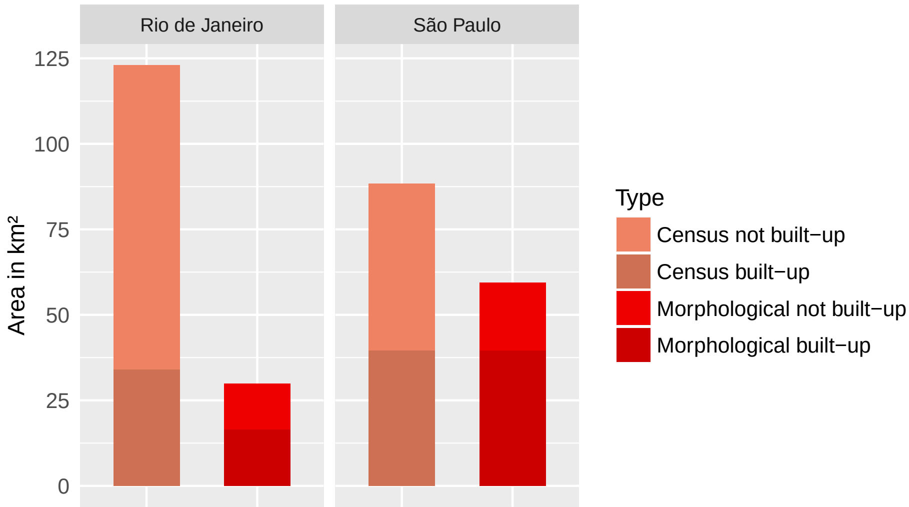

Figure 5.7: Comparison of built-up and not built-up area in km^2 (Data sources: Fricke (2015); Instituto Brasileiro de Geografia e Estatística (2010), own dataset. Own illustration)

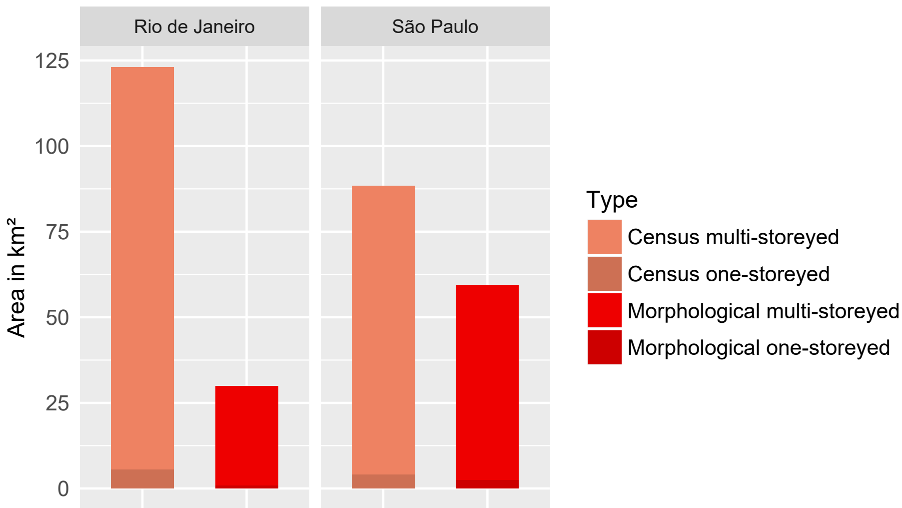

Figure 5.8: Comparison of share of one-storeyed and multi-storeyed slum area in km^2 (Data sources: Fricke (2015); Instituto Brasileiro de Geografia e Estatística (2010), own dataset. Own illustration)

5.3 Time

This section will analyse the dimension of time in matters of area and density. The time was assigned to the area with the highest share in the slum polygon so that these results do not represent absolute numbers.

Time and area

Figure 5.9 shows the area of slums in the four different time steps 1975, 1990, 2000 and 2010. Slums that are located on areas not classified as settlement area by the GUF are denominated "No Data".
In Rio de Janeiro, around 19% of the census slum area already existed in 1975. The highest proportion of 39% (48 km^2) added up until 1990. Concerning the morphological slums of Rio de Janeiro, 41% (12.3 km^2) are on area detected in 1975 and one third of the total morphological slum area added up until 1990. The last two time steps show a lower proportion of slum area for both classifications. For 2000, the analysis results in 32 km^2 (26%) of census slum area and 5.4 km^2 (18%) of morphological slum area. 2 km^2 of the census slums and 0.8 km^2 of the morphological slums did not match the GUF and were assigned "No Data".
In São Paulo, in 1975 around 33 km^2 of the total census slum area already existed. One third (29.5 km^2) of the total census slum area added up until 1990. Similarly, 45% of the total morphological slum area existed in 1975 and 35% (20.6 km^2) developed until 1990. As for Rio de Janeiro, the growth rates are smaller for the latest two time steps. In 2000, 18% (16.1 km^2) of the census slum area and 13% (7.5 km^2) of the morphological slum area emerged. Finally in 2010, 11% of the former and 7% of the latter were detected. In São Paulo, 0.3 km^2 census slum area and 0.8 km^2 morphological slum area count as "No Data".
Except from the census slums in Rio de Janeiro, all classifications show the highest percentage of slum area in 1975 with a gradually decreasing proportion of additional slum area until 2010.

Time and density

Figure 5.10 displays the distribution of slum area of the five density classes along the four time steps. In the first density class neither of the morphological slums of Rio de Janeiro nor São Paulo, slum area was assigned to 1975. The percentage in the other three years is not exceeding 1%. In contrast, the census slums of both cities show slum area with 0-20% building density in 1975. In Rio de Janeiro, the highest percentage (18%) of census slum area in this density class was detected in the year 1990. In São Paulo, the census slums show an almost equal distribution along the time steps in the first density class, with the lowest percentage in 1975.
As is evident for both cities as well as for both classifications, the percentage of slum area detected in 1975 and 1990 rises with higher density classes. For example in Rio de Janeiro, for 1975 21% and for 1990 10% of the morphological slum area were assigned to density class four. In São Paulo in 1975, 27% and in 1990 18% of the total morphological

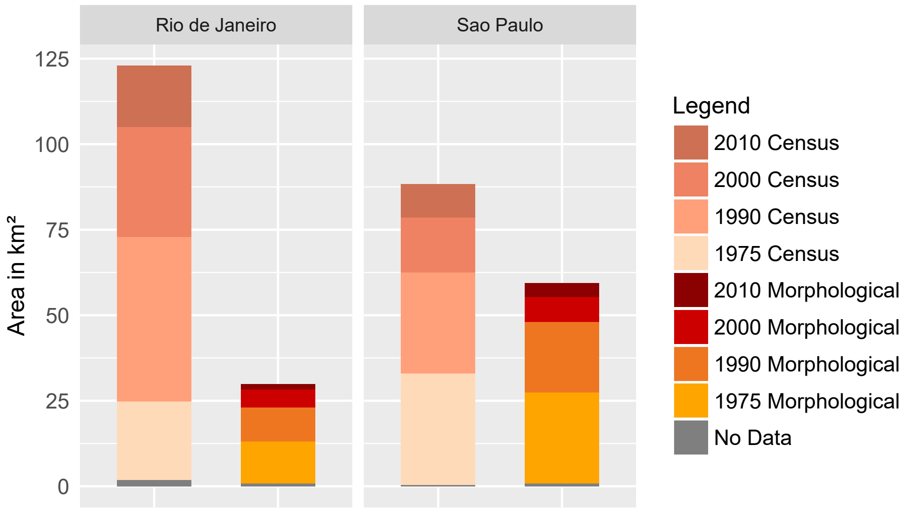

Figure 5.9: Comparison of slum area in km^2 along GUF time steps (Data sources: Fricke (2015); Instituto Brasileiro de Geografia e Estatística (2010), own dataset, Taubenböck et al. (2012). Own illustration)

slum area were assigned to this density class. Whereas only 2% were detected in 2010. In comparison, in 1975 11% , in 1990 8% and in 2010 0.2% of the total census slum area in São Paulo show a building density of 60-80%.
In Rio de Janeiro, the minimum proportion of slum area of both classifications was assigned to the fifth density class, where in contrast to the first class no polygon was allotted to the year 2010. On the contrary, in São Paulo, slum area of all four time steps can be found in density class five.
In essence, more area with 80-100% building density were related to the time steps of 1975 and 1990 in both classifications. Furthermore, it can be stated that in Rio de Janeiro and São Paulo the two classifications show a clear tendency of a higher share of older slums in higher density classes.

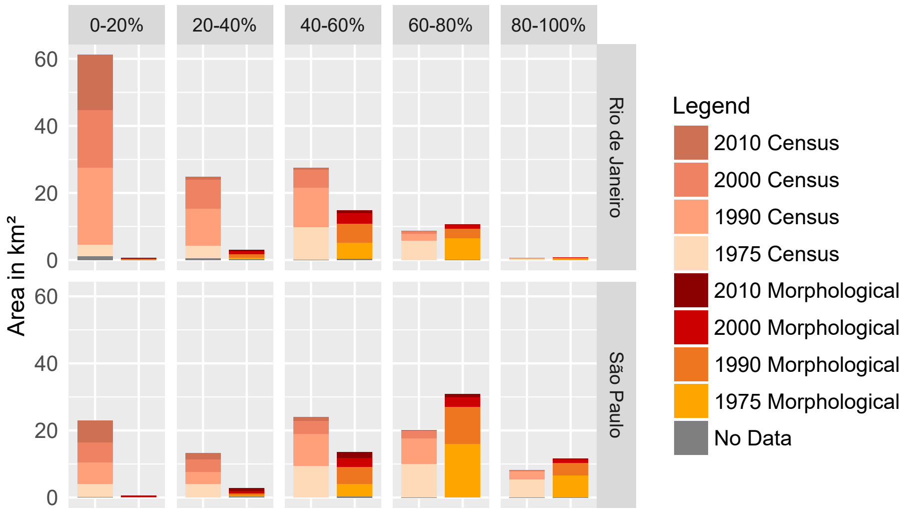

Figure 5.10: Comparison of slum building density in km^2 along GUF time steps (Data sources: Fricke (2015); Instituto Brasileiro de Geografia e Estatística (2010), own dataset, Taubenböck et al. (2012). Own illustration)

5.4 Location

This analysis dimension examines the location of the slums in respect to the distance to the city center. First, the distribution of slum area along the buffer zones of 5 km is compared. Second, these results are supplemented by the dimension of the time. While interpreting the following results, the shape of the two cities should be kept in mind (see figures 5.1 and 5.2) with an irregular urban sprawl in Rio de Janeiro and a circular shape of the urban area of São Paulo.

Location and area

Figure 5.11 shows the distribution of the slum area in percentage of the total slum area along the distance to the city center for both cities and classification methods. Firstly, in Rio de Janeiro, the highest share of census slum area with more than 10% can be found in the buffer zones 2-6 at a distance of 20-30 km to the city center. The maximum of census slum area can be located in zone 4 with 17% of the total census slum area. The minimum of census slum area can be found in zone 14 with around 0.04 km^2. Furthermore, the highest concentration of morphological slums in Rio de Janeiro can be found in buffer zones 2-5 with a maximum in zone 3 with 24% (7 km^2), followed by 20% in zone 4. With increasing distance to the city center, the proportion of morphological slum area decreases. In zones 8-10 and 13, a share of 1-2% can be observed. In 55-60 km distance, the minimum of slum area can be found.

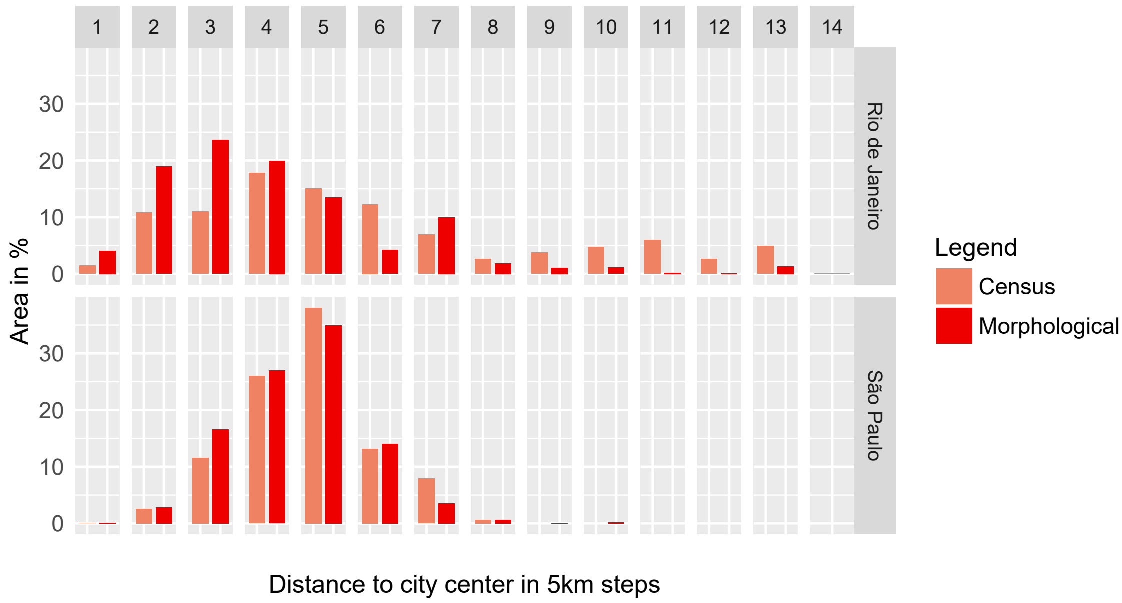

Figure 5.11: Comparison of slum area in percentage along distance to city center in 5 km zones (Data sources: Fricke (2015); Instituto Brasileiro de Geografia e Estatística (2010), own dataset. Own illustration)

In São Paulo, the distribution of slum area in distance to the city center is gradually increasing until the maximum in zone 5 in both classifications. Census slum area was detected until zone 8 and morphological slums until zone 10, though with a small share. The census slums show the smallest proportion of area in zone 1 with 0.05 km^2. Zones 3-6 can be seen as the zones with the highest share of slum area with the maximum of 33.6 km^2 which are 38% of the total census slum area in zone 5. The following zones 6 and 7 show a percentage of 13% and 8%.
As mentioned before, the morphological slums of São Paulo show a similar arrangement along the buffer zones. Zone 1 has 0.07 km^2 of morphological slum area and zone 3 10 km^2 thus 17%. Most of the morphological slum area of São Paulo is located at 15-25 km distance with proportions of 27% and 35%. The subsequent zone 6 has 8.3 km^2 (14%) morphological slum area and zone 7 2.1 km^2 (4%).
In São Paulo, a higher proportion of census and morphological slum area can be found from zone 3 which is a distance of 10-15 km with increasing concentrations until zone 5 in 20-25 km. In contrast, in Rio de Janeiro, the maximum concentration is lower, but a considerable amount of census and morphological slum area can be found in buffer zones within a distance higher than 50 km. Furthermore, in Rio de Janeiro more slums are located in proximate distance (0-10 km) to the city center.

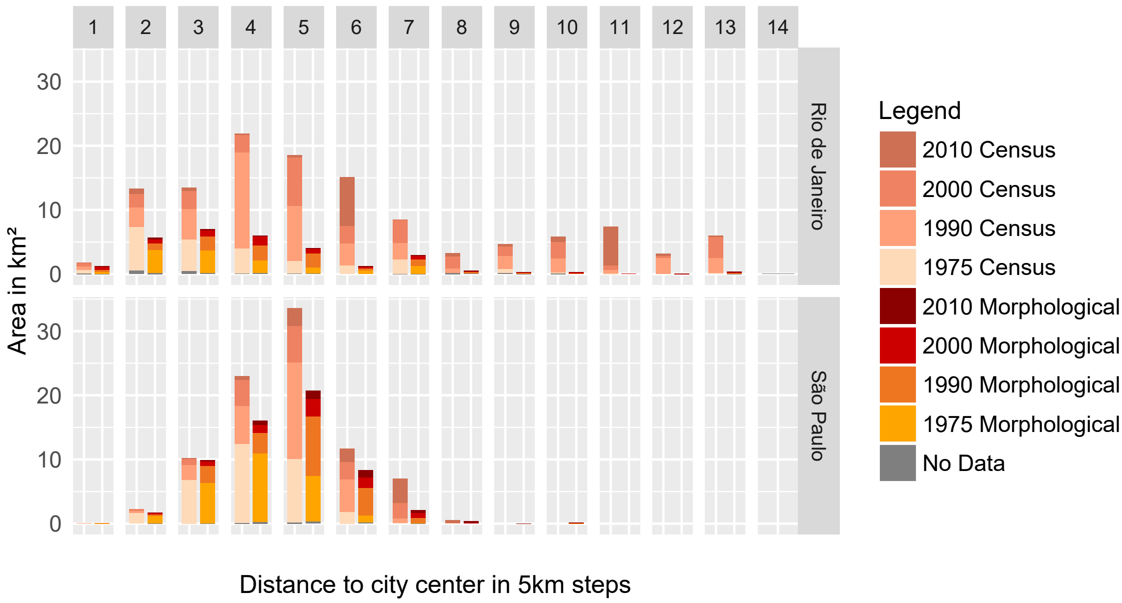

Figure 5.12: Comparison of slum area along distance to city center in 5 km zones and GUF time steps (Data sources: Fricke (2015); Instituto Brasileiro de Geografia e Estatística (2010), own dataset, Taubenböck et al. (2012). Own illustration)

Location and time

In figure 5.12, for both cities and classifications, the tendency is apparent that with increasing distance to the city center, the age of the slums decreases. Consequently, it can be stated, the closer to the center, the higher the proportion of older slums. For example in Rio de Janeiro in buffer zone 2, the maximum census slum areas in matters of the year are 6.9 km^2 (6%) in 1975 and in buffer zone 4, 15 km^2 in 1990. In distances of 25-30 km, the highest proportion of census slum area with 7.6 km^2 was detected in 2010. The distribution of the morphological slums in Rio de Janeiro is similar.
In São Paulo, in the buffer zones 2-4, the census and morphological slums show their maximum area in the year 1975, in zones 5 to 6 in 1990 and in further distance in 2000 and 2010.

6 Discussion

The following chapter firstly discusses the utilized data and applied methodology with the focus on existing differences, weaknesses and strengths. Secondly, the results of the two classifications will be compared and discussed.

6.1 Data and methodology

While analysing and interpreting the results, it should be considered that the utilized data show temporal differences. The census data was launched in 2010 and the Esri World Imagery Basemap is from the year 2014. Slums are a dynamic urban phenomenon so that due to this temporal disparity, differences in the distribution and area of the slums are possible. Within four years, new slums could have emerged or could have been eradicated. Also until today, in the year 2017, the classification for slums in Rio de Janeiro and São Paulo could be differently. Though, the utilized data was the best available option owing to the lack of comparable, more up-to-date, consistent data on slums including spatial information.
Furthermore, the dimension of the time depends on the accuracy of the GUF. Especially for the year 1975, the accuracy may not be as high as for the other years as the utilized imagery of Landsat MSS shows a lower spatial and spectral resolution which influences the classification results (Taubenböck et al., 2012).
It is important to note that the spatial data and structural information derived by VI of EO data is influenced by subjectivity of the respective interpreter. Through the creation of the local slum ontology for São Paulo as well as the reference slum polygons for the density classes, the factor of subjectivity was minimized but cannot be avoided entirely. Moreover, the morphological slums for Rio de Janeiro and São Paulo were delineated by two different interpreters wherefore differences in interpretation cannot be excluded. Notwithstanding, the extent and the high level comparability of the created datasets is unique in slum research.
Moreover, it should be remembered that a classification solely based on physical characteristics cannot be complete as, on the one hand, it does not include other factors such as the supply with basic services, status of the settlements in terms of legality or the social component including how the inhabitants define themselves. These factors are equally important for a holistic slum classification. An area which shows a characteristic slum morphology may have been upgraded so that the existing conditions do not indicate a slum anymore. This also counts vice versa, a formal settlement could have suffered degradation so that the internal conditions would indicate a slum but are not reflected in its morphology. On the other hand, the morphological classification is incomplete as

federal slums are excluded because they do not show comparable physical characteristics to the other slums. Additionally, not all the poor live in slums and not all slum inhabitants are poor. In essence, the morphological classifications in this study created comparable, consistent and area-wide slum datasets for the metropolitan regions of Rio de Janeiro and São Paulo. They do not represent the total urban poverty but rather do they represent the geographic distribution of settlements with particular characteristics depending on the applied definition.
As mentioned before, there is a lack of available spatial and statistical data on slums. Most of the existing classifications are fragmentary or rather focus on certain parts of the cities than on the entire area. In this study, the created dataset for São Paulo is areawide as well as consistent precisely because it is based on clearly defined parameters which were summarized and presented in the local slum ontology. These criteria were the fundament for the VI of EO. Due to the fact that the interpreter could always refer to the defined parameters during the process of classification and the criteria are comprehensible in hindsight, the ontology not only minimizes subjectivity, but also facilitates transferability as well as comparability with other classifications. Finally, it should be noted that the applied methodology of VI of EO data is very time consuming and therefore may not be appropriate or feasible for other studies.

6.2 Census versus morphological slums

The results presented above show that the applied contexts for the classification of slums in terms of definition, parameters as well as methodology influence their geography, meaning the location and distribution, as well as the prevailing structures. For both cities, the demographic census classified more area as slum than the morphological classifications. Co-occurent, the latter identified areas as slums that were not classified by the census. These differences mirror the aforementioned complexity and heterogeneity of the phenomenon slum and that there does not exist ”the one correct“ classification. This has also consequences for accuracy assessment in slum mapping. As different methods will have different results, they are not directly comparable and should always be assessed with regard to the applied definition.
As mentioned before, the demographic census in Rio de Janeiro classified big areas as slums that do not show settlement patterns. Accordingly, neither do they conform to the census criteria of at least 51 dwellings nor is the classification comprehensible in a morphological perspective. Nevertheless, these areas were also assigned further demographic information such as number of inhabitants. It is unlikely that this inconsistency is caused by the temporal differences of the data. Therefore, it would be interesting to know how and why these areas were classified.

Location

The analyses of the locational dimension were based on a monocentric city model with the city centers located in the CBDs. This assumption may be incomplete for the de-

scription of marginality since centrality is complex and influenced by multiple factors. Despite this, the monocentric approach was chosen as it is able to analyse the tendencies of peripheral development and marginalisation of the cities and its slums. Furthermore, a more detailed, polycentric analysis is more time-consuming and was not applicable due to the limited scope of this study.
For the interpretation of the locational analyses, it can be summarized that the distribution of the slums, in matters of the distance to the city center, reflects the general shape of the two cities. São Paulo has a circular urban shape which is mirrored by the steady increase of census and morphological slum area proportion until zone 5 at 20-25 km followed by a decrease. Furthermore, census slums can only be found until zone 8 and morphological slums until zone 10. In contrast, Rio de Janeiro has a more irregular shape with urban area on the west, north and east side of the Guanabara Bay. A continuous urban sprawl is also hampered by the hillsides. Compared to São Paulo, the maximum concentration of slums is smaller in Rio de Janeiro, but slums can be found at further distance to the city center. Moreover, the proportions of slum area varies rather than decreases steadily with increasing distance to the city center.
Even though, in Rio de Janeiro, a considerable amount of census and morphological slum area can be found in buffer zones within a distance higher than 50 km, a higher concentration of slums is located in proximate distance to the city center (0-10 km). In chapter 2.3.1, the slums in Rio de Janeiro were described as not particularly marginal. This can be stated true, although, slums can be found until a distance of 70 km, the highest proportion of census slums can be found at 10-15 km and morphological slums at 15-20 km distance to the city center.
Figure 5.12 indicates that with increasing distance to the city center, the age of the slums decreases. Consequently, it can be stated, the closer to the center, the higher the proportion of older slums. This supports the statements from chapter 2.3 that in the 1990s urban expansion happened in the cities peripheries which was combined with the marginalisation of the slums (e.g., O'Hare & Barke, 2003; Taschner & Bógus, 2001).

Structures

One of the examined structural parameters is the building density. For the morphological slums in both cities it can be observed that they show a small share in the lowest density class and an increasing proportion in higher density classes with their maximum in class three (Rio de Janeiro) and four (São Paulo). These results indicate that a high building density is an important criteria for the morphological slum mapping, although it was always combined with other parameters. Simultaneously, the census slums have a higher share in the lowest density class in both cities. In Rio de Janeiro, the difference between morphological and census slums in this density class is particularly high. One of the reasons could be that the demographic census classifies entire sectors as slum if they predominantly show slum characteristics. On the contrary, the morphological classifications mapped only the settlements with the physical slum characteristics. Furthermore, it can be assumed that the census slums comprise bigger areas, resulting in a lower average

density. This also holds true for the results of the calculation of the built-up and not built-up areas. The percentage of built-up area is smaller for the census slums in both cities.
The building density in combination with the temporal dimension shows the clear tendency of a higher share of older slums in higher density classes for both classifications as well as both cities. Consequently, this supports the hypothesis of settlement densification over time.
The second structural parameter is the building height. The results show that in all cases exist more multi-storeyed than one-storeyed slums. Whereas, the census slums show slightly more one-storeyed slum area in proportion to the total slum area. As the differences between morphological and census slums are very small, the results indicate a more general tendency than a contextual difference. It can be assumed that owing to the process of verticalisation, most of the slums are characterized by multi-storeyed buildings. It would be interesting to combine this parameter with the temporal dimension in order to verify if primarily younger slums were categorized as one-storeyed.

7 Conclusion and outlook

This study created an areawide and consistent spatial dataset including structural information based on a local slum ontology for the entire metropolitan region of São Paulo. The ontology summarizes definite criteria based on the local particularities for the classification of slums via VI of EO data. In total, 3577 polygons were classified as slums on block level resulting in an area of 59,83 km^2.
This data together with a spatial dataset on slums for Rio de Janeiro (Fricke, 2015) were compared to the spatial information of the demographic census from 2010. The comparison aimed at analysing the similarities and differences of the results concerning the geography and structure of the slums due to different contexts, specifically different definitions and parameters. The analyses were executed on three dimensions: area, time and location. Owing to the comparison of the two classifications in the two metropolitan regions of Rio de Janeiro and São Paulo, the results can be interpreted with more general assumptions. Beside the comparison of the two classifications, quantitative, structural, locational as well as temporal differences could be identified between the two megacities. The results were interpreted in the respective topographic, historical and urban context. Considering the results, the study concludes that different definitions and hence parameters applied for slum mapping will generate slums that differ in their geography and structures. Furthermore, the classifications represent only the slums that correspond to the framework of predefined criteria. Additionally, the results show both similarities as well as differences between the slums of Rio de Janeiro and São Paulo, that are defined as one mega-region. This emphasizes the aforementioned complex and heterogeneous character of slums.
Due to the limited scope of the study, only a certain range of analyses could be performed but the data has the potential for further examinations. For instance, the ASTER Digital Elevation Model could be applied as a supplementation for the dimension of location by the parameter slope. It could be analysed, if slums are primarily located on steep hillsides compared to the slope gradient in the entire urban area and how the results differ between the two cities and classifications. Moreover, the parameter size and its variance could be investigated with the following questions: What is the average size of slums in Rio de Janeiro and São Paulo in the different classifications and what are the extremes? Especially, how does the variance differ between the census and morphological slums? How is the distribution of slum sizes along the four time steps and the distance to the city center?
Further studies could also include the information provided by the Brazilian demographic census such as number of inhabitants. In comparison to these numbers, a slum population estimation could be established based on morphological characteristics (e.g., Taubenböck

& Wurm, 2015). Moreover, the created consistent datasets can be applied for research on automated slum classification methods.
With the expected annual increase of slum dwellers by six million, there is a growing need of data on slums in order to ensure the provision of infrastructure and basic services as well as to integrate these settlements as legal parts of the cities. Furthermore, these data are important to monitor and evaluate the effects of policies such as the SDGs. It is a challenge, especially for RS research, to develop methodologies that ensure a cost- and time-effective slum mapping with reasonable consistency. Moreover, these mapping approaches should be applicable in a low temporal frequency as urban areas, particularly slums, are dynamic. They change and grow permanently- both horizontally as well as vertically. Altogether, RS slum mapping techniques could build the basis for other classification methods. Considering the illustrated complexity and context-specifity of slums, it would be expedient to combine several mapping techniques that utilize different definitions and parameters for slums. In this process, the local population should be included in order to not solely map slums from an outside perspective.

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Appendix

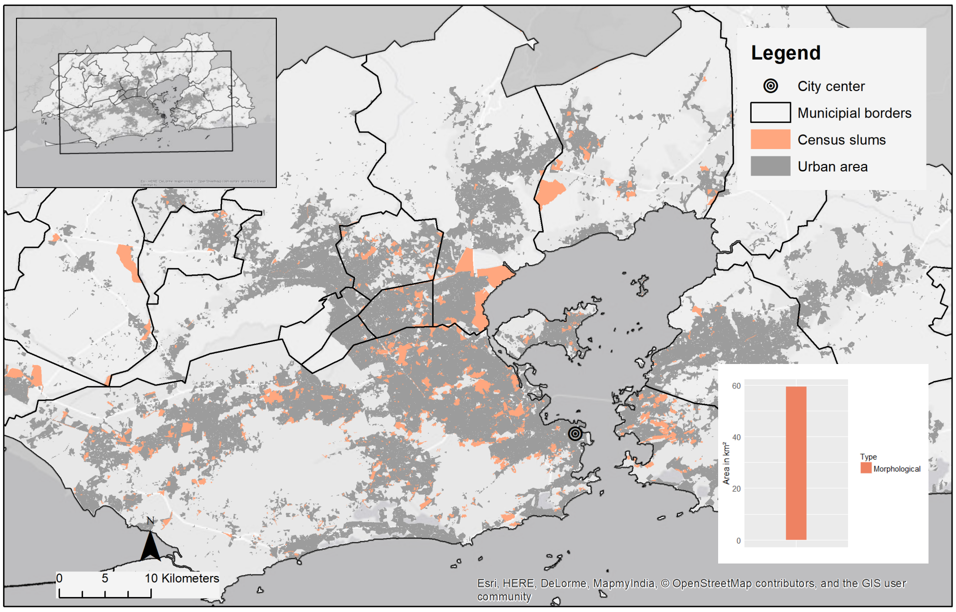

Figure A.1: Census slums Rio de Janeiro

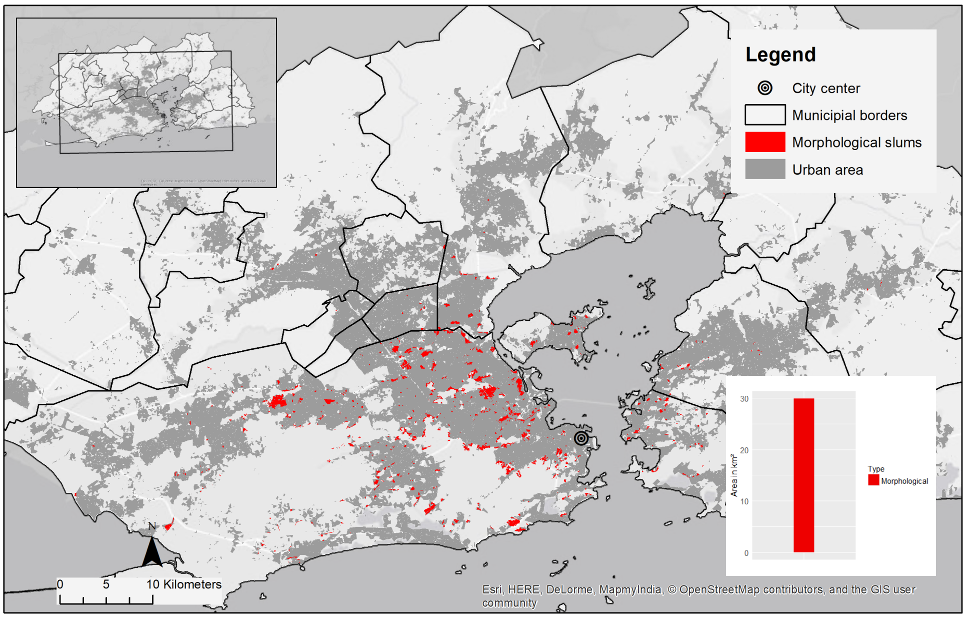

Figure A.2: Morphological slums Rio de Janeiro

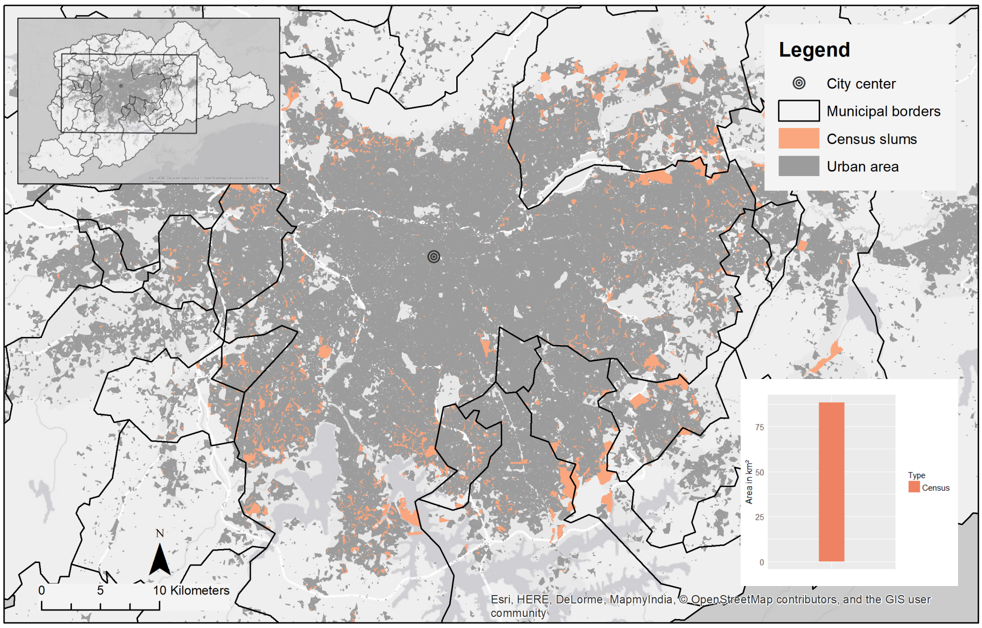

Figure A.3: Census slums São Paulo

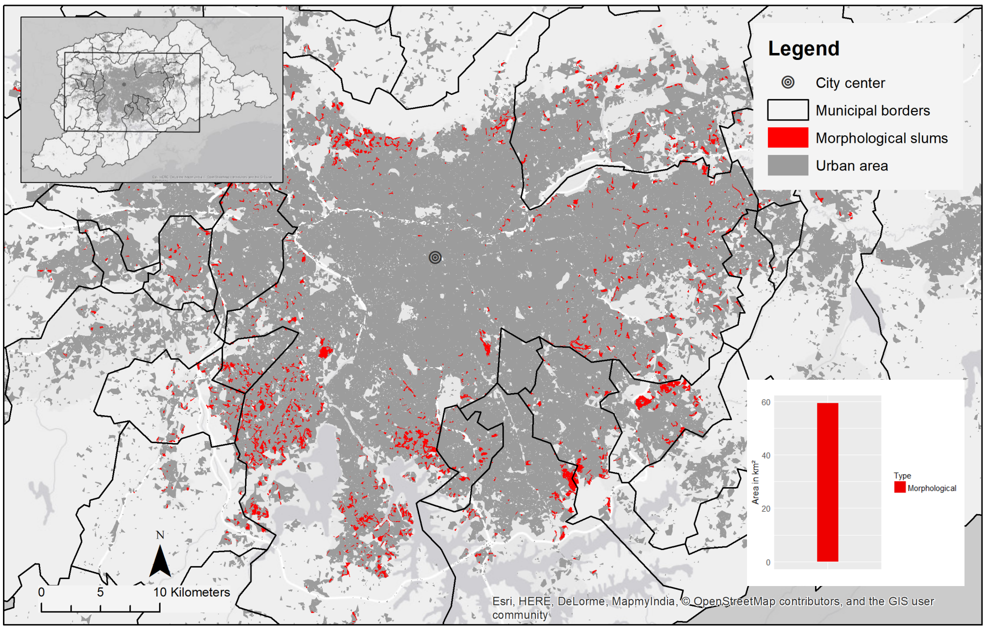

Figure A.4: Morphological slums São Paulo

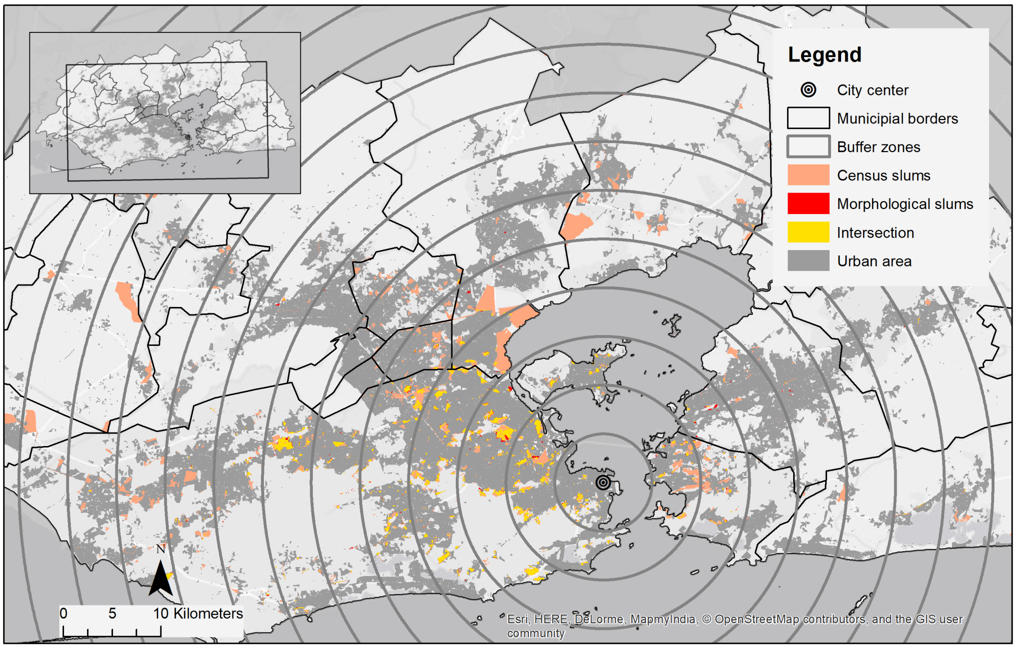

Figure A.5: Buffer zones Rio de Janeiro

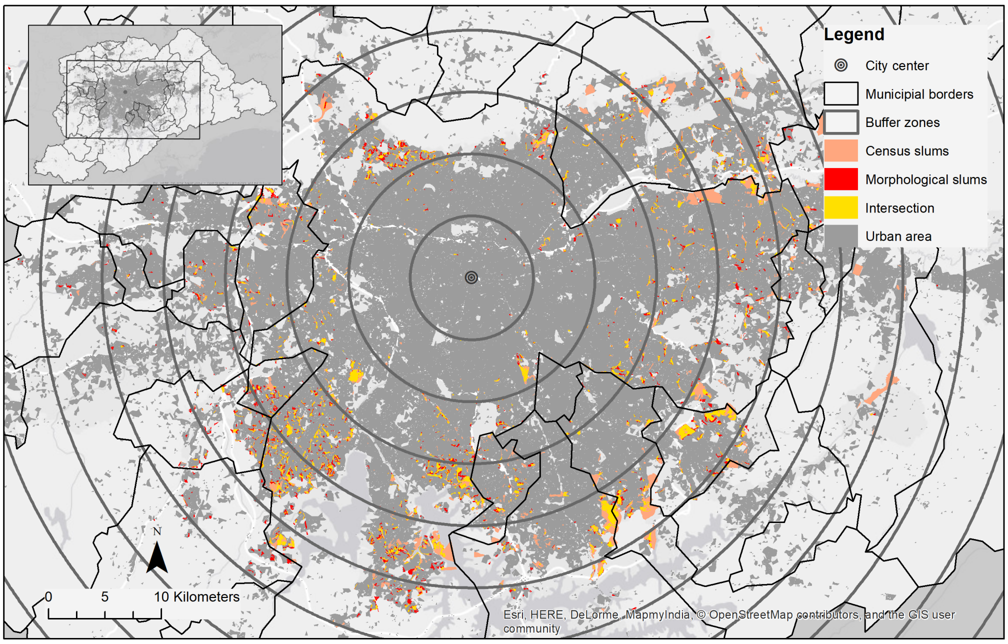

Figure A.6: Buffer zones São Paulo

Declaration

Herewith, I declare that this thesis has been completed independently and unaided and that no other sources other than the ones given here have been used.
Furthermore, I declare that this work has never been submitted at any other time or anywhere else as a final thesis.
The submitted written version of this work is the same as the one electronically saved and submitted on CD.

I agree to my thesis being checked for plagiarism, stored digitally by the Department of Geography of Kiel University, and that a printed copy will be publically available in the library of the Department of Geography. My rights as an author are unaffected by this approval. I can request a restriction note to the examination board at any time.

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