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URBAN OCCUPATION ON HILLSIDES IN METROPOLITAN REGION OF SÃO PAULO (MRSP), FROM 1990S TO THE PRESENT

Mayumi Cursino de Moura Hirye

Doctorate Thesis of the Graduate Course in Remote Sensing, guided by Drs. Diogenes Salas Alves, and Angelo Salvador Filardo Junior, approved in August 26, 2019.

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"These three crucial routes - to Northeast, through the Paraíba Valley; to the North, Campinas and Moji Mirim, to the West and South through Sorocaba and Itapetininga, towards the colony's Southern captaincies - these three, determined by the local relief, would be the main factors that would condition the colonizing of the São Paulo plateau. They represent the only possible routes for North and West and South. Flanking them in the northern region, rises the Mantiqueira, a continuous barrier of peaks that exceed 2000m. To the South is the Serra de Paranapiacaba, which with its rugged and steep topography impedes the passage and the settling of people. Therefore, settlements occur in the depressions that accompany those rough terrains, colonization occurs in these places. Moreover, all three converge in São Paulo, which is thus the node of this topographic system. "

(O fator geográfico na formação e no desenvolvimento da cidade de São Paulo, Caio Prado Jr.)

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ABSTRACT

The Metropolitan Region of São Paulo (MRSP) has, since its origins, been coexisting with hillsides that characterize the relief of the Atlantic Plateau. Although in the past this relief was a favorable physical factor - for the security of pioneer settlements and for the expansion of the metropolis over the sedimentary basin, formed by Tietê and Pinheiros rivers – currently, it is a risk factor for urban occupation, given the expressive number of landslide events registered. The Georeferenced Inventory of Geodynamic Events, published by the Geological Institute of São Paulo State, allowed a quantitative approach to model landslide phenomenon in the MRSP. Landslide data was integrated to remote sensing data, as well as Census and physical data in multidimensional arrays to perform statistical analysis, using a logistic regression framework and a bootstrap resampling strategy. A gridded interpolation methodology was developed to integrate datasets of different spatial and temporal resolution. Results showed a relationship between the occurrence of disasters and accumulated rainfall, steep slopes, precarious settlements and high construction density. Variables associated to household's income, sanitation and drainage infrastructure and the presence of vegetation yielded just a marginal contribution to landslide occurrence. Other variables such as the degree of settlement consolidation, measured by changes in the number of households, by change in settlements condition or by change in vegetation, as well as the educational level of household's head were not found to be associated with landslide occurrence. This model yielded a high level of discrimination, measured by an Area Under the Curve (AUC) value of 0.9. This result highlights the importance of a robust methodology to create, integrate and manipulate gridded data, and further suggests a great potential for use in urban socio-ecological studies. From a theoretical perspective, this thesis contributes to the understanding of cities as coupled socio-ecological systems, using in the case of the MRSP's hillsides occupation, the socio-ecological-technological systems (SETS) framework, in which the relationship between ecological-biophysical and social-behavioral domains are mediated by interventions materialized in the built environment, understood as the technological-infrastructural domain. Thus, this thesis presents an analytical and methodological framework for understanding the relationship between city and nature in the context of hillsides occupation.

Keywords: Urban socio-ecological systems. Urban landslides. Gridded data. Urban growth. Metropolitan Region of São Paulo.

OCUPAÇÃO URBANA DAS ENCOSTAS NA REGIÃO METROPOLITANA DE SÃO PAULO, DA DÉCADA DE 1990 ATÉ O PRESENTE

RESUMO

A Região Metropolitana de São Paulo (RMSP), em sua formação, tem convivido com as encostas que caracterizam o relevo do Planalto Atlântico. Embora em momentos passados esse relevo tenha sido um fator físico favorável – para a proteção do núcleo original e para a expansão da metrópole nas áreas da bacia sedimentar formada pelos rios Tietê e Pinheiros – atualmente ele é um fator de risco para a ocupação urbana, haja visto o número expressivo de eventos de deslizamento. O Inventário Georreferenciado de Eventos Geodinâmicos, publicado pelo Instituto Geológico do Estado de São Paulo permitiu uma abordagem quantitativa para a modelagem do fenômeno de deslizamentos na RMSP. Os dados de deslizamentos foram integrados a dados de sensoriamento remoto, dados censitários e de caracterização do meio físico, em matrizes multi-dimensionais possibilitando análise estatística baseada em modelo de regressão logística e re-amostragem por *bootstrap*. Uma metodologia para interpolação de dados para grades foi desenvolvida para integrar dados de resoluções espaciais e temporais distintas. Os resultados aqui apresentados apontam para a relação entre a ocorrência de desastres e chuvas acumuladas, encostas de alta declividade, ocupações precárias em alta densidade construtiva. Fatores associados à renda das famílias, à infraestrutura de saneamento e drenagem e à presença de vegetação apresentaram uma contribuição apenas marginal para a ocorrência de deslizamentos. Para outros fatores, como o grau de consolidação dos assentamentos, medido pelas mudanças no número de domicílios, nas condições dos assentamentos ou na cobertura vegetal, assim como o grau de instrução do chefe da família não apresentaram associação com os deslizamentos. O modelo apresentou um alto nível de discriminação, expresso pelo valor de 0.9 da Área Sob a Curva (AUC). Esse resultado ressalta a importância de uma metodologia robusta para a criação, integração e manipulação de grades de dados, apontando para as potencialidades da utilização dessa ferramenta em estudos sócio-ecológicos urbanos. Do ponto de vista conceitual, esta tese contribui para o entendimento das cidades como sistemas sócio-ecológicos acoplados, utilizando, para o caso da ocupação de encostas na RMSP, o esquema conceitual de sistemas sócio-ecológico-tecnológicos, em que a relação entre os domínios ecológico-biofísico e social-comportamental é mediado por intervenções que se materializam no próprio ambiente construído, entendido como o domínio tecnológico-infraestrutural. Apresenta-se, assim um quadro analítico e metodológico para o entendimento das relações entre cidade e natureza, no contexto da ocupação das encostas.

Palavras-chave: Sistemas sócio-ecológicos urbanos. Deslizamentos urbanos. Dados em formato de grade. Expansão urbana. Região Metropolitana de São Paulo.

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LIST OF ACRONYMS

AUC	Area Under the Receiver Operating Characteristics Curve
BIC	Bayesian Information Criterion
CPRM	Geological Survey of Brazil
CEM	Center for Metropolitan Studies
CEMADEN	National Center for Monitoring and Alert of Natural Disasters
CENAD	National Center of Risks and Disasters Management
CHIRPS	Climate Hazards Group InfraRed Precipitation with Station Data
DEM	Digital Elevation Model
DGI	Image Generation Division of National Institute of Space Research
DPI	Image Processing Division of National Institute of Space Research
EMPLASA	São Paulo Metropolitan Planning Company
IBGE	Brazilian Institute of Geography and Statistics
IG	Geological Institute of São Paulo State
INPE	National Institute of Space Research
IPMET	Institute of Meteorological Research of São Paulo State University
IPT	Institute for Technological Research of São Paulo State
MAUP	Modifiable Areal Unit Problem
MRSP	Metropolitan Region of São Paulo
NDVI	Normalized Difference Vegetation Index
NPPCD	National Policy of Protection and Civil Defense
PMSP	Prefecture of Municipality of São Paulo
QUAPÁ	Quadro do Paisagismo no Brasil
SETS	Social-Ecological-Technological System
SES	Social-Ecological System
SVM	Support Vector Machine
TIN	Triangulated Irregular Network
TM	Thematic Mapper
UN	United Nations
UNDRR	UN Office for Disaster Risk Reduction
USGS	U.S. Geological Survey
USL	Urban System Lab

SUMMARY

Page

1. INTRODUCTION

The relationship between cities and nature varies both temporally and spatially. Temporally, from the perspective of both the stages in each city - implementation, consolidation, and expansion - as well as the cycles determined by the influence of actions, policies, and practices that shape urban occupation. Spatially, related primarily to city location, whether built near the coast or riverbanks, embedded in mountain ranges or in plateaus within the territory, or among many other possibilities.

This relationship is also unequal, as ever more natural elements are overwhelmed by cities' expansion. Only the most impressive features, such as seafronts and mountain massifs, remain natural and as such form part of the urban landscape. Direct impacts on ecological and climate processes are the result of disturbance of water body and vegetation disturbances. On the other hand, natural site beauty attributes - such as forests, mountain peaks, and beaches - act as population attractors in a socially mediated process, where natural features are assigned social values, distinguishing between their value to society as a whole, specific interest groups and individuals with an emphasis on performance requirements rather than environmental determinants (SPIRN, 1985).

Thus, the distinction between city and nature, though useful in identifying elements that make up the landscape, does not correspond to the interdependence reality between these elements. After all, it is not about "a simple addition of disparate geographical elements. It is, in a given portion of space, the result of a dynamic, therefore unstable, combination of physical, biological and anthropic elements which, by reacting upon each other, make the landscape a unique and inseparable, ever-evolving ensemble" (BERTRAND, 1972). The characteristics of the urban landscape will, to a greater or lesser extent, respond to the imperatives of environmental (such as climate, physical support, and vegetation) and social structures (such as income distribution, means of production, as well as locomotion and state action).

Always permeating this work, the relationship between cities and nature was, at first, based on the urban landscape analysis, as carried out by researchers at QUAPÁ Laboratory[1]. In QUAPÁ's conceptual approach, the landscape consists in what can be perceived, with an observer and an observed object, as much as it is a system, since for "any action printed on it, there will be surely a corresponding reaction, in this case, equivalent to the emergence of a partial or total morphological alteration" (MACEDO, 1993). Moreover, the form that the city takes, based on the plots of buildings and free spaces, obeys the interaction between the proper logic of physical processes (geological and climatic) and the proper logic of social and cultural processes (MAGNOLI, 1982).

The understanding of the hydrological and climate processes in cities offers an integrated perspective to deepen this conceptual approach. Physical models are intended to represent "the proper logic" of the physical processes. Current hydrological models are quite sophisticated, both from a spatial point of view, with the possibility of incorporating elements with a high degree of detail, and regarding processes that are considered, combining the hydrological behavior of the system, in terms of volume and flow, the hydraulic characteristics, flow propagation through the urban system and even the transport of sediments and inorganic material to analyze water quality. Climate models, similarly, have made remarkable progress since the first measurements of the heat island phenomenon in early twentieth-century London, they are now used to measure the impacts of urbanization, translated by the increase in surface and mass built up in the cities that store and release heat differently from natural surfaces, both in the urban microclimate and in the regional climate.

The possibility of modeling a reality using universal relationships and sophisticated techniques to obtain definitive answers about what is beneficial and detrimental for cities or the region in which they operate is at odds with the fact that the greater complexity of the model does not necessarily result in a higher performance and, in

[1] QUAPÁ Laboratory, founded in 1994 at the Architecture and Urban Planning Faculty of São Paulo University (FAU-USP), covers issues related to landscape design, open spaces and landscape planning. QUAPÁ has created and coordinates a Brazilian research network, the QUAPÁ-SEL, since 2006.

cases where the available observable data is of good quality, empirical models tend to be sufficient (GRIMMOND et al., 2010; MASSON, 2006). Although models are useful tools for simulating future scenarios and assessing the consequences of each urban design proposition, concurring with the architect Eleonora Assis, model and planning limitations should be taken into account to avoid being led by the rationalist thought "that the world could be controlled and organized if I could grasp it and represent it correctly" (ASSIS, 2007).

Grasping and representing cities is not enough to control and organize them, as cities are complex systems, diverse and composed of multiple and interconnected elements. Jane Jacobs has envisioned cities as an "orderly complexity problem" (JACOBS, 1961), comprising simultaneously a measurable number of factors inter-related in an organic totality. Comparing extensive "collections of sets comprised of millions of the real particles which occur in the city," Christopher Alexander stated that cities are not like trees, since these sets are not wholly contained in the others or are else disjointed (ALEXANDER, 1965). Instead, this author used the semi-lattice idea to represent the existence of overlapping sets in the city structure.

Building on these fundamental ideas, Michael Batty recognized city order as an emergent feature, the result of bottom-up competitive and collaborative actions and the decisions of individuals and agents in response to their environment and each other (BATTY, 2007). Moreover, empirical evidence suggests that cities exhibit scaling properties, in the sense that their size and shape follow well-defined scaling laws, where urbanization increases implicated in further economic development and knowledge creation across different nations and times (BETTENCOURT et al., 2007), although this theory must still be applied to a system of cities or a region (BATTY, 2008).

In Urban Ecology field, cities are conceptualized by their complexity and in their relationship with nature. Both empirical and conceptual advances in this field as well as the diversity and progressive increase in the size of the study areas have directed researchers to a more robust and holistic city science (MCPHEARSON; PICKETT et al., 2016). Besides emergence property, urban ecologists have recognized nonlinear dynamics, feedbacks and learning and adaptative capacities in cities, framing them as coupled human-natural systems (PICKETT et al., 1997a; ALBERTI, 1999; PICKETT et al., 2001).

It is somehow ironic that, alongside the long theoretical way that I took, the object of this research – urban hillside occupation in the Metropolitan Region of São Paulo (MRSP) – emerged accidentally. In 2016, while in the tallest building of São Paulo city, I enjoy a 360° view of the city. I could see the downtown area, as a vast sea of windows rooftops and streets. I saw what I believed to be the Tietê and Tamanduateí rivers canals, which were, in fact, nothing more than elongated gaps in the sea of buildings. The only color that differed from the gray of the concrete and of the sky was the green of the República Square trees and the Atlantic Rainforest remnants protected by the steep slopes of the Cantareira Mountain Ridge, which made up the skyline to the North. At that moment, I realized that the only natural feature that resists the immensity of São Paulo was the shape of the terrain; its hills, like the one of the original site, its slopes, like the ascent to Paulista Avenue and the descent to the Jardins neighborhood, its small hills like those of the Morumbi neighborhood, or its foothills, like those of Cantareira Mountain Ridge itself. Indeed, had I decided to sail the Guarapiranga Dam that day; this thesis could have taken on another research object....

The site where the MRSP was founded is one of the exceptions to the rugged relief of the Atlantic Plateau, a geomorphological unit which covers the southeastern of Brazil, alongside the Atlantic coast. São Paulo's initial settlement was placed at the top of a hill, like many other Brazilian historic settlements, in a practice that can be traced back to the Lusitanian urban tradition of using steep slopes for protection (SIMÕES JUNIOR; CAMPOS, 2013). In earlier times, urban MRSP development took place in the Sedimentary Basin of São Paulo, comprising flatter areas, formed by the phanerozoic sediments, with soft hills and platforms, and by the extensive fluvial plains of the Tietê and Pinheiros river comprising quaternary sedimentary deposits. However, from the second half of 20th century, pioneer settlement expansion took over desirable areas and began to advance towards the hillsides of the Neoproterozoic mobile belts, formed over a crystalline basement of metamorphic and igneous rocks (MARCONDES, 1999; IBGE, 2009). Thus, the urban development in this unit is distinguished by coexistence with hills, discontinuous masses or blocks of raised plateaus, interspersed by valleys with a transversal profile well-marked by the dense river network (AB'SABER, 1958).

Different urban hillsides occupation typologies of the MRSP – favelas, high-income neighborhoods, gated communities, illegal settlements – were inspected during two field trips, carried out at the beginning of 2018. On these occasions, difficulties and advantages in living on hillsides were observed, along with diverse urban designs. Moreover, this revealed family stories that colored literature descriptions and impersonal data derived from the Brazilian Census and satellite imagery.

Alongside the object and the theoretical framework definition of this research, the methodological approach was developed from the Remote Sensing course disciplines undertaken, from the difficulties of using data from different sources or spatial cutouts in urban studies. Census data, due to their temporal and spatial scope and level of detail, are the most comprehensive source of information concerning the Brazilian population and the conditions in which they live, in both cities and in the countryside. Thus, the first objective of this research was to develop methods to better work with census data that end up configuring the "modifiable areal unit problem" (MAUP). The smallest census spatial units, census tracts, are delimited based on operational criteria, which may change over the years. In this sense, it is fair to say that analyses and conclusions derived from data associated with area units have no independent validity (OPENSHAW, 1983). This approach is presented in the first paper in Chapter 3, published in 2016. At this time, the city of Altamira, in the Amazonian State of Pará, offered controlled conditions to test the proposed data interpolation methodology.

The second paper, presented in Chapter 3, consists in the communication of the data interpolation results applied to MRSP. Inspired by approaches developed at INPE based on cellular space concept, this study addresses intra-urban scale problems and their assessment on a metropolitan scale, using the data interpolation methodology built in the previous paper and two different regular cell grids, one in a high spatial resolution and other in low resolution. This work was presented at the American Geophysical Union Fall Meeting in 2018, and a revised version was presented later in 2019, to researchers at the Center for International Earth Science Information Network of the Earth Institute at Columbia University.

Data integration using a gridded information was then applied in the third paper of this thesis to model landslide occurrence in MRSP. This model articulates hillsides occupation in a coupled human-natural system, in which disaster events are the effects of the relationship between urban systems components, comprising the second objective of this thesis. Landslides are the most critical impact of hillsides occupation. From 2003 to 2013, in all MRSP municipalities, except for São Paulo, a total of 30,685 events were registered, 12,311 (40,12%) classified as geological events, comprising: debris flows, rock or mudslides, erosion, riverbanks erosion, rock falls, soil subsidence, and collapse and mass movement. The majority of these events caused low-intensity damages to housing and infrastructure, and a few of them, only 305, resulted in loss of life (IG, 2017).

The extensive inventory of MRSP landslides publicized by the Geological Institute of São Paulo state (IG, 2017) provided the opportunity to use integrated spatial and temporal data to see the urban system "in motion", where biophysical social and built MRSP characteristics were assessed to identify which specific variables can be related to landslide occurrence and what are their importance in this process. These results are presented in the third and main paper of this research, also presented in Chapter 3, and were obtained during the period spent at the Urban Systems Lab (USL), at The New School, supervised by prof. Dr. Timon McPhearson.

This research project lays on the assertion that hillside occupations are a common MRSP and Atlantic Plateau feature and that these occupations encompass distinct different urban patterns, with different morphological and socio-economic characteristics. The aim of this research is to investigate urban hillsides occupation in the MRSP, from 1990 to now. Specifically, it aims to (i) use remote sensing and geoprocessing techniques to integrate biophysical, socio-economic and built environment data from different sources and format, to measure and characterize hillsides MRSP occupation, and (ii) based on this integrated data, articulate hillsides occupation in a coupled human-natural system, in which disasters events comprise the effects of the relationship between urban system components.

This thesis is organized in five chapters. Besides this first introductory chapter, Chapter 2 provides a literature review concerning the main topics discussed in this thesis. Chapter 3 comprises three papers, two published and a third one to be submitted. Chapter 4 presents a general discussion of the results and their consistencies, while chapter 5 concludes this thesis, providing an overview concerning the enhancements and future investigations of this research.

2. REVIEW

This chapter will introduce concepts and ideas related to social and natural coupled systems. Afterward, literature regarding the urban occupation of hillsides in the Metropolitan Region of São Paulo is presented to give the context of this research. Finally, we review previous knowledge built on urban landslides. Cities as coupled social-ecological systems

2.1. Cities as coupled social-ecological systems

2.1.1. Designing with nature: an approach to address the relationship between cities and nature

"Let us ask the land where are the best sites [to each land use]"(MCHARG, 1969). Thus, landscape architect Ian McHarg introduces his method of conceiving the coexistence between city and nature. 'Asking the Earth' expresses deference to nature and non-anthropic processes and places us, the human species, at a somewhat lower level. For McHarg, from this physiographic determinism, we can identify the best place for each human activity (McHARG, 1969). He denies nature the role of 'decorative background' to human activities or merely an element of amelioration or amelioration of urban sadness: she is the source of life, environment, teacher, sanctuary and challenge (McHARG, 1969).

He based his method on the ecological inventory: a comprehensive survey of the relationships between different aspects of the environment - climate, geology, hydrology, soils, vegetation, and wildlife (McHARG, 1967). The analysis' inventory uses concepts of fitness and adaptation and a hierarchy of environments concerning their suitability for particular uses, the more an environment is intrinsically suitable for a particular use, there will be less of a need to adapt (McHARG, 1969).

McHarg (1967) argues that his method is suitable not only to rural or urban-rural problems but also to intra-urban problems. In this case, however, knowledge should be based both on natural and cultural evolution, the former as a natural identity, the landscape form, and the latter as an accumulation of adaptations to the given form, which constitutes the modern city. Moreover, his method can deal with the "putrid parts of the city," slums, overcrowding, congestion and pollution, anarchy, and ugliness. He proposed to use the ecological inventory as a method to overlay characterization maps of population and its cultural aspects and physical aspects of interest in each kind of problem. The ecological method, then, would allow one to understand form as an exact point in the evolutionary process (MCHARG, 1967).

Moreover, using the ecological inventory as a diagnostic tool, one can examine all parts of a system to assess its symptoms (SPIRN, 2000). In this sense, it is interesting to note McHarg's attributes of a system: it could be ill-health or health. Simplicity, uniformity, instability with a low number of species, and high entropy lead to retrogression and are associated to an ill-health system. Conversely, complexity, diversity, stability (steady state), with a high number of species and low entropy are indicators of a healthy and evolving system.

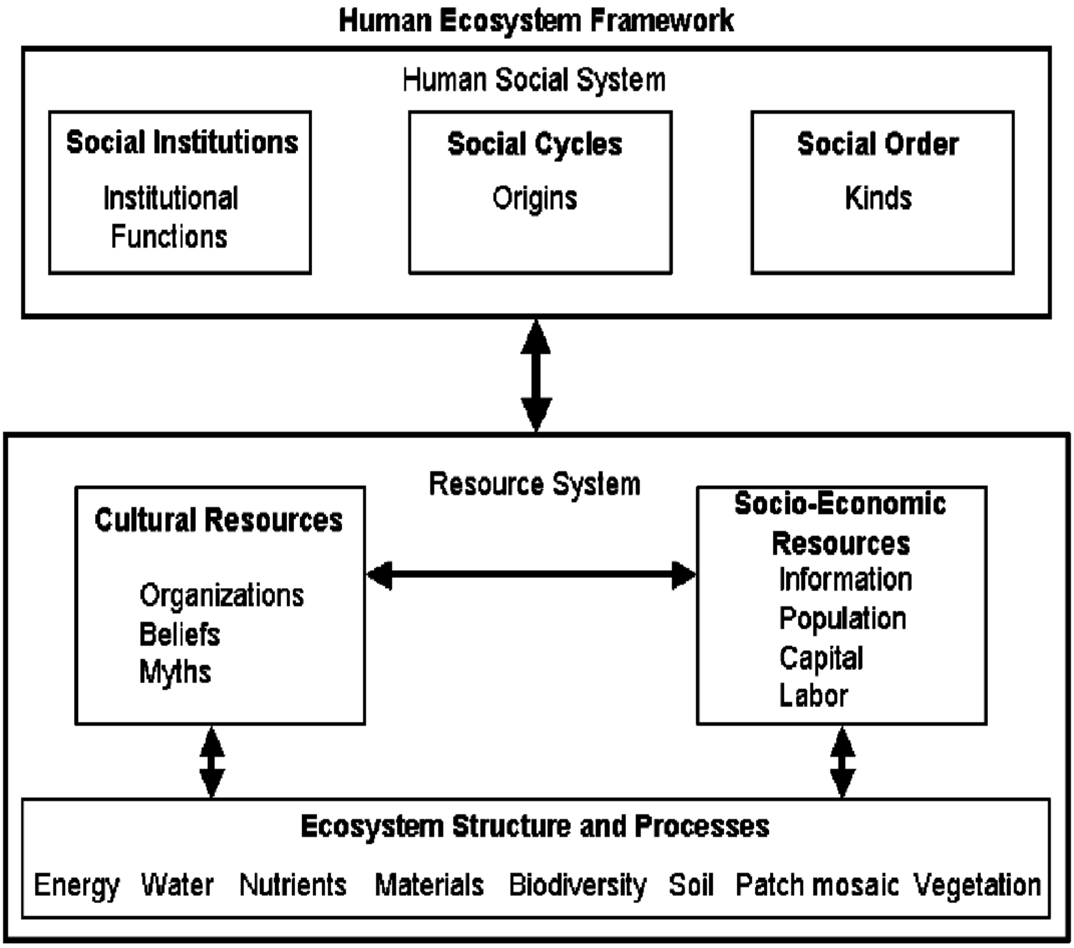
2.1.2. Urban ecology approaches

Traditional urban ecology studies focus on ecological processes and patterns, such as distribution and an abundance of animal and plant populations, patch-specific ecological pattern and processes, edge effects or exotic–native species interactions, within cities. However, as pointed out by Pickett et al. (1997a) and Grimm et al. (2000), urban ecology field has evolved from this conception, focused on natural patches within cities, to a more comprehensive understanding, in which cities themselves are ecosystems, with social and ecological components. This evolution can be posed as ecology in cities to the ecology of cities (PICKETT et al., 1997a; GRIMM et al., 2000) and it reflects a broadening of the empirical and methodological contents. Insofar, as it is recognized that relations within cities constitute an open system, far from equilibrium and potentially regulated by external forces (human actions), urban ecology takes on a new dimension and becomes an inter and transdisciplinary field of knowledge, involving physical, ecological and social sciences (MCDONNELL, 2011). Urban ecologists thus secured their place alongside planners and landscape architects, in understanding the relationship between cities and nature, and more specifically, the interaction between humans with the urban environment. The ecology of cities adds accurate and local-based knowledge of ecological processes, considering, at the same time, the impacts of human actions on such, as well as ecological feedbacks over the social system. They offer, indeed, a more comprehensive approach to planning and design.

Cities are, par excellence, transdisciplinary problems, to which the General System Theory, as the basis for an integrated science of complex organization (LASZLO, 1975), has provided common ground. Building on complexity theory and ecosystem's approach, which recognizes in cities emergent properties nonlinear dynamics, feedback, both the learning and adaptative capacities, framed as resilience (PICKETT et al., 1997b; ALBERTI, 1999; PICKETT et al., 2001), multiple frameworks have been proposed to identify and characterize urban components and their relationship. Following frameworks summarizes the conceptualization of urban systems developed within empirical and theoretical investigations: three of them were proposed in the context of Long-term Ecological Research Program conducted in the North American cities of Baltimore and Phoenix while the fourth one is based on empirical research conducted in Seattle, also in the United States.

In the context of Baltimore Ecosystem Study Long-Term Ecological Research, Pickett et al. (1997b) and Pickett et al. (2001) proposed a conceptual framework of a human ecosystem integrating the human social system and resource system, based on Machlis et al. (1997). In this framework (Figure 2.1) , they have addressed how to add humans to the ecological models used in urban ecology field and understand their role in ecosystems. The answer was to pose the ecosystem as the foundation for the socio-economic and cultural resource ecosystem. Details in the bio-physical ecological component are exemplary and specific questions and processes, such as which are the dominant social and natural phenomena and structures, which feedbacks operate effectively, which feedbacks operate with time lags, and so on, need to be specified in the empirical study.

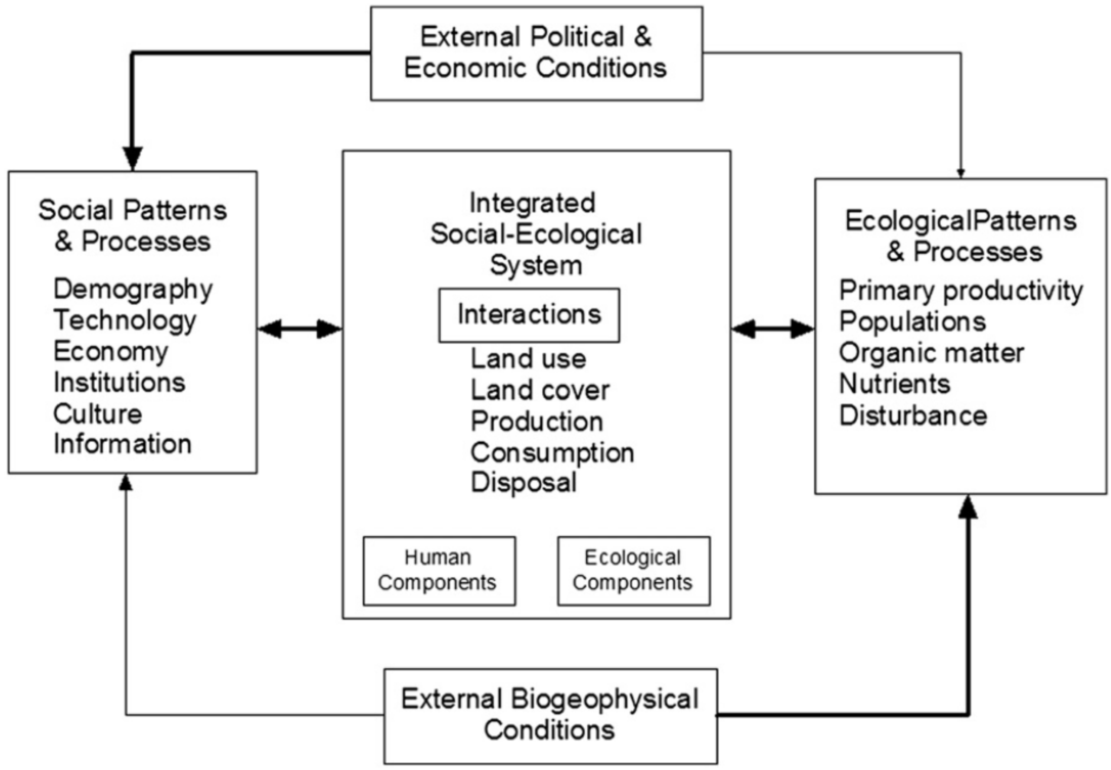
Figure 2.1 - Human ecosystem framework.



Source: Pickett et el. (2001).

After a decade of ecological researches in Baltimore and Phoenix, Pickett et al. (2011) reviewed the first theoretical preposition and presented a human ecosystem model template, in which the integrated social-ecological system, composed by human and ecological components, is emphasized (Figure 2.2). External social conditions and external biophysical conditions, capable of modifying the system through their effects on either the social or the ecological patterns and processes, are explicitly recognized. As a template, structural and interactive details from the human ecosystem causal framework are a suggestion of the content for a specific human ecosystem model.

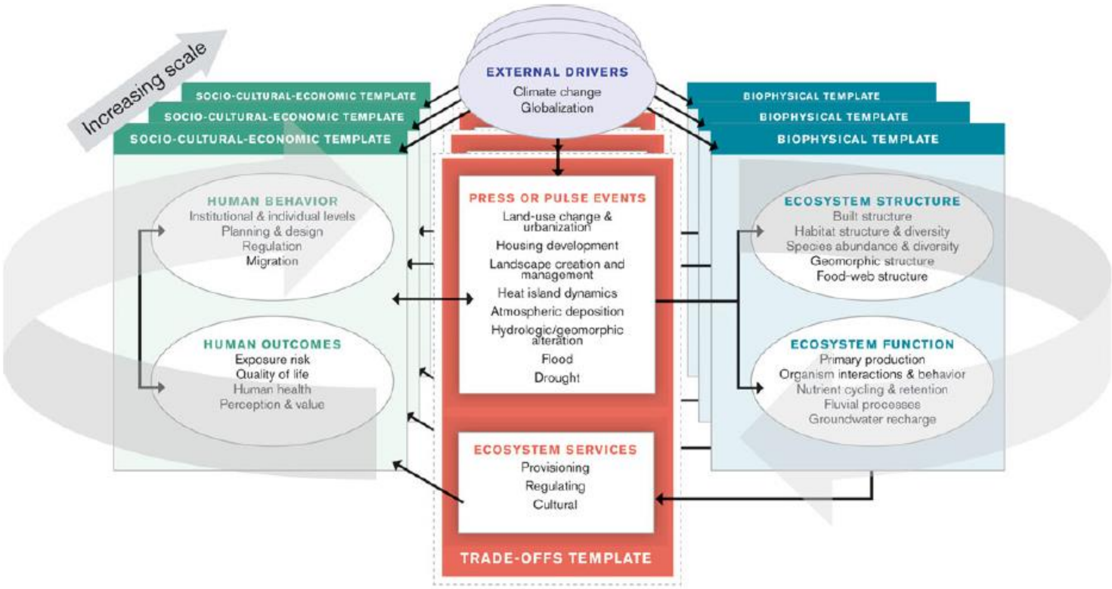
Figure 2.2 - Human ecosystem model template.



Source: Pickett et al. (2011)

A specific framework was developed to represent Central Arizona–Phoenix Long-Term Ecological Research (GRIMM et al., 2013). It addresses dynamic and potentially multiscalar characteristics of Central Arizona–Phoenix system (encompassing nested hierarchies of landscape scales and socioeconomic units), as well as socio-ecological interactions within parts and for the whole system (Figure. 2.3). Notably, it introduces urban infrastructure as part of built environment, as a component of the system, placed within the structure of the ecosystem, as well as ecosystem services which are recognized to be subject to a trade-off, based on human responses, such as perceptions and economic preferences or situations of disamenity. Ecosystems structure interact with and control rates of ecosystem processes and functions (e.g., primary production and nutrient cycling), which in turn are ‘inputs' to ecosystem services. Drivers of change are internal to the system – press events (e.g., air pollution, irrigation, land conversion, urban policies) and pulse events (e.g., flood, housing-market collapse) – or external, of long-term change (e.g., global climate change, macroeconomic fluctuations). Many of the actions taken by people are fed back to the ecosystem, often by changing the pulse or press events that affect ecosystem structure and function (e.g., irrigating residential landscapes affects biodiversity by altering microclimate).

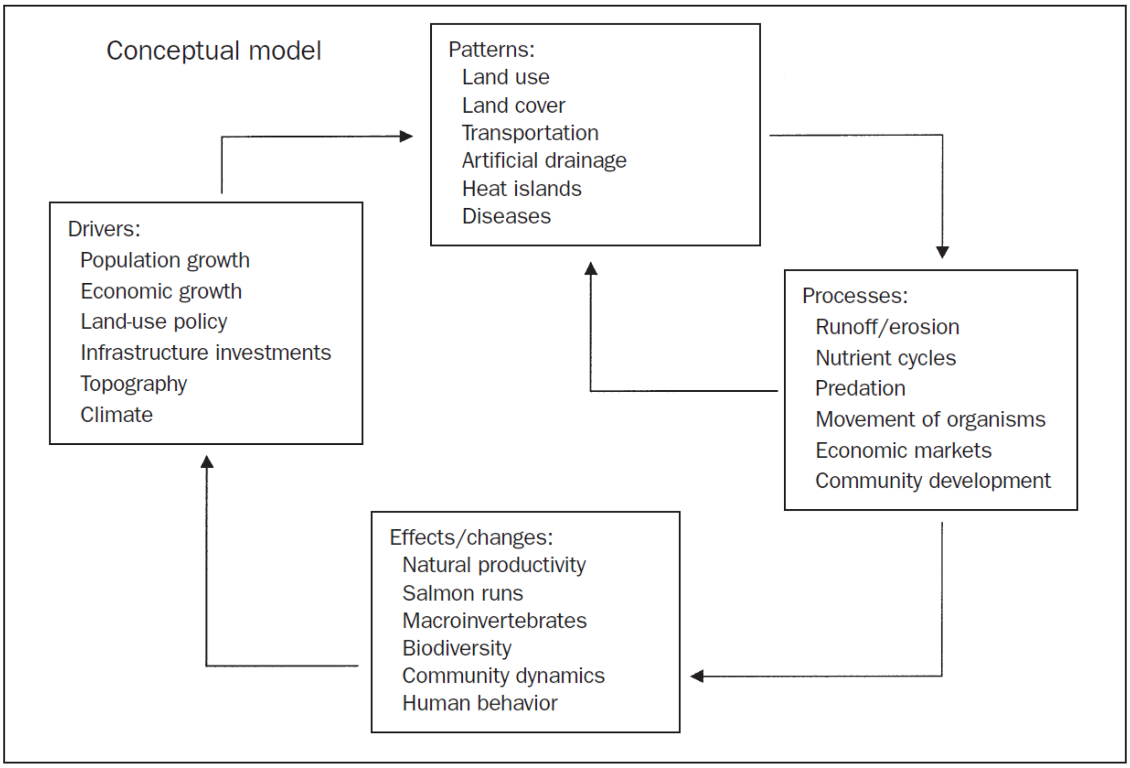
Figure 2.3 - Coupled social-ecological framework.



Source: Grimm et al. (2013).

In the integrated human and ecological processes model, proposed by Alberti et al. (2003), the emphasis on a cycle of actions and states allows testing formal hypotheses about the mechanisms (drivers and pattern-processes interaction) of the ecosystem dynamics and about the influence of these on the general characteristics of urban ecosystems, such as resilience or emergence (ALBERTI; MARZLUFF, 2004; ALBERTI, 2005; ALBERTI, 2007). In this framework, patterns of spatial and temporal distributions of social or biophysical variables interact with processes or mechanisms, such as runoff or community development, affecting human and ecological conditions, which, by their turn, will configure new drives of change (Figure 2.4).

Figure 2.4 - The integrated human and ecological processes model.



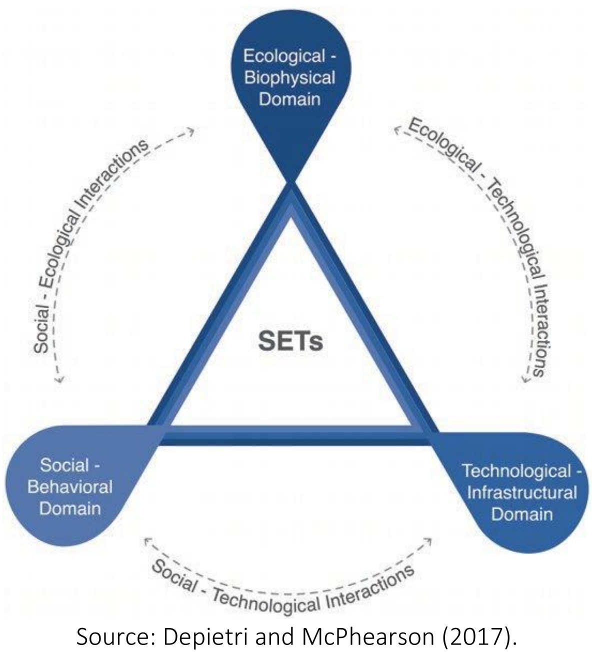
Source: Alberti et al. (2003).

Despite their specificities, these conceptual frameworks have envisioned cities as urban social-ecological systems (SES) composed by two inter-related (sub)-systems: human, which involves social, economic and cultural aspects of people and institutions; and natural, represented by biophysical elements.

Technology and infrastructure has been incorporated as a third (sub-)system, comprising the social-ecological-technological system (SETS) (MCPHEARSON et al., 2016). In this approach, ecological functions are included in a socio-technological framework whereas explicitly considers the role of technology and infrastructure within the social-ecological system (DEPIETRI; MCPHEARSON, 2017). From a management point of view, treating infrastructure integrated into a SETS can facilitate the identification and prevention of maladaptive issues that stem from SETS interactions, like lock-in, as well as offer new perspectives for adaptation strategies that may not be traditionally considered (GRABOWSKI et al. 2017; MARKOLF et al. 2018). Most importantly, the technical-infrastructural (sub-) system represents the built environment itself, that mediates the relationships between human actions and its environment, contributing to mitigate or to exacerbate impacts and stressors to this system.

SETS framework (Figure 2.5) is then based on core components of urban systems, grouped in three subsystems or domains: Ecological-Biophysical, Social-Behavioral, and Technological-Infrastructural. Since its only premise is the interaction between components of these domains, it is flexible enough to accommodate a variate type of analysis from distinctive perspectives to investigate urban system's dynamics and complexity (McPHEARSON; HAASE; KABISCH, 2016). Moreover, this approach can accommodate urban system's characteristics of openness and its multi-scalar nature (BAI et al., 2016).

Figure 2.5 - Theoretical framework of Social-Ecological-Technological Systems (SETS).



Source: Depietri and McPhearson (2017).

2.1.3. Vulnerability and resilience of social-ecological systems

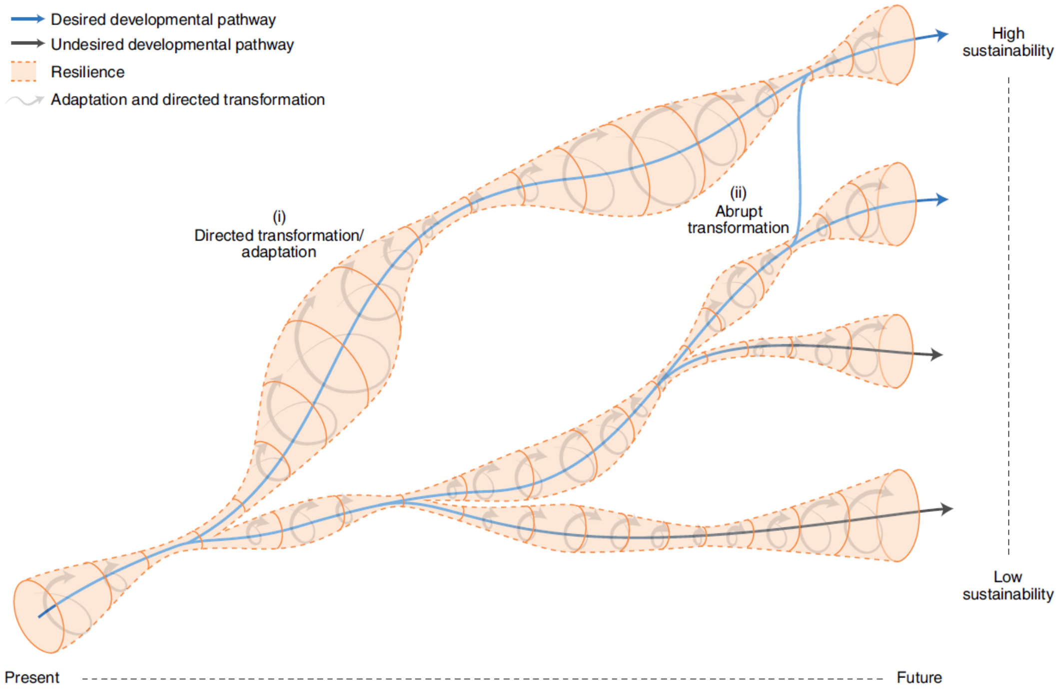
In Social-Ecological Systems' studies, resilience and vulnerability are both concepts commonly referred to. Within the field of Ecology, Holland has conceptualized resilience as "determinant of the persistence of relationships in the face of changes of state variables" (Holland, 1971), introducing the idea of multi-stable states instead of the single equilibrium paradigm dominant in that field. Resilience, therefore, is related to regime shifts and adaptation capacity to persist in one given state. This perspective became the theoretical foundation for studies of adaptive ecosystem behavior and management, in which aspects of the social and ecological theory were brought together with empirical practice, in a landscape-scale (FOLKE, 2006).

A broad definition of vulnerability is the susceptibility to be harmed as a characteristic of a system, group, person or even a place (BLAIKIE et al., 1994; CUTTER, 1996; McCARTHY et al., 2001). Vulnerability is rooted in underlying political and economic forces, which are not often apparent if the observation is limited to directly related unsafe conditions of a hazardous situation or a disastrous event (CUTTER, 1996). Social structures (as class structure, majority-minorities relationships or gender), government practices and conflicts and economic structures (such as distribution of wealth, economic priorities among others) regulate the access to resources in its several aspects, economic, social, natural, physical, human and political (BLAIKIE et al., 1994). In earlier studies of the human use of environmental resources and the risks associated with such usage, different disciplinary traditions concurrently understood vulnerability as an entitlement failure, focusing on its linked economic and institutional causative factors, or as explicitly related to risk, considering in this case environmental risks and underlying causes identified in a political ecology framework (Adger, 2006). This second approach has gathered physical science, engineering, and social science and was incorporated into social-ecological system's studies, alongside with resilience concept.

Building on the previous debate and framing vulnerability in the context of sustainability science, Turner et al. (2003) proposed a framework in which vulnerability consists of three components - exposure, sensitivity, and resilience. Nevertheless, some authors observed that resilience is also framed as loose antonym for vulnerability, in the sense that the latter is usually seen as a negative characteristic while the first is a desirable one, since it is related to self-organizing and learning skills in response to disturbances that concur to adaptation capacity (ADGER, 2000; McCARTHY et al. 2001, MEEROW; NEWELL, 2016).

Pointing out some misleading use and even interchangeable use of resilience and sustainability concepts, Elmqvist et al. (2019) present sustainability as a normative concept, representing a desired view that society envisions for its future, in opposite to resilience, a non-normative attribute of the system (or subsystems) that maintains function in the face of a disturbance, allowing its structures to undergo a transformation. They argue that in a trajectory to urban sustainability, resilience may be advantageous or not. A more resilient system would be kept in an ongoing trajectory, through a reactive response, pursuing a directed transformation or adapting, while non-resilient system could be induced to change. If there is a need for change in the ongoing trajectory, resilience may be an undesirable characteristic once a lack of it could lead to an abrupt transformation, as a proactive response (Figure. 2.6). Moreover, if sustainability is reduced to the pursuit of increased efficiency, it collides to resilience capacity, which stems from the character, diversity, redundancies, and interactions among and between the components that perform distinct, but sometimes, overlapping functions (ELMQVIST et al., 2019).

Figure 2.6 - Trajectories to urban sustainability.



Source: Elmqvist et al. (2019).

A complementary idea would be the proposition of Meerow and Newell (2016) to explicit recognize politicized decisions, scalar dimensions, and trade-offs inherent to applying resilience empirically. In this sense, they beg the question: resilience for whom? Resilience to what? At what temporal scale are disturbances noticed? Where is resilience applied, or what are the system's boundaries? Also, why build urban resilience? Indeed, this would also complement the third paradigm in urban ecology envisioned by Pickett et al. (2016) as a conjunction of ecology in the cities and ecology of the cities: the ecology for the cities, as a transdisciplinary linkage between ecological science and civic processes. They argue that this could bring researchers, professional practitioners, decision-makers, and urban residents into a dialog about ecological knowledge and its implications in addressing biophysical restoration, social revitalization, economic vitality, and environmental justice as essential processes contributing to urban sustainability.

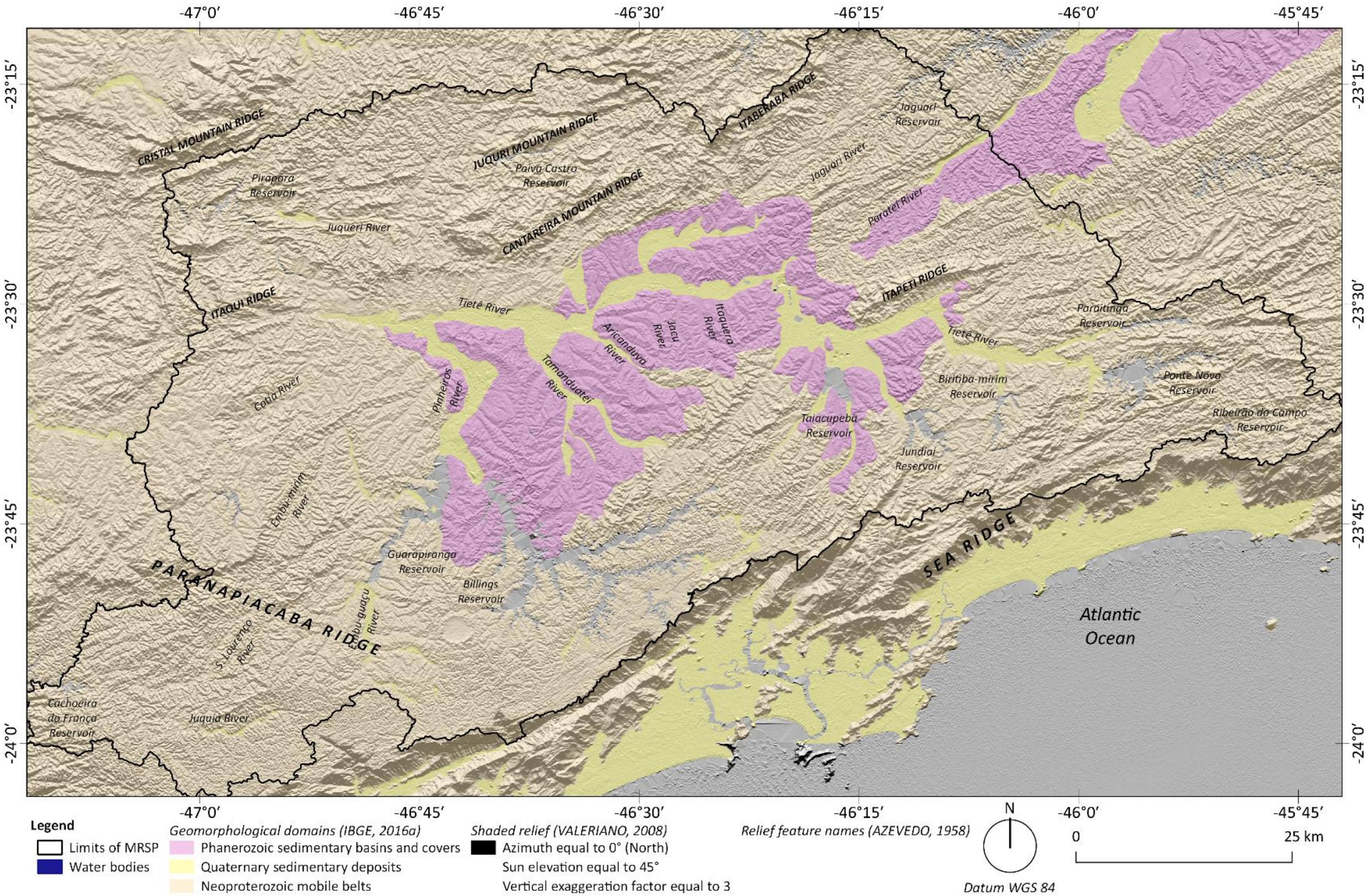
2.2. Urban occupation of hillsides in the Metropolitan Region of São Paulo

2.2.1. The original site of São Paulo

Throughout history, the occupation of hillsides has been motivated by security, health, religious purposes, or exceptionality of the place, among other reasons (OLSHANSKY, 1998; AFONSO, 1999). Salvador city is the most eloquent example of historic Brazilian settlement that took advantage of the relief – in this case, the geological fault that follows Todos os Santos Bay – for protection, following Portuguese urbanistic tradition (SIMÕES JUNIOR; CAMPOS, 2013). Moreover, geomorphological characteristics of part of Brazilian territory, over the Atlantic Plateau, presses the coexistence of cities and slopes. In its extension, in Atlantic coast and its immediate hinterland from the Paraná state through the states of São Paulo and Rio de Janeiro to the north of Espírito Santo, relief compartments large enough to accommodate big cities are rare (AB'SABER, 1958).

São Paulo was founded in one of these large compartments, called Sedimentary Basin of São Paulo, comprised by the extensive fluvial plains of the Tietê and Pinheiros rivers and soft hills and platforms formed by phanerozoic sediments (Figure 2.7). The top of a steep hill between the Anhangabaú and Tamanduateí rivers, tributaries of Tietê river, was chosen by Jesuits to establish their pioneer settlement (Figure 2.8).

Figure 2.7 - MRSP, geomorphological domains and relief.



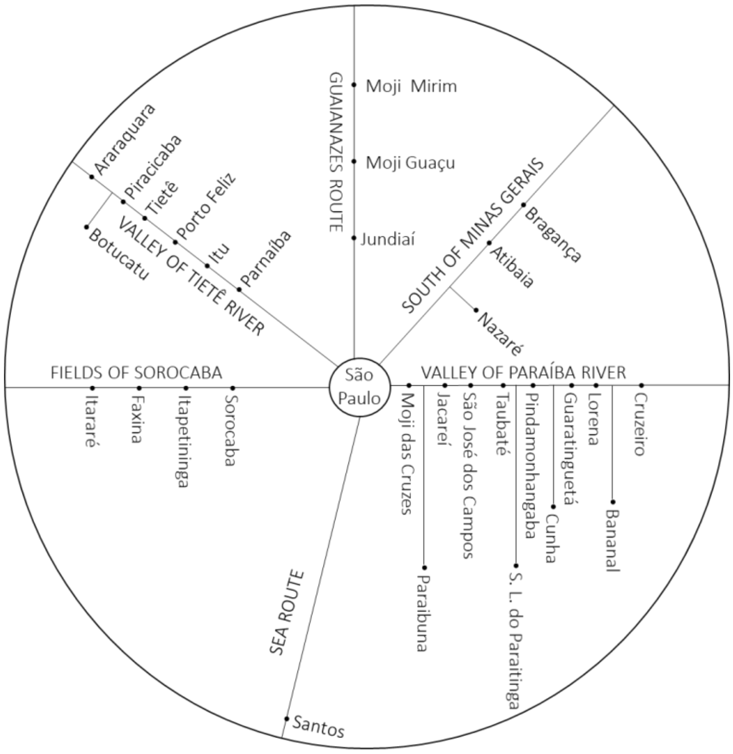
Source: Author.

Figure 2.8 - São Paulo original settlement in 1827, portrayed by Jean Baptiste Debret.

Watercolor depicting the entrance of São Paulo's original settlement, at the top of a hill, with the Tamanduateí river in the background.
Source: Lago (1998).

Prado Júnior (1935) points to regional geographical factors which influenced the establishment of a colonial nucleus in São Paulo: the narrow and underutilized coastal strip due to the presence of mangroves and low lands and the hot and humid climate, which forced the establishment of a colonizing nucleus in the plateau; the lowest height of the Serra do Mar near São Paulo (about 800m), which gave relative ease of transposition of this barrier and, finally, the vegetation, a reflection of the poor soil of clay tertiary river-lacustrine deposits, which was known as Campos from Piratininga. Also, the city's development was propitiated by its location, thus constituting a knot of the interior penetration and connection roads established by the conditions of relief and hydrography. Figure 2.9 shows in a schematic way the location of São Paulo as the center from which the connecting routes that followed the valleys of the Tietê and Paraíba do Sul Rivers or used passages through the mountains and depressions.

Figure 2.9 - Schematic regional connections from São Paulo.



Source: Adapted from Prado Júnior (1935).

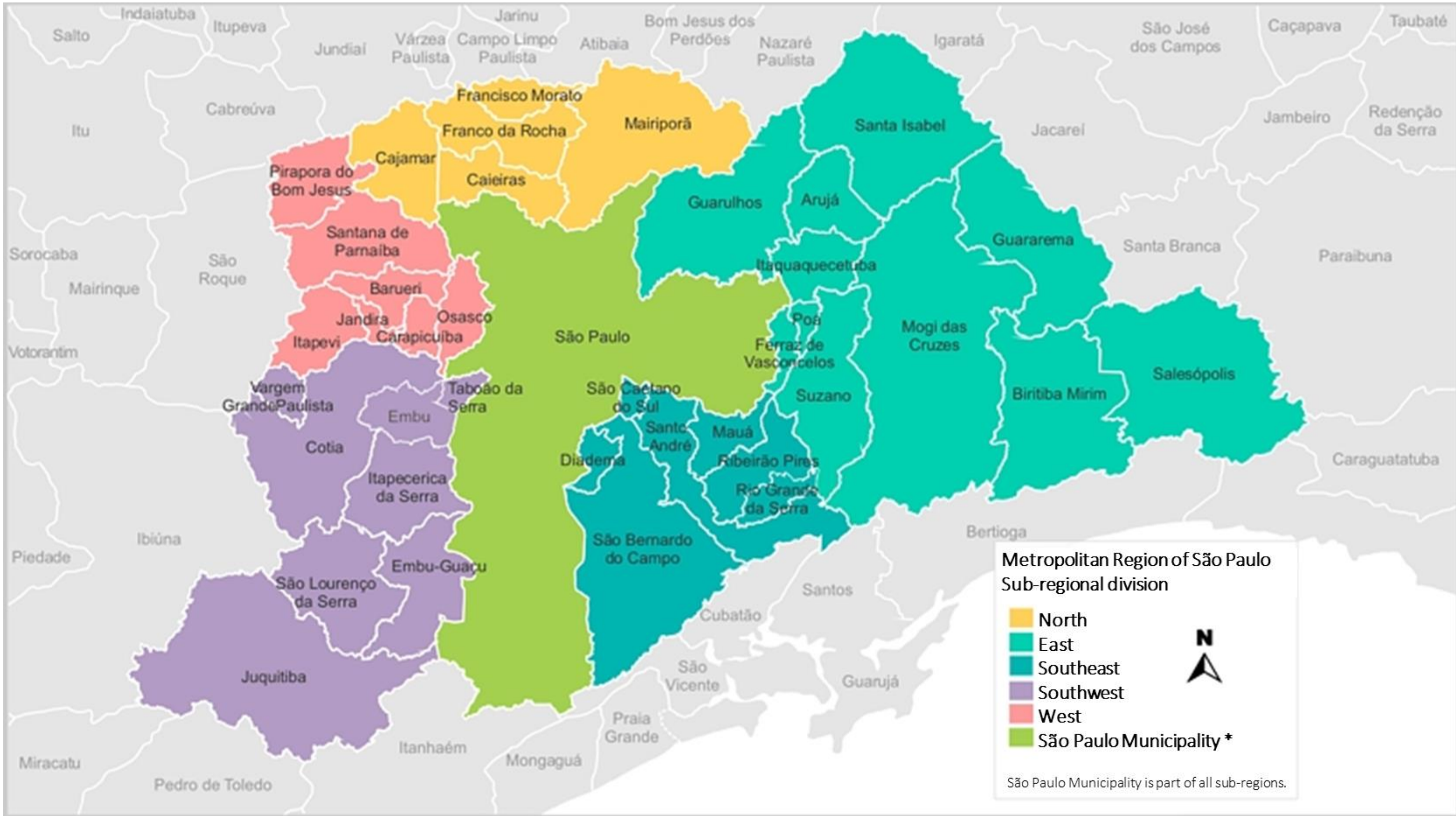
2.2.2. Metropolitan area: an early formation

At the beginning of XXth century, the economic cycle of coffee was responsible for the economic dynamism of São Paulo, placed in the connection of Port of Santos and production areas of coffee in the west of São Paulo state (in the valley of Tietê River and Fields of Sorocaba), that were established following the former connection and penetration routes. The coffee economy was succeeded by the implementation of an industrial park which at first, took advantage of the ease provided by the highway system and in vast flat areas on the rail system, establishing itself mainly in the southern quadrant of São Paulo, continuing through the cities of São Caetano e Santo André (LANGENBUCH, 1971). The pattern of urbanization that is beginning to develop is that of suburbanization, initially following the rail and tram lines, but later also relying on bus lines. This pattern is responsible for an early metropolization of occupation, albeit with many urban voids: allotments were created without the concern of maintaining the continuity of the urban sprawl. They are not yet entirely necessary for urban sprawl and remain sparsely occupied (LANGENBUCH, 1971).

From the second half of XX century, the continuous populational and industrial growth prompted the expansion of urbanization through the compaction of previously dispersed allotments, reducing the empty plots and giving raise to vertical buildings in specific parts of São Paulo city. The expansion of the rail system has been halted and this system has been replaced by the road system, which inherited the role of directing the urban expansion (LANGENBUCH, 1971). Urbanization would expand radially from São Paulo city. São Caetano do Sul, and Santo André, which had already a remarkable industrial park experienced, alongside with São Bernardo do Campo, Osasco and Guarulhos, exhibited a functional diversity and numerous urban facilities and, therefore, becoming independent from São Paulo (LANGENBUCH, 1971). By 1970, metropolitan area had virtually consumed suitable areas and began to advance to the hillsides of the Neoproterozoic mobile belts, formed over a crystalline basement of metamorphic and igneous rocks and prone to erosion processes (Figure 2.7) (MARCONDES, 1999; IBGE, 2009).

In 1973, the metropolitan entity was created by federal Law, nº 14, comprising 39 municipalities: São Paulo, Arujá, Barueri, Biritiba-Mirim, Caieiras, Cajamar, Carapicuíba, Cotia, Diadema, Embu, Embu-Guaçu, Ferraz de Vasconcelos, Francisco Morato, Franco da Rocha, Guararema, Guarulhos, Itapecerica da Serra, Itapevi, Itaquaquecetuba, Jandira, Juquitiba, Mairiporã, Mauá, Mogi das Cruzes, Osasco, Pirapora do Bom Jesus, Poá, Ribeirão Pires, Rio Grande da Serra, Salesópolis, Santa Isabel, Santana de Parnaíba, Santo André, São Bernardo do Campo, São Caetano do Sul, Suzano e Taboão da Serra. In 2011, Complementary Law nº 1.139, from State of São Paulo, reorganized MRSP in 5 sub-regions (north, east, southeast, southwest and west), maintaining its boundaries (Figure 2.10)

Figure 2.10 - Municipalities and sub-regions of Metropolitan Region of São Paulo.



Source: EMPLASA (2011).

2.2.3. The suburban growth pattern

Urban development occurred during the decades of 1960 and 1970 definitively shaped the distinctive pattern of urbanization in MRSP, the "suburban growth pattern" characterized by the development of suburban allotments, an active legal and illegal real estate market based on public transportation system and aimed at low- and medium-income working class (LANGENBUCH, 1971; MARICATO, 1982; ROLNIK, 1997; MEYER et al., 2004). Self-aided building was a common practice, and ordinances played a role in shaping this process by a contradictory relationship.

Maricato (1982) described self-aided building as the "possible architecture"; this is an essential means to tackle the housing problem, by which families, friends, and neighborhoods exchange hours of labor during weekends and days-off to be a bricklayer in someone's construction. Bonduki and Rolnik (1982) argued that self-aided building is a way to create a product, that will have an exchange value when rented or sold, what, according to their observations, is a widespread activity.

Strict ordinances and zoning resulted in a more expensive pattern of urban development, restricted to central areas occupied by a minority of the urban population, creating a differentiation between these areas and those more peripherical, destinated to low-income population (BÓGUS; PASTERNAK, 2009). On the other hand, a federal level ordinance, law nº 6.766, promulgated in 1979 to regulate land developing under civil, administrative and urbanistic aspects, resulted as a side-effect of the expansion of the illegal allotments, due to the number of urban and administrative requirements for their legal approval (SACHS, 1999). Another example of how ordinances played an unintended role was the creation of environmental protection areas in the watershed of Guarapiranga and Billings in 1975, which triggered a massive illegal occupation in these areas. Due to their restriction, they became unattractive to the real estate market, therefore, losing value. They were, then, developed as illegal allotments and lots sold at affordable prices to a population of migrants, employed in the industries (MARCONDES, 1999).

In illegal allotments, the price of the plot is defined based on dweller payment capacity and, to maximize profits, land developers restrict their investment to the minimum necessary: provision of streets and lots, without any infrastructure system or technical advisory for grading (BONDUKI; ROLNIK, 1982). Although there is a purchase contract, very often it has not a legal validity, in the sense that there is not a legal permit to the development what prevents to obtaining title deed. The history of illegal allotments shows tolerance followed by amnesty, without charging land developers the costs to provide infrastructure, which is eventually carried out by municipalities, indirectly subsidizing this activity (PASTERNAK, 2010).

Rolnik (1997) argues that legislation failures were intended and promoted by political, economic, and cultural means. These failures were not only in its applicability but, mainly in determining urbanization patterns that were incompatible with most of the the population's level of economic resources. In a more comprehensive perspective, Villaça (2001) observed that these means are used to a differential appropriation of the urban space, perpetuating the socio-spatial segregation in Brazilian metropolises.

"*Favelas*" (squatters or slums) are different from illegal allotments in the sense that they consist in the invasion of public or private land. Moreover, in illegal allotments there is a defined lot that is sold, whereas in favelas there are not individual parcels of land. Bonduki (1994) points to a correlation between suburban development and *favelas*: the vast offer of lots in suburban, and eventually illegal allotments constrained this housing alternative, in a process to also contribute the stigmatization of *favelas'* dwellers. Nevertheless, in the 1980s, there was a noticeable growth of the *favelas*. Observing São Paulo municipality data, in 1975 percentage of the population living in *favelas* was of 1.6%, in 1987 this percentage has raised to 7.53% and in 1991, to 9.24% (PASTERNAK, 2006).

In *favelas*, building techniques are not different from the legal and illegal allotments, based on self-aided building (MARICATO, 1982; BONDUKI; ROLNIK, 1982; PASTERNAK, 2006). As opposed to earlier *favelas*, where the predominant material was wood, there is an observable pattern of improvement of houses' building material, with the introduction of bricks and concrete slabs and blocks, the same materials used in self-aided buildings on illegal allotments (PASTERNAK, 2006).

Both *favelas* and illegal allotments are defined in the Demographic Census, carried out by the Brazilian Institute of Geography and Statistics (IBGE), as "subnormal settlements". This definition has changed over the years. In 1991, definition was as follows: "a set of housing units (shacks, houses etc.) occupying until recent period, land owned by others (public or private), with a disordered layout and dense occupation and absence of public and essential services and, in the moment of its development, absence of deeds" (IBGE, 1991). In 2010, it was: spatial units (censuses tracts) with 51 or more housing units characterized by the absence of title deeds and irregularity of the roadways and the size and shape of plots and / or lack of essential public services (such as garbage collection, sewage, water and electricity systems and public lighting) (IBGE, 2013). Although there are limits to IBGE's estimates concerning subnormal settlements, which could lead to an underestimated number of these settlements (MARQUES et al., 2003), the data uses the same methodological approach and concepts to all municipalities, allowing their comparability and contributing to a comprehensive characterization of this situation.

In 2010, according to Demographic Census, MRSP concentrated a significative percentage of subnormal settlements in Brazil: 1,703 units, representing 27% of the total number of Brazilian subnormal settlements, with more than 2 million people, or 19% of the total population in subnormal settlements (PASTERNAK, 2014). In MRSP, the main municipality, São Paulo, concentrated more households and households in subnormal settlements than the sum of the rest of the municipalities, and this preponderance has not changed over time (Table 2.1). However, in São Paulo municipality, the percentage of households in subnormal settlements was lower than in the rest of MRSP for 1991 and 2000; although for the last Census year, 2010, the situation was reversed. Nevertheless, the overall movement for the entire MRSP was of an increase in participation of households in subnormal settlements: from 5.7%, in 1991, to 9.8% in 2010 (Table 2.1). The proportion of households in subnormal settlements was higher than the average of MRSP in the municipalities of Taboão da Serra, Osasco and Embu (between 10% to 13%), Guarulhos (16%) and São Bernardo do Campo, Mauá and Diadema (around 20%) (PASTERNAK, 2014).

Table 2.1 - Total households and households in subnormal settlements in 1991, 2000 and 2010, for São Paulo municipality, other municipalities and MRSP.

		Year	São Paulo municipality	Other municipalities	Metropolitan Region of São Paulo
Total households	(units)	1991	2,630,138	1,580,306	4,210,444
		2000	3,039,104	2,040,084	5,079,188
		2010	3,576,864	2,512,983	6,089,847
Households in subnormal settlements	(units)	1991	146,891	93,972	240,863
		2000	225,133	188,220	413,353
		2010	355,756	240,723	596,479
	(% of total households)	1991	5.6%	5.9%	5.7%
		2000	7.4%	9.2%	8.1%
		2010	9.9%	9.6%	9.8%

Source: Adapted from Pasternak (2014).

São Paulo municipality exhibited a constant annual growth rate for the two periods, 1991-2000 and 2000-2010. These rates were lower for total households (1.6%) than for households in subnormal settlements (4.7% to 4.9%). On the other hand, for the rest of municipalities in MRSP, annual growth rates were higher in 1991-2000, both for total households and households in subnormal settlements. Remarkedly, in this latter case, the rate was very expressive: 8.02%, and this was reflected in MRSP's rate of 6.18% (Table 2.2).

Table 2.2 - Annual growth rate of total households and households in subnormal settlements 1991-2000 and 2000-2010, for São Paulo municipality, other municipalities and MRSP.

	Period	São Paulo municipality	Other municipalities	Metropolitan Region of São Paulo
Total households	1991-2000	1.62%	2.88%	2.11%
	2000-2010	1.64%	2.11%	1.83%
Households in subnormal settlements	1991-2000	4.86%	8.02%	6.18%
	2000-2010	4.68%	2.49%	3.74%

Source: Adapted from Pasternak (2014).

2.2.4. Hillsides occupation patterns in MRSP

In Brazil, the main feature considered in the approval of land development on hillsides is its slope. Brazilian Federal Law 6.766 / 1979 states that areas with a slope equal to or greater than 17° (or 30%) should not be occupied unless specific requirements of the competent authorities are met. Brazilian Forest Code (Federal Law 12651/2012) considers, as Permanent Protection Area (PPA), hillsides or parts of hillsides of slope higher than 45° (or 100%). Federal regulation is usually reproduced by local regulations in the MRSP (FARAH, 2003). A specific regulation from São Paulo State regards to watershed protection (No. 1172/1978, modified by 15913/2015) establishes that, in the four watersheds used for water supply, areas with a mean slope of more than 60% are not supposed to be occupied.

Bitar et al. (2012) based on geotechnical cartography and stability analysis of the relief of southeastern Brazil, point out a slope of 30° (58%) as a limit above which landslides occur with a significantly higher frequency. As a result of their work, they suggest consider that on hillsides of slopes between 17° (30%) and 25° (47%), urban occupation must be conditioned by implementation of measures resulting from detailed studies; between 25° and 30° (58%), special measures of even greater detail should be adopted to make urban occupation feasible; and between 30° and 45° (100%), urban occupation should be avoided.

Nevertheless, legal prohibition does not assure the preservation of Permanent Protection Areas, nor the security of the urban occupation on the hillsides. Schutzer (2012a) observed that the suburban growth pattern was somehow fragmented by major natural features, like the Cantareira Mountain Ridge, as well as by other local features, such as amphitheater valley heads or steep slopes. When located outside areas valued by the real estate market, not rarely these areas were where low-income populations found a solution for the housing problem, whether by the acquisition of illegal settlement's lots, whether by land invasion, under the condescending and discriminatory attitude of local authorities (MARICATO, 1995).

In MRSP, in 2010, 166,030 households were in subnormal settlements with a slope higher than 17° (or 30%), what corresponds to 27.8% of the total households in subnormal settlements (Table 2.3). This percentage is lower (25.4%) for São Paulo Municipality and higher for the rest of municipalities (31.4%), although, in absolute numbers, the situation is the opposite: 90,384 units São Paulo municipality against 75,646 units in the rest of municipalities) (Table 2.3). Important to note that these characteristics are based on observation *in loco* of predominant situations and they were compiled only to 2010 Census, as one of the methodological improvements made by IBGE to better characterize and measure subnormal settlements.

Table 2.3 - Number of households in subnormal settlements by topographic condition, in 2010, for São Paulo municipality, other municipalities and the MRSP, according to Survey of Territorial Information (IBGE, 2013a).

Topographic condition	**São Paulo Municipality**		**Other municipalities**		**Metropolitan Region of São Paulo**	
	(units)	**(%)**	**(units)**	**(%)**	**(units)**	**(%)**
Flat areas (up to 3° or 5%)	135,093	38.0%	70,063	29.1%	205,156	34.4%
Soft hills (from 3° to 17° or 5% to 30%)	130,279	36.6%	95,014	39.5%	225,293	37.8%
Steep slopes (more than 17° or 30%)	90,384	25.4%	75,646	31.4%	166,030	27.8%
Total	355,756	100%	240,723	100%	596,479	100%

Source: Author.

Many authors have described hillsides occupation in the MRSP, characterizing its landscape and relationship with relief (e.g. AFONSO, 1999; SCHUTZER, 2012a), as well as focusing on subnormal settlements in slopes (e.g., PELOGGIA et al.,1992; PELOGGIA, 1997; FARAH, 2003; SILVA, 2004; CHAGAS,2007).

The Cantareira Mountain Ridge are a distinctive relief feature in MRSP and encompass different patterns of hillsides occupation. The south face is in the municipality of São Paulo, while the north is in the municipality of Mairiporã. Herling (2002) theorized about the relationship between urbanization and Cantareira Mountain Ridge, in São Paulo municipality, proposing three main periods in which different processes characterized this relationship. In the first period, from 1870 to 1960, vast areas were acquired by the government to implement the Cantareira water supply system. Efforts were made to regenerate the forest, devastated by the sugarcane and coffee plantations of the colonial period, and to protect it, following the prevalent sanitary perspective of the time. From this point of view, due to the non-treatment of the city's sewage, the water supply should be as far as possible from it and, furthermore, to ensure water purity, the water supply should be in a forested area. The Cantareira State Park, opened in 1962 and extending over 7,900 ha, was created in this concept of protecting springs with the preservation (and regeneration) of the remaining Atlantic Forest vegetation.

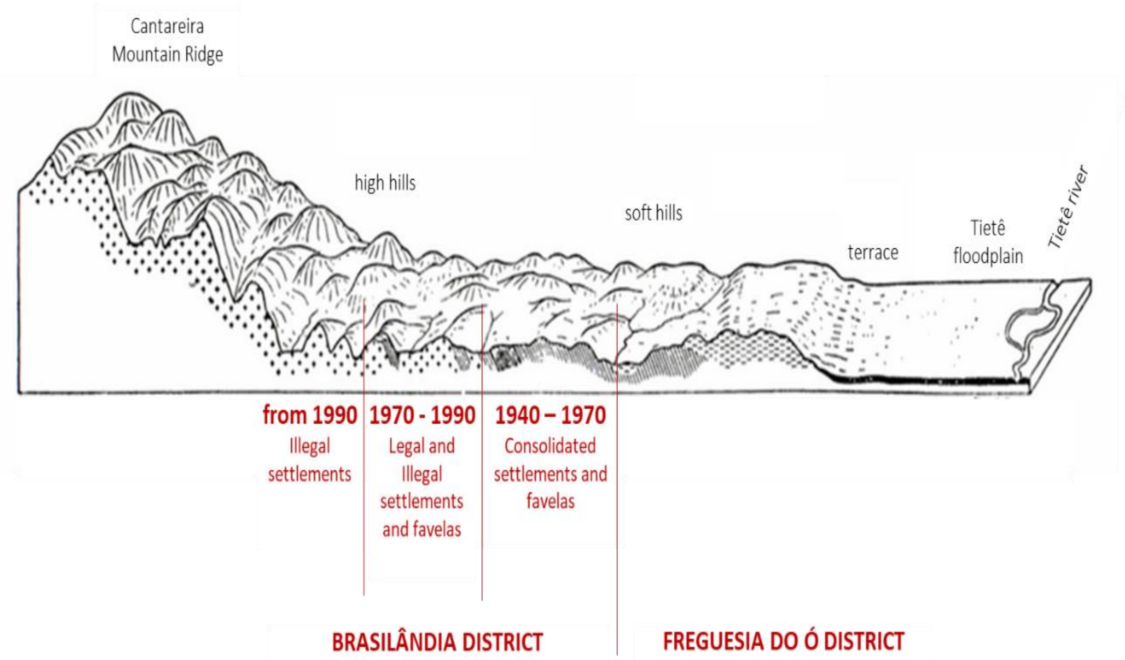
In the second period, between 1960 and 1990, Herling (2002) argues that technological advances in pumps and new water treatment techniques made the forested environment indispensable, as well as allowing the capture of water in areas farther from the city and the increased volume it demanded. During this period, the pattern of illegal and peripheral expansion reaches the areas occupied by decaying small farms, pushing down the price of land. The illegality, in this case, was in the transformation of rural areas, not allowed in zoning, to urban ones. Old rural roads that ran along relief ridges became avenues where bus lines met the growing demand. Drainage lines were transformed into valley floor avenues or were abandoned and serve as drainage for untreated sewage from new homes. Earthmoving solutions were taken individually for each lot, which were generally deployed across contours lines. This expedient requires more significant movement of land in the lots, but less movement for the implantation of the streets, relieving the burden of the land developer.

From 1990, Herling (2002) identifies a new period, marked by the advance of occupation to the limits of the Cantareira State Park and the occupation and invasion of increasingly precarious and fragile areas. In a way, public transport network consolidation and expansion and the opening of new roads in the North Zone contributed to the occupation of this area.

Despite being pressured by invasions and illegal allotments, Serra da Cantareira played an important attractive role for the implementation of high standard condominiums, with weekend or even suburban residential homes. Facilitated by the duplication of the Fernão Dias Highway, these allotments have suggestive names such as Cantareira Alps or Switzerland Cantareira Residential and occupy the entire north face of the Serra, already in the municipality of Mairiporã. Prior these allotments, this face of Cantareira was an abandoned pasture, and allotments have encouraged the regrowth of a secondary vegetation in this area.

The process described by Herling (2002) for the North Zone, in general, is detailed by Angileli (2012) for the Brasilândia district. The occupation of the district began in the 1940s, with the replacement of small farms by popular allotments, occupied at first by Japanese and Italian immigrants. This is currently the most consolidated portion of the district, with single-story houses and backyards. Angileli (2012) calls pre-hills, the soft hills area, which was occupied between 1970 and 1990 (Figure 2.11).

Figure 2.11 - Succession of relief shapes from Tietê floodplain to Cantareira mountain ridge (10,5km) and occupation by periods in Brasilândia district (São Paulo municipality).



Source: Adapted from Ab'Saber (1957) and Angileli (2012).

With the relaxation of the protection of the Cantareira water supply, there was a remarkable advance of occupation in this area with new neighborhoods, public housing developments, but also illegal allotments and slums. From 1990 onwards, the occupation, which was predominantly illegal, advanced on the more sloping areas, already in the ridge itself, being contained only by the southern limit of the Cantareira State Park and, more recently, by the establishment of the northern section of the *Rodoanel*, a beltway that encircles the urban areas of the MRSP.

In general, *favelas* will occupy the most prominent features of the relief, such as the grottos, amphitheaters, and drainage lines that had been relegated by the subdivisions (ANGILELI, 2012). Chakarian (2008) made a similar observation in the Jardim Ângela district, in the south of São Paulo municipality. Located in a region marked by precariousness and poverty, *favela* Jardim Solange, due to its location on a hillside (Figure 2.12), is even more precarious than the surrounding area. In this *favela*, domestic sewage is discharged into the open stairway channels, creating breeding grounds for rats and insects and garbage is thrown down the hillsides, as the collection trucks only reach the road of M`Boi Mirim.

Figure 2.12 - Overall view of Jardim Solange (São Paulo municipality).

Source: Chakarian (2008).

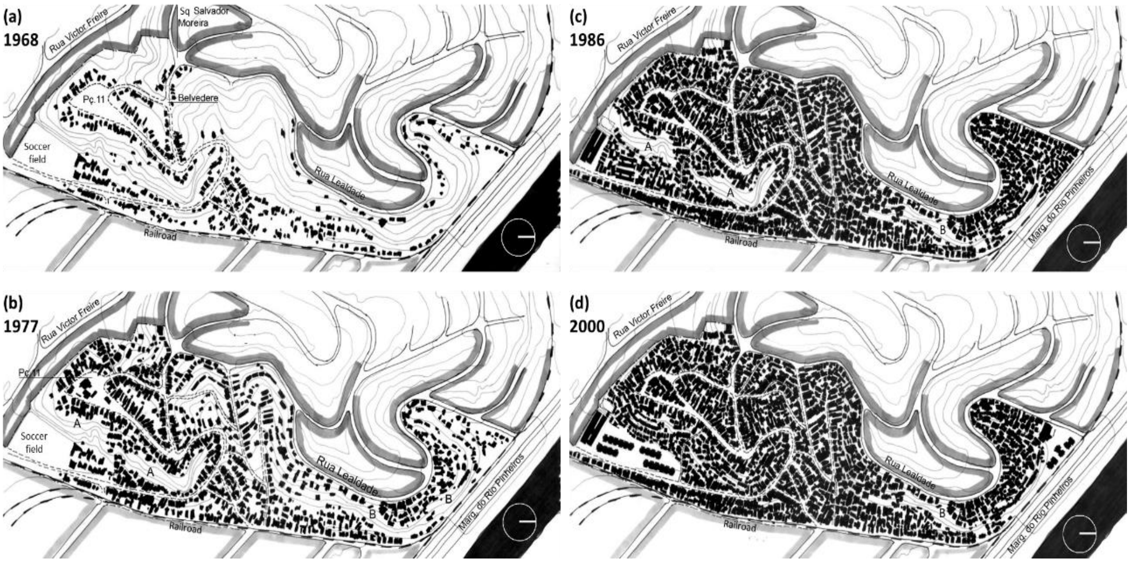
Moreover, even within a slum, the most fragile areas among the fragile ones are those that are occupied later and sometimes end up forming areas that do not consolidate. Angileli (2012) noted that the *favela* Jardim Paraná has two distinct areas, one occupied by residents at the time of the area's invasion in 1994, and other, the valley floor. In the first area, houses are masonry and already have two, three, and even four floors; Its residents together demanded public improvements, which gradually contribute to the consolidation of the area. In the second area, the conditions are unhealthier because this is the place of accumulation of garbage and sewage, brought by the natural drainage lines, and is a flooded area in times of rain. Houses are smaller and sometimes are wooden houses (Figure 2.13). Angileli (2012) noted that most of these residents see this situation as transitory and, thus, do not establish a link with the place.

Figure 2.13 - Two different areas in *favela* Jardim Paraná (São Paulo municipality): the oldest occupation (left) and the newest one (right).

Source: Author.

Freire (2006) studied *favela* Jaguaré, in the west zone of São Paulo municipality. The public area was invaded in 1962. The area, which was intended to be a park, was abandoned and used as a borrow area to the industrial areas nearby. Successive public investments in infrastructure and housing were directed to this *favela*, and finally, in 2015, deeds were granted to dwellers. The earlier occupation started at the bottom part of the *favela*, along the railroad line, and at the top, from the Salvador Moreira square, as observed in 1968 situation (Figure 2.14 (a)). As the occupation growths, areas of the steep slope were progressively being occupied (areas marked as A and B, in Figure 2.14 (b) and (c)). In 2000 situation, only the area known as “soap hill” (“*morro do sabão*”) remained unoccupied (area marked as B, in Figure 2.14, (d)).

Figure 2.14 - *Favela* Jaguaré (São Paulo municipality), in (a) 1968, (b) 1977, (c) 1986 and (d) 2000.



Source: Adapted from Freire (2006).

Sato (2008) documented an illegal allotment called Rancho Novo (Guarulhos municipality), in the Taquara do Reino basin, an amphitheater head valley. This area was developed at the beginning of 1990. The 1988 aerial photo shows the still rural occupation of interconnected sites along the tops of the hill (Figure 2.15, (a)). In the 1993 image, the southwest slope of the basin is occupied (Figure 2.15, (b)), with the opening of roads forming an orthogonal pattern of blocks and plots well defined (Figure 2.16). In the 2000 image, both the drainage head and the northeast face are occupied (Figure 2.15, (c)).

Figure 2.15 - Rancho Novo allotment (Guarulhos municipality), in (a) 1988, (b) 1993 and (c) 2000.

Source: Adapted from Sato (2008).

Figure 2.16 - Housing units in Rancho Novo allotment (Guarulhos municipality).

Yellow dots represent housing units.
Source: Sato (2008).

Despite the situation of illegality and the permanent threat of removal, this allotment has received public improvements and is progressively being consolidated. The 2007 photo shows two blocks of northeast slope without paving (Figure 2.17). In the 2017 photo, the settlement is consolidated, the roads are paved, and one can observe the densification process, with the construction of a second floor (Figure 2.18).

Figure 2.17 - View of east hillside Rancho Novo allotment (Guarulhos municipality), in 2007.

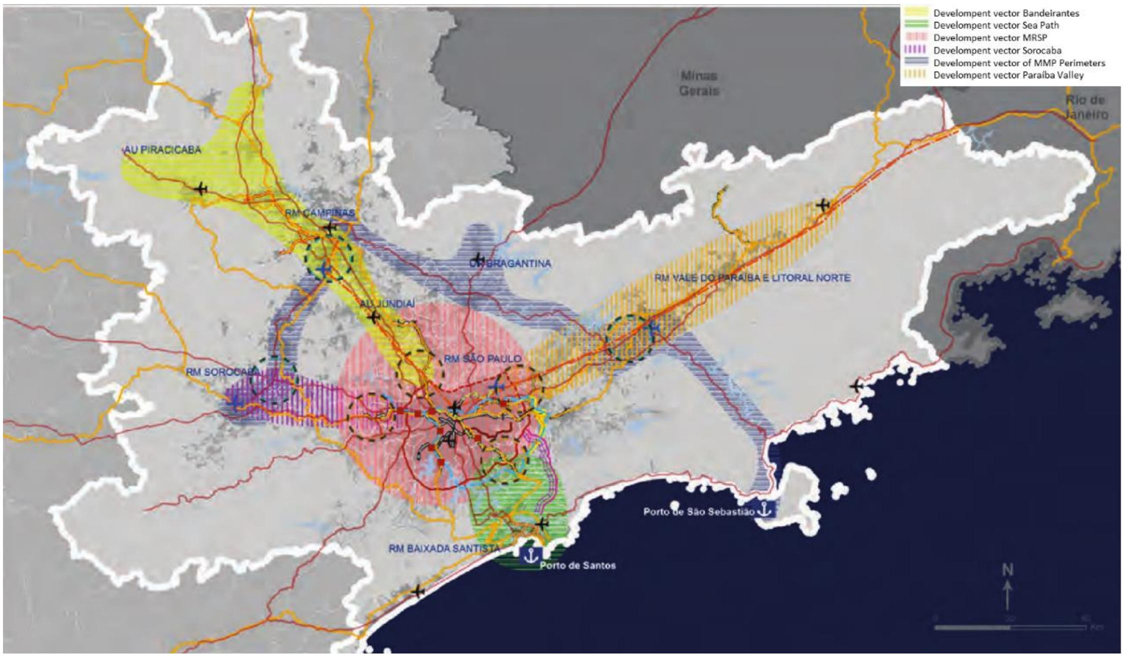
Source: Sato (2008).

Figure 2.18 - View of east hillside Rancho Novo allotment (Guarulhos municipality), in 2018.

Source: Author.

Urban and economic growth in MRSP points to an integration process with other metropolitan regions, Campinas; Vale do Paraíba and North Coast, Sorocaba and Baixada Santista. Together they are treated as a region for planning purposes, called "Macrometropolis of São Paulo" ("*Macrometrópole Paulista*" – MMP), comprising besides the five metropolitan regions, urban agglomerations of Jundiaí, Piracibaca, and Bragantina (EMPLASA, 2014) (Figure 2.19). Together they concentrate 172 municipalities, in a radius of approximately 200km from São Paulo city, with more than 30 million people and a gross domestic product of more than R$ 1 trillion, corresponding to 27% of Brazilian gross domestic product (EMPLASA, 2015).

Figure 2.19 - Macrometropolis of São Paulo and development vectors.



Source: Adapted from EMPLASA (2015).

Schutzer (2012b) has observed that the process of conurbation in Macrometropolis of São Paulo is based on the sprawl of residential and industrial areas, in an unplanned process in which non-contiguous areas are developed as new settlements. Plateaus and valley bottoms are the main features of relief to be occupied, leaving more difficult areas to a further stage (SCHUTZER, 2012) (Figure 2.20).

Low-income settlements tend to occupy the border of roads or fringes of urbanized areas, while high- and medium-income level settlements, often gated communities, are the main typology inducing this process of conurbation by sprawling and fragmenting. In this context, Schutzer (2012b) observes that a non-negligible number of these settlements exhibit the same landscape design of traditional compact areas, without a distinctive street layout or qualifications to promote soil perviousness, preservation of amphitheater valley heads and vegetation cover, besides further ecological attributes (SCHUTZER, 2012) (Figure 2.20). For now, urban sprawl and the fragmentation are unintentionally allowing the conservation of a significant amount of open spaces that potentially can be qualified and articulated for preservation, protection, recreation and socializing (COELHO, 2015).

Figure 2.20 - Example of distinct high-income gated communities, with different levels of occupation, each in a plateau (Santana do Parnaíba municipality).

Source: Quapá-SEL (FAUUSP) (2017).

2.3. Urban landslides

Human intervention, along with specific topographical, geotechnical, and geological characteristics result in hillsides prone to landslides. Hillsides urban development requires vegetation removal and modification the contours of the land in local and large scale (grading and mass-grading), which associated with paving alter the natural regime of runoff and infiltration of stormwater. Moreover, the introduction of new sources of surface and subsurface water associated with irrigation or leaky water from utilities, such as water or sewer lines, and the deposition of inadequate material (such as garbage or construction waste) in landfills alters geotechnical behavior of the natural terrain (FARAH, 2003; PELOGGIA, 1997; SCHUSTER; HIGHLAND, 2007). These alterations not only favor landslides but also are related to erosion and deposition of sediment in the riverbanks, contributing to floods (FARAH, 2003)

Hillsides urban occupation, because its higher population densities and greater concentrations of fixed capital are particularly vulnerable to landslide disasters (ALEXANDER, 1989). Alexander (2005) observed that most vulnerable settlements involve either multi-story buildings in well-established parts of major cities or precarious slums in more impoverished urban areas. In the former case, vulnerability arises from a combination of unregulated urbanization allowing dense hillsides occupation with torrential rainfall, often associated with other severe climatic hazards, such as typhoons, as in Hong Kong or Kuala Lumpur. The latter case is of informal housing that clings precariously to unstable slopes and can be washed away by debris flows and mudflows during episodes of torrential rain (ALEXANDER, 2005).

Literature review carried out by Guzzetti et al. (2007) revealed that there is not a consensus of a rainfall measurement or threshold that could trigger slope failures. They propose three broad categories to group empirical rainfall thresholds: (i) thresholds that combine precipitation measurements obtained for a specific rainfall event, (ii) thresholds that consider the antecedent conditions, and (iii) other thresholds, such as indexes derived from rainfall measurements in combination with other variables or discharge records. Considerable variability of thresholds can be attributed to diverse lithological, morphological, vegetation and soil conditions, different climatic regimes and meteorological circumstances leading to slope instability, as well as heterogeneity and incompleteness in the rainfall and landslide data, used to determine the thresholds (GUZZETTI et al., 2007).

Guidicini and Iwasa (1977) carried out a pioneer study in establishing a correlation between landslides and rainfall intensity, using nine Brazilian rural and urban areas. Their analysis showed that the landslides are likely to occur when precipitation records are between 8% and 17% of the mean annual precipitation. Also, they showed that a previous rain cycle is decisive in triggering the sliding processes, since these tend to occur when the rain cycle shows high cumulative values. Results obtained by Tatizana et al. (1987) in relating landslides to rainfall in Sea Mountains of São Paulo state were used as a reference to establish limits to the monitoring system in São Paulo state based on accumulated rainfall in 72 hours (SANTORO et al., 2010). In São Paulo municipality and the rest of MRSP thresholds of 60mm and 80mm accumulated over 72 hours, respectively, are adopted by Civil Defense to issue a risk alert (IG, 2017c). These thresholds are more restrictive than those observed by Molina et al. (2015) for urban landslides in São Bernardo do Campo. According to them, landslides occur with a rainfall of more than 100 mm in 24 hours or 150mm in 4 previous days (MOLINA et al., 2015).

Although triggered mainly by rainfall, urban landslides are polycausal phenomena (ALEXANDER, 1992). The lack of infrastructure systems or its inappropriate design or operation is clearly related to slope security (PELOGGIA et al., 1992; SMYTH; ROYLE, 2000; MIRANDOLA; MACEDO, 2014; ROSS, 2016; MENDES et al., 2018). Leakages in sanitary systems or directed disposal of wastewater into the soil, as illustrated in Figure 2.21, are a source of water infiltration that can lead to slope failure. The absence of stormwater drainage elements, including paved streets, accelerate slope erosion, and contribute to water saturation and a surcharge of the soil.

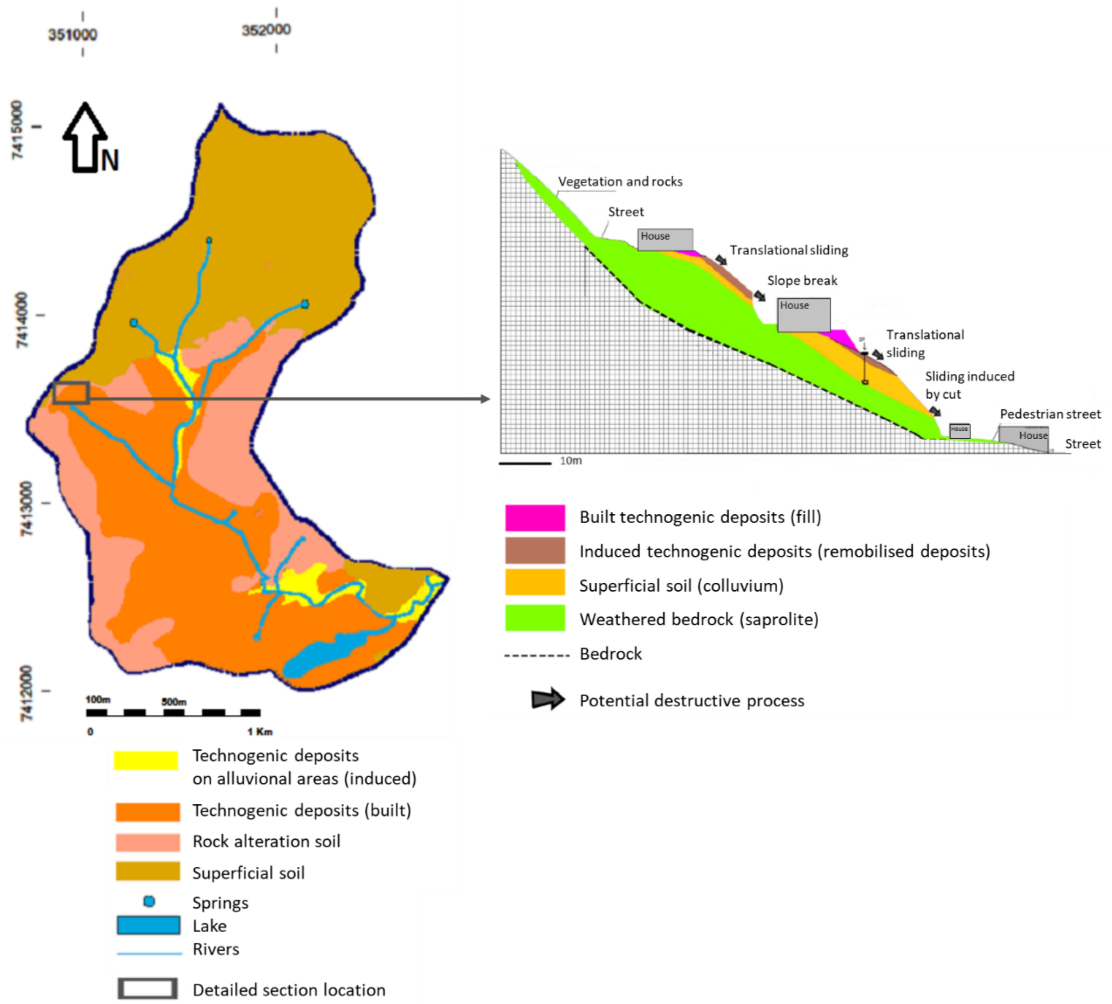
Inadequate construction techniques and insufficient design practices employed by families and land developers, as well as weak municipal ordinances and inspection, contribute to the occurrence of landslides. A common technique observed by Smyth and Royle (2000) in *favelas* of Rio de Janeiro is the cut-and-fill, e.g., removing soil from the rear of the site and depositing it at the front, creating a flat area, filled to the top, although, with unconsolidated material which is extremely susceptible to collapse. As this is carried out without engineering or calculating advice, frequently the angle of the headwall excavation is defined by pursuing the creation of a maximum flat area as possible, which increases slopes susceptibility and damage, if a failure occurs. Leaving cuts and landfills exposed are a subsequent common practice, favoring soil erosion and destabilization. In some cases, a plastic protective cover is used to prevent stormwater infiltration (Figure 2.21).

Figure 2.21 - Inadequate practices on hillsides occupation in MRSP.

On the left photo, two vertical cuts were made, and soil was protected with a plastic cover observed in Jardim Brilha neighborhood (Mairiporã city). On the right photo, sanitary system absence is observed in *favela* 'Encosta do CEU Paz': wastewater is disposed of directly into a drainage channel, which also carries garbage from upper areas.
Source: Author.

Peloggia (1997) observed that fills made with heterogeneous materials (organic debris, plastics, debris, wood, plant remains - trees, branches, leaves, and others), called technogenic deposits, are more unstable when compared to cuts, but they represent a minor risk because in general they are small-sized fills and mobilize less volume when a landslide occurs (MIRANDOLA; MACEDO, 2014). Braga et al. (2016) have mapped technogenic deposits in Jardim Fortaleza, in Guarulhos municipality, where mass grading created levels and landfills were executed in the bottom of the valley to provide the occupation. In the detail of a section of a block of the settlement, one can observe technogenic deposits used to small levels for the implantation of the houses. (Figure 2.22). Based on geological, geometrical, and technogenic conditions observed, potential landslides were then mapped (Figure 2.22).

Figure 2.22 - Technogenic deposits and landslide risk in Jardim Fortaleza (Guarulhos municipality).



Source: Adapted from Braga et al. (2016).

A different situation that implies in a higher level of risk occurs when entire settlements are over non-engineered fills, as in the case of *favela* Maria Luisa Americano, in São Paulo city, built over construction waste, or when they are close to these fills, like *favela* da Juta, in which a landslide of approximately 60,000 m^3 of building waste buried 17 houses in 1992 or *favela* Nova República, where a significant landslide of 100,000 m^3 of material killed 14 people in 1989 (PELOGGIA et al., 1992).

Deaths and severe economic losses are associated with intensive risks, drawing public and government attention. The more frequent and low-intensity losses are associated with considerable risk. Costs associated with this kind of events are not visible and tends to be underestimated, although they are not neglectable. An estimation made by 2009 Global Assessment Report on Disaster Risk Reduction, showed that costs of destroyed and damaged housing associated with enormous risks represent 44% of the total economic losses in the housing sector (UNISDR, 2009). Low-intensity impacts accumulated over time represents an ongoing erosion of development assets, such as houses, schools, health facilities, roads, and local infrastructure. They are absorbed mostly by residents and undermines their resilience (UNISDR, 2009). Burton et al. (1993) argued that intensive risk could encourage evasive changes, whenever it creates the sensation of an unacceptable environmental, whereas the long interval between catastrophic events can discourage any permanent shift.

According to Alexander (1989), reasons for numerous and frequent small-scale landslides are the presence of steep slopes in fractured rocks or highly erodible sediments; the propensity of past landslides to reactivate; the scarcity of structural mitigation works on unstable slopes; the invasion of unstable slopes by urban or suburban developers attracted by views, constrained by scarcity of building land or motivated by the desire for profit; the mismanagement of slope drainage and stability both during and after construction; finally, ignorance of geophysical risks, including the return period of major precipitation events, the location of rock avalanche or mudflow tracks, and other types of landslide.

2.3.1. Landslide risk management

Discussed in literature and carried out by policymakers, public agents and dwellers, actions to manage urban landslide risks comprises two groups of solutions designed to (i) eliminate the element at risk, by discouraging, restricting or removing urban occupation in landslide-prone areas, or (ii) mitigate the risk, diminishing system's vulnerability and increasing its resilience. Another set of measures can be adopted after a landslide occurrence, in order to mitigate its impacts, among which insurance, as loss-sharing schemes, economic subsides and physical recovery of damaged structures are common ones (CROZIER, 2005).

Discouraging development of hillsides can be achieved by the disclousure of urban landslide hazards and legal liabilities to potential property buyers, dwellers and general public. Posted warning signs and educational actions are tools to raise awarness of risk situations. Sulaiman (2018) suggested that education process based on dialogue and participation are more effective in building co-responsabilities to prevent risk situations than those based in uni-directional flux of information.

Economic measures to inhibit urban development, including tax credits and individual assessment, loans rejection, limited or even null public investment in facilities and prohibitive insurance costs (KOCKELMAN, 1986; CROZIER, 2005; SCHUSTER; HIGHLAND, 2007). Maricato (1995) highlighted a contradiction in public investments, on one hand, they are necessary to enhance quality in precarious settlements, on the other hand, they can encourage the occupation in unfavorable sites. The author referred to the major landslides occurred in the city of Petrópolis (Rio de Janeiro state) in 1987, where municipality paved streets and provided public illumination in areas that should not have been occupied and were severely affected by landslides (MARICATO, 1995).

To restrict and even avoid urban occupation on hillsides, available measures comprises land-use control, building, and grading codes and sewage disposal regulations (KOCKELMAN, 1986; ALEXANDER, 1989; CROZIER, 2005; SCHUSTER; HIGHLAND, 2007;

MORETTI et al., 2013). These regulations can be drawn upon security reasons, but also aesthetics, sustainable use of environmental resources, economic gains, among other reasons (OLSHANSKY, 1998).

Observing Brazilian legal system, Moretti et al. (2013) listed strategies that can be used by municipalities in order to control and order hillsides urban development based on security strategies. These include plot and streets design, considering a definition of permitted uses and miminum and maximum parameters for street width and longitudinal slope, building coverage, impervious surface, lot size and frontage.

Also, the municipality may, by law, establish situations in which the infrastructure must be implemented fully, and not partially and gradually, as well as requiring the installment of individual plots to be made concurrently with the implementation of the buildings and infrastructure. Thus, the infrastructure works and the buildings themselves are previously contemplated in the planned site and executed in an articulated and coordinated manner.

Different definitions, such as lot and building positioning, whether parallel or orthogonal to contour lines, can only be recommended. Farah (2003) observed that positioning lot with its larger side orthogonal to the contour lines decreases grading, however, this is not the usual solution, since it requires a higher density of streets, increasing the urbanization costs, or the combination of pedestrian and vehicle accesses. The author also points to legal restrictions based on the final longitudinal slope of this solution and cultural aspects, in the sense that dwellers and architects are resistant to housing units with pedestrian access (FARAH, 2003). In figure 2.23 there is an example of this solution, Pro-Morar neighborhood, promoted by local authority in the 1980 decade.

Figure 2.23 - Pro-Morar public housing (São Paulo municipality).

Source: Author.

Buildings or neighborhoods removal is a radical and traumatic measure that requires financial resources to public acquisition of the land (KOCKELMAN, 1986; SCHUSTER; HIGHLAND, 2007), or families' relocation, if the right to housing or social rights related to this aspects are assured in legal ordinances (MORETTI et al., 2013). MORETTI et al. (2019) pointed to the fact that removals are often the solution urged by society, to the detriment of solutions to enhance security and keep population in the place. Authors suggests that if removals eliminate the landslide risk, they can raise a different kind of vulnerability in the sense that removed families are prone to family desagregattion, unemplyement and violence due to social bounds breaking.

Mitigating landslide risks involves the so-called hard measures, or engineering works to protect and enhance security in specific areas, such as slope geometry modifications, drainage, counterfort berms that serve as buttresses, and protective barriers (KOCKELMAN, 1986; CROZIER, 2005). Ecosystem management measures can also be adopted to enhance slope safety, is appropriate in this case revegetation, through reforestation or small scale agriculture, and adoption of water management practices to reduce water runoff, through green roofs, greywater and stormwater collection and re-use (CHAN, 1996; GUADAGNO et al., 2013; LANGE et al., 2018).

The development of monitoring, warning, and evacuation systems are also used as a mitigation measure (KOCKELMAN, 1986; CROZIER, 2005). São Paulo State has been implementing actions of monitoring and management of disasters' risks since 1988, through Civil Defense Preventive Plans and Contingency Plans. These plans are prepared by the municipality in advance to rainy season each year and have a preventive conception. They organize technical teams and municipal and state civil defense to monitor rainfall levels and meteorological forecasting and to execute field inspections and, in extreme situations, people evacuation. They also organize actions in case of a landslide occurrence. In MRSP, all municipalities, since 2016, have a specific Civil Defense Preventive Plan for landslides.

It is important to note that all these measures must rely on susceptibility maps to proper planning as much as on risk maps to an effective policy design (CHAN, 1996; CASCINI et al., 2005; FELL et al., 2008; SOBREIRA; SOUZA, 2012), as much as they need to be followed by monitoring and inspection efforts, to ensure law enforcement and their long-term applicability (CHAN, 1996; CASCINI et al. 2005). Sobreira and Souza (2012) suggested an hierarchical approach, in which susceptibility map would represent the general physical aspects, identified in a scale of 1:25000 or higher while aptitude map would identify and describe geotechnical units according to its suitability and restrictions to urbanization, using a greater detailed scale, of 1:10000 to 1:5000 or higher. Risk maps are based on local observation of evidences of slope instability due to natural causes or man-made modifications and are produced in the finest scale, 1:2.000 or higher (SOBREIRA; SOUZA, 2012).

Since 2011, when a major landslide occurred in Rio de Janeiro mountainous region and caused more than 900 deaths (BANCO MUNDIAL, 2012), the Brazilian federal government has been strengthening its practices in risk management. The National Policy of Protection and Civil Defense (NPPCDE) was established by law in 2012 (Federal Law, no. 12.608), alongside with the National Center for Monitoring and Alert of Natural Disasters (CEMADEN) and the National Center of Risks and Disasters Management (CENAD). Based on the NPPCDE, for all Brazilian municipalities included in the national registry of municipalities with areas susceptible to high impact landslides, sudden floods or related geological or hydrological processes, it is mandatory to undertake susceptibility map and aptitude map for urban occupation, as well as risk zoning maps. The national registry, however, has not yet been implemented, although through federal coordination and financing, several risk maps, susceptibility analysis and aptitude maps were executed for an important number of municipalities (NOGUEIRA; CANIL, 2018).

The state of São Paulo is a pioneer in using susceptibility approach to map aptitude for urban development: in 1979, Institute for Technological Research (IPT) mapped the aptitude of the occupied areas of hillsides between the municipalities of Santos and São Vicente, and in 1984, this map was carried out for São Paulo Municipality. These maps have been used for municipal planning to inform zoning (BITAR et al., 2012) and, in a broader perspective, these activities have contributed to create a strong community of government actors and academics to discuss, propose and implement mitigation actions.

The Greater ABC region, constituted in 1990 encompassing seven municipalities of MRSP (Santo André, São Bernardo do Campo, São Caetano do Sul, Diadema, Mauá, Ribeirão Pires, and Rio Grande da Serra), has been implementing planning and management actions to reinforce regionalized public policies that aim at economic development, regional mobility and disaster risk management. (NOGUEIRA et al., 2014). Regarding risk situations, regional actions involved integration and expansion of the civil defense actions, execution of risk maps with the identification of more than 24 thousand units in risk areas (almost 10 thousand in areas of high risk), development of a regional medium-term plan and the establishment of agreements with state level agencies to execute the removal of 536 families (CONSÓRCIO INTERMUNICIPAL GRANDE ABC, 2016).

Despite the focus on the underlying factors causing vulnerabilities and disasters already proposed in the Sendai Framework of Action (2002) in Brazil, there is some difficulty (or denial) in understanding disaster as a result of social, economic and political construction, and not just as a natural event (NOGUEIRA; CANIL, 2018; SULAIMAN, 2018). This is reflected in the way risk is commonly faced: preparing people to deal with the occurrence and outcomes of extreme events, rather than a prevention-focused approach. In addition, while the National Policy for Civil Protection and Defense emphasizes the need for more focused management on prevention and participation, educational practices have mainly remained informative and procedural, with content and activities aimed at diagnosing at-risk elements and territories and at know how to act in an emergency aiming at safety and self-protection (SULAIMAN, 2018).

3. PAPERS

3.1. Paper 1

CENSUS DATA INTERPOLATION FOR URBAN ANALYSIS IN ALTAMIRA (PA) IN 2000 AND 2010

INTERPOLAÇÃO DE DADOS CENSITÁRIOS PARA ANÁLISE DA OCUPAÇÃO INTRAURBANA EM ALTAMIRA (PA) EM 2000 E 2010

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3.1.1. Introduction

The demographic censuses carried out by the Brazilian Institute of Geography and Statistics (IBGE), due to their territorial coverage and periodicity, are the main source of socio-demographic data in Brazil. In order to study and diagnose the occupation of cities, it is of interest not just population and home characteristics of each city or urban area but also the intra-urban characteristics, that is, the spatialization of these characteristics within cities, to others. Thus, aggregated data are used by census tracts, which correspond to the smallest spatial units in which census data is released.

Since these units are delimited from operational criteria (IBGE, 2013; IBGE, 2003b) and therefore may vary from census to census, they are not necessarily consistent with delimitations of zones, neighborhoods or space units suitable for study and city planning. Cities such as São Paulo and Belo Horizonte, when addressing this problem, designed municipal planning and management units compatible with the units of demographic data collection, which implied adaptations in the delimitation of both units (KOGA, 2005; OLIVEIRA et al., 1996).

In order to compare data from different years, one must consider modifications to criteria used to collect the data, as observed by Helfand and Brunstein (2000), or of delimitation of spatial units of data dissemination. Alves (2007), using the comparison between cumulative distributions of variables of interest for the analysis of census data in the Amazon, shows the limitation that the data and the available methodological framework for its analysis impose to reach the results (ALVES, 2007).

In Openshaw's formulation (1983), the arbitrary delimitation of units of areas and the consequent possibility of modifying their limits constitute the "modifiable areal unit problem" (MAUP), in which the analysis and conclusions derived from data associated with area units have no independent validity. According to the author, this is a "fundamental geographical problem, endemic to all studies of aggregate spatial data" (OPENSHAW, 1983).

Spatial data interpolation is a way of transferring data from one set of areas (source zones) to another (target zones), overcoming the limitations of MAUP (Ford, 1976; LAM, 1983). Since the 1970s, the literature has shown different methods for interpolating socio-demographic data, basically forming two groups: point interpolation methods and area interpolation (LAM, 1983; LIU, 2003; WU et al., 2005). The methods can be univariate, using exclusively the data to be interpolated, and multivariate, that use auxiliary information (AMARAL, 2004).

In point interpolation, areas are represented by a user-defined point (their centroid, for example) and values are estimated for a grid of points. In comparing existing methods, Lam (1983) points out the advantages of kriging compared to other methods (distance weighting, spline interpolation, and finite difference method). Wu et al. (2005) note that the method proposed by Bracken and Martin (1989), based on a moving bivariate function window to estimate the intensity of the dot pattern (kernel), ended up being widely used to treat census data in the United Kingdom.

For the interpolation of areas by univariate methods, Lam (1983) lists the overlay, the areal weighting, in which the variable is calculated based on the proportion of area of each intersection between zones and the pycnophylactic method proposed by Tobler (1979), which considers the neighborhood effects of each source zone in the modeling of the smoothing surfaces of the variable in the target zones.

Among the multivariate methods of interpolation of areas with the use of ancillary information, the simplest of these is the binary dashboard interpolation, which uses a classification map of populated or non-populated areas (LANGFORD; UNIVERSE, 1994; FISHER; LANGFORD, 1995; EICHER; BREWER 2001; HOLT et al., 2004). The dasymetric methods can be understood as "forms of mapping where the reported attribute is redistributed within original zones, based on information obtained from external auxiliary data" (AMARAL, 2004). Other works propose dasymetric methods with more than two classes, in which the density values associated with each class, are arbitrated (EICHER; BREWER, 2001; WALFORD, 2013) or estimated by means of regression (LANGFORD et al., 1991; YUAN et al. (1997), Harvey et al. The dasymetric method was also implemented with linear information, such as the road mesh (XIE, 1995; VOSS et al., 1999) or with point information such as the location of addresses for statistical purposes (D'ANTONA et al., 2013).

The authors who have focused on methods comparison proposed reached the general conclusion that the methods of interpolation of areas with the use of auxiliary data are those that present better results (FISHER; LANGFORD, 1995; COCKINGS et al., 1997; VOSS et al., 1999; REIBEL; BUFALINO, 2005; HAWLEY, 2005; WU et al., 2005; LANGFORD, 2006; LLOYD; NEJAD, 2014; LIN; CROMLEY, 2015).

In Brazil, several strategies were used to compare demographic census data. A simple strategy is the composition of comparable minimum areas, as adopted by Reis et al. (2010), which consisted of aggregating data from municipalities from the political-administrative limits in force in the different censuses conducted between 1872 and 2000. This strategy, in general, implies the loss of more detailed information provided by the original data. Jakob (2004) and Lobo (2009) proposed strategies based on the interpolation of data associated with the census tracts: kriging, in the first case, and transfer of data to a point mesh in the second.

Recently, the Brazilian Institute of Geography and Statistics has made the 2010 Census data available in a grid of 1km regular cells for data from rural areas and 200m for urban areas (IBGE, 2016b). Data by census tracts were aggregated or disaggregated into regular cells. Aggregation was adopted when either the census tract or more than 50% of the addresses of the National Register of Addresses for Statistical Purposes (CNEFE) related to that tract were totally contained in the cell. Otherwise, disaggregation was adopted using the following spatial interpolation methods, in order of increasing preference: interpolation with path data, dasymetric map from land cover data and zonal or area weighting.

In Altamira, the different boundaries of census tracts defined in 2000 and 2010 and the creation of new tracts in 2010, covering areas that were included in the urban perimeter by municipal legislation, make it difficult to compare census data directly and analyze the intraurban occupation. Thus, to make the data comparable, this work proposes multivariate spatial interpolation methodology based on the method reported as the simplest, the binary dasymetric interpolation, using a regular grid of points. This methodology allows the conversion of data from the source zones (census tracts) to the target zones (neighborhoods), and therefore, the temporal analysis of the occupation of the city of Altamira.

In the next section procedures of the proposed methodology are described and the census data and primary and secondary surveys that were used are presented in detail. The section begins with a brief description of the study area, the city of Altamira.

3.1.2. Material and methods

3.1.2.1. Study area

The city of Altamira is in the central portion of the State of Pará, on the left bank of the Xingu River. It is 720km from the state capital, being a sub-regional center, subordinated to the capital Belém itself (IBGE, 2008). The BR-320, Transamazônica highway, cuts the city in its northwest portion, connecting it to two important regional centers, Marabá to the east and Santarém, through highway BR-163 to the west.

The occupation of Altamira dates from the eighteenth century, for the exploration of the interior of the Amazon, undertaken by the Jesuits (UMBUZEIRO, 1988). In 1883, the village of Altamira was founded at the mouth of the Ambé River, to support the exploitation of native rubber. The municipality of Altamira was emancipated from Souzel in 1911.

Statistical data (IBGE, 2015) indicate that the period of greatest population growth in the city was in the 1970s, with the initiatives of the federal government to occupy the Amazon. The growth rate of the urban population at the time was of 16.4% per year: from 6 thousand inhabitants in 1970, the city began to house in 1980, roughly 27 thousand people. In the following period, between 1980 and 1991, the growth rate fell to 5.8% per year; in 1991, the urban population was about 50 thousand inhabitants. Between 1991 and 2000, the growth rate continued to decline, reaching 2.4% per year, lower than the state of Pará. Between 2000 and 2010, the urban population increased from 62 thousand to 84 thousand people and the growth rate registered was 3% per year, slightly higher than the state rate.

The growth of the city occurred, in part, with neighborhoods planned by the City Hall, the Prelature of the Xingu and private companies. Part of the population had as an alternative the occupation of the lowlands and floodplains of the outlying areas of the city and of the hills (UMBUZEIRO, 1988; BECKER, 1985). Thus, Altamira presents varying patterns of urbanization in terms of urban infrastructure and building conditions.

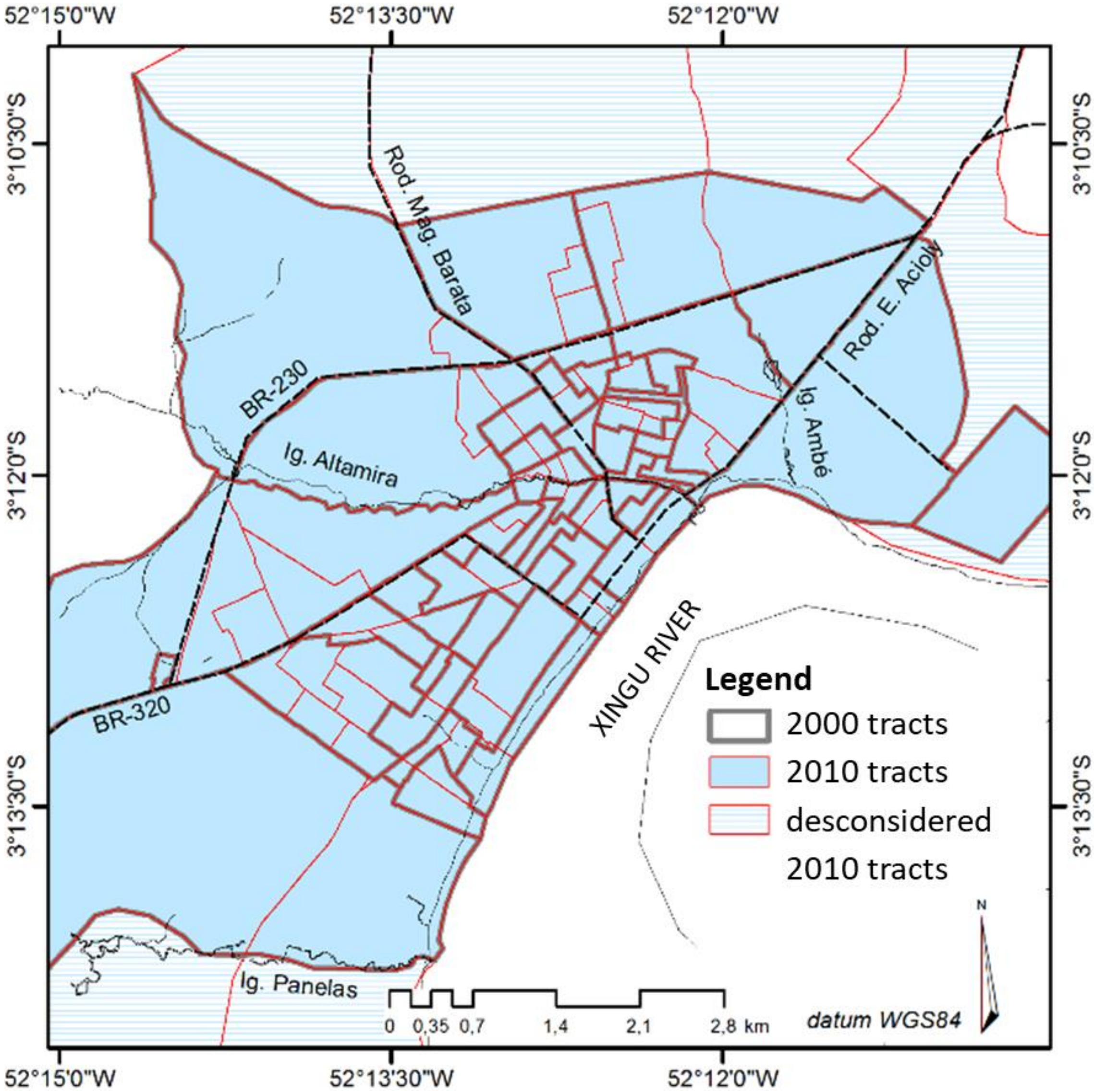
3.1.2.2. Census tracts: source zones

The census variable used corresponds to the number of permanent private households per census tract. Household data were associated with the vector bases of the census tracts delimited in each year. Feitosa et al. (2005, p.2660) had observed the generation of spurious polygons in the overlapping of the vector bases of census tracts of 1991 and 2000, resulting from the intersection of lines that represent the same features but which have different digital representations due to errors inherent in the base cartographic data. To overcome this problem, the authors recommended, following D'Alge (2001), the analysis of the original data to choose the best representation as a basis.

This same problem was observed in the overlapping of the bases of census tracts of 2000 and 2010 in Altamira. According to the documentation accompanying the dissemination of data by the IBGE, the vector base of the tracts of 2000 was made based on municipal maps and localities available at various scales (IBGE, 2003). The vector base of the 2010 census tracts was based on cartographic and remote sensing bases, which allowed the adjustment of the geometry and the road network of the urban tracts (IBGE, 2013). Therefore, the most accurate vector of 2010 was used to trace the tracts of 2000, based on the description of the perimeter of each tract.

In 2000, 45 census tracts were defined in the city of Altamira; in 2010, there were 108 tracts. To make a direct comparison possible of the census data for 2000 and 2010, minimum areas were composed that were comparable with the aggregation of the tracts of 2010 equivalent to the tracts of 2000 (Figure 3.1). For this direct comparison, the tracts created in 2010 without equivalence with tracts of 2000 were disregarded.

Figure 3.1 - Used and disregarded census tracts in defined for 2000 and 2010.



Source: Author.

3.1.2.3. Neighborhoods: target zones

Neighborhoods have a common sense of identity and are understood as homogeneous areas of cities (LAMAS, 1992). This identity is based on a spatial and at the same time social morphological unit (BARROS, 2004). As administrative units, neighborhoods are spatial units legally defined in ordinary law approved by the City Council and sanctioned by the Mayor.

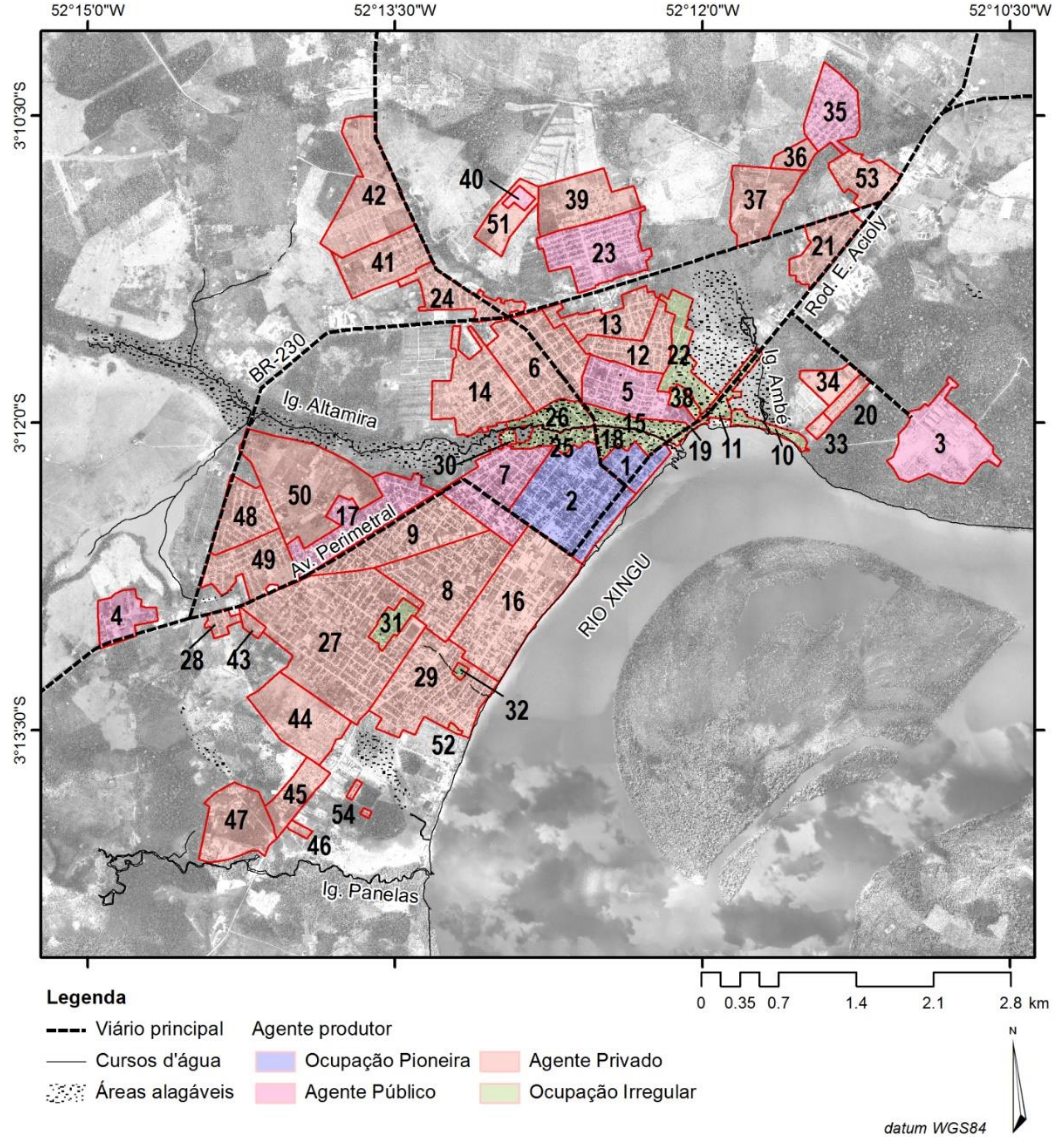
It was observed in Altamira that the legal definition of neighborhoods has undergone changes, both in its denominations and in its limits. Therefore, it was decided to delimit neighborhoods of Altamira (Figure 3.2) based on aerial photos and orthophotos (Table 3.1), as well as field interviews in July 2013 (HIRYE, 2014) and bibliographic data (UMBUZEIRO, 1988, 2012; LEME ENGENHARIA, 2009; TECHNUM CONSULTORIA, 2010), seeking to recompose the urbanization units as they have emerged over time.

Table 3.1 - Available aerial and orthophotos.

Year	Type	Scale / Resolution	Original Format	Source
1979	Aerial photo	1:5.000	Printed	Eletronorte
1987	Aerial photo	1:8.000	Printed	Eletronorte
1999	Orthophoto	1:8.000	Digital	Eletronorte / CDHU-PA
2010	Orthophoto	0,30m	Digital	Eletronorte

Source: Author.

Figure 3.2 - Target zones: neighborhoods according to developer agent.



Neighborhoods are:1 - Ocupação Pioneira; 2 - Centro; 3 - 51o BIS; 4 - DNIT (km 4); 5 - Aparecida; 6 - Brasília; 7 - SUDAM I; 8 - Premen; 9 - Jardim Uirapuru; 10 - Rua da Peixaria; 11 - Rodovia Ernesto Aciolly; 12 - Boa Esperança; 13 - Jardim Primavera; 14 - Jardim Altamira; 15 - Ocupação - Ig. Altamira; 16 - Esplanda do Xingu; 17 - SUDAM II; 18 - Açaizal; 19 - Ocupação Xingu; 20 - Alberto Soares; 21 - Colinas; 22 - Olarias; 23 - Mutirão; 24 - Liberdade; 25 - Baixão do Tufi A; 26 - Baixão do Tufi B; 27 - Jardim Independente I; 28 - Rancho Novo; 29 - Jardim Independente II; 30 - Ocupação - Ig. Altamira; 31 - Ocupação - Jardim Independente I; 32 - Ocupação - Jardim Independente II (A); 33 - Alberto Soares; 34 - Altaville I; 35 - Nova Altamira / São Domingos; 36 - Loteamento Bom Sucesso; 37 - Chácaras - Bom Sucesso; 38 - Invasão dos Padres; 39 - Jardim França; 40 - Paixão de Cristo; 41 - Santa Ana; 42 - Loteamento do Bacana; 43 - COPERFRON; 44 - Jardim Ibiza; 45 - Dom Lourenzo; 46 - Loteamento Elvira; 47 - Chácaras - Estrada do Sanatório; 48 - Parque Ipê; 49 - Bela Vista; 50 - Vista Alegre; 51 - Invasão Paixão de Cristo; 52 – Ocupação Jardim Independente II (B); 53 - Nova Altamira / São Domingos; 54 – Jardim Independente III.
Source: Author.

The available information also was used to identify the agents responsible for the development of each neighborhood (Figure 3.2). The pioneer occupation took place at the mouth of the Altamira River near the Xingu River. It is an area of mixed use (residential, commercial and institutional), with consolidated infrastructure (grid water supply systems, paving and public lighting).

The neighborhoods resulting from public action are predominantly residential and are partially served by infrastructure networks (isolated water supply networks). The neighborhoods deployed by private agents have varied infrastructure conditions (the ones closest to the center are better served) and are mixed use (residential and commercial) or predominantly residential use.

The occupations of the banks of water bodies and wetlands are irregular occupations, over permanent preservation areas, with precarious habitability conditions - the dwellings are made of wood, the circulation is made by plank bridges known as "*estivas*".

3.1.2.4. Land cover maps: ancillary information

Remote sensing data were used to generate land cover maps in 2000 and 2010 in raster format. The images of the TM sensor (scene 226/062), onboard the Landsat 5 satellite, dated 28 July 2000 and 24 July 2010 selected from the Data Generation Division (DGI / INPE) database, were classified with the linear spectral mixing model, as described in Hirye et al. (2015). Mapped classes were water, vegetation, waterproofed areas and soil, following the conceptual model of classification of urban areas proposed by Ridd (1995).

To validate, 169 and 193 samples with a size of 3x3 pixels (90m x 90m) were randomly selected for the evaluation of the maps of 2000 and 2010, respectively. The reference for validation was obtained by the visual interpretation of orthophotos of 2010 and 1999/2000. The overall accuracy calculated for the maps was of 85.2% (2000) and

88.1% (2010). The Kappa index was 0.668 (2000) and 0.751 (2010), with a confidence interval (95%) of ± 0.120 (2000) and ± 0.09 (2010). For a significance level of 5%, the Z test showed that both maps are better than a random classification.

The cover maps were reclassified, grouped in classes water, vegetation, waterproofed areas and permeable soil in two classes: occupied areas (classed as waterproofed and permeable soil) and unoccupied (class vegetation and water).

Finally, in order to obtain more accurate coverage maps, Moreira's (2005) proposed hybrid strategy was adopted, in which, the computational phase in which the images are classified by algorithms, is followed by the interactive phase in which the analyst visually edits the map, seeking to eliminate classification errors.

Thus, the following corrections were made:

a) Areas with no data in Landsat images (areas that were under clouds or cloud shadows) were interpreted visually from additional images. In the case of the present work, the interpretation was made from the orthophotos of 1999 and 2000.

b) Verification of urbanized areas isolated from the main spot to eliminate areas classified as occupied and which were, in fact, areas of exposed soil or pasture erroneously classified by the linear model of spectral mixing.

c) Elimination of transitions considered spurious. As the 2000 and 2010 mappings were done independently, these maps were overlapped to generate a cross-tabulation map that identifies all land cover transitions from 2000 to 2010.

The map areas of 2000 that were classified as occupied and, in 2010, as unoccupied were reclassified as not occupied.

3.1.2.5. Methodology for interpolating data from census tracts to neighborhoods

The ArcGIS geographic information system was used to prepare the data, to convert the data to the reference used in the work (datum WGS 84, UTM 22S) and to visualize them.

The R-project software (http://www.r-project.org/) was used to implement the proposed operations.

For the conversion of data from the source zones (census tract) to the target zones (neighborhoods), a regular grid was constructed, defined as the adjacent surface where each grid point is associated with a value. The regular grids were generated from the same source and with the same resolution of 30m. Each grid point corresponds to an area of 0.09ha, the result of multiplying the grid resolution (30m) in each direction.

In a simplified way, the methodology of binary dasymetric interpolation of census data for neighborhoods involved the following steps:

a) Calculating household density in each census tract: the total number of households in the tract was divided by the area occupied by each tract (according to land cover maps). The implicit premise in this calculation is that the density is homogeneous in the areas occupied in each census tract.

b) Generating regular census data grid: for each grid point coincident with the occupied area according to the land cover maps, the number of households was calculated by inversion of the density calculation. That is, the effective density of households in the tract, corresponding to the grid point was multiplied by the area associated with each point (0.09 ha).

c) Interpolating neighborhood census data, from the sum of the values of the points of the regular census data grid, inserted in each neighborhood.

3.1.3. Results and discussion

In this section, the results of the interpolation procedure are first presented and discussed. Following the interpolated data, the intra-urban occupation of the city of Altamira between 2000 and 2010 is characterized and analyzed.

3.1.3.1. Data interpolation

The results of the application of the proposed method were evaluated analytically, using the orthophotos and the original data. The sources of possible errors in the estimates made by the proposed method are two: (1) related to the degree of adherence of the data to the assumption of homogeneity of its distribution in the source zones and target zones and (2) related to the degree of accuracy of the auxiliary data used, in this cover maps of the soil.

As for the errors derived from adherence to the assumption, there is no way to correct or estimate them without incorporating new information, as proposed in other works (EICHER; BREWER, 2001; WALFORD, 2013; LANGFORD et al., 1991; YUAN et al., 1997; HARVEY, 2002; LLOYD; NEJAD, 2014; LIN; CROMLEY, 2015; XIE, 1995; VOSS et al., 1999). Differentiated approaches may also involve the definition of a third set of zones, the "control zones" (GOODCHILD et al., 1993) or the combination of the binary dasymetric method with a potential population occurrence surface, obtained by the simple mean of the selected auxiliary variables (AMARAL, 2004).

Where the source zones are more extensive - as in the outlying areas of the city of Altamira - the underestimation of the households in the target zones was observed. In these cases, the assumption of a spatially homogeneous distribution of households does not correspond to the observed situation of household concentration at certain points in the source zones.

As for the errors caused by the accuracy levels of the auxiliary data, Fisher and Langford (1996), when investigating the population estimation errors by the binary dasymetric method based on maps with different levels of classification errors, showed that errors in the pixel classification of a Landsat image (TM) of up to 40% do not compromise the performance of the binary dasymetric method in comparison with other regression-based methods.

Because the coverage maps presented classification errors of up to 15%, an interactive map refinement was performed. Nevertheless, one must take the errors into account due to the spatial resolution of the mapping, which may lead to the underestimation of isolated households that are smaller than the resolution of the pixel (30m), and those resulting from the characteristics of the image and the classification technique used, those that are unable to distinguish among the waterproofed areas, those that are effectively occupied by households, leading to the overestimation of households.

3.1.3.2. Intra-urban occupation

In 2000 and 2010, both in the area of Altamira legally defined as urban and, therefore, delimited by urban census tracts, regarding the spatial neighborhood level, there was an increase in the number of households (Table 3.2). The difference between the values in the two space levels can be interpreted as the sparse households in the urban perimeter, but which have a markedly rural use (farms and ranches).

Table 3.2 - Variation in the number of households by census tract and neighborhood, in the period 2000-2010.

Level	Households 2000 (units)	Households 2010 (units)	Households 2010-2000 (%)
Census Tract	14,326	20,617	44%
Neighborhood	12,569	18,128	44%

Source: Author.

The analysis of the data by census tracts, due to the changes in the limits of the tracts that do not make them comparable, makes it impossible to understand the changes that occurred in Altamira. The decrease of density observed in the calculated data for census tracts (Table 3.3) did not correspond to a real process - population decrease or modification of occupancy patterns.

Table 3.3 - Census tract and neighborhood area and household density, in 2000 and 2010.

Level	Area		Household Density		
	2000 (ha)	2010 (ha)	2000 (units/ha)	2010 (units /ha)	2010-2000 (%)
Census Tract	3,713	6,883	3.9	3.0	-22%
Neighborhood	1,030	1,460	12.2	12.4	2%

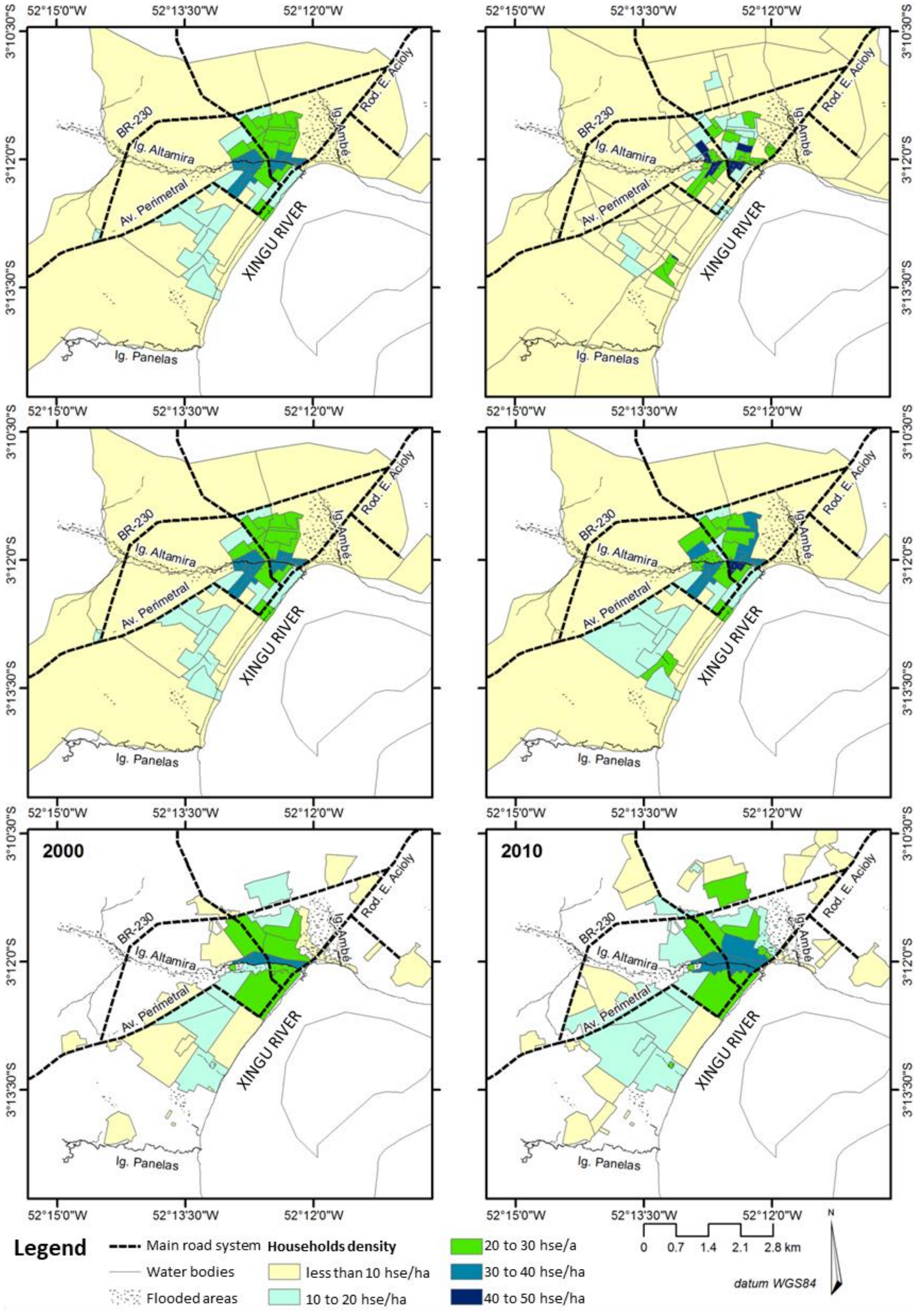
Source: Author.

In the analysis of the data by districts, little change in the average density was observed, whereas the calculation of the average density considering the limits of census tracts was distorted by the disproportionate increase in the area of the census tracts, reflecting the change in the law of urban perimeter, which resulted in an increase in the area of census tracts. Most of these areas remain unoccupied.

When the density was estimated by census tract, the same data analysis was impossible due to changes in tract perimeters (Figures 3.3 (a) and (b)). The aggregation of tracts in comparable minimum areas provided data for household density comparison in 2000 and 2010 (Figures 3.3 (c) and (d)). It was observed that the densest tracts in the two dates are those that are around the Altamira River and in the area located between this river and the BR-230, the Trans-Amazonian Highway. In 2010, there were changes in these tracts: density increase in the most peripheral tracts and decrease of density in two of the tracts closest to the Altamira River.

An increase in density was also observed in tracts that correspond to parts of the neighborhoods between Perimetral Avenue and the Xingu River, located to the west of the city center. The estimation of data by neighborhoods (Figures 3.3 (e) and (f)), in turn, revealed clear signs of density increase in the neighborhoods around the Altamira River and in the more peripheral area between this River and highway BR-230.

Figure 3.3 - Density of households by census tracts in (a) 2000 and (b) 2010, by comparable minimum areas in (c) 2000 and (d) 2010 and by districts in (e) 2000 and 2010.



Source: Author.

Unlike the analysis by aggregate tracts, in the analysis by districts it was observed an increase of the density in the districts north of highway BR-230 and in those between the Perimetral and BR-230 avenues. Density increased in the districts between the Perimetral Avenue and the Xingu River and in the areas of irregular occupation located inside these neighborhoods.

When tracts are smaller than the neighborhoods, as in the central area, the information by census tract allows the identification of each neighborhood's area has undergone alteration. This information is more accurate because it is the result of the census, not of the interpolation. Furthermore, in areas where census tracts are more extensive than neighborhoods, or in areas where tract boundaries have been modified, neighborhood-estimated data allow the changes to be localized and individualized.

In the analysis of the density of households in the neighborhoods classified according to their developer agent (Figure 3.4), it was observed that:

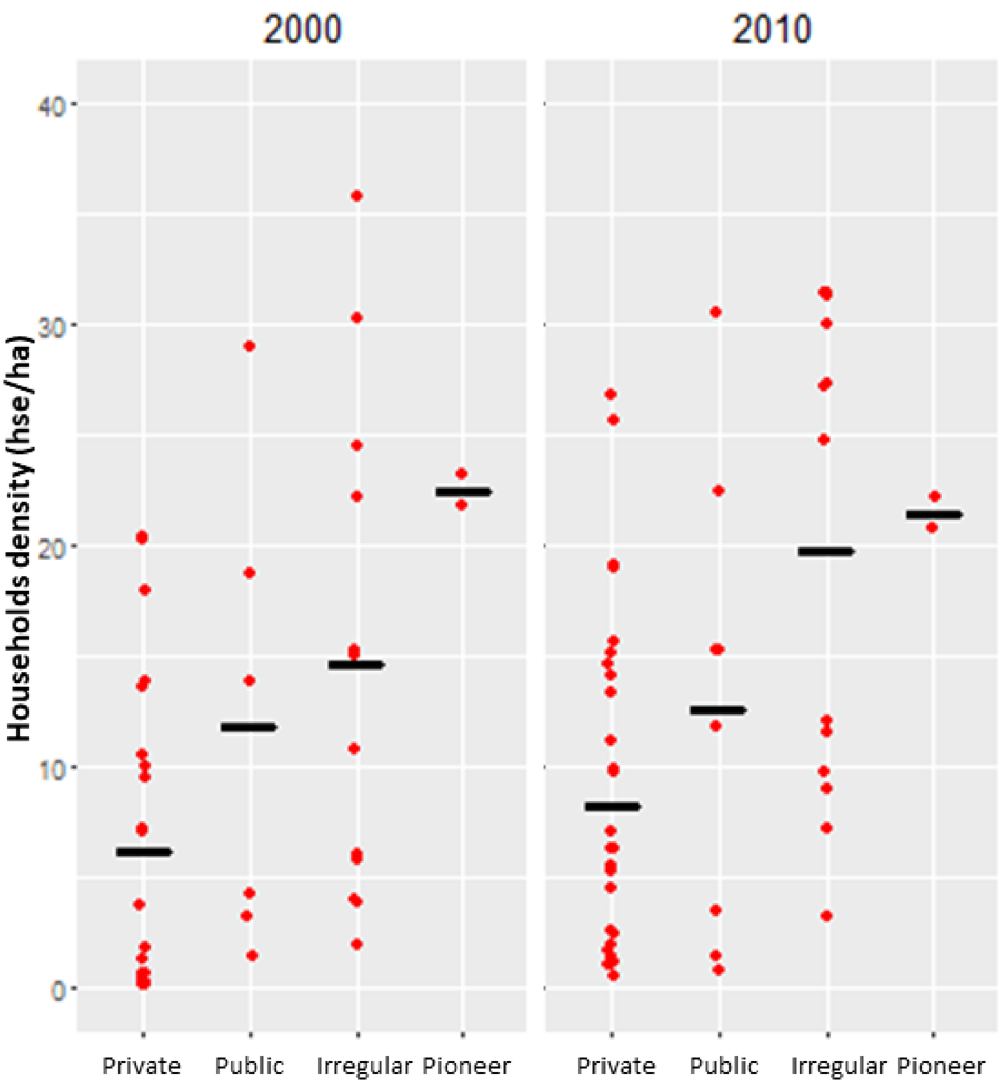
a) The neighborhoods with the earliest occupation had the highest average density of households in 2000, and between 2000 and 2010 this density decreased slightly. The two neighborhoods of the pioneer occupation have similar values of density, between 20 and 25 households per ha (hse/ha).

b) The neighborhoods resulting from irregular occupation had the highest increase in the average density of households (from 15 hse/ha to 20 hse/ha). If we only analyze the neighborhoods with more than 20 hse/ha, we find that the majority of these were occupied irregularly.

c) In both neighborhoods promoted by private and public agents, density increased between 2000 and 2010. Public-share neighborhoods have a higher average density (between 10 and 15 hse/ha) than those of the private-agent (between 5 and 10 hse/ha).

d) As with the neighborhoods of irregular occupation, the neighborhoods with origin in public and private actions have varying densities. With a density greater than 20 hse/ha, in 2000, there was only one neighborhood promoted by private agents and one neighborhood, by public agents; in 2010, two neighborhoods promoted by each agent were identified.

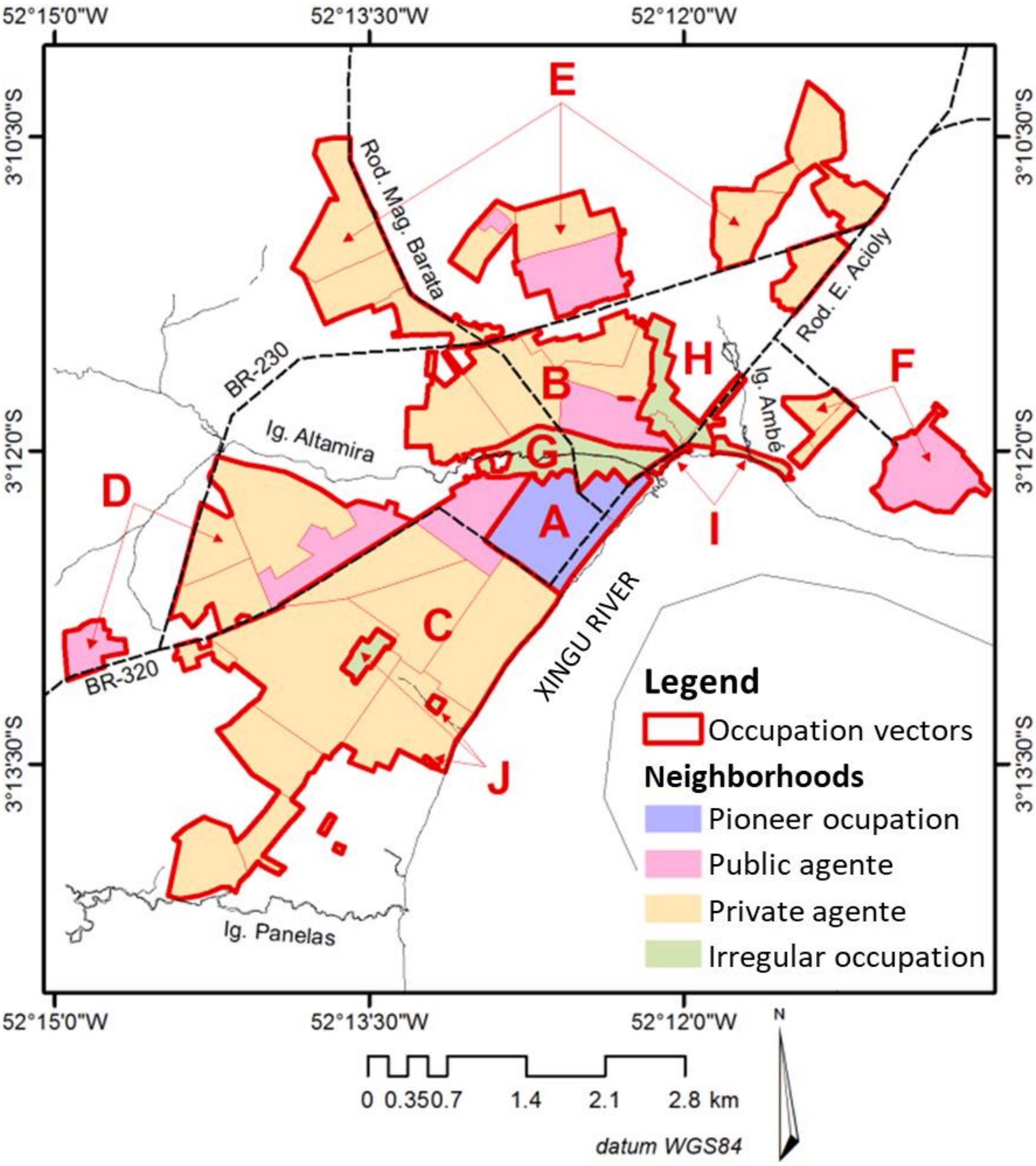
Figure 3.4 - Empirical distribution of density data of households in neighborhoods grouped according to developer agent.



Red dots represent household density in each neighborhood. Black traces represent mean household density by developer agent.
Source: Author.

To analyze the distribution of households in absolute terms, neighborhoods were grouped into 10 occupation areas according to location and developer agent (Figure 3.5). Thus, the neighborhoods that were the first to be occupied are part of the central area (A). The neighborhoods resulting from the public or private action were grouped in: (B) the northern area of the districts located between the Altamira River and highway BR-230, north of the city center; (C) the southwestern area, of the neighborhoods located southwest of the city center; (D) the area to the north of Perimeter Avenue; (E) the area to the north of Highway BR-320 (Trans-Amazonian Highway); and (F) eastern area of the districts located on the Xingu River, to the east of the center. The districts of irregular occupation correspond to the occupation sectors: (G) on the banks of the Altamira Igarapé; (H), on the banks of the Igarapé Ambé; (I), on the banks of the Xingu River; and (J), in the wetland areas of the neighborhoods between the Perimetral Avenue and the Xingu River.

Figure 3.5 - Areas of occupation.



Areas are: (A) central; (B) northern; (C) southwestern; (D) north of Perimetral Avenue; (E) north of BR-230; (F) eastern; (G) occupation of the banks of the Altamira River; (H) occupation of the Ambé River; (I) occupation of the Xingu river bank; (J) occupation of the swamps of the neighborhoods located between the Perimetral Avenue and the Xingu River, Jd. Independente I and II.

Source: Author.

In 2000, the most populous areas in the city, in descending order, were: the southwestern (C), northern (B) and central (A). In 2010, the same order remained, with the increase in the number of households in the southwest and northern areas. In the central area, an opposite process of decreasing households was observed, which shows a switching process from residential use to commercial use (Table 3.4).

The irregular occupation of the banks of the Altamira River (G) is the fourth most populous area in 2000. Although there has been an increase in the number of households in this area, the growth observed in the northern areas of Highway BR-230 (E) and the Perimetral Avenue (D) caused, in 2010, these two areas to surpass the occupation of the Altamira River (Table 3.4).

Table 3.4 - Households by area, in 2000 and 2010.

Area		Households			
		2000 (units)	2010 (dom.)	2000-2010 (dom.)	2000-2010 (%)
A	Central	1,919	1,760	-159	-8%
B	Northern	3,559	4,395	836	23%
C	Southwestern	4,431	6,060	1,629	37%
D	North of Perimetral Ave.	252	1,575	1,323	525%
E	North of BR-230	744	1,981	1,237	166%
F	Eastern	131	184	53	40%
G	Altamira Riverbanks	1,307	1,524	217	17%
H	Ambé Riverbanks	136	463	327	240%
I	Xingu Riverbanks	49	40	-9	-18%
J	Jd. Independente I and II	41	146	105	256%

Source: Author.

The largest increase in absolute terms occurred in the Southwest area (about 1,600 households), followed by the northern areas of Perimetral Avenue and the north of the BR-230 (approximately 1.3 and 1.2 thousand households respectively) (Table 3.4).

The other areas have small participation in the total number of households. Nevertheless, the relative growth of households in the areas of irregular occupancy of the Ambé River (H) and the wetlands (J) areas is shown (Table 3.4).

3.1.4. Conclusions

This work used a simple area interpolation method to overcome the limitations resulting from changes in the geographical coverage of the census tracts and to enable the analysis of intra-urban transformations in Altamira between 2000 and 2010. The method adopted, interpolated from binary, is reported as stable and robust (WU et al., 2005) and has been implemented relatively easily in R software.

Estimation errors were minimized with interactive mapping correction. Incorporating other data, such as the existing road system in 2000 and 2010, could further reduce errors. However, this study was limited to use data available in public databases - number of households per census tract, census tract boundaries and Landsat 5 satellite TM sensor images.

The spatial cut of the target zones - the neighborhoods of Altamira - was made by considering the limits of each subdivision (or occupation) that originated each neighborhood. Thus, the neighborhoods are related to the growth of the city, which contributed to enrich the analysis. From the estimation of household density by neighborhoods, it was possible to observe an increase in household density around the Altamira River and in the neighborhoods between this River and Highway BR-230.

The neighborhoods are homogeneous units and have been aggregated in occupation areas to capture the most relevant dynamics of the city's growth. It was observed that the areas with the highest number of households are the southwestern, northern and central. Of these areas, the Southwest had the highest growth in absolute terms, followed by the northern areas of Perimetral Avenue and north of Highway BR-230. In the first case, the growth occurred with the intensification of the occupation, although the density, in both dates, is still low (about 10 hse/ha). In the other two cases, growth was mainly due to the establishment of new neighborhoods. The density in 2010 in these areas is also low: many neighborhoods have less than 10 hse/ha and only one neighborhood has between 20 and 30 hse/ha.

In addition, there was an increase in the occupation of the banks of water bodies, especially the River Ambé. The occupations on the banks of the Altamira River have the highest observed density in the city (between 30 and 40 hse/ha). Although the estimate of growth in areas of irregular occupation in absolute numbers has not been so significant (around 600 new homes) compared to the total increase in the city (about 14 thousand households), the banks of the creeks and wetlands are densely occupied by population in inadequate conditions of habitability, without legal security of housing ownership and in disagreement with environmental protection standards.

Finally, it was observed that the central area, despite the incipient process of replacing dwellings by commercial establishments and services, still maintains the highest density in the city, which is fully compatible with the fact that, in the city, this area is the one that offers better urban infrastructure. Altamira is witness to several governmental initiatives to occupy the Amazonian territory and to exploit its resources. The proposed approach makes it possible to analyze intra-urban dynamics in different periods of the city's development, following the processes triggered by the opening of Highway BR-230 (Trans-Amazonian Highway) in the 1970s, for example, or by the construction of the Belo Monte Hydroelectric Plant which began in 2010.

3.2. Paper 2

DEMOGRAPHIC, ECONOMIC AND PHYSICAL DATA INTEGRATION: MEASURING HILLSIDE'S URBAN OCCUPATION IN METROPOLITAN REGION OF SÃO PAULO (BRAZIL)

3.2.1. Introduction

Geospatial data are crucial to Urban Science research and to policy and decision making. However, analysis of urban geospatial datasets must overcome differences due to measurements, spatial units of recollection and spatial and temporal resolution. Regarding demographic data, the smallest area of data recollection – census tract – is often delimited based on operational criteria. Temporal comparison is affected by differences in tracts limits that may vary between censuses. This configures a Modifiable Areal Unit Problem (MAUP), in which conclusions may not possess any validity independent of the units which are being studied (OPENSHAW, 1983).

Physical variables, on the other hand, have their own representation, depending on the way they are measured. This work proposes to overcome MAUP and different spatial representations with the usage of a cellular space, defined as a regular lattice of two dimensions. Urban growth, relief and economic conditions of population in Metropolitan Region of São Paulo (MRSP) is used as a case study.

3.2.2. Materials and methods

3.2.2.1. Study site

The Metropolitan Region of São Paulo (MRSP) is the most important agglomeration in Brazil, with more than 21 million inhabitants in an area that covers 39 municipalities in almost 80 km^2. Urban development in municipalities of the MRSP took place in the flatter areas, formed by the sedimentary basin, with soft hills and platforms, and by the extensive fluvial plains of the Tietê and Pinheiros rivers. In the second half of XXth century, urban expansion consumed favorable areas and advanced over the rugged relief of the Atlantic Plateau, surrounding MRSP.

3.2.2.2. Data

Data integration and estimative were performed with the following data:

a) Population in private households and average income of the individual responsible for the household (household’s head) from Census tracks in 1991 and 2010 (IBGE, 1991; 2010);
b) Landsat TM Collection Tier 1 images, as presented in Table 3.5, calibrated to top-of-atmosphere reflectance and made available by U.S. Geological Survey (USGS);
c) Georeferenced Digital Cartographic Base of Public Addresses of the Metropolitan Region of São Paulo, updated to 2018 (CEM, 2018);
d) Slope, calculated from topographic maps in scale 1:25.000 (EMPLASA, 1980).

Table 3.5 - Landsat TM Collection Tier 1 scenes and dates for MRSP.

Referenced Census year	Scene (Path / Row)		
	219/076	218/076	219/077
2010	2010-Aug-24	2010-Sep-02	2011-Jul-26
2000	1999-Aug-26	1999-Jul-02	1999-Aug-26
1991	1992-Sep-23	1992-Jul-30	1992-Sep-23

Source: Author.

3.2.2.3. Methods

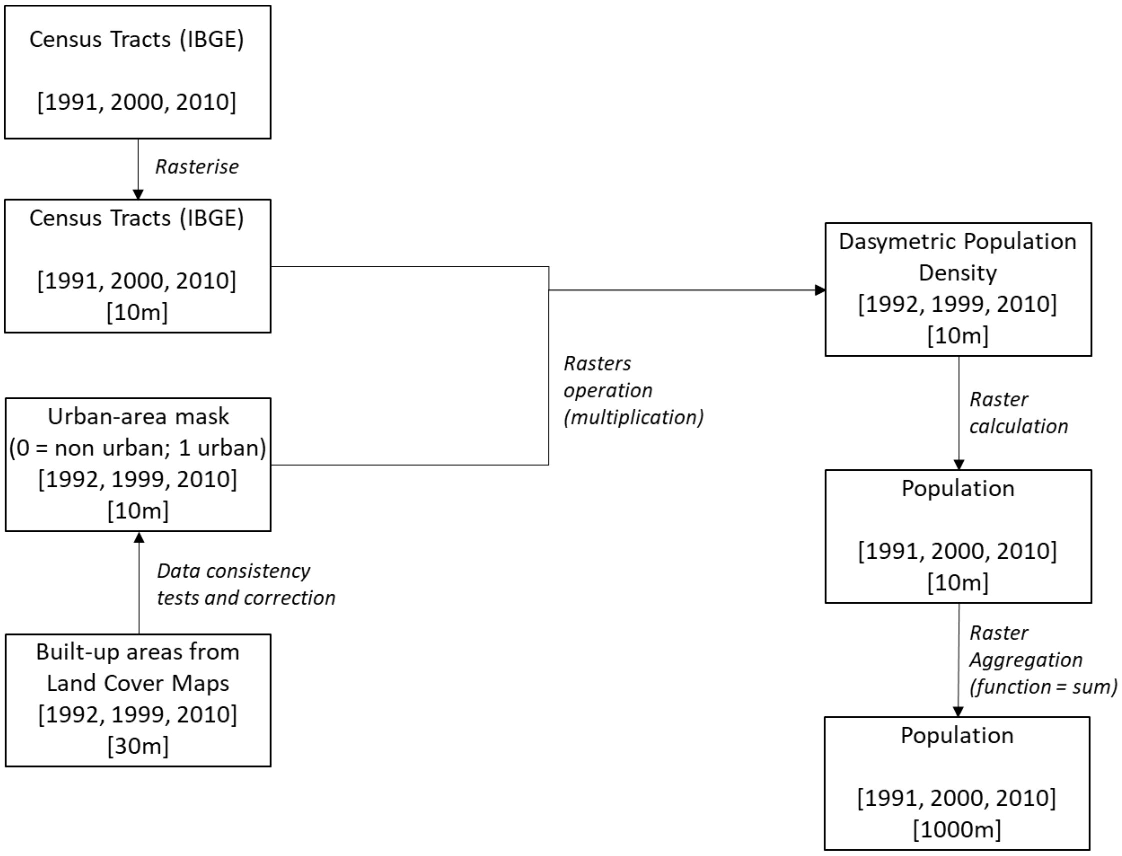
Built up areas were mapped from Landsat TM, at a spatial resolution of 30m, using a supervised classification approach based on support vector machine applied to visible and infrared bands (red, green, blue, and NIR bands), Normalized Difference Vegetation Index (NDVI), mean NDVI computed for summer season and mean NDVI of winter season. The classification model was built with 677 random samples visually classified on orthophotos of year 2010, divided into two equally sized groups for training and validation. Samples were visually classified into 4 classes: vegetation, built up areas, bare soil and water. Land cover classes corresponds to the following description:

- Vegetation: forest, crops, fields and grass.
- Built up areas: small sized horizontal buildings; small sized sparse horizontal buildings; medium sized building (as Brás neighborhood); medium sized building sparse (clubs); big sized buildings; mixed sized horizontal buildings; mixed buildings (small / medium sized and vertical / horizontal); verticalized block occupation; horizontal housing; vertical housing (social housing buildings – up to 5 floors); structures with little built volume (such as power station, tank storage area) open spaces and circulation system (such as roads, railroads, airports, parking lots).
- Bare soil: mining and bare soil.
- Water: reservoirs and ocean.

Two nested resolutions, 1km x 1km and 10m x 10m, were used. Calculations and data integration were performed in finer resolution grid and visualization and analysis, in coarser resolution grid.

A dasymetric interpolation was performed to obtain a gridded data of population from polygons of census tracts, following procedure illustrated in Figure 3.6.

Figure 3.6 - Dasymetric interpolation procedure.

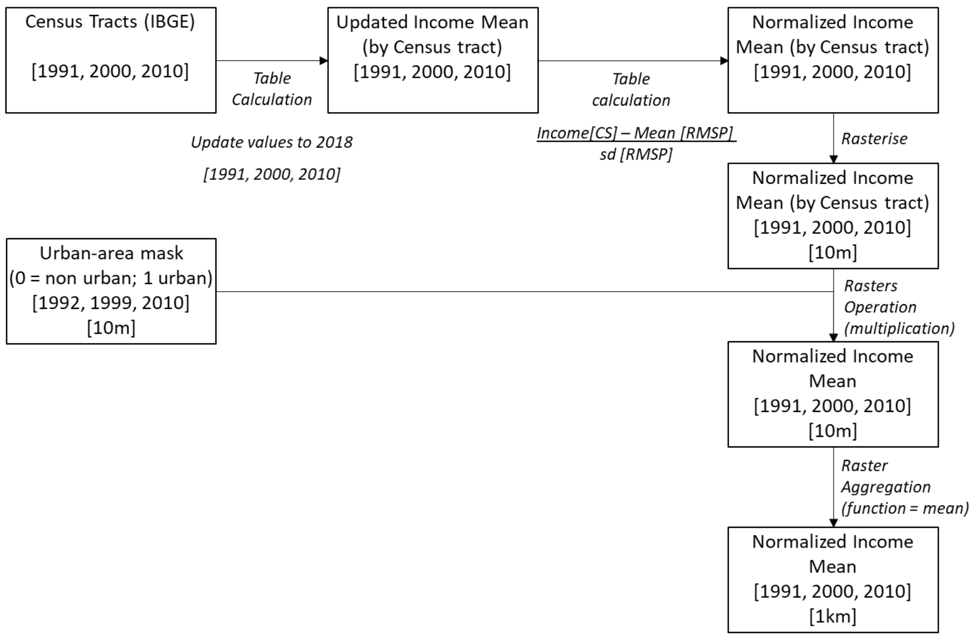


Source: Author.

In data consistency check, census tracts with assigned population but without built-up areas, as derived from land covers maps, were observed. In these cases, two procedures were adopted: if population was bigger than > 15 inhabitants, the entire tract was considered as urbanized area; if not, a buffer of 20m was created along roads, as an estimation of built-up areas. In both situations, these assumed built-up areas were added to the built-up areas derived from land cover maps to create an urban-area mask.

Normalized mean income of household's head were obtained following the procedures presented in Figure 3.7.

Figure 3.7 - Income data interpolation procedure.



Source: Author.

3.2.3. Results

The classification model achieved an overall accuracy of 89.8% (confidence intervals of [0.873, 0.920]), and Kappa Index of 0.844. Confusion matrix between classification and validation samples obtained from orthophotos is presented in Table 3.6.

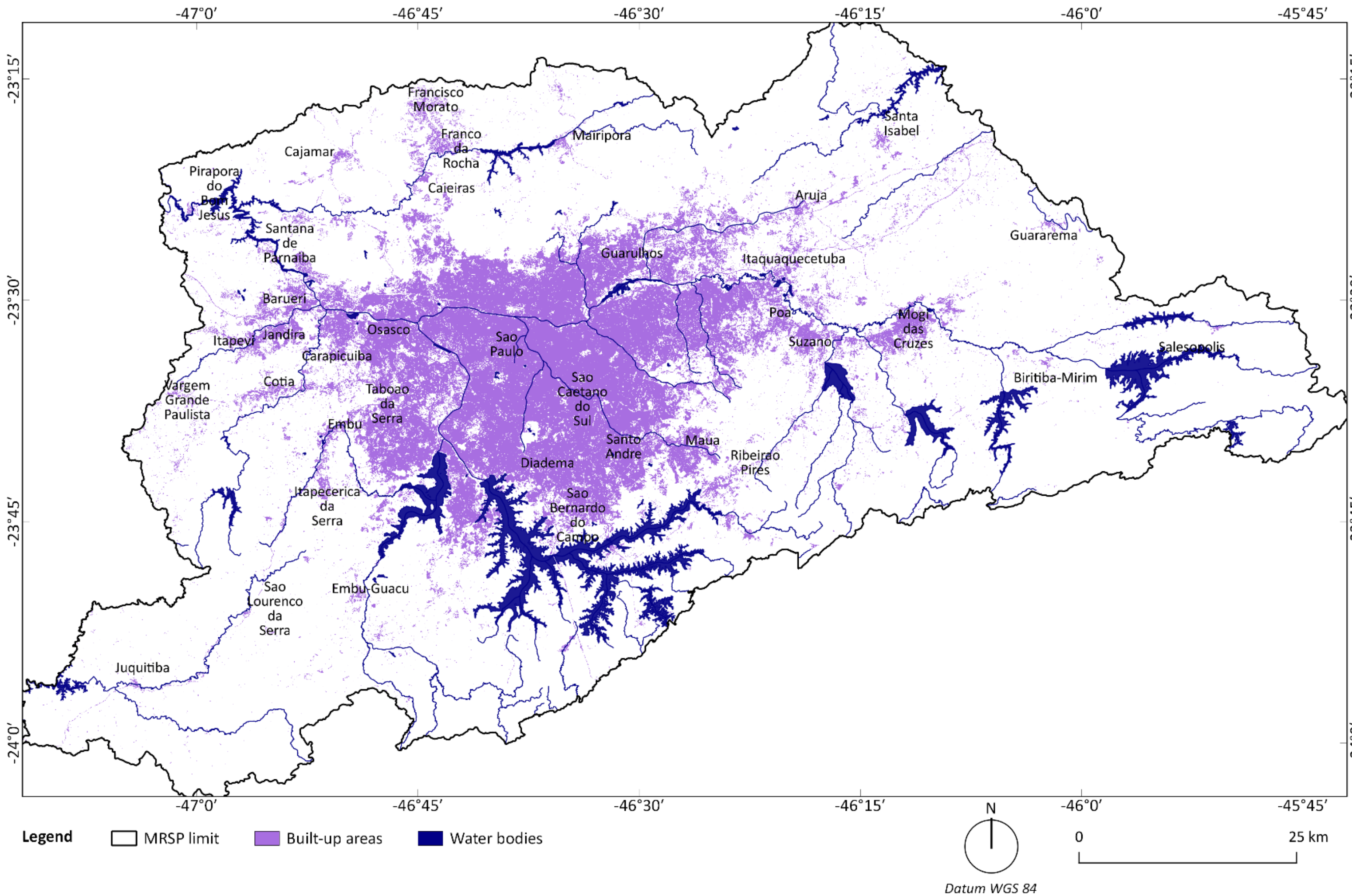
Table 3.6 - Confusion Matrix for land cover mapping.

Class		Reference: Vegetation	Reference: Built-up Areas	Reference: Bare Soil	Reference: Water	No. of classified points	User accuracy
Classification	Vegetation	222	19	2	3	246	0,90
Classification	Built-up Areas	19	269	19	0	307	0,88
Classification	Bare Soil	1	5	29	0	35	0,83
Classification	Water	0	0	0	89	89	1,00
No. of reference points		242	293	50	92	677	
Producer accuracy		0,92	0,92	0,58	0,97		

Source: Author.

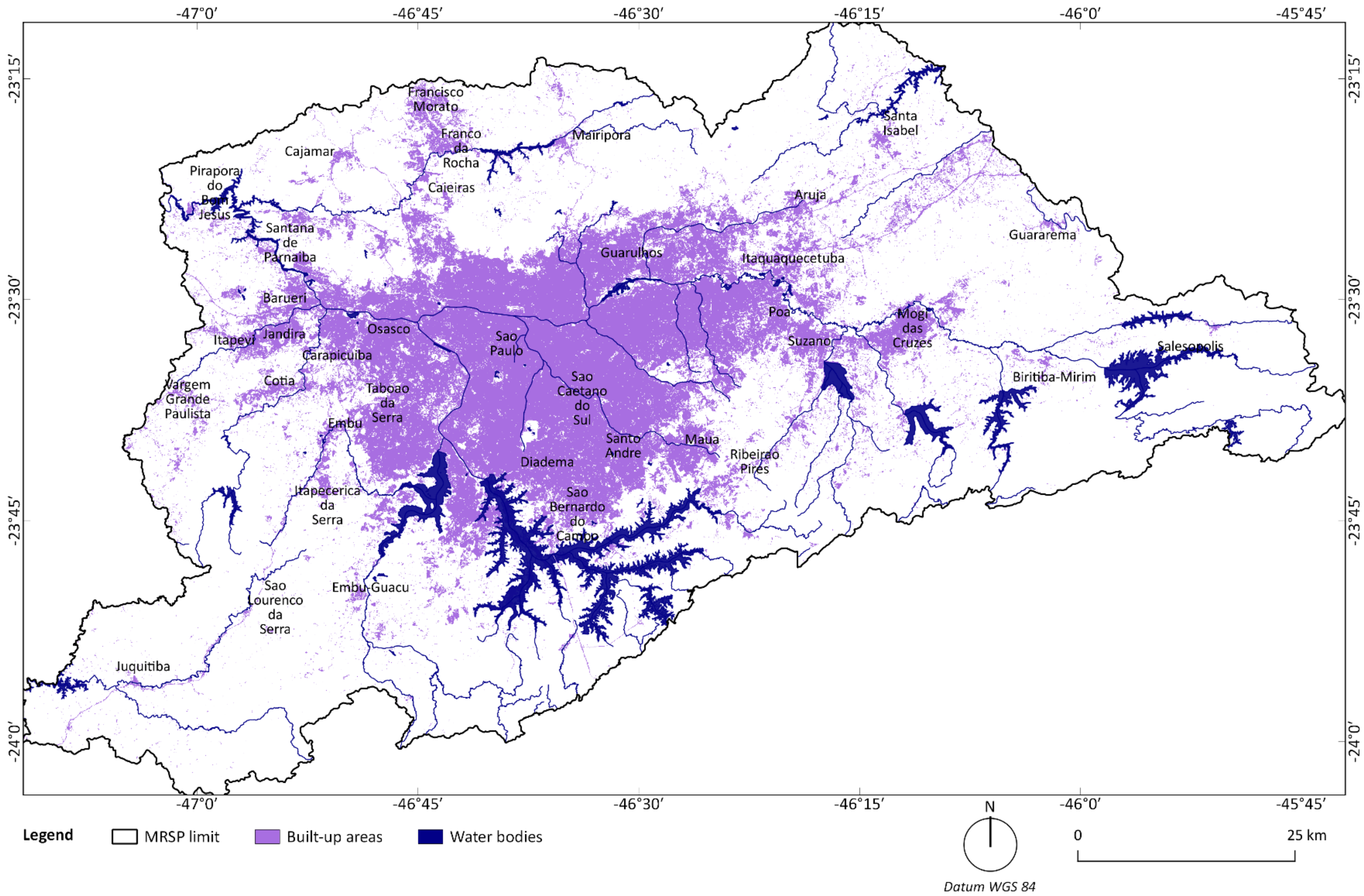
Land cover maps for 1992, 1999 and 2010 were obtained by applying this model to 1992, 1999 and 2010 images. Figures 3.8 to 3.10 present the built-up areas derived from these land cover maps.

Figure 3.8 - Built-up areas in the MRSP, 1992.



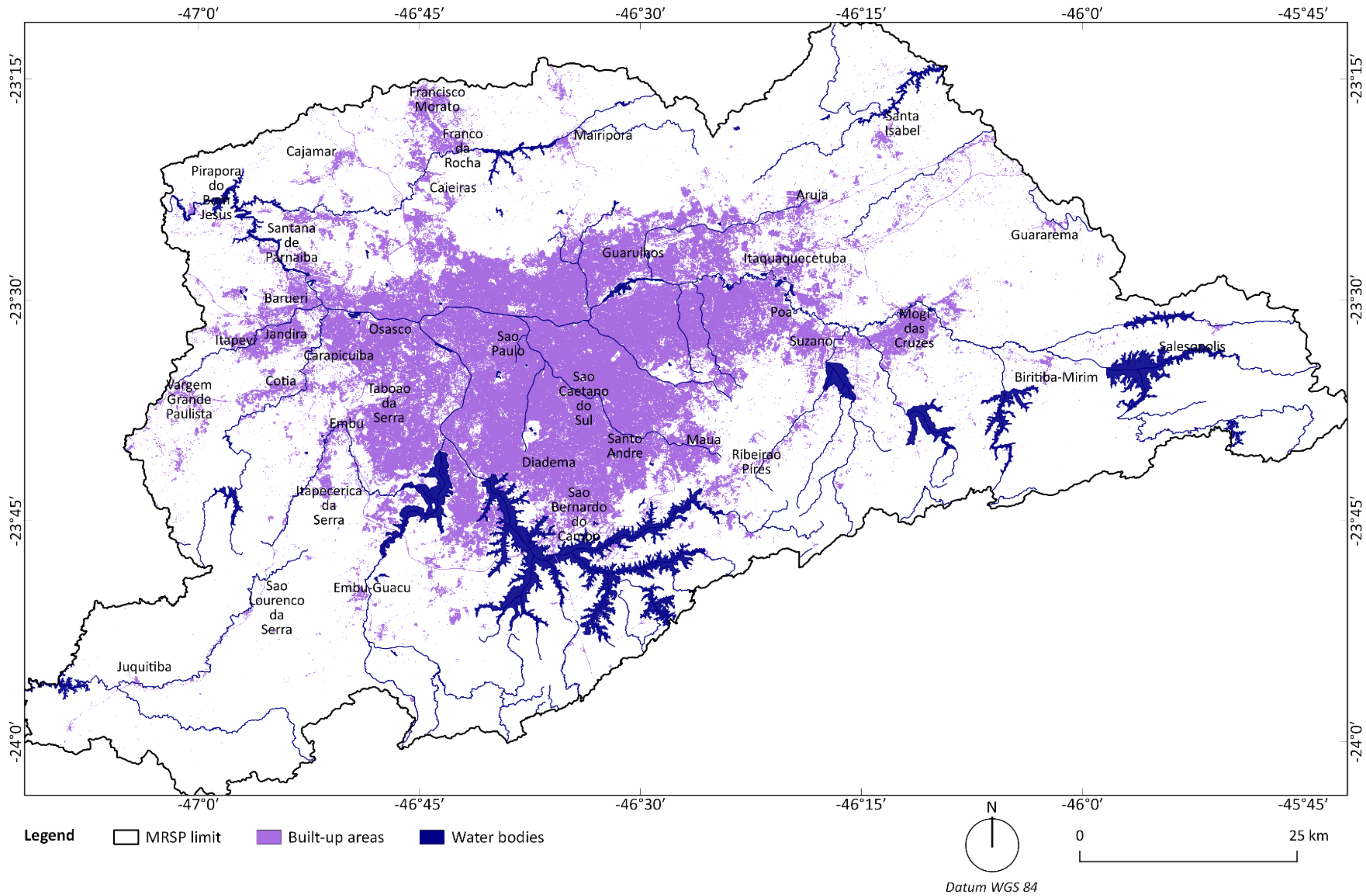
Source: Author.

Figure 3.9 - Built-up areas in the MRSP, 1999.



Source: Author.

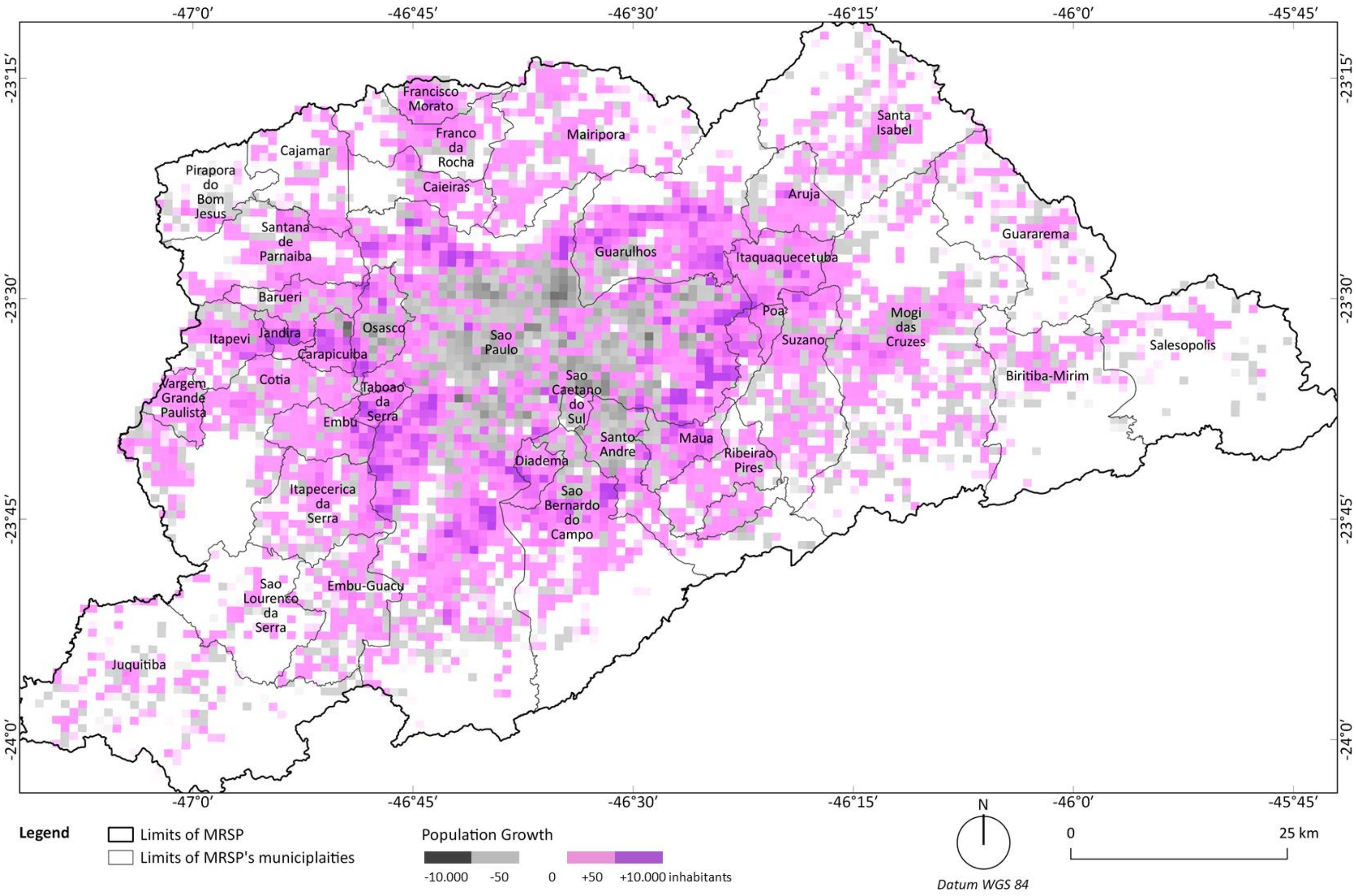
Figure 3.10 - Built-up areas in the MRSP, 2010.



Source: Author.

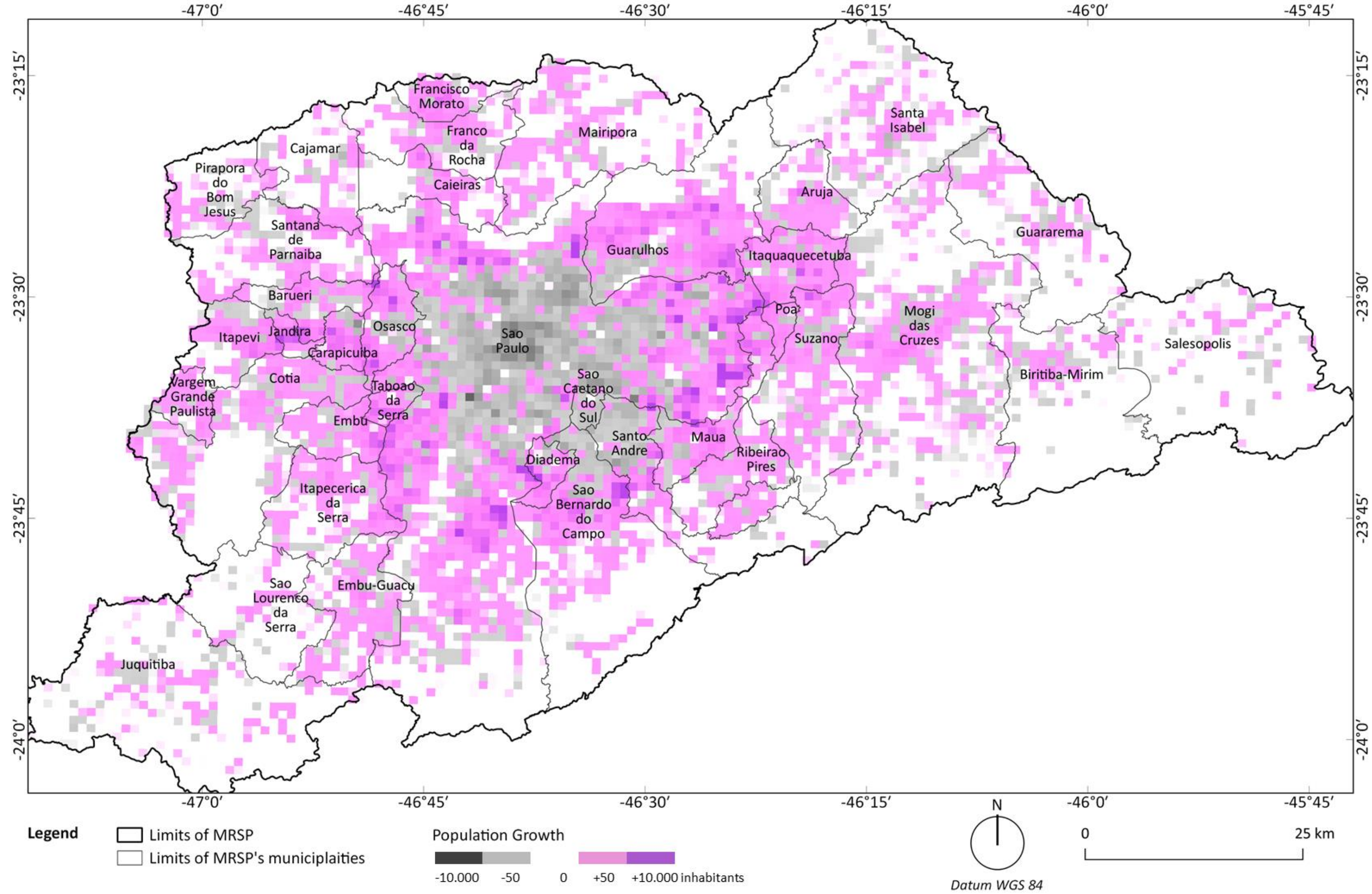
Between 1991 and 2010, population growth was characterized by a dual spatial pattern: population increase in urban fringes of all directions from downtown, and population decrease in central areas of MRSP main cities, São Paulo, Guarulhos, Osasco, São Bernardo do Campo, São Caetano do Sul and Santo André (Figure 3.11). While peripherical population growth pattern remained unaltered during the whole period, a population decline process was more pronounced in 1991-2000 period (Figure 3.12), while in the next inter-census period, this process was reversed for the central area of São Paulo and lost intensity in other main central areas of MRSP, such as Santo André, Guarulhos or Osasco (Figure 3.13).

Figure 3.11 - Population growth between 1991 and 2010 in the MRSP, aggregated using a 1km grid.



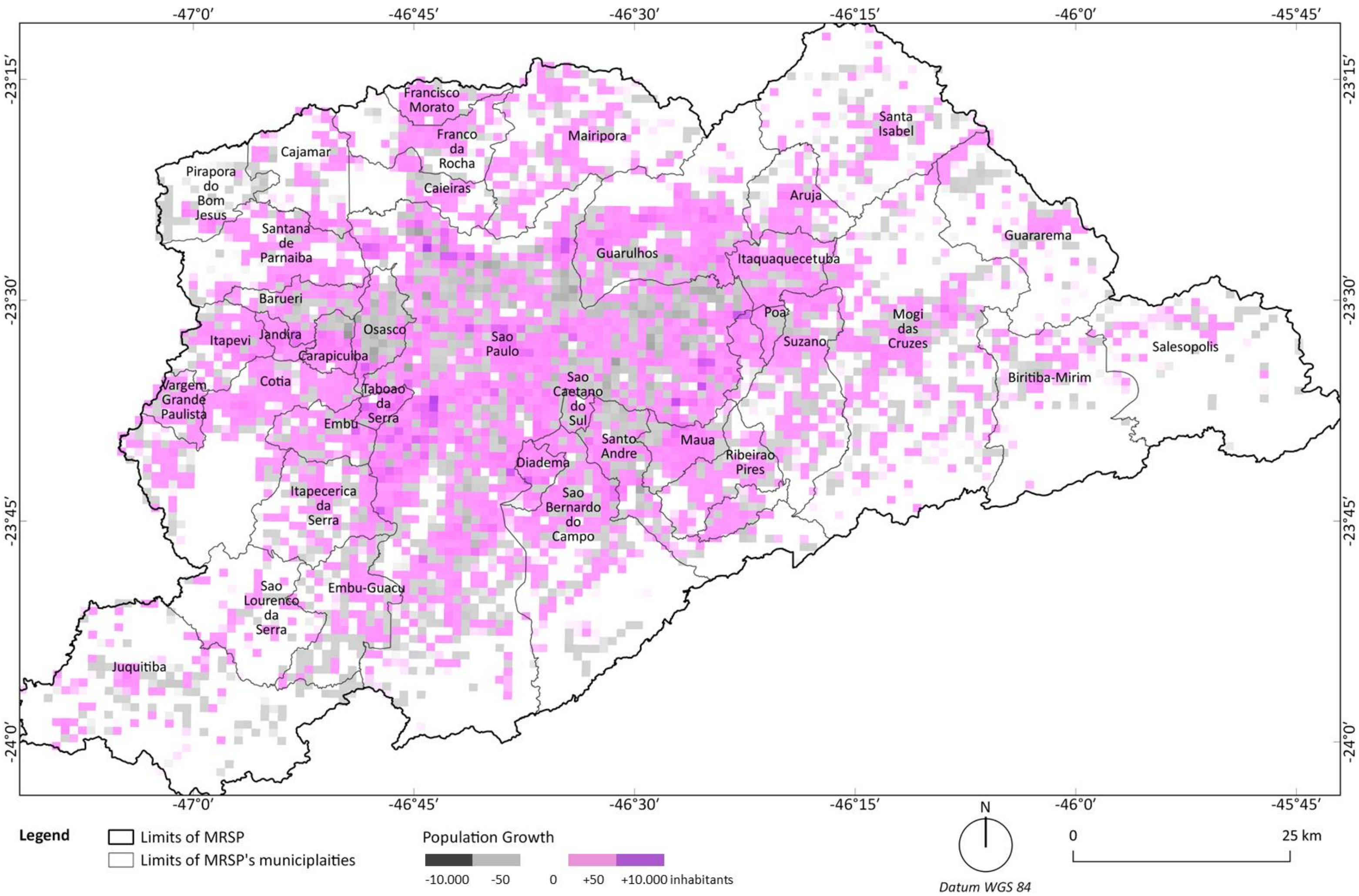
Source: Author.

Figure 3.12 - Population growth between 1991 and 2000 in the MRSP, aggregated using a 1km grid.



Source: Author.

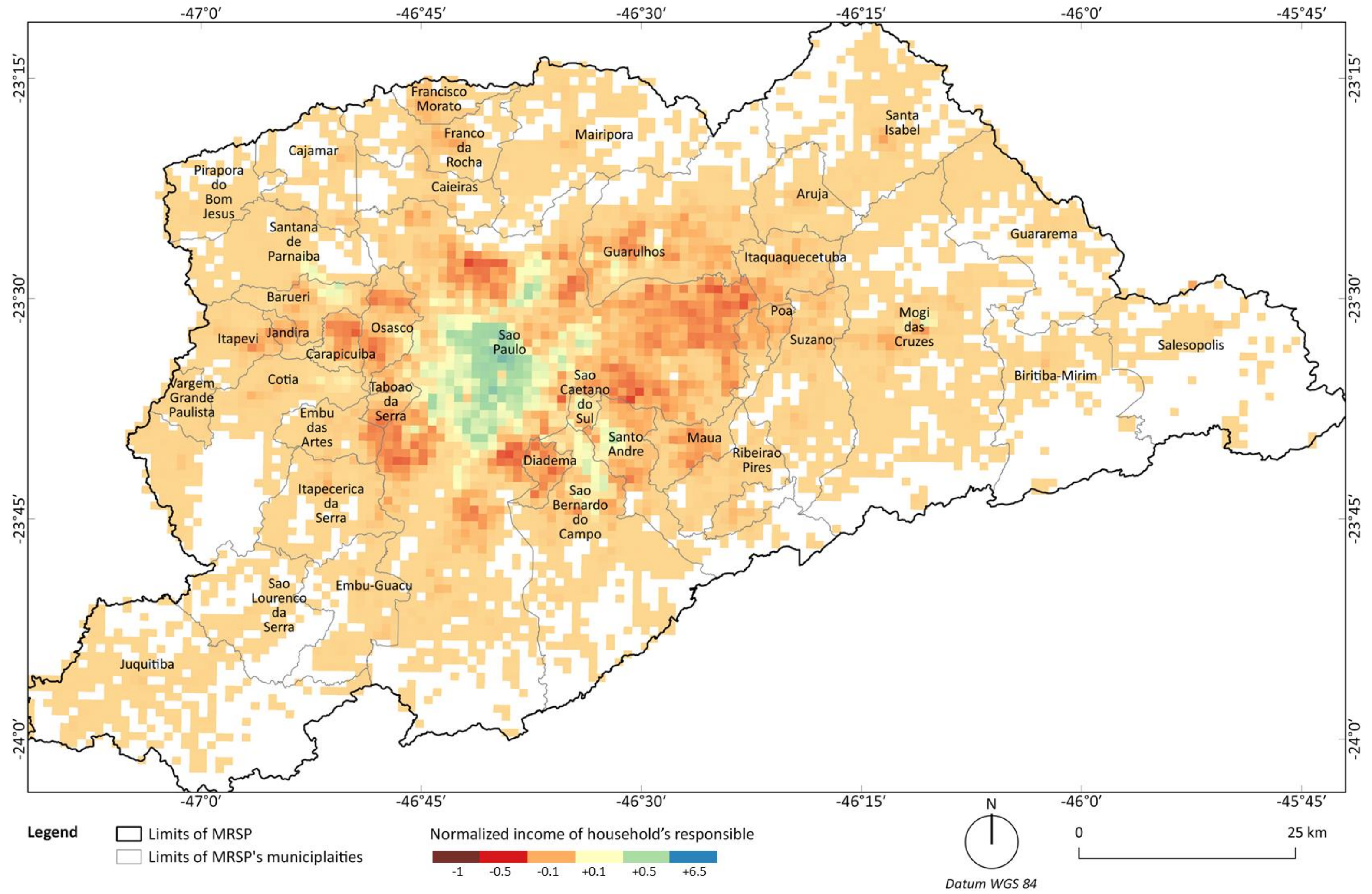
Figure 3.13 - Population growth between 2000 and 2010 in the MRSP, aggregated using a 1km grid.



Source: Author.

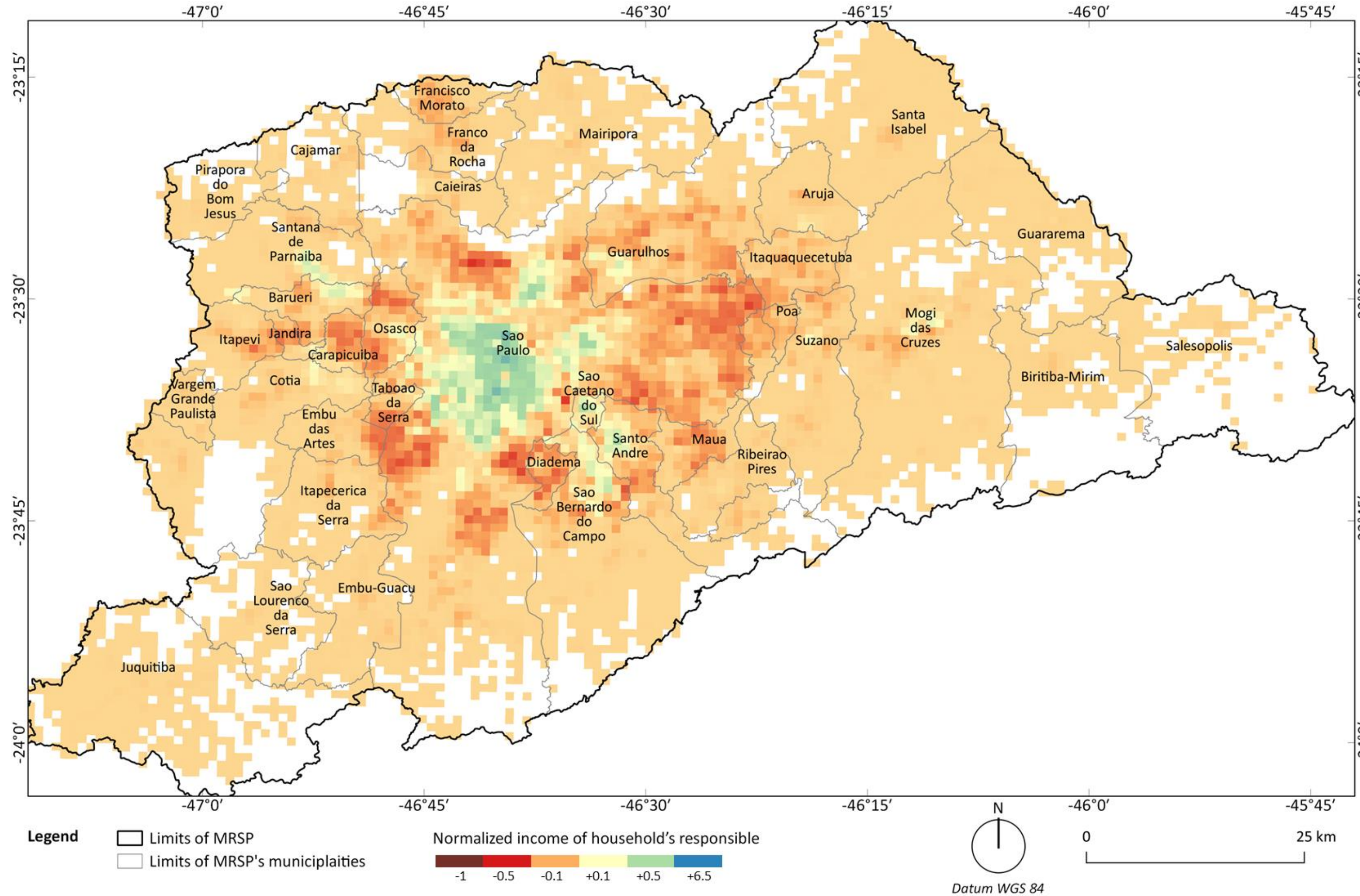
The spatial distribution of income has not changed during the period: there is a clear pattern of low-income areas in the fringes of the MRSP's core. Peripherical low-income areas are coincident with areas of population increase, conforming the suburban growth pattern that has been characterized MRSP's urban development since 1960's. Between 1991 and 2010, center and southwest of São Paulo municipality and contiguous areas in São Caetano do Sul, São Bernardo do Campo and Santo Andre municipalities remained as high-income areas (Figures 3.14, 3.15 and 3.16).

Figure 3.14 - Normalized income of household's head in the MRSP, aggregated using a 1km grid, in 1991.



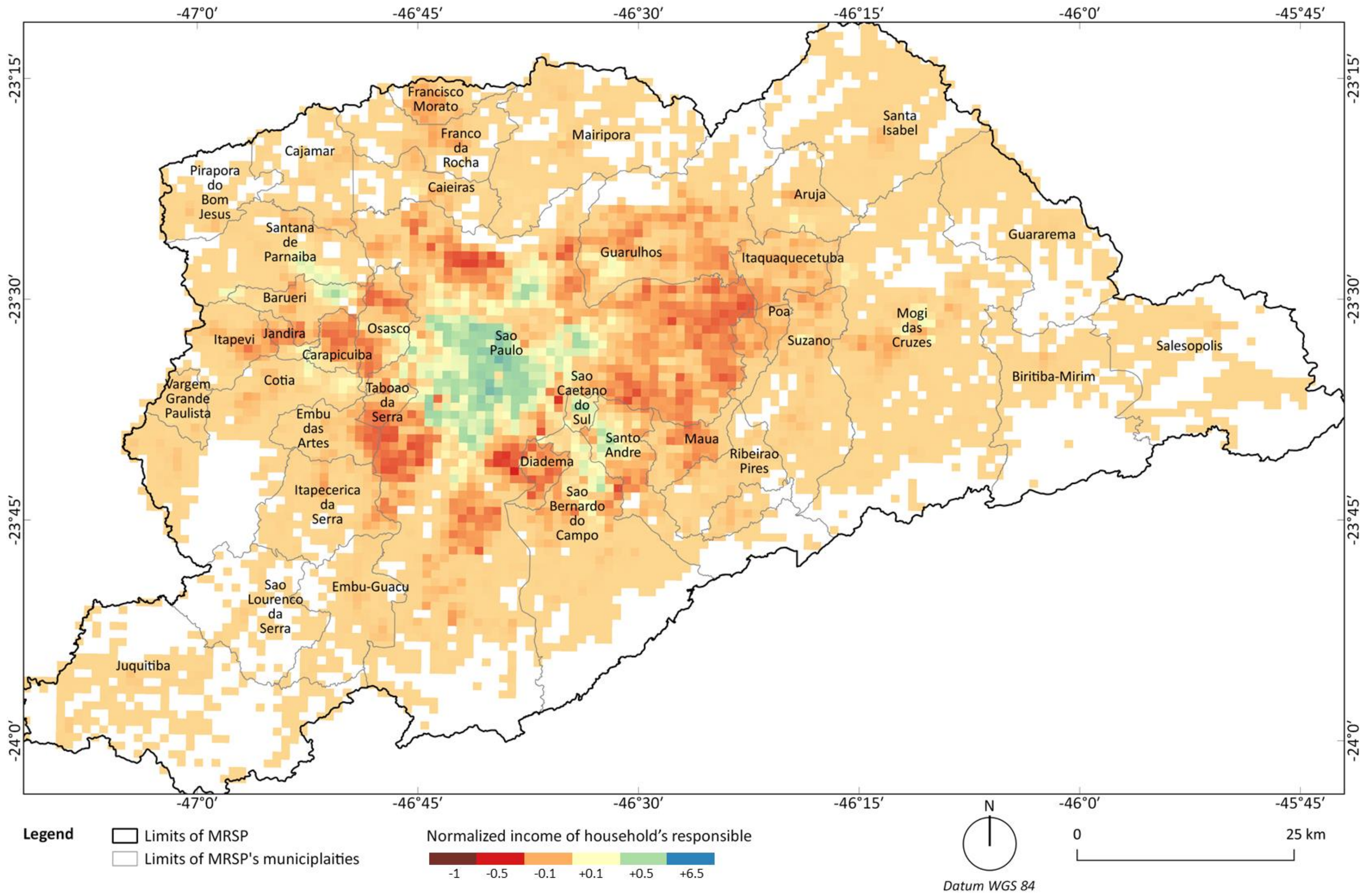
Source: Author.

Figure 3.15 - Normalized income of household's head in the MRSP, aggregated using a 1km grid, in 2000.



Source: Author.

Figure 3.16 - Normalized income of household's head in the MRSP, aggregated using a 1km grid, in 2010.

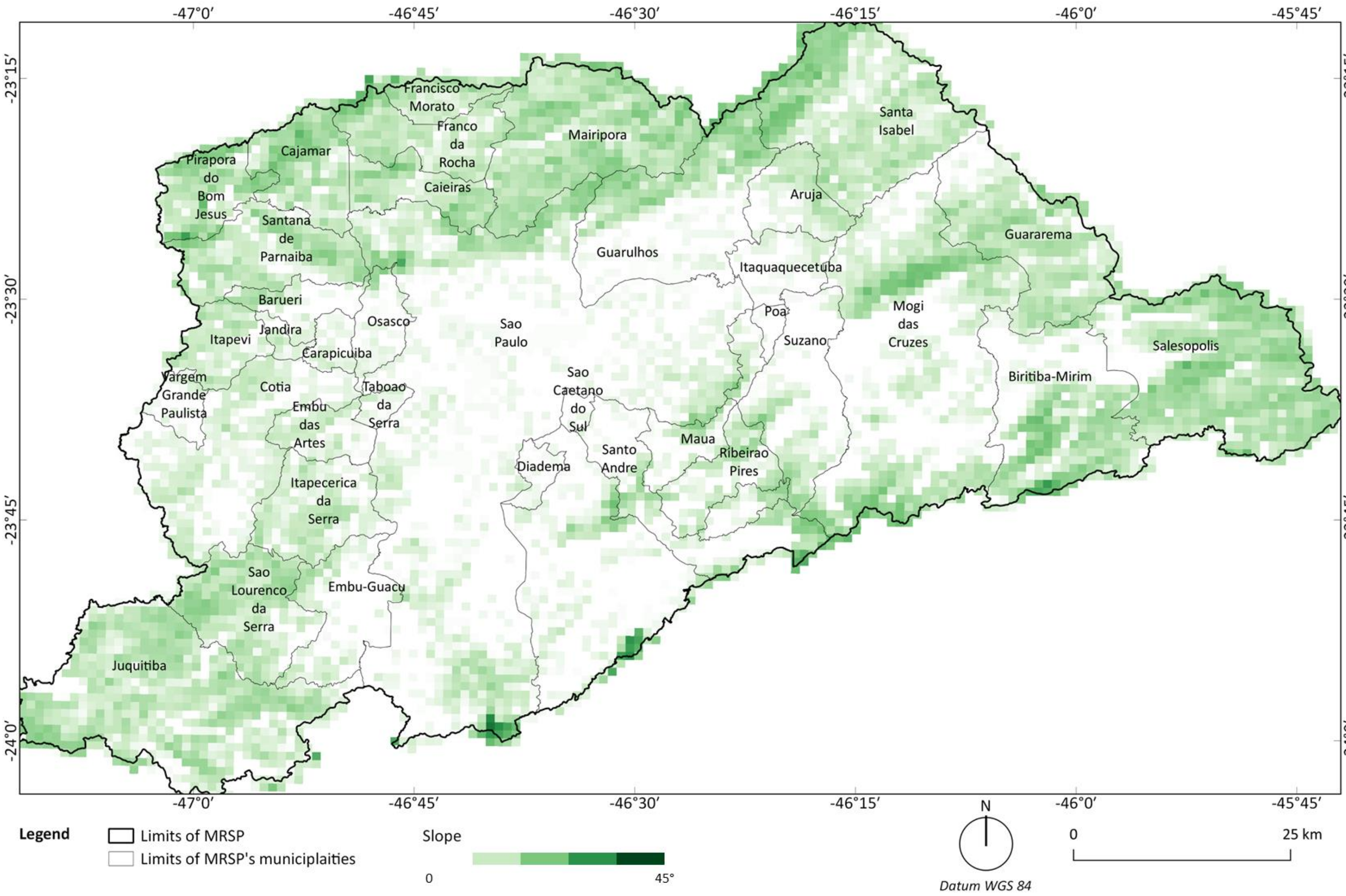


Source: Author.

The preponderance of steeper slopes in north of São Paulo municipality, making a barrier to urban development. Steeper slopes can also be observed in extreme east and west of MRSP (Figure 3.17). Population growth in slopes steeper than 17° (30%) occurred in the fringes of the urbanized area (Figure 3.18). Suburban train lines, that operate on the former railroad system (Line 7, 8 and 10), have contributed to the occupation of northernmost, westernmost southernmost areas or MRSP, characterized by high hills and steeper slopes. Population growth was also observed in steep slopes of the soft hills between São Paulo, Taboão da Serra, Embu and of the high hills of Cantareira Mountain Ridge in the north of São Paulo and Guarulhos municipalities.

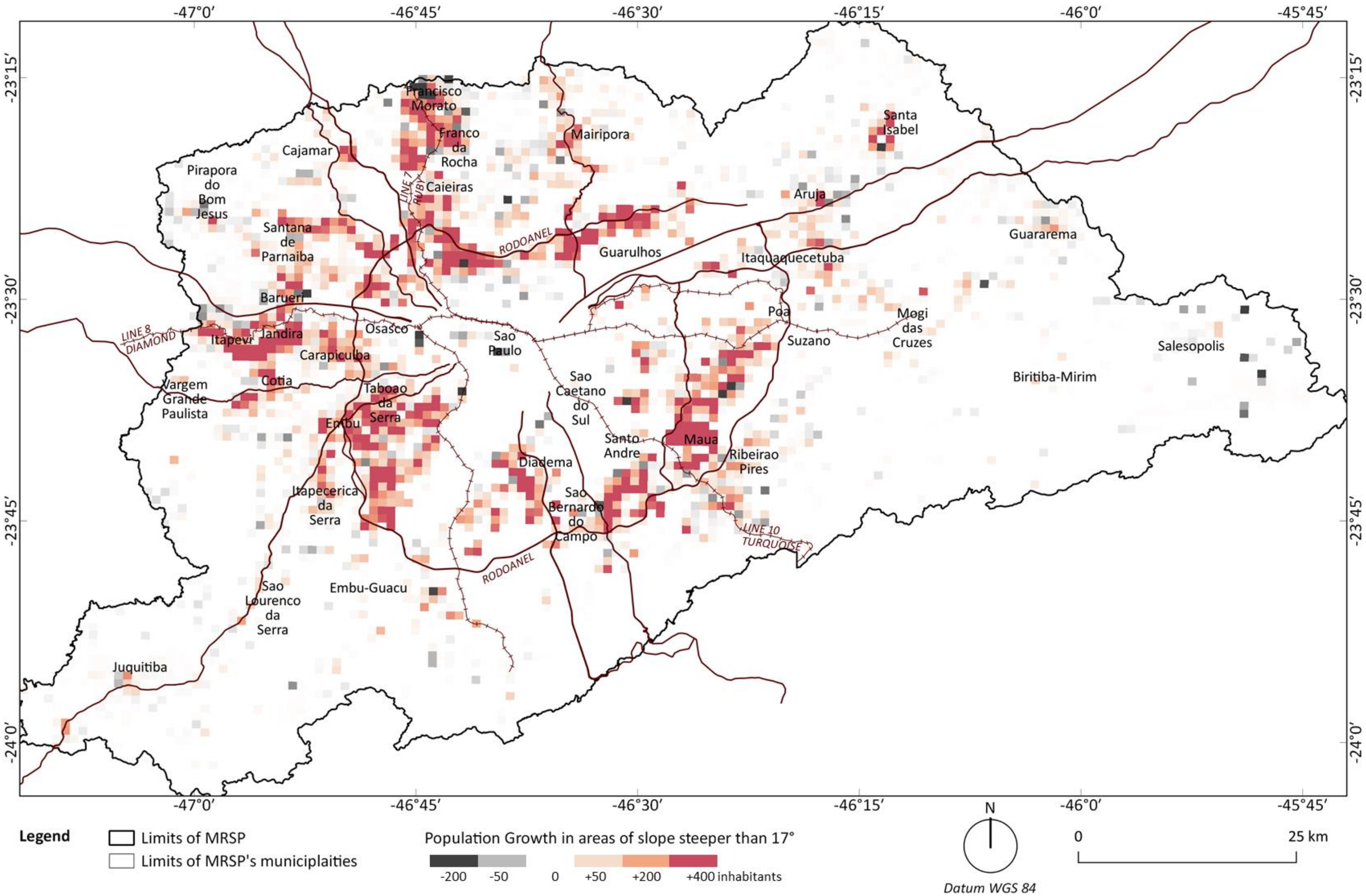
Population in MRSP increased 4,32 million people between 1991 and 2010 and its urban area expanded 24%, adding 44,272 ha of new urban areas. New occupied areas in slopes steeper than 17° (30%) were of 2,468 ha, or 5,6% of the new areas. However, in these areas population growth rate was of 4,15% per year, while in the entire MRSP, it was of 1,32% per year. We estimated a growth of 353,650 inhabitants in slopes.

Figure 3.17 - Terrain median slope (in degrees) in the MRSP, aggregated using a 1km grid.



Source: Author.

Figure 3.18 - Population growth between 1991 and 2010 in the MRSP in slopes, aggregated using a 1km grid.



Source: Author.

3.2.4. Conclusions

Transforming data from different sources and different characteristics into one type of representation can enable calculation, facilitate visualization and serve as inputs to modelling. The innovative approach presented in this paper – the usage of two different resolutions – keeps the spatial detail in calculations and data integration, preventing inaccurate conclusions, while makes possible the usage of a coarser resolution, more suitable to metropolitan areas. using this approach the population growth in MRSP slopes was estimated in 353,650 inhabitants. Population has increased at a higher rate on slopes than in flat areas. Estimated population growth rate in MRSP's slopes was of 4,15% per year, while the average growth of the entire population was of 1,32% per year.

3.3. Paper 3

3.3.1. Introduction

Cities concentrate more than half of world's population (UN, 2018a). From 1950 to 2050, the proportion of people living in urban areas will be raised from 30% to 68% (UN, 2018b). As points of concentration of people and infrastructure, cities are hotspots of risk when exposed to hazards (ALEXANDER, 1989; BURTON et al., 1993). Moreover, the interactions among urban activities can lead, themselves, to risk situations posed by technological failures, natural disasters, such as urban floods or landslides, or even social activities, as crime, riots or land invasion (HORLICK-JONES, 1995). In a context of increasing interaction of society and environment, risks are becoming systemic (UNDRR, 2019).

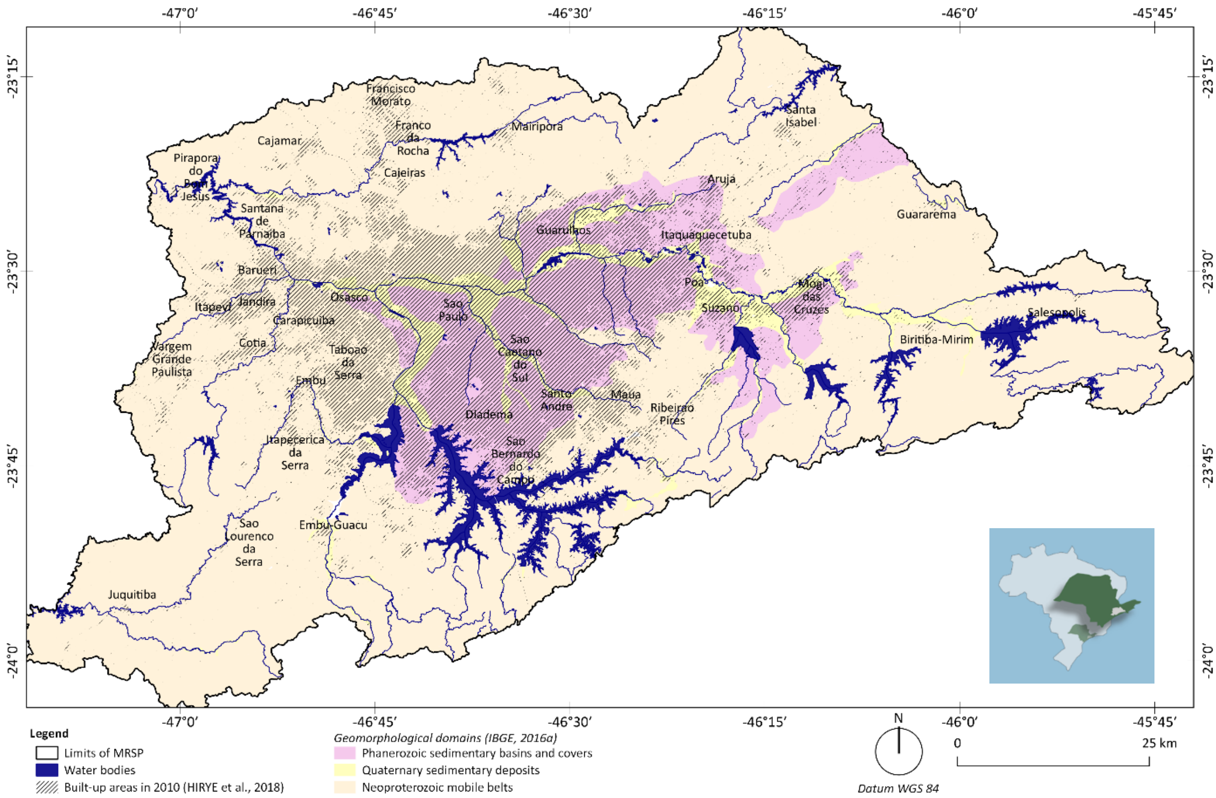
Landslides are common events in cities located in hilly areas. Triggered mainly by rainfall, urban landslides are polycausal phenomena (ALEXANDER, 1992). For example, in the Chinese city of Zhouqu, it has been shown that the storm triggered landslide that resulted in 1,765 casualties in 2010 was also related to a combination of factors such as human activity (deforestation and topsoil erosion) alongside geological conditions and terrain modifications caused by an earthquake (REN, 2014; EM-DAT, 2019). In 2017, another landslide following heavy rainfall caused more than 1,000 casualties in Regent neighborhood, city of Freetown (Sierra Leone). Poor conditions of a rapid and hazardous urbanization were a pre-scenario to this disaster, while increased erosion potential from clearance of hillsides' vegetation and weak emergency response acted to amplify its impacts (CUI et al., 2019). Globally landslide occurrence triggered by human activity is increasing, particularly in relation to housing and infrastructure construction, illegal mining and hill cutting. This supports the idea that human disturbance may be more detrimental to future landslide incidence than climate (FROUDE; PETLEY, 2018).

Landslides causing deaths and major economic losses draw public and government attention, although low-intensity landslides must not be underestimated. Associated with an extensive risk, these events are more frequent and result in non-neglectable material losses. An estimation made by Global Assessment Report on Disaster Risk Reduction showed that costs of destroyed and damaged housing can represent as much as 44% of the total economic losses in the housing sector (UNDRR, 2009). Low impacts accumulated over time are an ongoing erosion of development assets, such as houses, schools, health facilities, roads and local infrastructure. They are absorbed mostly by residents, undermining progressively their capacity to recover and subsist (UNDRR, 2009).

All countries are not equal concerning to landslide risk, and it has been observed that fatal urban landslides occur primarily in the less-developed tropical regions, likely because of loss of vegetation cover and alterations in terrain and drainage patterns demanded by urban development, associate with a thick weathering layers characteristic of tropical environments (PETLEY, 2009).

In this context, Sao Paulo is of primarily importance to understand how landslides occur in tropical cities. The Metropolitan Region of São Paulo (MRSP) is the most important agglomeration in Brazil, in economical and populational terms, and the fourth biggest urban agglomeration in the world (UN, 2018a), with 21.6 million inhabitants (IBGE, 2018). The site of MRSP is one of the exceptions to the rugged relief of the Atlantic Plateau, a geological unit which covers the southeast of Brazil, alongside the Atlantic coast. Urban development in MRSP municipalities took place in the flatter areas, formed by phanerozoic sediments, with soft hills and platforms, and by the extensive fluvial plains of the Tietê and Pinheiros rivers, formed by quaternary sedimentary deposits. However, from the second half of XXth century, the expansion of the pioneer settlement consumed favorable areas and began to advance to the hillsides of the Neoproterozoic mobile belts, formed over a crystalline basement of metamorphic and igneous rocks, Figure 3.19 (MARCONDES, 1999; IBGE, 2009). Thus, urban development in this unit is distinguished by the coexistence with hills, discontinuous masses or blocks of raised plateaus, interspersed by valleys with a transversal profile well marked by the dense network (AB'SABER, 1958).

Figure 3.19 - Urban occupation and geomorphological domains in the MRSP.



Source: Author.

In MRSP, more than 12,000 geological disasters events were recorded in a period of 20 years (from 1993 to 2013) and the majority of these events caused low-intensity damages to housing and infrastructure (IG, 2017). While it has been previously showed that landslides in Southern Brazil mostly occur during the rainy season (CEPED, 2013; FROUDE; PETLEY, 2018), for the urban system of MRSP, we are still lacking of an analysis including dynamic socioeconomic and infrastructural conditions alongside climatic and geophysical condition.

In this paper we propose to use the socio-ecological-technological system (SETS) approach (MCPHEARSON et al., 2016) to correlate dynamic and static social, biophysical and infrastructural conditions to landslide occurrence in the MRSP. The SETS is intended to look at the cities as complex urban systems, where ecological functions are included in a socio-technological framework that explicitly considers the role of technology and infrastructure within the social-ecological system (DEPIETRI; MCPHEARSON, 2017). The technical-infrastructural sub-system represents the built environment itself, that mediates the relationships between human actions and its environment and can contribute to mitigate or to exacerbate impacts and stressors to this system. From a management point of view, treating infrastructure integrated in a SETS can facilitate the identification and prevention of maladaptive issues that stem from SETS interactions, like lock-in, as well as offer new perspectives for adaptation strategies that may not traditionally be considered (GRABOWSKI et al. 2017; MARKOLF et al. 2018). Since its only premises are the interactions between components of these domains, it is flexible enough to accommodate a variate type of analysis from distinctive perspectives to investigate urban system's dynamics and complexity (MCPHEARSON et al., 2016). Moreover, this approach can support urban system characteristics of openness and its multi-scalar nature (BAI et al., 2016).

For the MRSP, we have identified SETS core components that belong to each of the SETS domains: Ecological-Biophysical, Social-Behavioral and Technological-Infrastructural. In urban environments, where human-induced changes are prominent, landslide occurrence is the outcome of the relationships between intrinsic characteristics of the biophysical domain with the extension, level and quality of alteration of slope geometry, surcharge and water related processes. These alterations are controlled by actions of dwellers, land developers and public administration, understood as components of the social-behavioral domain. These actions are materialized in the built environment, which comprises the technological-infrastructural domain and includes buildings, sanitation system and streets and drainage system. Rainfall, by its turn, is expected to have different effects in natural and altered slopes. In the next paragraphs, the relation of each SETS domain and its components with landslide occurrence are detailed.

Most literature about landslides is concerned with factors related to the biophysical domain. Rainfall is reported to be the main factor in triggering shallow landslides, i.e. single slope movements with planar slip surfaces and small lateral dimensions (GUIDICINI; IWASA, 1977; SCHUSTER; HIGHLAND, 2007; ÁVILA et al., 2016). There are different ways to measure their effect (SEGONI et al., 2018). In investigations of the relationship between antecedent rainfall and landslides, several authors considered different periods over which rainfall should be accumulated, ranging from hours to months, e.g. 24h (DAI; LEE, 2003), 3 days (SANTORO et al., 2010), 4 days (TATIZANA et al., 1987); 15 days (PASUTO; SILVANO, 1998), 21 days (et al., 2017), 31 days (MENDES et al., 2018), 3 to 4 months (GUZZETTI et al., 2010). Kirschbaum and Stanley (2018) proposed variable thresholds to an accumulated rainfall over 7 days to indicate potential landslide activity worldwide. Different periods are due to the type of landslide and regional/local meteorological and physical conditions (GUZZETTI et al., 2007). In MRSP, thresholds of 60mm and 80mm accumulated over 72 hours were adopted by Civil Defense to issue a risk alert (IG, 2017c). Larger periods are considered based on the assumption that the soil water capacity is not achieved by a single precipitation event (ÁVILA et al., 2016). Also, Ahrendt and Zuquette (2003) observed that rainfall temporal distribution is as important as the total amount of rainfall, since cumulative rainfall can lead to a complete saturation, while heavy intense rain may not infiltrate but be dissipated by surface runoff.

Common physical variables are those related to terrain characteristics as well as the geological and geotechnical characteristics. Besides, slope angle, other geometric features were found to influence landslides, such as slope aspect, drainage, surface roughness, topographic indices, elevation and slope length and curvature (SMYTH; ROYLE, 2000; CHAU; CHAN, 2005; SÜZEN; KAYA, 2012). Varnes (1978) presents a compilation of situations regarding composite materials of slopes, their texture and structure that account for geological setting that may be favorable to landslides. The assessment of mass-movement susceptibility in municipalities of MRSP considered drainage pattern, slope length and curvature, alongside with landform and substrate characteristics (BITAR, 2014). Rectilinear and concave slopes, with abrupt valley-head slopes, composed of shallow and early degree of pedogenic development over migmatites, granitic gneisses, were identified as more prone to develop landslides. These high-susceptible slopes were associated with high and low hills and high density of density of lineaments/structures.

Vegetation presence can prevent soil erosion (KANUNGO et al., 2009) and contribute to water infiltration (ROSS, 2016) as well to soil stability, in the sense that plant roots tend to hold soils together (ALEXANDER, 1992). Removal of vegetation cover, as a man-induced process, is often a factor that causes landslides in rural areas, as much as in urban areas as noted by many authors (e.g. IMAIZUMI et al., 2008; CUI et al. 2019), particularly in tropical regions.

Intrinsic characteristics and natural processes of the ecological-biophysical domain are altered by urban occupation of the hillsides. This process demand vegetation cut and modification of land contours in local and large scale (grading and mass-grading), which associated to paving, change strength stability of the slope, natural regime of runoff and infiltration of stormwater. Moreover, the introduction of new surface and subsurface water sources associated with irrigation or leaky water from utilities, and the deposition of inadequate material (such as garbage or construction waste) in fills, alters the geotechnical behavior of the natural terrain.

Inadequate building techniques and insufficient design practices employed by families and land developers as well as poor municipal ordinances and weak inspection are unfavorable factors. These are overlapping factors in illegal settlements, which are called *favelas* (squatters or slums) when families promote the invasion of public or private areas. A different type of illegal settlement is when there is a land developer who promotes the allotment and sell plots but fails to accomplish legal requirements to approve it. In both cases, there is not a previous design for the land development, that could set an appropriate use of terrain, enhancing safety among other obligatory requirements, as much as the sanitary system is absent.

A common technique observed by Smyth and Royle (2000) in *favelas* is the cut-and-fill, e.g. the soil removal from the rear of the site and its deposit at the front of the lot, creating a flat area, filled, although, with unconsolidated material extremely susceptible to collapse (SMYTH; ROYLE, 2000). As this is carried out without engineering or any calculation, frequently the angle at which the headwall is excavated is defined by pursuing the maximization of a flat terrain areas, which increases slopes susceptibility and damage, if a failure occurs. Leaving cuts and fills exposed are a practice commonly observed, favoring soil erosion and destabilization. In some cases, an ordinary plastic protective cover is used to prevent stormwater infiltration, resulting in a temporary protection. Peloggia (1997) found similar cut-and-fill practices in the MRSP, observing also fills made with heterogeneous materials (organic debris, plastics, debris, wood, plant remains - trees, branches, leaves etc.). These technogenic deposits are more instable when compared to cuts, but they may represent a minor risk because in general they are small-sized fills and mobilize less volume of heterogeneous materials when a landslide occurs (MIRANDOLA; MACEDO, 2014). The illegal settlements situation implicates that civil works and buildings public inspection that could enhance safety in these areas are not carried out.

Low-income level and limited formal education are components of families' vulnerability (BLAIKIE et al., 1994). As much as they are part of capabilities or resources that families have to cope and protect themselves from disaster events, they also can be related to landslide occurrence. Families with low income level would have less economic resources to execute adequate grading in their plots and buildings or to contract professional help. Low educational level, could also imply in less capabilities to build their houses through self-aided process, a common practice in illegal allotments (Figure 3.20).

Figure 3.20 - Self-aided building examples for a house (left) and a terrain cut (right).

Source: Author.

The lack of infrastructure systems or its inappropriate design or operation are clearly related to slope security (PELOGGIA et al., 1992; SMYTH; ROYLE, 2000; MIRANDOLA; MACEDO, 2014; ROSS, 2016; MENDES et al., 2018). Sewage collection is not universal, making solutions like septic tanks a possible source of water infiltration, as much as the direct disposal of wastewater (FARAH, 2003). Leakages in sanitary systems are also a source of water infiltration. The absence of storm water drainage elements, including paved streets, accelerate slope erosion and contribute to water saturation and soil surcharge.

High density of households, as concentration of human interventions, has also been related to slope instability. Besides that, settlement consolidation level, in the sense that its surfaces tend to become more impervious (PELOGGIA et al., 1992; SCHUSTER; HIGHLAND, 2007; ROSS, 2016) and with less vegetation cover (Figures 3.21) are also important.

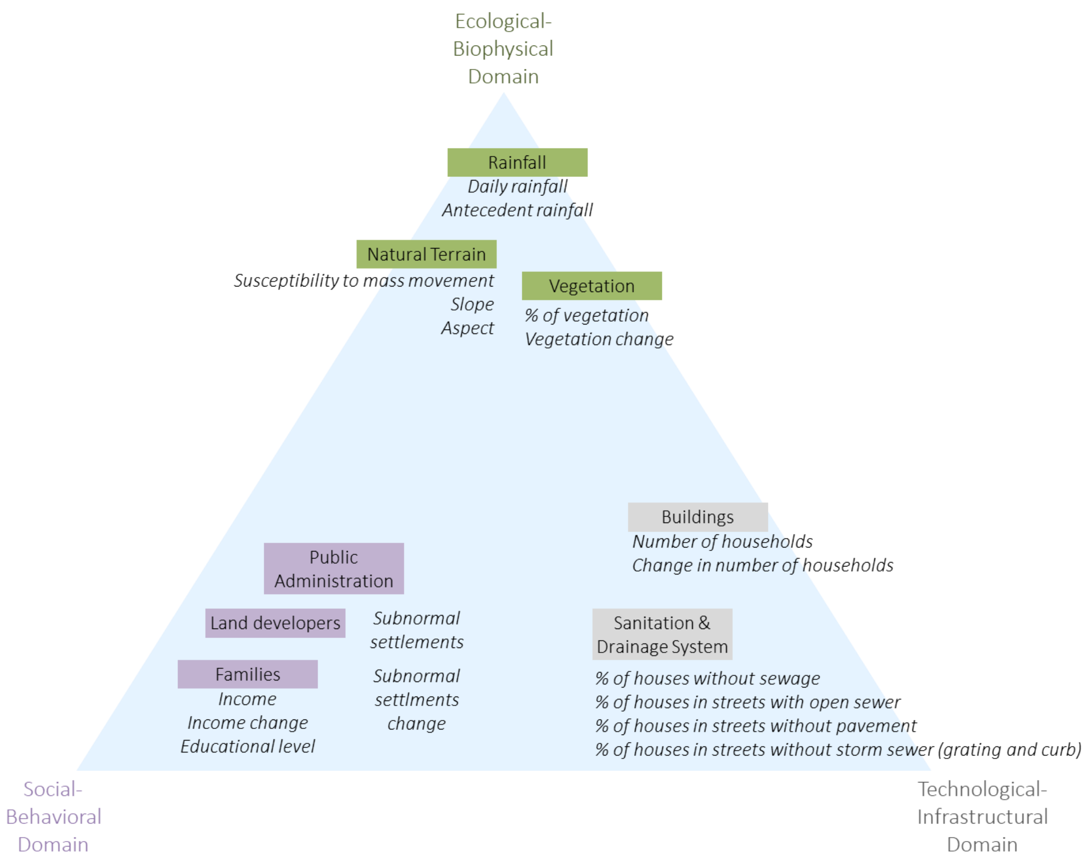
Figure 3.21 - Dense urban development of hillsides in the MRSP.

On left photo, a general overview of Jardim Paraná, a low-income neighborhood on hillsides of Cantareira Mountain Ridge, in São Paulo city. On right photo, looking to the opposite side of Jardim Paraná, a new *favela* is raising, where houses are substituting for native vegetation cover.
Source: Author.

Smyth and Royle (2000) observed that when *favelas* become more consolidated, materials used in the first dwellings are substituted by a more permanent and heavier building materials, implicating an increase load to terrain. This characteristic is common not only illegal settlements but also in low-income neighborhoods, in combination with unpaved streets and poor sanitary system conditions (SMYTH; ROYLE, 2000; ROSS, 2016).

Based on SETS components related to landslides and their relationships, we evaluated available data to MRSP and selected candidate variables to represent correlated factors to model landslide occurrence. Regarding to the Ecological-Biophysical domain, we selected antecedent rainfall, terrain slope and aspect, mass-movement susceptibility, which accounts for geological, geomorphological and hydrological-pedological conditions of natural terrain and, percentage of vegetation. Social-behavioral and technological-infrastructural variables were derived from Demographic Censuses, carried out every 10 years in Brazil. These data enabled us to characterize, on the one side, practices of the families, expressed by their income and educational level, and families, land developers and public administration practices associated with the settlement condition (if subnormal or not). On the other side, to characterize technological-infrastructural domain, we selected the sewage system and storm sewer system coverage and built environment conditions – density (expressed by the number of households) and conditions of the streets (if paved or if with open sewer). To account for settlement consolidation level, we included variables of the difference in vegetation cover, number of households and income, as well as if the settlement condition has changed. A framework with SETS domains, components and variables related to landslide occurrence is presented in Figure 3.22.

Figure 3.22 - Social-Ecological-Technological System framework: components and variables used to model the occurrence of landslides in the MRSP.



Source: Author.

Within this framework, the objectives of this study were (i) to investigate variables related to landslide occurrence based on the spatial incidence of landslides in MRSP in a logistic regression model, and (ii) to assess its role to SETS vulnerability and their potential contribution to strengthen system's resilience. These were achieved by modeling the landside occurrence in the MRSP. Going beyond a traditional susceptibility analysis, built upon static physical conditions such as lithology or slope degree, we included dynamic socioeconomic and infrastructure conditions inherent to urban systems. Furthermore, considering rainfall alongside, we were able to assess its importance in relation to other factors within MRSP.

To model the occurrence of landslides in the MRSP, the hydrological year of 2010 was selected, since for this period the most complete datasets of meteorological and census variables are available (see following section). Therefore the period between October 1st, 2009 and September 30st was adopted, contemplating the entire wet period ,from October to March, in one year, in accordance to recommendations to susceptibility and hazard mapping (FELL et al., 2008; GLADE; CROZIER, 2005; VAN WESTEN et al., 2008). A total of 2.038 landslide locations in the 2010 hydrological year were used to model the landslide occurrence.

3.3.2. Materials and methods

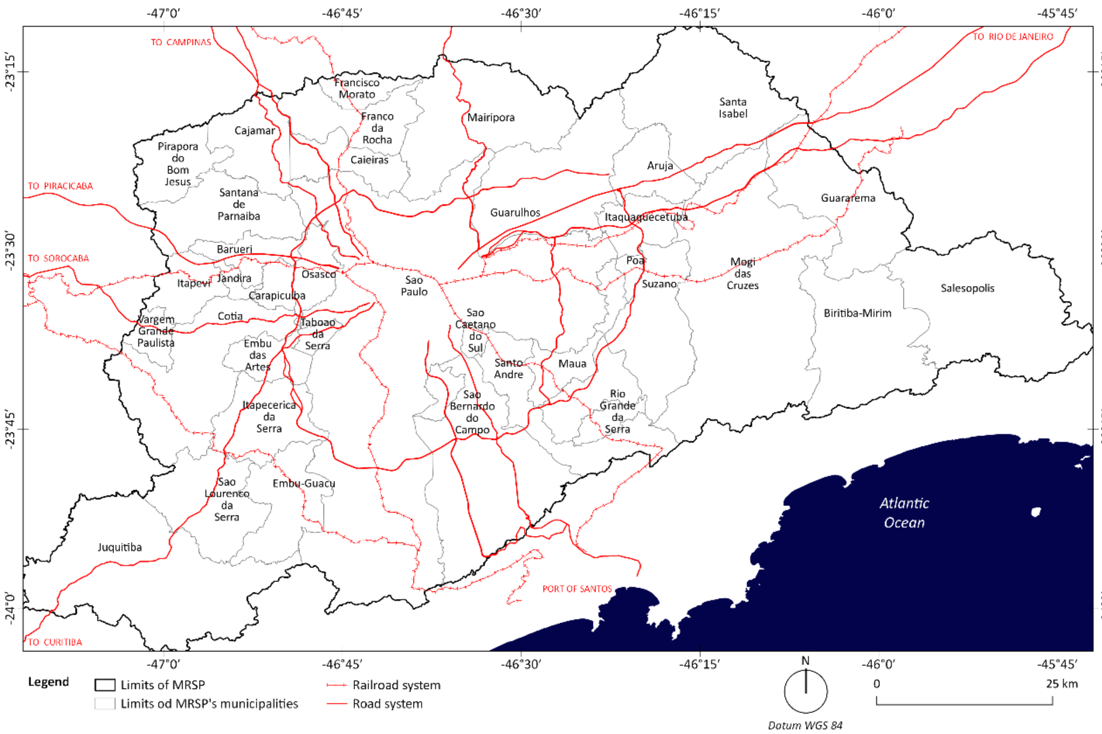
3.3.2.1. Study area

This study was undertaken in the Metropolitan Region of São Paulo (MRSP) which comprises 39 municipalities and covers an area of almost 80 km^2 (Figure 3.23).

MRSP has a humid subtropical climate, with a dry-cool winter and a wet-warm summer (Cwa in Köppen's classification). Climate is naturally controlled by relief, altitude (ranging from to 600m to 1,000m above sea level) and the short distance to the Atlantic Ocean (about 30km) (EMPLASA, 1980; PMSP, 2000). The mean annual rainfall is 1,400mm and it is unevenly distributed along the year and in the territory (NOBRE et al., 2011). During the summer season (December, January and February) rainfall reaches 1,100mm/year while during the winter season (June, July and August) it roughly reaches 400mm/year. Spatially, it can be observed a strong variation of rainfall SE-NW direction.

Long duration rainfall is associated with cold fronts and are spatially comprehensive while lines of instability and local movement of air, as well as summer storms, result in short duration (XAVIER et al., 1994).

Figure 3.23 - Municipalities, railroad and road systems in the MRSP.



Source: Author

Urban expansion in MRSP followed transportation systems (LANGENBUCH, 1971). In the beginning of XXth century, new settlements were laid out along the railroad system that connect Santos seaport with production areas of coffee in western São Paulo State. In the later period of MRSP's urban expansion, proximity to railroad was crucial to the establishment of the industrial areas in São Paulo municipality, but also in the municipalities of São Caetano do Sul, Santo André, Diadema and São Bernardo do Campo, in SE of São Paulo city, which comprises de area known as 'ABCD'. When the railroad system was substituted by a road system, from the second half of last century, urban expansion followed the main roads, radiating São Paulo's influence on municipalities around it. Following São Paulo, Guarulhos and Osasco, in NE and NW of

São Paulo, respectively, in conjunction to ABCD, are the most important of MRSP in population size and economic activity (MEYER et al., 2004).

3.3.2.2. Datasets

Data source and processing to obtain variables selected to represent causative factors in this study are described in subsequent sections, preceded by the description of the landslide inventory used.

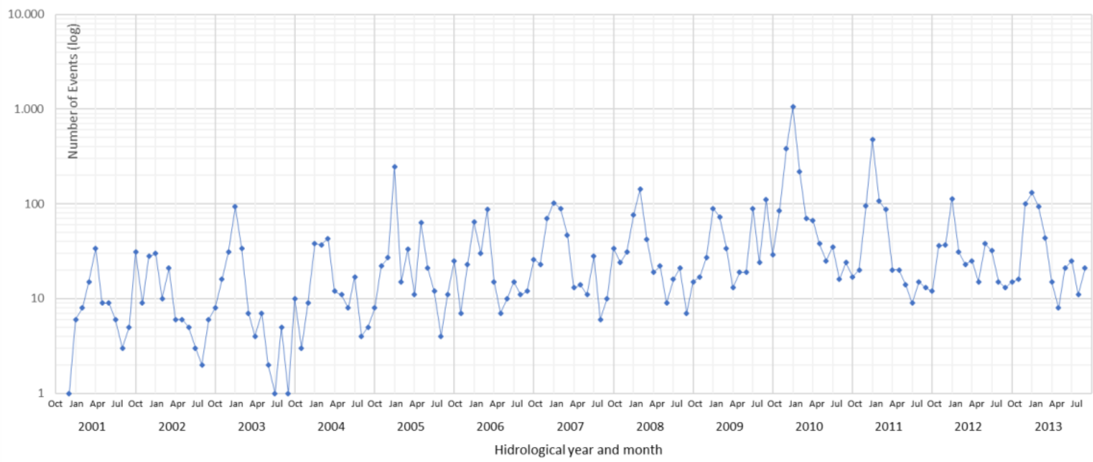
Landslide inventory

Coordinates and dates of landslides were obtained from the Georeferenced Inventory of Geodynamic Events, published by the Geological Institute of São Paulo State (IG) (IG, 2017). This database comprises geological, hydrological and meteorological disaster events registered from 1993 to 2013, in all municipalities of MRSP, except São Paulo. Events information is gathered from (i) public and private organizations, including State and Municipal Civil Defense Agencies, State and Federal road operators and concessionaires; (ii) news published in print and electronic media; and (iii) high resolution remote sensing data. All registers are classified according to a level of confidence concerning the date and the address of the event, based on the original information available for each event (IG, 2017). Since 1993, a total of 30,685 events were registered. Among them, 12,311 (40,12%) were classified as geological events, comprising: debris flows, rock or landslides, erosion, erosion of the riverbanks, rock fall, soil subsidence and collapse and mass movement. These events are mostly shallow landslides, that is, rotational or translational slides of engineering soils with small dimension; a few of them, however, are rockslides (VARNES, 1978).

After a consistency check, were excluded from the database: (i) events classified with low level of location accuracy or estimated/non-informed date; (ii) duplicated registers with the same coordinates and same date or with less than 5 days difference; (iii) registers with indication of an inexistent event recorded from field verification; and (iv) registers with location out of MRSP's municipal boundaries. Finally, we kept registers from 2001 to 2013, since until 2001 registers are not complete because data were collected only during the rainy season.

The majority of these events caused low-intensity damages to housing and infrastructure and only 26 resulted in casualties (IG, 2017). A higher number of landslide events were registered during the rainy season, from mid-December to mid-March (Figure 3.24), and January is usually the month with higher records. In this time series, 2010 was the year with most landslide records.

Figure 3.24 - Recorded landslide events from 2001 to 2013 in the MRSP.



Source: Inventory of Geodynamic Events, published by Geological Institute of São Paulo State (IG, 2017).

Rainfall data

Daily rainfall (mm) was obtained from the Climate Hazards Group InfraRed Precipitation with Station Data (CHIRPS) - version 2.0 (FUNK et al., 2015), available at GoogleEarth Engine. CHIRPS incorporates satellite imagery with in-situ station data to create gridded rainfall time series at a resolution of 0.05 arc degrees. In MRSP, 35 in-situ stations were incorporated to infrared Cold Cloud Duration (CCD) observations calibrated with the Tropical Rainfall Measuring Mission Multi-satellite Precipitation Analysis version 7 (TMPA 3B42 v7) to estimate daily, pentadal, and monthly rainfall.

Elevation-related variables

Variables related to terrain – slope and aspect – were based on a Digital Elevation Model (DEM), with 10 m spatial resolution. DEM was derived from the digital planimetric and topographic map of MRSP, with 25 m contours (EMPLASA, 1980) and spatial scale compatible to 1:25.000, using a Triangulated Irregular Network (TIN) calculated based on contour lines, measured points and river network. Terrain slope (in degrees) was obtained using the first-order derivative estimation, as proposed by Horn (1981). Aspect is the direction that a slope faces, measured from 0° (North) to 360°, in clockwise direction. This variable was categorized, adopting 4 directions, each one encompassing 90°, and centered in 0° for North, 90° for East, 180° for South and 270° for West, and related them to flat areas (where aspect in null).

Physical mass-movement susceptibility

Mass-movement susceptibility classification was performed based on geological, geomorphological and hydrological-pedological conditions (BITAR, 2014), by the Geological Survey of Brazil ("Companhia de Pesquisa de Recursos Minerais" – CPRM) for all municipalities in MRSP, except Vargem Grande Paulista, Pirapora do Bom Jesus, Juquitiba and São Lourenço da Serra. Maps are available as digital vector data, compatible to 1:25,000. Zones were classified into high-, medium- or low-susceptibility, according to predominant characteristics in each municipality. As an example, Table 3.7 presents each susceptibility class and its predominant characteristics for Santo André municipality.

Table 3.7 - Predominant characteristics of each mass-movement susceptibility class for Santo André Municipality.

Susceptibility class	Predominant characteristics
High susceptibility	- Relief: high and low hills; - hill shape: concave and rectilinear, with abrupt valley-head slopes; - amplitudes: 100 to 400 m; - slopes: > 25°; - lithology: migmatites, granitic gneisses, mylonitic gneisses, micaschist, meta-sandstones e mylonitic schist; - density of lineaments/structures: high - soils: early degree of pedogenic development and shallow depth; - processes: landslides.
Medium susceptibility	- Relief: high and low hills, and low hills; - hill shape: convex to rectilinear and concave, with valley-head slopes; - amplitudes: 60 to 100 m; - slopes: 10 to 30°; - lithology: mica schist, meta-sandstones and mylonitic schist; - density of lineaments/structures: medium; - soils: high degree pedogenetic development and medium depth; - processes: landslides.
Low susceptibility	- Relief: plains and floodplains, hills and low hills; - hill shape: convex smoothed and broad summits; - amplitudes: < 80 m; - slopes: < 15°; - lithology mica schist, meta-sandstones, mylonitic schist, clays, sands and gravels; - density of lineaments/structures: low; - soils: alluvial; high degree pedogenetic development and deep soils in hills and low hills; - processes: landslides.

Source: IPT; CPRM (2013).

Land cover data

Land cover classes of vegetation, built up areas, bare soil and water were mapped from Landsat TM, at a spatial resolution of 30m, using Landsat Collection Tier 1, processed and made available by U.S. Geological Survey (USGS). A supervised classification approach based on Support Vector Machine (SVM) was applied to visible and infrared bands (red, green, blue, and NIR bands), Normalized Difference Vegetation Index (NDVI), mean NDVI computed for summer season and mean NDVI of winter season. The classification model was built with 677 random samples visually classified on orthophotos of year 2010, divided into two equally sized groups for training and validation. An overall accuracy of 89.8% (confidence intervals of [0.873, 0.920]), and Kappa Index of 0.844 were obtained from the confusion matrix. This model was applied to 1992 images and land cover classes were remapped to obtain a vegetation cover map of 1992 and 2010. Year 1992 was chosen to be a reference to 1991 Census data. Additionally, the vegetation change between 1992 and 2010 was computed based on the vegetation cover maps.

Demographic census data

In this paper, the Demographic Census data from Brazilian Institute of Geography and Statistics ("Instituto Brasileiro de Geografia e Estatística" - IBGE) and georeferenced census tracts, processed and made available by Center for Metropolitan Studies ("Centro de Estudos da Metrópole" – CEM), were used. Selected variables from census data were: number of households, to account for built density, percentage of households without sewerage, in unpaved streets, in streets without storm sewer (curb and grating) and in streets with open sewage to characterize the built environment.

To characterize families, variables of average income of the individual responsible for the household (household's head) and percentage of literate household's head were selected to account for their level of education. To characterize families' and land developers'-built practices as well as public administration role the settlement's classification (regular or subnormal) was used. In Census database, subnormal settlements correspond to *favelas* and illegal allotments. They are identified as tracts with 51 or more housing units characterized by the absence of title deeds and irregularity of the roadways and the size and shape of plots and / or lack of essential public services (such as garbage collection, sewage, water and electricity systems and public lighting) (IBGE, 1991; IBGE, 2013).

Census data was interpolated into a grid, using a dasymetric mapping, following similar approaches for world data (JRC, 2017) and for regional and local data (LANGFORD; UNWIN, 1994; HOLT et al., 2004; HIRYE et al., 2016). Streets network made available by CEM, and built-up areas, from land cover map previously described, were used as ancillary data to spatially disaggregate census tracts.

3.3.2.3. Database preparation

The geocoding of landslide events reports the street name and the address number where the event occurred which consequently results in locations systematically along the streets. To estimate where the landslide likely occurred, 30 m was adopted as a mean distance from the center of the street to the interior of the plot to account for this mis-location. All points within the built-up area in MRSP and outside the 30 m buffers around landslide location were considered as points of non-occurrence of landslides. A random date was assigned to each of these points.

For each point, antecedent rainfall from 1 to 120 days were computed. In this paper, we selected different periods to be tested, ranging from rainfall in the same date of each point up to rainfall accumulated over 120 days. The upper boundary was defined based on the period between the beginning of the wet season (October) and the peak of landslide occurrence (January). Based on its coordinates and date, we extracted the antecedent rainfall of each point of occurrence and non-occurrence of landslides for all periods considered.

Before the extraction of each explanatory variable's value related to each location of disaster and non-disaster, all variables were resampled to a grid with a spatial resolution of 10m. Then, to account for the mis-location of landslide points of occurrence, variables were spatially aggregated using a sliding window of 7x7 gridcells in all 10 m-grids, using an appropriate function. For terrain slope, we used the maximum value; for mass movement susceptibility and subnormal condition of the settlement, the modal value; for households the sum of values; and, for vegetation and family's characteristics (income and literate status), the mean value. In the case of vegetation, since it is a binary map (0: non vegetation, 1: vegetation), the mean value also expresses the percentage of vegetation within the considered distance. From these focal filtered grids, we derived four other variables that account for changes in the conditions between 2010 and 1991: vegetation, households, income and subnormal condition change.

Landslide inventory and mass movement susceptibility maps did not cover all municipalities of MRSP. Therefore, analysis excluded the following municipalities: Biritiba-Mirim, Cajamar, Embú-Guaçu, Embú, Franco da Rocha, Itapevi, Juquitiba, Poá, Pirapora do Bom Jesus, Salesópolis, São Caetano do Sul, São Paulo, São Lourenço da Serra and Vargem Grande Paulista.

For validation purposes, we split the database, into an 80%-20% proportion, preserving the balance between categories of the dependent variable (landslide occurrence and non-occurrence).

Table 3.8 summarizes the selected independent variables and specific data preparation procedures that were taken. Database preparation was carried out using R-project software (http://www.r-project.org/) and Google Earth Engine (https://earthengine.google.com/).

Table 3.8 - Description of independent variables used in the statistical analysis.

Independent variable name	Source	Spatial resolution | Original format	Period / Year of reference	Specific data preparation procedures	Variable type	Variable unit
Daily rainfall [Rn0d]	Funk et al. 2015.	0.05 arc degrees | raster	2009-10-01 to 2010-09-30	-	continuous	mm
Antecedent rainfall			2009-06-01 to 2010-09-30	(1) Sum: rainfall of the event day and antecedent rainfall considering 1 to 120 days	continuous	mm
Terrain slope	EMPLASA	1:25.000 contour lines (interval = 25m) | vector	1980, updated in 2002	(1) Interpolation to a DEM (10m-resolution raster) (2) Slope calculation (3) Focal filter, using maximum function	continuous	degrees
Terrain aspect	EMPLASA	1:25.000 contour lines (interval = 25m) | vector	1980, updated in 2002	(1) Interpolation to a DEM (10m-resolution raster) (2) Aspect calculation (3) Focal filter, using median function (4) Remap to North, East, South, West and Flat	categorical – 5 levels	-
Mass-movement susceptibility	CPRM	1:25.000 | polygons	2013, 2017 and 2018	(1) Remap: Low to 1; Medium to 2; High to 3 (2) Convert to a 10m-resolution raster (3) Focal filter, using modal function	categorical – 3 levels	-
Percentage of vegetation in 2010	Landsat TM	30m | raster	2010	(1) Remap: vegetation to 1; non-vegetation to NA (2) Resample to a 10m-resolution raster, using nearest neighbor method (3) Focal filter, using mean function	continuous	%

to be continued

Table 3.8 - Sequence

Independent variable name	Source	Spatial resolution | Original format	Period / Year of reference	Specific data preparation procedures	Variable type	Variable unit
Percentage of vegetation change (2010-1991)	Landsat TM	30m | raster	1991 and 2010	(1) Remap (1991): vegetation to 1; non-vegetation to NA (2) Resample to a 10m-resolution raster, using nearest neighbor method (1991) (3) Focal filter, using mean function (1991) (4) Raster operation: vegetation in 2010 – vegetation in 1991	continuous	%
Average income of the individual responsible for the household (household's head) in 2010	IBGE	census tracts polygons	2010	(1) Update average income value to 2018 (2) Convert to a 10m-resolution raster (3) Mask areas without occupation using dasymetric interpolation of households (4) Focal filter, using mean function	continuous	R$ of 2018
Average income change of the individual responsible for the household (household's head) (2010-1991)	IBGE	census tracts polygons	1991 and 2010	(1) Update average income value to 2018 (1991) (2) Convert to a 10m-resolution raster (1991) (3) Mask areas without occupation using dasymetric interpolation of households (1991) (4) Raster operation: average income in 2010 – average income in 1991 (5) Focal filter, using mean function	continuous	R$ of 2018

to be continued

Table 3.8 - Sequence

Independent variable name	Source	Spatial resolution | Original format	Period / Year of reference	Specific data preparation procedures	Variable type	Variable unit
Percentage of literate individual responsible for the household (household's head) in 2010	IBGE, 2010	census tracts polygons	2010	(1) Calculate percentage of literate household’s head considering the total of household’s head (2) Convert to a 10m-resolution raster (3) Mask areas without occupation using dasymetric interpolation of households (2010) (4) Focal filter, using mean function	continuous	%
Subnormal settlements in 2010	IBGE, 2010	census tracts polygons	2010	(1) Remap: non-subnormal to 0; subnormal to 1 (2) Convert to a 10m-resolution raster (3) Focal filter, using modal function	categorical – 2 levels	-
Subnormal settlements change (2010-1991)	IBGE, 2000 and 2010	census tracts polygons	1991 and 2010	(1) Remap (1991): non-subnormal to 0; subnormal to 2 (2) Convert to a 10m-resolution raster (1991) (3) Raster operation: subnormal in 1991 + subnormal in 2010 (4) Focal filter, using modal function (5) Remap: 3 (‘no change’) to 0. Final levels are 0: no change; 1: worst in 2010; 2: better in 2010	categorical – 3 levels	-
Households in 2010	IBGE	census tracts polygons	2010	(1) Dasymetric interpolation to a 10m-resolution grid, using built-up class of land cover map (2) Focal filter, using sum function	continuous	households

to be continued

Table 3.8 - Sequence

Independent variable name	Source	Spatial resolution | Original format	Period / Year of reference	Specific data preparation procedures	Variable type	Variable unit
Households change (2010-1991)	IBGE	census tracts polygons	1991 and 2010	(1) Dasymetric interpolation to a 10m-resolution grid (1991), using built-up class of land cover map (2) Raster operation: households in 2010 - households in 1991 (3) Focal filter, using sum function	continuous	households
Percentage of households without sewerage in 2010	IBGE	census tracts polygons	2010	(1) Dasymetric interpolation to a 10m-resolution grid, using built-up class of land cover map (2) Focal filter, using sum function (3) Raster operation: Households without sewerage / Households in 2010	continuous	%
Percentage of households in unpaved streets in 2010	IBGE	census tracts polygons	2010	(1) Dasymetric interpolation to a 10m-resolution grid, using built-up class of land cover map (2) Focal filter, using sum function (3) Raster operation: Households in unpaved streets / Households in 2010	continuous	%

to be continued

Table 3.8 - Conclusion

Independent variable name	Source	Spatial resolution | Original format	Period / Year of reference	Specific data preparation procedures	Variable type	Variable unit
Percentage of households in streets without storm sewer (curb) in 2010	IBGE	census tracts polygons	2010	(1) Dasymetric interpolation to a 10m-resolution grid, using built-up class of land cover map (2) Focal filter, using sum function (3) Raster operation: Households in streets without storm sewer (curb) / Households in 2010	continuous	%
Percentage of households in streets without storm sewer (grating) in 2010	IBGE	census tracts polygons	2010	(1) Dasymetric interpolation to a 10m-resolution grid, using built-up class of land cover map (2) Focal filter, using sum function (3) Raster operation: Households in streets without storm sewer (grating) / Households in 2010	continuous	%
Percentage of households in streets with open sewage in2010	IBGE	census tracts polygons	2010	(1) Dasymetric interpolation to a 10m-resolution grid, using built-up class of land cover map (2) Focal filter, using sum function (3) Raster operation: Households in streets with open sewage / Households in 2010	continuous	%

Source: Author.

3.3.2.4. Exploratory analysis

To explore the association between landslide occurrence and climatic, biophysical and Census' variables exploratory analysis was conducted. Student's *t*-tests were performed to compare the mean of quantitative explanatory variables between the two groups: landslide and non-landslide. For the categorical variables, equality of proportion between the groups landslide and non-landslide was performed using the chi-squared test to test difference of the distribution within each category of these variables between the two groups. At this step, we made a first selection of the variables, removing variables that are not different within the two groups.

3.3.2.5. Modeling landslide occurrence

A logistic regression model was developed to obtain a quantitative estimation of landslide hazard and the contribution of each factor to its occurrence. This is a widely used approach in the literature related to landslides (BUDIMIR et al., 2015) and reported as yielding lower error rates and best generalization capabilities (BRENNING, 2005). This model has the following form:

$$g_{(x)} = \ln \frac{\pi_{(x)}}{1-\pi_{(x)}} = \beta_0 + \beta_i x \qquad \text{(Equation. 3.1)}$$

where $g_{(x)}$is the logit, $\pi_{(x)}$is the probability of the event occurrence given the independent variable's value (x), β_0 and $\beta_i x$ are the regression parameters.

Logit is a transformation applied to the probability of an event occurrence. It is also known as odds ratio and in our model, it expresses the chance of a landslide event given an increment in any of the independent variables' value. For continuous variables, e^{β_i} corresponds to the chance for an increase of 1 unit in this variable. For categorical variables, e^{β_i} will express the chance of a landslide occurrence when independent variable assumes one class in comparison to another class. In logistic regressions, parameters are obtained using maximum likelihood estimation. To assess the fit of the model adequacy several approaches have been proposed, frequently based on the log-likelihood, understood as an approximation for the deviance.

Our model-building strategy involved a multi-step approach fitting univariable and multivariable models. First, an univariable model was fit for each independent variable selected in the exploratory analysis. The variables with non-significant parameters in relation to landslide occurrence were removed. However, a high level of tolerance (p-value < 0.25) was used in order to prevent discarding variables that could add some level of explanation in the multivariable analysis.

Univariable models of each of the antecedent rainfall period were compared using a modified version of Cox and Snell's index adjusted to constrain the index value not to exceed 1 (eq. 3.2). This approach is analogous to R^2 in an ordinary linear model but adapted for logistic regression. Although it is useful to compare logistic regression models (HARRELL, 2015), it is not recommended to be used to report final results (HOSMER; LEMESHOW, 2000). This index, along with others pseudo-R^2, can lead to misinterpretations of the model's predictive strength in the sense that they yield lower values if compared to values of ordinary least squares R^2 obtained under similar conditions (SMITH; MCKENNA, 2013). It is expressed as

$$R_N^2 = \frac{1-\left({}^{L_o}/_{L_m}\right)^{2/N}}{1-\exp\left(-{}^{Lo}/_{N}\right)} \qquad \text{(Equation. 3.2)}$$

where R_N^2 is likelihood chi-squared test, L_o is likelihood functions for the constant-only model, L_m is likelihood functions for the fitted model N the sample size.

Then a multivariate model with all selected variables was fit to assess the main effects from variable interactions and to enable a second variable selection for which we applied a more restrictive level of significance (p-value < 0.05).

We included all the retained variables into a preliminary model, for which we looked for the best model according to the Bayesian Information Criterion (BIC) (SCHWARZ, 1978). The comparison between the preliminary model and others, fitted with a subset of variables, was performed with automated model selection ‘glmulti’ R package (CALCAGNO; MAZANCOURT, 2010). Contrary to stepwise approaches, this one is not iterative and, given the variables selected to the preliminary model, all possible combinations, were tested and ranked. BIC was used instead of the classically used AIC to avoid over-parameterization as this criterion is consistent and parsimonious for model selection with respect to large datasets (BURNHAM; ANDERSON, 2004). From this final analysis, we selected the model yielding the highest predictive strength and the smallest and most significative set of independent variables.

To assess the predictive information of each of the independent variables, we used an adequacy index, based on the likelihood ratio test (HARRELL, 2015). It is expressed as the ratio between the −2 log likelihood ratio statistic for testing the joint significance of a model with full set of variables and the −2 log likelihood ratio statistic for testing the importance of a model with only one variable. This index estimates the proportion of log likelihood explained by the variable with reference to the log likelihood explained by all variables, what can be understood as the contribution of each variable to the model.

The goodness-of-fit of the final model was evaluated using the Area Under the Receiver Operating Characteristics Curve (AUC). This was performed using the test samples. AUC ranges from 0 to 1 and values lower than 0.5 suggests that the model yields no discrimination between points of occurrence of landslides and non-occurrence. As a general rule, AUC values from 0.7 to 0.8 suggests an acceptable discrimination and from 0.8 to 0.9 an excellent discrimination. Values higher than 0.9 suggests an outstanding discrimination, although for logistic regression models it is extremely unusual to observe such high values (HOSMER; LEMESHOW, 2000).

Parameters and statistics, as well as their confidence intervals were estimated using bootstrap as a resampling technique with a probability of 95%. This is recommended to provide stable estimates with low bias (STEYERBERG et al., 2001; EFRON; TIBSHIRANI, 1994). All models were run 1,000 times with randomly generated sets of samples, each one with 1,000 points of landslide occurrence and 1,000 points of non-occurrence.

All analyses were performed using the R-project software (http://www.r-project.org/).

3.3.3. Results

3.3.3.1. Exploratory analysis

Exploratory analysis compared values of variables to points of landslide occurrence and points of non-landslide. Important to note, that points of non-landslide represent the totality of urbanized areas within considered municipalities, excluding landslide points and their squared 30m-buffer.

Considering continuous variables, almost all of them presented significative association with landslide occurrence (Table 3.9). At this stage three variables, average household's head income change, percentage of literate household's head and percentage of households in unpaved streets, were not found to be associated to landslide occurrence and therefore excluded from further analysis. Antecedent rainfall, slope, percentage of vegetation, average income of household's head, number of households and households change are notably different between the two groups (Table 3.9). For example, for the landslide points, the antecedent -14 days rainfall value was more than 2.5 times the value of non-occurrence points.

Table 3.9 - Results for the exploratory analysis of independent continuous variables.

Independent variable	Number of points of landslide occurrence *	Mean value in points of landslide occurrence	Mean value in points of landslide non-occurrence	T-Student Test	p-value
Rainfall in the event day	2,038	18 mm	6 mm	-31.45	< 0.001
Antecedent rainfall – day and previous day	2,038	37 mm	11 mm	-42.89	< 0.001
Antecedent rainfall – day and 7 previous day	2,038	124 mm	45 mm	-64.65	< 0.001
Antecedent rainfall – day and 14 previous days	2,038	216 mm	83 mm	-71.67	< 0.001
Antecedent rainfall – day and 21 previous days	2,038	294 mm	122 mm	-73.79	< 0.001
Antecedent rainfall – day and 28 previous days	2,038	367 mm	162 mm	-70.41	< 0.001
Antecedent rainfall – day and 60 previous days	2,038	684 mm	355 mm	-67.85	< 0.001
Antecedent rainfall – day and 120 previous days	2,038	1072 mm	741 mm	-53.75	< 0.001
Terrain slope	2,038	14.45 °	7.09 °	-32.43	< 0.001
Percentage of vegetation in 2010	2,038	22.7%	10.0%	-16.41	< 0.001
Percentage of vegetation change (2010-1991)	2,038	-14.4%	-22.0%	-12.48	< 0.001
Average income of the individual responsible for the household (household's head) in 2010	1,846	R$ 1,828 (updated to 2018)	R$ 2,647 (updated to 2018)	29.52	< 0.001

to be continued

Table 3.9 - Conclusion

Independent variable	Number of points of landslide occurrence *	Mean value in points of landslide occurrence	Mean value in points of landslide non-occurrence	T-Student Test	p-value
Average income change of the individual responsible for the household (household's head) (2010-1991)	1,588	-R$ 1,207 (updated to 2018)	-R$ 1,137 (updated to 2018)	2.15	0.032
Percentage of literate individual responsible for the household (household's head) in 2010	1,842	95%	95%	2.31	0.021
Households in 2010	2,032	20 households (222 households/ha)	13 households (144 households/ha)	-17.46	< 0.001
Households change (2010-1991)	2,031	10 households	6 households	-12.17	< 0.001
Percentage of houses without sewerage in 2010	2,028	17.8%	26.0%	13.74	< 0.001
Percentage of houses in unpaved streets in 2010	2,028	8.2%	7.8%	-0.72	0.471
Percentage of houses in streets without storm sewer (curb) in 2010]	2,028	12.6%	9.3%	-5.91	< 0.001
Percentage of houses in streets without storm sewer (grating) in 2010	2,028	39.8%	45.8%	7.83	< 0.001
Percentage of houses in streets with open sewage in 2010	2,028	4.6%	6.0%	5.08	< 0.001

* Eventual difference between the total of points of landslide occurrence (2,038) and points presented is due to the inexistence values for the variable.
Source: Author.

Concerning to categorical variables, all of them yielded statistically significant different distributions (Table 3.10) between points of landslide occurrence and non-occurrence. A fewer number of landslides occurred in east facing slopes while the proportion of non-landslide points is lower in south and north facing slopes. Comparing the distribution of mass-movement susceptibility classes in landslide and non-landslide points shows a clear pattern of landslide occurrence in areas of medium and high susceptibility. Almost 21.88% of the landslides occurred in subnormal settlements which contrasts to the distribution of these settlements in points of non-landslide, only 3.74%. While 8.83 % of the landslides fall in subnormal settlements created between 1991 and 2010, only 2.29% of points of non-occurrence fall in this class.

Table 3.10 - Results for the exploratory analysis of independent categorical variables.

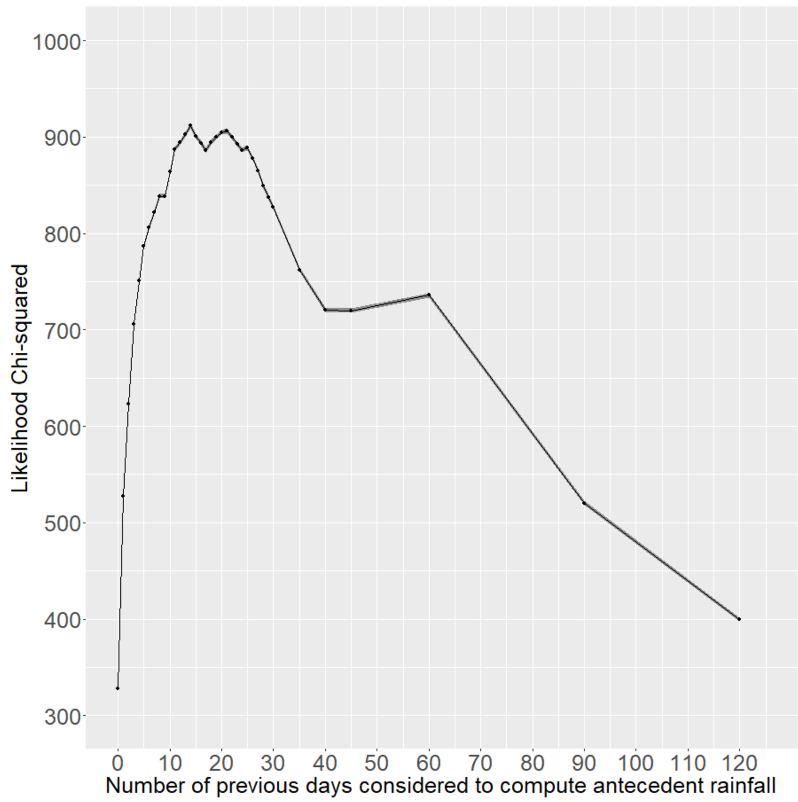
Independent variable and categories	Number of points of landslide occurrence *	Proportion in points of landslide occurrence	Proportion in points of landslide non-occurrence	Pearson's χ2	d.f.	p-value
Terrain aspect	2,038			170.94	4	< 0.001
North	464	22.77%	18.55%			
East	306	15.01%	21.91%			
South	479	23.50%	16.59%			
West	491	24.09%	21.64%			
Flat	298	14.62%	21.31%			
Mass-movement susceptibility	2,037			1338.73	2	< 0.001
Low	1,606	78.84%	95.44%			
Medium	305	14.97%	3.54%			
High	126	6.19%	1.02%			
Subnormal settlements in 2010	2,038			1858.21	1	< 0.001
regular	1,592	78.12%	96.26%			
subnormal in 2010	446	21.88%	3.74%			
Subnormal settlements change (2010-2000)	2,038			396.87	2	< 0.001
no change	1,839	90.24%	97.18%			
subnormal in 2010	180	8.83%	2.29%			
subnormal in 1991	19	0.93%	0.53%			

* Eventual difference between the total of points of landslide occurrence (2,038) and points presented is due to the inexistent values for the variable.
Source: Author.

3.3.3.2. Variable Selection

The importance of cumulative rainfall preceding the occurrence of landslides exhibits a clear behavior in the univariable model (Figure 3.25). Up to 14-20 days they have a raising significance, estimated by the high value of the likelihood chi-squared test. This importance is maximum if computed with the 14 days of previous rainfall and decline sharply with more than 25 days. Then, we selected, as antecedent rainfall, the sum of the rainfall in each considered day and in the 14 previous days.

Figure 3.25 - Likelihood chi-squared test values for univariable models of antecedent rainfall computed with periods from 1 to 120 days.



Source: Author.

From univariable model's analysis, we excluded from further analyses two variables: aspect and average except Average household's head income change. For variables related to the percentage of households in streets without storm sewer (curb) or with open sewer, parameters yielded a p-value of 0.025 and 0.085, respectively, while for others, p-values associated with their parameters are lower than 0.001 (Table 3.11).

Table 3.11 - Estimated coefficients, two-tailed p-values, 95% confidence intervals and estimated likelihood ratios χ2, for univariable logistic regression models.

Univariable models	Intercept	Coefficient	Coefficient Confidence Interval (95%)	P-value	Likelihood Ratio χ2
Antecedent rainfall (day and 14 previous days)	-2.4034	0.0160	[0.0160, 0.0161]	< 0.001	911.7
Terrain slope	-0.9148	0.0885	[0.0882, 0.0888]	< 0.001	296.3
Aspect	0.1027				38.8
North (in relation to flat areas)		-0.0104	[-0.0178, -0.0029]	0.578	
East (in relation to flat areas)		0.4934	[0.4858, 0.5010]	0.008	
South (in relation to flat areas)		0.6820	[0.6742, 0.6897]	< 0.001	
West (in relation to flat areas)		0.3958	[0.3884, 0.4033]	0.031	
Mass-movement susceptibility	-0.1870				130.5
Medium (in relation to low)		1.6395	[1.6281, 1.6509]	< 0.001	
High (in relation to low)		1.9794	[1.9579, 2.0008]	< 0.001	
Percentage of vegetation in 2010	-0.2445	1.6062	[1.5976, 1.6148]	< 0.001	94.0
Percentage of vegetation change	0.1536	0.8527	[0.8449, 0.8605]	< 0.001	32.9
Average income of the household's head in 2010	0.5021	-0.0002	[-0.0002, -0.0002]	< 0.001	73.8
Average income change of the household's head	-0.023631	-0.000021	-0.000019]	0.390	1.7

to be continued

Table 3.11 – Sequence

Univariable models	Intercept	Coefficient	Coefficient Confidence Interval (95%)	P-value	Likelihood Ratio χ2
Subnormal settlements in 2010	-0.2097				162.4
Subnormal (in relation to regular)		1.9845	[1.9737, 1.9954]	< 0.001	
Subnormal settlements change	-0.0668				41.8
Change (in relation to no change)		1.4055	[1.3918, 1.4192]	< 0.001	
Households in 2010	-0.5184	0.0319	[0.0316, 0.0321]	< 0.001	102.1
Households change	-0.2174	0.0289	[0.0286, 0.0292]	< 0.001	54.7
Percentage of households in streets without storm sewer (curb) in 2010	-0.0615	0.5771	[0.5666, 0.5876]	0.025	9.3
Percentage of households in streets without storm sewer (grating) in 2010	0.2189	-0.5114	[-0.5182, -0.5045]	0.003	16.2
Percentage of households in streets with open sewage in2010	0.0384	-0.7231	[-0.7393, -0.7068]	0.085	5.7
Percentage of households without sewerage in 2010	0.1922	-0.8958	[-0.9032, -0.8884]	< 0.001	38.8

Source: Author.

In the complete model, where we analyzed the joint effects of variables, we excluded variables associated with a p-value > 0.05, which were: those related to change of conditions (vegetation change, subnormal settlements change and households change), two variables related to the absence of infrastructure systems (percentage of households in streets with open sewage and percentage of households without storm sewer (grating)) and mass-movement susceptibility (Table 3.12).

Table 3.12 - Estimated coefficients, two-tailed p-values and 95% confidence intervals, for the complete logistic regression model.

Variables of the complete model	Coefficient	Coefficient Confidence Interval (95%)	P-value
Intercept	-3.4228	[-3.4369, -3.4087]	< 0.001
Antecedent rainfall (day and 14 previous days)	0.0164	[0.0164, 0.0165]	< 0.001
Terrain slope	0.0608	[0.0604, 0.0613]	< 0.001
Mass-movement susceptibility			
Medium in relation to low	0.2734	[0.2573, 0.2894]	0.399
High in relation to low	-0.0008	[-0.0358, 0.0343]	0.517
Percentage of vegetation in 2010	1.5938	[1.5736, 1.6140]	0,002
Percentage of vegetation change	0.3379	[0.3242, 0.3516]	0.293
Average household's head income in 2010	-0.000123	[-0.000125, -0.000121]	0.012
Subnormal settlements in 2010	1.9657	[1.9424, 1.9889]	< 0.001
Subnormal settlements change	-0.9398	[-0.9682, -0.9114]	0.143
Households in 2010	0.0384	[0.0379, 0.0390]	0.002
Households change	-0.0051	[-0.0057, -0.0045]	0.477
Percentage of households in streets without storm sewer (curb) in 2010	1.4845	[1.4646, 1.5044]	0.003
Percentage of households in streets without storm sewer (grating) in 2010	-0.1482	[-0.1598, -0.1365]	0.468
Percentage of households in streets with open sewage in2010	-0.9120	[-0.9394, -0.8846]	0.182
Percentage of households without sewerage in 2010	-1.6121	[-1.6264, -1.5978]	< 0.001

Observations (n)	2,000	Model Likelihood Test 1301.8
Points of landslide occurrence	1,000	Likelihood Ratio χ2 d.f. 15
Points of landslide non-occurrence	1,000	p-value < 0.001
Bootstraps	1,000	

Source: Author.

After this careful variable selection, we retained for the final model: antecedent rainfall (day and 14 previous days), two biophysical variables (slope and percentage of vegetation), two variables of the social domain (average household's head income and subnormal settlements) and three variables characterizing the built environment (households, percentage of households without sewerage and percentage of households in streets without storm sewer (curb) in 2010).

3.3.3.3. Model selection

The final analysis, performed using BIC criteria, showed that the model fitted with all selected variables is better than any other model fitted with subsets of these variables (Table 3.13).

Table 3.13 - Results for final model with subset of selected variables.

Final model and models with subset of selected variables	**Rank**	**Number of times as rank #1**	**BIC value**	**BIC value Confidence Interval (95%)**
Final model	1	549	1,561	[1,559, 1,564]
Final model, except Average household's head income in 2010	2	274	1,557	[1,554, 1,559]
Final model, except Percentage of households in streets without storm sewer (curb) in 2010	3	155	1,559	[1,556, 1,562]

Source: Author.

The value of AUC for selected model was 0.9087, denoting the high level of discrimination achieved by this model. Coefficients estimated to each variable in the final model are presented in Table 3.14. They all have a positive relation to landslide occurrence, expect for average household's head Income in 2010 and percentage of households without sewerage (Table 3.14).

Table 3.14 - Estimated coefficients, two-tailed p-values and 95% confidence intervals, for the final logistic regression model.

Variables of final model	Coefficient	Coefficient Confidence Interval (95%)	P-value
Intercept	-3.5869	[-3.5997, -3.5740]	< 0.001
Antecedent rainfall (day and 14 previous days)	0.0163	[0.0162, 0.0163]	< 0.001
Terrain slope	0.0621	[0.0617, 0.0625]	< 0.001
Percentage of vegetation in 2010	1.7894	[1.7699, 1.8089]	< 0.001
Average household's head income in 2010	-0.0001	[-0.0001, -0.0001]	0.019
Subnormal settlements in 2010	1.5335	[1.5180, 1.5489]	< 0.001
Households in 2010	0.0370	[0.0365, 0.0374]	< 0.001
Percentage of households in streets without storm sewer (curb) in 2010	1.1494	[1.1329, 1.1659]	0.007
Percentage of households without sewerage in 2010	-1.7180	[-1.7317, -1.7044]	< 0.001

Observations (n)	2,000	Model Likelihood Test	1280.3
Points of landslide occurrence	1,000	Likelihood Ratio χ2 d.f.	8
Points of landslide non-occurrence	1,000	p-value	< 0.001
Bootstraps	1,000		

Source: Author.

Antecedent rainfall plays the most important role in a landslide occurrence: alone this variable corresponds to 0.70 of the predictive information of all variables combined, according to the calculated index of adequacy (Table 3.15). For terrain slope, this index is of 0.20. Subnormal conditions and households have similar predictive information proportion,0.15 and 0.14, respectively. Other variables have smaller contribution with (index of adequacy below 0.06).

Table 3.15 - Index of Adequacy of each variable of the final logistic regression model.

Variable	Likelihood Ratio χ2	Adequacy
Antecedent rainfall (day and 14 previous days)	900.6	0.70
Terrain slope	262.2	0.20
Percentage of vegetation in 2010	20.7	0.02
Average household's head income in 2010	73.7	0.06
Subnormal settlements in 2010	191.3	0.15
Households in 2010	174.9	0.14
Percentage of households in streets without storm sewer (curb) in 2010	16.9	0.01
Percentage of households without sewerage in 2010	24.5	0.02
Combined	1280.3	1.00

Source: Author.

For the final model, we defined increments based on variables values and estimated the odds ratio, as shown in Table 3.16. Considering only antecedent rainfall, each increment of 10mm will raise the chance of a landslide by 1.177 times. Similarly, increments in terrain slope, percentage of vegetation cover, households and percentage of households in streets without storm sewer (curb) will result in a higher chance of a landslide occurrence. Increments in average household's head income and percentage of households without sewerage, on the contrary, will decrease the chance.

Remarkedly, landslides in subnormal settlements have 4.784 times more chance to occur than in a regular settlement.

Table 3.16 - Estimated Odds Ratio and 95% confidence intervals for variables of the final logistic regression model.

Variable	Increment	Odds ratio	Odds ratio Confidence Interval (95%)
Antecedent rainfall (day and 14 previous days)	10 mm	1.177	[1.176, 1.177]
Terrain slope	1°	1.064	[1.064, 1.065]
Percentage of vegetation in 2010	10%	1.197	[1.194, 1.199]
Average household's head income in 2010	R$ 100,00	0.9889	[0.9887, 0.9891]
Subnormal settlements in 2010	subnormal in relation to regular	4.784	[4.705, 4.863]
Households in 2010	1 household	1.038	[1.037, 1.038]
Percentage of households in streets without storm sewer (curb) in 2010	10%	1.122	[1.120, 1.124]
Percentage of households without sewerage in 2010	10%	0.842	[0.841, 0.843]

Source: Author.

3.3.4. Discussion

The fact that the majority of landslide fatalities occur in cities of less-developed countries points to its intrinsic vulnerability due to the existence of larger areas of precarious settlement (ALEXANDER, 1989; ALEXANDER, 2005; CASCINI et al. 2005). Moreover, hazardous climatic condition poses an additional challenge to landslide management and prevention (PETLEY, 2009). In the MRSP, both conditions occur: particularly intense rainfall during the summer season, when most of the landslides occurred, and precarious settlements exhibiting hazardous conditions.

Our results supported these characteristics, stressing the association of rainfall with landslide processes: this variable accounted for 70% of the predictive information of the model. Furthermore, such as previously observed by Tatizana et al. (1987) and followed by Civil Defense in São Paulo state, we also find an important contribution of the previous day rainfall, likely representing soil water saturation. Specifically, for the RSMP, we find that the cumulative precipitation of the 14 previous day was the best way to account for the soil water saturation. The mean antecedent rainfall considering 14 previous days was 216 mm for points of landslide occurrence while for points of non-occurrence the mean value was 83mm. Climate projections foresee a raising temperature of 2°C to 3°C between 2070 and 2100 and possibly the double of the days with intense rain (higher than 10mm) (NOBRE et al., 2011). Accumulated rainfall in this context will increase, and act to saturate the soil in a shorter period, concurring to undermine slope stability and raise landslide risk. In this context, planning infrastructures that enable to limit such problem are of great importance. Some of them are known for example limiting the impermeabilization of soil (HIGHLAND; BOBROWSKY, 2008; MORETTI. et al., 2013).

In addition to precipitation, three other variables responded for model's predictive information: terrain slopes, subnormal conditions of settlements and households, with, respectively, 20%, 15%, and 14%. Terrain slope accounts for natural terrain’s most important characteristic. Subnormal condition is associated to building practices of families and land developers, as well as to public administration lack of inspection in these areas. Number of households is taken as a representative measure of number of buildings, characterizing the built environment. This result reflected the inadequacy of the urban occupation of hillsides in MRSP, based on illegal allotments and favelas, inadequate practices of cut-and-fills, creation of technogenic deposits and self-aided building, in addition to high density of buildings, and, consequently, major slope interventions.

Variables related to families' income, infrastructure systems and presence of vegetation, yielded just a marginal contribution. Mean percentage of vegetation is of only 10% in points of non-occurrence of landslides, while in points of landslide occurrence, it is higher, 22.7%. Despite vegetation importance to water infiltration processes and to prevent soil erosion and instability, its presence was positively related to landslides. Vegetation cover likely represents an indirect indicator of open spaces and pervious surfaces, and its higher percentage in landslide points could denote areas that have been left unoccupied either because of severe physical restrictions or because it is a lot not sold yet. In any case, these areas may be surrounded by disturbed slopes, which would undermine their beneficial action in stabilizing slopes. Surprisingly income did not pose a major contribution to landslide occurrence. This may be due to a bias of Census data, caused by the declaratory nature of this information. Or it may suggest that housing and settlements precarious conditions are related to a structural problem of access to housing, rather than solely a matter of income. In other words, dwellers in hazardous areas may have a similar level of income than their neighborhoods, but circumstantial reasons made them occupy these areas.

Descriptions of landslide events reported the role of wastewater or storm water disposed directly into the soil. Strong evidence in literature supports the causal relation between water infiltration and landslides (e.g. MENDES et al. (2018) and MENDES et al. (2018)). Hence, variables of percentage of households without sewerage, without storm sewer (grating) and in streets with open sewage were expected to have a higher value in landslide occurrence points. Surprisingly, for MRSP, results were the opposite. Our hypothesis are either sewage and storm water leakages are very often and associated with a higher coverage of this infrastructure system or these results may be related to the fact that in MRSP extensive areas have low coverage of these systems and areas where landslides have occurred are not representative of this situation. Indeed, an average of 26% of the households within the buffer of each point of landslide non-occurrence does not have access to sewerage, while within the buffer of landslide occurrence points, average is of 17.8%. This same difference in situations is observed regarding the inexistence of storm sewer (grating) and the presence of open sewage in streets. To the former variable, averages are of 45.8% in areas of non-occurrence and 39.8% in areas of occurrence, while to the latter, averages are of 6% and 4.6%, respectively. These percentages suggest that areas of landslide occurrence are, on average, in better situation than areas of non-occurrence, and this difference, in the case of the variable related to sewerage, may have yielded a minor contribution (2%) to the predictive information of the model.

Also highlighted in landslide's literature, geological, geomorphological and hydrological-pedological aspects were treated in this research as areas of mass movement-susceptibility. Nevertheless, in urban areas of MRSP, medium- and high susceptibility classes were found to be correlated to steeper slopes and subnormal settlements, and these later variables had a greater explanation in landslide occurrence. For this reason, this variable was deprecated in fitting the logistic regression model performed in this paper, despite its importance to physical process-based models of landslides.

An extensive landslide inventory associated with gridded thematic data layers and a bootstrap strategy contributed to a robust result. While our modeling approach enable to describe the landslide occurrence with a high accuracy, for prediction it must be used with caution as for example, if one takes a value high enough of population, for instance, and calculate the probability, this could be equal to 1; in other words, if there is a high enough number of households, for sure this would lead to a landslide and this is not a reasonable scenario. Improvement of the model for prediction could include this by accounting for such nonlinearity. Nevertheless, the high level of discrimination achieved by this model suggests an overall linear behavior.

High spatial resolution built-up maps, showing buildings and open spaces, their layout related to contour lines, as well as pervious and impervious surfaces, could add a higher level of detail to characterize the built environment. This is not the case for variables related to ecological-biophysical domain: they often exhibit a compromise between spatial extent and spatial resolution, in the sense that a more detailed data is only available to restricted areas. As much as other variables of the social-behavioral domain could be incorporated, such as inspected areas, it seems that there is a crucial aspect related to its temporal resolution. The availability of decennial Census data is a constrain to a fully dynamic model. Apart from Census data, there is the same trade-off in terms of its spatial resolution pointed to physical-ecological variables, in addition to the fact that, except for rainfall, these variables tend to be more dynamic than those of ecological-biophysical and technological-infrastructural domains.

An intrinsic vulnerability of MRSP to landslides can be depicted from the occupation of its slopes associated with intense or frequent rainfall. Vulnerability raised from precarious settlements existence, on the other hand, are a combination of inadequate and precarious hillside occupation with social vulnerability of population that have this as the only solution to a housing problem. In both cases, government actors fail in their policies to ensure social and environmental protection.

In this scenario, public administration must take actions not only based on monitoring and warning systems, but mainly in preventing precarious occupation on hillsides. Moreover, a shift in culturally adopted techniques leveraging building practices, both related to buildings and cut-and-fills, would contribute to slope stability and could lead to a positive transformation in hillsides occupation patterns in the MRSP.

3.3.5. Conclusions

Based on descriptions of processes of shallow landslides found in literature, we identify variables that might be related to their occurrence and tested their contribution in a logistic regression model. An extensive landslide inventory, with more than 2,000 dated and geo-located events, associated with gridded thematic data layers and a bootstrap strategy contributed to a robust result, evaluated by an AUC of 0.9087.

Model’s coefficients were estimated to hydrological year of 2010. Its validity to distinct physical and climatic conditions demands further analysis. Nevertheless, they indicate a clear association of quasi-static and dynamic variables with landslide occurence, that includes, in order of importance antecedent rainfall, steeper slope, high households density and, subnormal conditions of settlements related to poor building practices and the lack of municipal inspection on civil works and buildings. These portray a typical scenario for landslide occurrence.

Finally, variables selection and their understanding in a social-ecological-technological framework provides a unique validation to ad-hoc vulnerability assessment to landslides.

4. DISCUSSION

4.1. Grids as tools to operationalize urban system's analyses

In Chapter 3.1, a first approach to deal with grids was presented as a solution to the modifiable areal unit problem (MAUP) observed for temporal analysis based on census tract data. The main idea was to use data interpolation techniques to "break" the census data of 2000 and 2010 into small and constant units during this first step, and, in a second step, aggregate them into distinct and significant territorial units, called target zones. The city of Altamira, in the state of Pará, was used as a case study. This is a medium-sized Amazon city that underwent major territorial changes from the 1970s, at the time of the agricultural frontier expansion acceleration of the in the Brazilian Amazon. New forms of urban occupation were juxtaposed to urban structures inherited from previous periods, at the same time as the urban area expanded. Between 2000 and 2010, the population growth rate in Altamira city was of 3% per year, increasing from 62,000 to 84,000 inhabitants. To express these different forms of occupation, census data was aggregated in neighborhoods, used as target zones. High population growth, in a relatively small city with neighborhoods defined by their homogeneity, common origin and sense of identity, offered ideal conditions. This study relied on dasymetric interpolation, using land cover map as ancillary data, obtained from Landsat imagery, being considered, therefore, an unweighted binary approach.

The study presented in Chapter 3.2 was developed based on the study carried out in Altamira, using the gridded data format instead of re-aggregating population data into targets zones. Data interpolation was performed to obtain a grid consisting of population and average income of the individual responsible for the household (household's head), in 1991 and 2010. Population grids for 1991 and 2010 were overlaid, to obtain population changes during this period. A normalized income inequality index was calculated, enabling the visualization of the unaltered spatial income pattern between 1991 and 2010. Additionally, the population change grid was overlaid on the slope grid, obtained from a triangulated irregular network (TIN) interpolation of contour lines, measured points and river network, extracted from the planimetric and topographic map of MRSP.

Although suitable for interpolation and data integration, the 10m-grid resulted in a very detailed representation that hampered result visualization in a metropolitan scale. Estimation and overlays were performed using a finer grid, in order to avoid errors that would occur by overlaying coarser population growth and terrain slopes resolution grids, since they could be considered as overlapping even if populational growth was within 1 km from a hillside. In addition, the 10 m-grid was resampled to a 1 km-grid using a suitable operator (sum, mean or median).

The first approach to this study was to use a 30 m-grid. Cell sizes were defined as as small as the data allowed, in this case, 30m, determined by the spatial Landsat imagery resolution. The assumption was that a finer resolution would not lead to new information concerning population distribution. However, when inspecting the resampling results, the total volume of population was not preserved, e.g. the total population in 2010 according to census tracts was of 19,601,268; when estimating the 30 m-grid, this became 19,601,034 inhabitants, while in the 1 km-grid estimative this was altered to 18,733,038 inhabitants. Two aspects were identified in relation to this error, the first concerning the grid resolution and the second, the procedure used to aggregate the finer resolution grid into the coarser one. The former aspect is related to the fact that census tracts can be smaller that 30m x 30m (900m2) or display an irregular form, not represented in the grid. The latter was found to be more relevant, related to the aggregation factor, which is the number of cells in each direction that will be aggregated, both horizontally and vertically. This was set as 33, which resulted in a 990 m-resolution grid that was then resampled to a 1 km-grid using the nearest neighbor value. Subsequently, the final solution was to use a 10 m-resolution grid, preserving the total population volume in the two grids (10m and 1km) and reducing the population difference observed between the census tracts and the grids (Table 4.1).

This remaining difference is due to rounding up of populational density values in each census tract.

Table 4.1 - Total population by census tracts, when estimating a 10 m- and 1 km-grids in 1991 and 2010.

Year	No. of census tracts (polygons)	Census tracts polygons (inhabitants)	10m-resolution grid (inhabitants)	1km-resolution grid (inhabitants)	Difference between grids and census tracts (inhabitants)
1991	15,299	15,275,506	15,275,474	15,275,474	32
2010	30,815	19,601,268	19,601,221	19,601,221	47

Source: Author.

Once the adequate grid size was set, other grids were obtained based on biophysical and census data, as presented in Chapter 3.3. Households grid was obtained using the dasymetric approach. Subnormal settlements and mass-movement suitability grids were obtained by rasterizing their polygons. Rainfall and vegetation grids were obtained by spatial disaggregation of their raster format data, using the nearest neighbor value. Grids for other socio-economic and infrastructural censuses variables were obtained by rasterizing their polygons and overlaying them on the household grid, to assure a relation to household locations. Grids for altered variables (vegetation, households, income and subnormal condition) were obtained by overlaying the 2010 and 1991/1992 grids.

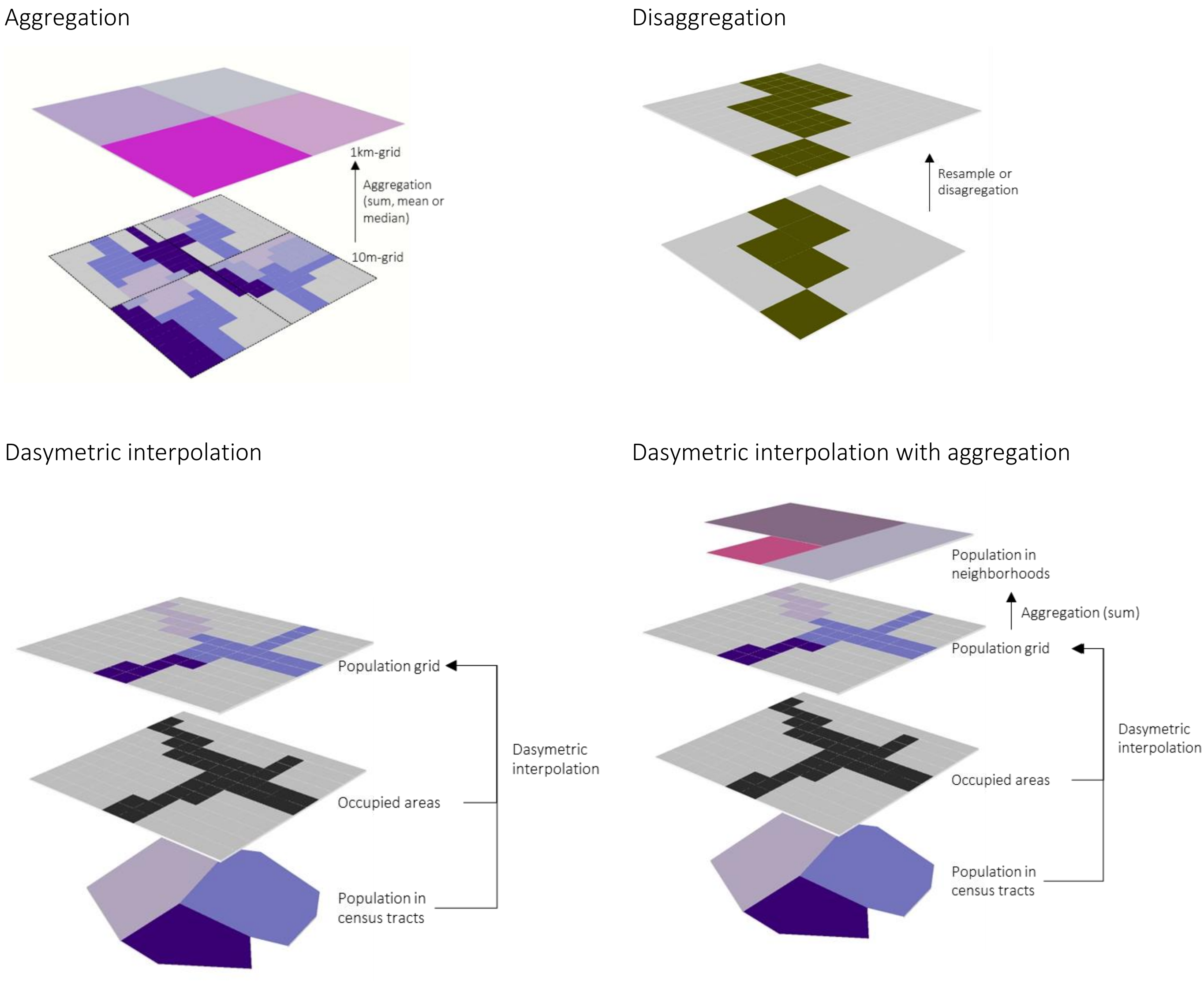
Because landslide point geocoding resulted in sites systematically located along streets, a rectangular 30 m buffer for each orthogonal direction was adopted to estimate where the landslide would have most likely occurred. To link the assessed variables to the cells, a focal filter was applied, consisting of neighbor cell value aggregation using a 'moving window', of 7x7 pixels in size and an appropriate function (sum, mean, modal or maximum, according to Table 3.8). It is important to note that grids calculated by applying focal filters do not maintain data volume. Moreover, depending on the chosen function, the obtained results are different. For example, the focal filter applied to the subnormal condition grid used a modal function and resulted in smaller subnormal settlements areas than the original polygon, thus yielding a more conservative result, while for a maximum function was used slope stressing high values.

Rainfall data was configured as image collections, in which the x and y axes stored location coordinates, while the z axis dates from 1 June 2008 to 31 October 2012 (1614 images). Two procedures were required to retrieve previous rainfall data for each point of the grid. First, a calculation of the previous rainfall and second, information extraction by date, considering that landslide points display a date of occurrence, while a random date was assigned for non-landslide points. To calculate the previous rainfall, a raster operation was performed to sum up images of corresponding previous periods (1 to 30 previous days, in daily intervals, then the 35, 40, 45, 60, 90 and 120 previous days), resulting in a new image collection for each considered previous rainfall period. This operation was performed using Google Earth Engine and the results were exported for further processing on the R software. In the R environment, they were imported as a multi-layer raster object, followed by a query set to search for specific x, y and z values in each set.

Based on distinct geographical representations summarized by Galton (2001), grids may be considered field-based models, in the sense that they are a “set of locations related to each other by such relationships as distance, direction and contiguity” with attribute values, while neighborhoods may be object-based models, composed of individual entities with several attributes, among which, necessarily, is their location. The former would be related to the raster format and the latter, to the vector format. The author aforementioned author highlighted that this distinction can be addressed in conceptual terms, as well as in purely technical terms (GALTON, 2001). This research applied grids to inform attribute values to both object-based models (neighborhoods) and field-based model (RMSP grids), suggesting that model definition should be based only on conceptual requirements, since, in technical terms, they are interchangeable formats.

Procedures and operations summarized previously were performed to assign attribute values to each urban system unit. These include dasymetric interpolation, rasterisation, aggregation, disaggregation and overlay and query operations, which created and manipulated gridded data, as illustrated in Figure 4.1.

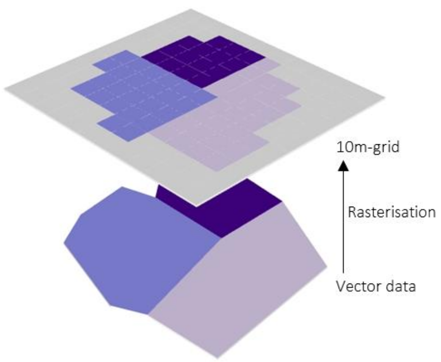
Figure 4.1 - Operations and procedures performed to create and manipulate grid data.



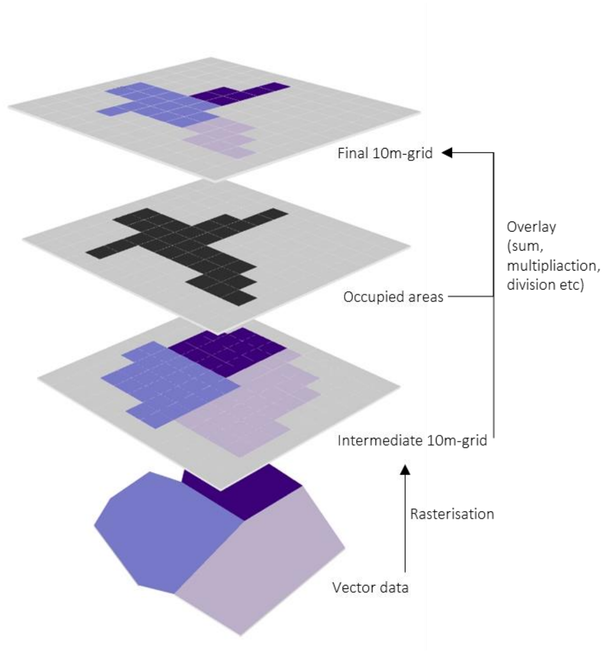
to be continued

Figure 4.1 -Sequence

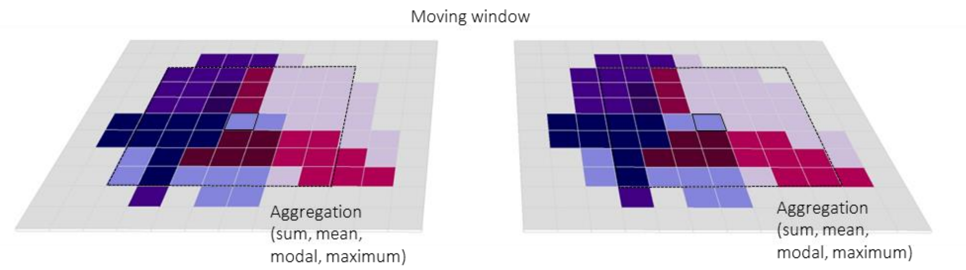
Rasterisation



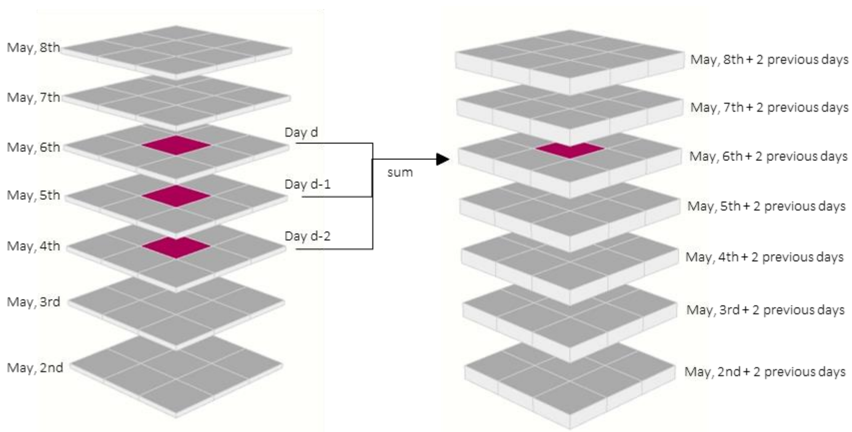
Rasterisation with overlay



Focal filter



Multi-temporal data manipulation



Source: Author.

The definition of the grid cell size is a key point in this approach. As demonstrated in this research, it should observe the smallest feature size (either from raster or vector data) and, if there is a need for scaling-up, appropriate procedures must be undertaken to preserve data volume. A straightforward solution is to adopt a coarser grid size that is, in turn, an integer product of a finer grid size. Additionally, performed operations and procedures are dependent on the defined unit of the system, attributes that will be assigned to each unit and to the analysis that will be performed based on these data.

A binary dasymetric approach, as applied herein, assumed a uniform population and household distribution within the occupied areas of each census tracts. This uniform distribution was also adopted to relate infrastructure variables expressed as a percentage of households in a given condition (e.g. without sewage). In this case, the uniformity assumption was that each grid cell would reproduce this percentage. More sophisticated approaches can be undertaken, such as those proposed by Marques et al. (2003), that apply mean and median population density values as weights to interpolate census tract populations to estimate *favela* population in the municipality of São Paulo, Amaral et al. (2012), who used environmental variables related to the presence of a human population (e.g. distance to rivers, forest covers) and fuzzy inference to generate population density surface data, or Stevens et al. (2015), that, instead of fuzzy inference, used a random forest-based dasymetric modeling approach. However, although it is a simplistic model, binary dasymetric approach is indicated as a stable and robust method.

To retrieve information from multidimensional array rainfall sets, a combination of tools was used, namely Google Earth Engine reducer (GORELICK et al., 2017) and R Raster package (HIJMANS, 2019) tools. A different approach, based on one query that retrieved rainfall information adding previous rainfall data at once, would allow for the maintenance of only one set of multi-dimensional arrays, optimizing procedures and consuming less memory. Indeed, the creation and manipulation of grid data as performed herein could have taken advantage of a structured data, such as multidimensional arrays, in the sense that they could have provided a more elegant and powerful tool to create, manipulate and integrate data grids. Used in programming languages, arrays can be extended to a flexible data structure for data-oriented sciences, comprising both spatial and a temporal dimensions, which may often be irregular, and built from both raster or gridded, as well as vector, data. Concerning array use, Lu et al. (2018) pointed out that, although they simplify data organization, the meaning of grid cell values are rarely made explicit in practice, e.g. grid cells may represent the point value at the location of the grid cell center or an aggregation of the variable over the grid region. Authors suggest that different possibilities may not matter significantly when combining arrays with identical properties, but play a role when comparing them to other arrays, converting (regridding) one to the cells of another, or combining them with other non-array data, such as features (points, lines, polygons) in a GIS (LU et al., 2018). Moreover, the performed procedures and operations (called meta-information) are crucial aspects of this data format and must be documented and informed (SCHEIDER et al., 2016).

Urban system modeling may benefit from recent advances in multi-dimensional arrays, formally structured as data cubes. Although this is still varied in the literature, in general terms it represents a multi-dimensional array alongside metadata describing axis, coordinate and cell semantics, and requires data presenting inherent attributes (usually referred to as coordinates) according to which they can be ordered in a way to facilitate management and analysis. Besides efforts to agree upon key data cube features, advances have been made in storing and serving data cubes in remote services (BAUMANN et al., 2018). New tools have been developed to construct, access, manipulate and analyze the stored data (and metadata) in-memory and in-disk, such as the gdalcubes R package (APPEL; PEBESMA, 2019) or the Stars R package (PEBESMA, [n.d.]), which can handle vector and raster data arrays.

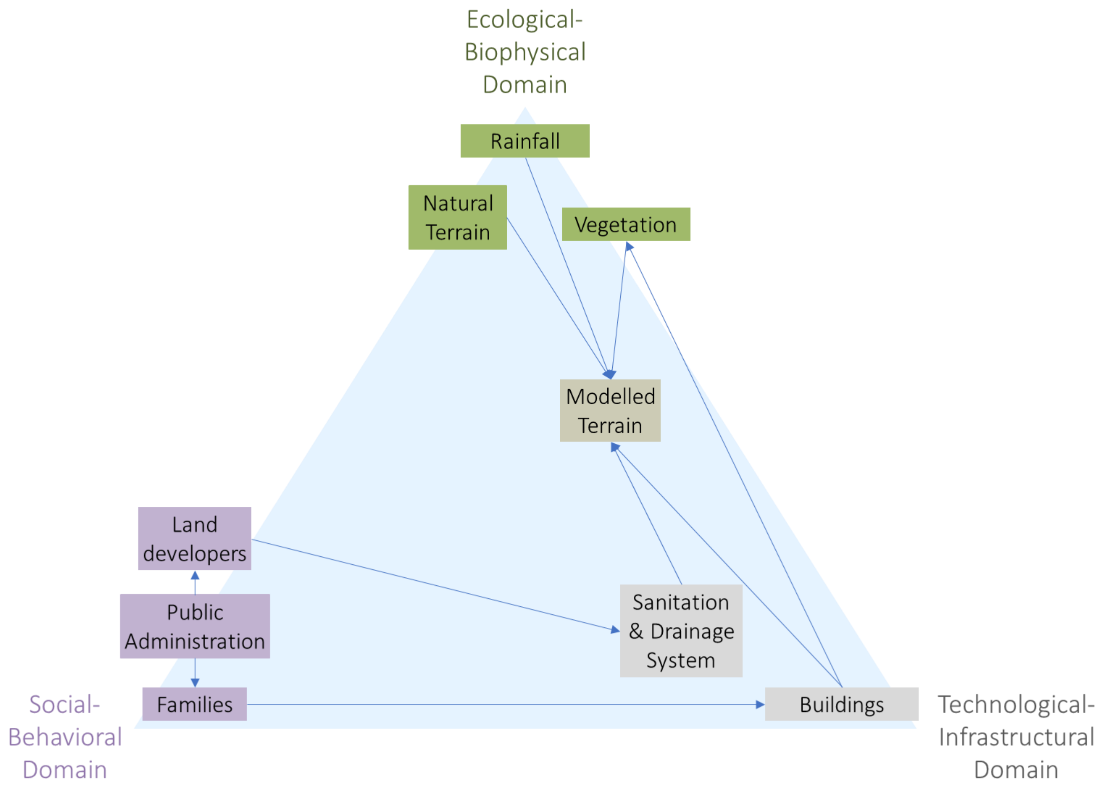
4.2. The Metropolitan Region of São Paulo as a Social-Ecological-Technological System

A Social-Ecological-Technological System framework was applied in the paper presented in Chapter 3.3 to disentangle MRSP in ecological-biophysical, social-behavioral and technological-infrastructural domain components, regarding hillside occupation. Based on landslide descriptions found in the literature (Chapters 2.3 and 3.3.1), ecological-biophysical domain (rainfall, natural terrain and vegetation), social-behavioral domain (families, land developers and public administration) and technological-infrastructural domain (sanitation and drainage systems and buildings) components and their relationship were identified and characterized.

Frequent and low-intensity urban landslides, as those recorded in the IG inventory, are a failure signal of mainstream hillside development. Therefore, a model strategy to assess the importance of SETS components to landslide occurrence was built based on bootstrap sampling to fit a logistic regression using the extensive IG landslide inventory associated with thematic grid data layers. The results portray a favorable scenario for landslide development, depicted, mainly, by the combination of intense antecedent rainfall steep slopes, subnormal settlements and high household density.

Poorly informed, and even deleterious family slope occupation practices include cut-and-fills, the creation of technogenic deposits and self-aided building. No previous design considering hillside occupation security aspects nor the definition of areas that should not be occupied ae available for subnormal settlements. In this sense, the actions of families and land developers are not based on previous and detailed knowledge of natural terrain characteristics. On the other hand, public administration actions to provide guidelines to land developers and families, as well as to control and inspect hillside occupations are inefficient. Besides the precariousness and unplanned characteristics of subnormal settlements, model results indicated the importance of the number of households for landslide occurrence. A higher number of households is related to a higher number of buildings and major natural terrain alterations. These condition the creation of a modeled terrain that belongs to both the ecological-biophysical and the technological-infrastructural domain. It is this modeled terrain that, during intense or persistent rainfall, is prone to landslides. Vegetated areas were associated to unoccupied areas where vegetation could not pose beneficial slope protection due to surrounding disturbances, thus increasing the chance of a landslide occurrence. This scenario is illustrated in Figure 4.2.

Figure 4.2 - The MRSP urban system depicted from landslide occurrence model results.



Source: Author.

Once the slope is occupied, measures to mitigate landslide risks comprise slope stabilization strategies and civil works aimed to enhance slope security. These include adequate water drainage, the construction of rock-fill buttresses or retaining walls, the use of plastic mesh reinforcements or adequate vegetation species, among others (LACERDA et al., 2013; HIGHLAND; BOBROWSKY, 2008). In addition, these may require building or neighborhood removal. This has been adopted in MRSP. The Greater ABC Inter-Municipal Consortium, for example, has developed a regional risk reduction and housing removal program that relocated 536 families from risk areas from 2014 to 2016 (CONSÓRCIO INTERMUNICIPAL GRANDE ABC, 2016). Considering the entire MRSP, a collaborative mapping has identified five *favelas* that have been totally removed, seven which have been partially removed and 281 which are under threat of removal due to high risk situations, between 2017 to 2019 (OBSERVATÓRIO DE REMOÇÕES, 2019). Removal is a radical and traumatic measure, that may lead to broken social bonds, thus perpetuating family vulnerability. Besides the family situation, the removal solution is constrained by financial resources regarding land acquisition and in providing housing or temporary income to removed families, usually a monthly rent (KOCKELMAN, 1986; SCHUSTER; HIGHLAND, 2007; CONSÓRCIO INTERMUNICIPAL GRANDE ABC, 2016).

Another set of actions that contribute to landslide risk mitigation is the development of monitoring and warning systems. In the state of São Paulo, these actions are structured as Civil Defense Preventive Plans and Contingency Plans, prior to each rainy season (summer season, December-March), involving a technical team on duty to monitor and analyze the weather situation, issue alerts and inspect emergency situations in risk areas. During the summer season of 2016-2017, the Civil Defense inspected seven areas in MRSP, two in the Itapevi municipality and five in the Francisco Morato municipality. All were landslide risk areas. In total, 10 houses were interdicted, and 40 people removed.

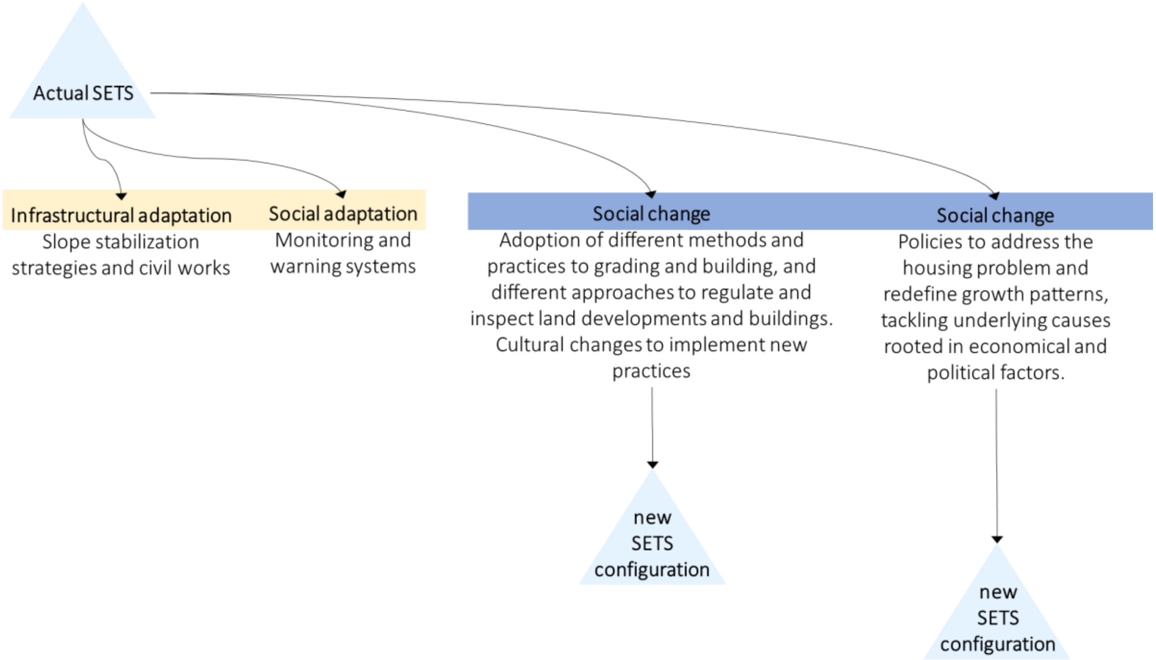
Measures aimed to restrict or control hillside urban occupation, such as zoning and building ordinances and specific regulations determined by local authorities, followed by regular compliance inspections, may drive changes in the building and design practices of land developments. More than technical knowledge, this shift will also require more effective mechanisms for their implementation. In this sense, understanding how landslides are perceived within the broader patterns of society may provide useful insights for building policies, since both risk perception and the resulting decision-making are deeply embedded in cultural consciousness and practices

(HORLICK-JONES, 1995). Educational campaigns and material consisting in technical instructions and recommendations to promote low-impact and risk interventions are also strategies applied to reinforce the adoption of new practices.

Finally, the remaining set of measures to manage landslide risk would be associated to a deeper transformation of the MRSP urban system. As observed by Cutter (1996), vulnerability is rooted in underlying political and economic forces. In the case of the MRSP, these forces materialized in a suburban growth pattern, shaped in the 1960s, 1970s and 1980s, which have not yet been surpassed. The population in illegal allotments and *favelas* located on slopes have grown faster than the rest of the MRSP, indicating that housing policies are failing. Moreover, the existence of illegal allotments, where lots are sold, suggests a dysfunctional real-estate market.

Figure 4.3 summarizes these measures emphasizing the difference between adaptation measures and those measures aimed to change practices or alter the underlying system vulnerability factor. The latter will set conditions to a more profound system transformation, while the former will promote a reactive adaptation of the urban system to landslides, strengthening the capacity of public administration and dwellers to cope with risk and enhance system resilience.

Figure 4.3 - Landslide risk management measures.

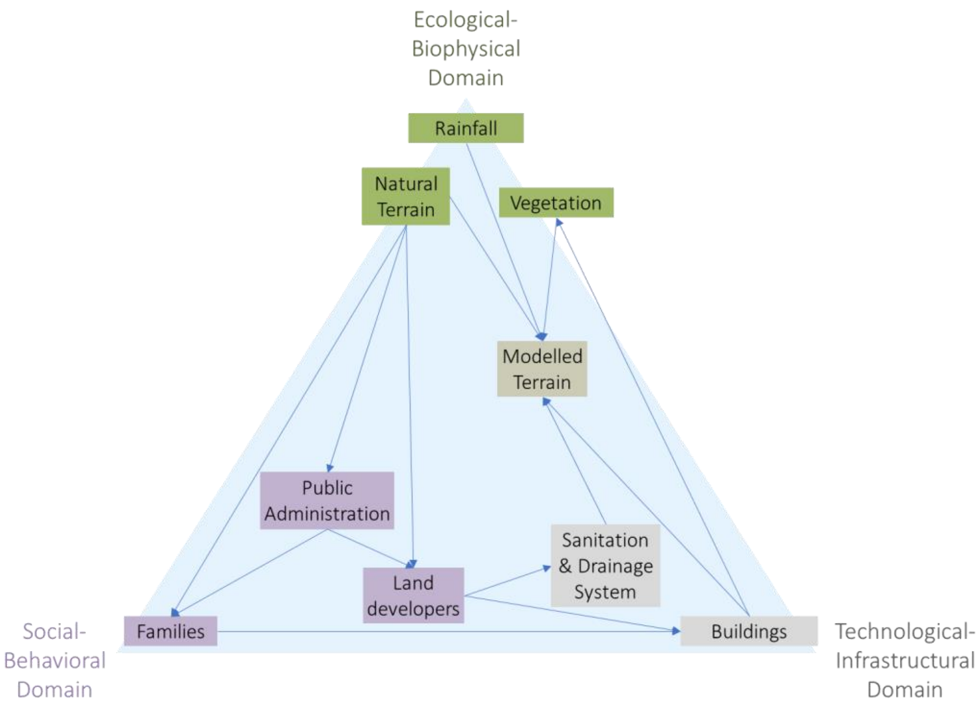


Fonte: Author.

Resilience is related to regime shifts and the adaptation capacity to persist in one given state (FOLKE, 2006), but, as much as adaptation measures ameliorate life conditions in slope occupations, they tend to impel the system to accommodate this state. Although adaptative measures and those aimed to promote system transformation are not excluding, Sulaiman (2018) observed a preponderance of actions concerning disaster preparedness in Brazil. Events occurred in the state of Rio de Janeiro in 2011 prompted the creation of a national level risk policy, the National Policy of Protection and Civil Defense (NPPCDE) established by law in 2012 (Federal Law, no. 12.608). Since this national response, Coutinho et al. (2015) observed that few municipalities have incorporated NPPCDE directions, shifting their focus to preventive actions rather than emergency responses. In the state of São Paulo, where risk management at the institutional level has a lengthier trajectory, important advances in mitigation actions have been made, as exemplified by the Civil Defense Preventive Plans. Regarding preventive measures, advances are observed in the technical field, in the sense that a robust knowledge concerning geotechnical terrain characteristics, materialized by susceptibility, aptitude and risk maps, is noted. Nevertheless, given the high population growth rates still observed in hillsides, this knowledge is not sufficient in itself to effectively restrict hillsides occupation, pointing out different difficulty levels in promoting adaptation measures and structural changes.

Practice changes are based on the knowledge developed on hillside occupation. Along with the transformation of underlying factors, they will set the conditions towards a system reconfiguration, requalifying and creating new relations among system components. A possible new configuration of the MRSP SETS is presented in Figure 4.4. The reinforcement of a cultural shift in building and design practices, along with more effective public administration actions, would lead to a more careful consideration of natural terrain and the development of occupation strategies that potentiate their attributes and promote the slope and built environment safety. These changes are represented in the new relations created between ecological-biophysical, social-behavioral and technological-infrastructural domain components.

Figure 4.4 - Envisioned MRSP's urban system in relation to hillsides occupation.



Source: Author.

Within the MRSP social-ecological-technological system applied to the hillside occupation problem, the relation between humans and nature is made explicit. The natural terrain is a biophysical constraint to hillside occupation. Potentialities related to this problem, such as defense recurrent in past times or scenic views, as well as their combination to other functions to enhance ecosystems services are disregarded. Rainfall poses an increasing threat, and the local vegetation, which could contribute to slope stability, acts in the opposite direction, favoring landslides. Design and building practices, in addition to risk mitigation and prevention actions, are materialized in building and infrastructure systems that, in turn, pose new risks to the system, instead of promoting a safe environment.

The SETS framework, on the other hand, allows for the identification of which components, process or relations should be strengthened. This corroborates the use of the SETS framework to develop and analyze qualitative scenarios, which, in combination with modeling strategies, can contribute to strategy assessment and transformational pathways uncovering city transitions to a more desirable and sustainable futures (MCPHEARSON et al., 2017).

5. CONCLUSIONS

The urban landscape of the São Paulo Metropolitan Region relies on hill, slopes and floodplains topography. As observed by MONBEIG (1954), such relief barely corresponds to metropolis needs, evidencing the relativity of the “favorable physical factor” where, if in one historical moment the physical factor is favorable to certain individuals with certain needs and equipped with certain techniques, at the next moment it may be an obstacle. In the case of the MRSP, in this following moment, the choice of the original site challenged its residents to conquer and tame the floodplains and hillsides, through channels construction and earth moving as well as to overcome the deep relief cuts and elevations, with viaducts and tunnels.

Afonso (1999) argue that urban hillsides’ occupations are, par excellence, an urban landscape design problem. Hillside values are both aesthetical and ethical, given their landscape predominance and, because of this, their role in city or neighborhood identity is paramount. However, as the urban sprawl process in the RMSP took place, this became the opposite of an identity, in the sense that hillside slopes are difficulty to occupy and are, therefore, despised by the formal real estate market and relegated to informal occupation. Thus, the MRSP slope occupation pattern is characterized as illegal, precarious and hazardous.

This research estimated that 44,272 ha were transformed to urban areas, representing a 24% expansion. Of these new areas, only 5.6% were developed in slopes steeper than 17° (30%). Nevertheless, populational slope growth was intense, as 4.15% per year against 1.32% per year in flat areas.

Landslides are the most noticeable consequence of this occupation. Based on shallow landslide processes descriptions found in literature, variables that might be related to their occurrence were identified and their contribution was tested by applying a a logistic regression model, using the landslide inventory with over 2,000 dated and geo-located events in the hydrological year of 2010. The AUC model value was of 0.9087, denoting a high level of discrimination.

This result supports the importance of the grid method and of the Social-Ecological-Technological System (SETS) approach in analyzing urban system. The SETS approach enabled the analysis of urban landslides as the outcome of dynamic socioeconomic and infrastructural conditions alongside climatic and geophysical conditions. Intrinsic characteristics and natural ecological-biophysical domain processes are altered by hillside urbanization. Alterations are controlled dweller, land developers and public administration actions, understood as social-behavioral domain components. These actions are materialized in the technological-infrastructural domain which comprises the built environment.

Antecedent rainfall plays the most important role in landslide occurrence, followed by terrain slope. Subnormal conditions, associated with poor building practices and lack of municipal civil works and buildings inspection, as well as the number of households, which represents built density and, therefore a greater hillside alteration, yielded a slightly lower contribution. Other variables, related to infrastructure systems and presence of vegetation, displayed only a marginal contribution.

In this study, grids were used as a tool for urban system modeling. These are flexible enough to be used for urban system data analysis and modeling, being a common format for data from different disciplines, different spatial and temporal resolution, and different system units. Jacobs (1961) suggested that planners should observe the particularities of cities, using an inductive, instead of deductive method. Currently, it seems that the challenge is to gather these particularities and observe them through a temporal perspective, using socio-economic or demographic data, environmental variables, satellite images time series, as used herein, in addition to microclimate data, climate model results, origin-destination matrices, traffic data, social media data, as well as any other relevant data, all ingested into a data cube.

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Climate Hazards Group InfraRed Precipitation with Station Data (CHIRPS)

Climate Hazards Center, UC Santa Barbara, USA, https://chc.ucsb.edu/data/chirps

Demographic Census Data

Brazilian Institute of Geography and Statistics (IBGE), Brazil, https://www.ibge.gov.br/estatisticas/downloads-estatisticas.html

Georeferenced Census Tracts

Center for Metropolitan Studies (CEM), Brazil, http://centrodametropole.fflch.usp.br/pt-br

Georeferenced Digital Cartographic Base of Public Addresses of the Metropolitan Region of São Paulo

Center for Metropolitan Studies (CEM), Brazil, http://centrodametropole.fflch.usp.br/pt-br

Georeferenced Inventory of Geodynamic Events

Geological Institute of São Paulo State (IG), Brazil, https://www.infraestruturameioambiente.sp.gov.br/institutogeologico/

Landsat Imagery

U.S. Geological Survey (USGS), Unites States, https://www.usgs.gov/land-resources/nli/landsat

Mass-movement susceptibility maps

Geological Survey of Brazil (CPRM), Brazil, http://www.cprm.gov.br/publique/Gestao-Territorial/Prevencao-de-Desastres-Naturais/Cartas-de-Suscetibilidade-a-Movimentos-Gravitacionais-de-Massa-e-Inundacoes---Sao-Paulo-5088.html