



Urban expansion and environmental risk in the São Paulo Metropolitan Area

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ABSTRACT: In this study, we simulated the expansion of the São Paulo Metropolitan Area (SPMA)—the largest metropolitan area in Brazil—by the year 2030 using the Dinamica EGO software with data extracted from Landsat TM 7 (orbit point 219 076, resolution 30 × 30 m). Based on the urban area in 2008, we used an urban growth scenario to analyze urban expansion up to 2030. Subsequently, we used ArcGIS to integrate the spatial information, combining layers to create risk maps. In this case, environmental risk factors, along with flood and landslide probabilities, were considered in order to identify high-risk areas. By 2030, the urban area was projected to increase by approximately 38.7%, and to cover 3250 km². With this growth, 807 km² of the region (and ~4.27% of urban expansion areas) will be in flood risk zones.

KEY WORDS: Climate change · Disasters · Intense precipitation · Flood · Landslide · Urban planning

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1. INTRODUCTION

In this study, we simulated the expansion of the São Paulo Metropolitan Area (SPMA) by the year 2030 with data extracted from Landsat TM 7, (orbit point 219 076, resolution 30 × 30 m). Then, based on the urban area in 2008, we constructed an urban growth scenario to analyse the change in 2030. In this case, environmental risk factors and threats for flooding and landslide were considered in order to identify the areas susceptible to high risk.

Climate change is expected to increase the risks of flooding and landslides in the SPMA, which are associated with extreme events like storms and heavy rainfall, as well as with the urbanization process (that causes soil compaction). The SPMA has been undergoing an intense growth, with distinct stages in the urbanization process. The challenge is to understand the main factors that are connected to the processes of spatial expansion and climate change that are taking place in the SPMA.

According to Carlos (2004), the clearest change is related to the displacement of São Paulo's industries to its peripheral areas, which has been observed in

other areas around the world and is caused by the changes that have occurred in the production process and as a condition for the businesses to remain competitive, forcing companies to modernize and reduce operating costs. Lower production costs are difficult to attain in densely built-up and extremely specialized metropolitan regions such as São Paulo, where the price of urban land is high compared to the surrounding regions.

The demand for land in the outskirts of the cities that comprise the SPMA is a cause for concern because of the lack of suitable building land, and because soil water capacity is limited by environmental conditions such as topography (slope) and water supply reservoirs. Fast, visible and critical changes in land use and settlement have been taking place at a remarkable and unprecedented pace, reshaping the landscape and affecting the environment. Ecological criteria are not taken into account in urban planning, and legal definitions are often ignored, thus magnifying the potential environmental risks (Ross 2004).

The cities of the SPMA are expanding, and the improved road system is encouraging building be-

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tween the suburbs and towns, reducing the distance between them. This expansion is in progress throughout the SPMA, spurred largely by labour, education, housing and consumption (Bógus & Pasternak 2009). Oliveira (2004) showed that these processes underway in the metropolitan area have led to the disappearance of immense rural areas that were part of what is now the SPMA as recently as 50 yr ago. Rural areas were turned into legal urban development projects or illegal squatter settlements. The so-called 'green belt,' which had been envisioned to surround the metropolitan area, was occupied due to the eagerness to appropriate income from land use.

For example, in the case of the land allotments for the low-income population, such as those in both the Guarapiranga and Billings watersheds (southern region), developers have broken the water source protection laws (Reydon 2005), splitting up the land without considering the slope of the terrain, its proximity to water bodies, and the existing vegetation. According to the Socio-Environmental Institute (ISA), more than half of the Guarapiranga watershed had been altered by human activities by 2003. Part of this change (16%) was related to land use, while the remainder (34%) was due to miscellaneous uses such as agriculture and mining. The region has suffered over the past few years from the consequences of an accelerated process of illegal occupation, with replacement of Atlantic forest by urban settlements (ISA 2003).

It is estimated that the urban growth in the Billings watershed was 31.7% between 1989 and 1999. More than 45% of settlement recorded in 5 municipalities of the region took place in areas where there were serious or severe restrictions on occupation, such as hillsides, flood areas or lowlands. The population living in slums was estimated at 161 000 (~19% of the total) and only 11.8% of urban expansion occurred in areas deemed as suitable for construction or subdivision into lots (ISA 2003).

Trespass and uncontrolled settlement of land protected by the Water Source Protection Act represents one of the most serious problems in the SPMA, and also affects the Cantareira Mountain Range (to the North) and the Ribeirão dos Campos and Ponte Nova reservoirs, in the municipality of Salesópolis (to the East). The illegal squatter settlements are devoid of any type of infrastructure, such as sewage disposal and treatment networks, running water or urban drainage systems. The vegetation is frequently removed, and soil compaction, due to increased urbanization, exceeds the tolerance limits of the natural system. Natural drainage is seriously impeded, be-

cause the rain that would normally seep into the soil has to flow across construction surfaces and through storm-water pipes, increasing the volume and velocity of runoff (Tucci 1995).

This study does not project an increase in inadequate dwellings, but to a significant demand for housing. Future urban expansion in the SPMA is not directly related to extraordinary population growth, but rather is occurring due to growth in production of housing, and also as a result structural changes that have taken place in people's lives, which are much more related to household size and family composition (i.e. a shift away from the nuclear family structure; Givisiez & Oliveira 2009).

The decrease in the fertility rate that Brazilian society has experienced in recent decades has led to home downsizing; however, the demand for houses and dwellings remains strong. The demand for housing takes into account the need for new residences, a result of the demographic dynamics themselves, but the demographic increase is not necessarily explosive (Givisiez & de Oliveira 2009). In the case of the SPMA, the population volume resulting from the replacement rate can be considered significant and, thus, so is the demand for new housing.

Givisiez & de Oliveira (2009) show that the average size of the Brazilian household in 1970 was 5.3 people, and that in 30 yr this number had declined to 3.8 individuals per household. According to the Brazilian Census, there was an average of 3.3 adults per household in 2010 (IBGE 2010). Furthermore, according to Givisiez & de Oliveira (2009), studies conducted by the Ministry of Cities regarding the demand for housing in Brazil for the period ranging from 1993 to 2023 pointed to a significant housing deficit.

The decline in the average number of adults per household reflects changes in family arrangement that propagate beyond the decrease in the fertility rate: e.g. the age of an individual when first married, mortality rates, trends of adults leaving their parents' homes earlier, divorces and relationship breakups and people living alone, among other factors (Givisiez & de Oliveira 2009).

These interconnected facts suggest that the SPMA is moving towards a new phase in the urban expansion process, thus experiencing a moment that favours the rethinking of the public policies concerning land use. As seen earlier, the industrial decentralization process also pushes urban expansion to increasingly peripheral territories, causing the region surrounding the city of São Paulo and the ABC (Santo André, São Bernardo e São Caetano) to expand at an

increasing rate, requiring additional infrastructure, access and services that also require space in order to be deployed.

As services specialize and become more sophisticated, more space is consumed because business opportunities grow and diversify, requiring the incorporation of new land. However, in this process of expanding and occupying increasingly distant peripheral areas, urbanization occupies areas with fragile soil, steep slopes, and conditions unsuitable for urbanization, regularly a significant loss of vegetation. For this reason, it is necessary to address problems of illegal settlements, which still persist and could gain new impetus in coming years, because they often do not comply with construction standards and do not respect land use and division rules, thus introducing new risk situations, largely associated with floods and landslides.

1.1. Urban growth patterns

According to Bhatta (2009), the urban growth pattern has a direct influence on urban development processes both at the city and neighbourhood levels, but on the other hand, the growth pattern is also affected by land and housing policy, population, economy, and other factors. Remote sensing and GIS techniques were used to analyse and model the urban growth pattern in Kolkata, India.

Pereira et al. (2011) calculated the probability of change between land uses in the Serras do Sudeste and Campanha Meridional (Rio Grande do Sul, Brazil). Through the use of a Markov model, they calculated the probability of a determinate land use (forest) staying the same or moving to another use (cattle) during a period of time. The main results are simulations based on the paradigm of Cellular Automata (CA), in which the forest areas are quantified and spatially distributed until the year 2016.

Almeida et al. (2012) built up a methodological process for modelling urban land-use change through GIS, remote sensing imagery and Bayesian probabilistic methods. The probabilities were obtained from a CA simulation model (Dinamica EGO) based on stochastic transition algorithms. Different simulation outputs were generated for the city of Bauru (São Paulo) for the period 1988 to 2000.

Merry et al. (2009) implemented complex models involving a huge amount of data and large number of advanced spatial algorithms for the Amazon timber industry on Dinamica EGO. Soares-Filho et al. (2010) ran applications that include modelling tropical de-

forestation in the Amazon. Teixeira et al. (2009) used a similar model to study the land use and cover change in the Atlantic forest.

Examples of Dinamica EGO applications include the analysis of land use transitions (Almeida et al. 2012, Godoy & Soares-Filho 2008); deforestation in the Amazon caused by logging, contributing to forest flammability (Merry et al. 2009); and forest fire risk (analysis of carbon emissions from tropical deforestation and peatland fires) (Silvestrini et al. 2011); as well as the patterns of drought in Mexican forests (Cuevas & Mas 2008). Furthermore, the application of Dinamica EGO was fundamental in developing the analysis of REDD (Reducing Emissions from Deforestation and Forest Degradation), a mechanism for compensating deforestation reduction in the Brazilian Amazon by payments for tropical forest carbon credits system (Nepstad et al. 2009), and modelling the co-benefits of REDD in Xingu for reducing carbon emissions caused by deforestation (Stickler et al. 2009).

Mas & Vega (2012) generated land cover projections based on transition matrices in order to produce land cover maps at different dates. Yi et al. (2012) developed dynamic models using Dinamica EGO, with data extracted from SPOT VGT NDVI, in order to understand the process and driving mechanism of land-use change in China in 2020. Maeda et al. (2011) simulated the expansion of agricultural and cattle raising activities within a watershed located in the fringes of the Xingu National Park, Brazilian Amazon. A spatially dynamic model of land cover and land use change was used to provide both past and future scenarios of forest conversion for such rural activities, aiming to identify driving forces of change in the study area.

2. MATERIALS AND METHODS

The SPMA is set in a sedimentary basin (Tiete river basin) centered near 23° 32' S, 46° 38' W, a low-lying region within the Atlantic Mountain Chain. It occupies ~8000 km² and is surrounded by hills that vary from 650 to 1200 m in height (above sea level). Its proximity to the ocean influences the atmospheric circulation patterns occurring there. The region is encroaching on the remaining portions of the Atlantic forest biome, which, in Brazil, despite the high levels of devastation, is still home to a significant amount of biological diversity. The vegetation of the region is therefore made up of only fragments of secondary Atlantic forest (known as Mata Atlântica).

São Paulo is the largest metropolitan area in Brazil, with almost 20 million inhabitants. It is located in São Paulo state (in south-eastern Brazil), ~600 km south-west of Rio de Janeiro and 80 km inland from the Atlantic Ocean, and has a population density of ~2500 inhabitants km⁻². The population grew by 0.98% from 2000 to 2010, due mainly to the difference between births and deaths, in spite of an out-flow due to migration (–1.62 per thousand inhabitants; 30 300 people yr⁻¹) (IBGE 2010).

According to SEADE (2010), the SPMA is also home to the largest employment base (9.7 million workers), with a GDP about \$347 billion, and a GDP per capita around \$17 666, and with a per capita income of about \$470. São Paulo's largest industries are slightly more diverse than those in other metropolitan areas. Its largest sector, services, makes up 50% of the economy, and since 1990, São Paulo has seen the largest growth in its information services (251%) and business services (105%).

We used the Dinamica EGO software to simulate the urban projection of SPMA for the year 2030 with data extracted from Landsat 5 and TM 7 (orbit point 219 076, resolution 30 × 30 m). Then, based on the present situation we assumed one scenario under which we could analyse the urban land use in 2030. Referring to Fig. 1, we see the extent of the expansion in 2001 (in orange) and 2008 (in gray).

First, we used a method of classifying satellite images that involved the identification of urban areas in the image as 'Training Samples' to seed the clustering algorithm in the ENVI 3.6 software. A Maximum Likelihood algorithm was used to categorize each location with the group that it is most similar to. The objective of the image classification was to automatically categorize all pixels in the satellite images into classes. The spectral pattern or signature of surface materials determines an assignment to a class, and a numeric description of the spectral attribute of each class is specified. In this case, we considered 3 classes: urbanized, non-urbanized areas and water (i.e. reservoir, rivers and channels).

The second step in the process was based on calculating the cell transitions using the software Dinamica EGO in order to obtain a cross-tabulation map between the initial (2001/2008) and final (2030) land-use map. The Dinamica graphical interface allows the design of a model that performs calculations on various types of data, such as constants, matrices, tables and raster maps. In this way, one can easily set up a model by establishing a sequence of operators involving an ample range of analytical and simulation algorithms. In an attempt to understand the

physical growth process, an algorithm was used to express or represent the urban expansion:

$$A(t) = A_0 (1 + i)t \quad (1)$$

where A_0 : initial growth, $A(t)$: growth after t yr, i : unit growth rate, and t : time measured in yr, i.e. number of yr elapsed.

The respective areas of the years 2001 and 2008 were calculated, as well as the urban growth rate (Table 1), which was determined for the elapsed time period (7 yr). To verify the consistency of the data obtained, satellite imagery data were compared to official data published by the São Paulo Metropolitan Planning Company (Empresa Paulista de Planejamento Metropolitana, Emplasa). It is noteworthy that Emplasa used orthorectified aerial photographs at a scale of 1:25 000, which afford a superior level of detail as compared to the Landsat imagery (1:250 000). One important aspect is the fact that Emplasa considered a period of 5 yr. Considering these factors, there may have been some variations between surveys.

In the sequence, a Markov chain was employed for the estimation of global transition in the case of simulation (urban forecast) through Dinamica EGO. According to Lambin (1994, p. 28), this is a 'mathematical model designed to describe a certain type of process that moves in a sequence of steps through a set of states', whose formula is defined as:

$$\pi(t+1) = P\pi(t) \quad (2)$$

where $\pi(t)$ is a column vector, with n elements, that represents the condition of the system at a certain time t (e.g. area percentages for each n land-use category or state); $\pi(t+1)$ is the vector representing the occupation of n_i states at a given future time $t+1$; and P is the transition probability matrix or the table for land-use transition rates.

It is important to highlight that according to Meyn & Tweedie (2005), the Markov model assumes that transition probabilities do not change over time. It is a mathematical system that undergoes transitions

Table 1. Urban area expansion and annual growth rate for the São Paulo Metropolitan Area (parentheses: year). Data source: Landsat satellite (2001/2008)

Initial area (km ²)	Final area (km ²)	Increase in area (km ²)	Growth rate
Emplasa 2193.1 (2002)	2318.7 (2007)	125.6	0.011
Satellite image 1901.8 (2001)	2123.4 (2008)	221.58	0.015

Table 2. Criteria used to isolate high risk areas in the São Paulo Metropolitan Area. Criteria were derived from a combination of factors associated with different risks

Land use (classes)	Patch no. (1st step)	Criteria (conjunction of factors)	Risk (classes)	Patch no. (2nd step)	Classification
Water	0	Water + non compactness	Middle	0	Non represented
Non urbanized	1	Non urban + non compactness		0	Non represented
Urbanized	2	Urban + compactness		1	High risk
Water	0	Water + non compactness	High	0	Non represented
Non urbanized	1	Non urban + non compactness		0	Non represented
Urbanized	2	Urban + compactness		1	High risk
Water	0	Water + non compactness	Very high	0	Non represented
Non urbanized	1	Non urban + non compactness		0	Non represented
Urbanized	2	Urban + compactness		1	High risk

from one state to another. The next state depends on the current state and not on the sequence of events that preceded it (Lambin 1994). Moreover, Lambin (1994, p. 32) highlights that 'given its stochastic nature, the Markov chain masks the causative variables; for this reason, it is not an explanatory model and cannot be used to understand the causes and driving factors of land-use transition processes.' Nevertheless, according to Lambin (1994, p. 29, 32) the Markov chain analysis has the great advantage that 'the model parameters are easily estimated' and 'simple trend projection involves no more than matrix multiplication and the only data requirement is the current land-use information'.

Through the Dinamica EGO, we used 2 complementary transition functions: the Expander and the Patcher. The first process, the Expander was dedicated to the expansion of previous patches of a certain class (i.e. urbanized areas). The second process, the Patcher, was applied to generate new patches (a patch is a number varying from 0 to 2). The Patcher function searches for cells around a chosen location for a combined transition. This is done electronically, first by electing the core cell of the new patch and then selecting a specific number of cells around the core cell, according to their transition probabilities.

Subsequently, we used ArcGIS to integrate the spatial information, where each theme was linked. By overlaying the spatial information layers, such as hydrography, land use, slope, flooding points, and precipitation, we were able to arrange all the information spatially.

Environmental risk factors and threats for flooding and landslides were considered (through specific criteria), in order to identify the areas susceptible to high risk (Table 2). In other words, since the criteria were based on the objective of identifying high-risk areas, the urbanized areas were considered more

representative and significant than the non-urbanized and water areas, due to compacting (soil sealing) and drainage problems without adequate infrastructure (including construction). We then used the ArcGIS 'math' module to perform mathematical operations that allowed us to integrate and analyse the patterns and trends of the region in 2030.

3. RESULTS

The results obtained from transition function analysis are presented in Fig. 1. They were central in terms of providing fundamental connections between empirical observation and mathematical expression.

By simulating the expansion in 2030, we found that urban spread will intensify in the peripheral area of the SPMA. The urban expansion trend reveals 2 important aspects: the consolidation of urban space in the city of São Paulo; and the expansion of surrounding areas, which will exert strong pressure on the existing natural resources (e.g. the Serra da Cantareira and Serra do Mar, Billings and Guarapiranga dams).

By 2030, the urban area will have spread ~38.7%, and will cover 3254 km². With this growth, the region will have 807 km² of areas subject to the risk of floods, ~46.1% increase during the period. The areas at risk are projected to spread towards the water supply sources (Alto Tietê River Basin, in the Eastern Zone; and the Billings and Guarapiranga dams, in the Southern Zone).

The results showed that the areas susceptible to flooding accounted for 23.5% of urban area in 2008, and 22.3% in 2030. These areas at risk increased ~254 km² in a total area of 1141 km².

Likewise, the map showing areas vulnerable to landslides in 2030 (Fig. 3) shows that ~4.27% of the

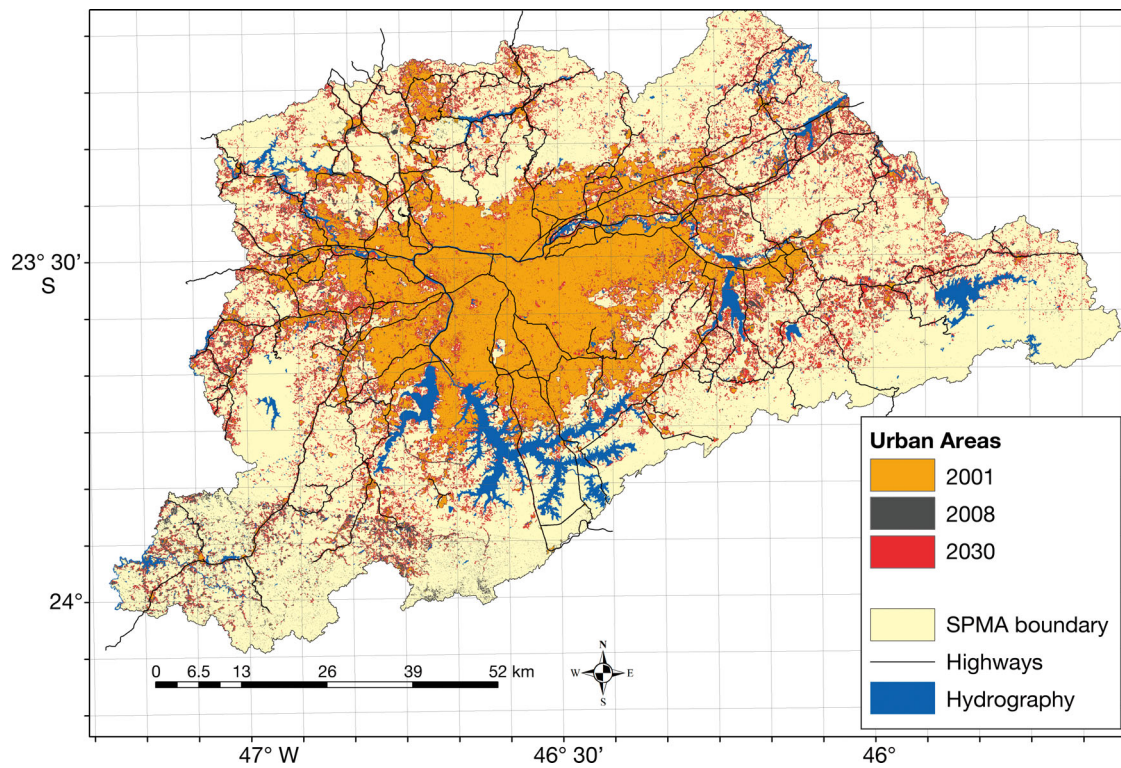


Fig. 1. Urban areas of São Paulo Metropolitan Area (SPMA) in 2001 (orange) and 2008 (gray), and urban expansion in 2030 (red)

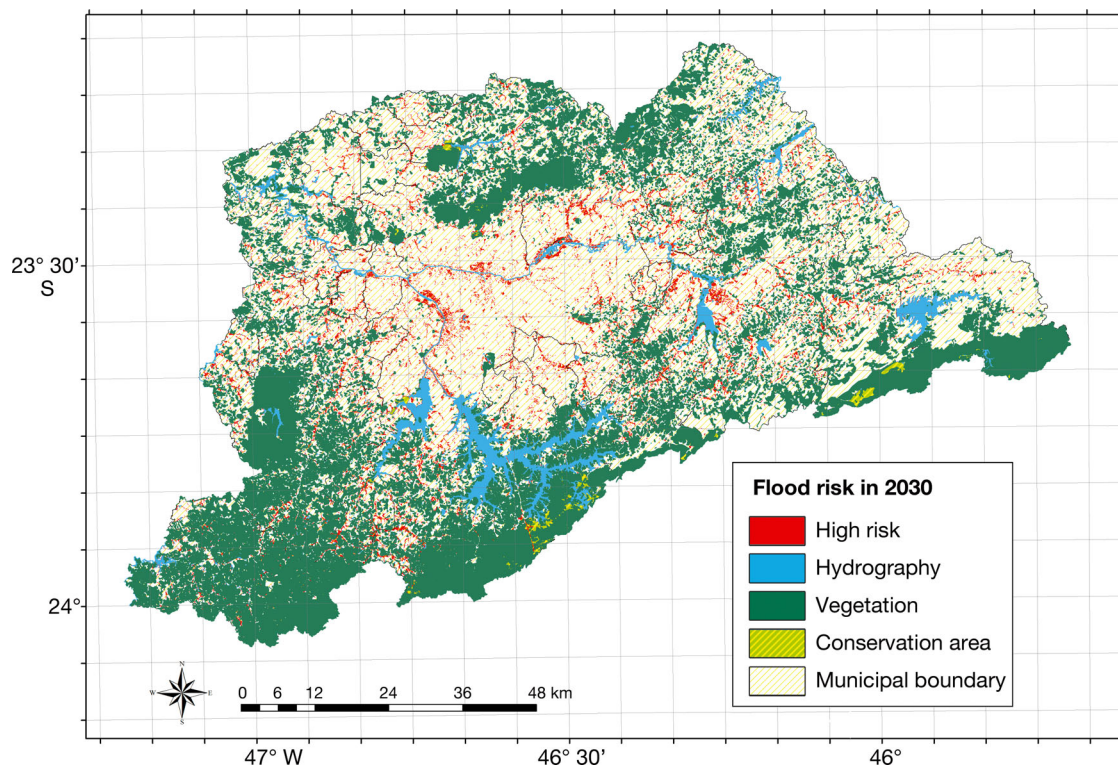


Fig. 2. Areas in São Paulo Metropolitan Area vulnerable to floods in 2030

expansion areas may become new areas at risk. This seemingly small percentage represents a relative increase upwards of 200% in the period, or in other words, the area currently prone to landslides (0.9%) could almost triple, from 21.21 km² in 2008 to 69.88 km² in 2030.

These areas are located mainly in the Serra da Cantareira, Serra do Mar and in São Lourenço da Serra, which are not yet fully occupied since they are considered Areas of Environmental Protection. The areas consist of land located on steep slopes that contain alluvial deposits, and therefore require special care in the implementation of any kind of urban settlement; they are also unstable due to a combination of upstream erosion greater river energy and increased surface runoff.

4. CONCLUSION

The combination of Dinamica EGO's transition function, GIS and remote sensing techniques provides a powerful tool with respect to the generation and evolution of spatial patterns of change. Through the transition function, we performed a simulation of future land use change (2030), utilizing land use maps from 2 different dates (2001 and 2008).

This simulation provides important input to urban planning and broader political analyses, since urban development can increase environmental risk in the SPMA due to local changes in hydrological and hydrometeorological conditions (which increase flood hazard) and landslide vulnerability. It makes clearer the relationship between urban growth, flooding and landslides due to increased impermeability, which is aggravated by rainfall via microclimatic changes.

The land use in the SPMA is diverse (e.g. trade, services, industry, settlements with high standard of wealth); however, the concentration of low-income populations along the Tiete basin, in areas of protection (riverbanks and floodplains) causes concern in view of the precarious housing conditions, obstruction of water bodies and weathering and erosion.

Altogether, urbanization is causing serious changes in the remaining areas of the watershed, stretching into its tributaries and occupying its slopes and headwaters as well. If this process persists through 2030, new areas of risk will appear and vulnerability will increase, with regard to both floods and landslides.

The region of the SPMA where changes are felt most intensely, with 80% of the already urbanized, is the stretch that includes the Tiete and Pinheiros River basins. These areas are located on the flood plain or stream terraces, where the natural vegeta-

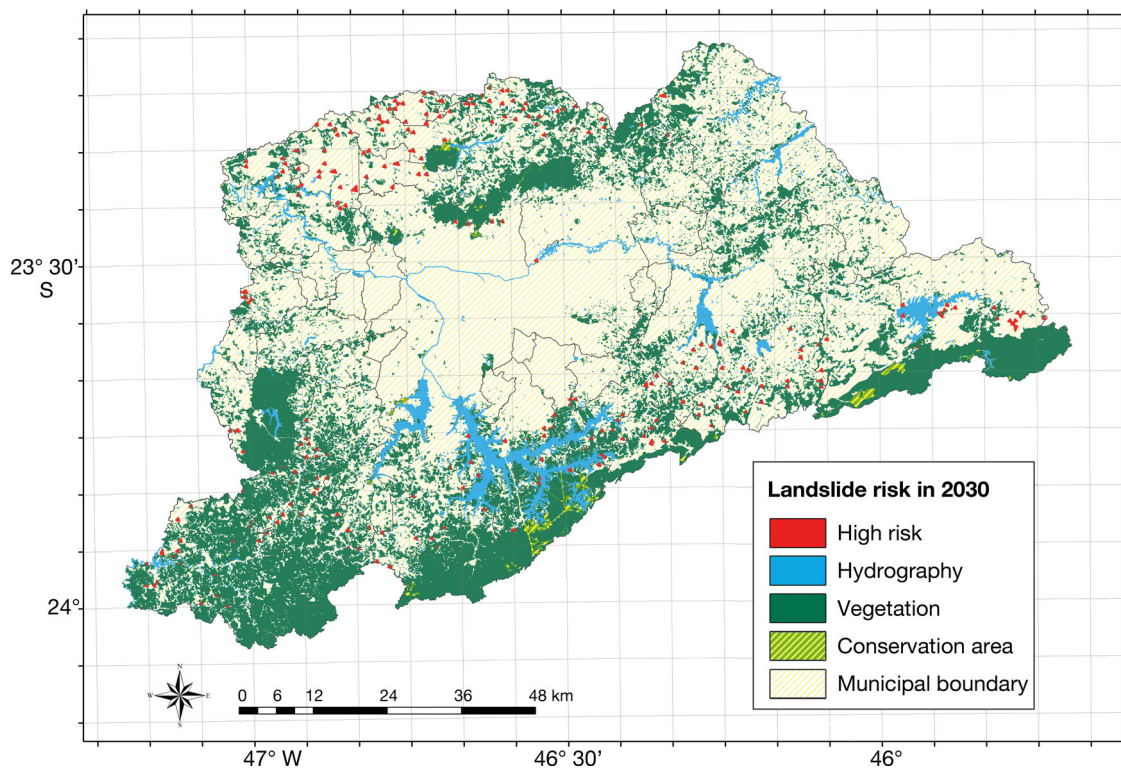


Fig. 3. Areas in São Paulo Metropolitan Area vulnerable to the risk of landslides in 2030

tion cover was removed and where there was excessive soil surface sealing. These flood plains are already under intense pressure from urban expansion, and by 2030 the phenomenon will have spread through the landscape if effective measures are not implemented to regulate the expansion process. The demand for new housing is crucial for all social classes, and may not be and/or should not be restricted by the housing market.

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