Land Use Change and Hazard Exposure in Bogotá, Colombia

MASTER THESIS

For the fulfilment of the requirements for the Degree of Master of Science in - Environmental Science. Soil, Water & Biodiversity

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Declaration of Authorship

I, Laura Catalina Quintero Uribe, declare that this thesis titled, "Land Use Change and Hazard Exposure in Bogotá- Colombia" and the work presented in it are my own. I confirm that:

• This work was done wholly or mainly while in candidature for a research degree at this University.

• Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated.

• Where I have consulted the published work of others, this is always clearly attributed.

• Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.

• I have acknowledged all main sources of help.

• Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself.

Signed:

Date:

List of Abbreviations

UNDRR United Nations Office for Disaster Risk Reduction

SDP Secretaría Distrital de Planeación - Ministry of city Planning

POT Plan de Ordenamiento Territorial- Territorial Organization Plan

PD Development Plan

LUC Land Use Change

IDIGER District Institute for risk management and climate change

GFDRR Global Facility for Disaster Reduction and Recovery

Dyna-CLUE Dynamic conversion of land use and its effects model

DRR Disaster Risk Reduction

DRM Disaster Risk Management

CLUE Conversion of Land Use and its Effects

CEPAL Comisión Económica para América Latina y el Caribe

Abstract

Rapid and unplanned growth of urban centers leads to a higher number of elements at risk to natural hazards. There is high consensus that urban planning is an effective tool to reduce these risks by managing possible land use change patterns. However, in order to successfully implement land use planning practices, it is necessary to understand the spatio temporal patterns of land use change. This can be done by evaluating future scenarios of land use change and their driving factors. The analysis of the different scenarios generated by these models can help implement more effective land use policies considering disaster risk management. The City of Bogotá is the political, cultural and economic center of Colombia. The rapid growth and the densification of the urban areas, both a result of demographic change and institutional instability, led to complex and highly various scenarios of land use change. Hence, the implementation of Disaster Risk Management policies and Sustainable Land Use Plans has been challenging. The aim of this thesis is to assess such spatio-temporal land-use dynamics in Bogotá. Using the Dyna- CLUE model together with information of landslides hazards, potential driving factors of change were identified and evaluated. For Bogotá the main drivers of change were associated to the development of transport infrastructure and the spatial distribution of the socio-economical strata. These factors reflect the strong influence that the socio-economic dynamics have on urban planning in Bogotá, as these dynamics define the land use conversion patterns. Also, It was shown that the implementation of the Dyna CLUE model might have limitations in larger cities such as Bogotá, as a consequence of having to deal with very heterogeneous information and should therefore be further explored. Finally, for this thesis it was observed a direct link on land use change and the increase of exposure to landslides, were the expanding ´Bulls-eyes effect` was observed.

Zusammenfassung

Das rasche und ungeplante Wachstum städtischer Zentren führt zu einer höheren Anzahl von Elementen die Risikos durch Naturgefahren ausgeliefert sind. Stadtplanung ist ein wirksames Instrument, um diese Risiken durch das Management von Landnutzungsänderung(LUC) zu verringern. Es ist jedoch zunächst erforderlich, die räumlich-zeitlichen Muster des LUC zu verstehen. Dies kann durch die Bewertung zukünftiger Szenarien der LUC und ihrer treibenden Faktoren erreicht werden. Die Analyse der verschiedenen modellierten Szenarien kann dazu beitragen, effektivere LUC richtlinien unter Berücksichtigung des Katastrophenrisikomanagements zu erstellen. Die Stadt Bogotá ist das politische, kulturelle und wirtschaftliche Zentrum Kolumbiens. Das schnelle Wachstum und die Verdichtung der städtischen Gebiete, sowohl infolge des demografischen Wandels als auch der institutionellen Instabilität, führten zu komplexen und sehr unterschiedlichen Szenarien des LUC. Ziel dieser Arbeit ist es, eine solche räumlich-zeitliche Landnutzungsdynamik in Bogotá zu untersuchen. Unter Verwendung des Dyna-CLUE-Modells wurden, zusammen mit Informationen zu verschiedenen Gefahrentypen, potenzielle treibende Faktoren für Veränderungen identifiziert und bewertet. Für Bogotá waren die Haupttreiber des Wandels die Entwicklung der Verkehrsinfrastruktur und die räumliche Verteilung der sozioökonomischen Schichten. Diese Faktoren spiegeln den starken Einfluss der sozioökonomischen Dynamik auf die Stadtplanung in Bogotá wider, da diese Dynamik die LUC muster definiert. Es wurde gezeigt, dass die Implementierung des Dyna-CLUE in größeren Städten wie Bogotá aufgrund seines Umgangs mit sehr heterogenen Informationen Einschränkungen aufweisen kann und daher weiter untersucht werden sollte. Schließlich wurde für diese Arbeit ein direkter Zusammenhang zwischen LUC und der Zunahme der Exposition gegenüber Erdrutschen festgestellt, wenn der expandierende "Bulls-Eyes-Effekt" beobachtet wurde.

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1. Introduction

In the recent decades, there has been a notable increase in the frequency and magnitude of natural hazards. Despite the numerous initiatives to reduce the impact of these climatic events, the number of people and elements at risk continues to rise. As a matter of fact, in the last four decades about a million people died from natural hazard (CRED, 2015) causing an immense impact on the economy and community's structure. According to the World Bank, (2019) The economic damage of natural hazards had an increase of more than $200 billion since 1994. Nevertheless, it is important to note that risk and natural hazards are not solely a result of climatic events, but rather they are the result of both human and natural factors. Cammerer et al. (2013) states that a higher exposure to natural hazards is related to the changing dynamics of physical (housing), environmental (land management) and humans (population) assets. For example, the rapid growth and the densification of urban areas are leading to a higher concentration of elements at risk (Ashley, Strader, Rosencrants, & Krmenec, 2014; Cardona et al., 2012; Kahn, 2009).

The growth rate of the cities is outpacing the capacity of the governments to adapt and mitigate the effects of climate change. Therefore, the ongoing urbanization processes are increasing the populations exposure to natural hazards (Ashley et al., 2014; Cardona, 2004; Freeman & Ashley, 2017; IPCC, 2014). Considering that by 2050 around 70% of the world's population will live in cities (IOM, 2015; UNDRR, 2014), it is pertinent to include Disaster Risk Management (DRM) policies in the debate of developing resilient cities (King, Harwood, Cottrell, Gurtner, & Firdaus, 2016; The GFDRR, 2015; World Bank, 2012).

For this reason, the concept Disaster Risk Management (DRM), has gained attention and can be found in several sustainable development frameworks such as, UNDRR (2019). DRM promotes initiatives that strengthen resilience, such as, the SENDAI Framework for Disaster Risk reduction 2015-2020 and The New Urban Agenda, Habitat III 2017. However, in order to properly implement the initiatives within DRM, it is essential to understand the socio-economic and environmental factors that create higher risk scenarios. For instance, land use models have been implemented to access the influence of land use change on the spatio-temporal dynamics of exposure to natural hazards (Price et al., 2015; World Bank, 2012).

It is well known that exposure to climate events are heavily influenced by Land Use Change (LUC) and Spatial Planning policies (Cardona, 2004; Dadashpoor, Azizi, & Moghadasi, 2019; King et al., 2016; Price et al., 2015). In the past decades, there has been an increasing pressure on land to allocate the growing population. This is leading to the settlement of communities and businesses in high risk areas. Poor planning and unsustainable growth are one of the primary causes for the expansion of disaster risk (Cammerer et al., 2013; Chen & Huang, 2013; GFDRR, 2015; World Bank, 2012). It has been proved that one of the most effective tools to reduce exposure is through Land Use Management and effective Spatial Planning (GFDRR, 2015).The growth of urban centers gives the opportunity to build up resilient cities to natural hazards, by identifying and zoning high risk areas (Kahn, 2009; GFDRR, 2015).

Consequently, there is a rising need for spatially land use models to further understand the dynamics of future land use trajectories. Land use models provide land managers and policy makers the opportunity to identify uncertainties and possible drivers that boost disaster risk. Therefore, models that address spatio-temporal dynamics of land use have become a major tool for Land Use Management and Urban Planning (Ashley et al., 2014; Cammerer et al., 2013; Price et al., 2015; Verburg et al., 2002).

Fast growing cities like Bogotá, Colombia, represent the perfect case study to evaluate the effectiveness of land use change models to address the spatial temporal dynamics of exposure to natural hazards. The combination of the complex political systems, fast growing economy and rapid population growth makes Bogotá an ideal candidate for research on effects and impacts of different socio-economical drivers that in turn can reduce or boost the exposure to natural hazards. Colombian cities are well known for being leaders on the implementation of DRM in the national and regional development programs (World Bank, 2012, 2019). Nevertheless, the effective implementation of DRM policies is hindered by the capacity of regional public administrators to implement territorial organization plans (SDP, 2018; World Bank, 2012). Due to the fact that present land use normativity to reduce risk do not represent the current and future demands of land. For instance, in Bogotá the different land use planning processes were based on the housing market and land speculation rather than DRM and sustainable development (SDP, 2018a). As a result, land use change in Bogotá has been driven by the price of land instead of a controlled growth regulated by the regional normativity (Montoya, 2018). Therefore, it is necessary to develop better spatial planning policies that can accommodate the changing dynamics of land use but also can reduce the exposure to natural hazards.

1.1 Research objectives

The present study aimed to understand how spatial planning can reduce exposure to natural hazards through the simulation of future land use scenarios in Bogotá, Colombia. In order to accomplish such objective, the thesis is based on different scenarios that represents both the spatial and socio-economical dynamics of Bogotá by 2050, with the intent to evaluate and understand the complexity of key land use change processes that results in a higher exposure to natural hazards. As a result, this work aims to contribute to more effective land use policies with respect to Disaster Risk Management, through the evaluation of the current land use policies.

Also, for this thesis work it is intended to evaluate the possible limitations and capabilities of the land use model Dyna-CLUE to represent future land use dynamics in fast growing cities. Thus, testing the capacity of the model to simulate complex socio-political scenarios such as, the increase of informal settlements in hazard prone areas due to the exacerbated socio-economic polarization. In summary, for the elaboration of this thesis 3 hypothesis were elaborated:

- **The main driving factors of land use change in Bogotá, Colombia are distance to main transport infrastructures, distribution of socio economical strata and biophysical factors such as slope and temperature**

  In order to implement adequate policies to reduce and manage disaster risk it is necessary to identify the potential processes that influence the evolutionary trajectory of the landscape. Therefore, in this thesis through the construction of the model Dyna clue potential driving factors (social, political, environmental) will be tested and identified.

- **Land use change until 2050 has in particular a direct effect on the spatio-temporal dynamics of exposure to natural hazards.**

  A higher exposure to natural hazards is usually associated to change in the land scape. Therefore, understanding the processes that derive in land use change is crucial to formulate better policies for Disaster Risk Management. In this Thesis, 6 possible (Spatial and socio-economical) land use scenarios and 3 restriction configurations will be tested, in order to address how different land use policies can reduce the exposure to natural hazards.

- **Land use models, such as, Dyna-Clue can be used to successfully simulate the possible effects of urban planning on land use change.**

  Dyna Clue is relatively a young land use model. It is used to simulate the dynamic competition of land allocation. Up to date the model is frequently used for large areas (continental level) rather than smaller areas like cities. The goal in this thesis is to evaluate the application of this model to simulate complex scenarios in urban areas and its possible application as a tool for urban land use planning.

1.2 Thesis outline

The thesis is structured into 5 chapters. Chapter 1 provides the reader a general overview of the problem statement and the main research objectives. Followed by Chapter 2, which is a literature review of the main topics addressed in this thesis: Disaster Risk Management, Exposure to natural hazards, Land use Change and the Dyna-Clue model. This was followed by the description of the study area In Chapter 3. Also in this chapter a review on the spatial planning policies was also provided to the reader.

In Chapter 4, the methodology implemented in the research is explained. It is important to mention that the methodology will be structured as a step by step guide of how to construct the Dyna Clue Model. In Chapter 5 and 6, the data generated to build up the model was presented and discussed. Also, general outcomes, such as an analysis of the spatio-temporal dynamics of exposure to landslides were analyzed and discussed. Finally, in Chapter 7 and 8 the conclusions and outlook of the research were presented.

2. Theoretical framework/ Literature Review

Recent studies have highlighted the increase of natural hazards and their impacts to our society. From 2008 to 2017 a total of 630 catastrophes were registered. In 2018 this number of catastrophes increased almost 15% compared to 2017 (Munich Re, 2018). A result of this the number of deaths related to natural catastrophes has increased over the past two decades. It is estimated that between 2008 and 2017 a total of 60.000 people were killed from natural hazards, an increase of 70% from the period 1994-2003 (CRED, 2015; Munich Re, 2018). According to the (UNDRR, 2009), a Natural Hazard is defined as " Natural process or phenomenon that may cause loss of life, injury or other health impacts, property damage, loss of livelihoods and services, social and economic disruption or environmental damage". The occurrence of natural hazards is a combination between environmental and socio-economic factors. (Cardona et al., 2012; Smith, 2013).

The role that society plays on the impact of natural hazards its key, since it determines if an extreme event has the potential to become a natural hazards (Cardona et al., 2012; Smith, 2013). In fact, the interaction of exposure to natural hazards and human vulnerability is defined as Disaster Risk. The UNDRR, 2009, defines Disaster "A serious disruption of the functioning of a community or a society involving widespread human, material, economic or environmental losses and impacts, which exceeds the ability of the affected community or society to cope using its own resources" and Disaster Risk as the potential adverse effects of a disaster in the future. As mention above the key components for a disaster are the physical exposure and human vulnerability, both factors represent the capacity of a community to adapt and respond to Natural hazards. The rapid growth and densification of urban centers, the unequal distribution of wealth, governments with poor institutional capacity and climate changes derive in a higher risk for natural hazards to happen (Berrouet, Machado, & Villegas-Palacio, 2018; Cardona et al., 2012; Smith, 2013; Thomas, 2015; Winsemius et al., 2018). Therefore, it is necessary to implement actions that can reduce both the exposure and vulnerability of communities. The set of actions and policies that aim to reduce disaster risk are defined as Disaster Risk Management (Birkmann et al., 2013; Cardona et al., 2012; Smith, 2013; Fuchs et al., 2017; UNDRR, 2019).

2.1 Disaster risk management (DRM)

The set of initiatives, policies and strategies for Disaster Risk Reduction (DRR) are defined as Disaster Risk Management (Cardona et al., 2012; Smith, 2013; UNDRR, 2019). The UNDRR, 2009, 2019) states that DRM is the "Systematic process of using administrative directives to implement strategies and policies that improved coping capacities in order to reduce the impacts of natural hazards". The implementation of these initiatives integrates risk transfer solutions through the incorporation of measurements for prevention, mitigation and preparedness. These measures intend to manage and reduce the existing risk, the residual risk and prevent new disaster risk (Smith, 2013; UNDRR, 2019; Winsemius et al., 2018).

The DRM approach is important for building resilience in communities, as it provides tools and guidelines that facilitate the development of more effective policies that understand and addresses vulnerability and exposure. Also, DRM helps to identify the different socio, political and economic factors that result in higher risk (UNDRR, 2017, 2019). Therefore, promoting practices that limit and prevent the adverse impacts of existing and future hazards. (UNDP, 2015; UNDRR, 2017, 2019).

In particular, DRM has become an important approach for Disaster Risk Reduction (DRR) and Climate Change Adaptation (CCA) in Latin America (Benson, 2016; World Bank, 2012). As it helped to design and reinforce sustainable development policies with as special focus on capacity building, reducing vulnerability and institutional strengthening. In Fact, the Latin American Region is known for leading various initiatives to reduce risk. For example, in Colombia the elaboration of the National and Regional development plans is centered on the concept of DRM. The National Development Plan 2014-18 focus on a number of initiatives on minimizing loss of life, reducing exposure and improving post-disaster recovery and rehabilitation (GFDRR, 2019; UNDRR, 2019).

2.1.1 Risk

Understanding Risk is an important component for the effective implementation of DRM. Risk is defined by de UNDRR as the combination of the probability of an event and its negative effects. This can be expressed as the convolution of hazards and vulnerability, in specific physical vulnerability which is related to exposure (Cardona, 2004; Smith, 2013; UNDRR, 2009). According Fuchs et al. (2013) and Renn,(2008) there are 3 main components of risk: 1) the probability of occurrence or its uncertainty 2) the context where the risk will materialize and 3) the outcomes that may have an impact on humans value. The relationship of these 3 components is expressed by the following equation:

$$R_{i.j} = f\ (p_{\ si},\ \ c_{Oj}) \tag{1}$$

Risk ($R_{i.j}$) is quantified by the probability of occurrence of a hazard (P_{si}) and the associated consequences on the objects at risk (c_{Oj}). In order to quantify the consequences of risk it is necessary to take into account the elements at risk (A_{Oj}) and the extent of damage through the assessment of vulnerability ($V_{Oj.Si}$) and the probability of exposure ($P_{Oj.Si}$) to $j$elements (Fuchs & Keiler, 2008; Fuchs et al., 2013; Smith, 2013;).

$$R_{i.j} = f\ (\ p_{si}, A_{Oj}, V_{Oj.Si}, P_{Oj.Si}) \tag{2}$$

The analysis of risk and its main components remains a challenge for the scientific community, mainly because it is usually approached as a static factor. But, in fact the main components of risk are subjected to dynamics elements such as, climate change, social, political and economic factors. Therefore, in order to understand risk it is necessary to approach its spatio-temporal variability in order to enhance prevention, protection and preparedness initiatives (Fuchs et al., 2013; Renn, 2008).

According to Cardona et al., 2012 the factors of risk are: natural hazards, exposure, vulnerability, land use and territorial planning as they play an important role for risk reduction. The terms of vulnerability, exposure and land use will be addressed in the following sections.

2.1.2 Vulnerability

The popularity of the term vulnerability has increased over the past years. This is mainly because the use of this term is broad, and its intention can change according to the disciplinary context (e.g. social sciences or natural sciences). In fact, several studies recognize the challenge to integrate the different approaches that this term embark. In a more general consensus, vulnerability is "defined as the set of characteristic and circumstances of a community, system or asset that make it susceptible to the damaging effects of a hazards" (Cardona, 2004; Cardona et al., 2012; Fuchs, Kuhlicke, & Meyer, 2011; UNDRR, 2009). It is important to highlight that Vulnerability is the result of the interaction of social, economic and environmental factors. Moreover, it is a term related to the predispositions, susceptibilities, deficiencies that favor adverse effects on the community or object exposed to natural hazards (Cardona et al., 2012; Fuchs et al., 2011).

The evolution of the research on vulnerability is linked to the development of the estimation of risk. For instance, it was first studied in a more technical way, by sectioning vulnerability in the coping capacity of people or systems (internal) and the exposure to stress or perturbation (external). This approach is defined as physical vulnerability, which is related to the degree of exposure. Nowadays, this concept is not only centered on the capacities to cope with and adapt to hazardous events (physical vulnerability) but also it addresses the notion of temporality defined as global vulnerability. Here vulnerability is linked to social aspects (education level, income, social networks) but also the level of development of the communities (Cardona, 2004; Fuchs et al., 2011).

Said that, the main factors of vulnerability are: population growth, inappropriate urban development, increase in socio economic inequalities, failures in governance and environmental degradation (Cardona, 2004; Cardona et al., 2012), the factors previous mention can be summarized in 3 main categories:

- Physical fragility or exposure: susceptibility or lack of resistance of a human settlement to the damaging effects of a hazard.
- Socio economical fragility refers to the social predispositions to suffer harm due to the disadvantageous conditions of social and economic factors
- Lack of resilience: the incapacity and limitations to respond when it comes to cope with the damaging effects of a hazard.

Vulnerability is measured with the Prevalent Vulnerability Index (PVI) (equation 3). The PVI aims to measure exposure in prone areas, socioeconomic fragility and lack of social resilience with the factors mentioned above (Cardona, 2019).

$$PVI = PVI_{ES} + PVI_{SF} + PVI_{LR} \tag{3}$$

Where PVI_{ES} is the physical fragility, PVI_{SF} is de socio-economical fragility and PVI_{LR} is the lack of resilience.

According to Figure 1 in Latin America and in specific Colombia, the main determinants of vulnerability are physical fragility and exposure, such as, the rapid increase of urban population (PVI_{ES}) , failures in governance and environmental degradation (PVL_{LR}) (Cardona et al., 2012; World Bank, 2012). Colombia's urban population increased from 39% in 1950 to 73% in 2005. Adding to this, the unplanned growth of its main cities is increasing disproportionally the vulnerability of communities. Most of the cities follow a pattern of environmental degradation, poor transport infrastructure and increase in informal settlements in high risk areas (World Bank, 2012).

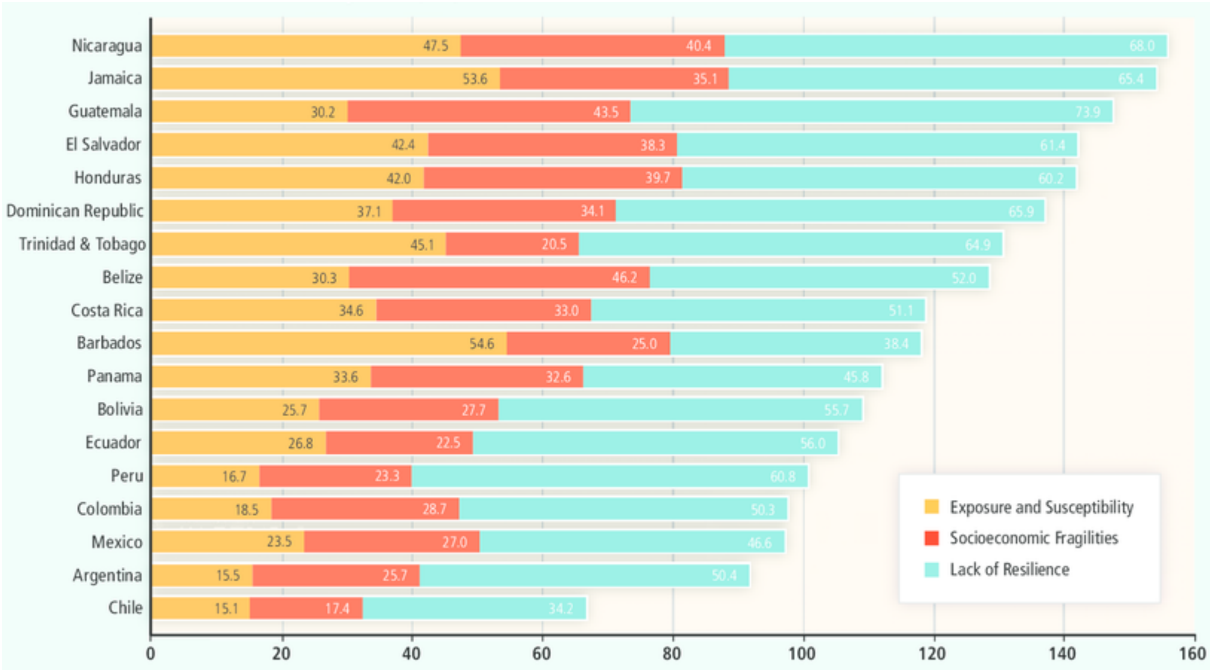


***Figure 1**. Aggregate Prevalent Vulnerability Index (PVI) for 19 countries of the Americas for 2007. Source Cardona et al., 2012.*

2.1.3 Exposure

Exposure is usually referred as the physical component of risk, it addresses the situation of people, property, infrastructure and other tangible human assets that are present in hazard zones and are prone to potential losses (Cardona et al., 2018; Pesaresi et al., 2017; UNDRR, 2009).

It is important to note that exposure is not the same as vulnerability, it is possible to be exposed but not vulnerable to a hazardous event, for example, a community that is exposed to landslides but have the capability to implement structural measures to mitigate and adapt its behavior towards building resilience. Whereas a community that is vulnerable to a natural hazard is also exposed to these extreme events (Cardona 2012, Cardona et al. 2018; Fuchs et al. 2013; Fuchs et al. 2015).

Adding to this, exposure refers to the inventory of elements and population in an area were hazards may occur in a determined time. Therefore, the location of this elements (economic and population) in potentially hazardous areas derives in a higher disaster risk. In other words, if there is not exposure to natural hazards, the disaster risk would not exist. Nevertheless, it is important note that even though the exposure is a central determinant of risk it is not sufficient. Without taking into account the vulnerability and the occurrence of the natural hazards the assessment of disaster risk cannot be conducted (Cardona 2012, Cardona et al. 2018; Fuchs et al. 2013; Fuchs et al. 2015).

As it was mention above, exposure is the combination of the location elements and population in hazardous areas. Most of the studies that address exposure quantify it as the changes over time of the population and building stock surface interested with natural hazards data (Cardona et al., 2018; Pesaresi et al., 2017; Fuchs et al., 2015). This term covers 3 main dimensions, these are:

- Physical: Built up environment such as number of houses, building codes and land use plans.
- Social: Population distribution and urban densification.
- Economic: Capital stocks, location of businesses and industry, employment density.

The combination of the physical and social dimension describe human settlements patterns shaped by dynamic socio-political-economic and ecological processes (Freeman & Ashley, 2017; Pesaresi et al., 2017). Most of the researches highlight the challenges to quantify exposure due to the "independent and dynamic dimensions of exposure and their variability across spatial and temporal scales" (Pesaresi et al., 2017). This is because of the fast and changing nature of human settlements., that are the result of demographic changes, environmental factors (land degradation, climate change), land use codes and urban planning frameworks. (Birkmann et al., 2013; Cardona et al., 2012, 2018; Pesaresi et al., 2017; Fuchs et al., 2015).

According to Pesaresi et al., 2017 in the past years the exposure of building stocks and population has double in the last 40 years. Earthquakes and Floods are the main hazards that human settlements are exposed over the past 40 years. From 1975 to 2015 the number of people exposed to earthquakes increased 1.4 to billion (+ 93%) (Figure 2.A). Likewise, the building stock exposed to earthquakes increased around 145%, from 97.000 to 238.00 Km^2 between 1975 and 2915 (Fi 2.B). For flooding's the number of people exposed double from 52 million to 1.04 billion in 40 years (Figure 3.A). Also the number of built up area increased a 180% , from 28,677 km^2 to 80,483 km^2 (Figure 3.B) (Pesaresi et al., 2017).

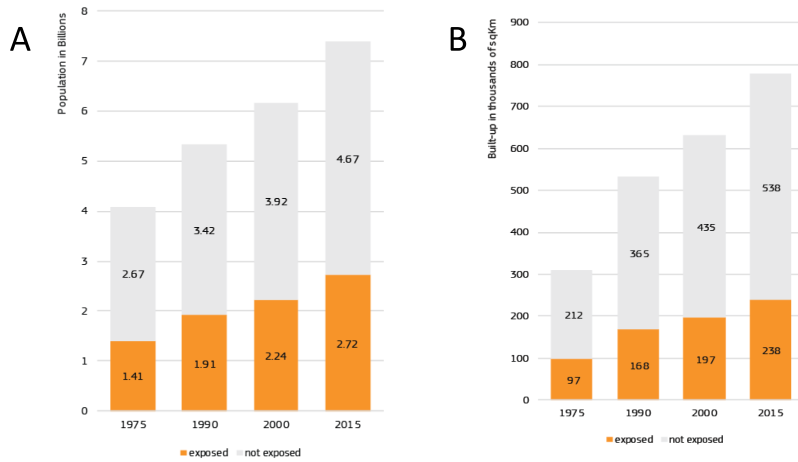


Figure 2. *Global population (A) and Built up (B) potentially exposed to seismic hazard of class from 5 to 8, 475 years RP (1975-1990-2000-2015). Source Pesaresi et al., 2017.*

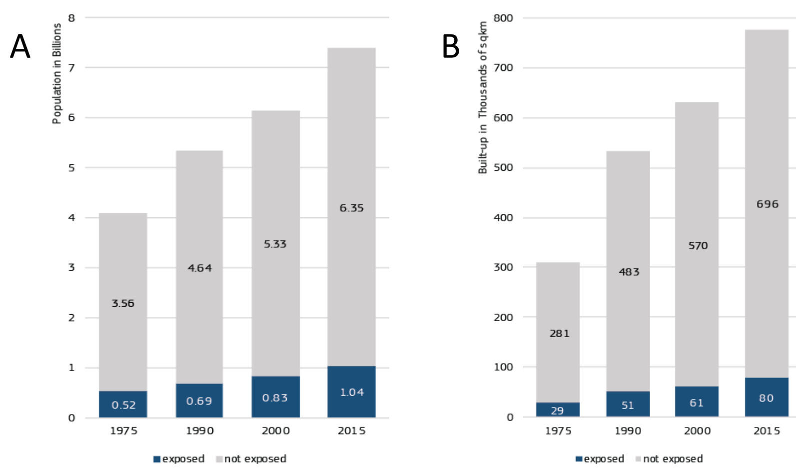


***Figure 3**. Population (A) and Built up (B) potentially exposed to flood hazard, 100 years RP (1975-1990-2000-2015). Source Pesaresi et al., 2017.*

In Colombia 84.7% of the population and 89.6% of its assets are exposed to two or more natural hazards. The exposure to natural hazards is divided between low frequency/high-impact such as earthquakes and volcanic eruptions, and high frequency/low-impact hazards such as landslides and floods (World Bank, 2012).

Among the scientific community there is a high agreement that exposure is mainly a result of development processes that did not take into account the risk of natural disasters associated to poor living conditions, inadequate management of the environmental and its natural resources, and the rapid growth of cities and the unplanned urbanization (Cardona et al., 2012)

When addressing disaster risk and therefore disaster risk management most of the studies tend to center their research on natural hazards and its projections. Due to this studies that analyze the dynamics of exposure are rare. In particular, studies that analyze the spatio temporal dynamics of exposure related to land use change (Price et al., 2015).

In the past years, the interest over the better understanding of the relation between land use change and exposure has notably increased. This is because most of the DRM initiatives are looking for effectively mitigating the underlying risk, through the implementation of non-structural measures. After the Sendai Framework for Disaster Risk Reduction 2015-2030, the reduction of exposure through land use planning and reinforcement of building codes has become a key factor for reducing risk and for building resilience (King et al., 2016; Shaw & Banba, 2017; GFDRR 2015).

The increase in population migrating to urban centers, climate change and the unplanned growth of cities is leading to a higher exposure and vulnerability to hazardous events (Chen & Huang, 2013; King et al., 2016; Shaw & Banba, 2017; GFDRR 2015). In order to implement DRM polices it is necessary to understand the spatio temporal drivers of change in land allocation. According to, King et al., 2016 there are 3 main areas where planners can reduce exposure and vulnerability, these are as following:

- Zoning: Division of the land according to preferred development and control over the new developments in hazardous areas.
- Settlement Design: Design of cities/ urban settlements through the incorporation of protective structures and the built up of resilient infrastructure to natural hazards.
- Information and Mapping: Identification and mapping of hazard prone areas for land use decisions.

These 3 main concepts share a main component which is the study of land use patterns and land us change. In the past decades, the study of land use change and land use modeling has become a crucial component for urban planning. The study of explorative scenarios allows researchers and policy makers the identification of potential processes that influence the evolutionary trajectory of the landscape (Price et al., 2015; Verburg & Overmars, 2009; Verburg et al., 2002).

Land use is defined as " the arrangements, activities and inputs people undertake in a certain land cover type to produce, change or maintain" (Di Gregorio, 2005) in other words it is the way humans use the land (Fisher, Comber, & Wadsworth, 2005). These set of arrangements or activities are subjective to drivers of change that comprise social and natural processes, the relation between these drivers and the land use is defined as Land Use Change (Price et al., 2015; Verburg et al., 2002; Verburg et al. 2004). As Verburg et al., (2004) states Land Use Change is the result of the complex interactions between the socio, political and economic factors and the physical environment.

It is important to note that these interactions are not independent, for example the effect of one driver can influence the overall effect of other drivers. Equally important, land use change patterns are not static, thus, they can change over time and according to its spatial reference. Therefore, to understand changes in the land use and its impacts it is necessary to address its complex and dynamic nature of its driving forces (Claessens et al, 2009; Verburg et al., 2002; Verburg et al., 2004).

Landscape change driving forces can be classified between proximate and underlying drivers of change. The proximate drivers refer to human actions or activities that have a direct impact in the landscape, such as the expansion of urban areas or the degradation of native forest due to agricultural expansion. On the other hand, underlying drivers of change refers to processes in the society or nature that support and nurture the proximate drivers. The underlying drivers consist of political, economic, cultural and natural factors (Plieninger et al., 2016) .

Natural driving forces can be categorized as biophysical site factors such as, slope, topography, climate, soil characteristics and natural disturbances. These factors determine the potential location of an x land use. For instance, soil characteristics and geology determine the location of new residential areas. **Political** factors are closely related to socio economic and technological factors, since the land demands are usually expressed in land use planning frameworks. Land use policies influence the spatial patter of land use change, for example, the creation of protected areas or the determination of areas for urban expansion. Finally, the **Socioeconomic** drivers gather factors that are sensitive to the global market. For example, land speculation, land price and industrialization. Socioeconomic drivers are strongly related to the potential profitability. (Bürgi, Hersperger, & Schneeberger, 2005; Plieninger et al., 2016; Verburg et al., 2004).

2.1.4 Land use change and Disaster Risk Management

There is high agreement among the scientific community that urban sprawl is the main driver of change in the past century. Over the past years, the rapid growth of cities is adding pressure on land use demand. As a result, the expansion of the urban periphery is leading to an abrupt, rapid and non-planned changes in the land use. The un-planned growth results in a higher risk and a higher exposure of people and assets to natural hazards (Cardona et al., 2018; Shaw & Banba, n.d.; Sutanta, Rajabifard, & Bishop, 2013; UNDRR, 2019).

There is high consensus that spatial planning is an effective a tool to reduce risk. Due to the fact that land use planning practices aims to influence the possible land use changes for a determined time and place (Verburg & Overmars, 2009). Taking into account this, the elaboration spatial planning frameworks for DRM, consist on the examination of possible future land use scenarios that can result in a higher or lower exposure to natural hazards. This can be done by modeling possible scenarios of land use change to understand the future land use trajectories and how they are related to the spatio-temporal dynamics of exposure to natural hazards. The elaboration of this scenarios allows the researches and policy makers to identify the main components and drivers that can effectively reduce risk and later transform this results in mitigation and adaptive measures. Adding to this, the study of the different land use trajectories gives the opportunity to identify how effective are the current land use policies for urban planning and DRM (Verburg et al., 2002; Price et al., 2015).

2.1.5 Land use modeling

As it was mention above, the assessment of land use change is essential for landscape management and land use planning (Verburg et al., 2004). Nevertheless, land use change is the result of complex interactions between socioeconomical, political and environmental factors. Addressing all possible relations between drivers of change, land use types and its outcomes can be challenging (Verburg & Overmars, 2009).

One of the principal methods used to study land use change dynamics is through modeling. The use of models helps to understand the causes and consequences of land use change through the time (Price et al., 2015; Veldkamp & Lambin, 2001; Verburg & Overmars, 2009; Verburg et al. 2006; Verburg et al., 2004, 2002). Models like dyna Clue, not only assess the change of land use patterns over time but it also allows the user to incorporate socio-political factors that might hinder or facilitate land use change and consequently a higher exposure to natural hazards (Verburg & Overmars, 2009).

Due to the fact that land use models became a common tool used by economist, land use planners and researches there is a large diversity of modeling approaches. The models can be differentiated according to the land-use change processes in the model, the simulation technique and the underlying theory. The main distinctions between the main models components can be summarized as following (Verburg et al., 2006):

- **Spatial versus Non spatial:** This is an important category since it defines the user research question. Spatial-explicit models explore spatial variation in land use change and account for variation according to the social and biophysical drivers of change. On the hand, non-spatial modelling process do not focus on the spatial distribution of the land use change processes (Veldkamp & Lambin, 2001; Verburg et al., 2006).

- **Dynamic versus Static:** Models can be differentiated according to temporal characteristics. Static models are used to test and identify possible drivers of land use change in a determined time period. The outcome of static models are the calculation of coefficients of a regression model. On the other hand, dynamic models are used to project future land use classes. Contrary to Static models, the coefficients and the regression models are used as an input to predict future land use change (Veldkamp & Lambin, 2001; Verburg et al., 2006).

- **Descriptive versus Prescriptive:** Descriptive models are based on actual land use data, they are used to test different land use scenarios based on the current land use system and drivers of change that can lead to land use change. Prescriptive models on the other hand, are based of the calculation of optimized land use configurations. Prescriptive models are useful for policy analysis as it evaluates the optimal solution to achieve the subjected policy objectives (Verburg et al., 2006).

- **Deductive versus Inductive:** The main difference between inductive and deductive models is the data that they are based on. Inductive models are constructed around the statistical correlations between land use change and its drivers of change. Whereas deductive models are based on theory that predicts land use patters. The inducive approach is the most used for land use models, as it is the most straightforward processes to deal with the complexity of the spatio temporal patterns of land use change (Verburg et al., 2006).

Due to the narrow scope of this thesis work the main focus of the research was on the spatially explicit models. The spatial-explicit models are among the most used type of models for land use planning and management. Some of the well-known models are Cellular Stomata and CLUE models (Irwin & Geoghegan, 2001). These types of models can be divided in three main categories: Simulation, Estimation and Hybrid. Simulation models for urban growth are based on probabilistic rules that determine the states of a cell based on the states of the neighboring cells. These models help to understand how complex structures can arise from the interaction of individual cells. Contrary to this, the estimation models are based on the interaction of remotely sensed data of land use change patters and the explanatory variables such as biophysical and socio-economic drivers. Opposite to simulation models, which are based on static data, the estimation models account for the spatio-temporal change of land use. Finally, the Hybrid type models are built up with both simulation and estimation data. Here the modelling process start with the estimation of remote sensed data on land use change. Then, the parameters obtained in the estimation model are added to the simulation model to predict the effect of different land use scenarios and driving factors on land use change patterns (Irwin & Geoghegan, 2001). In conclusion hybrid land use models are used to determine the complex spatio-temporal dynamics of land use change. The CLUE model family is classified as a hybrid models, as they allow the user to estimate the dynamic change of land use according to the simulated scenarios and the driving factors (Irwin & Geoghegan, 2001; Verburg et al., 2002).

2.1.6 The Clue model family and Dyna-CLUE

The name CLUE stands for the Conversion of Land Use and its Effects, this model was first developed by Veldkamp and Fresco in 1996 (Piazza, 2016). The clue model family is composed by: CLUE, CLUE-S Dyna CLUE and CLUE Scanner. The first version of the CLUE model was developed to simulate land use change the dynamic and complex relations between land use and its driving factors (Verburg et al., 2002). The initial CLUE model was developed to be tested at the national and continental level, thus only allowing large extent of spatial resolutions. For this reason, modifications to the model were applied in order to apply this model at a regional level (Verburg et al., 2002). The new model named CLUE-S (Conversion of Land Use and its Effects at a Small regional stent) was developed by Peter Verburg and collaborators in 2002. The aim of this model was to develop a model suitable the simulation of land use change trajectories and scenario analysis, were the different scenarios help to evaluate the overall effect of the driving factors of change. Nevertheless, it is pointed out that the model cannot simulate land use dynamics (Verburg et al., 2002). The latest version of the CLUE model family is the Dyna-Clue model (Dynamic conversion of land use and its effects model)

The Dyna Clue model as well as its older versions, was developed to simulate the dynamics of land use change trajectories and scenarios analysis to individual grid cells (Verburg & Overmars, 2009; Verburg et al., 2002). In the latest version of this model, demand driven changes are introduced in the modeling process. The Dyna Clue model combines 'top-down' and 'bottom-up' processes to address cross-scale interactions in land use models (Liu et al, 2013; Verburg & Overmars, 2009). Even though there is consensus that cross-scale dynamics are crucial for land use modeling, most of the models do not address this component due to the difference in scale and units of analysis. The Dyna Clue model is able to introduce this through the elaboration of demand driven changes in land area with locally determined conversion processes, giving the model the novelty of allowing large scale processes interact with local dynamics (Verburg & Overmars, 2009). In Figure 4. It can be evidenced the cross-scale dynamics between regional and local processes that determine the land use allocation. The theory behind Dyna Clue , as well as the main components and process to elaborate the land use model are explained in the section of the methodology (Chapter 4).

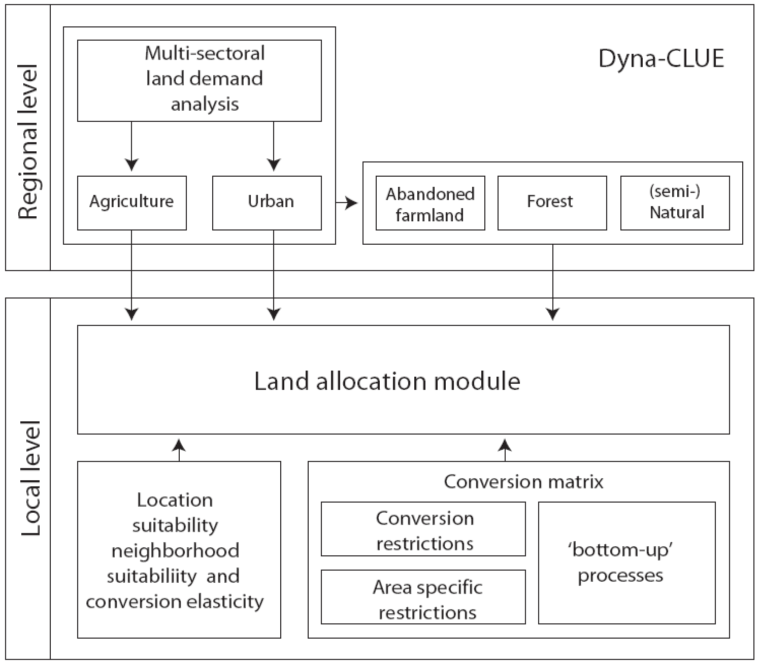


Figure 4. *Overview of the Dyna-CLUE model. Source Verburg & Overmars, 2009.*

3. Study area

Bogotá the capital city of Colombia, is located in the eastern mountain range of the Andes in the plateau named as the savannah of Bogotá with an altitudinal range from 2550 and 2660 mamsl (Figure 5). The city has an extension of 163,635 hectares of territory of which 23.2% are categorized as urban ,75% rural and 1.8% of land for urban expansion. The main land uses found in the urban area are: Residential with a 68.61%, Commerce with a 21.03%, Services with an 8.31% and industrial with 1.95%. As well the rural land use category can be subdivided in areas for natural conservation and agriculture, were the majority is allocated for conservation of natural areas with a 60% and only a 10% designated for agriculture (Angel, 2010; SDA, 2017b; SDP, 2017b).

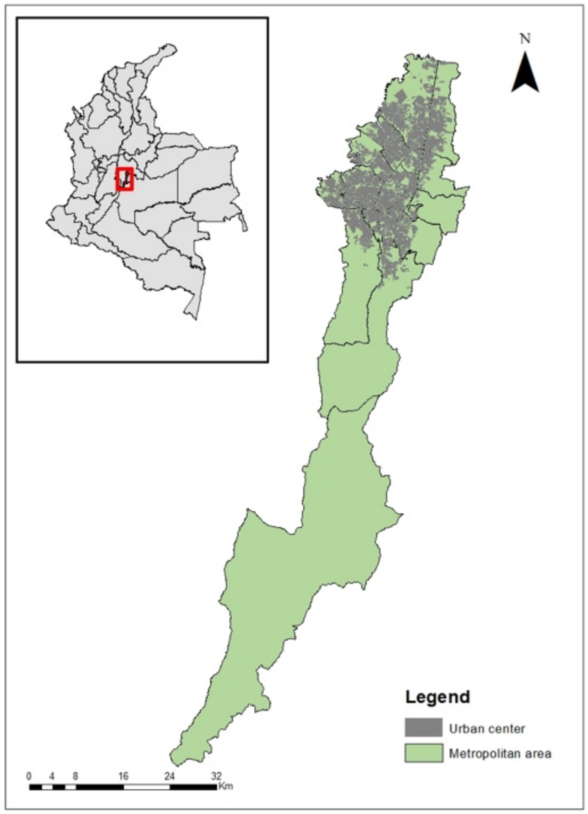


***Figure 5**. Urban perimeter of Bogotá.*

To the east the city is bordered by the Eastern Hills of the Andean mountain range, this a feature has a strong influence on both the landscape of the city and the climate. Bogotá has a mountain climate with a low oscillation of the temperature through the year: The average temperature is 14.8 ($\pm$3) ºC and an average precipitation of 862 mm^2 per year, but depending on the season (rain or drought) it can change between 550 mm^2 and 1300 mm^2. Nevertheless, its high altitude and the influence of the Eastern Hills the relative humidity is relatively low with a year average of 77.5% (Angel, 2010).

Bogotá is divided in 20 zones or districts. The current administrative structure of the city is the result of the adhesion of 6 neighboring municipalities in 1954. This was denominated as the first time that Bogotá "experienced the first institutional process of absorption of neighboring municipalities"(Guzman, Oviedo, & Bocarejo, 2017). The adhesion of these new 6 municipalities gave birth to what is called nowadays as the Capital District of Bogotá (Bogotá D.C.). In order to cope with the rapid demographic growth and the increasing pressure on land, the city opted for a decentralized administrative structure. As a result, 20 independent administrative districts were created for the regulation and implementation of the land use plans (Guzman et al., 2017; Montoya, 2018).

It is important to mention that this thesis work only focused on one district of the city. This was done to test how effective the Dyna Clue model can recreate the spatio-temporal dynamics of land use change. The reason behind the decision is based on the quality of the maps given by the Ministry of city Planning (Secretaria Distrital de Planeación (SDP)). Most of the maps that contained information about the land use of the city were saved in a high spatial resolution. Considering that the lowest resolution that Dyna CLUE can take is 13x13 pixels it was necessary to reduce the quality of the base map. Nevertheless, while doing this process it was evident the loss of valuable data of land use. For this reason, one district was chosen to test the implementation of this model at relatively high spatial resolutions 25x25 meters and 100x100 meters.

Said that the study area for this thesis is the district: Usaquén located at the northeast of Bogotá. This district was one of the 6 municipalities added in 1954 under the decree 3640 for the expansion of the urban perimeter of the city (Guzman et al., 2017; Montoya, 2018). Because it is a relatively young district, were a lot of new areas are being constructed made this district a perfect sample area for this thesis. The district has an area of 6.520 Ha, representing only the 3,98% of the total area of Bogotá. The urban area represents the 51.6% of the total area with an average of 3360 Ha, then it is followed by the rural area with 2869 Ha, 44% and 289 Ha of land for urban expansion, a 4.4 % the total area of the district. The urban area is divided in 5 main land use classes: Residential (51%), Industrial (0.6%), Institutional (26%), Commerce (7.2%) and Others (15.6%) (Figure 6.) (SDP 2017c).

As it can be seen in Figure 6, the predominant land use classes in Usaquén are the Residential and institutional. In fact, this district has the largest area assigned for institutional purposes (SDP, 2017a, 2017b).

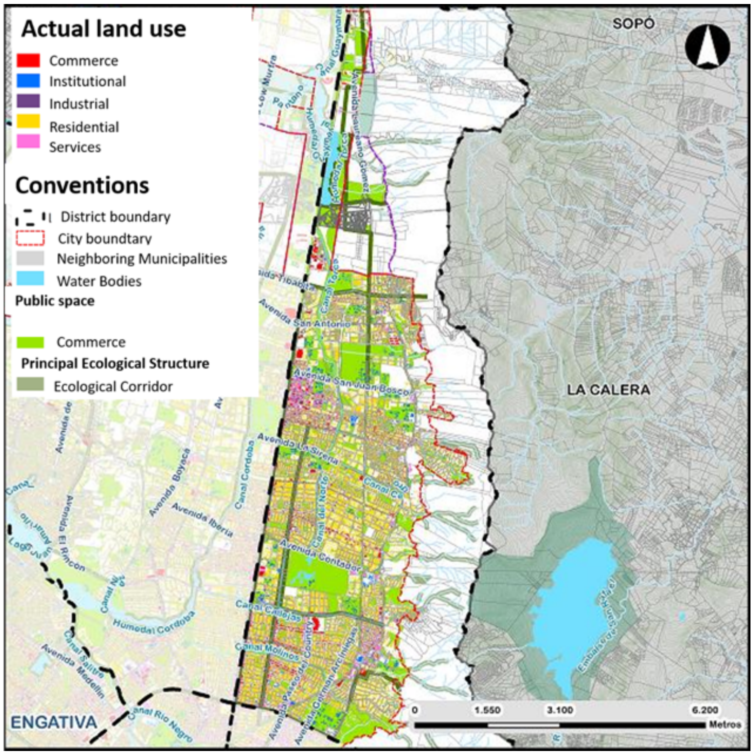


***Figure 6**. Land use classes for the District of Usaquén in 2016. Map adapted from SDP, 2017b.*

3.1 Population

According to the latest report of the Territorial Organization Plan (POT), Bogotá has a population of 7.980.000 inhabitants with an annual increase of 103.626 inhabitants between 2005-2016. Even though the population in the city keeps growing, the annual growth rate has decreased from 2.58% (1993-2005 period) to 1.55% between 2005 and 2016. It is projected that by 2030 the population of Bogotá will be 9'362.122 and by 2050 it will reach 11'048.721 inhabitants with an overall increase of 38% (SDP, 2017). According to Montoya, (2018) the population growth in the city is experiencing a small but gradual demographic contraction. This contraction is associated to two factors, first the reduction of migration from the rural areas to the city and second the expulsion of the poor population to the periphery of the city and to neighboring municipalities. Contrary to the growth rate of Bogotá , the neighboring municipalities are experiencing a rapid increase on its population (Montoya, 2018; Rincón et al., 2009; SDP, 2017, 2018).

For the District of Usaquén it is observed a strong decrease of the annual growth rate from 0.98% in 2004 to 0.27% in 2017. As a matter of fact, the decrease on the annual growth rate in Usaquén is 3 times higher than the one observed for Bogotá (SDP, 2017a).

Regarding the demand for housing, the city has been registering a progressive decrease in the amount of people per household. For instance, in 2005 the number of people per household was 3.49, this number decreased to 3.13 people per household in 2016. Accordingly, the percentage of increase on the number of homes has slightly decreased over the past 10 years. Nevertheless, the demand for new houses is still significant, thus being a main driver of land use change and expansion of the urban periphery (SDP, 2017). In Usaquén the number of people per household has also decreased over the past years, it went from 3.16 people per household in 2005 to 2.63 in 2006. Due to the fact that there are less people living per household there is a moderate increase on the housing demand for Usaquén. Consequently, there was an increase of 33% on the number of households registered from 2005 to 2016 (SDP, 2017, 2017b).

3.2 Socio-economic factors

In 1994 the socio-economic strata classification system was stablished. The idea behind this classification was to asses which part of the population needs subsidies the most. Nowadays this classification system is also used for the planification and execution of different development plans that aim poverty alleviation. This system gives the households a number from 1 to 6 based on the average income and the housing condition of the people. The number 1 is assigned to households in conditions of poverty and 6 for the richest (DANE, n.d.; SDP, 2017a).

In the latest assessment of the POT the predominant strata for the city are the low and medium classes were class 3 and 4 sums up 46.5 % for Bogotá and 36.9% for Usaquén. Opposite to this, the social strata 1 and 6 only accounted for less than a quarter of the total city area, were the poorest and the richest occupied 9.8% and 7.52% respectively (SDP, 2017b). In Figure 7 it is possible the evidence the socio spatial segregation in Bogotá, where the majority poor households can be found in the periphery of the city, whereas medium and high-income households can be found closer to the city center and areas with high economic activity. This is the result of the complex dynamics of migration towards the city between the 1990s and the 2000 (Montoya, 2018).

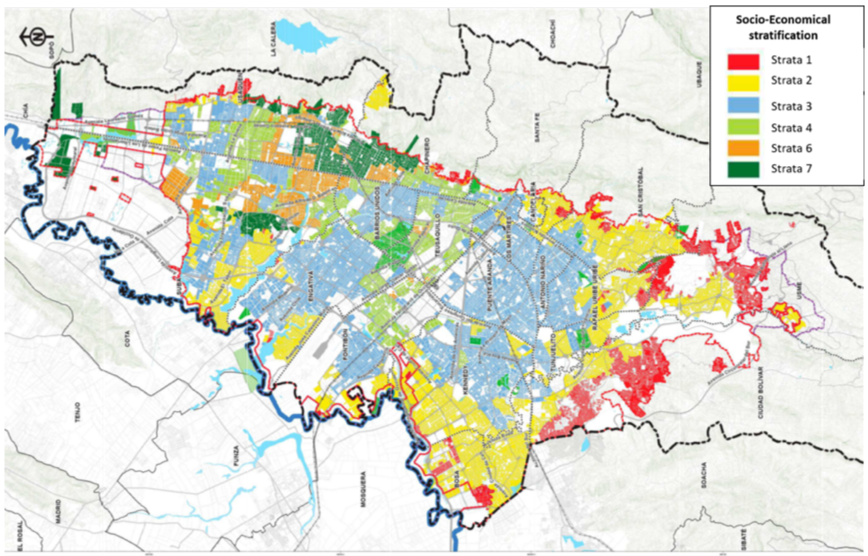


Figure 7. *Distribution of the different socio-economical strata in 2016, Bogotá. Map adapted from SDP, 2017b.*

Due to the intensification of the armed conflict in Colombia, the number of people forced to migrate to the capital city increased significantly. Between 1997 and 2009, it is estimated that around 268.368 people migrated to the city to scape violence and poverty. The fast flow of people towards the city added pressure to the demand of housing, overpassing the capabilities of the local government to cope with this new demand of land. This led to the uncontrolled and unplanned growth of informal houses around the periphery of the city were the land was cheap (Carmargo & Hurtado, 2013; Contreras, 2005; Montoya, 2018; Yunda & Sletto, 2017).

During this period of time the urban growth of the city was strongly linked to the so called "urbanization of displacement". This type of growth was characterized by the densification of houses in protected areas or with a high a risk to natural hazard, high rates of unemployment and a high criminal rate. Up to date, the informal settlements have occupied a total of 8.056 Ha of the urban and rural soil in Bogotá. In the specific case of Usaquén, the development of informal settlements occurred in protected areas with a high recurrence of landslide leaving the population exposed to natural hazards (Montoya, 2018; SDP, 2017a, 2017b).

3.3 Growth

The growth pattern of the city since the 1970s can bear resemblance to an oil spill (Figure 8). In other words, the development of the city has followed a trend of uncontrolled growth towards the periphery of the city. As a result, the city experienced an increase of almost 3 times its size in the past 40 years (Montoya, 2018; Rincón et al., 2009; Sierra & Darío, 2010).

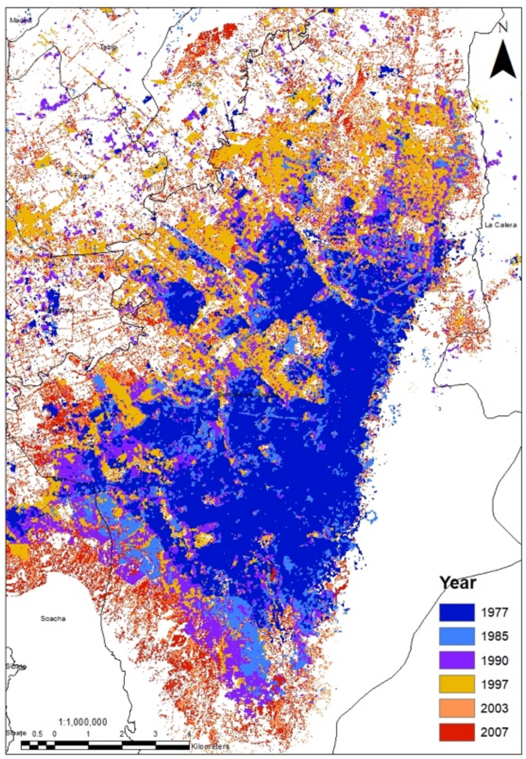


***Figure 8**. Urban growth of Bogotá (1997-2007). Map Adapted from Montoya, 2018.*

In the beginnings of 1970s when the large number of migrants gave place to the development of new residential areas in the south and the west of the city. The main drivers of urban growth at this time were the transport infrastructure and the construction of satellite cities funded by the local government. Figure 8 shows the presence of this satellite cities as blue spots to the west and south-west of the city. The development of this new residential areas fostered the urban growth towards the west of the city, giving the shape that Bogotá has nowadays. By 1977 Bogotá had increased its size 5 times compared to the 1950s, with a total area of 19.456 Ha (Annex 4) (Montoya, 2018).

The 1990s were characterized by the rapid growth towards the north and north-west of the city. This was driven by the densification and infilling of the non-occupied areas left from the urban development between the 1970s and 1980s. By the ends of the 1990s the local government stopped funding the construction of houses of social interest, which gave rise to the self-constructed houses that do not comply with the construction codes of the city (Guzman, Oviedo, & Bocarejo, 2017b; Montoya, 2018).

The city development between the period of 2003 and 2007 was characterized by the densification and consolidation of the urban areas, nevertheless the city continued its slow expansion towards the neighboring municipalities. The growth over the past 20 years was characterized by two opposite tendencies. On one hand, the metropolitan expansion, which gives rise to a dispersed urbanization and conurbation with the neighboring towns but limited by the lack of proper roads that connect the towns with peripheries of the city. On the other hand, the densification of the central city, through the urban renewal plans that seeks to reactivate the center of Bogotá as an administrative and economic axis (Montoya, 2018; Rincón et al., 2009; SDP, 2018; Sierra & Darío, 2010).

As it can be seen in Figure 8 and 9 the expansion of the city towards its neighboring towns was dispersed and non-planned (SDP, 2018). As a result, the urban growth of the capital city boosted the transformation of rural areas to urban settlements. The expansion of the urban periphery in the first decade of the 21st century, was driven by the relocation of industries and the construction of informal and formal housing in areas that were classified as rural soils (Figure 9) (Montoya, 2018; Rincón et al., 2009; SDP, 2017c, SDP, 2018). Opposite to this, the different regulations for the densification of the city boosted the constructions of business centers, malls and large condominiums in so called gated communities. Therefore, the different policies allowed the mixed use of the land (Residential, commercial and services) giving rise to the large heterogeneity of land use that Bogotá presents nowadays (Figure 9). Also, the renovation of the city center pushed the relocation of low-income families to high risk areas near the periphery of the city (Figure 8) (Montoya, 2018; SDP, 2018).

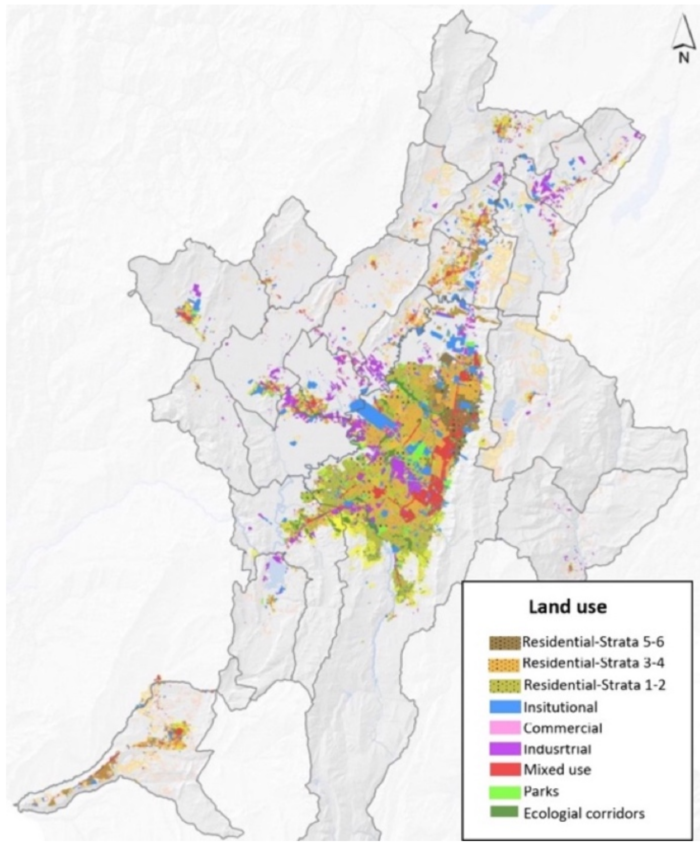


Figure 9. *Predominant land use classes for the Metropolitan Region of Bogotá. Source SDP, 2018*

To summarize, the area of the city increased almost 16% since 1977 (Table 1). Nevertheless, the growth rate of the city was not as high as it was between the 1977 and 1987, due to the migration of the population to the neighboring municipalities (Montoya, 2018; SDP, 2018). As a result, the city is showing a tendency of conurbation with 20 neighboring municipalities, were the growth rate of the population in the municipalities is almost 5 times higher in 2017 than in 1997. The expansion of the urban area to the neighboring cities is characterized by the occupation of the territory in an inefficient way, with the construction of low-density housing developments, were the density of decreased 35% between 1977-2017 (Table 1) (Rincón et al., 2009; SDP, 2018).

***Table 1**. Development of the population, density and area of the Metropolitan Region of Bogotá, composed by the Bogotá as the urban center, 20 Neighboring Municipalities.*

	1977			2017		
	Bogotá	**20Municipalities**	**Region**	**Bogotá**	**20Municipalities**	**Region**
Area (Ha)	31.334	6.530	37864	36.143	27.309	63.451
Population	5.956.995	722.052	6.679.047	7.980.001	1.969.893	9.949.894
Density (pop/Ha)	190	111	176	221	72	157

There is high agreement that the main drivers of LUC in Bogotá are the transport infrastructure, cost of the soil, house demand and the POT as it sets the normativity's of LUC (Alfonso, 2012; Bocarejo, Portilla, & Pérez, 2013; Montoya, 2018; Rincón et al., 2009; SDP, 2015, 2016a; Sierra & Darío, 2010). For example, in Figure 9 it can be seen that the expansion of the city to the north is linked to the presence of highways. It was demonstrated that the connectivity with the periphery of the city is a main factor that determines the selection of suitable land to be built (Bocarejo et al., 2013; Montoya, 2018; Rincón et al., 2009). Also, because the cost of living in Bogotá and the cost of land has increased significantly in recent years, has forced poor classes to migrate to the peripheries of the city where the price of land is cheaper. Also, the high cost of land has led to the increase of informal housing in the eastern hills where there is a high risk landslides (Montoya, 2018; Ramos C, Trujillo-Vela, & Prada S, 2015; Rincón et al., 2009; Salcedo, 2008; SDP, 2018; Yunda & Sletto, 2017).

3.4 Natural hazards, Risk and Disaster risk management

Due to its geographic location Bogotá is exposed to several natural disasters, such as floods, landslides, earthquakes and fires. Landslides correspond to the third most common natural hazard, the steep hills and the high precipitation during 'La Niña' makes the city a good candidate to a higher probability of occurrence of this event (IDIGER, Instituto Distrital de Gestión de Riesgos y Cambio Climático (IDIGER), 2016; Mergili, Marchant Santiago, & Moreiras, 2015; Ramos C et al., 2015). However, due to the city's unplanned growth and climate change, it is expected that the city will be more exposed and, therefore, facing a greater risk to climatic events. For Bogotá it is projected an increase in rainfall between 10% and 20% between 2011 and 2070. Therefore, it is expected that in the following years the number of people exposed to floods and landslides will increase (SDA, 2017; Yamin et al., 2013). According to the Plan for Disaster Risk Management and Climate Change 2015-2050, Bogotá is a city with a high vulnerability to the effects of Climate Change, where the most recurrent events will be floods and landslides. (SDA 2017b).

Since this study was based on the town of Usaquén, where the predominant risk is landslides, the next section will only refer to this natural hazard. In 2017, a total of 11.017 Ha (30%) of the urban area of Bogotá was located in areas of risk to landslides with approximately 3´550.693 people exposed to this natural hazard (Figure 10). Within this percentage of exposed areas, 16.8% are categorized as high risk, 52.6% medium risk and 30.6% as low risk to landslides (SDP, 2017b). For Usaquén a total of 1.329 Ha area is exposed to landslides, where 8% is classified as high risk, 49% medium risk and 43% low risk to landslides (SDA, 2017b).

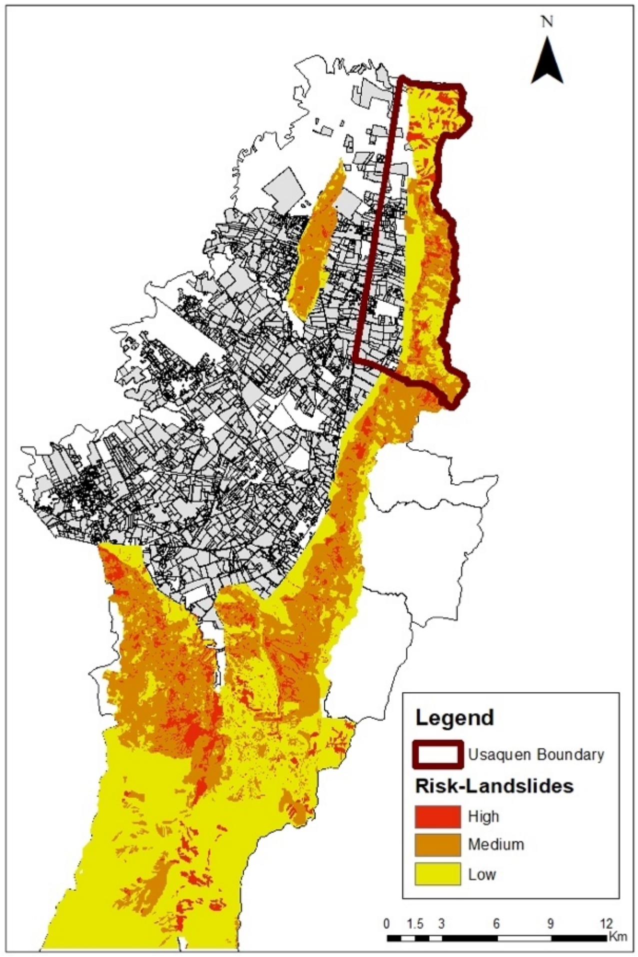


Figure 10. *Landslide Risk in for Bogotá and the district of Usaquén in 2017. Map based on data provided by the SDP, 2018.*

For Bogotá, most of the events were recorded in areas with steep slopes, such as the district of Usaquén. Likewise, these events were influenced by the construction of informal settlements in areas previously dedicated to mining extraction and in protected areas near creeks. Also, the increase in risk is directly influenced by the intensification of the "La Niña", where the increase in rainfall leads to landslides. For example, between 2010 and 2011 the notorious increase of landslides where associated with extreme events of "La Niña" (Ramos , Trujillo & Prada , 2015; SDA, 2017b).

3.5 Land use Scenarios 2050

For this thesis, a total of six scenarios were selected to evaluate the effect of land use change on the exposure to natural hazards. In order to understand the possible spatial and socio-economic changes, three scenarios assess the effect of land use planning regulations on LUC (spatial planning scenarios)(SDP, 2018) and the remaining three represent the effect of transport infrastructure development on possible socio-economic drivers and hence on LUC (socio-economic scenarios) (Guzman, Peña, & Cardona, 2018).

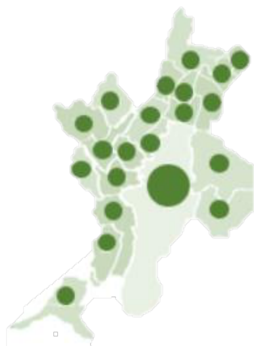
3.5.1 Spatial Planning Scenarios:

In order to promote the organized expansion and planned densification of the city. The Ministry of city Planning (SDP) prepared 3 scenarios that consider possible growth patterns of the city according to the implementation of land use plans at the district and municipal levels (SDP, 2018). The scenarios are as following:

Tendential or business as casual: Is based on what would be the growth of the city if it keeps its current trend of expansion. This model is characterized by having 4 major trends:

- Deregulation of the land market.
- Urban growth conditioned by the infrastructure of mobility.
- Population migration towards the neighboring municipalities
- The infrastructure of institutional land use as a basic need for location of the population

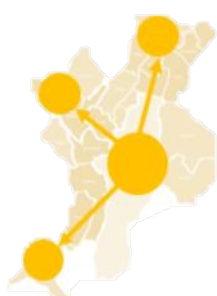
***Figure 11**. Tendential Scenario based on SDP,2018.*



Municipal: It is centered on the projections of urban growth of the Municipalities POT. This model aims to stop the migration of the population from Bogotá to the neighboring municipalities, as well to control the growth in the protected areas. The model is based on 4 criteria

- Strengthening of the local normativity
- Densification of the city center of Bogotá
- Prohibition of occupations on Ecological Structure.
- The restriction of migration patterns towards the municipalities

Figure 12. *Municipal Scenario based on SDP, 2018.*



Regional: Based on the actual conurbation with the neighboring municipalities, this scenario aims for the planned expansion of the city. With this a minimum regional consensus is needed for consolidation of the metropolitan region of Bogotá with the establishment of a POT at a regional level. This scenario allows the expansion but also fosters the densification of the urban centers. Its main characteristics are:

- Minimun Regional Consensus- Regional POT
- Public transport at the regional level
- Provision of a network of regional public services.
- Incorporation of the protected areas into the POT

Figure 13. *Regional Scenario based on SDP, 2018.*

3.5.2 Socio-economic scenarios:

Transport infrastructure is one of the main drivers of LUC. For example, the access to public transport leads higher densification of residential areas, as well, it has a strong influence on land value. Therefore, it is necessary to consider the possible implications that the development of transport infrastructure can bring. The following scenarios were based on the study done by Guzman et al., (2018)for the SDP, it is important to note that in the original studio there were 8 scenarios, but for practical purposes only 3 scenarios where selected for the construction of the Dyna-CLUE model. The scenarios are the following:

<u>Tendential/ Business as casual:</u> The transport infrastructure remains the same, there is no expansion of the city towards the neighboring municipalities. The main characteristics are:

- Strict use of agricultural soils for house construction
- Perimeter of the city remains the same

Figure 14. *Tendential socio-economic scenario based on Guzman et al., 2018.*

<u>50% Development:</u> As its name describes it, in this scenario 50% of the projects for the development of the transport infrastructure were completed, like the metro Bogotá. It is characterized by:

- Improved connectivity with the neighboring towns
- Expansion of the city is allowed, but with limitations in some areas for agriculture

Figure 15. *50% development of transport infrastructure. Socio-economic scenario based on Guzman et al., 2018.*

<u>100% Development:</u> It represents the best-case scenario were all infrastructure projects get completed by 2050. This scenario includes the improvement of the public transport and the construction of highways that connect the neighboring Municipalities. It is characterized by:

- Improved connectivity with the neighboring towns
- Expansion of the city allowed
- Construction of houses, industry or malls in rural soils is allowed

Figure 16*.* *100 % development of transport infrastructure. Socio-economic scenario based on Guzman et al., 2018.*

4. Methodology

In order to evaluate the effect of complex spatio-temporal dynamics of land use change on the exposure to natural hazards, a model was elaborated following the guidelines from Verburg et al., (2002).

4.1 The Dyna-CLUE

As described above, the Dyna-CLUE model is a hybrid model built up with simulated and estimated data. The estimate data is composed by GIS parameters and a logistic regression equations to assess the effect of drivers on LUC (Liu et al., 2013; Verburg et al., 2002). Then, the results obtained in the estimation model were added to the simulation model taking into account different spatio temporal scales, such as future land use demand and elasticity for conversion. The Model is sub-divided into two modules: Non-spatial demand and spatially-explicit allocation exposure (Verburg et al., 2002):

- **Non-spatial demand module:** it consists of land use trends, land use conversion settings (conversions elasticities), land use transition sequences and land use scenarios. This module calculates the area of change for all land use classes. For this thesis, the information of land use scenarios was taken from the land use modelling studies done by the SDP (2018).

- **The spatially-explicit model:** it was made from the location characteristics defined by a set of driving factors of change. These driving factors determines the location suitability to change according to the land use demands. In this module the non-spatial demands were translated into LUC.

After preparing all the inputs for the model, it calculates the most likely changes in land use based on the determination of all grid cells are allowed to change (Verburg et al., 2002). For each grid cell the probability of change was calculated according to the following formula (Verburg & Overmars, 2009):

$$Ptot_{i.tlu} = Ploc_{i.t.lu} + Pnbh_{i.t.lu} + Elas_{i.u} + Comp_{t.lu} \qquad (3)$$

The final allocation of land use defined as the total probability of change ($Ptot_{i.tlu}$) was calculated at a specific time (t) for each location (i) and land use class (lu). The total probability was the sum of the location suitability ($Ploc_{i.t.lu}$), neighborhood suitability ($Pnbh_{i.t.lu}$), conversion elasticity ($Elas_{i.u}$) and competitive advantage ($Comp_{t.lu}$).

The location suitability ($Ploc_{i.t.lu}$), was determined by the construction of a conversion matrix that indicates which conversion were or were not allowed for each land use class. The conversion matrix is governed by bottom up processes such as, spatial restrictions and current location characteristics. The neighborhood suitability ($Pnbh_{i.t.lu}$), was represented by the dynamic analysis for neighborhood interactions which aims to incorporate positive spatial correlations. Nevertheless, when the specific location requirements are unknown, a uniform suitability is assigned (No neighborhood interactions considered). The conversion elasticity ($Elas_{i.u}$) was related to the cost of conversion of one land use type in a specific time and space to another land use type. Finally, The competitive advantage ($Comp_{t.lu}$). was determined by the land use demand and the current land use patterns (Verburg & Overmars, 2009).

The final land use allocation was based on the combination of spatial analysis, empirical data and dynamic simulation. For this the information was subdivided in 4 main categories: Location Characteristics, Spatial policies and restrictions, Land use type conversion settings and land use requirements.

4.2 Collection and preparation of the data

All maps and data used to build the model were provided by the Ministry of city Planning (SDP, 2018), the Ministry of Environment (SDA, 2017a), District Institute for risk management and climate change (IDIGER, 2018) and the Cadaster Database of Bogotá (IDECA, 2018).

It is important to note that the maps used to build up the spatially explicit model comes from different institutions; therefore, it was necessary to convert all spatial data to a similar projection. Adding to this, the maps provided by the SDP, (2018) that contained information about the land use from 2009-2017 were not in the right format to be added to the model (e.g. high resolution and no data cells). Therefore, it was necessary to transform the data in order to be entered into the Dyna Clue Model. The subsequent steps to achieve this were the following.

1. Convert all spatial to similar projection: In ArcGIS go to Arctoolbox > Data management tools > Projections and Transformations > Project. The XY coordinate system selected was PCS_CarMaGBOG.
2. Due to the fact that the district "Usaquén" was selected for this study it was necessary to cut out the land use and drivers maps to the boundary of this district. First, create a layer that contains the shape of Usaquén. Then, use this shape to cut the maps with ArcGIS go to Arctoolbox > Analysis tools > Extract > Clip.
3. The data from the land use maps from the SDP did not have information about streets parks, natural areas and rural soils, it was necessary to merge the maps generated by the SDA that contain this information. In ArcGIS go to > Data management > general > merge.
4. Prepare a 'mask' that contains value 1 inside the study area and 'NoData' outside. Go to create new shapefile and save is as shape, right click on the new shapefile, go to edit mode > Start editing > create feature > choose rectangle > draw rectangle on top of the Usaquén shape file > save and Stop editing. Then go to Erase Arctoolbox > analysistools > overlay > Erase. Save this file as Usaquén mask.
5. Multiply all layers with the mask.

4.3 Current land use:

It is necessary to define the current land use patterns in order to create the base scenario for the model. To do this it is important to define the land use types that will be evaluated in the land use change model. For this case study, a total of 7 land use classes were derived from the original land use map from 2009 provided by the SDP (2018) (Table 2). To obtain 7 land use classes, it was necessary to merge the following classes: industrial and mining into industrial land use class; services and institutional into institutional; residential and neighborhood parks into residential; Greenhouses, agricultural land and forestry intro rural; native forest (Table 2).

Once the land use classes were defined, it is necessary to change into a nomenclature of 0 to 6, and no data as "-9999". The code for each land use class was summarized in Table 2. This can be done with the help of ArcGIS, go to Arc toolbox> Spatial analyst tools > reclass > reclassify. Then it is important to define the resolution to 100x100 with the tool resample: ArcGIS, go to Arc toolbox> data management tools > raster processing > raster > resample. This method was repeated for all land use maps from 2009-2017.

After the classification was completed, the base map of 2009 was further transformed to obtain each land use class separately. The latter will be used for the statistical analysis. To generate these maps the procedure was the following: Arc toolbox> Spatial analyst tools > reclass > reclassify. For the cells that contain the information of land use class x reclassify it to 1 and for the rest 0, keep no data as -9999. For example, for the land use class 0 (Residential) the value is changed to 1 and the remaining land use classes were reclassified to 0. This process was repeated to all 6 land use classes. Finally, following the suggestions of the user manual from Verburg et al., (2002) the files were saved as: cov_all.0 for all land use classes and cov1_x.0 where x is the land use class code.

Table 2*.Coding and Definition of the land use classes used for the Dyna CLUE model. The Original Land use classification was taken from the data provided by SDP, 2018.*

Code	Land use Class	Original Classification	Filename
0	Residential	Housing	Cov1_0.0
0	Residential	Residential parks	Cov1_0.0
1	Institutional	Institutional (e.g. Schools)	Cov1_1.0
1	Institutional	Services	Cov1_1.0

2	Industry	Industry	Cov1_2.0
2	Industry	Mining	Cov1_2.0
3	Commerce	Commerce	Cov1_3.0
4	Rural	Agricultural Land	Cov1_4.0
4	Rural	Forestry	Cov1_4.0
4	Rural	Green Houses	Cov1_4.0
5	Native Forest	Native Forest	Cov1_5.0
6	Others	Others	Cov1_6.0

4.4 Driving factors

Land use change is the result of complex processes that interact in a specific time and space. The variables that have a strong influence on LUC are called driving forces of change. These forces or driving factors can be divided into: Demographic (population), Economic (economic growth), Accessibility (distance to street), biophysical (slope, altitude), cultural and political factors. In order to avoid spatial correlations, the determination of possible driving factors was based on expert knowledge and theoretical background on its effects on land use change (Verburg et al., 2002, 2004; Verburg et al., 2004). The drivers selected for this thesis were summarized in Table3.

Table 3. *Driving factors for Land use evaluated for the Dyna-CLUE model.*

Type	Code	Name	Description	Filename
Biophysical	0	Elevation	DEM (meters)	Sc1gr0
	1	Ecological corridors	Urban ecological corridors: Ecological buffer zones	Sc1gr1
	2	Temperature	Average annual temperature between 2009-2017	Sc1gr2
	3	Riparian buffer zone	Riparian buffer zone designated for conservation	Sc1gr3
	4	Precipitation	Average annual precipitation between 2009-2017	Sc1gr4
	5	Protected area	Delimitation of areas for Conservation and Ecological Restoration	Sc1gr5
	6	Slope	Based on DEM data (Deg (0-90°)	Sc1gr6
	7	Aspect	Based on DEM data (Compass deg (0-360°)	Sc1gr7

Socio-economical	8	Development potential	Land with opportunity to be further developed into residential or commercial areas	Sc1gr8
	9	Temporal use of soil	areas which use is to be defined	Sc1gr9
	10	Social stratification	Social stratification from 1-6. 1 the poorest and 6 the richest	Sc1gr10
	11	Building codes	Building normativity	Sc1gr11
	12	Height of Buildings	Height of buildings	Sc1gr12
	13	Land use designation	definition of urban, rural and protected areas	Sc1gr13
	14	Density per Ha	Density (pop/Ha) for each zone	Sc1gr14
	15	# of businesses	No of business registered in 2017 per zone	Sc1gr15
	16	# of shops/malls	No of shop, malls and small businesses registered in 2017 per zone	Sc1gr16
Accessibility	17	Areas of Transport Infrastructure (ATI)	Projected areas for possible location of transport infrastructure	Sc1gr17
	18	Distance to main ATI	Distance to TIA (km)	Sc1gr18
	19	Distance from Highways	Distance to highways (km)	Sc1gr19
	20	Distance from Transport nodes	Distance from the main transport nodes (km)	Sc1gr20

These driving factors can either influence the location or the magnitude on which land use change can occur. Based on the relations between land use and its driving factors a suitability map was created. The suitability indicates the preference of a specific grid cell to be allocated a land use type in a specific time and space. The suitability was evaluated using a stepwise logistic regression (Verburg et al., 2002, 2004; Verburg et al., 2004).

But, before performing the statistical test it was necessary to transform the land use driver maps into same projection, cell size and extension. To do this the same procedure of section 4.2 and 4.3 were followed.

4.4.1 Statistical Analysis

First it was necessary to do a preliminary correlation analysis in order to avoid possible biases from spatial autocorrelation. To do this the method followed was suggested by Piazza, (2016) and Overmars, (2003). For this an autocorrelation analysis was run to select the driving factors that do not present spatial correlation. The final drivers were saved as ASCII files, with the names "sc1grx-fil" where x stands for the code of the driving factor (Table 3).

After this in order to evaluate the relations between land use and its driving factors it was necessary to perform a stepwise logistic regression. Taking into account that the data is to heterogeneous it was not possible to use the software provided by the Dyna-Clue model to transform raster data into tables. Instead the following process was done:

- Convert base land use map for 2009 into point features: Arctoolboxes > System toolboxes > Data Management tools > Features > Feature to point
- Merge the driving factors and the land use classes maps created in section 4.3 into the same attribute table: Arctoolboxes > System toolboxes > Data Management tools > Extraction > Extract Multi values to points.

- Export Table: Arctoolboxes > System toolboxes > Geostatistical analyst tools > Simulation > Extract values to table

The result was a table ready to be opened in SPSS (IBM Corp., 2017) to perform the statistical analysis for each and use class. Based on the assumption that land use change is expected to take place at locations with the highest preferences for a land use class x in a specific time. According to Verburg et al., (2002), preference represent the outcome of the relation between driving factors and land use. The calculation of the preference is the following (Verburg et al., 2002):

$$R_{ki} = a_k X_{1i} + b_k X_{2i} \ldots \ldots + z_k X_{ni} \qquad (4)$$

The preference (R_{ki}) to location (i) to a land use type (k) is the sum of the drivers (X_n) that have influence on the location(i) and their relative impact (Z_k) for a land use (k). Nevertheless, since the preference cannot be observed or measured directly it was necessary to calculate its probability. The relation between probable land use and its driving factors can be evaluated through a binomial logit model. Here the preferences, assumed as probability, were based of two options: convert location into land use type k or not.

The probability was evaluated through stepwise logistic regression with the following formula:

$$\log \frac{P_i}{1-P_i} = \beta_0 + \beta_1 X_{1,i} + \beta_2 X_{2,i} \ldots \ldots + \beta_n X_{n.i} \qquad (5)$$

Where:

Pi stands for the probability of a grid cell occurrence of a land use type on location i

$X_{1 \ldots n}$ are the driving factors.

β were the coefficients estimated through the logistic regression with the actual land use patter as a dependent variable.

This statistical analysis was done using the forwards stepwise selection, with a probability threshold of 0.01 and 0.02 for removal from the model (this value was suggested by Verburg et al., (2002) for large data sets). At the end the variables that did not have a significant value ($\rho \leq 0.05$), hence that did not explain the current land use pattern, were excluded from the final regression equation. This process was repeated for each land use class map and its possible driving factors of change, obtaining at the end 5 different regression equations (the land use class “others” will be considered as a static land use therefore it was not included in this analysis).

Finally, it was necessary to measure the goodness of fit of the regression model with the Relative Operating Characteristic (ROC) method. This method is the area under the curve that connect the plotted points between the predicted probabilities versus the observed values. A ROC value of 1, can be translated as a perfect fit or that the drivers describe the current land use patter in a 100%. On the other hand a value of 0.5 reflects a completely random model that does not explain the current land use patter, a good ROCfit can be considered above 0.65 or 65% (Pontius & Schneider, 2001; Verburg et al., 2002).

Finally, the results from the stepwise logistic regressions are added to the Dyna-CLUE model. These values were used by the model to determine the suitability of a location (i) to a land use type (k). In order to enter the data to the model, the files are added in the “alloc1.reg” file, with the following structure:

Line 1: Code for the land use type (k). (e.g Residential-> 0)
Line 2: constant of regression of the equation (ß0). (4.22426)
Line 3: The coefficient (ß1, ß2, etc.) of the driving factors and their code 8 (e.g -0.00248 0)

4.5 Spatial policies and scenarios

4.5.1 Restrictions policies and hazard zoning

The spatial policies or the restriction maps, indicates the areas where land use change is restricted due to policies or tenure status. The definition of the restriction policies is important since it can hinder or boost the future development of a land use class. For this thesis, the restriction maps were elaborated taking into account the normativity and land use plans defined by the POT and the Development Plan (PD) for Bogotá (SDP, 2016b; SDP, 2017b).

The development of Bogotá is based on three pillars: equality and well-being, urban democracy and community building. In particular the second pillar, urban democracy, aims to improve the living conditions of the city through land use planning. The ideal development scenario for Bogotá is the sustainable growth of the city which respects and conserves the environment, the public space and the urban growth fully complies with the normativity of land use (e.g. disaster risk reduction and urban growth zoning) (SDP, 2016b; SDP, 2017b). This premise was taken into account in order to build the different restriction maps at three different restriction levels (Table 4).

Table 4. *Criteria taken into account to define the restriction maps for Dyna-CLUE. The parameters for the land use restrictions were based on SDP, 2016b; 2017c.*

	Level of Restriction		
Parameter	**Light**	**Medium**	**High**
Environment	-Only the protected areas for native forest are taken into account. -Construction over Water bodies and rivers not allowed	-Urban development in Native forest and grasslands is not allowed. -Water bodies and rivers not allowed	-Restoration and conservation of the principal ecological structure, urban development under these areas is not allowed. -Water bodies and rivers not allowed.
Public space	There is no restriction for this category.	Parks and recreational areas are not allowed to change.	-Parks and recreational areas are not allowed to change.
Land use normativity	There is no restriction for this category.	Further development in areas with a high landslide risk is not allowed.	-Further development in areas with a high and medium landslide risk is not allowed. -The designated areas by the SDP for urban conservation and consolidation are not allowed to change.

To prepare the restrictions files for Dyna-CLUE it was necessary to transform the files to raster. Arctoolbox > Conversion Tools > To Raster > Polygon to Raster. Then the files were projected to the same coordinate system, extent and spatial resolution (section 4.2)

Then the maps were reclassified with the following code (Figure 17):

- 0: area outside the restricted area, land use change is allowed
- ´-9998': area where land use change is not allowed
- 'No Data' or -9999: all other grid cells, map mask

Finally, these maps were converted to ASCII format and named as "region_x.fil", where x stands to the restriction level applied. A total of 4 region maps were defined:

Region0.fil = No spatial policies included
Region1.fil = Light restriction map
Region2.fil = Medium restriction map
Region3.fil = High restriction map- it represents the best possible scenario

4.5.2 Spatial planning scenarios

The spatial allocation of demands for different land use types represent the top down effects of land use change. In fact, the definition of the land use demand scenarios is used to represent the different land use policies and land use projections on LUC. Additionally, these files define the magnitude of LUC, as it defines the total area to be allocated to a land use class during a determined period of time (Verburg et al., 2002).

For this thesis work a total of 7 land use scenarios were generated to model LUC in Dyna-CLUE. One scenario contains the information of the actual land use change form 2009-2017 (scenario used for the model calibration), three scenarios assess the effect of land use planning regulations on LUC (spatial planning scenarios) (SDP, 2018), and the remaining three represent the effect of transport infrastructure development on possible socio-economic drivers and hence on LUC (socio-economic scenarios) (Guzman, Peña, & Cardona, 2018) (Table 5.).

***Table 5**. Definition of the land use scenarios based on the information from Guzman, Peña, & Cardona, 2018; SDP, 2018.*

Type	Scenario	Filename
Spatial planning scenarios	Tendential	Demand.in1
	Municipal	Demand.in2
	Regional	Demand.in3
Socio-economical scenarios	Tendential	Demand.in4
	50% Development	Demand.in5
	100% development	Demand.in6
Calibration scenario	Base line scenario	Demand.in7

It is important to note that there was no information about the percentage of change for each land use class for both spatial planning and socio-economic scenarios. Therefore, the information had to be deduced from the description of the scenarios and adapted to this specific study case. The elaboration of the scenarios was as follows:

1. **Spatial planning Scenarios:** The construction of these scenarios was based on the results of the study "Huella Urbana" by the SDP in 2018. The land use scenarios to 2050 were based on projections of population growth, housing demand, increase or decrease of density and LUC in agricultural and protected areas. The percentage of change was calculated with the following formula.

$$\%\, change = \frac{(V_2 - V_1)}{|V_1|} x\ 100 \qquad (6)$$

Where V_2 is the area in Ha for 2050 and V_1 is the area in Ha for 2016.

With this method it was only possible to estimate the % of change for the residential, rural and protected areas. For the land use classes; commercial, industrial and institutional the % of change was deducted from the % of change from 2009-2012 and the actual Ha 2009. This was done is such way, so the total land area required equals the size of Usaquén.

2. **Socio Economic Scenarios:** Likewise, the spatial planning scenarios, the information taken to build up the scenarios was based on the study "" by Guzman, Peña, & Cardona, in 2018. Opposite to the land use scenarios information about LCU for the classes; residential, industrial, commercial and institution was already defined in the results of the report. The estimation of % change was done following the same process used for the Spatial Scenarios.

3. **Downscaling**: Because the values are representative for Bogotá, it was necessary to adapt this scenario for the case study area Usaquén. For this thesis the process for downscaling the data was the one suggested by Piazza, (2016) in his master thesis and by Vuuren, Smith, & Riahi, (2010). The steps were as following:

1	r	[% Bogotá]/ [% Usaquén]	Relative area (%) of a land use class for Bogotá divided by relative area for Usaquén
2	f	[% change] / r	r Downscaling factor for change to the local spatial distribution.
3	δ%_Usaquén	[% change] - f	f Adapted for the area variation in percentage 2006-2050.
4	Change (Ha)	[V1]* δ%_Usaquén	Change in Ha for 2050 for a land use class

Finally, when the determination of change in Ha from 2009 until 2050 for each demand scenario was completed, it was necessary to calculate the annual growth rate (%) in order to add the land use scenarios to Dyna-CLUE. According to Verburg et al., (2002) for the Dyna-CLUE model it is necessary to specify for each year of the simulation (2009-2050) the area for each land use class. When all values were defined , the values were selected and pasted into the text editor Notepad. Then it was necessary to insert a line with the number of years of the simulation (41 years) so the program can read the file during the simulation. The files were saved with the name "Demand.inx" where x is the code for the demand scenario (the final scenarios can be found in Annex 1).

4.6 Matrix, elasticities and main settings

The land use specific conversion settings can be defined by the conversion elasticities and the conversion matrix. Both variables determine the temporal dynamics of the simulation. For each land use class, the following parameters were defined:

4.6.1 Conversion Elasticities

The conversion elasticity is defined as the land use class factor that determines the temporal dynamics in the simulation. This value is related to the reversibility of land use change, based on the conversion cost (e.g. capital investment) for each land use class (Verburg et al., 2002; Verburg & Overmars, 2009). Thus, for the land use model a value from 0 to 1 was assigned for each land use class (Table 6). The value 0 means that all changes are allowed in that specific land use class, independent from the current land use for examples agricultural land to urban settlements. On the other hand, 1 represents a land use class that cannot be transformed, this value is giving to land use classes that are difficult to convert (e.g protected areas). Also, values between 0 and 1 can be assigned, the closer the value is to 1 the higher is the preference that the location will no change. The elasticity values for each land use class were specified in the line 11 of the "main1.txt" file in the Dyna-CLUE interface (Verburg et al., 2002).

Table 6. *Settings of the conversion elasticities.*

land use class	Code	Value
Urban	0	0,7
Institutional	1	0,5
industrial	2	0,3
commercial	3	0,5
Rural	4	0,2
Native	5	0,8
Others	6	1

4.6.2 Conversion Matrix

The land use transitions sequences are specified in the conversion matrix (Verburg et al., 2002). Here the land use class specific conversion settings and their temporal characteristics were assessed (Table 7).

The conversion matrix defines which sequence of possible conversion, can or cannot happen. Thus, in the matrix each land use class was indicated in which possible land use time it can be converted during the next time step (Verburg et al., 2002). For example, while Residential land use classes can be only converted into Commerce, all land use classes can be converted into residential areas. To add this information to the Dyna-CLUE model, the values of the conversion matrix were saved in a text file named “allow.txt.”.

Table 7. *Specification of the land use transition sequences in the conversion matrix.*

			Land use (t+1)						
	Land use class	**Code**	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Time 0	**Residential**	**1**	1	0	0	1	0	0	0
	Institutional	**2**	1	1	1	1	0	0	0
	Industrial	**3**	1	1	1	1	0	0	0
	Commerce	**4**	1	1	1	1	0	0	0
	Rural	**5**	1	1	1	1	1	0	0
	Native	**6**	1	1	1	1	1	1	0
	Others	**7**	0	0	0	0	0	0	1

4.7 Model calibration and validation/ Exposure Analysis

The model calibration and validation it is necessary to assess the accuracy of the simulated land use change. In other words it is a measure of how well the model performed and how well it is recreating land use change. (Pontius & Schneider, 2001). In order to calibrate the model and its inputs parameters, it was necessary to run a scenario that reflects the land use pattern from 2009-2017 (demand.in7). The simulated outputs were confronted with the actual values (real map-2017) first using the null resolution and then the Figure of merit (Pontius & Schneider, 2001). Due to the fact that the model did not give conclusive results this step was not done as well as the exposure analysis for the future land use scenarios in 2050. Nevertheless, for descriptive purposes an exposure analysis was performed for Bogotá from the 1977until 2017.

4.7.1 Exposure analysis

In order to evaluate the spatio-temporal dynamics of exposure to landslides in Bogotá, a map with the growth of the city perimeter from 1977 until 2017 was developed from the base maps produced by Montoya, (2018) and the latest land use maps from the SDP (2018). Then, the resulting maps were overlapped with the landslides risk maps of Bogotá in order to observe the pattern of exposure to landslides linked to land-use change. The analysis was done by counting the pixel (area) which lay under the mask that contains the different landslide risk levels. The landslide risk maps were taken from the IDIGER, (2018). Also, in order to assess the characteristics of the population located on the areas under risk to landslides, the risk maps were overlapped with the latest map for social strata (2017).

5. Results

5.1 Statistical Analysis

5.1.1 Autocorrelation Analysis

The Autocorrelation analysis was sub-divided into the following categories: Biophysical, Socio-economical and Accessibility (Table 3). A total of four drivers were dropped, ending with a total of 17 driving factors to be added into the logistic regression. The “accessibility” land use drivers did not show autocorrelation within them, whereas, most of the factors that showed spatial autocorrelation were under the category of socio-economic factors. This can be attributed to the closeness that these factors have to each other. For example, the driver ‘Designation of land uses’ delimits the effect of other socio-economic drivers of change. This factor is composed of information that delimits where the urban land use begins and where it ends. Therefore, the presence of this factor was strongly correlated with others that determine the urban periphery like Density per Ha. Likewise, the # of shops and malls were strongly correlated with the business factor. This is due to the strong coexistence of these two factors in mixed land use zones.

Adding to this, the driving factor for ‘Protected areas’ showed a strong autocorrelation with the slope and altitude. This may be due to the fact that biophysical factors such as Slope and Height are determinants of the presence of native trees and therefore the delimitation of protected areas.

Table 8. *Variable excluded from the land use model based on the spatial autocorrelation analysis.*

Type	Driver
Biophysical	Protected areas
Socio-economical	Development potential
Socio-economical	Land use designation
Socio-economical	# of shops/malls

5.1.2 Binary Logistic Regression

Based on the results from the autocorrelation analysis a total of 17 driving factors were taken into account for the Binary Logistic Regression. In overall the ROC values for each Binary Logistic Regression were high, within a range from 0.85 to 0.94. These values showed that the regression models were accurately representing the effect of the driving factors on the presence of a land use class (Table 9).

According to the results of the binary logistic regression (Table 9), 'Social stratification' and 'Distance to the main transport nodes' were the main drivers of land use allocation for the 5 different land use categories studied. This was followed by biophysical driving factors such as 'Slope' and 'Temperature', which explained 4 out of 5 land use classes. Finally, the presence of socio-economical driving factors such as 'Height of buildings' or 'Density per Ha' were found only in 4 and 3 land use categories.

The variable that was explained with the highest number of driving factors, was the Institutional land use class with a total of 11 driving factors (Table 9). According to the data provided by the SDP, (2018) this land use classification is composed by School, Universities, Hospitals and Administrative institutions of the government. Therefore it is expected that the main driving factors that explain the presence of this land use class are related to the accessibility (Distance to ATI,- 0.4) to this areas as well factors that determine the suitability, hence the competition, for the best land location (Montoya, 2018; Yunda & Sletto, 2017).

The presence of residential land use class in 2009 was explained by factors that account for the densification of the urban center: 'Height of the Buildings' (+0.19), 'Construction codes' (+0.02) and 'Social stratification' (+0.5) (Table 9). For instance, allowing the city to grow in height and not in its periphery is a measured implemented by the government of Bogotá to promote the renovation and densification of the city center.

Similar to the other land use classes, the presence of Industrial land use classes is determined by the accessibility to main transport nodes and the social stratification. In fact, over the past years the relocation of industries in Bogotá was driven by the densification of the city center (SDP, 2017b). This is why factors like 'Proximity to highways' (-2.11) had in overall a negative effect on the allocation of this land use class (Table 9). Another factor that had a high negative effect on the presence of industries in Bogotá was the 'Temperature'. On the other hand, similar biophysical driving factors such as 'Slope' and 'Precipitation' had in overall a positive relation to the presence of the industrial land use class.

The main drivers for the presence of commercial land use classes were the 'Areas of transport infrastructure' (+ 3,223) and 'Social stratification' (-0,637). Similar to the institutional land use classes, the commercial land use class was strongly influenced by the competition of land for the best location (Table 9). In Bogotá the conversion of land to commercial use was driven by the cost of the plot or the area, usually associated with the income and per capita GDP. In fact, for this study the presence of commercial areas was negatively influenced by the social stratification. For instance, in high income neighborhoods there were few areas assigned for commercial use, due to the high price of the land.

Taking into account that rural land use classes are the ones projected to be easily converted into other land use classes. It is expected that the socio economical drivers have an overall negative effect, due to the fact they add pressure on its conversion (Table 9). On the other hand, factors such as 'Aspect' (+ 0,0026) 'Temperature' (+0,732) and 'Distance to main ATI', had an overall positive effect. For the specific area studied, these factors can be used to describe suitable areas for agriculture. Finally, the Native forest was negatively influenced by urban growth factors such as, 'Height of the buildings' (-1.03), 'Density per Ha' (-0.07) and 'Distance to main ATI' (-0.3). But it was positively influenced by factors that promote the conservation and restoration of the native forest such as, the presence of 'Ecological corridors' (+0.84), 'Temperature' (+0.56) and 'Slope' (+0.1).

***Table 9**. Results of the Binary Logistic Regression and ROC analysis of 17 driving factors (The factors that showed autocorrelation were not included in the statistical analysis). The Drivers selected showed a significant correlation (p < 0.01).*

		Residential	**Institutional**	**Industrial**	**Commercial**	**Rural**	**Native**
Driving Factor	**Code**	**0**	**1**	**2**	**3**	**4**	**5**
Constant	β_0	4,224262	-0,167603	0,345887	-3,419446	-10,955871	-19,885394
Elevation	**0**	-0,00248					0,003349
Ecological corridors	**1**		-1,090972				0,840266
Temperature	**2**	-0,372666	-0,994537	-1,06256		0,732578	0,569572
Riparian buffer zone	**3**		-1,63266				
Precipitation	**4**	0,004303	0,013776	0,012725			
Slope	**6**		-0,216711	0,138325	-0,179866	-0,053546	0,104924
Aspect	**7**	0,001663			-0,002277	0,002643	
Social stratification	**10**	0,503681	-0,508497	-0,60804	-0,637412	-0,059464	0,077611
Building codes	**11**	0,020347	-0,029939			-0,55434	
Height of Buildings	**12**	0,197938	0,111628		0,206494	-1,01653	-1,036656
Density per Ha	**14**	0,0062			0,003151	-0,014146	-0,007242
# of businesses	**15**		-0,000084	-0,00012	0,000034		
Areas of Transport Infrastructure (ATI)	**17**				3,223486		
Distance to main ATI	**18**		-0,454652	-2,11511		0,250134	-0,303659
Distance from Highways	**19**			0,001877		-0,000298	0,001026
Distance from Transport nodes	**20**	-0,000457	-0,000199	-0,00086	0,000325	-0,000282	0,000126
ROC		0,863	0,879	0,935	0,864	0,858	0,94

5.2 Spatial policies and scenarios

5.2.1 Restrictions policies

The final restriction maps were summarized in the Figure 17 where the darkest color represents the areas that were restricted for growth and LUC and the light color areas were further development and LUC is allowed to happen. In the 'Light' restriction map a total of 2156 Ha (33%) were allocated to a restricted land use change and 4364 Ha (67 %) under the not restricted use. These were mainly the protected areas in Bogotá such as wetlands and the native cloud forest. In this restriction map it was represented a light policy enforcement for disaster risk reduction and for an orderly growth of the city.

The Medium restricted map resembles the actual policy reinforcement of the local movement of Bogotá, including the restriction of construction in areas with high risk of landslides. The total area under restricted use in the medium level were 3020 Ha (46%), opposite to the 3500 Ha (54%) under the no restriction areas. Aside from the implementation of disaster risk management policies this maps also represents the interest of the city to maintain green areas in the urban zones. Finally, the High restricted map resembles the goals for a planned and organized growth of the city until 2050. In this map it was included the restriction of risk areas for landslides, the conservation of nature and the restriction of LUC in specific areas in the city. These areas were defined by the SDP as areas for urban consolidation. For the high restricted map, the areas where non-LUC was allowed represented 4500 Ha (69%) of the study area, leaving just a 2020 (41%) for further development.

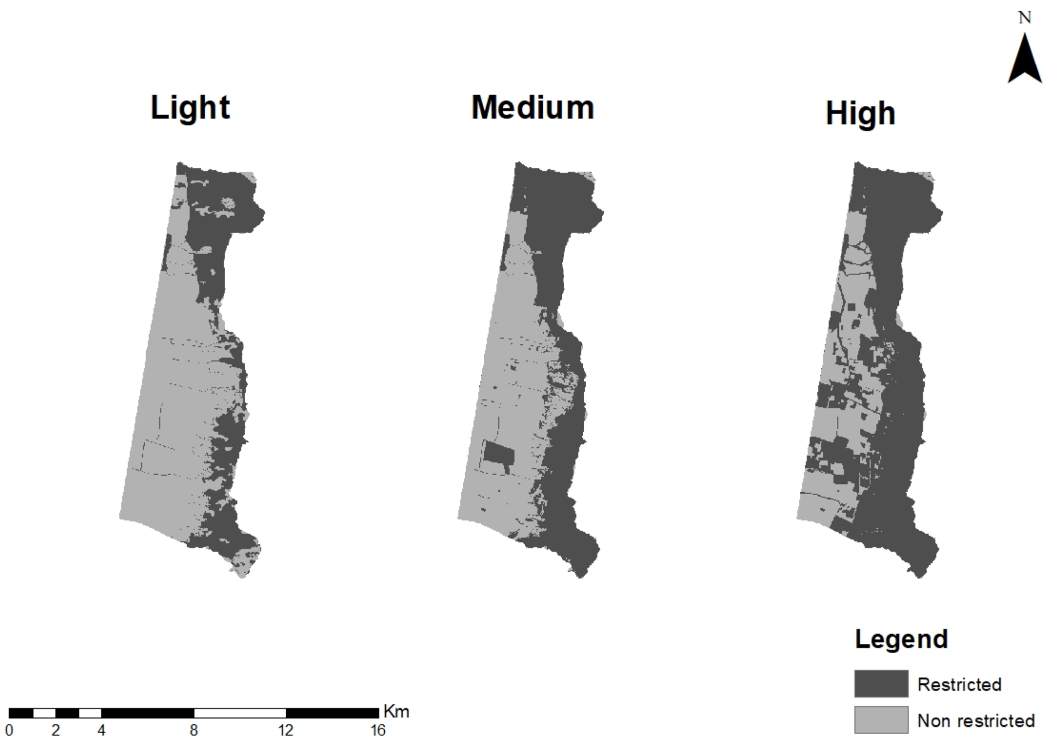


Figure 17. *Spatial policies and restrictions of land use change.*

5.2.2 Spatial planning scenarios

The land use planning regulations on LUC or the spatial planning scenarios (Scenarios 1-3) were based on a study from the Ministry of city Planning (SDP). The different simulations in the SDP case study were performed in order to test the development goals for urban growth of Colombia (Plan Nacional de Desarrollo 2018-2022) which is to obtain a 'System of cities' by 2050 (DNP, 2014). As it was previously explained, the spatial planning scenarios chosen for this study were: Business as casual, Municipal and Regional.

The results obtained for these scenarios (Annex 1), showed a trend were the most likely conversion of land use until 2050, would be to residential areas and the native forest. In fact, the annual growth of the housing areas (5 - 6.38%) was in overall 3 to 5 times higher than the growth for the commerce, institutional and industrial land uses. Also, the areas with the native cloud forest benefited from these growth scenarios. For instance, in the business as casual scenario the predicted annual growth was 7.44%, representing the highest value compared to the different land use classes studied (Annex 1). The high annual growth rate of forested areas in this scenario was the result of policies that promote the migration of the population to nearby towns and the conurbation, leaving space for conservation of protected areas in the city. Thus, according to the SDP scenarios, the growth of the city was mainly based on the substitution of Institutional and industrial areas with housing. Hence, the highest decrease in Ha was found for the institutional areas with a total -400.27 Ha and an annual decrease of -9.76%.

It is important to note that the annual growth of the native forest for the other spatial planning scenarios were smaller than the business as casual scenarios, with a growth of 4.44% and 4.32% for the Municipal and Regional scenario respectively. Whereas, the growth for the residential areas was higher in these scenarios, with a growth of 6.28% and 6.35% respectively. This is linked to the spatial policies that prioritize the densification of the city, primarily the city center. Therefore, as it can be observed in the Annex 1, the annual growth for the land use classes of industrial, commerce, and institutional was in overall negative, showing an exchange of this classes for housing.

Similar to the scenarios previously explained, the Socio-Economical Scenarios (Scenarios No. 4-6) were based on a study done by the University of the Andes, Colombia and the Ministry of city Planning (SDP). This study was selected for the thesis because it addresses the effect of transport infrastructure in LUC. The development of the transport infrastructure was previously mention by various authors as one of the main drivers of LUC in Bogotá, thus assessing this factor for this master thesis was crucial to model scenarios closer to the reality of the socio-economic dynamics of urban growth in Bogotá.

As it can be seen in Annex 1, depending on the % of development of the transport infrastructure by 2050 the higher the % of change in each land use class. Therefore, these scenarios were showcasing the direct relationship that the improvement of the transport infrastructure could have on LUC. For the scenario 4, where no development of new transport infrastructure happened, the percentage of change on the different land use classes was notably smaller compared to the scenario 6 where the full completion of all the projects for the transport infrastructure was expected. For example, the decrease of areas for agriculture was directly linked with the increase of the constructions of new streets, being the highest rate of change in the scenario 6. In the scenario with no development (scenario 4) the annual decrease was -2.45%, this value increased as the development of infrastructure increased, where the scenario of 50% (scenario 5) of the development had a rate of -4.29% and the scenario of 100% (scenario 6) with a rate of -5.22%.

Adding to this, other land use classes such as housing and institutional areas benefited from the improvement and development of new roads, better public transport and a notable improvement in the connectivity with the neighboring towns. Therefore, the highest annual growth rate was found in the scenario 6 were 100% of projects transport infrastructure were completed. Nevertheless, not all land use classes followed the same pattern related to the transport infrastructure. For instance, the not construction of new main road favor the growth of commerce areas with an annual growth of 1.90%. But the development of new areas for commerce was hindered by the development of the different infrastructure projects, with an annual decrease of -1.68% and -1.62% for the scenarios with the 50% of development and 100% of development.

5.3 The Dyna CLUE

For this thesis it was initially planned to model the land use change for 2050. Nevertheless, the results of the were not conclusive. The following section is going to address the possible factors that could have contributed to this outcome.

Before addressing the possible factors, it is important to mention that Dyna-CLUE input data requires to be transformed before it can be added to the model. For example, it is important to transform and homogenized al maps into the same coordinate system, extent and pixel resolution (Dyna Clue, 2019). This is done, so the program has a template to work with in order to avoid possible errors during the land allocation procedure. Therefore, for the specific case of this master thesis it was necessary to transform the data to the correct format before it was added to the Dyna-CLUE interface .The procedure to do this was specified in Section 4.5 of the master thesis under the title Collection and preparation of the data. After doing this, all maps generated were crosschecked in order to see if all maps had the same values for the nrows, ncollumns, resolution and XY coordinate system. Once all the maps had the same layer extent the model was run. Nevertheless, after all these processes were taken into account the model gave the following error:

" error: regression cannot be calculated due to large value in cell 1,38 for land cover 0 "

This error means that there was a problem with one of the pixels, either the simulated value did not matched the information that the pixel contained or there was 'No Data' defined for this pixel (Dyna Clue, 2019). Most of the suggestions to fix this problem were based on using the raster calculator using the function 'Fill Null' in order to get rid of the cells that had no information. This process was replicated following the instructions given, but still the model did not run. Other way to change 'No Data' cells was through the reclassification tool from ArcGIS. Nevertheless, none of these procedures mentioned above worked. Therefore, it is possible that the problem relies on the transformation of the maps before they were added to the model. The possible causes why the model did not work are presented below:

- Technical issues: In order to build the Dyna-CLUE model it was necessary to transform the maps raster data into ASCII format. It is most likely that during the transformation process to ASCII, there were overlapping issues so in the file no all pixels were properly represented. It was suggested to use other programs, such as, R Studio.

- Original maps not adequate for DynaClue: as it was mentioned before, the information provided by the government was not in the right format to be used for the Dyna Clue model. First the original shapefiles had a resolution higher than the one Dyna-CLUE is used to worked with. Therefore, it was necessary to reduce the resolution of the maps. But when the resolution was reduced it was evident that a significant amount of information was being lost in this process (Figure 19). Therefore, the resulting scenarios would have not been representative to the actual land use change patterns in Usaquén. This can be evidenced in the Figure 18.

Second, the original base maps contained to many ‘No Data’ pixels (Figure 19, Shape file). One of the requirements for the Dyna-CLUE model was to avoid the ‘No Data’ pixels as it causes trouble while running the program. Thus, these pixels should be transformed or reclassified as -9999 or allocated to other land use classes. Due to the fact that the ‘No Data’ pixels covered big portions of the map; it was necessary to make decisions to transform the ‘No Data’ areas. As it can be observed in Figure 18, the decisions made were biased and therefore the final maps did not represent land use patterns of 2009.

- High Heterogeneity of the data: It is important to highlight, that until today most of the research using Dyna CLUE was based on maps with very low resolutions and with clearly defined areas. Most of the studies were focused at the National, Regional and Municipal scale, but not to a city level. (Cammerer et al., 2013; Chen & Huang, 2013; Liu et al., 2013; Verburg et al., 2002; Verburg et al., 2004). In particular, there have not been studies which deal with high resolution maps and highly heterogenous data. Therefore, it has not been yet assessed the capabilities or limitations of the Dyna CLUE to model in heterogeneous areas.

In megacities like Bogotá, the land use was characterized by the mixed use of soils and highly heterogeneous areas where more than 2 land use classes can be found within an area of $50m^2$ (Figure 18). In fact, promoting the establishment mixed use of land is one of the goals of the local government to achieve a more densely populated area (Montoya, 2018; SDP, 2018). Therefore, it is key to be able to recreate these land use patterns, as they represent current tendencies in land use change.

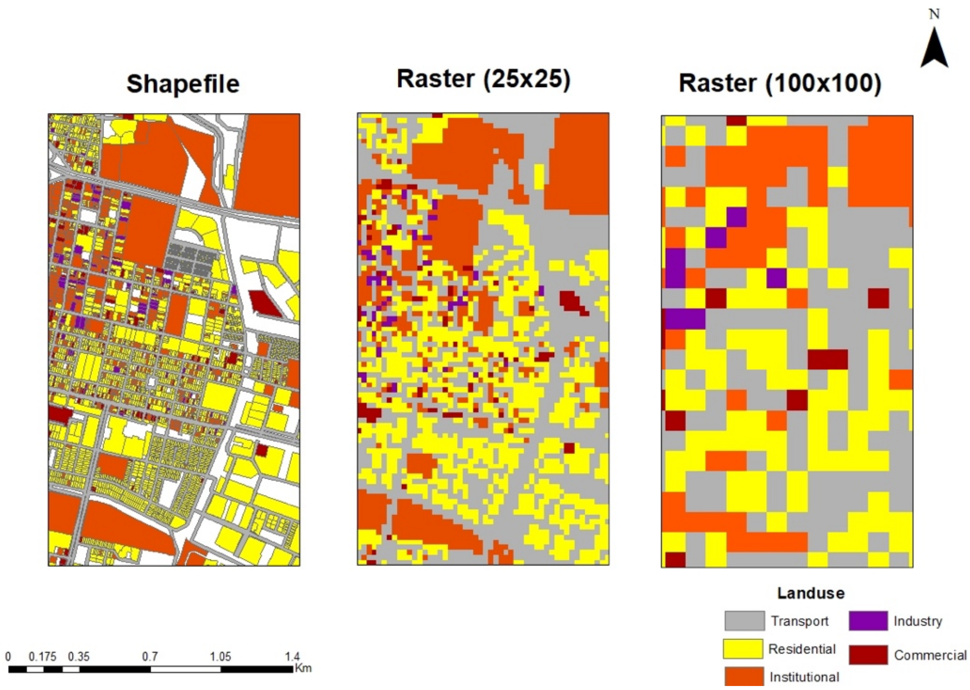


Figure 18. *Effect of different pixel resolution on the distribution of the land use classes for Usaquén.*

5.4 Exposure To landslides

The Figure 19 shows the rapid expansion or the urban area of Bogotá from 1977 with 19456 Ha to 2017 with 44055 Ha. Over the past 40 years the city expanded its urban perimeter approximately a 24599 Ha (126%). The largest increase of the perimeter can be seen from 1977 until 1997 were the city increased its urban area around 55% with an addition of 10630 Ha (Figure 20). In relation to the spatio temporal change of exposure to landslides, it is noticeable the progressive increase of areas under the classification of high and medium risk (Figure 20). The total increase of exposed areas to landslides from 1977 until 2017 was 8010 Ha with an 3.99% increase per year (Table 10, Figure 20). As it can be evidenced in the map the largest increase of exposed areas was located in the south of the city were the largest increase was between 2000 and 2007 (Figure 19,20). On the other hand, the increase of exposed areas in the center and north of the city was between the 1997 and 2017 (Figure 19).

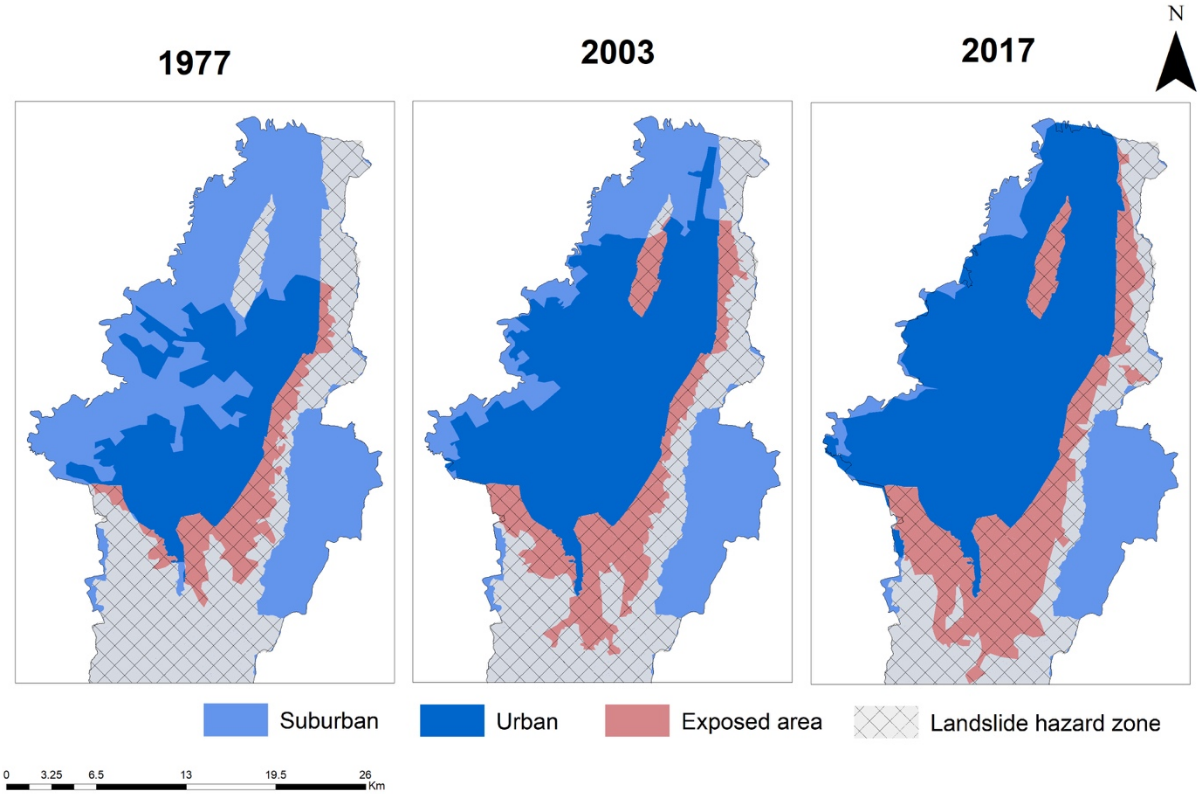


Figure 19. *Expanding bull's-eye effect on the spatio-temporal change of exposure to Landslides in Bogotá from 1977 until 2017.*

The increase of exposure to landslides in Bogotá was not distributed equally along the city. For instance, the amount of areas under medium exposure to landslides was higher compared to areas in low and high exposure (Figure 20). This is related to an increase of exposure to landslides in the south of the city, were most of these areas fall into the category of medium and high exposure. On the other hand, in the north side of the city most of the increase occurred in the areas with low to medium exposure. The highest amount of urban areas was located in a medium exposure to landslides with 6832 Ha, followed by areas under low exposure with 4519 Ha and areas with high exposure to landslides with 1684 Ha (Figure 20). Even though, most of the urban areas can be found in medium exposed areas, the highest increase of urbanized areas was found in places under high exposure to landslides with an annual growth of 5.5% compared with 4.2% for medium exposed areas.

Table 10.*Change of the total area (Ha) within each exposure level over the past 40 years.*

year	Exposure level (Ha)			
	low	medium	high	Total
1977	1938	2549	538	5025
1985	2196	2837	474	5507
1990	2992	3527	718	7237
1997	2986	3846	830	7662
2003	3231	4452	1125	8808
2007	3485	5183	1238	9906
2013	4465	6713	1675	12853
2017	4519	6832	1684	13035

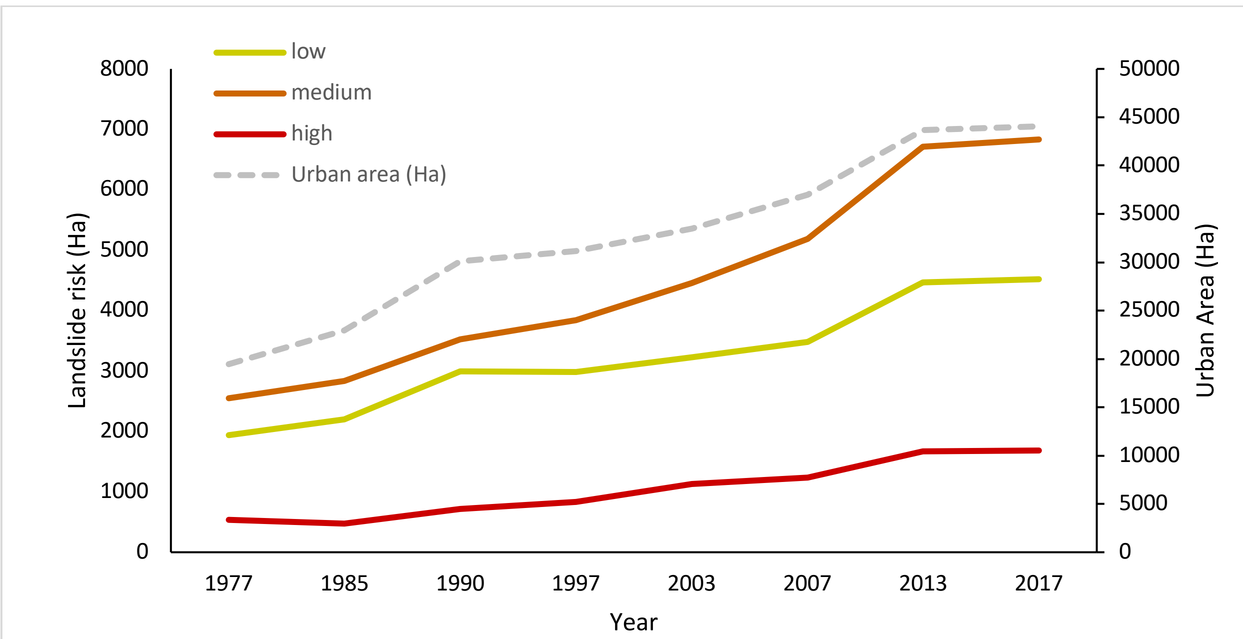


Figure 20*. Effects of the urban growth of Bogotá linked on the temporal change of areas under low, medium and high exposure to landslides between 1977-2017.*

Likewise, the distribution of the different levels of exposure, the distribution of the different social strata exposed to landslides varied along the city (Figure 21). As it can be appreciated in Figure 21, most of the areas exposed to landslides did not fall into the category of housing (grey areas) but rather in natural (Native forest) or mining areas. These areas represented around 66% of the total area exposed to this hazard with a total of 4637 Ha (Table 11). The poorest population (social strata 1 and 2) represented the largest group settled in areas under exposure to landslides, with a total of 1355 Ha (19.31%) where 139 Ha were found in high exposure to landslides (Table 11). As it can be observed in Figure 21, the lowest income population were located in the south of the city, with exception of some areas situated in the north of the city. It is important to highlight that the lowest income population found int the north was mainly settled in areas under high exposure to landslides. Another social stratum frequently found in areas exposed to landslides was the highest income population (strata 6), with a total of 474 Ha (6.75%) but with only 24 ha found in high exposure to landslides (Table 11). It is important to note that most of the houses for this social stratum were found in areas under low exposure to landslides, opposite to the lowest social stratum where more than half of the built houses were located in high to medium exposure to landslides. Similarly, to the social strata 1 and 2, the highest income population was found in the north of the city.

For this study it was found that in Bogotá the distribution of exposed areas to landslides were strongly linked to the social strata. As it can be seen in Figure 10. most of the areas under high and medium risk can be found in the south of the city, due to the topography and past land use classes that favored soil erosion (mining). As a result, the largest number of houses were found in the south of the city, composed mainly of low-income residential areas (Figure 21). The low-income residential areas were characterized by being compacted and highly densified (271-400 inhabitant per Ha). Adding to this the houses were mainly built over old mines and abrupt topography (steep slopes), therefore, not complying the constructions codes of Bogotá (Annex 2).

Table 11*.Level of Exposure to landslides associated to the Social Strata level in Bogotá, 2017. The number of the social strata represent the income of the population being 1 the lowest and 6 the highest.*

	Exposure level			
Social Strata	**Low**	**Medium**	**High**	**Total**
not defined	676	1272	2689	4637
1	65	456	382	903
2	74	143	235	452
3	20	57	212	289
4	30	29	77	136
5	6	69	49	124
6	24	78	372	474

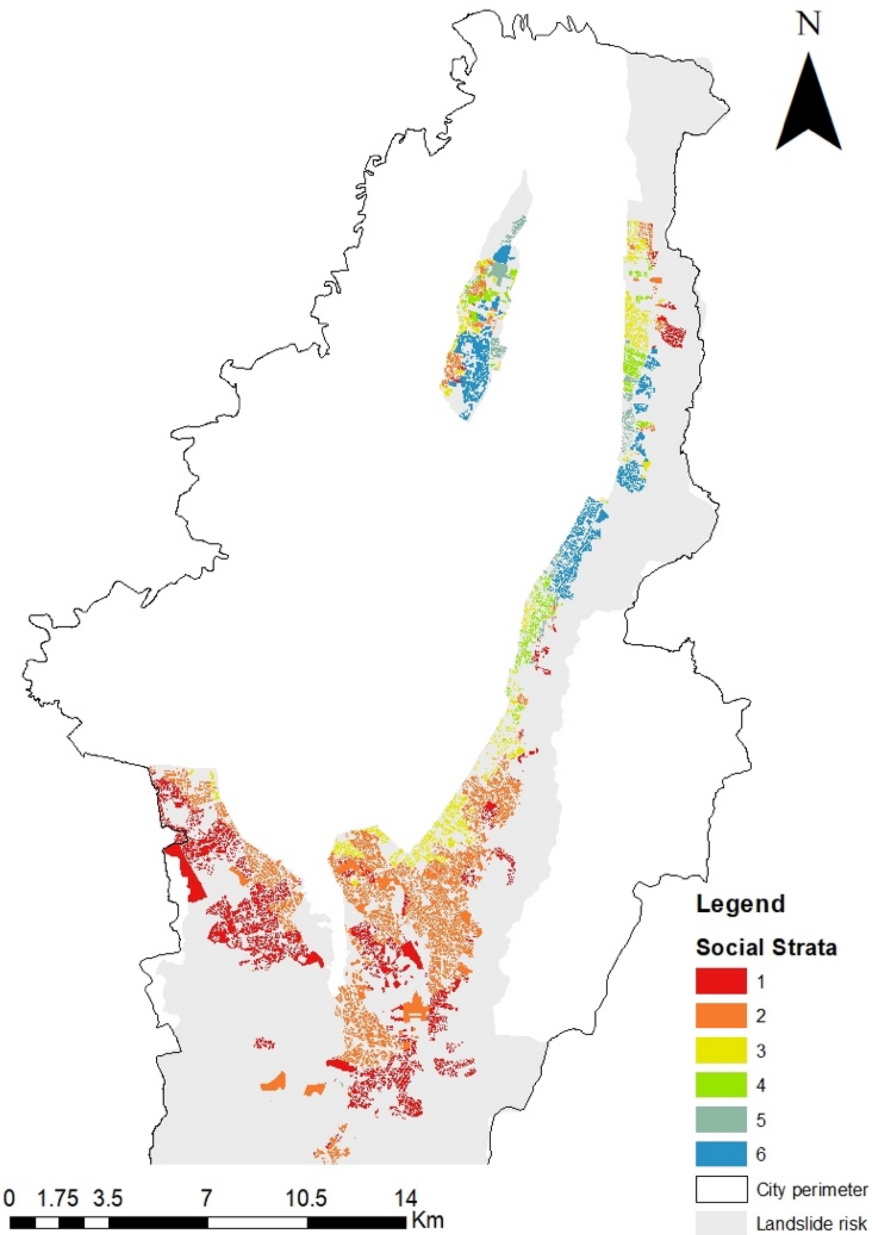


Figure 21*. Distribution of the social strata in the different areas exposed to landslides in Bogotá for 2017. The lowest social strata were represented with the number 1 and the highest strata with the number 6.*

6. Discussion

6.1.1 Land use Drivers

In accordance with the information gathered from the government of Bogotá (SDP, 2017b), and various studies about urban growth in the city ,it was highly agreed that the main drivers of LUC for Bogotá over the past years were the transport infrastructure and the distribution of wealth (Aguilar, 2017; Bocarejo et al., 2013; Guzman, Guzman, & Nates, 2017; Guzman, 2015; Guzman & Bocarejo, 2017; Guzman, Oviedo, & Bocarejo, 2017b; Montoya, 2015; SDP, 2018; SDP, 2015). Correspondingly, the results found in this master thesis the key drivers were the 'distance from the main transport nodes' and 'social stratification' (Table 9). According to Montoya (2018), the growth of Bogotá between the 1960s and the 1980s was strongly delimited by the proximity to the main roads. In fact, nowadays the price on real estate properties is strongly linked to the proximity to the main highways that cross the city (Guzman et al., 2017; Guzman & Bocarejo, 2017). This is because Bogotá has large area with a strong pattern of conurbation with the neighboring towns, thus the commuting hours to work or to school can be very long. As a result, the decision or building of buying a house depends on the proximity to the main transport nodes, because it can considerably decrease the commuting hours to the city center (Guzman, et al., 2017; Guzman & Bocarejo, 2017; Montoya, 2018).

It is important to note that the current growth pattern of Bogotá is based on a balance between a controlled expansion towards the neighboring towns (conurbation) and the densification of the city center (Montoya, 2018; Rincón et al., 2009; Salcedo, 2008; SDP, 2018; Sierra & Darío, 2010). The current growth pattern of Bogotá can be linked to the evolution of the city's economy. As a result, over the past years specific sectors in the city has benefited from this. For instance, the service and commerce sectors grew almost a 25% whereas the industry sector has been experiencing a reduction of 10% over the past 5 years (Guzman et al., 2017b; Montoya, 2013; SDP, 2017b). The proximity to main roads plays a key role on the conversion of industrialized areas to housing or commerce areas. This is due to two main patterns of LUC in the city and its neighboring towns. First, the expulsion of the industry to nearby towns were the cost over the land is lower than in Bogotá. Secondly, the consolidation of Bogotá as work place of main enterprises of the country and for residential areas (Guzman et al., 2017b; Montoya, 2018; SDP, 2017b, SDP, 2018). For this reason, the overall effect found in this thesis of the distance to the main highways in the industrial areas was negative whereas for residential areas was positive (Table 9).

Another key driver found in this thesis was the social stratification (Table 9). The distribution of wealth in Bogotá over the years has been strongly marked by both the land use price and the formal and informal economy. Due to the migration patterns to the city and different policies over land use price, the low-income population cannot access to affordable housing close to the city center. Thus, forcing poor people to the self-construction of houses near the periphery and in areas with high risk to landslides (Aguilar, 2017; Carmargo & Hurtado, 2013; Ojeda & Donnelly, 2006; Salcedo, 2008; Yunda & Sletto, 2017). As a result, the areas closer to the periphery of the city are subjected to a faster and uncontrolled conversion of the land, whereas areas closer to the city center experience slower conversion to different land use types. In other words, for this study it was found that the driver 'social stratification' can be an indicator of the effect of the different economic policies implemented in the city over the past years. For example, the economic development of the city guided under the neoliberalism ideals benefited the middle and upper classes, favoring the consolidation and construction of housing in areas closer to the city center. While these same policies limited access to housing credit to people of low strata, therefore forcing these groups to self-construction of housing on the periphery of the city. This is why in the LUC of the city follows different patterns depending on the area and the socio-economic stratum of the population (Garza, 2008; Montoya, 2013, 2015; Torres, 2012).

Regarding the biophysical factors found significant for this study, they were mainly selected in order to represent the different climatological and environmental factors that were associated to a higher risk to landslides (IDIGER, 2018; Mergili, Marchant, & Moreiras, 2015; Ojeda & Donnelly, 2006; Ramos et al., 2015). Also, for Bogotá and in specific the study area selected for this thesis, the biophysical factors were also indicators of the distribution of natural areas. In fact, the areas with a steep slope, high annual precipitation and low temperature overlapped with the native forest (Annex 3) (IDEAM, 2005). Thus, it was expected that the main drivers of land use change in Bogotá were linked to initiatives and policies related to disaster risk reduction and conservation of the natural areas surrounding the city. The fact that these drivers were found significant for different land use classes highlights the importance of promoting laws that take into account biophysical factors to limit the expansion of the urban perimeters into high risk areas. This is in accordance with the main goals of the local government to build a more resilient city, by reinforcing the connectivity of the environment and the promotion of programs for the mitigation and adaptation to natural hazards (SDP, 2017b).

Finally, in this study it was found that drivers such as 'Height of buildings' and 'Density per Ha' had in overall a positive effect in the residential and institutional land use classes, whereas it had a negative effect for rural land use class. Based on this results, it is possible to assume that the occurrence of both drivers were the result of the different land use regulations defined by the SDP (Rincón et al., 2009; SDP, 2018). For instance, the height of the buildings was related to the densification and renovation of the city center. This is the result of the urban norms, "Ley 388 de 1997" and "DECRETO 079 DE 2016" which allows the construction of taller buildings as an initiative for the densification of the city center. Also, these laws prioritize areas for renovation and consolidation, with the aim to increase the density per Ha of inhabitants in areas that were of low density (north of the city) (Montoya, 2018; SDP, 2018).

6.1.2 Land Use Scenarios

Due to the fact that the city expansion was following a pattern of uncontrolled growth towards the neighboring towns, the local government of Bogotá in cooperation of the national government proposed a set of goals and guidelines for the urban growth by 2050. As it was stated by the DNP, 2014, the main goal of Bogotá is to reach a system of well interconnected cities, with the capital as the administrative and economic center. These systems aims for a better geo-political control of the urban growth of the city, with a more active participation of the different entities for a sustainable development, climate change adaptation and disaster risk reduction (DNP, 2014; SDP, 2018). For this reason, it was found pertinent for this master thesis to test how these scenarios would impact the LUC patterns in Bogotá and how effective they could be in order to reduce the exposure to landslides.

The spatial planning scenarios accessed in this master thesis evaluated different approaches of urban growth. The first scenario, 'Base' or 'Business as casual' simulated an uncontrolled growth towards the neighboring towns. As it was stated by the SDP (2018), this scenario was strongly guided by the neoliberal policies stablished in the 1990s. The housing market and the cost over land were not regulated, and the government played little role on controlling the urban growth of the city (Cobos, 2014; Garza, 2008; Guzman & Bocarejo, 2017; Guzman et al., 2017b; Montoya, 2015). In addition, this scenario was marked by the migration of the population that used to live in Bogotá towards the neighboring towns as a result of the high rents in the city (Guzman et al., 2017b; SDP, 2018). In fact, this is related to the results found in this thesis (Annex 2), where the 'Base' scenario showed the lowest annual growth rate (4.86%) compared to the other studied scenarios.

Consequently, the pattern of conurbation would just not have increased but also the uncontrolled growth of Bogotá will create a domino effect of unorganized and informal urban growth in the neighboring towns (Montoya, 2015; SDP, 2018; Sierra & Darío, 2010). This led to today's situation where the housing market, controlled mainly by the private sector, is virtually inaccessible to the lowest income population in Bogotá (Cobos, 2014; Contreras, 2005; Garza, 2016). Hence forcing the migration of the poorest people to the live-in places around the periphery of the city and into nearby towns. Nevertheless, it is important to note that this migration pattern over the past years was equally distributed along the city landscape. For instance, in the south of the city there is a strong tendency towards the construction of houses in high risk areas in city limits. On the contrary, in the north of the city due to the fact the market was heavily controlled by the private sector there was a strong pattern of patches of un-constructed areas and a lower density per Ha (Montoya, 2018; SDP, 2017b). This pattern was observed in the results for the 'Base' scenario, where this patter only applies to the north east of the city, as the case study was based on this area. Said that, the high prices on land and a market heavily controlled by the private sector, lead to a higher migration rate towards the neighboring towns. Thus, resulting in low dense areas with big un-constructed patches. As a result, by 2050 land use classes such as agriculture and native forest areas benefited from this land use pattern. Whereas, the presence of institutional, industrial and commerce classes decreased as a response to the high prices.

It is also important to highlight that in this scenario, the role of the state as a regulatory entity was minimum. In fact, the absence of Estate on regulating the land price led to a fast increase of the housing prices based on land speculations, controlled primarily by the private sectors. As a result, the sectors that might benefit from this scenario would be the ones that have enough financial resources to cope with the rising prices and the competition over land in Bogotá. While, the most vulnerable population will be forced to continue the path of informal housing in areas not suitable for construction (Carmargo & Hurtado, 2013; Garza, 2008, 2016; Inostroza, 2017; Montoya, 2013, 2015; Yunda & Sletto, 2017).

Taking into consideration that this scenario is heavily influenced by the neoliberal ideology, the state acts as a facilitator rather than a regulator on land use change (Montoya, 2015). The role of the state on regulating and reducing the exposure of the houses in landslides zones would be ineffective. Not only because the state does not have the institutional capacity to monitor and control the growth over these areas, but also because the state cannot control the housing market prices. As long as the land use prices are regulated by the private sector and by informal land re-sellers (Pirate land owners), people under conditions of poverty will keep building houses under precarious conditions in these areas. Therefore, the already existing policies for DRR would be ineffective on the long term because the communities will keep coming back to the landslide risk zones (Contreras, 2005; Guzman et al., 2017b; Montoya, 2015; Salcedo, 2008; Yunda & Sletto, 2017).

The ‘Municipal’ scenario highlights the importance of taking into account the land use plans defined by the surrounding towns. In this scenario the expansion of the city was limited by the individual land use policies of the neighboring towns. In other words, in the city of Bogotá is not allowed to continue expanding to the neighboring towns due to the strict land use conversions laws (SDP, 2018). As a result, there is a strong pattern of densification of the central areas in Bogotá, as evidenced by a higher annual growth for the residential areas compared to the 'Business as casual' scenario (Annex 2). Adding to this the higher demand of land in the city requires the implementation of a set of policies that prioritize the development of specific land use in order to obtain a compact and dense city. As it can be seen in the Annex 2, for the municipal scenario there was a clear evidence that land conversion towards housing units will dominate the market by 2050. Various authors stated that after the densification of Bogotá started, land use types such as the institutional and industrial were unfavored by the high rent prices forcing their relocation into the neighboring towns a similar pattern observed in the 'Base' scenario (Cróquer et al., 2006; Guzman & Bocarejo, 2017; Guzman et al., 2017a; Montoya, 2013, 2018).

In fact, for the study area of this thesis, Usaquén, there was a strong tendency towards the conversion of institutional and industrial areas to mainly residential areas (SDP, 2017a). This located in the northern part of the city, where most of the middle and high stratum were settled. Consequently, there was a high pressure of the consolidation of this area as a mainly residential place, which is in accordance with the results found for the municipal scenario (Annex 2). The study area perfectly exemplifies the current land use change dynamics in most of the Latin American cities, where most were going through a consolidation phase of the territory. This phase consists on the in-filling of areas that were not previously developed during the expansion of the city periphery and the densification of low dense areas (Barros, 2004; CEPAL, 2017; Montoya, 2018; Schneider & Woodcock, 2008).

This scenario proposes a more active role of the state as a regulatory entity, since it was necessary a stricter control on land use change in order to obtain a denser and more compacted city. As a result, in this scenario it was expected that the growth towards the periphery and in the high-risk areas will be reduced. Nevertheless, due to the high demand on housing units and the rising prices of land the relocation of the most vulnerable population can be challenging on a fast-growing city like Bogotá (Contreras, 2005). Thus, even though the informal growth of housing in highly exposed areas to landslides will be reduced, the already settled communities will continue to live in these areas.

It is important to note that in the ‘Municipal’ scenario the ultimate goal was not a collaborative effort between the government of Bogotá and the neighboring towns. But rather it proposed an individual enforcement of law by respecting the boundaries of both the city and the closest towns. Nevertheless, this represents rather an unrealistic scenario where the city acts as an isolated entity from the surrounding towns. Over the past years the government of Bogotá has been working closely with the neighboring towns to elaborate a joint land use plan (DNP, 2014; SDP, 2018; The World Bank, 2009). Opposite to the ‘Municipal’ scenario, the ‘Regional’ scenario aims to simulate the effect of a regulatory policy at the regional level rather than at the local level. The proposal of this scenario was based on the idea of obtaining a ‘System of cities’, a main trend followed by the principal Latin American cities (CEPAL, 2017; The World Bank, 2009).

The ‘Regional’ scenario aimed to articulate the land use plans of Bogotá and the neighboring towns, in order to create a joint development plan. In other words, this scenario was made to define the ground rules of the transition of Bogotá from a metropolitan area into a ‘System of cities’ (DNP, 2014; SDP, 2018; Sierra & Darío, 2010). This new urban agenda was based on the idea that urban growth was inevitable and that the controlled growth of the cities will simultaneously boost the economic growth of the region. The ‘System of cities’ was designed in such a way that both the central city and the secondary towns or cities benefited from the transformation of land into urban areas. Therefore, most of the policies and laws in this scenario targeted on facilitating the transformation of the rural areas into the urban system, highlighting the importance of efficiently balancing the cost of LUC (DNP, 2014; SDP, 2018; The World Bank, 2009).

In the ‘Regional’ scenario it was not only necessary a more active participation of the government of Bogotá but rather a joint effort at the local, municipal and regional level in order to achieve these goals (SDP, 2018). Opposite to the ‘Tendential’ scenario where the housing market was controlled by the private sector, in the ‘Regional’ scenario the LUC will be closely monitored by the regional and local authorities. Consecutively, it adds another level of regulation of the urban sprawl. For instance, in the ‘Municipal’ scenario, the LUC in the city was only controlled by the authorities in Bogotá, whereas in the 'Regional' scenario, the LUC was managed by the national government, the municipal government and the local government of Bogotá (DNP, 2014; SDP, 2018).

The key points to obtain a system of city can be summarized as following: first, the development of the transport infrastructure in the city and the neighboring towns. The improvement of the connectivity between the main towns and the city will result in a more efficient economy and a better life style for its inhabitants. This is because, a better transport infrastructure improves the access to better housing, hospitals, education and a bigger job market. Second, it was necessary to define a stricter regulation over land use prices. One of the main goals in this scenario is to achieve a more compacted and denser city but at the same time allowing the expansion when it was necessary (DNP, 2014; SDP, 2018; Sierra & Darío, 2010; The World Bank, 2009). In order to do this, it was important to define policies that regulate the land and housing market. As the World Bank (2009) stated 'it is necessary to pay attention to critical policies that transcend the competence of the government of a single city. Cities should update urban planning standards for allowing a higher density and to prevent the pressures of demand for housing and land scarce goods from increasing prices excessively'. The effect of these policies can be observed in the higher rates of annual growth for the housing class and a negative growth for the agricultural land use class. This is the result of policies that aimed for a more effective use of land in the boundaries of the city, thus requiring the conversion of rural to urban areas for the construction of new housing units (Annex 2).

This new urban agenda promotes equity and poverty reduction through the sustainable growth of the city (DNP, 2014; SDP, 2018). A more active role of the state on the housing market will allow low income families access to better housing opportunities (Carmargo & Hurtado, 2013; Inostroza, 2017), reflected on a higher annual growth of the housing class (Annex 2). Thus, the construction of houses in high risk areas to landslides will not only be reduced but also the relocation of families will be possible in this case study scenario. This is because the high prices over land was one of the main driving factors that limited the successful relocation of families (Contreras, 2005). Due to the fact that benefited families either sold the new properties because it was more profitable, or they were not properly relocated in places that guaranty a better lifestyle. As a result, most of the families returned to their homes in the slums (Contreras, 2005; IDIGER, 2016).

A viable solution to this problem is to reinforce the role of the state on LUC and to control the price markets to avoid speculation over land. As it was mention before, families will not only have better housing opportunities but also will have the possibility to improve their lifestyles (DNP, 2014; SDP, 2018; The World Bank, 2009). Therefore, in order to reduce the exposure to landslides in Bogotá it will be necessary a joint cooperation between the authorities of Bogotá and the neighboring towns to restrict the growth in areas surrounding the periphery of the city.

Aside from the land use prices and the role of the state as a regulator on LUC, another key driver found in this thesis was the access to the main transport nodes. Various authors affirm that the actual form of the city was shaped by the main roads across the city. Therefore, a direct link between the construction of new roads and the development of new areas was observed. For instance, the growth over the north-east during the 1970s was boosted by the construction of two main roads: 'La septima' (the 7th) and the 'Autopista norte' (north highway) (Montoya, 2015). In the first instance, the reason for the construction of these roads was to connect the city with the country houses of the rich population. However, the development of new roads favored the access to new land. As a result, it began the process of settlement of satellite cities, which later set the ground for the expansion of the urban perimeter to its actual shape. This pattern of growth has continued to occur over the past years, where first low-density settlements were created on the outskirts of the city and over time the spaces between the city and these settlements were filled (Bocarejo et al., 2013; Guzman & Bocarejo, 2017; Guzman et al., 2017b; Montoya, 2015, 2018). Thus, forcing the local authorities to expand its perimeter. This land use pattern encouraged by the construction of new roads is called "leap-frogging". This growth pattern can also be found in major cities in the world, such as Washington, Brasilia, Mexico D.F., among others (Schneider & Woodcock, 2008; Zhang, Wrenn, & Irwin, 2012, 2016).

For this thesis, in order to address the socio-economic effects of transport infrastructure on LUC dynamics 3 scenarios were selected from the study from Guzman et al. (2018).These scenarios might not reflect the effect of LUC policies on the reduction of exposure to landslides. But rather it reflects the change of the socio economical dynamics of the city landscape through time. As Guzman & Bocarejo (2017) stated, the transport plays a key role on fighting inequity in the city. A more developed transport infrastructure can be used as a tool for the redistribution of opportunities for low income families to access housing and better jobs.

As it can be seen in the Annex 2, for the scenarios 4-6, the % of increase per year was directly linked to the level of development of the transport infrastructure. As a result, the highest rates of LUC were observed in the scenario were all planned transport infrastructure was developed (scenario 6). For instance, the highest annual growth for the housing land use was evidenced in the scenario 6 with a 1.19%, followed by the scenario 5 with 0.95% and finally with 0.27%. This is in accordance with what many authors suggest, which was a better transport infrastructure leads to a higher accessibility to land and a bigger housing market (Bocarejo et al., 2013; Guzman et al., 2017; Guzman & Bocarejo, 2017).

Various authors suggest that the construction of roads had a direct link over the prices of land. Where a gradient was observed from the closer areas with a higher cost per m^2 to farther areas with lower costs per m^2. At the same time this gradient played a key role on defining the rate of LUC resulting in the so-called leap-frogging development (Guzman et al., 2017; Guzman et al., 2018; Zhang et al., 2016). Therefore, it was expected that for this thesis the development rate of the roads will result in a higher rate of change in the observed lands use classes. This statement could be evidenced in the results as the higher rates of annual change were observed for all the land use classes in the scenario 6. These results put into evidence the effect that the construction of roads had on the socio-economical dynamics of the city. For instance, in the scenario 6 new roads boosted the construction of areas for services provision (Institutional land use), such as hospitals or universities, while it can significantly trigger the conversion of rural areas into new urbanized areas (Annex 2).

6.1.3 Spatio-temporal change of exposure to Landslides

In order to understand the current exposure to landslides of the different communities in the city, it is important to understand the growth patterns and the dynamics of LUC through time. In fact, for this thesis it was found that the different policies implemented since the 1950s were key factors on LUC and urban growth, since their effects can still be observed (Guzman et al., 2017b; Montoya, 2018). Therefore, in order to explain the reason why families settled in high risk areas it is necessary to explain the set of decisions and policies that led the city to its actual state.

The urban sprawl of Bogotá occurred in two big waves, the first in the 1950s and the second in the 1980s and 1990s. These two waves were triggered by both the globalization, the agricultural recession and the violence driven by land tenure. Poverty, violence and the search for a better future resulted in a great migration from the countryside to the city (Contreras, 2005; Guzman et al., 2017b; Montoya, 2015; Salcedo, 2008). During the first wave, the city had a greater economic power and therefore a greater capital to finance the construction of social housing. Also, during the 1950s Bogotá had a greater offer of jobs from the industrial and technological boom that the city experienced. This allowed the poorly trained population to adapt to the new market. As a consequence, the number of formal jobs grew, together with the number of inhabitants, real-estate market and the income per capita (Guzman & Bocarejo, 2017; Guzman et al., 2017b; Montoya, 2013, 2018). To summarize, the situation found by the migrant population could be described as ideal, since it had broad financial support from the government, significantly reducing the construction of informal housing in the periphery of the city (Salcedo, 2008). This perfectly showcase the effect of the state as a regulator on the informal housing and therefore the construction over areas of high risk to landslides.

The role of the state as a regulator institution was reflected in the more compacted and slower growth of the city. In fact, during the first migration wave, the city experienced the highest annual growth rate of its population resulting in a higher density per Ha, which positioned the city as one of the densest in Colombia (Annex 4) (Guzman et al., 2017b). During the 1960s, the city decided to add new districts in order to cope with the rapid growth of the population. With the addition of new areas, the city opted for the construction of satellite cities, a pattern that was still observed until 1977 (Figure 19) (Guzman et al., 2017b; Montoya, 2018; SDP, 2018). This set of measures were important to reduce the sprawl of informal housing in the periphery of the city, as it reduced the pressure on land in the southern and northern points of the city (Montoya, 2018). Nevertheless, in the long term these initiatives were not enough to hinder the construction of informal houses in high risk areas to landslides, by 1977 the construction of houses in the high-risk areas represented 25% of the total urbanized area (Figure 19 and 20). This was because social housing subsidies were not sufficient to meet the demand for housing by the 1970s. Various authors point out that the policies implemented during and after 1950s were not intended to be implemented in the long term. Therefore, the capacity of the local institutions was limited by the lack of appropriate land use plans. In fact, the lack of long-term land use plans led to a set of cascading events that boosted the informal housing during the second wave of migration (Garza, 2016; Guzman & Bocarejo, 2017; Montoya, 2015; Torres, 2012).

The second wave was marked by a slightly more hostile environment. The families that migrated in this second instance did not find the same opportunities as those in the 1950s. By 1990s the government of Bogotá stopped providing housing subsidies for poor and displaced families, mainly due to the strong economic recession that the city was going through. This is why for these families, under the neoliberal policies of the 1990s, it became almost impossible to buy or rent an apartment or house in the city. As a result, it encouraged low income families into the acquisition of illegal plots in the pirate market and the construction of homes that did not meet the construction standards in Bogotá (Contreras, 2005; Guzman et al., 2017b; Montoya, 2015; Salcedo, 2008).

Between 1985-1995 the city remained as the main destination of families displaced by the violence since Bogotá consolidated its role as the economic center of the country (Guzman et al., 2017b; Montoya, 2013; Portes & Roberts, 2005). However, after the introduction of neoliberal policies, in 1998 the city as well as the country entered into a strong financial crisis. Several authors reported that the demand for formal housing decreased significantly, a factor that was offset by the increase in illegal housing in the south and north of the city (Garza, 2008; Montoya, 2015, 2018). This can be evidenced with the fast growth of the settlements the high-risk areas from 1995 onwards (Figure 20), where the total exposed areas increased from 7662 Ha to 12853 Ha (Table 10).

Apart from the effect of the financial crisis that neo-liberal policies introduced, this economic movement also generated a profound impact on the city's economic growth policies. For instance, the government went from an active and interventionist role in several activities such as the regulation of the land market to a government that lead the economic liberation and transferred most of its responsibility on the creation of housing to the private sector (Garza, 2007; Montoya, 2015). As it was mentioned earlier, the state went from having a role of a regulatory entity to a facilitator of land transfer. This had great consequences at the institutional level because the state lost the ability to effectively monitor and regulate the increase in land prices and the sprawl of settlements in areas of high landslide risk (Contreras, 2005; Salcedo, 2008).

It is important to emphasize that neo-liberal policies favored only a few social classes in Bogotá (upper-middle and upper classes). As a result, these polices in the 1990s contracted the number of formal jobs and increased the gap among the different social classes. Pattern that can be observed in the social segregation in the city, where the families of the lower strata were in the south, while in the center and north are the families with the highest income (Figure 21) (Guzman et al., 2017b; Montoya, 2015, 2018; Salcedo, 2008). By the 2000s, more than half of the population that migrated in the 1990s had no job or had informal jobs, which gave rise to the informal economy of Bogotá. Consequently, this was reflected in a higher number of houses built in areas exposed to landslides (Figure 19). But even more important the crisis in the 1990s exacerbated the social segregation in the city. As it can be observed in Table 11. the highest proportion of low and medium exposed areas to landslides were occupied by low income families. In fact, most of the houses built in the high and medium exposed areas to landslides were located mainly in the south of the city (Contreras, 2005; Montoya, 2018) (Figure 21).

The results found in this thesis proved that the uncontrolled and rapid growth of the city placed more people and their assets into areas with a higher exposure to landslides (Figure 19). Thus, resulting in a higher risk to landslides. This relationship between LUC and exposure to landslides was defined as the expanding 'Bulls eye effect' (Ashley et al., 2014; Rosencrants & Ashley, 2015). This effect addresses the link between the urban sprawl and a higher exposure to landslides, where most of the cities grew into hazardous areas (Thaler, Fuchs, Priest, & Doorn, 2017). Similar to other cities, in Bogotá the frequency and magnitude of natural disasters increased over the past years. Nevertheless, the biggest factor for a higher exposure to landslides can be attributed to uncontrolled growth of the city. Various authors agree that the lack of proper policies that regulated the informal settlement since 1950s summed with the low institutional capacity to control the sprawl resulted in a higher number of people vulnerable and at risk of landslides (Contreras, 2005; Salcedo, 2008; Thaler et al., 2017).

7. Conclusions

The aim of this thesis was to understand how spatial planning can reduce exposure to natural hazards with the help of land use models. Even though, it was not possible the obtain results for the future land use scenarios in Usaquén. It was possible to observe the so-called 'Bulls eye effect' where the city over the past years grew towards areas exposed to landslides. Therefore, the conversion of land into urbanized areas, mainly for housing, was identified as a main factor towards a higher probability of natural disasters to occur. Likewise, it was observed an unequal distribution of exposure along the different social stratums, approximately 57% of population settled in the exposed areas to landslides were in the lowest income class (strata 1 and 2).

Adding to this it was possible to identify specific driving factors of change through the Binary logit regression. The driving factors that had a higher influence on the land use classes were, 'Social stratification' and 'Distance from transport nodes'. Taking into account that the latter, were factors heavily influenced by land use planning. Adding to this, biophysical factors such as 'Slope' and 'Temperature' were also found significant. The presence of this factors was an indicator of protected areas, thus, limiting the growth of the city towards areas with a steep slope and a low temperature. These results confirm the **first hypothesis** proposed for this thesis, where the main **driving factors** fall into the socio-ecological and biophysical categories.

Second, it was not possible to evaluate the effect of the different land use scenarios on the spatio temporal dynamics of exposure to natural hazards. Nevertheless, the effect of the different policies proposed in each scenario were evaluated. As a result, it was possible to conclude that the most viable scenario for DRR and prevention is scenario 6. Since it poses a more active role of the government in the regulating LUC and it proposes different levels of monitoring the growth of the city. Adding to this, in order to have an orderly and compacted growth it will be necessary to recognize the role of highways plays in LUC .Finally, it was concluded that the **LUC** patterns, boosted by current land use policies, was directly linked to the **increase in exposure** to landslides, thus **confirming the second hypothesis**.

Finally, it was **not possible to confirm the third hypothesis** mainly due to the fact that the model did not give significant results for this study. The possible factors that led to a negative result can be due to technical issues on the conversion of the file formats, the maps used for were not suitable for the model simulation and finally the model was not able to recreate the high heterogeneity of the landscape.

8. Outlook

The inconclusive data of this thesis should not be interpreted as the inability of the Dyna CLUE to model land use change in large capitals such as Bogotá. On the contrary, these results should be interpreted, as there is still more to be understood about the complexity of the dynamics of land use change. Further research should focus on the implementation of this model in fast growing cities, to test its capabilities and limits to simulate complex real-world situations. With a special focus on simulating the heterogeneous landscapes. In fact, most of the land use models account for factors that can cause heterogeneity in land use change models, but most models do not work with the already existing heterogeneity in the past land use maps. Therefore, it is necessary further research on how to successfully recreate the past and future heterogenous distribution of the land use classes.

In large Latin American cities, there is a clear trend towards building compact, where small areas more than one land use class can be allocated. This trend towards heterogeneity of land use classes should be further studied as it represents a key factor of land use change in Latin American capital cities. Adding to this it is necessary more studies that addresses the effect of the different land use policies on LUC and exposure to landslides, as it will be one of the main challenges that fast-growing cities will experience in the next years.

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Annex 1

Land use demand scenarios used to calculate the magnitude of land use change in Usaquén.

Spatial Scenarios

Scenario 1

	Land use	Code	2009 (Ha)	Change %	Change Ha	2050 (Ha)	Increase per year (%)
BASE	Housing	0	1,286.00	15.52	199.56	1,485.56	4.867317453
	Institutional	1	621.00	-64.46	-400.30	220.70	-9.763352258
	industrial	2	109.00	-64.46	-70.26	38.74	-1.71369629
	Commerce	3	163.00	-64.46	-105.07	57.93	-2.562683443
	Agricultural	4	894.00	7.71	68.89	962.89	1.680335802
	Native	5	1,891.00	16.24	307.18	2,198.18	7.492078737
	Others	6	1,556.00	0.00	0.00	1,556.00	0
	Total		6,520.00		0.00	6,520.00	

Scenario 2

	Land use	Code	2009 (Ha)	Change %	Change Ha	2050 (Ha)	Increase per year (%)
Municipal	Housing	1	1,286.00	19.00	244.33	1,530.33	5.959244754
	Institutional	2	621.00	-54.26	-336.93	284.07	-8.217925811
	industrial	3	109.00	-54.26	-59.14	49.86	-1.442437864
	Commerce	4	163.00	-54.26	-88.44	74.56	-2.157040108
	Agricultural	5	894.00	6.34	56.70	950.70	1.382956114
	Native	6	1,891.00	9.70	183.48	2,074.48	4.475202915
	Others	7	1,556.00		0.00	1,556.00	0
	Total		6,520.44		0.00	6,520.00	

Scenario 3

	Land use	Code	2009 (Ha)	Change %	Change Ha	2050 (Ha)	Increase per year (%)
Regional	Housing	1	1,286.00	19.18	246.62	1,532.62	6.015088107
	Institutional	2	621.00	-54.52	-338.56	282.44	-8.257662553
	industrial	3	109.00	-54.52	-59.43	49.57	-1.44941259
	Commerce	4	163.00	-54.52	-88.87	74.13	-2.167470203
	Agricultural	5	894.00	6.74	60.21	954.21	1.46862458
	Native	6	1,891.00	9.52	180.02	2,071.02	4.390832659
	Others	7	1,556.00	0.00	0.00	1,556.00	0
	Total		6,520.44		0.00	6,520.00	

Socio-economical (based on transport infrastructure

Scenario 4

no development

Land use	Code	2009 (Ha)	Change %	Change Ha	2050 (Ha)	Increase per year (%)
Housing	1	1,286.00	0.85	10.94	1,296.94	0.266896763
Institutional	2	621.00	8.54	53.03	674.03	1.293345825
industrial	3	109.00	-37.58	-40.96	68.04	-0.999040669
Commerce	4	163.00	47.73	77.80	240.80	1.897482438
Agricultural	5	894.00	-11.28	-100.81	793.19	-2.458684356
Native	6	1,891.00	0.00	0.00	1,891.00	0
Others	7	1,556.00	0.00	0.00	1,556.00	0
Total		6,520.00		0.00	6,520.00	

Scenario 5

50% development

Land use	Code	2009 (Ha)	Change %	Change Ha	2050 (Ha)	Increase per year (%)
Housing	1	1,286.00	3.06	39.34	1,325.34	0.959429291
Institutional	2	621.00	39.61	245.95	866.95	5.998829268
industrial	3	109.00	-36.84	-40.16	68.84	-0.979414634
Commerce	4	163.00	-42.30	-68.94	94.06	-1.681562023
Agricultural	5	894.00	-19.71	-176.19	717.81	-4.297281902
Native	6	1,891.00	0.00	0.00	1,891.00	0
Others	7	1,556.00		0.00	1,556.00	0
Total		6,520.00		0.00	6,520.00	

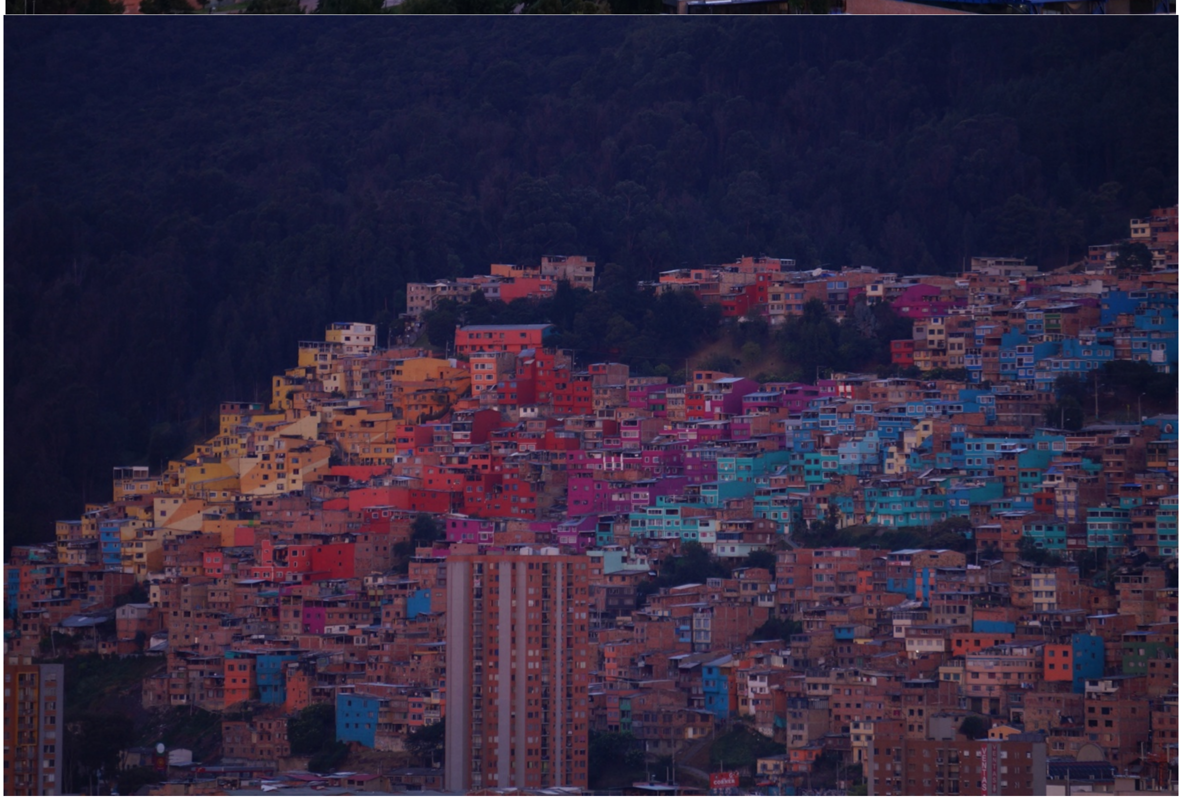
Scenario 6

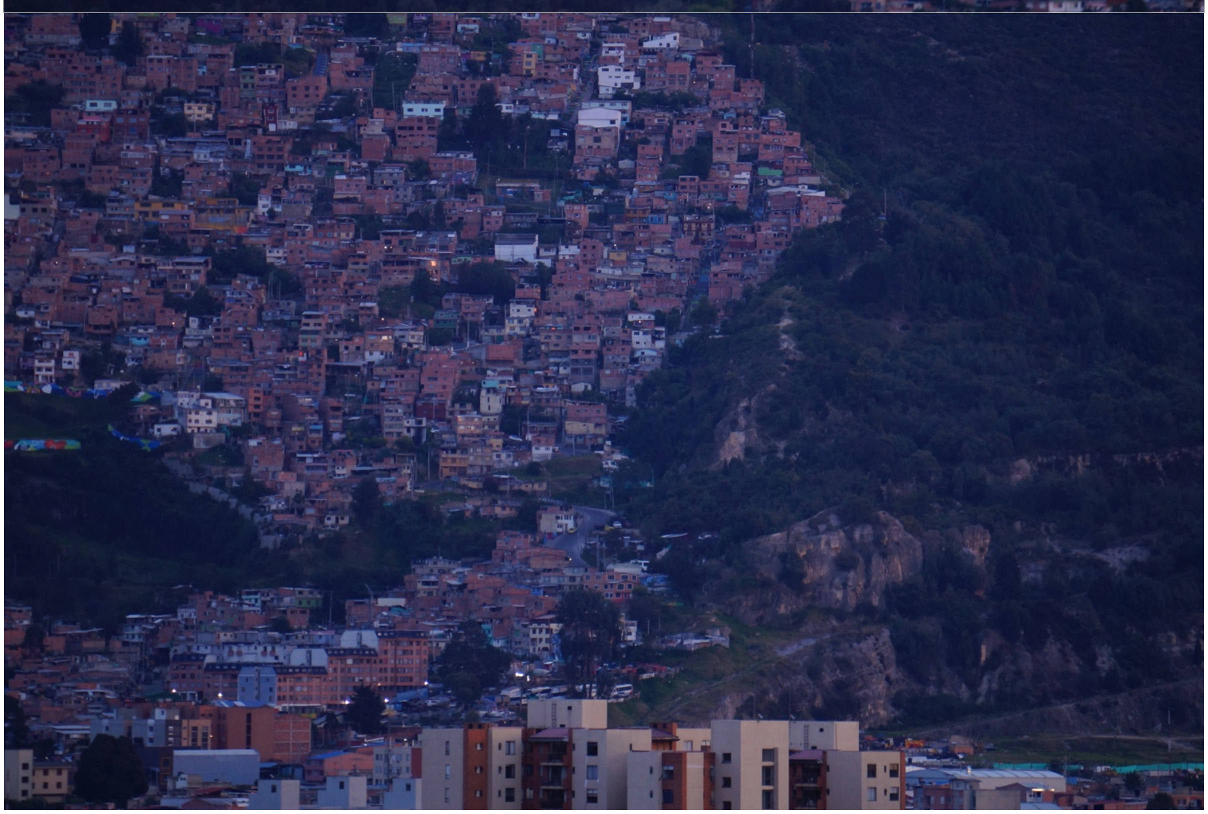
100% development

Land use	Code	2009 (Ha)	Change %	Change Ha	2050 (Ha)	Increase per year (%)
Housing	1	1,286.00	3.81	48.97	1,334.97	1.194309204
Institutional	2	621.00	43.63	270.93	891.93	6.607981909
industrial	3	109.00	-35.93	-39.17	69.83	-0.955259514
Commerce	4	163.00	-40.90	-66.66	96.34	-1.625946158
Agricultural	5	894.00	-23.94	-214.06	679.94	-5.221085441
Native	6	1,891.00	0.00	0.00	1,891.00	0
Others	7	1,556.00	0.00	0.00	1,556.00	0
Total		6,520.00		0.00	6,520.00	

Annex 2

Examples low-income residential areas located in high to medium exposure to Landslides in the district of Usaquén (North of the city)





Annex 3

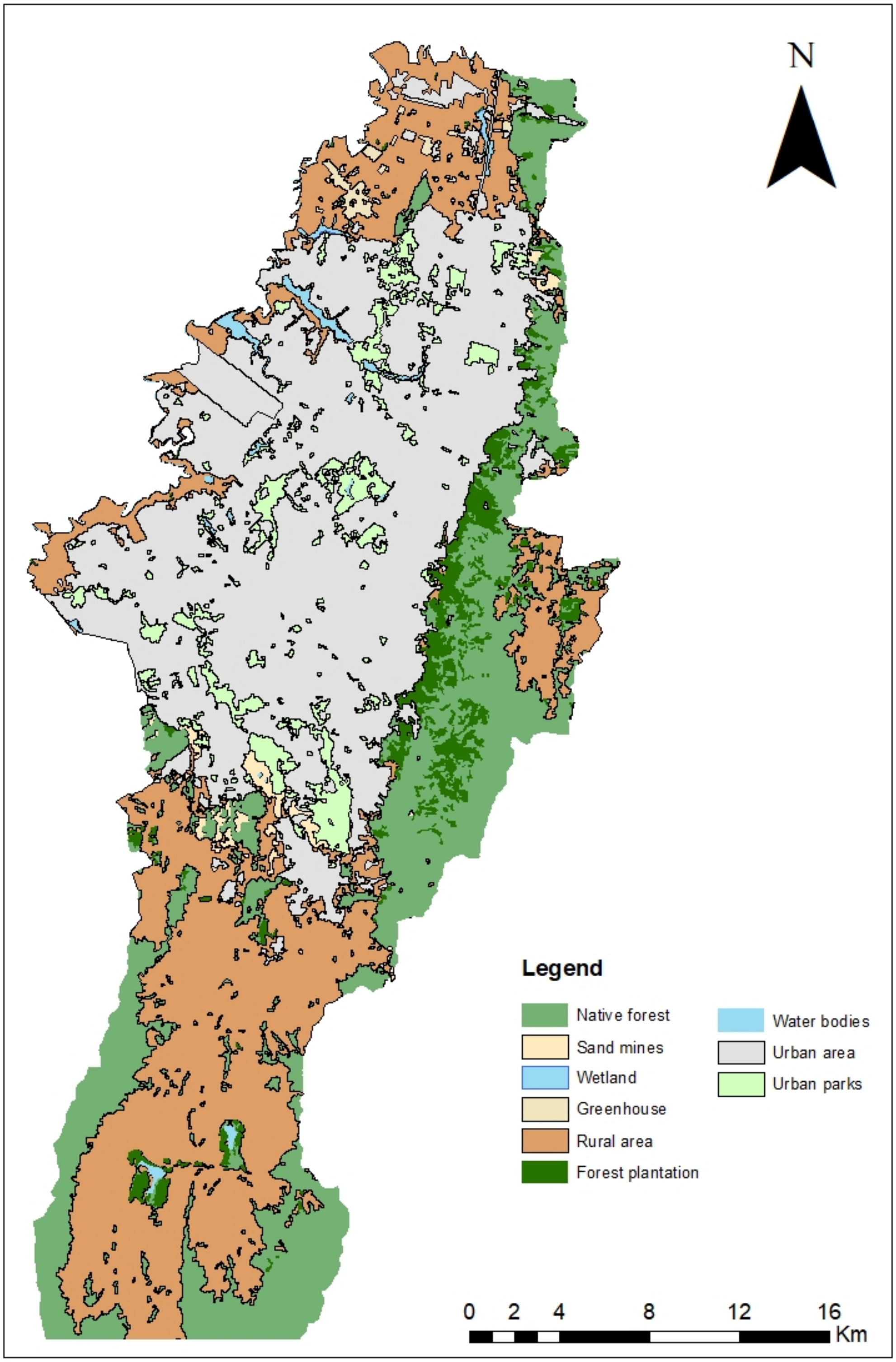


Figure 22.*Zoning of the main land use classes in Bogotá. The areas under the Native forest, Wetlands and waterbodies are assigned the category of protected areas (SDP, 2017)*

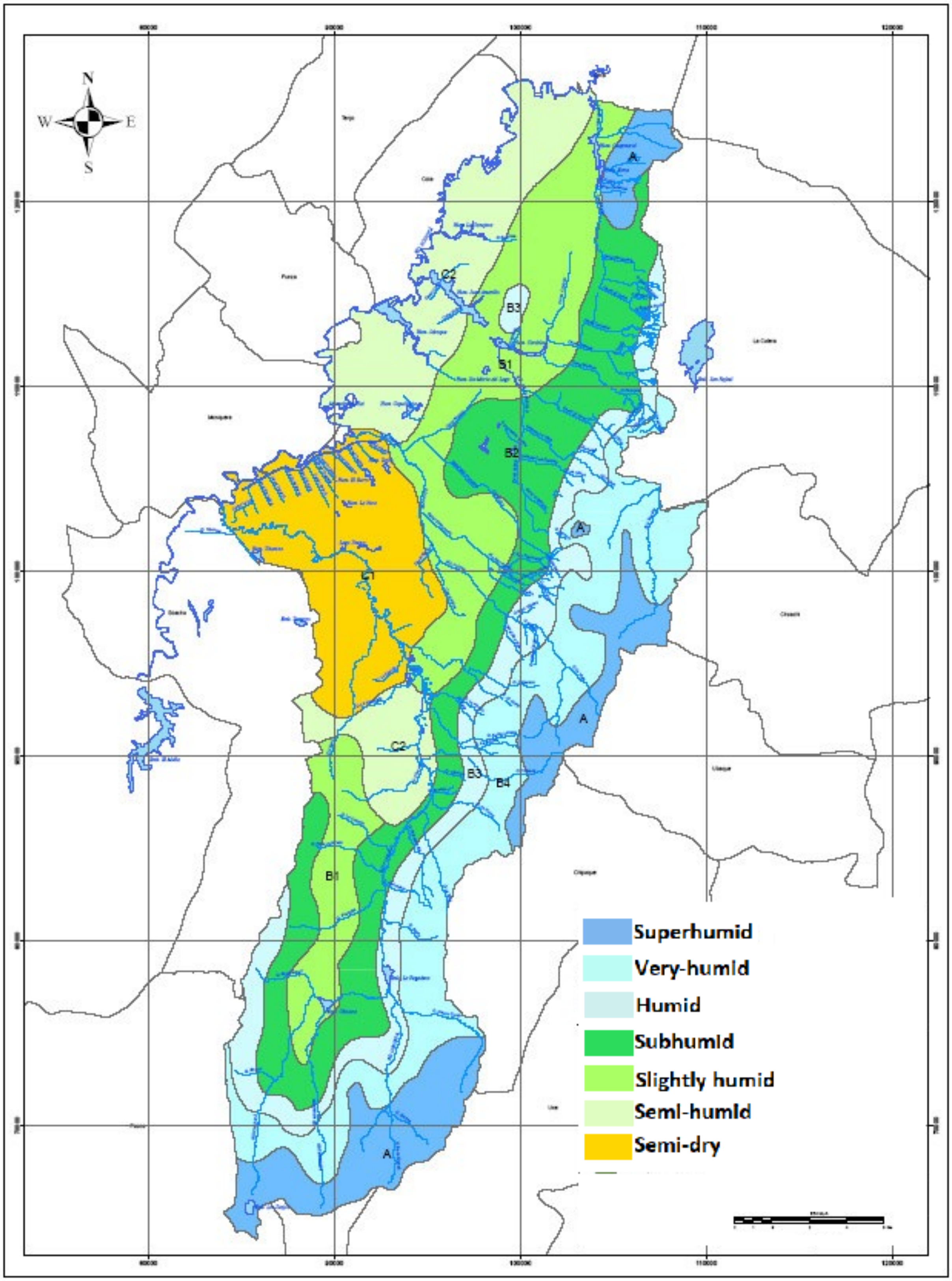


***Figure 23**. Zoning of the different bio-climatic categories for Bogotá. Source IDEAM, 2005.*

Annex 4

Table 12. *Urban and population growth of Bogotá from 1950s until 2016. Source Roa, 2016; SDP, 2017b,2018.*

Year	Urban area (Ha)	Population	Density (inh/Ha)	Growth rate (%)
1951	4511	715.250	158	5.9
1964	7915	1’697.311	214	6.6
1973	13985	2’868.123	205	4.6
1985	22772	4’273.461	188	3.6
1993	27214	5’848.224	198	2.7
1999	29668	6’322.702	210	2.6
2005	33506	6’840.116	202	2.2
2016	36146	7.980.001	226	1.6