Landslide risk in Haiti and land management in Port au Prince

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Landslide risk in Haiti and land management in Port au Prince

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Master Thesis
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ABSTRACT

This master thesis, called “Landslide risk in Haiti and land management in Port au Prince”, has been made by David Álvarez Castro, thank to Universidad Politécnica de Madrid (UPM) and to Technische Universität München (TUM), during an Erasmus Exchange between both Universities.

This thesis aims to identify landslide risk zones in Haiti as a whole (regional scale) and Port au Prince specifically (local scale) and to evaluate how this landslide risk can affect them, especially to Port au Prince, in order to elaborate recommendations in priority zones of the city.

Landslide risk priority zones are marked in order to apply land management recommendations supported in the Haitian land tenure to reduce, mitigate or delete at maximum the possible damages that these zones can suffer in the future due to landslides. These recommendations are collected in order to stakeholders decide which of them are the best options for each priority zone.

Different types of maps are generated in order to locate all landslide risk zones and priority zones.
1. Introduction

Haiti is a Caribbean country that suffers many economic and political troubles due, in part, to natural disasters.

Haiti is situated in the Greater Antillean archipelago in the western third of the island of Hispaniola, which it shares with the Dominican Republic. It lies in the middle of the hurricane belt and is subject to severe storms from June to October, occasional flooding and earthquakes and periodic droughts too (CIA, 2013).

It is one of the poorest countries in the world and the poorest in the Western Hemisphere with 80% of the population living under the poverty line and 54% in abject poverty (CIA, 2013).

Poverty, corruption, vulnerability to natural disasters and low levels of education for much of the population are among Haiti’s most serious impediments to economic growth (CIA, 2013). An example of these impediments is the earthquake suffered on 2010. It inflicted $7.8 billion in damage and caused the country’s GDP to contract by 5.4%. Estimates are that over 300,000 people were killed and some 1.5 million left homeless (CIA, 2013). While the primary damage from an earthquake is due to ground shaking, secondary hazards are phenomena that can cause additional loss to people and property at risk. The most relevant secondary hazards are liquefaction and landslide—both of which played a role in increasing the damage and loss to the island nation of Haiti (RMS, 2010).

Landslides are one of these natural hazards that Haiti suffers. They can be produced by an associated effect of other natural hazards like earthquakes, or they can be caused by the inherent characteristics of the terrain, like relief of mountains and land degradation. Also deforestation can influence in landslides occurrence. Forest canopies serve as natural buffers against wind and rain, and the deep roots of trees help keep the granular soil from shifting. The destruction of Haiti’s natural forests is almost total. As Haiti’s trees have disappeared landslides have become a major concern, especially during the rainy season, and the destabilizing effects of an earthquake on soil only worsen the problem (Than, 2010).

Over the past several decades, there has been a global trend toward urbanization, with an exodus of populations from the countryside to major cities. As rural poor migrate to the major cities, they often take up residence in shanty towns on the city margins, as seen in Port-au-Prince. They live in self-constructed residences, built using available materials. The substandard construction cannot stand up to the natural hazards that are present across so many capital cities—from hurricanes to landslides and earthquakes (RMS, 2010). That increases vulnerability zones and decreases city resilience.

As the World Bank has reported, “on many Caribbean islands, frequent heavy rains, mountainous topography, and volcanic geology combine to create high-hazard conditions for landslides. On some slopes, landslides are common even when rainfall is only mild. For communities living on such slopes, this creates conditions of perpetual uncertainty and frequent losses from landslide damage” (World Bank, 2013).
Landslides are natural hazards, but landslide risks are not natural. Landslides occur because of natural geological processes. Risks are the effects or impacts that the natural hazards produce on the population and in the environment, like the destruction of houses and loss of lives. There is no such thing as a “natural” disaster, only natural hazards (UNISDR, 2013). A disaster's severity depends on how much impact a hazard has on society and the environment (UNISDR, 2013).

Many areas of the world are at risk from landslides and their consequences. Population increase, rapid urbanization and the associated growth of unauthorized and densely populated communities in hazardous locations, such as steep slopes, are powerful drivers in a cycle of disaster risk accumulation (World Bank, 2013).

Disaster risk reduction is the concept and practice of reducing disaster risks through systematic efforts to analyse and reduce the causal factors of disasters. Reducing exposure to hazards, lessening vulnerability of people and property, wise management of land and the environment, and improving preparedness for adverse events are all examples of disaster risk reduction. (UNISDR, 2013).

Landslides are a common phenomenon in tropical areas. It is a highly significant process in the evolution of landscapes. At the same time, a rapid population growth, with its increasing socioeconomic problems promotes a disordered settlement of hazard-prone areas. Slope instability and landslides have thus increased their impact in Central America and the Caribbean (DeGraff et al, 1989; Mora, 1989). The zonation of landslide hazards then becomes a very valuable tool for disaster mitigation and preparedness (Mora & Vahrson, 1994).

"The more governments, UN agencies, organizations, businesses and civil society understand risk and vulnerability, the better equipped they will be to mitigate disasters when they strike and save more lives", Ban Ki-moon, United Nations Secretary-General (UNISDR, 2013).

1.1. Main objectives of the project

- To identify landslide risk zones in Haiti as a whole and Port au Prince specifically, in order to elaborate land management recommendations to reduce landslide risk in priority zones of Port au Prince.

1.2. Other specific objectives

Next objectives are formulated at two work scales: regional for the whole territory of Haiti and local for the capital, Port au Prince:

- To identify the landslide susceptibility zones of Haiti and Port au Prince
- To identify the landslide hazard zones of Haiti and Port au Prince
- To identify the exposure elements situated in Haiti and Port au Prince
- To identify the landslide risk zones of Haiti and Port au Prince
- To analyse how risk can affect the population of Port au Prince defining priority areas
- To analyse the land tenure situation of Port au Prince
To elaborate specific prevention measures to reduce exposure in priority areas of Port au Prince

1.3. Research questions

- Where are the zones with greatest landslide susceptibility of Haiti and Port au Prince?
- Where are the zones with greatest landslide hazard of Haiti and Port au Prince?
- What are the exposure elements that are located Haiti and Port au Prince?
- Where are the zones with greatest landslide risk of Haiti and of Port au Prince?
- How can these landslide risks affect to the population of Port au Prince in priority areas?
- How is the land tenure system organized in Haiti?
- What are the main potential mitigation measures that can be applied in priority zones in order to reduce the risk?

The project has been structured in five parts. After this introduction, a theoretical framework is exposed, where important terms related to landslides and land management are explained to understand the framework of the study. Also a conceptual framework of what is going to be explained in chapter 3 is exposed. Next chapter is about the information and methodology used, where there are exposed how information was obtained and which methodologies were followed in every step of the thesis in order to get the landslide risk zones and the land management of the selected priority zones. Chapter 4 is about results and analysis, where there are explained the results that were obtained using methodology exposed in chapter 3 and also some analyses of theme. The fifth part is about conclusions, where there are collected and commented the main results obtained as a summary of all the case of study and also future lines of action are collected.

An index of figures, tables and images is attached after these five chapters and also a list of references was introduced, where it can be observed all resources used. Finally, there are the annexes that consist on maps that show the susceptibility, hazard and risk of landslides at regional and at local scale. Also maps about exposure elements at risk at local scale are included.
2. Theoretical framework

2.1. Landslides

2.1.1. Important landslide terms

**Landslides:** is a type of "mass wasting." Mass wasting is down slope movement of soil and/or rock under the influence of gravity. A landslide is a movement of mass rock, debris, or earth down a slope. The failure of the slope happens when gravity exceeds the strength of the earth materials (Goltz, 2003).

The term “landslide” describes a wide variety of processes that result in the downward and outward movement of slope-forming materials including rock, soil, artificial fill, or a combination of these. The materials may move by falling, toppling, sliding, spreading, or flowing (Highland L., 2004).

**Landslides susceptibility:** the probable degree of slope failure (Geological Survey of Alabama, 2013).

**Hazard:** A dangerous phenomenon, substance, human activity or condition 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 (UNISDR, 2009).

**Natural hazard:** 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 (UNISDR, 2009).

**Vulnerability:** The characteristics and circumstances of a community, system or asset that make it susceptible to the damaging effects of a hazard (UNISDR, 2009).

**Exposure:** People, property, systems, or other elements present in hazard zones that are thereby subject to potential losses (UNISDR, 2009).

**Risk:** The combination of the probability of an event and its negative consequences (UNISDR, 2009).

**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. Disasters are often described as a result of the combination of: the exposure to a hazard; the conditions of vulnerability that are present; and insufficient capacity or measures to reduce or cope with the potential negative consequences (UNISDR, 2009).

2.1.2. Causes of landslides

Landslides can occur virtually anywhere in the world. The traditional viewpoint that landslides are restricted to extremely steep slopes and inhospitable terrain does not accurately reflect the real nature of the problem. Most countries in the world have been affected in some
manner by landslides. The reason for such wide geographic coverage has much to do with the many different triggering mechanisms for landslides (Highland & Bobrowsk, 2008).

One of the main causes of these natural hazards are earthquakes, with a high destruction power. Typically those of 4.0 magnitudes and above can create stresses that weaken slopes. Earthquakes tend to produce the largest and most destructive landslides (Goltz, 2003).

Also volcanic eruptions, rainfall, snowmelt, failure of landslide and moraine dams, river bank failure, and man’s activities, such as excavation and mining can cause a landslide (USGS, 2010). All of them are called triggers.

Figure 1 shows a slope with its main parts that form part of a landslide (Goltz, 2003).

- Scarp: a scar of exposed soil on the landslide.
- Crown: stable top soil at the head of the landslide. Sometimes the crown will fall and form a new scarp.
- Slip Plane: failure surface of a landslide.
- Toe: material pushed out at the base of the landslide beyond the slip plane, supports the landslide.
- Rubble: debris from the landslide.
- Bedrock: solid rock beneath the soil. The most common bedrock for a landslide to occur on is shale.
- Head: used to be part of the original ground surface.
- Soil: loose upper layer of earth, clay soil often leads to landslides.

2.1.3. Landslide Warning Signs
There are several landslides warning signs that can be observed (Geological Survey of Alabama, 2013).

- Springs, seeps, or saturated ground in areas that have not typically been wet before.
- New cracks or unusual bulges in the ground, pavement, or sidewalks.
• Soil moving away from foundations.
• Ancillary structures such as decks and patios tilting and/or moving relative to the main house.
• Tilting or cracking of concrete floors and foundations.
• Broken water lines and other underground utilities.
• Leaning utility poles, trees, retaining walls or fences.
• Offset fence lines.
• Sunken or down-dropped road beds.
• Sticking doors and windows, and visible open spaces indicating jambs and frames out of plumb.

2.1.4. Landslide types
The various types of landslides can be differentiated by the kinds of material involved and the mode of movement (USGS, 2004). Table 1 summarizes the characteristics of the different types of landslides.

Table 1. Abbreviated version of Varnes' classification of slope movements. Varnes, 1978.

<table>
<thead>
<tr>
<th>TYPE OF MOVEMENT</th>
<th>TYPE OF MATERIAL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>BEDROCK</td>
</tr>
<tr>
<td></td>
<td>Predominantly coarse</td>
</tr>
<tr>
<td>FALLS</td>
<td>Rock fall</td>
</tr>
<tr>
<td>TOPPLES</td>
<td>Rock topple</td>
</tr>
<tr>
<td>SLIDES</td>
<td></td>
</tr>
<tr>
<td>ROTATIONAL</td>
<td>Rock slide</td>
</tr>
<tr>
<td>TRANSLATIONAL</td>
<td></td>
</tr>
<tr>
<td>LATERAL SPREADS</td>
<td>Rock spread</td>
</tr>
<tr>
<td>FLOWS</td>
<td>Rock flow (deep creep)</td>
</tr>
<tr>
<td>COMPLEX</td>
<td>Combination of two or more principal types of movement</td>
</tr>
</tbody>
</table>

FALLS: Falls are abrupt movements of masses of geologic materials, such as rocks and boulders that become detached from steep slopes or cliffs. Separation occurs along discontinuities such as fractures, joints, and bedding planes and movement occurs by free-fall, bouncing, and rolling (Figure 2). Falls are strongly influenced by gravity, mechanical weathering, and the presence of interstitial water (USGS, 2004).
TOPPLES: Toppling failures (Figure 3) are distinguished by the forward rotation of a unit or units about some pivotal point, below or low in the unit, under the actions of gravity and forces exerted by adjacent units or by fluids in cracks (USGS, 2004).

![Topple](image)

Figure 3. Topple. Varnes, 1978

SLIDES: Although many types of mass movements are included in the general term "landslide," the more restrictive use of the term refers only to mass movements, where there is a distinct zone of weakness that separates the slide material from more stable underlying material. The two major types of slides are rotational slides and translational slides (USGS, 2004).

- Rotational slide: This is a slide in which the surface of rupture is curved concavely upward and the slide movement is roughly rotational about an axis that is parallel to the ground surface and transverse across the slide (USGS, 2004). (Figure 4)

![Rotational landslide](image)

Figure 4. Rotational slide. Varnes, 1978

- Translational slide: In this type of slide, the landslide mass moves along a roughly planar surface with little rotation or backward tilting (USGS, 2004). (Figure 5)

![Translational landslide](image)

Figure 5. Translational slide. Varnes, 1978
Landslide risk in Haiti and land management in Port au Prince

- Block slide is a translational slide in which the moving mass consists of a single unit or a few closely related units that move downslope as a relatively coherent mass (USGS, 2004). (Figure 6)

![Block slide](image)

**Figure 6. Block slide. Varnes, 1978**

**LATERAL SPREADS:** Lateral spreads are distinctive because they usually occur on very gentle slopes or flat terrain. The dominant mode of movement is lateral extension accompanied by shear or tensile fractures. The failure is caused by liquefaction, the process whereby saturated, loose, cohesionless sediments (usually sands and silts) are transformed from a solid into a liquefied state. Failure is usually triggered by rapid ground motion, such as that experienced during an earthquake, but can also be artificially induced. When coherent material, either bedrock or soil, rests on materials that liquefy, the upper units may undergo fracturing and extension and may then subside, translate, rotate, disintegrate, or liquefy and flow. Lateral spreading in fine-grained materials on shallow slopes is usually progressive. The failure starts suddenly in a small area and spreads rapidly (Figure 7). Often the initial failure is a slump, but in some materials movement occurs for no apparent reason (USGS, 2004).

![Lateral spread](image)

**Figure 7. Lateral spread. Varnes, 1978**

**FLOWS:** There are five basic categories of flows that differ from one another in fundamental ways (USGS, 2004).

- a. Debris flow: A debris flow is a form of rapid mass movement in which a combination of loose soil, rock, organic matter, air, and water mobilize as slurry that flows downslope (Figure 8). Debris flows include <50% fines. Debris flows are commonly caused by intense surface-water flow, due to heavy precipitation or rapid snowmelt that erodes and mobilizes loose soil or rock on steep slopes. Debris flows also commonly mobilize from other types of landslides that occur on steep slopes, are nearly saturated, and consist of a large proportion of silt- and sand-sized material. Debris-flow source areas are often associated with steep gullies, and debris-flow deposits are usually indicated by the presence of debris fans at the mouths of gullies.
Fires that denude slopes of vegetation intensify the susceptibility of slopes to debris flows (USGS, 2004).

b. Debris avalanche: This is a variety of very rapid to extremely rapid debris flow (USGS, 2004). (Figure 9)

c. Earthflow: Earthflows have a characteristic "hourglass" shape. The slope material liquefies and runs out, forming a bowl or depression at the head. The flow itself is elongate and usually occurs in fine-grained materials or clay-bearing rocks on moderate slopes and under saturated conditions (Figure 10). However, dry flows of granular material are also possible (USGS, 2004).

d. Mudflow: A mudflow is an earthflow consisting of material that is wet enough to flow rapidly and that contains at least 50 percent sand-, silt-, and clay-sized particles. In some instances, for example in many newspaper reports, mudflows and debris flows are commonly referred to as "mudslides" (USGS, 2004).
e. Creep: Creep is the imperceptibly slow, steady, downward movement of slope-forming soil or rock. Movement is caused by shear stress sufficient to produce permanent deformation, but too small to produce shear failure (Figure 11). There are generally three types of creep (USGS, 2004):

(1) Seasonal, where movement is within the depth of soil affected by seasonal changes in soil moisture and soil temperature.

(2) Continuous, where shear stress continuously exceeds the strength of the material.

(3) Progressive, where slopes are reaching the point of failure as other types of mass movements. Creep is indicated by curved tree trunks, bent fences or retaining walls, tilted poles or fences, and small soil ripples or ridges.

![Figure 11. Creep. Varnes, 1978](image_url)

**COMPLEX**: Combination of two or more of the above types is known as a complex landslide.

### 2.1.5. Conceptual landslide framework

Landslides are hazards or threats that occur usually at high and sloped areas due to topographic conditions, such as slope, aspect, stream areas and the size of the slopes, among others, and also by geological conditions, geotechnical properties, climate and vegetation. With these inputs, scientists can know which areas of a territory have a high susceptibility factor to the occurrence of these natural phenomena. Knowing this landslide susceptibility and a triggering factor, landslide hazard is generated.

After landslide hazard is known, exposure elements of the study zone have to be known in order to assess which infrastructures are in landslide hazard zones. In other words, it is to obtain the parts of the population that are in landslides risk. A risk map shows which zones can be affected and the level of affection.

This methodology was formulated at two different work scales: regional and local scale. Local scale study was developed taking into account the results of the regional scale study, where the selected location was a city with high and very high landslide risk at regional scale.

Figure 12 shows the interaction between both work scales.

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2.2. Land management

2.2.1. Important land terms

**Land tenure:** It is, at every historical moment, for every society, a question of striking a balance between the need for social control and fairness in access to land, and an equally pressing need for private initiatives to ensure efficiency, and satisfaction of the human yearning for territorial association (Doebelej, 1987).

Land tenure is the relationship, whether legally or customarily defined, among people, as individuals or groups, with respect to land. Land tenure is an institution, i.e., rules invented by societies to regulate behaviour. Rules of tenure define how property rights to land are to be allocated within societies. They define how access is granted to rights to use, control, and transfer land, as well as associated responsibilities and restraints. In simple terms, land tenure systems determine who can use what resources for how long, and under what conditions (FAO, Food and agriculture organization of the united, 2002).
Governance of tenure: The governance of tenure is a crucial element in determining if and how people, communities and others are able to acquire rights, and associated duties, to use and control land, fisheries and forests. Many tenure problems arise because of weak governance, and attempts to address tenure problems are affected by the quality of governance (FAO, 2013).

Land access: Opportunities for temporary or permanent use and occupation of land for purposes of shelter, productive activity or the enjoyment of recreation and rest. Land access is obtained by direct occupation, by exchange (purchase or rental), though membership of family and kin groups or by allocation by government, other land owners or management authorities (Mitchell, 2011).

Land administration: The processes of determining, recording and disseminating information about the ownership, value and use of land when implementing land management policies (Mitchell, 2011).

Land rights: Socially or legally recognized entitlements to access, use and control areas of land and related natural resources (Mitchell, 2011).

Land management: (Muro-Faure, 1996)

"Land: any portion of the earth over which rights of ownership, stewardship, or use may be exercised, including: the earth’s surface, water covered lands, water and mineral resources, as well as features and resources attached to the earth whether they are natural or artificial. (Barlowe, 1986)

"Management: the process of making decisions about the allocation and use of resources to meet defined goals and objectives."

Sustainable land-use planning and land management can only happen if there is agreement on land rights and access to land and natural resources. It is often quite a difficult process to determine and document all existing land-use rights (Mitchell, 2011).

Risk management: The systematic approach and practice of managing uncertainty to minimize potential harm and loss. Risk management comprises risk assessment and analysis, and the implementation of strategies and specific actions to control, reduce and transfer risks (UNISDR, 2009).

Disaster risk reduction: The concept and practice of reducing disaster risks through systematic efforts to analyse and manage the causal factors of disasters, including through reduced exposure to hazards, lessened vulnerability of people and property, wise management of land and the environment, and improved preparedness for adverse events (UNISDR, 2009).

Resilience: The ability of a system, community or society exposed to hazards to resist, absorb, accommodate to and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions (UNISDR, 2009).
2.2.2. Land tenure

Land tenure is an important part of social, political and economic structures. It is multi-dimensional, bringing into play social, technical, economic, institutional, legal and political aspects that are often ignored but must be taken into account (FAO, Food and agriculture organization of the united, 2002).

Land tenure is often categorised as (FAO, Food and agriculture organization of the united, 2002):

- Private: the assignment of rights to a private party who may be an individual, a married couple, a group of people, or a corporate body such as a commercial entity or non-profit organization.
- Communal: a right of commons may exist within a community where each member has a right to use independently the holdings of the community.
- Open access: specific rights are not assigned to anyone and no-one can be excluded.
- State: property rights are assigned to some authority in the public sector.

In broad terms, land tenure rights are often classified according to whether they are “formal” or “informal”. Formal property rights may be regarded as those that are explicitly acknowledged by the state and which may be protected using legal means. Informal property rights are those that lack official recognition and protection. In many countries, illegal property holdings arise because of inappropriate laws. In other cases, property may be “extra-legal”, i.e., not against the law, but not recognised by the law. Formal and informal rights may exist in the same holding (FAO, Food and agriculture organization of the united, 2002).

These various forms of tenure can create a complex pattern of rights and other interests. A particularly complex situation arises when statutory rights are granted in a way that does not take into account existing customary rights. An enforcement or protection component is essential to effective land administration since rights to land are valuable when claims to them can be enforced (FAO, Food and agriculture organization of the united, 2002).

Efficient procedures allow transactions to be completed quickly, inexpensively, and transparently. However, in many parts of the world, formal land administration procedures are time-consuming, bureaucratically cumbersome and expensive. In such cases, high transaction costs may result in transfers and other dealings taking place off-the-record or informally. In many countries, formal and informal land administration co-exist when legal records do not replace customary rights, or when newly created informal rights come into existence (FAO, Food and agriculture organization of the united, 2002).

Information on land, people, and their rights is fundamental to effective land administration since rights to land do not exist in a physical form and they have to be represented in some way. In a formal legal setting, information on rights, whether held by individuals, families, communities, the state, or commercial and other organizations, is often recorded in some form of land registration and cadastre system. In a customary tenure environment, information may be held, unwritten, within a community through collective memory and the use of witnesses. In a number of communities, those holding informal rights may have
“informal proofs” of rights, i.e., documents accepted by the community but not by the formal state administration (FAO, Food and agriculture organization of the united, 2002).

Security of tenure is the certainty that a person’s rights to land will be recognized by others and protected in cases of specific challenges. Without security of tenure, households are significantly impaired in their ability to secure sufficient food and to enjoy sustainable rural livelihoods (FAO, Food and agriculture organization of the united, 2002).

Land administration is the way in which the rules of land tenure are applied and made operational. Land administration, whether formal or informal, comprises an extensive range of systems and processes to administer (FAO, Food and agriculture organization of the united, 2002):

- Land rights: the allocation of rights in land; the delimitation of boundaries of parcels for which the rights are allocated; the transfer from one party to another through sale, lease, loan, gift or inheritance; and the adjudication of doubts and disputes regarding rights and parcel boundaries.
- Land-use regulation: land-use planning and enforcement and the adjudication of land use conflicts.
- Land valuation and taxation: the gathering of revenues through forms of land valuation and taxation, and the adjudication of land valuation and taxation disputes.

With clear land tenure, land management can be developed in order to improve the situation of a country. Land use master plans provide an opportunity to develop a strategy for land management that provides protection for livelihoods, helps to improve food security, and includes preparedness activities to reduce vulnerability to future natural disasters. They also provide an opportunity to assess which communities are most vulnerable to future natural disasters and which would benefit from resettlement (Mitchell, 2011).

2.2.3. Conceptual land management framework
With the knowledge of the Haitian land tenure system and also having a good knowledge of landslide risk zones, it is necessary to mark priority zones and to make a land management in order to try to mitigate, reduce and or remove as possible the damages that landslides can cause in these places in the future.

Land management can help in different kind of aspects, like in economy, in social and in political issues too. It pretends to arrange the land and responds the problems that land tenure has about landslides, making land recommendations to reduce and mitigate the landslide risk. In this case of study, land management measures will try to answer the problems of landslides in priority zones where there is not any kind of land tenure or it has to be improved.

Figure 13 shows how these terms are related between them.

David Álvarez Castro.
Master Thesis
Figure 13. Land management. Own figure, 2013.

Figure 14 shows how landslide risk and land management are related in the project. It shows the lineal process of the Master Thesis.
Green boxes are related to the landslide risk obtainment at regional scale (Haiti). After landslide risk at regional scale was known, a high and very high landslide risk zone was selected in order to carry out the study at local scale with more precise and detailed data. The city selected was Port au Prince, the capital of the country.

Blue boxes are related to the landslide risk obtainment at local scale (Port au Prince) in the same way as was made at regional scale.

Once landslide risk at local scale was obtained and land tenure system of Haiti (red box) was known, it was possible to make a land management of Port au Prince (orange boxes) in order to reduce landslide risks. The main objective of this part is to propose to create a new and modern cadastre, relocations of neighbourhoods, defining uses of land and using land monitoring systems.
3. Methodology

It is important to indicate that this master thesis presents a direct connection with the master thesis of Sandra Ruiz. Both projects combine partial results obtained in the different phases of each one, as it is shown in the following figure:

![Diagram showing the connection between Ruiz and Álvarez Thesis]

Figure 15. Connexions between Ruiz and Álvarez Thesis
The methodology followed in this study can be structured in two parts aimed at estimation of landslide risks and land management, respectively.

3.1. Landslide risk information and methodology used
This landslide risk study was developed in two different ways. The first one was made at regional scale for the country of Haiti; and the second one was made at local scale for a specific city that was in high and very high landslide risk according to the results of the previous study, in order to have a better knowledge of the landslides reality.

In order to achieve these, it was necessary to develop some intermediate steps. These intermediate steps were described in Figure 12 (Landslide risk process. Own figure, 2013).

3.1.1. Landslide risk at regional scale
Landslide risk study at regional scale provides a global view of the parts of the country according to their landslide risk level, where the zones with the highest landslide risk are located and how this risk can affect to people and infrastructures.

3.1.1.1. Landslide susceptibility at regional scale.
Landslide susceptibility zoning involves certain degree of interpretation. Susceptibility zoning involves the spatial distribution and rating of the terrain units according to their propensity to produce landslides. This is dependent on the topography, geology, geotechnical properties, climate, vegetation and anthropogenic factors such as development and clearing of vegetation (Fell, et al., 2008). With the integration of these data in a GIS software, which provides a geographic frame and allows homogenizing, treating, analysing and disseminating the geographic data and the results, it is possible to identify which parts of the study zone can be susceptible to the occurrence of landslides.

To get it, it was followed the methodology of Mendoza and Dominguez (Mendoza, M.J; Dominguez, L., 2002). They use topographical and historical factors, combined with geotechnical, geomorphologic and environmental factors. It is a qualitative, quantitative and empiric methodology in order to assess the landslide susceptibility. It is a modified and extended version of Suárez (1998) criteria and qualifications (Mendoza, M.J; Dominguez, L., 2002).

Every factor was classified in different intervals according to the level of susceptibility that can produce with a specific weight that means the degree of importance in landslide susceptibility. Factors defined by Mendoza and Dominguez (2002) are presented in Tables 2, 3 and 4.
### Table 2. Topographic and historic factors. Mendoza and Dominguez, 2002

<table>
<thead>
<tr>
<th>Factor</th>
<th>Intervals or categories</th>
<th>Weight</th>
<th>Observations</th>
<th>Calification</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Slope</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>More than 45°</td>
<td>2.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>35° - 45°</td>
<td>1.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>25° - 35°</td>
<td>1.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>15° - 25°</td>
<td>1.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Less than 15°</td>
<td>0.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Hillside</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Less than 50 m</td>
<td>0.6</td>
<td>Gradient between the top and the valley. Use leveling or topographic maps.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>50 - 100 m</td>
<td>1.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>100 - 200 m</td>
<td>1.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>More than 200 m</td>
<td>2.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>History of landslides</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Do not known</td>
<td>0.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Some shallow</td>
<td>0.4</td>
<td>Credible stories of locals.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Yes, aslo with dates</td>
<td>0.6</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table 3. Geotechnical factors. Mendoza and Dominguez, 2002

<table>
<thead>
<tr>
<th>Factor</th>
<th>Intervals or categories</th>
<th>Weight</th>
<th>Observations</th>
<th>Calification</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type of soil or rock</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Compacted granular soils moderately to loose. Soften soil with water absorption. Poorly consolidated formations</td>
<td>1.5 - 2.5</td>
<td>Vulnerable to soil erosion or soft consistency</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Metamorphic rocks (shales, slates, schists) of slightly to highly weathered</td>
<td>1.2 - 2.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clay soils compact consistent or sandy loam</td>
<td>0.5 - 1.0</td>
<td>Multiplied by 1.3 for cracks</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sedimentary rocks (sandstones, conglomerates) and tuffs competent</td>
<td>0.3 - 0.6</td>
<td>Multiply by 1.2 to 1.5 according to the degree of weathering</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Igneous healthy rocks</td>
<td>0.2 - 0.4</td>
<td>Multiply by 2 to 4 according to the degree of weathering</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Thickness of the layer of soil</strong></td>
<td></td>
<td></td>
<td>Check cuts and ravines or manual examination</td>
<td></td>
</tr>
<tr>
<td>Less than 5 m</td>
<td>0.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 - 10 m</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10 - 15 m</td>
<td>1.4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15 - 20 m</td>
<td>1.8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Driven from the discontinuities</strong></td>
<td></td>
<td></td>
<td>Consider contact planes, cracks and joints and planes of weakness</td>
<td></td>
</tr>
<tr>
<td>Less than 15°</td>
<td>0.3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>25° - 35°</td>
<td>0.6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>More than 45°</td>
<td>0.9</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Angle between the dip of the discontinuities and slope inclination</strong></td>
<td></td>
<td></td>
<td>Differential angle positive if the cast is greater than the angle of the slope</td>
<td></td>
</tr>
<tr>
<td>More than 10°</td>
<td>0.3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0° - 10°</td>
<td>0.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0°</td>
<td>0.7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0° - (-10°)</td>
<td>0.8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Less than -10°</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Angle between the direction of the discontinuities and course of the direction of the slope</strong></td>
<td></td>
<td></td>
<td>Consider the direction of the most representative discontinuities</td>
<td></td>
</tr>
<tr>
<td>More than 30°</td>
<td>0.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10° - 20°</td>
<td>0.3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Less than 5°</td>
<td>0.5</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table 4. Environmental factors. Mendoza and Dominguez, 2002

<table>
<thead>
<tr>
<th>Factor</th>
<th>Intervals or categories</th>
<th>Weight</th>
<th>Observations</th>
<th>Calification</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Geomorphological evidence of contiguous hillside holes</strong></td>
<td></td>
<td></td>
<td>Shells or funnel shapes (flows)</td>
<td></td>
</tr>
<tr>
<td>Nonexistent</td>
<td></td>
<td>0.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moderate volumes</td>
<td></td>
<td>0.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Large volumes missing</td>
<td></td>
<td>1.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Vegetation and land use</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Urban zones</td>
<td></td>
<td>2.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Annual crops</td>
<td></td>
<td>1.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Intense vegetation</td>
<td></td>
<td>0.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moderate vegetation</td>
<td></td>
<td>0.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deforested area</td>
<td></td>
<td>2.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Water Regime in the hillside</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shallow water table</td>
<td></td>
<td>1.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nonexistent water table</td>
<td></td>
<td>0.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ditches or depressions where water accumulates on the slope</td>
<td></td>
<td></td>
<td>To detect possible evolution of water in the slope</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Once all factors were classified, the next step was to discern the relative importance of each susceptibility factor. This was done by a multi criteria evaluation (MCE), where every factor got a weight standing for the relative importance of each factor, as compared with the others. It was made with the Analytic Hierarchy Process tool of ArcGIS (AHP).

AHP was introduced by Saaty (1977) and is a very popular means to calculate the needed weighting factors by help of a preference matrix where all identified relevant criteria are compared against each other with reproducible preference factors (Satecs, 2013).

All criteria/factors which are considered relevant for a decision are compared against each other in a pair-wise comparison matrix which is a measure to express the relative preference among the factors (Table 5). Therefore numerical values expressing a judgement of the relative importance (or preference) of one factor against another have to be assigned to each factor (Satecs, 2013).

Since it is known from psychological studies that an individual cannot simultaneously compare more than 7 ± 2 elements, Saaty (1977) and Saaty & Vargas (1991) suggested a scale for comparison consisting of values ranging from 1 to 9 which describes the intensity of importance (preference/dominance). A value of 1 expresses “equal importance” and a value of 9 is given for those factors having an “extreme importance” over another factor (Satecs, 2013).

<table>
<thead>
<tr>
<th>Intensity of importance</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Equal importance</td>
</tr>
<tr>
<td>3</td>
<td>Moderate importance of one factor over another</td>
</tr>
<tr>
<td>5</td>
<td>Strong or essential importance</td>
</tr>
<tr>
<td>7</td>
<td>Very strong importance</td>
</tr>
<tr>
<td>9</td>
<td>Extreme Importance</td>
</tr>
<tr>
<td>2, 4, 6, 8</td>
<td>Intermediate values</td>
</tr>
<tr>
<td>Reciprocals</td>
<td>Values for inverse comparison</td>
</tr>
</tbody>
</table>

The obtained result shows how factors are important between them with a weight factor, where higher weight means a more importance of the factor. Once all weights were established, each factor was multiplied by its own weight in the GIS software and landslide susceptibility values of the study zone were obtained.

A regional-scale landslide susceptibility map was generated. In the Annexe chapter it is attached.

3.1.1.2. Trigger at regional scale

The trigger selected in this case of study was a seismic action. It was selected due to the fact that this is an important landslide triggering factor in the study zone, and also because ‘Grupo de Investigación en Ingeniería Sísmica’ (GIIS) (Earthquake Engineering Research Group, translated) has expertise in these topics. Hence, it was possible to consult them and to get information too.
The seismic triggering factor was obtained through a probabilistic hazard study. The necessary inputs were a seismic catalogue, the seismogenic zones and the faults with their own characteristic parameters of the study zones, and attenuation models.

The methodology followed in the study was a hybrid model of seismogenic zones and faults as independent seismogenic units. The seismogenic zones were characterized with the Gutenberg-Richter law, which coefficients were obtained by maximum likelihood regression, and the faults were characterized by two models. The first one was the Gutenberg-Richter law, based on the Bungum approach (Bungum, 2007). Bungum proposes 4 different methods and the final result was an average of all of them. The second one was the characteristic earthquake.

3.1.1.3. Landslide hazard at regional scale
Landslide hazard was obtained combining the landslide susceptibility with the seismic hazard in GIS software. To combine them, it was necessary to use the Llorente and Palacios (Llorente, L.; Palacios, E., 2010) table (Table 6). This methodology was used previously by the Earthquake Engineering Research Group (GIIS) in the master thesis of Jorge Navarro (Navarro, 2012), due to its easy and clear application.

This table shows how landslide susceptibility values are combined with seismic hazard values (trigger values) in order to get the landslide hazard.


<table>
<thead>
<tr>
<th>SUSCEPTIBILITY</th>
<th>SEISMIC HAZARD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very High</td>
<td>Very High</td>
</tr>
<tr>
<td>Very High</td>
<td>High</td>
</tr>
<tr>
<td>Very High</td>
<td>Moderate</td>
</tr>
<tr>
<td>Very High</td>
<td>Low</td>
</tr>
<tr>
<td>High</td>
<td>Very High</td>
</tr>
<tr>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>High</td>
<td>Moderate</td>
</tr>
<tr>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Moderate</td>
<td>Very High</td>
</tr>
<tr>
<td>Moderate</td>
<td>High</td>
</tr>
<tr>
<td>Moderate</td>
<td>Moderate</td>
</tr>
<tr>
<td>Moderate</td>
<td>Low</td>
</tr>
<tr>
<td>Low</td>
<td>Very High</td>
</tr>
<tr>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Low</td>
<td>Moderate</td>
</tr>
<tr>
<td>Low</td>
<td>Low</td>
</tr>
</tbody>
</table>

A regional-scale landslide hazard map was generated. In the Annexe chapter it is attached.
3.1.1.4. Exposure elements at regional scale
Once the landslide hazard was known, it was necessary to know the exposure elements that are located in the study zone.

This geospatial information was obtained from geodata bases thanks to Earthquake Engineering Research Group (GIIS), and also from the internet (OpenStreetMap and HaitiData websites).

The most important exposure elements in this scale of study (regional scale) were the main cities and the main roads. This geoinformation shows where these elements are disposed in the terrain and how population and their communications ways are distributed in the country.

3.1.1.5. Landslide risk at regional scale
Landslide risk was obtained overlapping in GIS software the landslide hazard values with the exposure elements of Haiti. The results show which cities and main roads can be affected by landslide hazard. It shows in a qualitative way where the highest risk zones are located.

With this study, it could be possible to know the main zones that can suffer landslide risk. It provides a global view of the parts of the country where landslides can occur, where zones with the highest risk are and how this risk can disturb cities or communications ways.

After this study, it would be necessary to make similar studies at local scale in the zones with the highest landslide risk values, with more precise data and with better spatial resolution, in order to study every zone with more detail.

A regional-scale landslide risk map was generated. In the Annexe chapter it is attached.

3.1.2. Landslide risk at local scale
Landslide risk at local scale aims to assessing with a higher level of detail and better precision than at regional scale, where landslide risk zones are and how important they are.

3.1.2.1. Landslide susceptibility at local scale
This landslide susceptibility study at local scale was conducted in a similar manner as at regional scale. It was based in the same methodology (Mendoza, M.J; Dominguez, L., 2002) because, as the authors said, “the described procedure is practically invariant of the scale”. That means that this methodology can be used in a specific hillside, in a village or in a city, using the appropriated topographical and geological data in GIS software.

Weights of each factor were obtained with the AHP tool too. Landslide susceptibility values were obtained combining these weights with their factors in GIS software.

A local-scale landslide susceptibility map was generated. In the Annexe chapter it is attached.
### 3.1.2.2. Trigger at local scale

The seismic trigger at local scale was obtained with a deterministic hazard study. In a deterministic hazard scenario, the ground motion caused by a single earthquake is the landslide triggering factor. This earthquake is the so-called ‘controlling earthquake’, which is the earthquake that contributes in the highest measure to a given hazard-consistent target motion.

Hazard deaggregation was used in order to obtain the magnitude and distance defining the ‘controlling earthquake’. A deterministic hazard study was developed with the ground motion prediction equation (or attenuation law) of Boore and Atkinson (2011). The local effect was considered through the vs30 factor. In order to get this, it was used a micro-zonation of the study zone.

Applying the selected ground motion prediction equation and the micro-zonation, the acceleration values for each section of the study zone were obtained.

### 3.1.2.3. Landslide hazard at local scale

Landslide hazard was obtained combining the landslide susceptibility with the seismic hazard in GIS software. To combine them, it was necessary to use the Llorente and Palacios (Llorente, L.; Palacios, E., 2010) table.

A local-scale landslide hazard map was generated. In the Annexe chapter it is attached.

### 3.1.2.4. Exposure elements at local scale

The geospatial information was obtained in geodata bases provided by the Earthquake Engineering Research Group (GIIS) and also from the internet (OpenStreetMap and HaitiData websites).

The important exposure elements in this scale of study (local scale) were streets, highways, settlements, water pipes and hospitals. This geoinformation shows where the elements are disposed in the terrain and how population and their communications ways are distributed in the city.

### 3.1.2.5. Landslide risk at local scale

Landslide risk was obtained overlapping the landslide hazard and the exposure elements at local scale in GIS software. It can be observed how streets, highways, settlements, water pipes and hospitals can be affected by landslide hazard. It shows in a qualitative way where the main risk zones are located. This landslide risk map is a tool for decision makers in order to reduce the disasters associated with this risk. Sustainable land management measures are possible with this knowledge.

With this result, analyses about which settlements, roads, water pipes and hospital could be affected by landslide hazard were made.

A local-scale landslide risk map and different maps of the analyses made were generated. In the Annexe chapter they are attached.
3.2. Land tenure information and methodology used

After landslide risk study at local scale was obtained, it was possible to know which zones of the selected city were in the highest landslide risk area. These zones were called priority zones. It is in them where it is more urgent to implement a land management in order to reduce the risk.

The information used was the current land tenure of Haiti and the landslide risk map at local scale.

3.2.1. Land tenure

Land tenure is the relationship, whether legally or customarily defined, among people, as individuals or groups, with respect to land. Rules of tenure define how property rights to land are to be allocated within societies. They define how access is granted to rights to use, control, and transfer land, as well as associated responsibilities and restraints. It is an important part of social, political and economic structures. It is multi-dimensional, bringing into play social, technical, economic, institutional, legal and political aspects that are often ignored but must be taken into account (FAO, Food and agriculture organization of the united, 2002).

Land tenure information was obtained through Haitian governmental agencies, experts and inhabitants of Haiti in order to have different points of view of the Haitian reality. The collected information was about which is the predominantly land access, if a cadastre is developed and if strategic plans exist, among others.

It is necessary to know how the country is structured in land tenure terms, but also to know if different land management plans are implanted to formulate new land management measures inside them in order to mitigate the landslide hazard.

3.2.2. Land management at landslide risk zones

When land tenure of the study zone was known, it was important to join it with the zones where landslide risk is significant.

Landslide risk has to be solved in terms of land tenure. Landslides risk zones must have a regulation in order to reduce landslide disasters. Land tenure is an important tool to reduce the possible disasters that can happen.

To solve the possible land tenure insecurity, it is necessary to make studies of the infrastructures and settlements of the study zone that are located in these priority areas, in order to know how they can be affected by the landslide risk.

Infrastructures and settlements in priority zones have to be studied. Alternative locations or landslide-resistant policies must be investigated. Recommendations should be given to mitigate the damages in order to make the city less vulnerable to the risk but more resilient.
4. Results and analysis
This chapter presents the results obtained after applying the methodology explained in chapter 3 and some analyses of the achieved results. The chapter is structured in two parts aimed at showing results of landslide risk and land management respectively.

4.1. Landslide risk results and analysis
The landslide risk study was developed using several software tools which have provided the zones with highest risk in Haiti (regional scale) and in Port au Prince (local scale). It was possible due to interaction of different inputs of information, like a digital terrain model (DTM), geological maps, exposure elements and seismic hazard studies among others.

These landslide risk results and analyses are structured, as well as chapter 3, in two parts: regional scale studies and local scale studies.

4.1.1. Landslide risk results at regional scale
This study was made using data with 20 meters of spatial resolution, which it is not enough to know with high precision how landslides can be, but for a regional scale it is enough, because it is just to identify the places with highest risk.

The study was made in an UTM projection, zone 18 North, with WGS84 ellipsoid of reference and the software tools used were ArcGIS v 10 (ESRI), Crisis and Expel.

4.1.1.1. Landslide susceptibility results at regional scale.
In this case of study, based on Mendoza and Dominguez (2002) methodology, it was only possible to work with topographical and geological factors. Geomorphologic, environmental, historical and part of geotechnical factors were not possible to find due to the fact that Haiti is a developing country and nowadays all these required data are not available.

Nonetheless, the Earthquake Engineering Research Group (GIIS), from Technical University of Madrid (UPM), implemented the methodology with other inputs based on available data which were considered important to be included. These new inputs were the slope orientation and water flows in the land.

- Slope orientation factor is important because it can influence in the start of the slide, due to the moisture retained. The humidity condition is a factor that affects landslides susceptibility.
- Water flows in the land is another important input due to the fact of the humidity conditions too. It locates the place where water can run over the land.

The ArcGIS v 10 (ESRI) software was used in this part.
Topographical factors

Topographical factors were made with a digital terrain model with a 20 meters resolution (Figure 16). This digital terrain model was obtained through contour equidistance of 20 meters. The most western part of the country was not available in the digital terrain model, so the study was limited to the part with available data.

![Figure 16. Digital terrain model of Haiti. Own figure, 2013](image1)

The next factors were obtained with the digital terrain model:

**Slope factor:** this factor identifies the inclination degree of the slopes from each cell of a raster surface (ArcGIS, 2013). The susceptibility is proportional to the slope inclination degree (Figure 17). The slope degree values are between 0 and 86.42 degrees.

![Figure 17. Slope factor of Haiti. Own figure, 2013](image2)
This factor was classified in 5 intervals, as Mendoza and Dominguez (2002) methodology establishes (Table 7). Figure 18 shows the classification of the country in these intervals.

Table 7. Slope factor at regional scale. Mendoza and Dominguez (2002).

<table>
<thead>
<tr>
<th>GRADE</th>
<th>0° - 15°</th>
<th>15° - 25°</th>
<th>25° - 35°</th>
<th>35° - 45°</th>
<th>More than 45°</th>
</tr>
</thead>
<tbody>
<tr>
<td>FACTOR</td>
<td>5</td>
<td>10</td>
<td>14</td>
<td>18</td>
<td>20</td>
</tr>
</tbody>
</table>

In Figure 18, it can be observed that the zones with high reliefs have the highest factor while the lowest factor corresponds to the planar zones.

**Slope orientation**: this factor identifies the down slope direction of the maximum rate of change in value from each cell to its neighbours. The values of the output raster were the compass direction of the aspect (ArcGIS, 2013), classified in 8 intervals (North, North-East, East, South-East, South, South-West, West and North-West). Slope orientation can influence in the initiation of a landslide due to the moisture retained (Figure 19).
This factor was classified in four different intervals depending on the moisture retained of every orientation (Figure 20). A higher value was given to the orientations where the rainfalls are more intensive (the North and North-East hillsides) and a lower value in the remaining orientations (the South and South-West hillsides) (Canal Socio, 2013), (GIIS). Table 8 shows these values. Figure 21 shows the classification of the country in these intervals.

Table 8. Slope orientation factor at regional scale. Own classification, 2013.

<table>
<thead>
<tr>
<th>GRADE</th>
<th>SLOPE ORIENTATION</th>
<th>FACTOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>0° - 67.5°</td>
<td>0° - 112.5°</td>
<td>20</td>
</tr>
<tr>
<td>67.5° - 112.5°</td>
<td>112.5° - 157.5°</td>
<td>15</td>
</tr>
<tr>
<td>157.5° - 202.5°</td>
<td>202.5° - 247.5°</td>
<td>10</td>
</tr>
<tr>
<td>247.5° - 292.5°</td>
<td>292.5° - 337.5°</td>
<td>15</td>
</tr>
<tr>
<td>337.5° - 360°</td>
<td>360° - 45°</td>
<td>20</td>
</tr>
</tbody>
</table>

In Figure 21, it is observed how down slope orientations are distributed in the country. The majority of the down slope directions are in North, North-East, South and South-West, while the rest of directions are in minority. It shows that the relief of the country follows North-West to South-East direction.
Hillsides factor: this factor identifies the length of every hillside. The landslide susceptibility is proportional to this factor (Figure 22).

It was classified in 4 intervals as Mendoza and Dominguez (2002) methodology establishes (Table 9). Figure 23 shows the classification of the country in these intervals.

<table>
<thead>
<tr>
<th>HILLSIDE FACTOR</th>
<th>0-50 m</th>
<th>50-100 m</th>
<th>100-200 m</th>
<th>More than 200 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>RAMP</td>
<td>6</td>
<td>12</td>
<td>16</td>
<td>20</td>
</tr>
<tr>
<td>FACTOR</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 23 shows where the longest hillsides are distributed. It can be observed that the majority of the longest hillsides are located in the same places where the slope factor is also the highest.

**Water flows in the land:** this factor shows the direction that a raindrop can follow in the land due to the gravity force and the topographic conditions (Figure 24). A numeric order is assigned to segments of a raster representing branches of a linear network, following the Strahler method (ArcGIS, 2013).
In the Strahler method, all river segment links without any tributaries are assigned an order of 1 and are referred to as first order. The stream order increases when streams of the same order intersect. Therefore, the intersection of two first-order links will create a second-order link, the intersection of two second-order links will create a third-order link, and so on. The intersection of two links of different orders, however, will not result in an increase in order (Figure 25). For example, the intersection of a first-order and second-order link will not create a third-order link but will retain the order of the highest ordered link. The Strahler method is the most common stream ordering method. However, because this method only increases in order at intersections of the same order, it does not account for all links and can be sensitive to the addition or removal of links (ArcGIS, 2013).

The factor was classified in 4 intervals by the Earthquake Engineering Research Group (GIIIS), following own criteria, according to the importance of each river segment in landslide susceptibility (Table 10), being less important the big and consolidated rivers (river segment with a high order in the Strahler method) but more important the small streams that are in the top of the mountains (river segment with low value in Strahler method), due to the fact that reliefs in these parts are not consolidated and they are more susceptible to produce landslides. This factor was considered important because Haiti has a tropical climate, with heavy frequent rainfalls and also has many deforested zones. Figure 26 shows the classification of the country in these intervals.

**Table 10. Water flows in the land at regional scale. Own classification, 2013.**

<table>
<thead>
<tr>
<th>CATEGORY</th>
<th>WATER FLOW IN THE LAND FACTOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>FACTOR</td>
<td>Unconsolidated streams</td>
</tr>
<tr>
<td>20</td>
<td>15</td>
</tr>
</tbody>
</table>
Figure 26 shows that there are a lot of unconsolidated streams due to the relief of the country.

**Geological factor**

The geological factor is based on the geological map of Haiti. It was obtained from the Earthquake Engineering Research Group (GIIS). It shows the different types of geology zones and their different types of soils that appear in the study zone. These different types of soil were classified according to the landslide susceptibility degree by the Earthquake Engineering Research Group (GIIS) criterion (Table 11). The classification of the country according to this factor is shown in Figure 27.

<table>
<thead>
<tr>
<th>DESCRIPTION OF GEOLOGY ZONES</th>
<th>FACTOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ecoglite</td>
<td>4</td>
</tr>
<tr>
<td>Cretaceous andesitic to silicic volcanic rocks</td>
<td>8</td>
</tr>
<tr>
<td>Cretaceous plutons, mostly intermediate to silicic</td>
<td>8</td>
</tr>
<tr>
<td>Mesozoic amphibolites and associated metasedimentary rocks</td>
<td>8</td>
</tr>
<tr>
<td>Mesozoic metasedimentary and metaigneous rocks, low to intermediate metamorphic</td>
<td>8</td>
</tr>
<tr>
<td>Volcanic rocks</td>
<td>8</td>
</tr>
<tr>
<td>Ultramafic rocks</td>
<td>8</td>
</tr>
<tr>
<td>Tertiary and Cretaceous plutons, mostly intermediate to silicic</td>
<td>8</td>
</tr>
<tr>
<td>Mesozoic metavolcanic and associated metasedimentary rocks</td>
<td>12</td>
</tr>
<tr>
<td>Mesozoic sedimentary and volcanic rocks</td>
<td>12</td>
</tr>
<tr>
<td>Tertiary marine strata</td>
<td>12</td>
</tr>
<tr>
<td>Tertiary volcanic rocks</td>
<td>12</td>
</tr>
<tr>
<td>Upper Cretaceous marine strata</td>
<td>12</td>
</tr>
<tr>
<td>Cretaceous sedimentary and volcanic rocks</td>
<td>12</td>
</tr>
<tr>
<td>Cretaceous volcanic rocks</td>
<td>12</td>
</tr>
<tr>
<td>Eocene and Paleocene volcanic flows and associated pyroclastic and volcanoge</td>
<td>16</td>
</tr>
<tr>
<td>Eocene and(or) Paleocene marine strata</td>
<td>16</td>
</tr>
<tr>
<td>Post-Eocene marine strata</td>
<td>16</td>
</tr>
<tr>
<td>Quaternary and Tertiary volcanic edifices, flows, tuff, silicic pyroclastic</td>
<td>16</td>
</tr>
<tr>
<td>Quaternary volcanic edifices, flows, and pyroclastic deposits</td>
<td>16</td>
</tr>
<tr>
<td>Quaternary alluvium</td>
<td>20</td>
</tr>
</tbody>
</table>
Figure 27 shows that the majority of the geological materials present high or very high landslide susceptibility, because green zones (less susceptible zones) are not very common. It means that the geology factor is important in this case of study of landslide susceptibility.

After all landslide susceptibility inputs were known and as Mendoza and Dominguez (2002) methodology indicates, it was necessary to review the weight of every interval of each factor. In this study, the weight of every interval of each factor was homogenized in values ranking between 0 and 20 (0 means that it is not important and 20 means that it is very important), due to have all data in the same scale of values.

The next step was to know the value of importance of the different susceptibility factors. It was done by a multi criteria evaluation (MCE), where every factor got a weight that explained how important is compared against each other. An example is shown in Table 12. It was made with the Analytic Hierarchy Process tool of ArcGIS (AHP).

Table 12. Example scale for comparisons, (Saaty & Vargas, 1991)

<table>
<thead>
<tr>
<th>Intensity of importance</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Equal importance</td>
</tr>
<tr>
<td>3</td>
<td>Moderate importance of one factor over another</td>
</tr>
<tr>
<td>5</td>
<td>Strong or essential importance</td>
</tr>
<tr>
<td>7</td>
<td>Very strong importance</td>
</tr>
<tr>
<td>9</td>
<td>Extreme importance</td>
</tr>
<tr>
<td>2, 4, 6, 8</td>
<td>Intermediate values</td>
</tr>
<tr>
<td>Reciprocals</td>
<td>Values for inverse comparison</td>
</tr>
</tbody>
</table>
A value of 1 expresses “equal importance” between factors and a value of 9 is given for those factors having an “extreme importance” over another factor (Satecs, 2013).

These values were assigned by the Earthquake Engineering Research Group (GIIS) criteria, with the knowledge of previous studies of landslides in the Caribbean and South America (Table 13).

Table 13. Weight matrix of susceptibility factors at regional scale. Own figure, 2013.

<table>
<thead>
<tr>
<th></th>
<th>Slope</th>
<th>Geology</th>
<th>Slope orientation</th>
<th>Water flows</th>
<th>Hillside</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slope</td>
<td>1</td>
<td>2</td>
<td>4</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>Geology</td>
<td>0.5</td>
<td>1</td>
<td>5</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Slope orientation</td>
<td>0.25</td>
<td>0.2</td>
<td>1</td>
<td>0.333333</td>
<td>3</td>
</tr>
<tr>
<td>Water flows</td>
<td>0.5</td>
<td>0.5</td>
<td>3</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>Hillside</td>
<td>0.2</td>
<td>0.5</td>
<td>0.333333</td>
<td>0.25</td>
<td>1</td>
</tr>
</tbody>
</table>

This matrix of Table 13 was introduced in software tool of ArcGIS (AHP), in order to obtain the real weight of every factor in a normalized way.

The final weight factors were the next:

- \( \text{Slope factor} = 0.3734 \)
- \( \text{Geological factor} = 0.2694 \)
- \( \text{Slope orientation factor} = 0.0937 \)
- \( \text{Water flows in the land factor} = 0.1974 \)
- \( \text{Hillside factor} = 0.0661 \)

With these results, it is important to observe that the most important factors of landslide susceptibility are the slope and the geology, and the less important was the hillside, only with a 6% of importance. After obtaining these weights, the next step was to calculate the landslide susceptibility values. It was made adding to the raster calculator of ArcGIS the raster factors multiplied by their own weights, according to the next equation:

\[
\text{Landslide Susceptibility} = (\text{Slope factor} \times 0.3734) + (\text{Geology factor} \times 0.2694) + (\text{Water flows in the land factor} \times 0.1974) + (\text{Hillsides factor} \times 0.0661) + (\text{Slope orientation factor} \times 0.0937)
\]

The landslide susceptibility values obtained were normalized between 0 and 20, and classified in 5 intervals (Table 14). The results obtained in our case (Figure 28) show that “very low” susceptibility zones are not found in Haiti, so values between 0 and 4 do not appear in any case.

Table 14. Susceptibility classification at regional scale. Own figure, 2013.

<table>
<thead>
<tr>
<th>SUSCEPTIBILITY</th>
<th>VALUES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very low</td>
<td>0–4</td>
</tr>
<tr>
<td>Low</td>
<td>4–8</td>
</tr>
<tr>
<td>Moderate</td>
<td>8–12</td>
</tr>
<tr>
<td>High</td>
<td>12–16</td>
</tr>
<tr>
<td>Very high</td>
<td>16–20</td>
</tr>
</tbody>
</table>
The map of landslide susceptibility factor shows how the terrain could be affected by landslides. In Figure 28, it can be observed that the larger part of the country has a ‘moderate’ landslide susceptibility value. In mountainous areas, the landslide susceptibility values are higher, from ‘high’ to ‘very high’ values. These values are located especially in the South and the South-East of the country. The Northern part of the country has ‘low’ and ‘moderate’ landslide susceptibility, especially in the North-East.

In general, landslide susceptibility increases with slope and in weaker rocks (Geological Survey of Alabama, 2013). In this study, the slope factor and the geological factor were the most important ones in landslide susceptibility.

To sum up, the highest values of landslide susceptibility at regional scale are located in mountainous regions, especially in the South and the South-East of Haiti.

A map called ‘Landslide susceptibility of Haiti’ is attached in the annexes.
4.1.1.2. Trigger at regional scale
Landslides can occur without the influence of an earthquake, but strong shaking can act as a trigger for multiple slope driven ground failures that otherwise might not occur simultaneously (RMS, 2010).

Seismic trigger was obtained following the Probabilistic Seismic Hazard Assessment (PSHA) and using a hybrid model of seismogenic zones and faults as independent units. The necessary inputs were a seismic catalogue, the seismogenic zones and the faults with their own characteristic parameters, and attenuation models. The software needed were Expel, Crisis and ArcGIS. This result was obtained from Ruiz (2013) master thesis, called ‘Multi-hazard analysis and identification of priority settlement for land management in Haiti’, where seismic hazard of Haiti was investigated.

With this methodology and with these inputs, the seismic hazard was estimated in terms of peak ground acceleration (PGA) in a 0.1° interval grid in the study zone. These data were interpolated using ArcGIS, giving a seismic hazard map for the return period of 475 years.

This map was generated with the same spatial resolution as the landslide susceptibility map (20 meters), in order to make both compatible with each other.

Figure 29 shows the distribution of seismic hazard values of Haiti. It can be observed that the highest values of PGA are located in the South of the country, especially close to Port au Prince. The maximum PGA values obtained are around the Enriquillo fault reaching values of up to 440 cm/s² (Ruiz, 2013).

Figure 29. Seismic hazard at local scale. Ruiz, 2013.
This factor was classified in different intervals in order to know how strong the hazard is. It was classified with the GIIS criterion (Table 15).
Table 15. Classification of seismic hazard values at regional scale. Own figure, 2013

<table>
<thead>
<tr>
<th>SEISMIC HAZARD</th>
<th>GAL VALUES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>171.63 &lt; gal &lt; 196.2</td>
</tr>
<tr>
<td>Moderate</td>
<td>196.2 &lt; gal &lt; 251.6</td>
</tr>
<tr>
<td>High</td>
<td>261.6 &lt; gal &lt; 327</td>
</tr>
<tr>
<td>Very high</td>
<td>327 &lt; gal &lt; 440.79</td>
</tr>
</tbody>
</table>

4.1.1.3. Landslide hazard at regional scale
The landslide susceptibility map of Haiti was combined with the seismic hazard results, in order to obtain the landslide hazard map of Haiti.

Figure 30 shows that most part of the country presents values of landslide hazard in the classes ‘moderate’ and ‘high’. The zones with highest landslide hazard are located in the South of the country, especially in the South of Port au Prince, the capital of the country. Also, in the
Northern part of the country the landslide hazard is ‘high’. ‘Low’ values are only located in small zones in the North-West of the country.

"Anywhere you have strong motion and steep terrain, you have extremely high risk of slope failure and landslides, and they can be extremely large," said Colin Stark, a geophysicists at the Lamont-Doherty Earth Observatory in New York (Than, 2010).

A map called ‘Landslide hazard of Haiti’ is attached in the annexes.

4.1.1.4. Exposure at regional scale
Exposure elements at regional scale are the main important infrastructures and cities of the country. In this case, main cities and main roads were taken into account. There are only these types of elements due to the scale of study.

Figure 31 shows the distribution of this geographical information across the country.

4.1.1.5. Landslide risk at regional scale
The regional-scale landslide risk map has been calculated joining the landslide hazard map and the exposure elements at regional scale. It is observed which cities and infrastructures are located in ‘high’ and ‘very high’ hazard areas.

David Álvarez Castro.
Master Thesis
Figure 32 shows that Port au Prince is one of the cities with the highest landslide risk, especially in its Southern part, with values between high and very high. Also, in the Western part of Port au Prince, there is another city called Léogâne with high and very high landslide risk.

There are also highways that can be affected by landslides, especially in the Southern part of the country, like the highway that connects Port au Prince and Léogâne and also the highway that starts in Port au Prince and continue to the Eastern part of the country. These two highways are the most risky roads.

A map called ‘Landslide risk of Haiti’ is attached in the annexes.

Once the highest landslide risk zones at regional scale have been obtained, it is the moment to choose the place in which landslide risk at local scale should be studied, with more precise data in order to know in a better detail how this place can be affected by landslides.
4.1.2. Landslide risk results at local scale

The selected place to make this study was Port au Prince. This city was chosen because it presents high and very high landslide risk values as it can be observed in landslide risk at regional scale (Figure 32), especially in the hilly Southern part of the city. It was also selected because it is a very populated city, where inhabitants live widespread in an irregular way. These inputs made Port au Prince an interesting place to study landslide risk.

The study was made in an UTM projection, zone 18 North, with WGS84 ellipsoid of reference and the software used were ArcGIS v10 (ESRI), Crisis and Expel. This study also followed the steps described at figure 12.

4.1.2.1. Landslide susceptibility at local scale

This case of study was based on Mendoza and Dominguez (2002) methodology too. As well as at regional scale, it was possible to work with topographical and geological factors. As for the study sites, the land use factor at local scale was available, this was incorporated in the calculation. Geomorphologic, environmental, historical and part of geotechnical factors were not found neither at local scale. The slope orientation and water flows in the land factors were implemented in the methodology as in the regional scale approach.

ArcGIS software was used in this part.

Topographical factors

Local-scale topographic factors were obtained from LiDAR data, available online in OpenTopography website (OpenTopography).

These LiDAR data were collected between January 21st and January 27th, 2010, in response to the January 12th Haiti earthquake. These data have a density of 3.40 points/m², which provide high quality detailed results of the city.

The data collection was performed by the Center for Imaging Science at Rochester Institute of Technology (RIT) and Kucera International under sub-contract to ImageCat, Inc., and funded by the Global Facility for Disaster Recovery and Recovery (GFDRR) hosted at the World Bank.
Once LiDAR data were processed, a digital terrain model with one meter of spatial resolution was created, only with points that were in the ground and avoiding point of buildings and vegetation (Figure 34).

![Digital terrain model of Port au Prince. Own figure, 2013.](image)

In this case, the topographical factors obtained were: slope factor, slope orientation factor and water flows in the land factor. At local scale, the hillside factor was not considered because in the regional scale study it was concluded that this factor was not as important as the others (its weight of importance was only the 6%).

**Slope factor:** this factor identifies the inclination degree of the slopes from each cell of a raster surface (ArcGIS, 2013). The slope inclination degree is proportional to the landslide susceptibility. The slope degree values are between 0 and 82.55 degrees (Figure 35).
This factor was classified in 5 intervals (Table 16), according to the methodology of Mendoza and Dominguez (2002). Figure 36 shows the distribution of this factor in Port au Prince.


<table>
<thead>
<tr>
<th>GRADE</th>
<th>0° - 15°</th>
<th>15° - 25°</th>
<th>25° - 35°</th>
<th>35° - 45°</th>
<th>More than 45°</th>
</tr>
</thead>
<tbody>
<tr>
<td>FACTOR</td>
<td>5</td>
<td>10</td>
<td>14</td>
<td>18</td>
<td>20</td>
</tr>
</tbody>
</table>

It is appreciated that the main part of the city has a ‘low’ inclination degree and only in the South-West, South and South-East of the city there are some parts with ‘high’ and ‘very high’ inclination degrees. As it was shown previously, slope factor is one of the most important factors in landslide susceptibility, so the main landslide susceptibility zones are going to be focused in the South-West, South and South-East parts of the city.

**Slope orientation**: this factor identifies the down slope direction of the maximum rate of change in value from each cell to its neighbours. The values of the output raster were the compass direction of the aspect (ArcGIS, 2013). It was classified in 8 intervals (North, North-East, East, South-East, South, South-West, West and North-West). The slope orientation can have significant influence in the initiation of a landslide due to the moisture retained (Figure 37).
This factor was classified in four different intervals, depending on the intensity of rainfalls in the different slopes orientations, similarly to the regional scale study (Figure 38).

Table 8 shows these values. Figure 39 shows the classification of the country in these intervals.

Table 17. Slope orientation factor at local scale. Own classification, 2013.

<table>
<thead>
<tr>
<th>SLOPE ORIENTATION</th>
<th>GRADE</th>
<th>FACTOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>0° - 67.5°</td>
<td>20</td>
<td>15</td>
</tr>
<tr>
<td>67.5° - 112.5°</td>
<td>15</td>
<td>10</td>
</tr>
<tr>
<td>112.5° - 157.5°</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>157.5° - 202.5°</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>202.5° - 247.5°</td>
<td>10</td>
<td>15</td>
</tr>
<tr>
<td>247.5° - 292.5°</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>292.5° - 337.5°</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>337.5° - 360°</td>
<td>15</td>
<td>15</td>
</tr>
</tbody>
</table>
**Water flows in the land:** this factor shows the direction that a raindrop can follow in the land due to the gravity force and the topographic conditions. The Strahler method (ArcGIS, 2013) was followed, as in the regional scale assessment.

As the spatial resolution was one meter, it was necessary to increase the width of the rivers, because the consolidated rivers have more than one meter of flow width. In order to know the width of the different rivers and streams of the city, it was necessary to measure some of them in aerial photos. The average of the each different type of rivers and streams gave a width value for them. In this case, for big and consolidated rivers a width of 8 meters was established, for consolidated medium rivers 4 meters, for streams 2 meters and for unconsolidated streams 1 meter.

This factor was considered important because Haiti has a tropical climate, with abundant rainfalls and also has extensive deforested zones. "If you remove the trees, you have no buffer. So the water"—and soil—"tends to very quickly move downhill," said Mark Ashton, a professor at the Yale School of Forestry and Environmental Studies (Than, 2010).

The factor was classified in different intervals according to the importance of all categories, being less important the big and consolidated rivers and more important the small streams that are in the top of the mountains, due to the fact that they are not consolidated and are more susceptible to produce landslides. It was classified in 4 intervals following the Earthquake Engineering Research Group (GIIS) criterion (Table 18). With this classification the distribution of this factor in Port au Prince is shown in Figure 40.

**Table 18. Water flows in the land factor. Own classification, 2013.**

<table>
<thead>
<tr>
<th>CATEGORY</th>
<th>Unconsolidated streams</th>
<th>Streams</th>
<th>Consolidated medium rivers</th>
<th>Consolidated big rivers</th>
</tr>
</thead>
<tbody>
<tr>
<td>FACTOR</td>
<td>20</td>
<td>15</td>
<td>10</td>
<td>5</td>
</tr>
</tbody>
</table>

Figure 39. Slope orientation at local scale classified. Own figure, 2013.
Geological factor

The geological factor was obtained from the Haiti data website (Haitidata). It shows the different types of geological zones and the different types of soils that appear in the study zone. These different types of soil were classified according to the landslide susceptibility degree following the Earthquake Engineering Research Group (GIIS) criterion, as well as it was done at regional scale (Table 19).

Table 19. Description of geological zones at local scale. GIIS classification, 2013.

<table>
<thead>
<tr>
<th>DESCRIPTION OF GEOLOGICAL ZONES</th>
<th>FACTOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Af - Artificial fill forming reclaimed land west of the mapped 1796 shoreline</td>
<td>15</td>
</tr>
<tr>
<td>EMS/ems - Biomicrites pelagic of Presquie of the South and the Southern slope of the Massif of No*</td>
<td>5</td>
</tr>
<tr>
<td>En/eep - Conglomerates and sandstone volcanogenes of Massif de la Selle (fm. Margot); matrix, grès et*</td>
<td>7</td>
</tr>
<tr>
<td>Lmst - limestone bedrock exposed along rangefront</td>
<td>5</td>
</tr>
<tr>
<td>Mpb - Tanglecerate/olus deposits consisting of coarse, angular “breccia”</td>
<td>8</td>
</tr>
<tr>
<td>Pf - Pliocene fan deposits forming a deeply dissected paleo fan complex along the rangefront</td>
<td>13</td>
</tr>
<tr>
<td>Ppl - Broad, deeply incised strat surface (or fan deposit veneer) developed over Pliocene fan</td>
<td>8</td>
</tr>
<tr>
<td>Ga - Alluvial, fall, mangroves</td>
<td>13</td>
</tr>
<tr>
<td>Chic - Stream channel alluvium; typically well sorted, bedded, unconsolidated sand, silty sand</td>
<td>20</td>
</tr>
<tr>
<td>Chad - Delta fan deposits along the western margin of the map area</td>
<td>15</td>
</tr>
<tr>
<td>Cham - Marine/exmarine deposits interfingered with alluvial fan deposits and local fill</td>
<td>16</td>
</tr>
<tr>
<td>Ch1 - Lower alluvial terrace deposits/surfaces with areas of historic flood inundation</td>
<td>14</td>
</tr>
<tr>
<td>Ch12 - Raised alluvial terrace deposits/surfaces bordering major streams and margins of intermont*</td>
<td>14</td>
</tr>
<tr>
<td>Cpl - Fan deposits forming steep fans at the rangefront</td>
<td>14</td>
</tr>
<tr>
<td>Cphf - Alluvial fan/plain deposits</td>
<td>15</td>
</tr>
</tbody>
</table>
Figure 41 shows how the geological factor is disposed in Port au Prince. The southern part is less susceptible than the shoreline zone. However, some long and narrow zones in the South have very high susceptibility. These zones correspond to the materials with the highest susceptibility behaviour.

**Land use factor**

The land use factor was obtained in Haiti data website (Haitidata). Land use factor provides the use of land of every part of the study zone. Each land use corresponds to a different in landslide susceptibility due to its own characteristics. The factor assigned to each land use, based on Mendoza and Dominguez (2002) methodology, is shown in Table 20.

<table>
<thead>
<tr>
<th>LAND USE</th>
<th>FACTOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urban continuous</td>
<td>0</td>
</tr>
<tr>
<td>Urban discontinuous</td>
<td>3</td>
</tr>
<tr>
<td>Industrial zones</td>
<td>0</td>
</tr>
<tr>
<td>Ports and airports</td>
<td>0</td>
</tr>
<tr>
<td>Savannas with the presence of other</td>
<td>8</td>
</tr>
<tr>
<td>Outcrop of rocks and bare soil</td>
<td>20</td>
</tr>
</tbody>
</table>

Table 20. Land use factor at local scale. Mendoza and Dominguez, 2002.
Many landslides start in zones with scarce vegetation or deforested zones (García Rodríguez, 2008). Figure 42 shows how land uses are distributed in Port au Prince with its landslide susceptibility factor.

![Figure 42. Land use factor classified at local scale. Own figure, 2013.](image)

Once all susceptibility factors were known, it was possible to obtain the landslide susceptibility values of Port au Prince.

In order to obtain these values, it was necessary to compare every factor against each other to get the weight of everyone in the same way as at regional scale, with the Analytic Hierarchy Process tool of ArcGIS (AHP). These values were assigned by the Earthquake Engineering Research Group (GIIS) criteria, with the knowledge of previous studies of landslides in the Caribbean and South America (Table 21).

<table>
<thead>
<tr>
<th></th>
<th>Slope</th>
<th>Geology</th>
<th>Slope orientation</th>
<th>Water flows</th>
<th>Land use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slope</td>
<td>1</td>
<td>2</td>
<td>4</td>
<td>2</td>
<td>7</td>
</tr>
<tr>
<td>Geology</td>
<td>0.5</td>
<td>1</td>
<td>5</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>Slope orientation</td>
<td>0.25</td>
<td>0.2</td>
<td>1</td>
<td>0.333333</td>
<td>0.333333</td>
</tr>
<tr>
<td>Water flows</td>
<td>0.5</td>
<td>0.5</td>
<td>3</td>
<td>1</td>
<td>0.5</td>
</tr>
<tr>
<td>Land use</td>
<td>0.142857</td>
<td>0.2</td>
<td>3</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 21. Weight matrix of susceptibility factors at local scale. Own classification, 2013.
This matrix of Table 21 was introduced in software tool of ArcGIS (AHP), in order to obtain the real weight of every factor in a normalized way.

The final weight factors were the next:

- \( \text{Slope factor} = 0.4128 \)
- \( \text{Geological factor} = 0.2902 \)
- \( \text{Slope orientation factor} = 0.0536 \)
- \( \text{Water flows in the land factor} = 0.1262 \)
- \( \text{Land use factor} = 0.1172 \)

With these results it is important to remark that, as a conclusion of this local scale study of landslide susceptibility, the most important factors are the slope and the geology. A similar conclusion was derived at regional scale. The less important factor was the slope orientation factor, only with a 5% of importance. When all these weights were known, the next step was aimed at the calculation of the landslide susceptibility values by combination of the different factors with their corresponding weights. It was made adding to the raster calculator of ArcGIS the raster factors multiplied by their own weights.

\[
\text{Landslide Susceptibility} = (\text{Slope factor} \times 0.4128) + (\text{Geology factor} \times 0.2902) + (\text{Water flows in the land factor} \times 0.1262) + (\text{Land use factor} \times 0.1172) + (\text{Slope orientation factor} \times 0.0536)
\]

After that, the landslide susceptibility values were normalized between 0 and 20, classified in 5 intervals (Table 22).

**Table 22. Landslide susceptibility values at local scale. Own classification, 2013.**

<table>
<thead>
<tr>
<th>SUSCEPTIBILITY</th>
<th>VALUES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very low</td>
<td>0--4</td>
</tr>
<tr>
<td>Low</td>
<td>4--8</td>
</tr>
<tr>
<td>Moderate</td>
<td>8--12</td>
</tr>
<tr>
<td>High</td>
<td>12--16</td>
</tr>
<tr>
<td>Very high</td>
<td>16--20</td>
</tr>
</tbody>
</table>
It can be observed in Figure 43 that the average of the landslide susceptibility value is ‘low’ in the city centre but ‘moderate’ and ‘high’ in the Southern part of the city and also in some parts of the East. ‘Very high’ values are only localized in the South-West part of Port au Prince and some parts of the South-East. These zones contain the steepest slopes and the most susceptible materials. In the city centre landslide susceptibility is ‘low’ due to the fact that it is a planar zone with little slopes.

The Southern parts of Port-au-Prince, as well as the upland region along the Enriquillo-Plantain Garden fault zone, have many areas where steep slopes combined with long-term deforestation have created high landslide susceptibility (RMS, 2010). In the South-Western part of the study zone, where ‘very high’ landslide susceptibility values are located, steep slopes and deforested zones concur.

A map called ‘Landslide susceptibility of Port au Prince’ is attached in the annexes.

It is important to note, that some zones with ‘high’ or ‘very high’ landslide susceptibility values are not located in mountainous zones. These places correspond to water-courses. Slopes that surround them are very high and also geological materials make that landslide susceptibility increases, because the most susceptible material is ‘stream channel alluvium; typically well-sorted, bedded, unconsolidated sand, silty sand’, where water courses go. Therefore, these zones have to be also considered and taken into account as a landslide susceptibility zone. Some of these zones are marked in Figure 44.
4.1.2.2. Trigger at local scale

The seismic trigger at local scale was obtained through a deterministic hazard study. In a deterministic hazard scenario, the ground motion caused by a single earthquake is the landslide triggering factor. This earthquake is the so-called ‘controlling earthquake’, which is the earthquake that contributes in the highest measure to a given hazard-consistent target motion.

The magnitude and distance which define the ‘controlling earthquake’ were 7 Mw and 10 km, respectively, which were obtained in the hazard deaggregation. A determinist hazard study was developed with the ground motion prediction equation (or attenuation law) of Boore and Atkinson, (2011). The local effect was considered through the vs30 factor. In order to get this, it was used a micro-zonation of the study zone.

Applying the selected ground motion prediction equation (GMPE) and the micro-zonation, it was obtained the acceleration values for each section of Port au Prince (Figure 45).

This result was obtained from Ruiz 2013, (Ruiz, 2013).
Figure 45. Seismic hazard at local scale. Ruiz, 2013.

These PGA values were classified in different intervals in order to identify classes according the seismic hazard, following the GIIS criterion (Table 23).

Table 23. Classification of seismic hazard as a function of the PGA values at local scale. GIIS classification, 2013

<table>
<thead>
<tr>
<th>SEISMIC HAZARD</th>
<th>PGA VALUES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very low</td>
<td>PGA &lt; 0.001g</td>
</tr>
<tr>
<td>Low</td>
<td>0.001g &lt; PGA &lt; 0.04g</td>
</tr>
<tr>
<td>Moderate</td>
<td>0.04g &lt; PGA &lt; 0.2g</td>
</tr>
<tr>
<td>High</td>
<td>0.2g &lt; PGA &lt; 0.6g</td>
</tr>
<tr>
<td>Very high</td>
<td>PGA &gt; 0.6g</td>
</tr>
</tbody>
</table>

The expected values of PGA in Port au Prince range in the interval of 0.26 to 0.34 g. Therefore, the entire city falls in the High Seismic Hazard category (Figure 46).
4.1.2.3. Landslide hazard at local scale
When landslide susceptibility and seismic hazard values of Port au Prince were known, it was possible to obtain the landslide hazard values of the study zone. As well as at regional scale, Llorente and Palacios (2010) methodology was used.

In this case, the classes of landslide hazard were defined from the combination of classes of landslide susceptibility and seismic hazard, according the criterion of Table 24.

Table 24. Landslide hazard classification at local scale. Own classification, 2013.

<table>
<thead>
<tr>
<th>SUSCEPTIBILITY</th>
<th>SEISMIC HAZARD</th>
<th>LANDSLIDE HAZARD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very low</td>
<td>High</td>
<td>Very low</td>
</tr>
<tr>
<td>Low</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Moderate</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>High</td>
<td>High</td>
<td>Very high</td>
</tr>
<tr>
<td>Very high</td>
<td>High</td>
<td>Very high</td>
</tr>
</tbody>
</table>
The obtained result in Figure 47 shows that the average value of landslide hazard is ‘low’, according to the classification given in Table 24. This is because there are many parts of the city that have a planar orography, especially at downtown. In the hilly South-Western part of the city landslide hazard presents ‘high’ and ‘very high’ values, as well as in the Eastern part. Between both zones, some very disperse ‘very high’ values may be found.

Figure 48 shows in a perspective way one of the water-courses marked in figure 44 with high and very high landslide hazard values. In some parts the slope can have 7 meters of difference from the top to the bottom.

Landslide hazard can be observed in Figure 49 in a perspective way. It can be appreciated that the high and very high landslide hazard values are in mountainous areas, but also in the water courses as it was indicated in previous sections.
Landslide risk in Haiti and land management in Port au Prince

4.1.2.4. Exposure at local scale
Exposed elements that were used at local scale include different types of roads (highways, primary roads, secondary roads, arterial streets and unclassified roads); surface elements like forest, parks and water zones; location of hospitals; also rivers and water ways like water pipes. Figure 50 shows the distribution of these elements. These data were collected from OpenstreetMap and Haitidata websites and also from the GIIS group.

Additionally, an aerial image from Google Earth was used in order to know where and how settlements are distributed in Port au Prince (Figure 51).

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4.1.2.5. Landslide risk at local scale
Landslide risk at local scale was obtained joining landslide hazard and exposure elements. Next figure shows the merge of both inputs.

Figures 52 and 53 show the location of exposed elements atop the landslide hazard map of Port au Prince. Elements located in ‘high’ and ‘very high’ landslide hazard values are at ‘high’ and ‘very high’ risk, respectively, so they have to be evaluated in order to reduce, mitigate and/or eliminate possible damages.
A map called ‘Landslide risk of Port au Prince’ is attached in the annexes.

In land management and in risk reduction purposes it is interesting to delimit the areas containing exposed elements that are at potential risk for the initiation of a landslide. In order to identify which exposed elements are in potential risk, ‘very high’ landslide hazard values were collected in different areas. These areas were determined with the following procedure:

1. ‘Very high’ landslide hazard values were plotted over the digital terrain model, in order to identify their location. It was observed that the majority of them are situated along different watersheds (Figure 54).
2. Different polygons surrounding ‘very high’ landslide hazard locations that were in the same watershed were traced, forming different so-called ‘very high landslide hazard zones’ (Figure 55).
3. These ‘very high landslide hazard zones’ are considered the areas with the greatest chance might be affected by an earthquake-triggered landslide.

This is a simplification of the reality that allows analysing which exposed elements can be potentially damaged by the occurrence of landslides. Specifically, the settlements, roads, water pipes and hospitals that were located in these ‘very high landslide zones’ were assessed. Zones with the largest amount of exposed elements at risk have to be catalogued as priority zones.
Figure 56. Landslide hazard values with the different zones of very high landslide hazard values selected. Own figure, 2013.

Figure 56 shows the selected zones that define the watersheds in which landslide can occur in the study zone. It is important to note that not all the selected watersheds have the same amount of ‘very high’ landslide hazard values. South-West zones have more ‘very high values’ than in the South and in South-East. South and South-East zones have the ‘very high values’ more disperse.

A map called ‘Vey high landslide hazard zones of Port au Prince’ is attached in the annexes.

In these zones (Figure 57), there were made some studies about which exposure elements are at risk. Studies of settlements, roads, water pipes and hospitals are explained below.

Figure 57. Zoom of the different zones of very high landslide hazard values selected. Own figure, 2013
Studies of settlements: In order to know which settlements are located in the zones selected previously, it was necessary to intersect the settlements with these zones. It can be observed that many of the zones are covered by large settlements (Figure 58).

Figure 58. Settlements in very high landslide hazard zones. Settlements in risk. Own figure, 2013.

A map called ‘Settlements in risk of Port au Prince’ is attached in the annexes.


If these settlements in landslide risk zones are overlapped with the different land uses, it can be observed that many of these settlements are in the deforested zone (Figure 59). This zone is one of the most risky zones of Port au Prince.

A map called ‘Settlements in risk in the different land uses of Port au Prince’ is attached in the annexes.

**Study of roads:** Roads that are in risk zones were obtained in the same way as risky settlement study was calculated. It can be observed that there are more roads at risk in the Eastern zone than in others, as shown in Figure 60.
A map called ‘Roads in risk of Port au Prince’ is attached in the annexes.

**Study of water pipes**: this study shows that there are several pipes at risky zones, but not in all zones. There is a long pipe in a zone of the East, while the others pipes are shorter (Figure 61).

Figure 61. Water pipes in very high landslide hazard zones. Water pipes at risk. own figure, 2013.

A map called ‘Water pipes in risk of Port au Prince’ is attached in the annexes.

**Study of hospitals**: this study shows that there is not any hospital in the selected zones of very high landslide hazard, but there are four of them that are close to several zones. These hospitals have a circle around them (Figure 62).

Figure 62. Hospitals close to very high landslide hazard zones. Hospitals at risk. Own figure, 2013.

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Once all these analyses were carried out, it was necessary to identify priority zones in order to develop mitigation measures to reduce the risk associated to them.

![Figure 63. Exposure elements in very high landslide hazard zones. Exposure elements at risk. Own figure, 2013.](image)

Figure 63 shows all the factors at risk that were analysed (settlements, roads, pipes and hospitals) and the ‘very high landslide hazard values’, over the very high landslide hazard zones selected in Figure 57. It can be observed how landslide risk zones could be affected and consequently the population of Port au Prince, due to the fact that all these exposed elements are which are leading the common live of the inhabitants of these zones. If settlements, roads, water pipes and hospital suffer any damage due to landslides, repercussions in the society are produced.

Zones with more concentrated ‘very high landslide hazard values’ are in the West and also these values concur with big amount of settlements. It can be observed that settlements in the Eastern zones are not specifically in the ‘very high landslide hazard values’ but in the surrounding zones. If zones of settlements in risk are compared with very high landslide hazard zones where ‘very high landslide hazard values’ are located, it can be observed that affected settlements in Western zones are about 70%, while that affected settlements in Eastern zones are about 55%. It means that there are more people in risk in the Western zones than in the Eastern zones. There are more roads in risk in the Eastern zones than in Western zones because these zones are bigger than the Western zones. Pipes are distributed in several zones, but the longest one is in one zone of the East. About hospitals, there is not anyone in any risky zone, but there are hospitals that are close to them, especially in the Eastern zones.

A map called ‘Exposure elements in risk of Port au Prince’ is attached in the annexes.

All in all, after the analyses of all these factors, the selected zones to be catalogued as priority zones were the Western zones (zone called Leclerk Bidonville and its surrounding zones), because in these places there are more population living than in the others. Also, watersheds at risk that are not in mountainous zones (water-courses) are taken into account as priority zones.
zones because they are close to the city centre and a huge amount of people are living in their proximities (Figure 64).

These priority zones have to be studied and mitigation measures must be developed in order to reduce landslide risk with land management and land tenure criteria.

A map called ‘Priority zones of Port au Prince’ is attached in the annexes.

4.2. Land tenure

Land tenure information was obtained through government agencies, experts and through inhabitants of Haiti in order to have different points of view of the Haitian reality.

Ministry of Planning and External Cooperation of Haiti has developed the implementation of the first national strategy document for growth and poverty reduction for the period 2008-2010 (Ministere de la Planification et de la Cooperation Externe, 2011).

In this document, it is explained how the situation was in 2008 and how measures are improving the country. In urban development terms, the document shows that the urban system is subjected to a set of obstacles in the development process where the most important are: the housing shortage, sanitation and drinking water problems, inadequate infrastructure / equipment and services in the face an ever increasing population, the
proliferation of slums and squatter settlements, the problems of the urban road network and transport, lack of urban zoning insecurity and juvenile delinquency; erection of slums in inappropriate sites (banks and beds of ravines, floodplains and coastal) sprawl on farmland. The general purposes to achieve are to contribute to sustainable urban development and poverty reduction through 1) the development and support for the implementation of development plans and slum upgrading and 2) mastery of growth (Ministere de la Planification et de la Cooperation Externe, 2011).

In planning terms, in 2008 there was a situation of chronic imbalance characterized by ultra polarization of the capital, Port-au-Prince and desertification across the country, and the misuse of natural resources, poor occupation of space, unplanned urbanization, the rural crisis, accelerated soil erosion, and the accentuation of poverty of rural households and the absence or scarcity of services and basic infrastructure in smaller towns and in rural areas. The expected situation that this document reflects can be summarized as follows: regional disparities mitigated; developed watersheds; enforcement on land, facilitating a better use of public funds, investment orientation towards integrated actions for structuring the space, rational and efficient use of national resources, infrastructure and regional facilities on the basis of complementarities (Ministere de la Planification et de la Cooperation Externe, 2011).

More information obtained from government agencies mentioned the establishment of plans and measures that the governments are using in order to improve the quality of life of their inhabitants. Some of these measures are CIAT (Comité Interministériel d’Aménagement du Territorie), where its mission is to define the government’s policy in what regards regional planning, protection and management of watersheds, sanitation, urban planning and equipment (Haiti, 2009); and PARDH (Plan d’action pour le relèvement et le développement d’Haiti) in order to reconstruct the country after the earthquake of January, 12 of 2010 (Ministry of Planning and External Cooperation of Haiti, 2012).

Information collected from experts in land tenure of Haiti, explain that there is a severe problem in the land tenure arrangements. Land tenure arrangements are marked by two parallel systems—one legal and the other informal (Murray 1977; Barthélémy 1996), (Smucker, White, & Bannister, 2000).

Based on the Haitian legal framework, there are two ways to process land acquisitions: i) private buying/selling; and ii) land designation through the national cadaster (Land Tenure, 2010, pp. 19-20, quoted by The Earth Institute at Columbia University international and Public Affairs Capstone, 2012).

The steps to acquire land through private means are as follows:

![Diagram of the steps to acquire land through private means.](Image)

*Figure 65. The steps to acquire land through private means. The Earth Institute at Columbia University international and Public Affairs Capstone, 2012.*
Through the national cadaster, the steps are as follows:

The formal documentation system is not utilized for two main reasons: i) people do not perceive the legal system to be convenient, effective, or essential when dealing with family or community members (i.e. they do not ‘value’ it); and ii) people lack the means to pay for legal services. These legal services are the next (The Earth Institute at Columbia University international and Public Affairs Capstone, 2012):

Costs of action:

- Surveyor: cost depends on the size of the property in terms of square meters, which may be 10,000 gourdes for areas below 500 m², 15,000 gourdes for areas between 500 m² and 1,000 m², and 50,000 gourdes for one “tile earth” (according to the Decree of February 26, 1975: “Fee schedule and surveyors”).
- Notary: Fees to the buyer can range from 1.5 to 2.5 percent of the amount of the sale (generally it is 2 percent, but complex sales may increase rates); additional charges may apply if further documentation is required for the transaction. There is no charge for the seller unless the case is complex; a flat fee not to exceed 0.75 percent of the transaction amount is charged.

Fiscal costs:

- Seller: A gain tax (no fixed scale) on profits incurred through the sale is required based on a set of criteria for the previous acquisition, the number of years the seller owned the property and changes to the land (according to Act Gain Taxes decree of October 5, 2005, Article 100). In the event of a sale by individuals who inherited land, an additional “transfer fee” tax is applied which varies between 3 and 9 percent of the sale amount, depending on the relationship between the deceased and the heirs (according to the Act of September 28, 1977). An additional 1 percent of the transaction value must be added as an overhead charge for DGI (General Directorate of Taxation).
- Buyer: The buyer must pay a registration fee (3 percent), the right of transcription (1 percent), the write permission (6 gourdes), the right of proportional selling price (0.2
percent), stamps (17.50 gourdes), and one percent of the sale price (according to the Decree of September 28, 1977). However, public utility organizations recognized by the Haitian government are exempt from registration; they are only required to pay the transcription right service to the Land Conservation. An example of such exemptions includes religions organizations.

The formal land tenure system suffers from widespread inconsistency and a general lack of transparency, which hamper its ability to function properly. Without a comprehensive land registry or historical account, land acquisition in Haiti, particularly in rural areas, is often dominated by undocumented or partially documented informal practices. These practices supplement or commonly supplant the formal systems of determining and transferring land ownership, as well as resolving disputes (The Earth Institute at Columbia University international and Public Affairs Capstone, 2012). Through discussion among family members, many disputes are resolved before they escalate. In general, family members are reluctant to go to the court, even if they feel that a family’s decision was unfair. In cases where families do not reach a solution or if disputing parties are not related, the conflict will be most likely mediated by ASECs (Communal Section Administrator) or CASECs (Advisor to Communal Section Administrator), (Nofeliz and Tymote, personal interview; and OFDAN (Organization of Women for Development, Agriculture, and Sustenance) personal interview, quoted by ‘The Earth Institute at Columbia University international and Public Affairs Capstone, 2012’). Given the high level of respect within their communities, their decisions are generally followed by the disputing parties. Many people prefer this resolution mechanism because it is cheaper. Additionally, churches, NGOs or mayors can mediate land conflicts (Focus group, personal interview; and Sun, personal interview, quoted by ‘The Earth Institute at Columbia University international and Public Affairs Capstone, 2012’). Disputes over boundaries are sometimes solved by surveyors, although they do not possess the legal authority to do so (Raymond, personal interview, quoted by by ‘The Earth Institute at Columbia University international and Public Affairs Capstone, 2012’). Even notaries can be called on for advice regarding land conflict (Nofeliz, personal interview, quoted by ‘The Earth Institute at Columbia University international and Public Affairs Capstone, 2012’).

In general, peasant land transactions reflect scepticism of notaries, land surveyors, and virtually all agents of the state including the judiciary (Smucker, White, & Bannister, 2000), so informal system is the most common. In (The Earth Institute at Columbia University international and Public Affairs Capstone, 2012), there are exposed how judges, lawyers, notaries and surveyors are perceived:

- **Judges:** Many Haitian judges are not licensed to practice law; unlicensed judges have reportedly been appointed on the basis of connections rather than merit (Vaval, personal interview, quoted by ‘The Earth Institute at Columbia University international and Public Affairs Capstone’, 2012). Even among the judges who are licensed, few have received training in rural land law (Nofeliz and Tymote, personal interview; and Seigel, personal interview, quoted by ‘The Earth Institute at Columbia University international and Public Affairs Capstone’, 2012).

- **Lawyers:** Though demand for lawyers with land tenure experience is high, there are few with such experience (Ewald and Elgorriaga, personal interviews quoted by ‘The Earth Institute at Columbia University international and Public Affairs Capstone’,...
2012). Those with the experience may charge fees higher than the value of the disputed land itself (Geffard Thys, surveyor, 15 March 2012 (S-2.3) Thys, Geffard (Surveyor). Personal interview. 12 March 2012 in Les Cayes, Haiti, quoted by ‘The Earth Institute at Columbia University international and Public Affairs Capstone’, 2012) making the official justice system prohibitively expensive for many people. Lawyers have been observed provoking conflicts in the countryside to enhance their incomes (Etheart, personal interview, quoted by ‘The Earth Institute at Columbia University international and Public Affairs Capstone’, 2012).

- Notaries are nominated by the President and then appointed to specific sites without necessarily receiving training in land law or the local laws of the region they are being placed in (Godfried Toussaint, personal interview, quoted by ‘The Earth Institute at Columbia University international and Public Affairs Capstone’, 2012). They are noted as often lacking current knowledge of land law, and have been observed creating both false documents as well as providing improperly certified documents (Bernard Etheart, INARA National director, 15 March 2012 (S-10.19), quoted by ‘The Earth Institute at Columbia University international and Public Affairs Capstone’, 2012).

- Surveyors’ services, like lawyer’s fees, are known to be prohibitively expensive. This has led to informal arrangements within families or villages that create unofficial documents that could be challenged successfully in the formal system (Vitale, Julnore (Notary). Personal interview. 12 March 2012 in Port-a-Piment, Haiti, quoted by ‘The Earth Institute at Columbia University international and Public Affairs Capstone’, 2012). Additionally, since professional schools for surveyors were abolished in the 1980s, formal surveyor training and certification does not currently exist (Etheart, personal interview, quoted by ‘The Earth Institute at Columbia University international and Public Affairs Capstone’, 2012). Surveyor aides can become apprentices and often inherit the job at a young age. This is in contrast to the notaries who are required to be older to practice their profession (ibid, quoted by ‘The Earth Institute at Columbia University international and Public Affairs Capstone’, 2012)

FAO/INARA notes that the courts are interminably slow, corrupt, and politicized (Smucker, White, & Bannister, 2000). The current formal land tenure system suffers from both mismanagement and a lack of transparency (Vaval, personal interview, quoted by ‘The Earth Institute at Columbia University international and Public Affairs Capstone’, 2012.)

In ‘Transparency International’ website (Transparency International, 2013), it can be observed the level of corruption of Haiti. The country is in the 165th position out of 176 countries, with a score of 19 out of 100. This Corruption Perception Index of 2012, ranks countries/territories based on how corrupt a country’s public sector is perceived to be. It is a composite index, drawing on corruption-related data from expert and business surveys carried out by a variety of independent and reputable institutions. Scores range from 0 (highly corrupt) to 100 (very clean), (International Transparency, 2013). Control of corruption reflects perceptions of the extent to which public power is exercised for private gain. This includes both petty and grand forms of corruption, as well as "capture" of the state by elites and private interests. Haiti is located in the percentile rank 7%, with a score of -1.255541722. Point estimates range from about -2.5 to 2.5 where higher values correspond to better governance outcomes. This factor is one of the six dimensions of the Worldwide Governance Indicators (Source: World Bank).
Judicial Independence is another indicator in the Global Competitiveness Index produced by the World Economic Forum. It measures the perceived extent in which the judiciary of the country is independent from influences of members of government, citizens, or firms. Haiti is in the 140th position out of 142, with a score of 1.7. Scores range from 1 (heavily influenced) to 7 (entirely independent). Rule of law is another indicator of the six dimensions of the Worldwide Governance Indicators, which captures perceptions of the extent to which agents have confidence in and abide by the rules of society, and in particular the quality of contract enforcement, property rights, the police, and the courts, as well as the likelihood of crime and violence. Haiti is located in the percentile rank 5% with a score of -1.353256864. Point estimates range from about -2.5 to 2.5. Higher values correspond to better governance outcomes (Source: World Bank).

The most frequently referenced gap in the Haitian land administration system was the absence of a cadaster (Elgorriaga, personal interview, quoted by ‘The Earth Institute at Columbia University international and Public Affairs Capstone’, 2012). International organizations and donors have emphasized the importance of a modernized cadaster in order to attract foreign investment and increase tax revenues for Haiti’s economic recovery (Modernization of Cadastre and Land Rights Infrastructure in Haiti (Organization of American States. March 2010.Pg. 1)), (The Earth Institute at Columbia University international and Public Affairs Capstone, 2012). The institution responsible for Haiti’s cadaster (ONACA) has only mapped 5 percent of the country since its creation in 1984 (ibid), (The Earth Institute at Columbia University international and Public Affairs Capstone, 2012). The current land administration system is managed by ONACA (National Cadastral Office), DGI (General Directorate of Taxation), CIAT (Inter-ministerial Committee for Territorial Development) and, in certain contexts, INARA (National Institute for the Application of Agrarian Reform). The absence of a cadaster has left each administrative body with limited resources, information and cross-agency communication, causing duplicity and inefficiency. The result has been divergent methods with little uniformity in the way information is collected or transferred between stakeholders. This exacerbates land tenure insecurity across the country (The Earth Institute at Columbia University international and Public Affairs Capstone, 2012).

The lack of clear land tenure information in Haiti is one of the most significant challenges. Land tenure data prior to the earthquake 2010 was already scarce and often times outdated or unclear. This situation was further exacerbated after the January 2010 earthquake, as many of these documents were lost or destroyed (HAITI, 2012).

The information obtained thanks to inhabitants of Haiti revels that there is a big insecurity of land tenure. There is not any legal system that controls land tenure. Haitian laws on cadastre have never been implemented and cadastre projects have generally failed (Smucker, White, & Bannister, 2000).

As it was commented at the beginning of this document, Haiti is one of the poorest countries in the world. Condition of the building stock and infrastructure is a reflection of this poverty.
Unlike more developed countries, there is no national building code to which structures are designed and water and power distribution systems are extremely limited (RMS, 2010).

According to the Institut Haïtien de Statistique et d'Informatique (IHSl or Haitian Institute of Statistics and Informatics) (IHSl, 2010), over 70% of the country’s building stock is low rise (i.e., one story in height). L’ajoupas or cottages (translated “country homes”) represent over 15% of the country’s construction, with much higher concentrations in rural regions (e.g., 92.5% in rural and 7.5% in urban regions). Multi-story buildings represent less than 10% of Haiti’s property at risk and are concentrated in urban regions (RMS, 2010).

Over 90% of the walls of buildings are constructed using one of four material(s): concrete/blocks, earthen materials, clisse (translated “woven wood mats”), or bricks/rocks; with all materials, there is often no reinforcement (e.g., steel rebar). In rural regions, earthen materials are most common; in urban regions, concrete/blocks are utilized for close to 80% of the built walls. Similar patterns are seen in flooring materials, with hard-packed earth in rural regions and concrete in urban regions. Close to 70% of roofs are constructed using light metal (i.e., tin) (RMS, 2010).

After all this information is known, it is possible to say that important land tenure insecurities exist. There is no any official organization that can tell owners where their parcels start and/or end. Haiti is a country that suffers lot of disasters due to natural hazards, like earthquakes, landslides, hurricanes and so on. After one of these natural hazards, inhabitants cannot know the boundaries of their land parcels. A clear cadastre is essential. Also building conditions are inexistent without any type of control and constructions are made with bad materials.

### 4.2.1. Port au Prince

Once land tenure of Haiti was known, Port au Prince was put on the focus in order to know how settlements where inhabitants live are distributed.

Port au Prince has a serious problem of informal planning. A 2009 UN planning study for Port-au-Prince highlighted that over 90% of the informal settlements were in ravines or on hillsides, with almost 40% in the latter category (UN-HABITAT, 2009). Concentration of informal housing in these susceptible areas is a common theme in many developing countries (RMS, 2010).
The images show how formal planning of Port au Prince is nonexistent over mountainous areas. In these informal settlements it is almost impossible to perceive where the main roads are. There is not any infrastructure which defines the type of land planning. Inhabitants could build their houses in these places because the regulations were not enforced. There is not any cadastre and any effective planning.

Another point to be indicated is the use of land. Port au Prince has several and different uses of land. The main land uses are urban, urban with discontinuities, moderate vegetation and deforested land. Figure 67 can show this information which was created by the Haitian National Centre for Geospatial Information (CNIGS) in September, 2008.
Overlapping the zones of Port au Prince where settlements are located to the different land uses, it can be observed that the majority of the study zone is occupied by settlements. There are little zones of moderate vegetation and urban discontinuities in the South of Port au Prince where there is not any settlement. Figure 68 shows this result.

![Figure 68. Land use of Port au Prince and urban settlements. Land tenure study. Own figure, 2013.](image)

This is a result that suggests that the city is highly populated. There is not enough space in this study zone in order to try to move people that are living in non urban use to urban use.

Inadequate land tenure and an inexistent cadastre make this situation occurs. The situation would improve if a better land tenure would be applied. It is necessary that governments focus in these problems and try to solve them in order to get a better city and a better lifestyle for their inhabitants. Also inhabitants have to be aware about the situation and help to improve these facts. It is necessary to transform the ‘informal’ situation in a formal situation.

This is especially important in Port au Prince because it is a city with many urban settlements in precarious conditions and also some of them are located in very high landslide hazard zones. It means that these settlements are in risk. That is why priority zones have been selected in the previous landslide risk zones study. It is in these priority zones where land tenure is one of the most important elements to reduce the risk. A management of the land is essential to face this hazard.

Therefore, mitigation measures must be implemented in these priority zones supported in land tenure and land management criteria. The target of these measures is to get that the landslide that can occur in this priority zones produce the least damages as possible and that these damages do not disturb to the population. Prevention is the solution.
With clear land tenure, land management can be developed in order to improve the situation of a country or city. Land use master plans provide an opportunity to develop a strategy for land management that provides protection for livelihoods, helps to improve food security, and includes preparedness activities to reduce vulnerability to future natural disasters. They also provide an opportunity to assess which communities are most vulnerable to future natural disasters and which would benefit from resettlement (Mitchell, 2011).

4.2.2. Land management recommendations to reduce landslide risk in priority zones of Port au Prince

It is crucial to implement measures to reduce the landslide risk in the selected priority zones. These zones are the highest risk areas so they are the first ones where governments have to act.

In the next paragraphs, some recommendations and ideas are analyzed. They try to help stakeholders in the decision-making. They are who have to decide which strategies have to be developed.

Cadastre is essential. This tool provides a very important knowledge about land tenure. It sets all property records in a structure way. Owners can know which their properties are, where they are located, their economic values and also their uses, among other data. It is useful to reduce tenancy problems between owners, for the purchase and sale of land between citizens and also to recognize land properties after a natural hazard that can caused damages. Current land administration system has to be reorganized and structured in order to be successful. Duplicities and inefficiencies have to be changed in order to get a modern cadastre. This tool supplies an easy control of the land.

Cadastre is an expensive data infrastructure. A realistic way to start to implement the cadastre can be in a progressive way. It means that cadastre should be implemented at first in the priority zones and after that it can be implemented in other places progressively till get a complete cadastre of the entire country. Also, this new cadastre has to assume zero or low cost to the owners of the land and process in land registration should be simple and short in time in order to encourage people to register their lands. A simple legislation with low or zero cost to the land owners can also help to reduce corruption.

Another complementary proposition is to relocate people who are living in landslide risk zones to other places with no risk or at least with low risk. This is a complex idea because people usually do not want to leave their original parcels. In these places they have their houses, their jobs, their lives and also it is quite difficult to move a big number of people from one place to another. On 19th of March of 2010, the government issued the first public use Decree in which there are declared certain perimeters of public use in order to answer the need of a new land use plan after earthquake of that year. Also this Decree allows providing confiscated terrains to relocate earthquake’s affected families (Gobierno de Haití, 2010). This Decree also could be useful in this case of landslide risk as an answer to the priority zones in order to improve their lifestyles. These people can be relocated in these safety zones with better conditions and also with fewer hazards.
An excessive centralization of Port au Prince is the current situation of the city. That is why government of Haiti is considering rebuilding the affected houses of the earthquake 2010 in other cities. They want to distribute the population in the territory in order to produce new development regional poles. The government has decided that in Cabaret sector, near Fond Mombin zone there will be installed a new pole of growth and development. This zone will have a great inversion to make infrastructures, equipments and main services in order to offer a good quality of life to the new inhabitants (Gobierno de Haití, 2010). This new regional pole can help people who are living in landslide risk priority zones. These people can begin a new life in this place if jobs and houses are facilitated to them. New settlements must be located in places with no risk or with the least risk as possible. If it is not, the problem is only changing the place. In landslide risk at regional scale study, it seems that the average value of landslide hazard in Cabaret is low-moderate but with some high values, but landslide risk at local scale studies should be made there in order to know if it is a correct place to relocated settlements. Taking in consideration Ruiz (2013) document, it is observed that Cabaret zone is in risk priority area 1, which means that this place is located in an area with very high or high earthquake and landslide hazard, situated in charged Coulomb areas and near a fault. Therefore, before choosing a place to build a new regional pole it should be necessary to study all possible natural hazards that can affect it.

Besides, another option is to move inhabitants temporarily to other places to improve the conditions of the original place at risk, such as:

- Reducing landslide susceptibility improving the materials and slopes characteristics of the zone:
  - Removing hazardous materials: these materials should be removed in order to have safer places. For example, unstable rocks or soils have to be taken away when they suppose a hazard for settlements, roads or other exposure elements that can affect to the population.
  - Flattening of slopes: slopes can be flattened in order to be less susceptible. The less degree of slope the less landslide susceptibility.
- Making terraces in slopes: formal land planning can be developed making terraces in the slopes. With this structure of the land, roads and other infrastructure can define the type of land planning to lead the life of its inhabitants. It can be achieved a place less susceptible and with a consolidated urban road network.
- Also slopes can be reinforced with structural elements that hold the soils and rocks, like walls of stones, metal walls in order to make slopes more resistant.

These measures can be developed progressively in order to minimize the need of relocation in some cases. This requires research studies of all of them.

A land management plan can be developed in order to delimit places in which settlements should be forbidden. With a correct land management risk can decrease. In these forbidden places to build settlements, a reforestation can be performed in order to decrease landslide susceptibility. Roots of trees can help to hold the soil.
Also a land monitoring system can be implemented in the priority zones. All recollected data have to be analyzed in order to know how these slopes can move and when these movements are big enough, an early alarm has to be communicated to the population. The problems of this method are that it is expensive and it is difficult to say when landslides will occur.

Apart from these measures to reduce landslide risk in priority zones, it is important to highlight the importance of the people. Public participation in all process is fundamental. They are the people who are going to live there once measures will have been developed. Their opinions are important and these opinions have to be considerate. People have to feel the empowerment of the mitigation measures like these measures were made by them, because if they do not trust in the measures, they are not going to take them in consideration and after a period of time, the situation could become as now.

All these recommendations have to be studied, analyzed and improved by stakeholders in order to reduce landslide risk in priority zones.
5. Conclusions

Once all results have been obtained, here there are exposed the main conclusions of every part of the study.

Landslide risk at regional scale

Landslide susceptibility study at regional scale was based on Mendoza and Dominguez (2002) methodology. In this case, there were used as inputs the slope, slope orientation, water flows in the land, hillside and geological factors. Unfortunately other factors were not included in the study due to the fact that there was not possible to find them because Haiti is a developing country and nowadays does not have all these necessary data. The combination of all these factors generated a map with different landslide susceptibility values of Haiti. In this map it can be observed that the majority part of the country has a moderate level of landslide susceptibility but the highest values of landslide susceptibility are in the zones where mountains are located, especially in the South and South-East of Haiti, due to slope factor.

Landslide hazard at regional scale map was obtained joining landslide susceptibility values and the seismic trigger values. The result shows that the principal landslide hazard values in the country are between moderate and high, according to our established classification of five intervals (very low, low, moderate, high and very high). The most important landslide hazard zones are located in the South of the country, especially in the South of Port au Prince. Also, in the North part of the country landslide hazard is high. Low values are only in small zones in the North-West of the country.

Landslide risk map at regional scale was developed joining landslide hazard map and the exposures elements (in this case the main important infrastructures and cities of the country). In the map it is observed that Port au Prince is one of the cities with the highest landslide risk, especially in the South part. Its values are between high and very high. Also, in the West part of Port au Prince, there is another city called Léogâne that can be affected by high and very high landslide risk. About infrastructures, there are some highways that can be affected by landslide, especially in the South part of the country.

Once landslide risk at regional scale was developed, it was possible to know which part of Haiti should be studied with more detail. The selected place was Port au Prince because it is a city with high and very high landslide risk values especially in Southern and because it is a place very populated, where inhabitants live widespread in an informal way. These inputs made Port au Prince an interesting place to study the landslide risk at local scale.

Landslide risk at local scale

Landslide susceptibility study at local scale was based on Mendoza and Dominguez (2002) methodology too. In this case the used inputs were the slope, slope orientation, water flows in the land, geology and land use. Hillside factor was not taken in consideration because its importance at regional scale was minimum and was changed by land use factor. Also at local scale it was difficult to find more inputs in order to complete the methodology followed. The

David Álvarez Castro.
Master Thesis
average of landslide susceptibility value is low in the city centre but moderate and high in the South part of the city and also in some parts of the East. Very high values are only localized in the South-West part of Port au Prince and little parts of South-East. These zones are where more steep slopes are located and where more susceptible materials are distributed in general terms. Also, there are some zones with high or very high landslide susceptibility values that there are not in mountain zones. These places correspond to water-courses and they have to be in consideration because the slopes that surround them are very inclined. In the city centre landslide susceptibility value is low due to it is a planar zone with little slopes, thus in this place there are not expected that landslides will occur.

Landslide hazard at local scale map shows that the average value of landslide hazard is low. This value is because there are many parts of the city that have a planar orography, especially at downtown. In the South-West of the city, where mountains are common, it is where landslide hazard has high and very high values. Also in the East part there are some zones with high and very high values.

Landslide risk at regional scale map was done joining landslide hazard map and the exposures elements (in this case the settlements, different types of road, water pipes and hospitals). Analyses about which of these exposure elements are in very high landslide hazard zones were developed in order to obtain the highest landslide risk zones. With them it was obtained that the South-West zone of Port au Prince is the most landslide risk zone of the city. This part has a big amount of people living there and that was why it was catalogued as a priority zone to reduce the risk. Also watersheds on risk that are not in mountainous zones (water-courses) were taken into account as priority zones because they are close to downtown and a huge amount of people are living in their proximities.

**Land tenure**

Land tenure in Haiti is a complex term because arrangements are marked by two parallel systems, one formal and the other informal, where informal system is the common one due to the fact that the formal land tenure system suffers from widespread inconsistency and a general lack of transparency, which hamper its ability to function properly (The Earth Institute at Columbia University international and Public Affairs Capstone, 2012). Also, there is an absence of cadastre, which makes difficult to have records of geographical information of all properties. Current land administration system is managed by several administrative bodies, so the little amount of data collected can be duplicated and be inefficient (The Earth Institute at Columbia University international and Public Affairs Capstone, 2012). Therefore, important land tenure insecurities exist.

Many settlements in precarious conditions have been developed on the slopes of Port au Prince. This is a consequence of inadequate land tenure and an inexistent cadastre or land information system. This is even more problematic if in these places landslide risk exists. It means that these settlements are in risk. That is why priority zones were selected in the landslide risk zones study. It is in these priority zones where land tenure is one of the most important elements to reduce the risk. A management of the land is essential to face this hazard.
Therefore, mitigation measures must be implemented in these priority zones supported in land tenure and land management criteria. Some of these recommendations that can be implemented as mitigation measures are the next: to make a modern and efficient cadastre in a progressive way, starting in the priority zones and implementing it with other zones progressively till get a complete cadastre of the entire country; to move people to another cities or places with less landslide risk; a temporally displacement of the people in order to improve the conditions of the original place at risk; a new and efficient land management plan; and also to install a land monitoring system to know how slopes can move. Of all of them, cadastre is the most essential tool in order to start to produce mitigation measures. It cannot be forgotten the role of citizenship, their opinions are important and these opinions have to be considerate in order to get success in the mitigation measures.

All these recommendations have to be studied, analyzed and improved by stakeholders in order to reduce landslide risk in priority zones.

Repeating the words of Ban Ki-moon, United Nations Secretary-General “The more governments, UN agencies, organizations, businesses and civil society understand risk and vulnerability, the better equipped they will be to mitigate disasters when they strike and save more lives” (UNISDR, 2013).

**Future lines of action**

Here there are explained some future lines of action in order to continue with this case of study.

Precipitation data should be included in a new landslide risk calculus due to the fact that Haiti and Port au Prince are places where rainfalls are important and because it is a type of trigger that can produce landslides. Also more inputs should be included in order to get results closer to reality.

Every priority zone that has been selected should be studied with more detail by stakeholders to know which mitigation measures align better with the real situation. A more exhaustive study of all of them is necessary.

After landslide risk in Port au Prince has been known, it is necessary that other natural disasters that can affect the city will be taken in consideration to produce mitigation measures that can solve all possible problems. Maybe, mitigation measures for landslides are not enough for seismic hazards or for floods e.g. If they are not considered, probably natural disasters will appear again.
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David Álvarez Castro.

Master Thesis
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Landslide hazard of Haiti

LEGEND
- Boundary of Haiti
- Landslide Hazard
  - Low
  - Moderate
  - High
  - Very High

Author: David Álvarez Castro
Coordinate System: WGS 1984 UTM Zone 18 North
Projection: Transverse Mercator
Datum: WGS 1984
False Easting: 500,000
False Northing: 0
Central Meridian: -75.0000
Scale Factor: 0.9996
Latitud of Origin: 0.0000
Units: meters
Scale: 1:1,500,000

August, 2013.
Landslide hazard of Port au Prince

LEGEND
Landslide hazard
- Very low
- Low
- High
- Very high

Author: David Álvarez Castro
Coordinate System: WGS 1984 UTM
Zone 18 North
Projection: Transverse Mercator
Datum: WGS 1984
False Easting: 500,000
False Northing: 0
Central Meridian: -75.0000
Scale Factor: 0.9996
Latitude of Origin: 0.0000
Units: meters
Scale: 1:40,000
August, 2013.
Landslide risk of Port au Prince

Author: David Álvarez Castro
Coordinate System: WGS 1984 UTM
Zone 18 North
Projection: Transverse Mercator
Datum: WGS 1984
False Easting: 500,000
False Northing: 0
Central Meridian: -75.0000
Scale Factor: 0.9996
Latitude of Origin: 0.0000
Units: meters
Scale: 1:40,000
August, 2013.
Very high landslide hazard zones of Port au Prince

LEGEND
- Very high landslide hazard zones

Landslide hazard:
- Very low
- Low
- High
- Very high

Author: David Álvarez Castro
Coordinate System: WGS 1984 UTM
Zone 18 North
Projection: Transverse Mercator
Datum: WGS 1984
False Easting: 500,000
False Northing: 0
Central Meridian: -75.0000
Scale Factor: 0.9996
Latitud of Origin: 0.0000
Units: meters
Scale: 1:40,000

August, 2013.
Settlements in risk of Port au Prince

Legend:
- Settlemens in risk
- Very high landslide hazard zones

Landslide hazard:
- Very low
- Low
- High
- Very high

Author: David Álvarez Castro
Coordinate System: WGS 1984 UTM
Zone 18 North
Projection: Transverse Mercator
Datum: WGS 1984
False Easting: 500,000
False Northing: 0
Central Meridian: -75.0000
Scale Factor: 0.9996
Latitud of Origin: 0.0000
Units: meters
Scale: 1:40,000
August, 2013.
Settlements in risk in the different land uses of Port au Prince

Author: David Álvarez Castro
Coordinate System: WGS 1984 UTM
Zone 18 North
Projection: Transverse Mercator
Datum: WGS 1984
False Easting: 500,000
False Northing: 0
Central Meridian: -75.0000
Scale Factor: 0.9996
Latitud of Origin: 0.0000
Units: meters
Scale: 1:40,000
August, 2013.

Legend:
- Settlement in risk
- Urban land
- Urban discontinuities land
- Moderate vegetation land
- Deforested land

Units: meters
Scale: 1:40,000
August, 2013.
Risks of landslides in Port au Prince, August 2013.

Legend:
- Roads in risk
- Very high landslide hazard zones

Landslide hazard:
- Very low
- Low
- High
- Very high

Author: David Álvarez Castro
Coordinate System: WGS 1984 UTM
Zone 18 North
Projection: Transverse Mercator
Datum: WGS 1984
False Easting: 500,000
False Northing: 0
Central Meridian: -75.0000
Scale Factor: 0.9996
Latitud of Origin: 0.0000
Units: meters
Scale: 1:40,000

August, 2013.
Water pipes in risk of Port au Prince

LEGEND
- Water pipes at risk
- Very high landslide hazard zones

Landslide hazard
- Very low
- Low
- High
- Very high

Author: David Álvarez Castro
Coordinate System: WGS 1984 UTM
Zone 18 North
Projection: Transverse Mercator
Datum: WGS 1984
False Easting: 500,000
False Northing: 0
Central Meridian: -75.0000
Scale Factor: 0.9996
Lattitude of Origin: 0.0000
Units: meters
Scale: 1:40,000
August, 2013.
Exposure elements in risk of Port au Prince

LEGEND
- Hospital
- Very high landslide hazard
- Water pipes in risk
- Roads in risk
- Settlements in risk
- Very high landslide hazard zones

Author: David Álvarez Castro
Coordinate System: WGS 1984 UTM
Zone 18 North
Projection: Transverse Mercator
Datum: WGS 1984
False Easting: 500,000
False Northing: 0
Central Meridian: -75.0000
Scale Factor: 0.9996
Latitud of Origin: 0.0000
Units: meters
Scale: 1:40,000

August, 2013.
Priority zones of Port au Prince

LEGEND
- Priority zones
- Landslide hazard
  - Very low
  - Low
  - High
  - Very high

Author: David Álvarez Castro
Coordinate System: WGS 1984 UTM
Zone 18 North
Projection: Transverse Mercator
Datum: WGS 1984
False Easting: 500,000
False Northing: 0
Central Meridian: -75.0000
Scale Factor: 0.9996
Latitud of Origin: 0.0000
Units: meters
Scale: 1:40,000
August, 2013.