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VULNERABILITY TO NATURAL DISASTERS IN SELECTED HYDROGRAPHIC BASINS IN PANAMA, USING GIS AND REMOTE SENSING

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ABSTRACT

This paper describes the application of useful techniques and procedures for vulnerability determination in selected watersheds with different forest coverage and anthropogenic intervention levels. Our scope is to manage and evaluate the occurrence and consequences of natural disasters caused by hydrometeorological phenomena.
Natural disasters such as heavy rainfalls related to extreme hydrometeorological phenomena, may cause landslides, floods, floodwaters of rivers and streams. The population and local authorities lack of adequate preparation or knowledge about the magnitude and consequences of these events. By applying modern technologies like Remote Sensing and GIS we can characterize and describe the general conditions of the study area.
One of the main aspects analyzed in this study was the role of soils in the occurrence of natural disasters, specifically landslides.
The benefits of remote sensing digital processing techniques high-resolution satellite imagery and aerial photography, added to digital terrain models and fieldwork to identify, map and characterize vulnerability areas were tested. Hydrological parameters were also considered to characterize the water regime of the sub-basin on site.

Keywords: Remote Sensing; landslides; GIS; soils sampling.

1 INTRODUCTION

Natural disasters related to extreme hydrometeorological phenomena, cause landslides, floods, floods of rivers and streams. With modern remote sensing technology and Geographic Information Systems (GIS) it is possible to characterize and describe in detail the general biophysical, environmental and socioeconomic conditions of a given basin and its vulnerability to natural disasters. The areas chosen as pilot basins for this study (Gatun and Gatuncillo rivers) have similar conditions and characteristics that allow us to cover the natural and anthropogenic environments existing in the rest of the country.
The aim of this study is to develop an adequate methodology to identify vulnerable areas and to minimize the consequences by establishing the vulnerability to hydrometeorological natural disasters bevor the event. Panama, like other countries in the Central American region, is classified as highly vulnerable to the impacts of climate change.
One of the topics evaluated in this study was the role of soils in the occurrence of natural disasters, specifically landslides. Slope is an important variable to determine the vulnerability of soils to landslides. Besides slope, there are other parameters that determine the vulnerability of soils to landslides such as precipitation and the plastic nature and consistency of the soil. The plastic nature of the soil is the property that some soils have to modify their consistency as a function of humidity content. On the other hand, the consistency is the firmness of materials that compose it or the resistance of the soils to deformation and rupture. Precipitation index determines the humidity that a soil will have at a given moment, the greater the precipitation, the greater the humidity in the soil.
The plastic nature of the soil is determined by the humidity content, this humidity is conditioned by other properties (like texture, bulk density, liquid and plasticity limit).
The aforementioned variables were analyzed with the help of different methodologies in order to determine the vulnerability of soils to landslides.
Soil vegetative coverage modifies the vulnerability of soils to landslides making environments less vulnerable. The soil samples analyzed in this study belong to the sub-basins of the Gatún and Gatuncillo rivers, located at the Panama Canal Hydrographic Basin, province of Colón.

2 METHODOLOGY

The modeling of the topography, slope and hydrological behavior of the study area was achieved by applying digital processing to high resolution satellite images and to photographs taken from an Unmanned Aerial Vehicle (UAV) or drone. Also, on site digital terrain models served for the determination of the baseline Soil vegetative coverage, allowing identification, mapping and characterization of zones with a range of vulnerability grades along each sub-basin.
A baseline was created to carry out a general characterization and on the basis of onsite observations a more specific oriented one, including maps of soil vegetative coverage, slopes, isohyets, populated areas, road infrastructure, etc.
High-resolution satellite images (RapidEye and PlanetScope) were acquired and aerial photographs were taken with drones. In addition, topographic maps 1: 25000, and digital terrain models were supplied by the National Geographic Institute "Tommy Guardia".
A set of soil samples was collected from the sub-basins (see Figure 3) and analyzed in a soil laboratory.
The methods used demonstrated that given the characteristics of soils, these are vulnerable to the occurrence of landslides, even before the occurrence of hydrometeorological events. We focused on determine the influence of humidity on soils, since humidity determines their state, being classified according to their constitution in semi-solid, plastic or dense liquid soils. The soils are susceptible to abrupt changes of humidity content, and during a hydrometeorological event (rain) absorb a large amount of water. In this case, a humidity limit to maintain the plastic state, avoiding the change to a liquid state is overstepped, soil will lose its resistance and flow like a dense liquid, thus causing landslides, rural disaster that occurs regularly in our country in the rainy season, causing economic and human losses.
The slope was determined through the digital terrain model processing, generating slope maps, distributed in 6 ranges, which are from 0 to 8%, 9 to 15%, 16 to 25%, 26 to 45%, 46 to 75%, and more than 76%, with the help of these slopes ranges, areas of greater or lesser vulnerability were identified (see Figure 1).
The second variable considered was precipitation, which was determined through precipitation data supplied by hydrometeorological stations located in and around the study area, belonging to the Electric Transmission Company (ETESA) and the Panama Canal Authority (ACP). The stations collect daily data, generating an important database, the precipitation data was used to generate an isohyets map.
The last variable taken into consideration was the soil plasticity, this is a characteristic that co-depends on texture and density.
To determine the texture of soils whether it is sandy, silty or clayey, the Bouyoucos hydrometer method was used together with the Volumetric Ring Method which is necessary to determine the apparent density of the soil. To complete the determination of the plastic nature of the soil, the Atterberg limits (liquid limit, the plastic limit and the plasticity index) were applied.

3 RESULTS

3.1 Slope map

The map in **figure 1** shows the slope range expressed in percentages and represented in different colors. The results show that the steep slopes are predominant in the sub basins of the Piedras and Gatún rivers (26 to 45% and 45 to 75%), to the north while in the sub-basin of the Gatuncillo river, to the south, the gentle slope type predominate (0 to 8% and 9 to 15%). Observing the composition of the map, the areas of greatest vulnerability to landslides can be identify. These areas are marked red and represent the steeper slope type (46 to 75%). The white color mark the areas of >76%, which are generally associated to the watershed of the sub-basin.

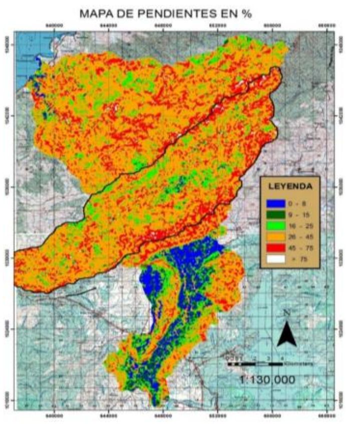

Figure 1: Slope map of the study area. Isohyets map

The map in **figure 2** shows the result of the extrapolation of precipitation data based on the annual averages of the hydrometeorological stations considered in this study. The map shows that the highest precipitation is concentrated in the upper reaches of the sub-basins with values above 4600 mm per year. The layer map in **figure 3** shows the overlap of the slope, isohyets and the monitoring points for soil.

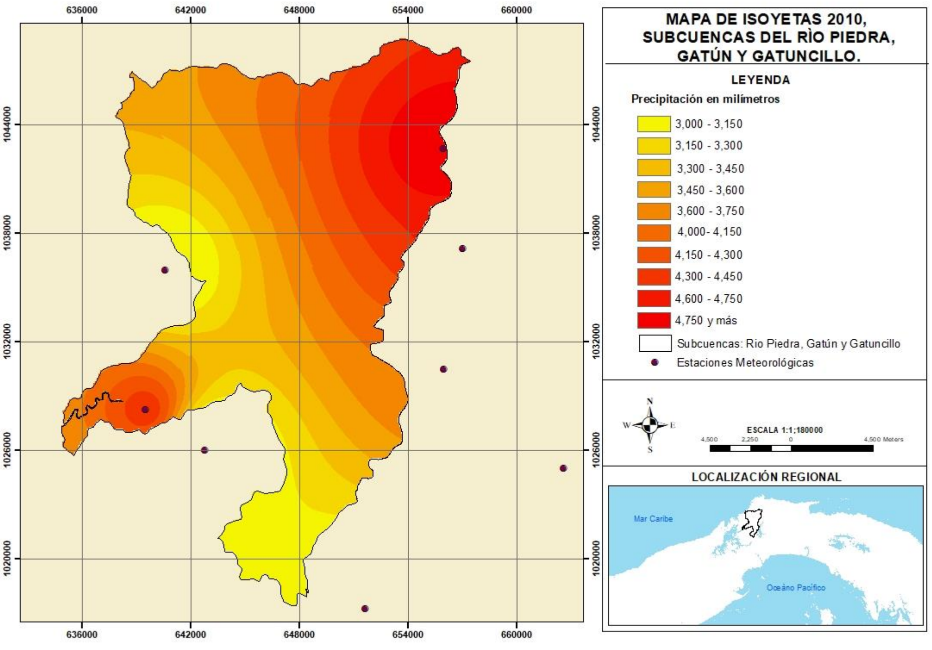

Figure 2: Isohyet map

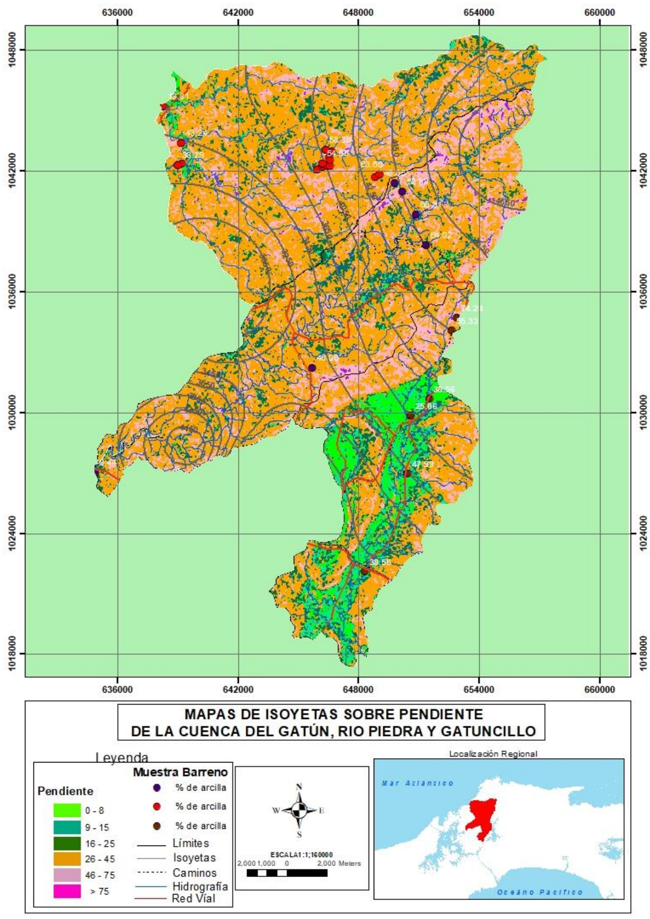

Figure 3: Isohyet and slopes map

3.2 Map of forest cover on the Gatun River Sub-basin

As mentioned before, forest coverage is important to determine the vulnerability to landslides. The map in **figure 4** shows the unprotected areas, with lack of vegetation being this the most vulnerable sites. The forest cover map shows mature forests still well conserved in the upper part of the sub-basin. Here, two factors might affect vulnerability to landslides: slope and precipitation, in the dry season with low rainfall, there will be little risk of landslide, in the event of extreme rainfall the forest coverage will not have much influence, since the soils are saturated with water, hence landslides may occur.

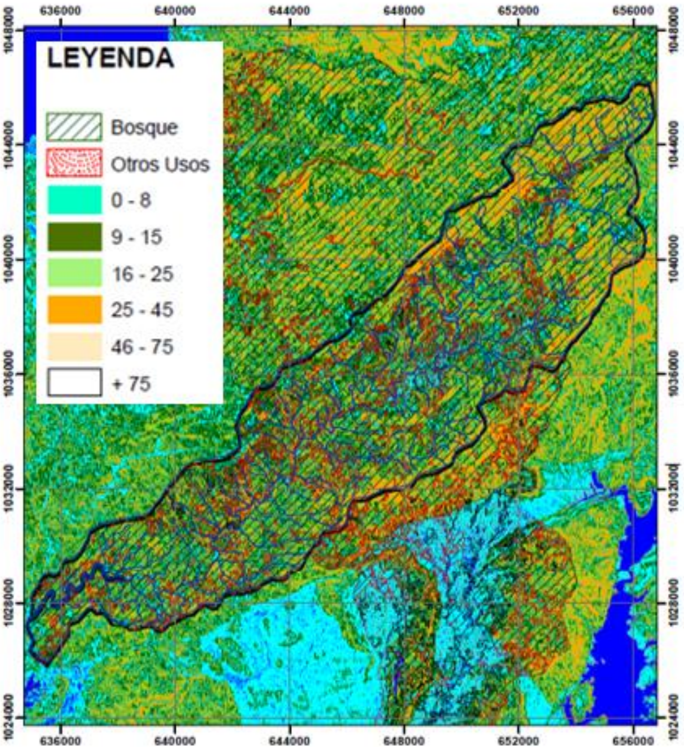

Figure 4: Slope map, on forest coverage of the sub-basin of the Gatún River.

The map shown in **figure 5** shows the slopes for the area of the sub-basin of the Gatún River. It shows also the soils used for forestry or agricultural purposes. The areas with a greater vulnerability to landslides are those with following characteristics: high slope, greater precipitation and lower index of plasticity. Land or soil use might modify vulnerability; in this specific case, the areas in which developed agricultural activities are much more vulnerable than those where the forest is still conserved.

The areas associated with the watershed of Gatun sub-basin are those with the highest slopes and the highest rainfall, therefore the most vulnerable to landslides.

3.3 Results obtained from laboratory tests.

Table 1: Results obtained after analyzing the soil samples.

Parameter	Units	Slope range					
		0-8%	9-15%	16-25%	26-45%	46-75%	>76%
Sand	%	68.37	27.72	15.58	26.20	21.96	26.25
Clay	%	8.44	64.02	66.81	46.06	46.05	52.88
Silt	%	23.17	8.25	17.21	27.74	31.98	20.86
Texture (USDA)	---	Sandy loam	Clay	Clay	Clay	Clay	Clay
Apparent density	g/cm^3	1.10	0.77	0.98	1.23	0.67	0.71
Liquid Limit	%	29.85	63.85	63.67	47.6	60.0	61.5
Plastic Limit	%	28.15	50.24	53.91	41.45	56.0	52.26
Plasticity Index	%	1.7	13.61	9.76	6.15	4	9.24

3.4 Texture

The samples of soil analyzed showed a high percentage of clay in their structure, this was corroborated by the % of clays obtained in our sub basin. The highest clay percentage (66.81%) was found in soil samples within the slope range of 16 to 25 %, followed by 64.02 percent of clay for slope ranges between 9 and 15%, and a clay percentage of 52.88 for slopes greater than 76 %. Clay texture predominates in soils of the sub-basin, except the soil sample belonging to the gentle slope ranging from 0 to 8%, these soils can be found in the lower or lower reaches of the sub-basin, located at the mouth of the river. The results for this soil showed a clay percentage of 8.44 mixed with sand (68.37 %), typical for textured soils also known as sandy loam or free sand according to USDA and SICS classifications respectively.

3.5 Apparent density
Our results showed the lowest apparent density value of 0.67 g / cm^3 for soils from the samples that are located in the slope range between 46 to 75% this was the lowest value obtained. The relationship between soils and mature forest in the upper part of the sub-basin, where there is little or almost no anthropogenic intervention, might suggest a soil with good porosity and good drainage capacity. On the other hand, the highest density value obtained for this sub-basin was found in the 26 to 46 percentage slope range.
The above-mentioned slope range covers the largest area in this sub-basin, where agricultural activities such as livestock keeping are developed. Livestock produces soil compaction due to the animal load, here an apparent density of 1.23. g / cm^3 indicating poor porosity and low infiltration but high runoff rates.
3.6 Liquid limit
The highest values for the liquid limit parameter were obtained in the slope range ranging from 8 to 15 percent, with a plasticity index of 63.85 %. The next highest liquid limit of 63.67 % was obtained for the slope range from 16 to 25 percent.

3.7 Plastic limit
As mentioned before, plastic limit is related with the texture of the soil and clayey soils will show a high percentage of plastic limit. Therefore, the highest plastic limit obtained was in the slope range from 46 to 75% being as high as 56.0 %. The next highest was found in the slope range from 16 to 25% with a plastic limit of 53.91. The lowest plastic limit of 28.15 % was obtained in the range from 0 to 8% due to its low percentage of clay.

3.8 Plasticity Index
In general, our results were low regarding plasticity index. For the slope range from 0 to 8%, a plasticity index of 1.7% was obtained, the lowest of the entire sub-basin. Soils under this range are considered non-plastic soils. The slope ranges from 46 to 75% showed a plasticity index of 4%, while in the slope range from 26 to 45% a value of 6.15% was obtained. The values are characteristic for very hard soils, sensitive to changes in humidity, a small increase in the moisture content will cause them to pass from a semi-solid state to a liquid state.
On the other hand, we have the soil with the highest plasticity index for the slope range between 9 and 15 % with an index of 13.61 %, followed by the plasticity index of 9.76 % for the slope range of 16 to 25 %. This might indicate that this kind of soils need moisture, to move from a semi-solid state to a liquid state, classifying them as less vulnerable to landslides.

3.9 Map of slope, isohyets and forest coverage.
The map showed areas vulnerable to landslides in the upper part of the sub-basin since this area presents a steeper slope (with ranges of 46-75% and of more than 76%), greater annual precipitation (more than 4,650 mm), a low plasticity index (4% and 9.24%) and a high percentage of clay (46.06%, 52.88%). An event of heavy prolonged precipitation, might cause the saturation of the soil and therefore promote landslides. It is important to mention that the upper sub basin is still under natural conditions. Areas with forests coverage are less vulnerable to landslides. Landslides will occur naturally because the upper basin possess all the factors that may facilitate the event.
Areas with slope of 26-45% are also vulnerable, but less prone than the previous ones, when the slope was man treated. This type of slope is predominant in the sub-basin, and cover the largest area, therefore they are associated with agricultural activities. Results for variables such as low plasticity index of 6.15% with a clay percentage of 46.06 %, makes them more susceptible to moisture changes, together with high precipitation (4,450 mm per year) index. Given this condition, soils can change from a plastic to liquid state, which might cause landslides. Vulnerable communities Santo Domingo, La Escandalosa, Sierra Llorona were identified where high anthropogenic intervention (pastures, soil erosion, livestock) was observed.
The areas with a slope value of 9-15 percent and those between16 and 25 percent are less vulnerable since they present, besides their gentle slope, a moderate precipitation (4,250 mm per year), but also high plasticity indexes, comparing to others. The plasticity indexes found in the sub-basin are 13.61 %, 9.76 %, with clay amounts up to 6 4.0 and 66.81 percent respectively. Therefore, the vast majority of townships located in the sub basin occupy the gentle slope areas.

Finally, our results for the lower part of the basin characterized by their lowest slope in the basin with values between 0 and percent and located near the river mouth, showed also plasticity indexes lower than 1.7% and a low clay percentage of 8.44, for the sampled area.

4 CONCLUSIONS

• The studies carried out with Geographic Information Systems of different biophysical and socio-environmental variables together with soil analysis are a useful tool to determine the vulnerability of soils to natural disasters such as landslides.
• The soils that predominate in the study area are soils with clay texture and low percentages of sand and silt, which indicating their heavy nature, poor aeration and drainage.
• The areas of greatest vulnerability to landslides are related, not only to slope with a high percentage, but also to increased rainfall and vegetative cover.
• A low percentage in the plasticity index of soils generates in most cases, vulnerability to landslides.
• Soils that are unprotected, without forest cover, with a high percentage of slope, high rainfall index and low plasticity index are more susceptible to landslides.
• There are sectors vulnerable to flooding in the lower section of the sub-basins, and large-scale landslides can occur in the medium and high sections when soils get saturated after extreme weather events which may trigger multiple landslides.

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