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Geoespacial Analysis and Modelling to Map Socioenvironmental Sensitivity of Landscape to Impact of Extreme Events in the Usumacinta Watershed

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Abstract: Climate change continues to be a major research thrust within global environmental change and sustainability research, but with increasing emphasis on how society may adapt to future stresses. There is an increasing recognition of the importance to consider the social vulnerability equally with the biophysical vulnerability, thus presenting vulnerability on the whole as a function both of physical characteristics of climate change and of social system's inherent sensitivity. Sensitivity is regarded as the potential for and the probable magnitude of change within a physical system in response to external effects and the ability of this system to resist the change. One of the major concerns over a potential change in climate is that it will cause an increase in extreme weather events. In Mexico, the exposure factors as well as the sensitivity to the extreme weather events have increased during the last three or four decades. From the biophysical point of view, the extreme weather events, particularly heavy rains lead to flooding, increase soil erosion and landslide. In this study spatial analysis and modeling were used to assess and map socio-biophysical sensitivity of Landscape to extreme weather events in the Usumacinta watershed. Indices for Hydric erosion susceptibility, landslide susceptibility, flooding susceptibility and land use intensity were calculated and combined using a decision model to construct a biophysical sensitivity index. Disabled population, population higher than 65 years older, population less than five years old, indigenous population, population without access to health services, and population in households with famine head, were used to constructs a social sensitivity index. The social sensitivity index and the environmental sensitivity index were combined by decision model to construct a landscape sensitivity index. The final results indicate that the biophysical sensitivity is higher in the lowlands, but the social sensitivity is higher in the highlands. The landscape sensitivity index indicates that around 815.000 (24.2%) have a high social-environmental sensitivity index, 1,540.000 (45.7%) moderate and 1,010.000 has (30.0%) low.

Key words: Geospatial analysis, socio-environmental sensitivity, Landscape

1. Introduction

Climate change continues to be a major research thrust within global environmental change and sustainability research, but with increasing emphasis on how society may adapt to future stresses [1]. There is an increasing recognition of the importance to consider the social vulnerability equally with the biophysical vulnerability, thus presenting vulnerability on the whole as a function both of physical characteristics of climate change and of social system's inherent sensitivity.

There is general agreement that changes in the frequency or intensity of extreme weather and climate events would have profound impacts on both human society and the natural environment. At present, such events affect a wide variety of natural and human systems, and future changes in their frequency and magnitude could have dramatic ecological, economic, and sociological consequences [2-5].

In southern Mexico, the climate change is beginning to be visible in the form of an increase in the intensity and number of extreme weather events.

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Thus, until some decades ago, strong precipitations events were on the order of 200 mm per day, while towards the end of the past century the intensity of severe storms reached around 300 mm per day; between October 28 and 30, 2007, heavy rains between 300 and 400 mm occurred, showing that extreme events are now stronger and more frequent [6].

The Usumacinta watershed, an important trans-boundary basin, encompasses of 77.265 km^2, from which the 43.6% is located in Mexico, 56.3% in Guatemala and 0.04% in Belice (Fig. 1). In Mexico is one of the most important watersheds and includes 5 municipalities of Tabasco State, 15 of Chiapas, and one of Campeche. The area has an average annual precipitation ranging from 1200 to 4000 mm; supports a population of about 1.000.000 inhabitants distributed in 5000 localities. The area includes 12 natural protected areas (8.500 km^2).

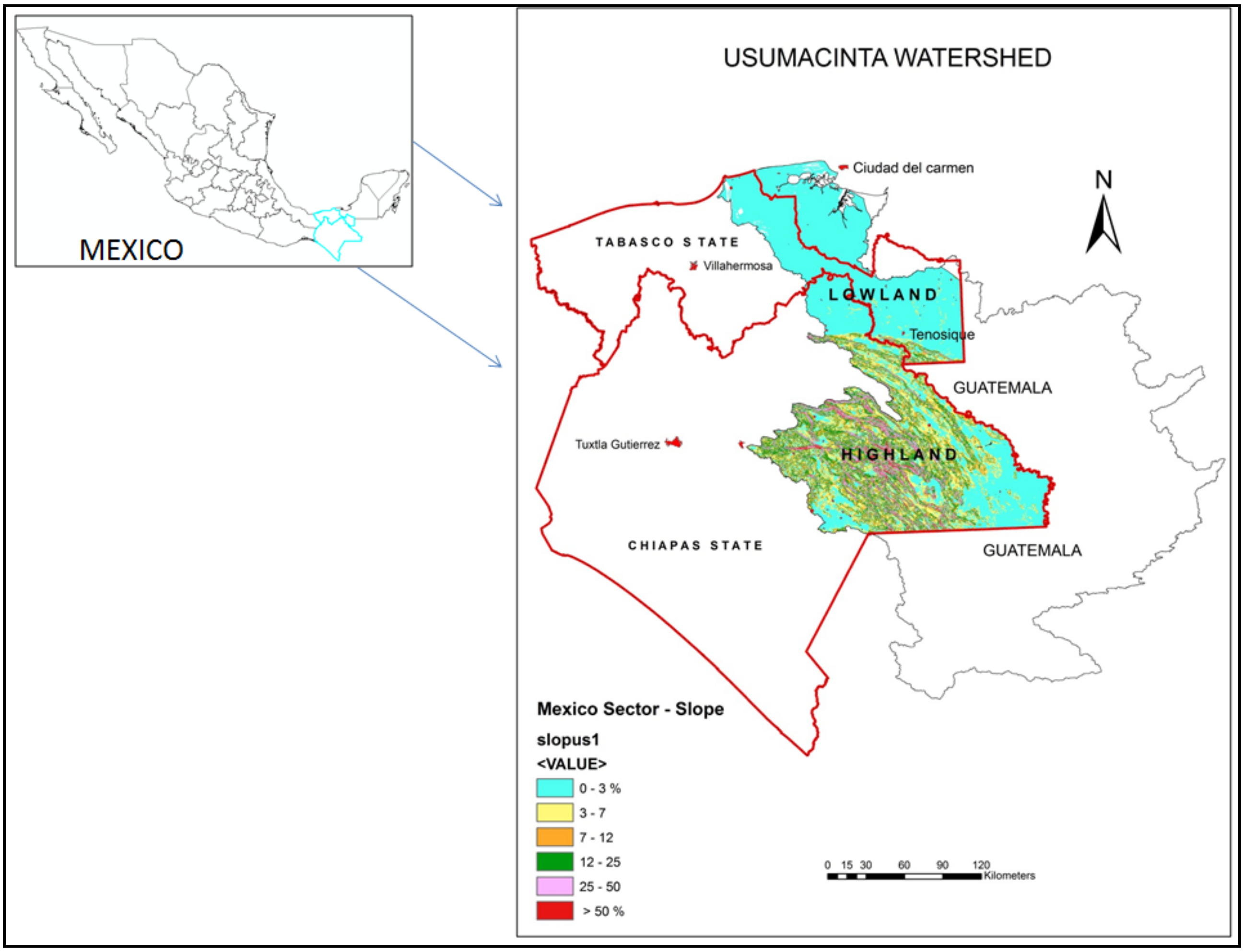

Fig. 1 Usumacinta watershed, localization.

The Usumacinta watershed is constituted by two well defined sectors: Low land (low Usumacinta) and highland (Lacantun-Chijoy). The first sector includes eight municipalities, from which seven have a medium marginalization grade, and one low. In this area the livestock is the principal activity (65%) and the crops 35%. The highland area (Lacantun-Chijoy) has 23.237 km^2, include 13 municipalities; more than 50% of population is native, in some municipalities the proportion of native population range from 73% to 100%. The marginalization grades from high to very high in 12 municipalities, and just in one is medium.

The poor and the high marginalization of population imply a high social vulnerability to climatic risk in this area. The principal activity is the slash and burn cultivation (62%) and livestock (36%). According to CENAPRED, between 2000 and 2010, 14 climatic events considered as disasters were reported, 30 in the lowland 2.662.705 inhabitants were affected and 18 in the highland with 6.655.128 inhabitants were affected [7].

The floods in the lowland, are related to the high environmental degradation caused by intense deforestation activities and inadequate farming crop systems management that has taken place in the upper part of the watershed. In addition, the coastal zone of Tabasco is considered to be highly vulnerable to sea level rise in the delta zone. The most serious factor is that a large percentage of the population at high risk of flood or landslide, lives in poverty conditions, mainly in Chiapas State. In the Usumacinta watershed the two sectors that are particularly exposed to the adverse effects of extreme weather events, such as hurricanes, cyclones, and river flooding, are the crop systems and the settlement infrastructure.

In this context, assessment and mapping of the current sensitivity to climate change (in the context of the adverse effects of extreme weather events) in the Usumacinta watershed is an important part of formulating adaptation strategies both regionally and nationally; besides, it constitutes the basis for a concept of sustainable management of natural resources [8]. A sensitivity analysis and mapping can pinpoint areas and sectors where the sensitivity is high, and thus where adaptation strategies should be developed.

2. Assessing and Mapping Landscape Sensitivity

Several ways of analyze landscape have emerged and sensitivity, a type of landscape appraisal, is one of this. Here, landscape sensitivity is regarded as the potential for and the probable magnitude of change within a physical system in response to external effects and the ability of this system to resist the change [8, 9]. Climate and human activities are — to different extents — important driving forces for changes and development of landscapes and landforms worldwide. Thus, the sensitivity issue concerning both these changes is one of the most relevant ones (Thomas and Allison, 1993). Assessments of landscape sensitivity are the basis for decision making about Watershed Management strategies [8, 10, 11]

Landscape sensitivity as it is conventionally found in various aspects of the environmental and geographic literature has been conventionally associated with geo-biophysical phenomena. Beyond physical geography, perhaps one of the most common constructions of landscape sensitivity appears under the rubric of environmental impact assessment (EIA) and related methodologies used to assemble environmental inventories and audits. But perhaps the real weakness of the models discussed above concerns the way that they are frequently decoupled from human societal processes and especially the politics of management.

Despite the continuing popularity of concepts such as “sensitivity” and “vulnerability” and, indeed, their centrality to environmental impact assessment programs, they are basically inadequate as descriptors of complex socio-natural systems. A clear problem shared by most methodologies is the separation between the physical environment and what is perceived as a distinctive social and cultural environment. However, it needs to be remembered that the physical environment has evolved in concert with (and as a product of) human action, forming a reciprocal socio-natural system [8]. Thus, any approach to landscape sensitivity that focuses exclusively on the biophysical aspects of the system (e.g., climate, geomorphological processes, hydrology etc.) is seriously incomplete as are presentation of the complexity of human-environment relations. The starting point for this work is the recognition that "landscape" considered as a socioecological complex systems, must be analyzed having account the biophysical, economic and social dimensions as a whole [12].

3. Methodology for Analysis and Mapping the Socio-Environmental Sensitivity of Landscape

In this study, spatial analysis and modeling were used to assess and map the socio-environmental sensitivity of landscape to impact of extreme events in the Usumacinta watershed. Fig. 2 shows a diagram of the methodological approximation used in this study. Two sectors were considered: crop systems and settlement infrastructure.

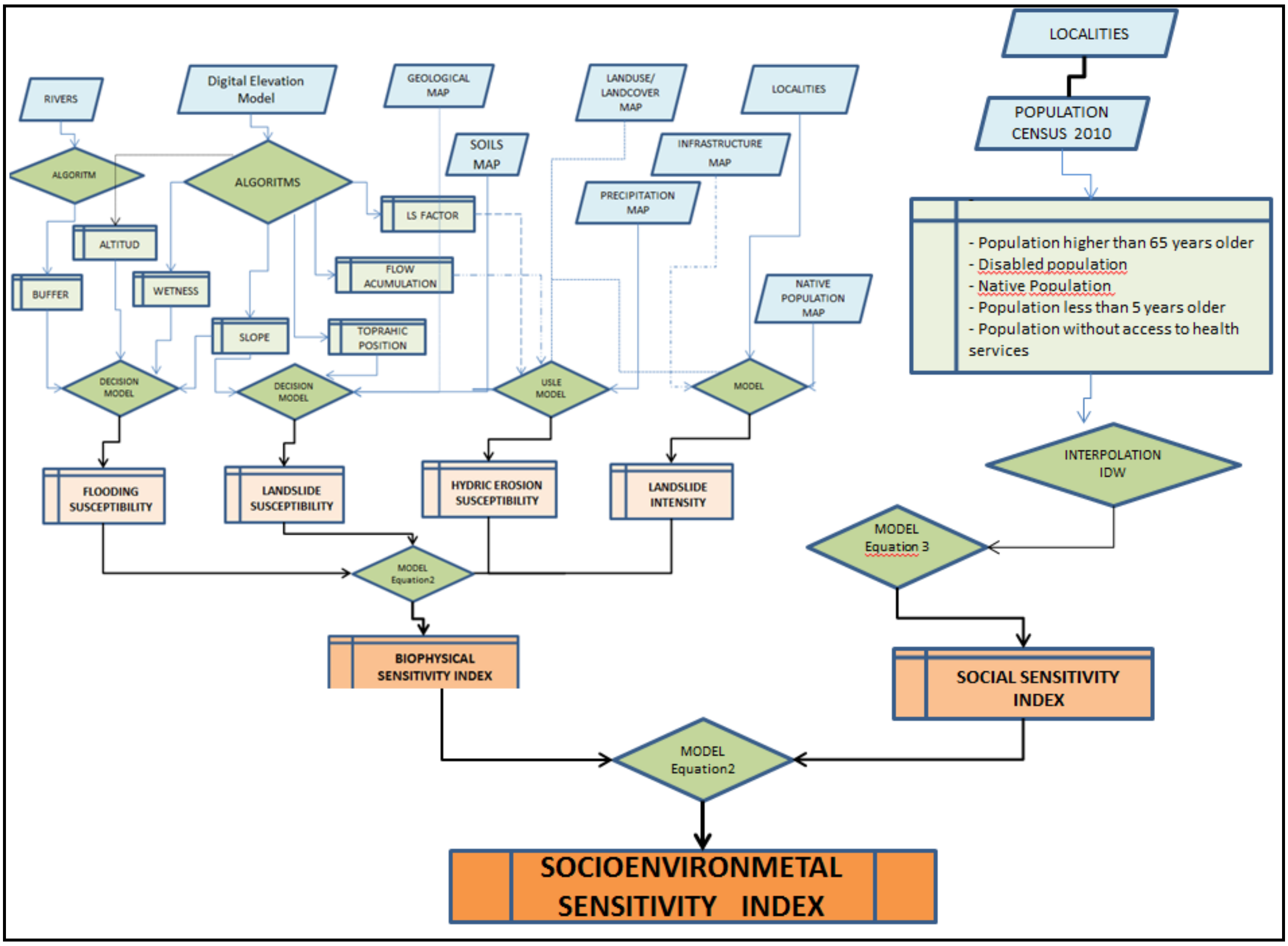

Fig. 2 Methodological approximation for analysis and mapping the socio-environmental sensitivity.

Database: The data used in this study include:

- A digital elevation model, spatial resolution 15 meters, Instituto Nacional de Estadística, Geografía e InformáticaDirección General de Estadística — INEGI. From this data a slope map, topographic wetness index, landscape position and flow accumulation were calculated.
- River segment, scale 1:250,000. From this layer several buffers (< 2.5, 2.5-5.0 and > 5.0 km) were calculated.
- Land use and land cover map, scale 1:250,000, series I and V, INEGI. This map was reclassified in two categories, forest vegetation and agriculture (the latter includes grasslands).

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- Population census, INEGI (2010)
- Soil map, serie II, INEGI (2007)
- Geological map, INEGI
- Indigenous population map, INAH
- Precipitation map, UNIATMOS – UNAM, SMN, CONAGUA (2011)
- Infrastructure map, INEGI
- Localities map, INEGI (2010)

For analysis and modelling ERDAS Imagine, version 10.0 and ArcMap GIS version 10.0 software were used.

3.1 Biophysical Sensitivity Index (BSI)

In this study a biophysical sensitivity index was constructed by integrating and modelling hydric erosion susceptibility, flooding susceptibility, landslide susceptibility and land use intensity. The hydric erosion was calculated using the universal soil equation (USLE). The Table 1 shows the variables and the calculations used for each factor of this equation.

$$\text{Hydric erosion} = R*K*LS*C \quad (1)$$

The flooding susceptibility was calculated based on slope, altitude, river distance and topographic wetness index; the Table 2 shows the ranges used for each one of these variables. The flood susceptibility was obtained by combining these variables by a decision model. The result was a flood susceptibility map with five categories of flooding susceptibility: very high, high, moderate, low, and no flooding.

The landslide susceptibility index was constructed based on geological map, slope, topographic position and land use. These variables were combined in a decision model to produce a landslide susceptibility map with five categories: very low), 2 (low), 3 (médium), 4 (high) and 5 (very high). Table 3 shows the variables and ranges used.

The land use intensity index was calculated based on land use, intervention time, distance to roads, distance to settlements (localities less than 5000 inhabitants were considered), indigenous population and protected areas. Table 4 shows the variables and ranges used. These variables were combined by a summary model. The model is an adaptation on the land us intensity model of Etter et al. (2010).

Table 1 Variables and calculations for factors of USLE equation.

Factor	Variables, Calculations and source
Erosivity (R)	$Y = 2.4619x+0.006067x^{2.}$ [13]
Erodability K)	Soil texture, soil units (FAO, 1980)
Longitud/grade of slope (LS)	LS = (accumulation flow* cell zise/22.13)0.4* (Sen of slope (radians)/0.0896)$^{1.3}$ [14]
Land use cover (C)	Land use and cover factor [13]

Table 2 Variables and ranges used for flooding susceptibility index.

Pendiente (%)	Altitud (m)	Distance to river (km)	Topograhic Wetness index	Flooding Susceptibility
1. > 3	1. < 5	1. > 2.5	1. > 10.5	0.No susceptible
2. 3-9	2.5-10	2.2.5-5	2. 9.5-10.5	1. Low
3. > 9	3.10-25	3. > 5	3. 8.0-9.5	2. Moderate
	4.25-50		4. > 8.0	3. High
	5.50-100			4. Very high
	6.100-500			
	7. > 500			

Table 3 Variables and ranges used for landslide susceptibility index.

Geology	Slope (grades)	Topographic position	Soils	Susceptibility grade to landslide
1-No susceptible	1. > 6	1-Valleys and foot slope	1. Low	0. No susceptible
2-Low	2.6-12	2-Crestas	2. Moderate	1. Low
3-Moderate	3. 12-20	3-Laderas	3. High	2. Moderate
4-High	4. > 20	4- Planos	4. Very high	3. High
				4. Very high

Table 4 Variables and ranges used for land use intensity index.

Contribution on land use intensity	Land use	Intervention time	Road distance (km)	Settlement distance (km)	Indigenous Population (%)	Natural protected Area
0	Natural vegetation	0	>20	> 25	> 90	0
1	Secondary vegetation	0-30	8-15	15-25	75-90	1
2	Perennial crops		5-8	10-15	50-75-	
3	Pasture, Semi-permanent crops		3-5	6-10	25-50-	
4	Annual crops		1.5-3	3-6	10-25	
5	Settlements		0-1.5	0-3	< 10	

Indices of Hydric erosion (He) susceptibility, landslide susceptibility (Ls), flooding susceptibility (Fs) and land use intensity (Ui) were combined and normalized to a scale between 0 (low) and 100 high, to construct a biophysical sensitivity index (equation (2))

$$BSI = (He + Ls + Fs + Ui) * 100/\sum (He\ max + Ls\ max + Fs\ max + Ui\ max) \quad (2)$$

3.2 Social Sensitivity Index (SSI)

Disabled population (poblim), population higher than 65 years older (pob65), population less than five years old (pob5), indigenous population (pobind) and population without access to health services (pobsinder) were used to constructs a social sensitivity index. All the variables considered are expressed as a percentage in relation to total population of the locality, and ranked in percentiles, then, each one of these variables were interpolated using inverse distance weighted (IDW) algorithm, the result was a raster surface for each one variable. These maps were combined and normalized to a scale between 0 (low) and 100 high, to construct a Social sensitivity index (Eq. (3))

$$SSI = (poblim+pob65+pob5+pobind+pobsinder) * 100\sum(poblimmax+pob65max+pobindmax+pobsindermax) \quad (3)$$

3.3 Socioenvironmental Sensitivity Index

The Biophysical sensitivity and the social sensitivity indexes were combined by a decision model to construct the Socioenvironmental sensitivity index.

4. Results and Discussion

The results of the models of hydric erosion susceptibility, flooding susceptibility, landslide susceptibility and land use intensity are shown in the Figs. 3-6. In most part of the Lowland the slope have values less than 3%, so the hydric erosion susceptibility is very low. Contrary, in the Highland the slope range from 3 to more than 50%, with a predominance of slope 7-12%, 12-25% and >25%, this factor in combination with the presence of soils more susceptible to hydric erosion, and the agricultural use in some sectors, explain the values of moderate to very high of hydric erosion susceptibility for this part of the watershed (Fig. 3). The hydric erosion susceptibility map was compared with the soil degradation map [15] and it was found that the areas

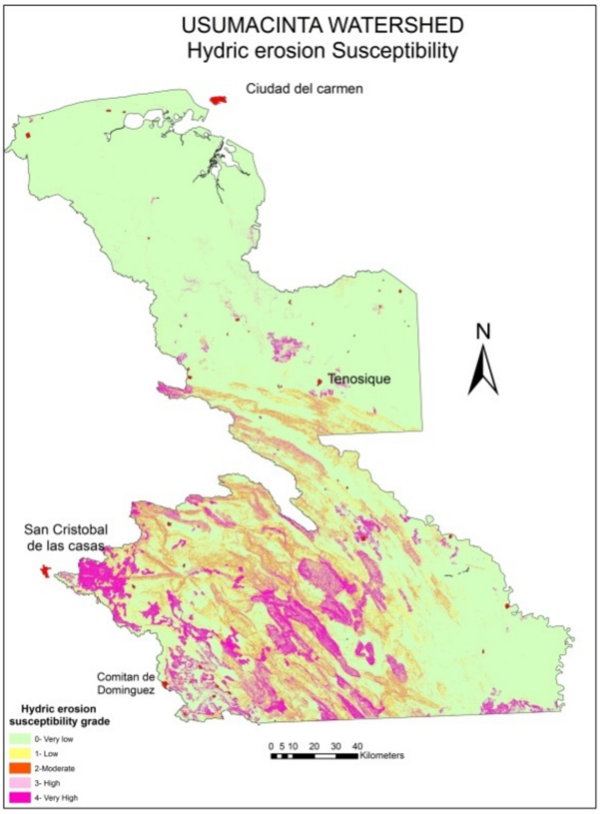

Fig. 3 Hydric erosion susceptibility.

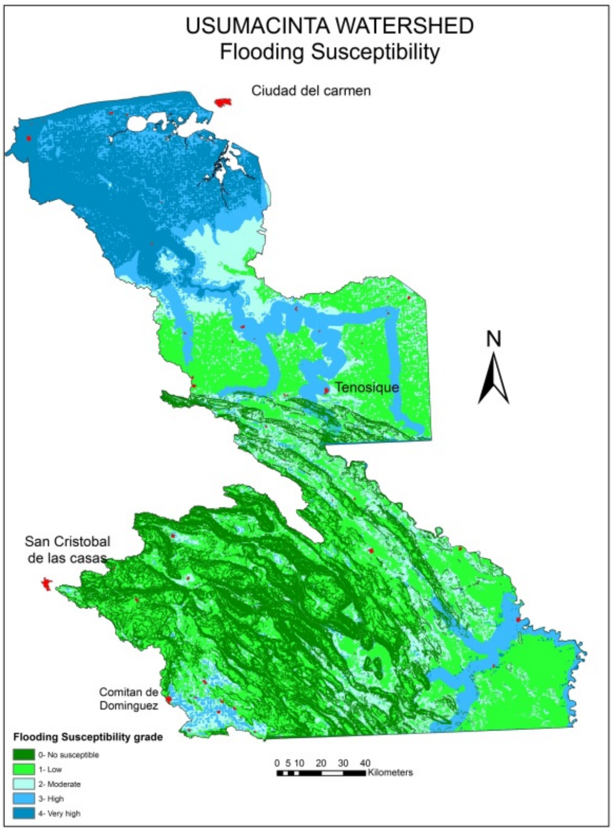

Fig. 4 Flooding susceptibility.

ranked from moderate to very high hydric erosion susceptibility correspond to areas of low productive capacity (as a result of the hydric erosion process), as reported in the soil degradation map. In effect, according to some observations in the field, in some areas where the index of hydric erosion is very high, and correspond to area of crops use, calves and rills of erosion are evident already.

The Flooding susceptibility index (Fig. 4) show that approximately more than 50% of the lowland area range from moderate to very high susceptibility. This is in accordance with its physiographic position, this area corresponds to a floodplain of the Usumacinta watershed; most part of the area is below 50 meters of sea level.

To validate the flooding susceptibility map, the flooded areas resulting from extreme precipitation (400 mm/day) in October 2007 were considered. The flooded area was mapped using MODIS and SPOT satellite images. When this map was compared with the flooding susceptibility map, the following relations were found: 75% of the inundated area was mapped as high to very high susceptibility and 88% of the inundated area was mapped as moderate to very high susceptibility.

The Landslide susceptibility index (Fig. 5) shows that some sectors range from moderate to high and in small parts is very high. This index was validated using a QuickBird satellite image to realize an inventory of landslides in the area; as a result fifteen landslides were mapped. A comparison of this map with the landslide susceptibility index, showed that 60% of the landslides mapped are localized in areas were the index is high to very high and 87% of the landslides are localized in areas were the index is moderate to very high.

The land use intensity index (Fig. 6) indicates that in 39% of watershed the land use intensity is low to very low, in 21% is moderate and in around 40% of

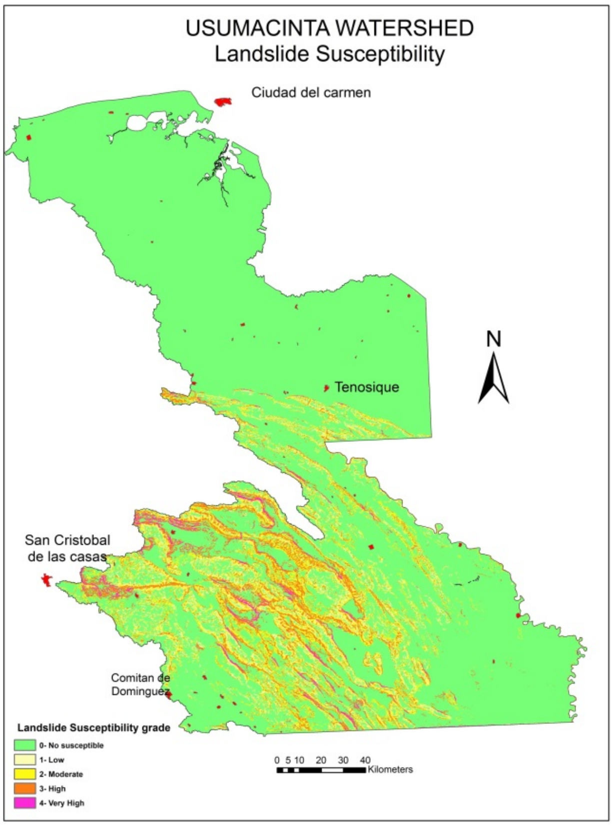

Fig. 5 Landslide susceptibility.

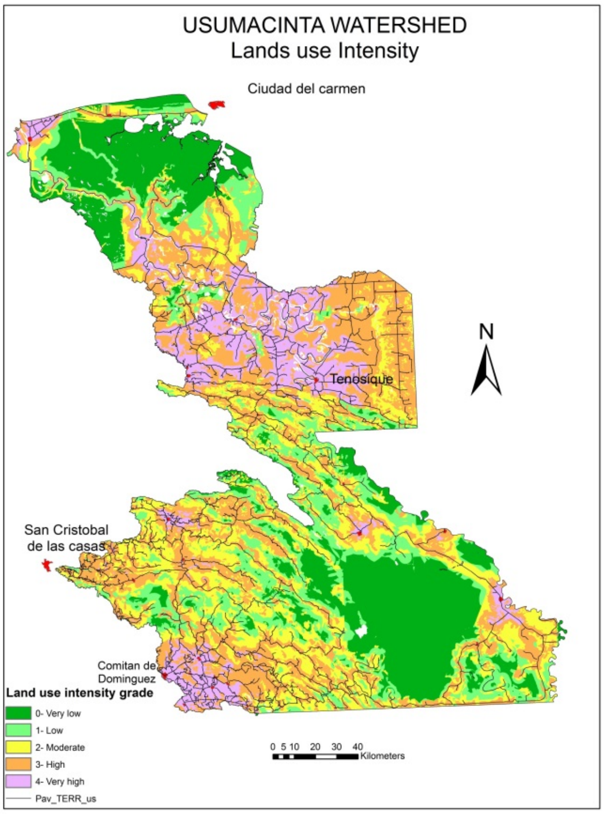

Fig. 6 Land use intensity.

the watershed the land use intensity range from high to very high. In the lowland area two factors explain the lowest land use intensity, one the presence of a protected area and the other the fact that this area is occupied by wetlands, were the agricultural activities are restricted; however must be considered that this area are affected by contaminations problems due to oil exploration activities that take place on it. In the areas mapped as moderate to very high use intensity, the factors that can explain it are related with land use (agricultural activities) and the time of intervention (for area mapped as very high use intensity); in this latter case some of this areas have been used for agricultural activities mores that 100 to 150 years.

The biophysical sensitivity index (Fig. 7) indicates that in around 55% of the watershed the sensitivity index range from very low to low, in 41% is moderate and in 3% of the watershed is high. It can be said that two factors have been contributed to the low sensitivity of the watershed, the presence of natural protected areas and to the high percentage of native population in the highland area mainly. It is widely recognized that the native population live in more armory with the natural resources that means that its activities have in general a lesser impact on the landscape. The areas with a moderate to high index correspond to areas dedicated to agricultural activities, and the most area with high sensitivity index is concentrated in zones where the land have been used for a long time (100 to 150 years a more) in agricultural activities.

The social sensitivity index (Fig. 8) indicates that in around 47% of the watershed (localized in the lowland mainly) the sensitivity index range from very low to low, 52% is moderate and 1.3% is high. In the lowland area the moderate sensitivity is explained by the high to very high percentages of disabled population, population higher than 65 years older and population less than five years old, mainly. In the highland the moderate sensitivity index is explained by the high percentages of native population and

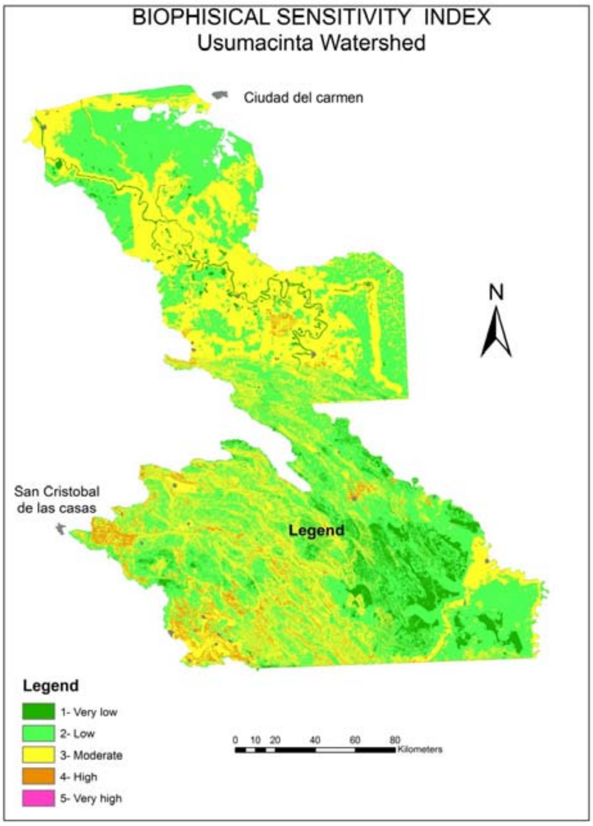

Fig. 7 Biophysical sensitivity index.

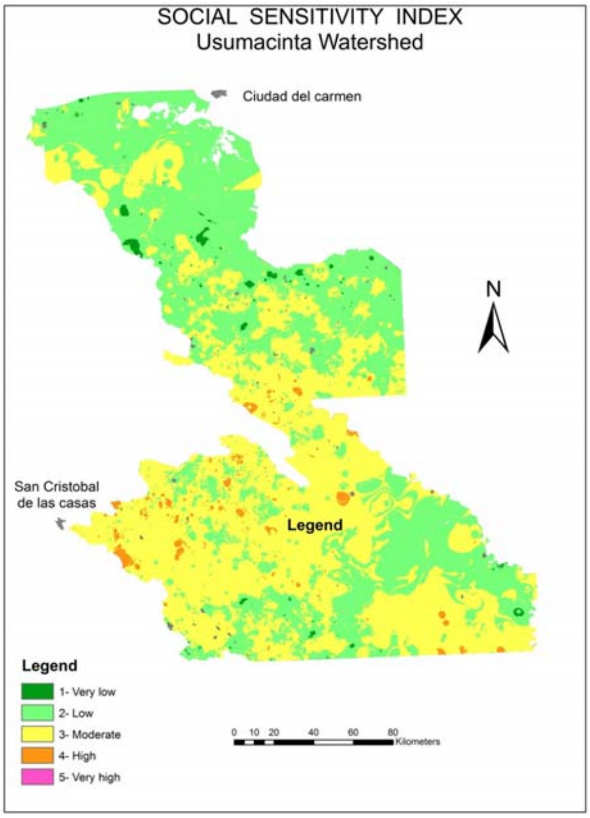

Fig. 8 Social sensitivity index.

population without access to health services mainly; in this part of the watershed more area is related with a moderate sensitivity that in the lowland.

The socio-environmental sensitivity index (Fig. 9) indicates that in around 30% of the watershed in 30% the index range from very low to low, in 46% is moderate and in 24% of the watershed the index is high. In the lowland the moderate to high sensitivity is a result of combination of flooding susceptibility and the high to very high percentages of disabled population, population higher than 65 years older and population less than five years old, mainly; in short, in the lowland, this are the kind of population that require more attention when a flooding event occur. Contrary in the highland the index is a combination, on one hand, of hydric erosion susceptibility, landslide susceptibility and land use intensity, and on the other hand of, native population and population without access to health services mainly. So in the highland,

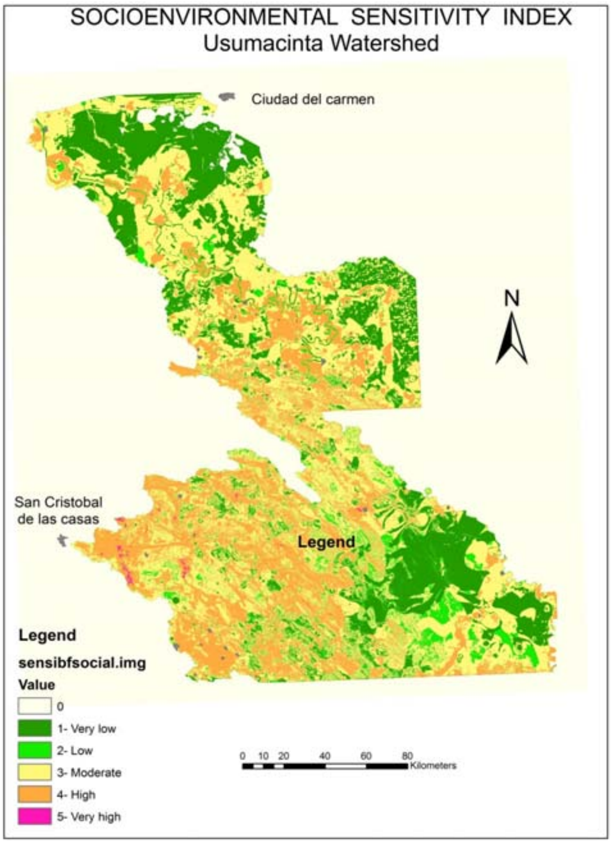

Fig. 9 Socio-environmental sensitivity index.

this is the population that requires more attention when a landslide event occurs.

5. Conclusions

In the Usumacinta watershed, the Socio-environmental sensitivity index indicates that around 815.000 has (24%) have a high social-environmental sensitivity index, 1,540.000 (46%) moderate and 1,010.000 has (30.0%) low. In the lowland the sensitivity is related with flooding susceptibility and the high to very high percentages of disabled population, population higher than 65 years older and population less than five years older. In the highland the sensitivity is related with high percentage of native population and population without access to health services mainly, exposed to landslide events. The biophysical sensitivity index indicates that in around 55% of the watershed the sensitivity index range from very low to low; two factors have been contributed to this low sensitivity, the presence of natural protected areas and the high percentage of native population in the highland area. From data point view it is important to point out, that digital elevation models is a very important source of data for analysis and modelling environmental problems.

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