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Spatial analysis and modeling to assess and map current vulnerability to extreme weather events in the Grijalva – Usumacinta watershed, México

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Abstract. 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 vulnerability to the extreme weather events have increased during the last three or four decades. In this study spatial analysis and modeling were used to assess and map settlement and crop systems vulnerability to extreme weather events in the Grijalva – Usumacinta watershed. Sensitivity and coping adaptive capacity maps were constructed using decision models; these maps were then combined to produce vulnerability maps. The most vulnerable area in terms of both settlement and crop systems is the highlands, where the sensitivity is high and the adaptive capacity is low. In lowlands, despite the very high sensitivity, the higher adaptive capacity produces only moderate vulnerability. I conclude that spatial analysis and modeling are powerful tools to assess and map vulnerability. These preliminary results can guide the formulation of adaptation policies to an increasing risk of extreme weather events.

1. INTRODUCTION

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 or magnitude could have dramatic ecological, economic, and sociological consequences [1, 2, 3, 4]

In Mexico, the exposure factors as well as the vulnerability to extreme weather events have increased over the last the three or four decades. The numbers of events could still be within the limit of occurrence determined by the natural variability of the climate. Nevertheless, in the medium or long term, it is expected that these phenomena will undergo a gradual increase in intensity or frequency tied to the effects of global warming [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. 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 of between 300 and 400 mm occurred, showing that extreme events are now stronger and more frequent [5].

The Grijalva–Usumacinta watershed, located in southern part of Mexico[1] (see Figure 1), is one of the most important watersheds in the country; it contains between 27 and 40% of the stored water

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[1] The part of the Usumacinta watershed that is located in Guatemala, is not considered in this study.

volume in the country, and represent 43% of the installed effective electricity capacity. One third of the watershed is used for agriculture. The watershed encompasses of 87,687 km^2 and includes Tabasco State, a large part of Chiapas State, and small parts of Campeche, Veracruz, and Oaxaca States; it consists of 119 "municipios" (counties). The area has an average annual precipitation ranging from 1200 to 3000 mm; and supports a population of about 5.300.000 inhabitants [6]. In most of the area (Chiapas State) the marginalization grade ranges from medium to very high.

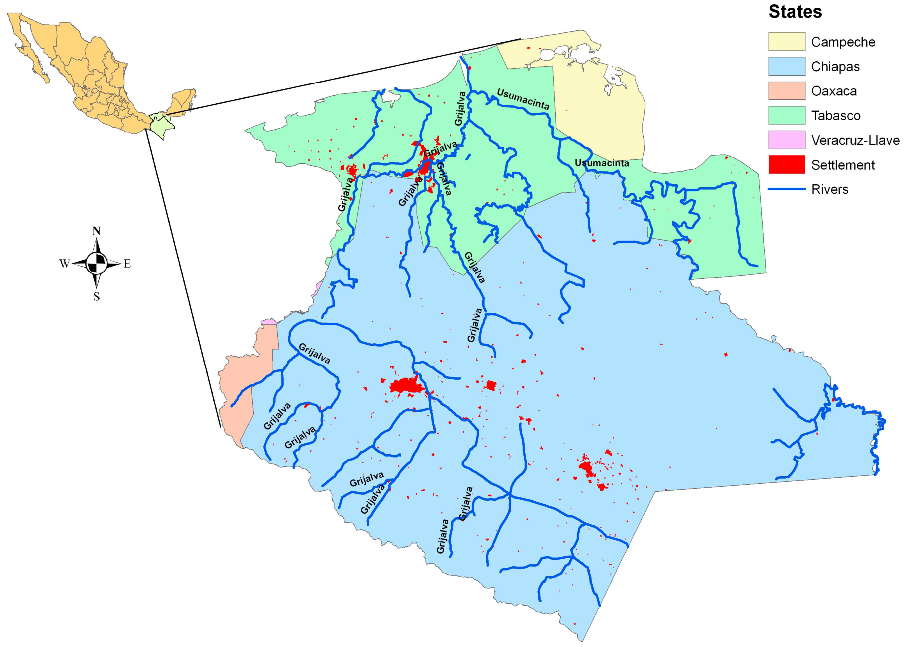


Figure 1 Study area: the Grijalva-Usumacinta watershed, Mexico

Tabasco State, located in the lower part of the watershed, is very susceptible to frequent floods; two of the most important occurred in 1999 and 2000. The floods 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 lives in poverty conditions, mainly in Chiapas State (see figure 2).

In the Grijalva-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. Table 1 lists some of the extreme hydro-meteorological events and their impacts registered over the last few decades for this region [5].

According to Landa [5], the floods of 2007 in Tabasco State caused by intense rains were a manifestation of the lack of social and institutional preparation of the country for extreme weather events. Under conditions of climate change, actions will need to go beyond aid to the victims, involving a long-term preventative vision that solves basic problems because events like the one in October 2007 may increase in intensity and frequency.

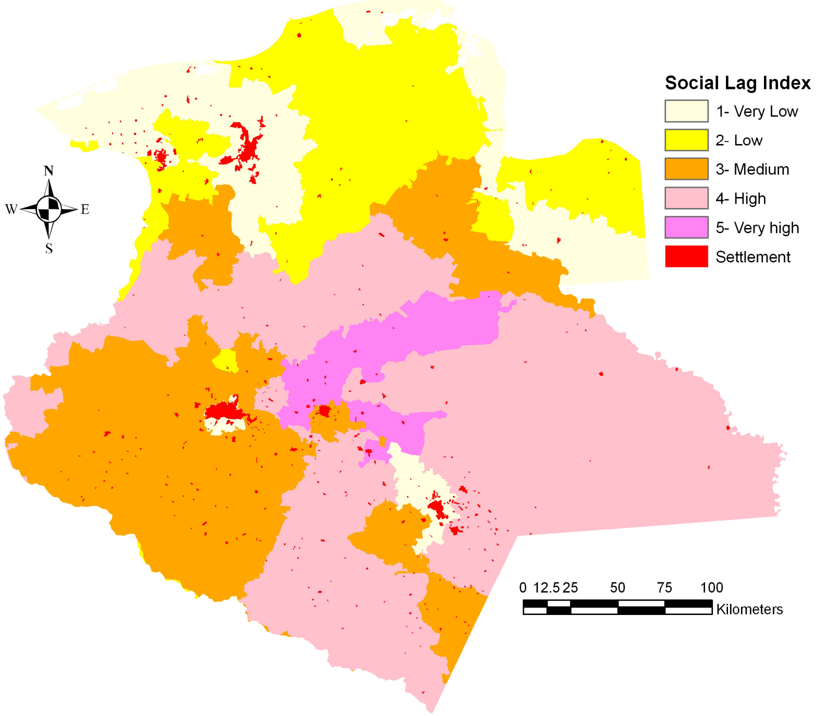


Figure 2. Social lag index in the Grijalva-Usumacinta watershed, Mexico (Source: CONEVAL, 2007)

Table 1.Some extreme weather events and their impacts in the Grijalva –Usumacinta watershed. Source: Landa, Magaña, Neri, 2008, after CENAPRED 2001-2005.

Event	Impact	Date
Heavy rains	417 dead , 353 settlements affected, and 30.000 persons homeless	1998
Heavy rains, landslide, flooding	95 dead, 126.854 persons affected, 10,000 houses damaged	2001
Heavy rains and flooding	800 persons affected, 171 houses damaged, 8.000 hectares of crops damaged	2002
“Larry “ Storm, Heavy rains and flooding	52, 885 persons affected, 10,577 houses damaged	September-November 2003
“Stan” Hurricane, Heavy rains, flooding and Landslide	86 dead, 162.570 persons affected, 32.514 houses damaged, 305 schools damaged, 208.064 hectares of crops and grasslands damaged, 5.669 km roads affected. Total costs: 15.031 millions Mexican pesos	October 1- 5 - 2005
Heavy rains	617 persons affected, 1 road – bridge damaged. Total Costs: 3.3 million Mexicans pesos	2005
Heavy rains, flooding and Landslide	1.100.000 persons affected, 670 settlements affected, damage to the urban and road infrastructure. Total costs between 7.500 and 50.000 millions Mexican pesos.	October, 2007

In this context, assessment and mapping of the current vulnerability to climate change (in the context of the adverse effects of extreme weather events) in the Grijalva-Usumacinta watershed is an important part of formulating adaptation strategies both regionally and nationally. A vulnerability assessment can pinpoint areas and sectors where the vulnerability is high, and thus where adaptation strategies should be developed. A structured approach to the vulnerability assessment should provide comparability among regions (States, counties) so that common and integrated adaptation policies can be identified.

2. Assessing and Mapping Vulnerability

Vulnerability describes a central concept in climate change research as well as in the research communities dealing with natural hazards and disaster management, ecology, public health, poverty and development, secure livelihoods and famine, sustainability science, and land change [7, 8, 9 10,11, 12].

Vulnerability can be described as a lack of security against environmental threats. It results from a combination of processes that shape the degree of exposure to a hazard, sensitivity to its stress and impacts, and resilience in the face of those effects. All people, ecosystems, and regions confronting environmental or socio-economic stresses are potentially vulnerable to the impacts, of environmental hazards, but the level of vulnerability varies widely [13]. According to [14], the conceptual framework of vulnerability recognizes and builds upon the three major dimensions of vulnerability exposure, sensitivity, and adaptation/resilience; characterizing them in “causal maps” of the roots of vulnerability, where causal linkages are carefully depicted, is an important analytic task.

The assessment of vulnerability is important as it enables the identification of areas or resources at risk, as well as the threats posed by the reduction or loss of such resources or human lives, that could threaten future sustainable development. A number of studies have examined, either qualitatively or quantitatively, the individual components of vulnerability. This includes the sensitivity of agricultural systems [15, 16, 17] and human vulnerability [18, 19, 20] to climate change. In Mexico, several studies investigating vulnerability have been conducted, mainly related to the agricultural sector in general [21, 22, 23] and to specific crops such as rainfed maize [24, 25], coffee production [26], and water resources [27, 28]. However, in Mexico there are no reports regarding the spatial analysis of vulnerability using GIS and remote sensing environmental data.

Mapping the distribution of vulnerability—either in terms of the attributes of sensitivity, exposure, or adaptive capacity, or in terms of outcomes and impacts—has become a central tool for communicating the results of vulnerability research to other academics, researchers, policy makers, and the community at large [15, 23, 28, 29]. However, according to [29] the challenge remains of accounting for the dynamic nature of vulnerability and spatially representing some indicators (e.g., social capital, institutional relations) that may well be the determinant of vulnerability in particular places. Current challenges in future vulnerability analysis include: addressing multiple, interacting stressors, capturing socioeconomic and biophysical uncertainty, accounting for cross-scalar influences and outcomes, and emphasizing equity and social justice. In addition, when mapping vulnerability, some questions remain incompletely answered, such as: What is the role of spatial analysis as a whole in relation to analyzing and mapping vulnerability? How can we link global, regional and local scales? How should we treat the exposure unit as a coupled social ecological system and identify its interactions?

The goal of this work was to address the analysis and mapping of vulnerability in terms of the dynamic, cross-scalar influences interacting with and threatening the exposure unit as a coupled social ecological system. Some aspects included in the social system are poverty and inequity. The analysis presented in this article focused on assessing and mapping the current vulnerability of crop systems and settlement infrastructure to extreme weather events. One special focus of this work is the explicit, spatial illustration of the distribution of sensitivities and differential adaptive capacities, and how these two elements are spatially related.

3. Methodology for Vulnerability Assessment and Mapping

Methodological approaches to assess vulnerability (both sensitivity and adaptive capacity) that include cross-sectoral, multi-scale, and multi-stress relationships are an emergent area of research. Following Adger [30] the vulnerability of a particular community or livelihood system is a function of three main factors:

- ***Exposure***–the nature and extent of changes to which a place's climate is subjected including changes in climate variability, hereunder the magnitude and frequency of extreme events.
- ***Sensitivity***–how systems can be either positively or negatively affected by the change in climate.
- ***Adaptive capacity***–how much capability a society has to adapt to the changes so as to maintain, minimize loss of, or maximize a gain in welfare.

In this study, spatial analysis and modeling (inference modeling) were used to assess and map the vulnerability to climate change (in this case, based on the assumption of an increase in intensity and frequency of extreme weather events) in the Grijalva–Usumacinta watershed. Two sectors were considered: crop systems and settlement infrastructure. The evaluation of ***adaptive capacity*** was based on economic and demographic characteristics. The s***ensitivity*** of crop systems was evaluated based on the susceptibility of cropland to flood and hydric erosion. The settlement infrastructure **sensitivity** was evaluated based on the susceptibility of the population to floods and landslides. Figure 3 shows a diagram of the methodological approximation used in this study.

3.1. *Database*

The data used in this study include:

- A digital elevation model. Elevation data were obtained from the Shuttle Radar Topographic Mission/C-Band Synthetic Aperture Radar SRTM/C-SAR, with a spatial resolution of 90 meters. From this DEM, the topographic position [31], topographic wetness index [32], and slope were calculated [33].
- River segment, scale 1:250,000 [34]. From this layer several buffers (<2.5, 2.5-5.0 and >5.0 km) were calculated using the ArcMap GIS software.
- Land use and land cover map, scale 1:250,000, [35]. This map was reclassified in two categories, forest vegetation and agriculture (the latter includes grasslands).
- Soil map, scale 1:250,000 [36]
- Population data [37]
- Social lag index [38]

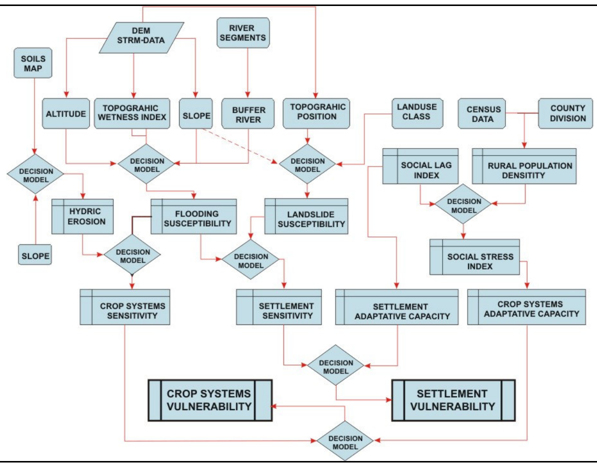


Figure 3. Methodological approximation for mapping vulnerability

3.2. *Adaptive Capacity Indicators*

In this study, the socio-economic conditions used to indicate adaptive capacity include demographic and economic characteristics. Economic capacity was estimated using a social lag index [38] and demography was estimated by population density. For settlements, the adaptive capacity was estimated by the social lag index and for crop systems the social stress index was used. The social lag index provides estimates for the multidimensional measurement of poverty. This index was calculated by CONEVAL [38] using the principal components technique, which numerically synthesizes different dimensions of poverty, including education, access to health services, quality of housing, and basic services. The indicators used to construct the social lag index are listed in Table 2. The rural population density was calculated taking into account the populations of localities with less than 2.500 inhabitants, referred to as the county area. Four grades of density were considered: low (<10 inhabitants), medium (10–50 inhabitants), high (50-100 inhabitants), and very high >100 inhabitants). Finally, the social lag index and population density were joined in a simple index (social stress index) according to the criteria listed in Table 3.

3.3. *Sensitivity Indicators*

Sensitivity was calculated for settlements and crop systems. For each sector, two indicators were selected that represent aspects of the sector that could be quantitatively modeled. For crop system sensitivity the indicators used were cropland at flood susceptibility and cropland at hydric erosion susceptibility; it was assumed that total or partial agriculture production could be affected by both of these processes. For settlement sensitivity, the indicators used were population at flood susceptibility and population at landslide susceptibility.

Three variables were considered for the construction of the landslide susceptibility map: slope, topographic position, and land use. These variables were combined in a decision model to produce a landslide susceptibility map with five categories of landslide susceptibility: 1: very low, 2: low, 3: medium, 4: high and 5: very high. Table 4 shows the rules used to combine the variables. The flood susceptibility was obtained by combining the following variables in a decision model: altitude, topographic wetness index, slope, and the distance from a river. The result was a flood susceptibility map with five categories of flooding susceptibility: very high, high, moderate, low, and no flooding. Tables 5 shows the rules used to combine the variables. The total potentially affected population for each unit of the flood and landslide susceptibility map was assigned using a GIS zonal operation.

Table 2. Indicators used to construct the social lag index [CONEVAL, 2007]

Education	Percentage of literate population 15 years or older. Percentage of the population between 6 and 14 years that does not attend school Percentage of households with members between 15 to 29 years of age, with one household member having less than 9 years of education. Percentage of the population 15 years or older with incomplete basic education
Access to health services	Percentage of the population without rights to health services.
Quality and space in the household	Percentage of occupied housing with bare floor Average number of persons per room
Basic services in the household	Percentage of occupied housing without toilet (w. c.) Percentage of occupied housing without clean water from a public aqueduct Percentage of occupied housing without sewer Percentage of occupied housing without electrical energy Percentage of occupied housing without clothe washing Percentage of occupied housing without a refrigerator

Table 3. Criteria to define Social Stress Index [23]

Criteria	**Social stress index**
1. If the social lag index is medium to very low and the population density is low	1. Low
2. If the social lag index is low - very low and the population density is medium 3. If the social lag index is high and the population density is low	2. Moderate
4. If the social lag index is low to very low and the population density is high 5. If the social lag index is medium to very high and the population density is low to medium	3. High
6. If the social lag index is medium to very high and the population density is high 7. If the social lag index is very high and the population density is medium	4. Very high

Table 4. Criteria used to define landslide susceptibility [31, 39, 40]

Criteria – Rules	**Landslide susceptibility**
1. Slope < 6 grades 2. Slope 6 – 12, Topographic position =2* and land use = forest.	1. No susceptibly
3. Slope 6 – 12, Topographic position =2 and land use = agriculture. 4. Slope 6 – 12, Topographic position =3	2. Very Low
5. Slope 6 – 12, Topographic position = land use = forest. 6. Slope 12 – 20, Topographic position = 2 and land use = forest. 7. Slope 12 – 20, Topographic position = 3 8. Slope > 20, Topographic position = 3 and land use = forest	3. Low
9. Slope 12 – 20, Topographic position = 1 and land use = agriculture. 10.Slope 12 – 20, Topographic position = 1 and land use = forest 11. Slope 12 – 20, Topographic position = 2 and land use = agriculture 12. Slope > 20, Topographic position = 2 and land use = forest 13. Slope > 20, Topographic position = 3 and land use = agriculture	4. Medium
14. Slope 12 – 20, Topographic position = 1and land use = agriculture. 15.Slope > 20, Topographic position = 1and land use = forest 16.Slope > 20, Topographic position = 2 and land use = agriculture	5. High
17. Slope > 20, Topographic position = 1and land use = agriculture	6. very high

*Topographic position: (1) valley and foot slopes, (2) Rectilinear slope, (3) Convex slope and crests

Table 5. Criteria used to define flood susceptibility

Criteria – Rules	**Flood susceptibility**
1. Slope <3%, altitude <5 m, river buffer <5 km	1.Very high
2. Slope <3%, altitude <5 m, river buffer >5 km and wetness* <3	
3. Slope <3%, altitude 5-10 m and river buffer <2.5 km	
4. Slope <3%, altitude 5-10 m, river buffer <2.5-5.0 km and wetness <3	
5. Slope <3%, altitude <5 m, river buffer >5 km and wetness >2	2. High
6. Slope <3%, altitude 5-10 m, .river buffer 2.5-5.0 km and wetness >2	
7. Slope <3%, altitude 5-10 m, river buffer >5.0 km and wetness <4	
8. Slope <3%, altitude 10-25 m, river buffer <2.5.0 km	
9. Slope <3%, altitude 10-25 m, river buffer 2.5-5.0 km and wetness <3	
10. Slope <3%, altitude 25-50 m, river buffer <2.5 km and wetness <3	
11. Slope <3%, altitude 25-50 m, river buffer 2.5-5.0 km and wetness =1	
12. Slope <3%, altitude 50-100 m, river buffer <2.5 km and wetness <3*	
13. Slope <3%, altitude 100-500 m, river buffer <2.5 km and wetness>1	
14. Slope <3%, altitude 100-500 m, river buffer 2.5-5.0 km and wetness=1	
15. Slope<3%, altitude >500 m and wetness <3	
16. Slope =3-9%, altitude <500 m and wetness <3	
17. Slope <3%, altitude 5-10 m, river buffer >5.0 km and wetness >3	3. Moderate
18. Slope <3%, altitude 10-25 m, river buffer 2.5-5.0 km and wetness >2	
19. Slope <3%, altitude 10-25 m, river buffer >5.0 km and wetness <4	
20. Slope <3%, altitude 25-50 m, river buffer <2.5 km and wetness >2	
21. Slope <3%, altitude 25-50 m, river buffer 2.5-5.0 km and wetness=2	
22. Slope <3%, altitude 25-50 m, river buffer >5.0 km and wetness <4	
23. Slope <3%, altitude 50-100 m, river buffer 2.5-5.0 km and wetness =2	
24. Slope <3%, altitude 50-100 m, river buffer >5.0 km and wetness <3	
25. Slope <3%, altitude 100-500 m, river buffer 2.5-5.0 km and wetness>1	
26. Slope <3%, altitude >500 m and wetness=3	
27. Slope 3-9%, altitude <500 m and wetness >2	
28. Slope 3-9%, altitude >500 m and wetness<3	
29. Slope <3%, altitude 10-25 m, river buffer >5.0 km and wetness >3	4. Low
30. Slope <3%, altitude 25-50 m, river buffer 2.5-5.0 km and wetness >2	
31. Slope <3%, altitude 25-50 m, river buffer >5.0 km and wetness >2	
32. Slope <3%, altitude 50-100 m, river buffer <2.5 km and wetness>2	
33. Slope <3%, altitude 50-100 m, river buffer 2.5-5.0 km and wetness >2	
34. Slope <3%, altitude 50-100 m, river buffer >5.0 km and wetness >2.0	
35. Slope <3%, altitude 100-500 m, river buffer >5.0 km	
36. Slope <3%, altitude >500 m and wetness>3	
37. Slope 3-9%, altitude >500 m and wetness>2	

*Topographic wetness index: (1) >10.5, (2) 9.5 – 10.5, (3) 8 – 9.5, (4) >8.0 Non-dimensional

Hydric erosion susceptibility was estimated by combining the slope and soil map in a decision model according to the rules listed in Table 6. To assess the sensitivities of settlement and crop systems, the indicators for landslide susceptibility, flooding susceptibility, and hydric erosion susceptibility were combined in a decision model, according to the rules listed in Tables 7 and 8.

Table 6. Criteria used to define hydric erosion susceptibility [41, 42]

Criteria - Rules	**Hydric erosion susceptibility**
1. Slope < 3%, any soil, except lithosols	None
2. Slope of 3 -9 %, any soil, except litosols	Low
3. Slope of 10 – 15 %, litosols, or a combination of a slope of 10 – 15%, and acrisols or vertisols, other soil and slope of 3 -9 % and lithic contact < 50 cm	Moderate
4. Slope of 16 – 30% or a combination of slope 16 – 30% and acrisols or vertisols, or litosols and a slope 3 -9 %, other soils and slopes of 10 -15 %, and lithic contact < 50 cm	Moderate - high
5. Slope of 30 – 50% or a combination of a slope of 30 – 50% and acrisols or vertisols, or lithosols and a slope of 10 -15%,other soils and slopes of 16 -30% and lithic contact < 50 cm	High
6. Slope of 50 – 70%, or a combination of a slope of 50 – 70% and acrisols or vertisols, or lithosols and slope of 16 -30%, other soils and slopes of 30 -50%, and lithic contact < 50 cm	Very high
7. Slope > 70%, any soil	Extremely high

Table 7. Criteria used to define the settlement sensitivity

Criteria - Rules	**Settlement sensitivity**
1. Flood susceptibility is very high and landslide susceptibility is very high	Very high
2. Flood susceptibility is high and landslide susceptibility is high	High
3. Flood susceptibility is moderate and landslide susceptibility is moderate	Moderate
4. Flood susceptibility is low and landslide susceptibility is low to very low	Low

Table 8. Criteria used to define crop system sensitivity

Criteria - Rules	**Settlement sensitivity**
1. Flood susceptibility is very high and hydric erosion susceptibility is very high to extremely high	Very high
2. Flood susceptibility is high and hydric erosion susceptibility is high	High
3. Flood susceptibility is moderate and hydric erosion susceptibility is moderate to moderately high	Moderate
4. Flood susceptibility is low and hydric erosion susceptibility is low	Low

3.4. *Settlement and Crop Systems Vulnerability*

The Vulnerabilities of settlement and crop system was defined by combining the sensitivity and adaptive capacity indicators in a decision model according to the criteria indicated in Tables 9 and 10 Figure 4 shows an example of how these rules I combined in a decision model to assess, in this case, settlement vulnerability.

Table 9. Criteria used to define Settlement vulnerability

Criteria – Rules	**Grade of vulnerability**
1. Settlement sensitivity is high to very high and social lag index is very high	1. Very high
2. Settlement sensitivity is medium and social index is very high	
3. Settlement sensitivity is high to very high and social lag index is medium	2. High
4. Settlement sensitivity is medium and social index is lag high	
5. Settlement sensitivity is low and social index is very high	
6.. Settlement sensitivity is high to very high and social lag index is low	3. Moderate
7. Settlement sensitivity is medium and social lag index is medium to low	
8. Settlement sensitivity is low and social lag index is high	
9. Settlement sensitivity is low and social lag index is medium to low	4. Low

Table 10. Criteria used to define the crop system vulnerability

Criteria	**Grade of vulnerability**
1. Crop sensitivity is high to very high and social stress index is very high	1. Very high
2. Crop sensitivity is medium and social stress index is very high	
3. Crop sensitivity is high to very high and social stress index is medium	2. High
4.Crop sensitivity is medium and social stress index is high	
5. Crop sensitivity is low and social stress index is very high	
6.. Crop sensitivity is high to very high and social stress index is low	3. Moderate
7. Crop sensitivity is medium and social stress index is medium to low	
8. Crop sensitivity is low and social stress index is high	
9. Crop sensitivity is low and social stress index is medium to low	4. Low

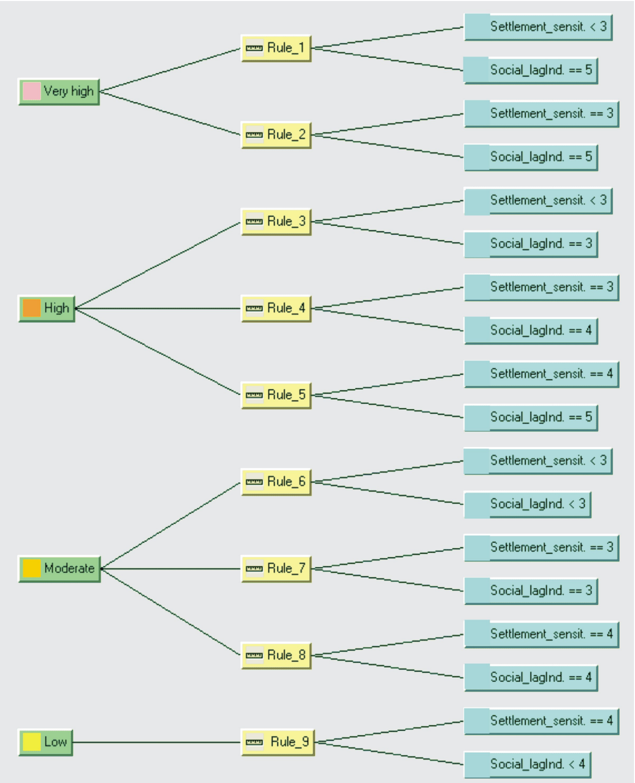


Figure 4. Decision model used to assess the settlement vulnerability

4. Results and discussion

4.1. *Coping and Adaptive Capacity*

Figures 5 and 6 show the rural population density and the social stress index of the Grijalva-Usumacinta watershed. In the low part of watershed the low rural population density is related to the presence of rangeland use, and in the upper part to the presence of conservation areas (forest use). The highest population density area, in general, corresponds to agricultural lands, which are located in the upper part of the watershed, including areas under shifting cultivation. Figure 6 shows the social stress index, a combination of the population density and the social lag index. This index is low in the lowlands of the study area (which includes most of Tabasco State), which can be interpreted as a high adaptive capacity and reflects good social conditions. On the other hand, in most of the upper watershed, this index ranges from high to very high; reflecting poor social conditions, and therefore, the adaptive capacity in this area can be interpreted as low.

Because the database used in this study to estimate the adaptive capacity was taken from a secondary, but credible source [37, 38], and very simple GIS operations were implemented, validation of these data was not considered here.

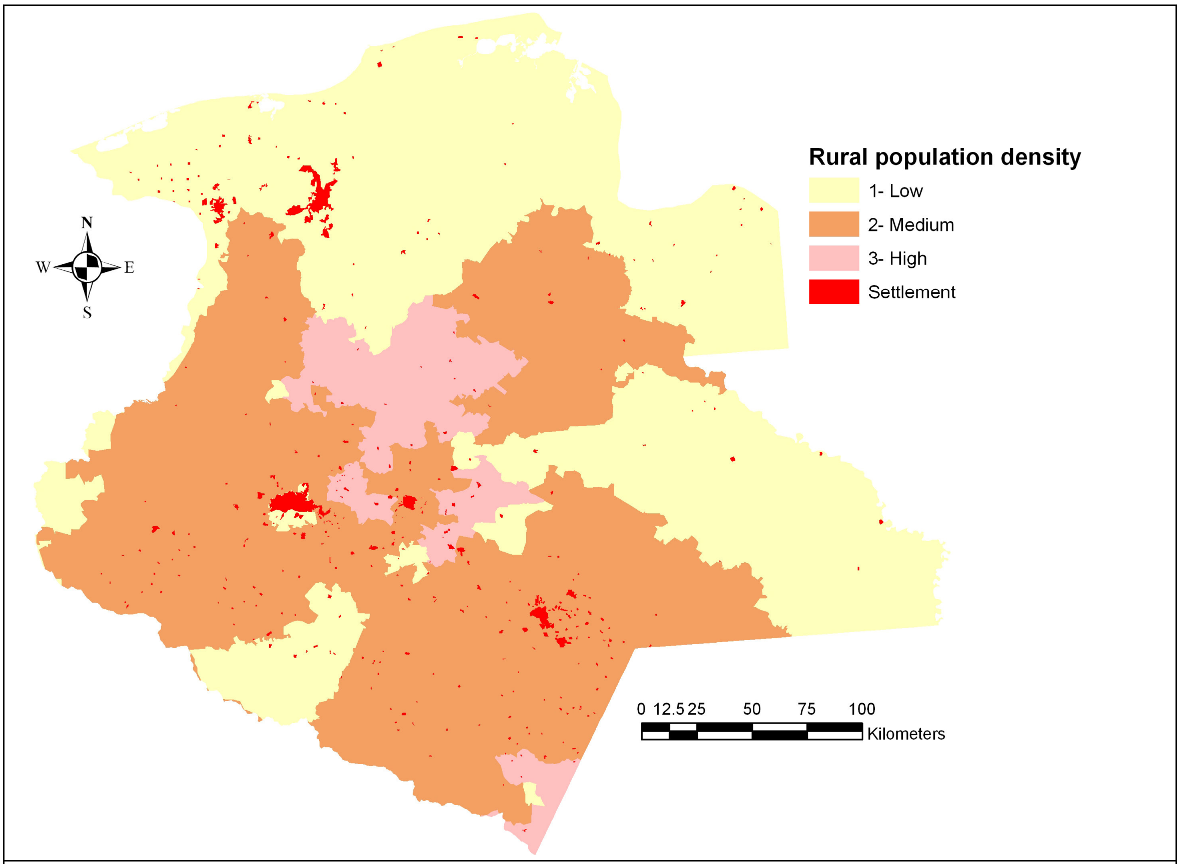


Figure 5. Rural population density in the Grijalva-Usumacinta watershed, Mexico

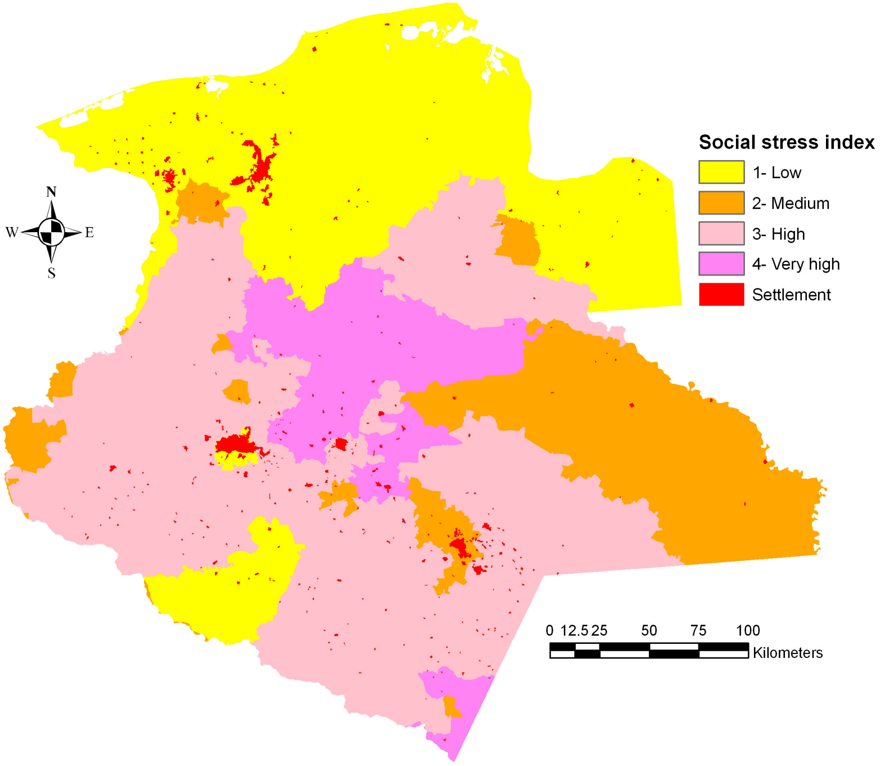


Figure 6. Social stress index in the Grijalva-Usumacinta watershed, Mexico

4.2. *Sensitivity*

4.2.1. Validation of Sensitivity Indicator. The indicators used to estimate the settlements and crop system sensitivity were hydric erosion susceptibility, flooding susceptibility, and landslide susceptibility. The results of the decision models implemented for each of these indicators were validated, as described in the following paragraph. The hydric erosion susceptibility map was compared with the soil degradation map [43] and it was found that the areas 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. 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 (Figure 7): 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. Finally, using a QuickBird satellite image, an inventory of landslides was developed and fifteen landslides were mapped. A comparison of this map with the landslide susceptibility map showed that 60% of the landslides mapped as high to very high susceptibility and 87% of the landslides as moderate to very high susceptibility (Figure.8). As described herein, the forecast capacity of the models to estimate sensitivity fluctuated about 90%. In future works regarding flooding and landslide susceptibility models, the forecast capacity can be increased by using DEMs with better resolutions, which are now available (5 and 30 meters).

Figure 7. Percentage of inundated area by extreme precipitation of november 2007 in related to Flooding susceptibility map

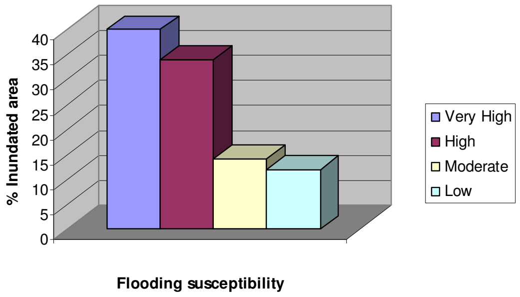
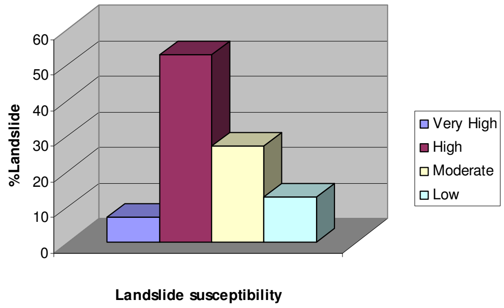


Figure 8. Percentage of landslide in related to Landslide susceptibility map



4.2.2. Settlements and Crop System Sensitivity. Figures 9 and 10 show the distribution of settlements sensitivity and the total population potentially affected. In the lowlands the high sensitivity is related to flooding risk and in the highlands to landslide susceptibility. The figures show that, in terms of area and the affected population, flooding poses the greater risk. Most of the potentially affected area corresponds to Tabasco State, which is located in the lower part of the watershed.

An important aspect of the sensitivity indices, particularly those based on flood susceptibility, is that the degrees of susceptibility may be interpreted as an indirect measure of a) flood height -- estimating the water table height for different zones gives an idea of the amount of water that would be needed to evacuate from those zones; and b) flood duration -- making a qualitative estimate of flood duration is possible. Information about these two aspects will be of great utility for decision makers: a) to make decisions about how to provide help to the people after the inundation takes place, and b) to implement measurements for adaptation.

Another important aspect of the flooding susceptibility map is the great contribution of the DEM (digital elevation model) data in the model. As can be seen in Figure 3, except for the river buffer, the information for the model is obtained from DEM data. Nevertheless, at the present time, this type of data is not being fully used in Mexico. The quality of this information can be substantially improved by the use of more detailed elevation data (5 and 30 meters of spatial resolution) that are now partially available.

In relation to the settlements potentially affected by inundation or landslides, the total population affected in each spatial unit was considered (e.g., very high or high), although it is also possible to obtain the location of each settlement or household unit. This is not shown in the map because it is not practical to display 35,000 localities. Figure 11 shows an example of the spatial distribution of localities in the area mapped as having a very high susceptibility to inundation. Figure 12 shows, for each spatial unit of susceptibility, the total number of localities. This spatial information is very useful for decision makers, as it provides an idea of the ease or difficulty associated with helping people; the more widely distributed the population, the more work there is to do.

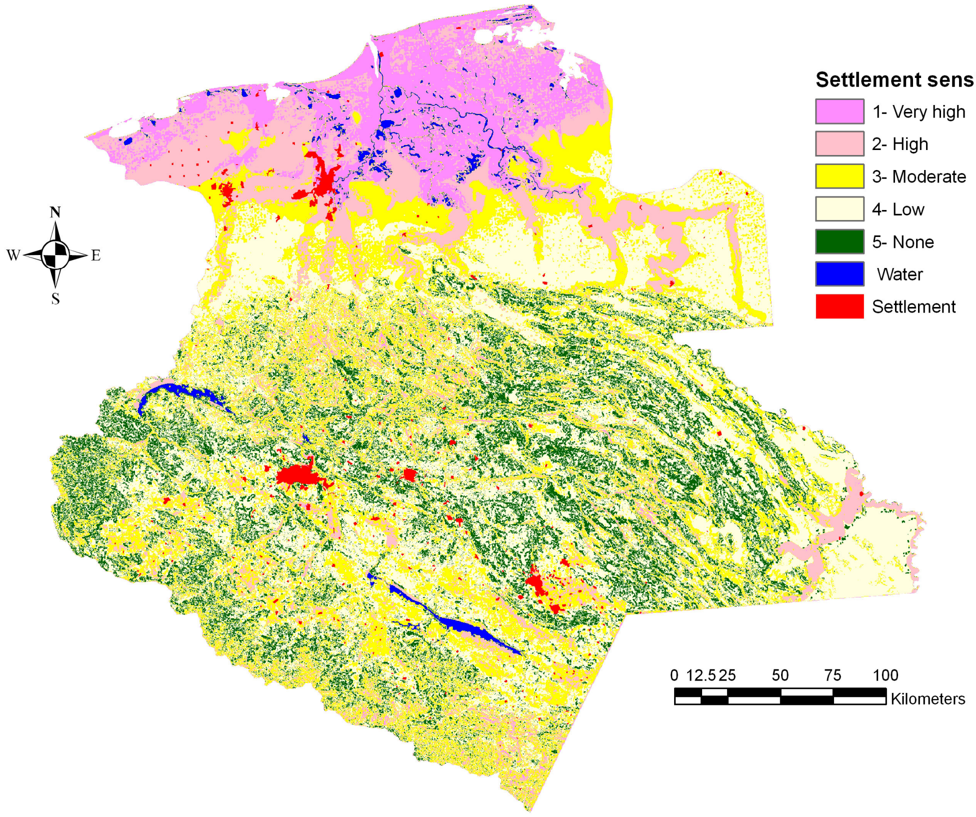


Figure 9. Settlement sensitivity in the Grijalva-Usumacinta watershed, Mexico

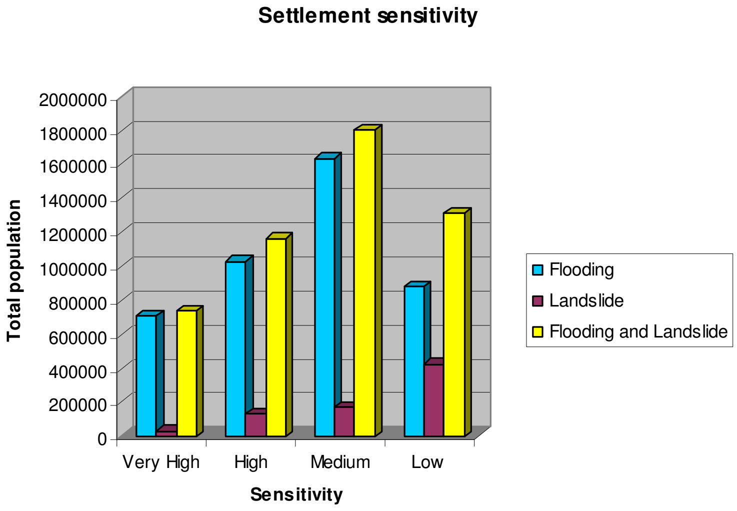


Figure 10. Settlement sensitivity and total population potentially affected for each grade of sensitivity, the Grijalva-Usumacinta watershed, Mexico

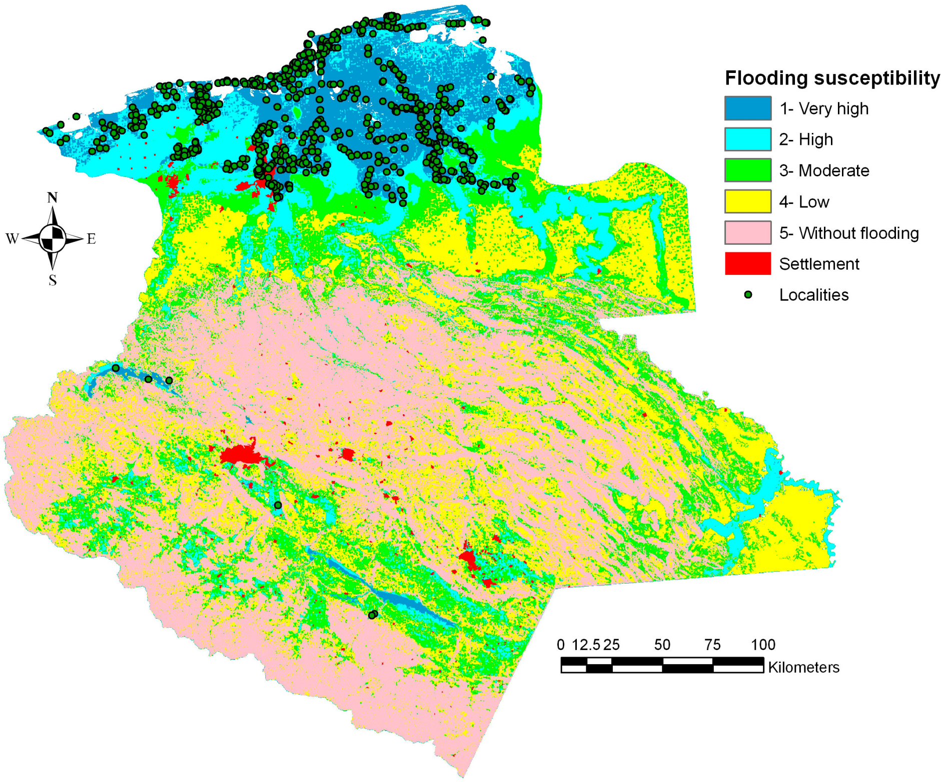
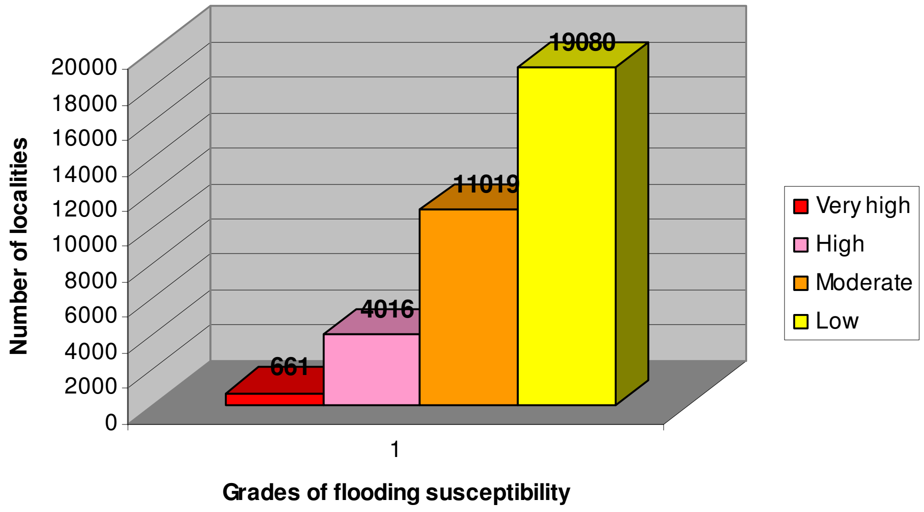


Figure 11. Spatial distribution of localities in areas with a very high susceptibly to flooding in the Grijalva-Usumacinta watershed, Mexico

Figure 12. Number of localities for each spatial unit of flooding susceptibility, the Grijalva-Usumacinta watershed, Mexico



Figures 13 and 14 show the distribution of crop system sensitivities and the total area affected. In the lowlands the sensitivity is related to flooding, and in the highlands to hydric erosion. The figures show that both hazards are important for the cropland; about 500.000 hectares are potentially affected at high to very high grades by flooding or hydric erosion. These two processes are related to each other, because growing crops on unsuitable lands in the upper part of the watershed can contribute to an increased sensitivity of the lowlands. Information on flood severity would be immensely useful for decision-makers for evaluating the magnitude and cost of damages and implementing adaptation measures accordingly.

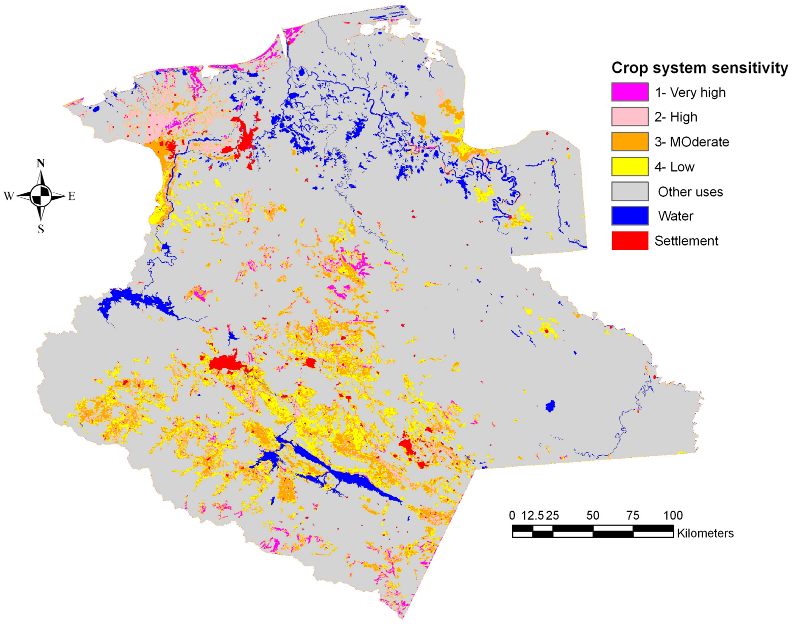


Figure 13. Crop system sensitivity in the Grijalva-Usumacinta watershed, Mexico

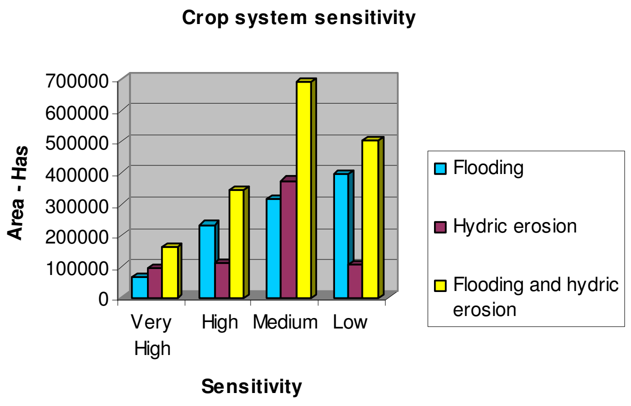


Figure 14. Crop system sensitivity and total area potentially affected for each grade of sensitivity, the Grijalva-Usumacinta watershed, Mexico

4.3. *Settlements and Crop System Vulnerability*

Figures 15 and 16 show the distribution of settlements and crop system vulnerabilities. For both sectors, the higher grades of vulnerability occur in the upper part of watershed as a consequence of a combination of high grades of *sensitivity* and a very low *adaptive capacity* (high grades of the social stress index or the social lag index).

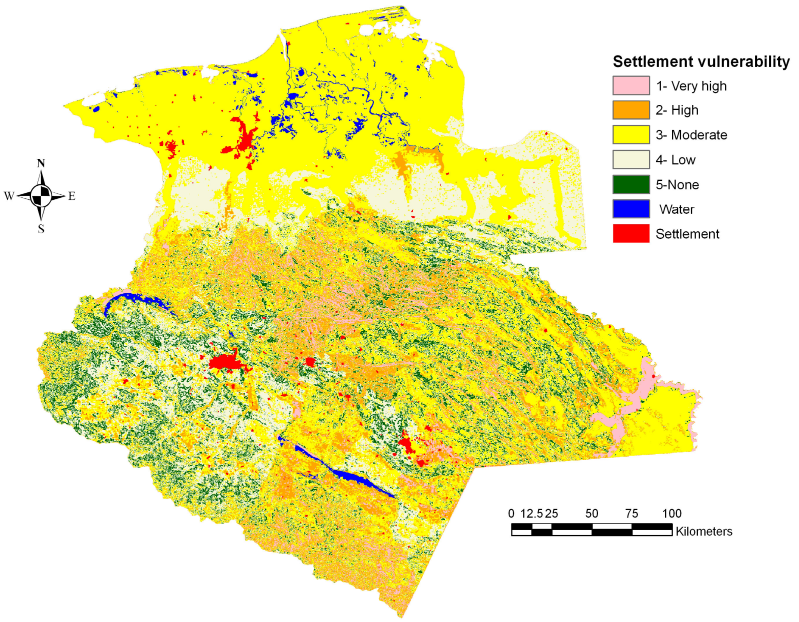


Figure 15. Settlement vulnerability, the Grijalva-Usumacinta watershed, Mexico

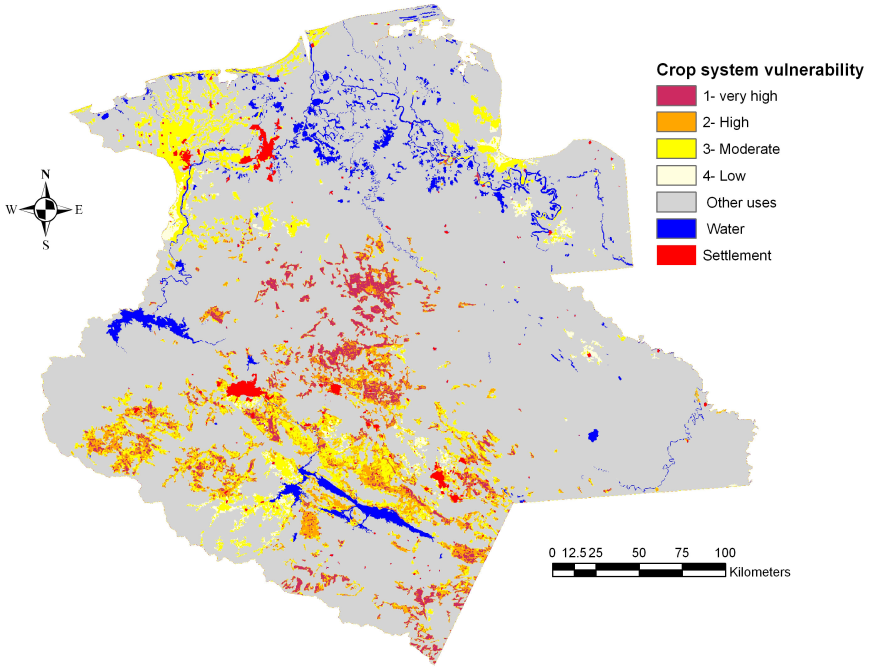


Figure 16. Crop system vulnerability, the Grijalva-Usumacinta watershed, Mexico

In the lowlands, although the *sensitivity* ranges from high to very high, the *adaptive capacity* is high (low grades for the social stress index or the social lag index); therefore, the final result is a moderate vulnerability. The vulnerability maps illustrate which areas are vulnerable at different grades, and the importance of theses maps relies on their ability to show the interactions between sensitive and adaptive capacities. In terms of social impacts and adaptation measurements theses maps help decision makers to establish priorities that help the affected people and implement adaptive measurements. However, because these indices occur in the final step of the synthesis process (the information is aggregated), they must be taken as a first approximation. For further analytical purposes, the constituents of vulnerability, the sensitivity (which has been discussed before) and the adaptive capacity index must be assessed separately. Finally, a more detailed analysis of each indicator must be carried out to achieve a better and more specific decision-making process (in terms of help and adaptive measurements).

The results of this study agree with Landa [5] who states that the Grijalva-Usumacinta catchment area exhibits conditions of high vulnerability to intense rainfall and that this vulnerability of rural areas is highly related to the stress that natural resources are under at present. This area is perhaps one of the regions of Mexico where the land use has changed drastically in last three decades, during which large areas of tropical forests have been transformed to agricultural use. The same author points out that Mexicans who lives under poverty conditions are particularly susceptible to the effects of extreme weather events; this condition increases the vulnerability in greater proportion than the population grows. On the other hand, if it is considered that in this area the most of the rural population depends on agricultural systems for their livelihoods, the vulnerability of crop systems has a special meaning for theses communities. It means that for these groups, food security is threatened. If it is considered that in this region the population has a high level of food poverty [38], and therefore the potential impacts of extreme weather events can cause additional inequities, special attention needs to be paid to indigenous people with subsistence livelihoods and groups with limited means of adaptation.

The identification and characterization of the way in which human and natural systems are sensitive is key input for targeting, formulating and evaluating adaptation policies [44]. The approach and partial results presented in this paper can hopefully contribute to the knowledge of the current characteristics of settlement and crop systems sensitivity and adaptive capacity in the Grijalva - Usumacinta watershed, and therefore guide the formulation of adaptation policies of these sectors to climate variability, focused on extreme weather events. Equally, it is expected that these results will help to improve the management of current and future climate risk. The development of adaptive capacity in relation to the potential impacts of climatic change depends on the decisions that we make today in the technological, social, economic and environmental fields; in the use of tools of climatic prognosis that allow us to deal with uncertainty, and in the development of preventative actions against extreme events [5]

5. Conclusions

The preliminary results presented here demonstrate a method to assess and map vulnerability to extreme weather events, considering both physical and societal aspects. I conclude that spatial analysis and modeling are powerful tools for assessing and mapping vulnerability. Compared to other current approaches to climate vulnerability assessment, the inference modeling approach has particular features that augment its transparency, reproducibility and comparability. The use of inference models allow us to analyze how different elements of vulnerability can contribute to the final vulnerability as well as the interactions that occur between the elements. Although at the present time the reduction of vulnerability is focused on constructing adaptive capacity for the population, in Grijalva-Usumacinta watershed, actions related to the adequate use of natural resources in concordance with sustainable development are needed to reduce the high sensitivity of natural resources, particularly the crop systems.

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