6TH INTERNATIONAL CONFERENCE
ON FLOOD MANAGEMENT
September 2014 - São Paulo - Brazil

THE ROLE OF HYDROLOGICAL UNCERTAINTIES IN FLOOD RISK ANALYSIS: TONALA RIVER, MEXICO.

M. Laverde-Barajas[1]. A. Pedrozo Acuña[1] A. Breña-Naranjo[1]. G. Corzo-Perez[2]
1. *National Autonomous University of Mexico UNAM, Institute of Engineering*
2. *UNESCO-IHE, Institute for Water Education, Delft - The Netherlands*

ABSTRACT:

Around the world, there is a scarce mention of the role of the different sources of uncertainty during the assessment of flood risk. Given the magnitude of the stakes at risk during the incidence of extreme events, it is necessary to somehow consider and inform how uncertainties may modify a given prediction. As a result of the necessity to make decisions in the light of uncertain scientific input, this is especially true in the flood risk analysis process, where the lack of accuracy in the results may induce significant deviations and mistakes.

Within this context, the aim of this work is to present a practical framework for flood risk analysis, where the Source-Pressure-Response-Consequence model is used for the assessment of both probability and consequences due to flooding. For this, two methodological units are introduced, one aimed at the hazard characterisation and mapping and other related to the holistic characterisation of vulnerability. The first is carried out by means of an integrated approach comprised by a cascade of models; a distributed hydrological model and a standard 2D hydrodynamic model. While for the second part, the vulnerability of the system is dissected in five dimensions: physical, social, economic, ecologic and cultural. It is reflected that this enables the characterisation of the vulnerability in terms of both the degree of exposure and the fragility of the system to flooding. Uncertainty is considered in the hydrological model through the estimation of possible hydrographs for a given rainfall. The characterisation of the runoff by the multiple possibilities opens the door to a probabilistic estimation of flood maps.

Key Words: Food risk, uncertainty, cascade modelling

1. INTRODUCTION

Around the world, the influence of the flood events in the social development is enormous. When a flood disaster arrives, all the local, regional and national goals changes immediately. Flooding is the most common and devastating of all natural disasters. Direct losses include damages and injuries to infrastructure, agricultural and industrial production. Over the long term, food damages include health problems by waterborne infection, exposure to chemical pollutants released into flood waters, and vector-borne diseases (Levy, J. K., & Hall, J.,2005). During the last twenty years, we have experimented a rapid increase of the frequency and magnitude of flood events. Only in 2010, flood damage affected 178 million of people around the world. The economic losses were estimated at more than 40 million of dollars. (Jha A. et al 2012).

In many regions flooding is more devastating and frequent than others, Lowland regions, for example, are particularly vulnerable to flooding, where the main danger to life is associated with the wide lateral extent of inundated areas. Since 2007, this has been experienced on a yearly basis in the Mexican state of Tabasco, leaving large costs and damages. In this region, different rivers have flooded large parts of the state. In particular, the 2007 event flooded 70% of the lowlands of the state with depths up to 4 m in some locations and with circa~1.2 million of affected people (Aparicio et al. 2009). These events in combination with the yearly incidence of tropical storms (i.e. Hurricanes), revealed the need for a better flood management strategy.

According to Plate (2012), risk management can be interpreted as a process involving three different sets of actions depending on the actors who are involved. The first one includes the necessary to operate an existing system action. On the other hand, when the system is not adequate to meet the needs of people, for example, land use change, increased population and climate change, there is a second set of actions aimed at a review of the system or planning a new one, which will seek to adapt to new conditions forcing on it. As a result of the planning process can determine the creation of a new system. Hence the third set of actions, doomed to a process that aims to optimal design for the construction of a project arises.

In hydraulic engineering risk assessment is focused only on the third set of activities (Plate 2002, Hall et al, 2011). Within this approach, the solution consists in the evaluation of physical parameters (e.g. Climatic, hydrological geographical) in order to make a solution of a structural system (e.g. Protection levees). However, everyone has recognized the need to change strategies to cope with the floods (Pedrozo-Acuña, 2012). The new strategy for the management of risk generated by these extreme events, lies not only in building defensive works as levees, floodgates bypass and dredging of rivers; but also incorporating other mitigation measures that reduce the severity of injuries associated with these phenomena (e.g. Changes in land use through land use planning or reduction of exposure or vulnerability).

Thus, within this framework, it is necessary to view risk management from a holistic perspective (Schumann 2011) in which not only look involvement, it also involves public safety, equity and the environment (Hall et al. , 2011).

This work shows the influence of the uncertainty in the risk analysis: We applied an integrated cascade model on the lower Tonala Basin in Mexico. The Cascades modelling are composed of a semi-distributed hydrologic model and two-dimensional hydrodynamic modelling to estimate the flood hazard and holistic approach to assess the uncertainty. The uncertainty analysis is realized using a GLUE model running on Monte Carlo simulations. The characterisation of the runoff by the multiple possibilities opens the door to a probabilistic estimation of flood risk maps.

2. STUDY AREA

The Tonala River is located in the southeast of México (Figure 1). The river is about 150 km long and defines the boundary between the states of Veracruz and Tabasco. This natural watercourse flows into the Gulf of Mexico discharging more than 11.389 million m^3 water for year (CONAGUA, 2012).

The climate of Tonala has an average mean temperature between 24-28°C strongly influenced by an intense wet season (September-December) in combination with the incidence of hurricanes and storms arriving from the North (Pedrozo-Acuña et al., 2011). The region has a mean precipitation between 200-300 mm/year and with a range of 80-86% of relative humidity for most part of the year. The hydrologic characteristics play in concert with the morphological setting in the lowland area to increase the susceptibility of the region to extreme floods.

Indeed, in 2009 severe floods were experienced along the river's floodplain. High water levels were recorded at different locations, especially in the southern part of the domain (see panel c, Figure 1). There are several urban areas and locations along both sides of the river and river-mouth: the towns of Tonalá, Agua Dulce and Gavilán in Veracruz, and Cuauhtemoczin and La Venta in Tabasco.

Furthermore, the area is populated with industrial facilities associated with the national oil company (PEMEX). Thus, severe floods may cause large socio-economical damage along this region.

A recent hydrological study, presented by Fuentes, et al. (2010) indicate that extreme values of discharge for the Tonala River area between 500-1000 m^3/s for return periods in the interval of 5 to 1000 years. Therefore, in this study the utilised extreme discharges for the analytical base in terms of these numbers. Four discharges are selected for this purpose being 700, 900, 1100 and 1300 m^3/s.

Figure 1. a. Overview of the lower reach of the Tonalá River; b. Location of the study area in the México; c. Photographic evidence of the severe flood experienced in the study area during 2009.

3. METHODOLOGY

The flood risk analysis under design conditions is based on a cascaded modelling that describe the inundation processes and its impact on the Tonala River. In this approach uncertainties inherent to hydrological modelling are propagated in each modelling step with the aim to describe the effects of this uncertainty in the resultant flood risk. The analysis is integrated by following steps

- Hydrological modelling
- Hydraulical modelling
- Hazard estimation
- Assessment of the vulnerability
- Flood risk Analysis

During the process, we required a diverse field measurement data as historical precipitation as discharge, bathymetry and elevation data, and physical, social and economic characteristics in the basin. In Pedrozo et al (2012) the field measurement data are described.

3.1 Hydrologycal modelling

The hydrological modelling was derived from a statistical analysis of extreme values in the Tonala River based on the annual maximum series from 1969 to 2010. Five precipitation stations around the basin were fitted to the best distribution function with the purpose to simulate a design discharge corresponding 100 years return period (Figure 2) . We analized the uncertainty in the hydrological model based on the semi-distributed SWAT (Soil and Water Assessment Tool Model) by the U.S. Department of Agriculture's (USDA's) Agricultural Research Service (Arnold et al., 1998). SWAT model is an eco-hydrological model used to assess the impact of different soil management practices on water production, sediments and chemical products. This model is composed of eight modules: hydrology, weather, sedimentation, soil temperature, crop growths, nutrients, pesticides and crop management. These components allow to calculate widely processes of the hydrological cycle based on knowledge of the characteristics of the environment, climate, soil properties, topography, vegetation and land management practices present in the basin.

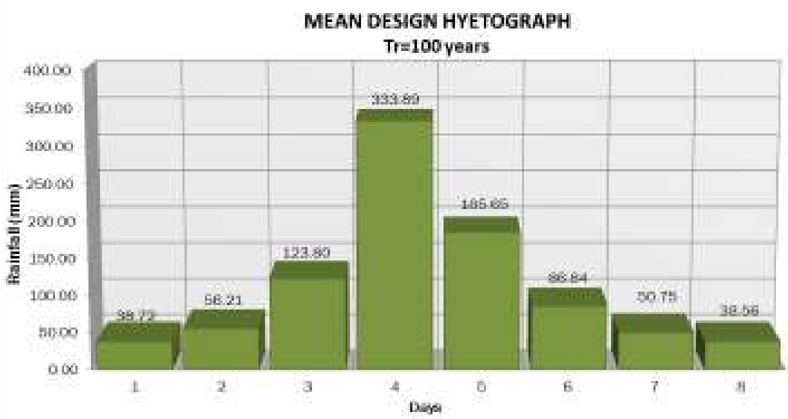

Figure 2 Mean design hyetograph in the Tonala basin

The process in the hydrology modelling is shown in the figure 3. The input data could be divided into three groups: physical, climatic an discharge data. The physical variables are composed of topographic information from the LiDAR Digital Elevation Model and physiographies information obtained from Environmental and Natural Resources Secretary (SEMANAT).Climatic data corresponding to daily precipitation and wind, temperature was obtained from Hydrometeorological stations installed by the National Water Commission of Mexican Government (CONAGUA). Finally, discharge data are composed by flow series of hydrometric stations in the Tancochapa river.

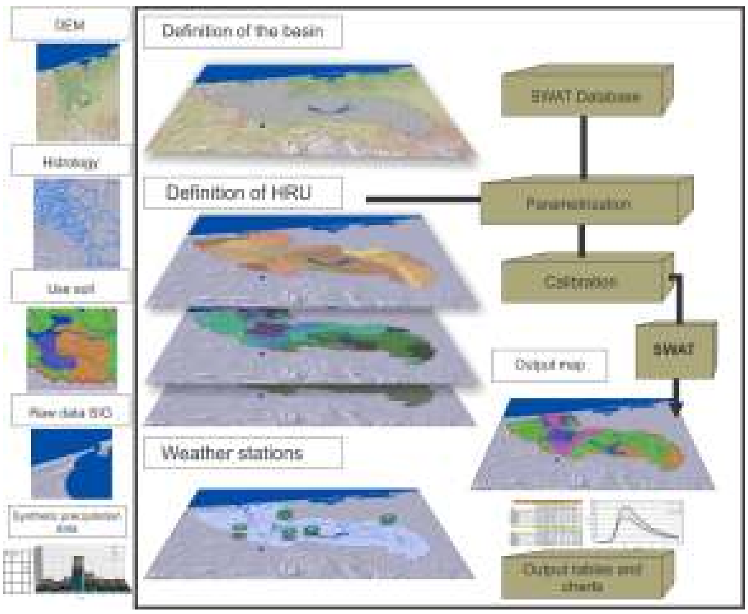

Figure 3. Schematic of the hydrological modelling

3.2 Uncertainty

There are diverse sources of error associated with hydrological modelling (Pedrozo et al. 2013). The uncertainty In this study is associated with the hydrological model set-up, in particular to those embedded in the model structure and its capacity to adequately describe the link of processes within the catchment. The first step in the uncertainty estimation was analysed the sensitivity of the parameters in the model. Parameterization of spatially-distributed hydrologic models can potentially lead to a large number of parameters (Yang, 2008). To estimate the sensitivity of the parameters, the simulation model combines Latin Hipercube (LH) (McKay et al., 2000) and the One-Factor-At-a-Time (OAT) analysis in an iterative model type. This analysis permitted to select the most five sensible parameters, its parameters were included in the uncertainty methodology.

The selected method employed to estimate the uncertainty in estimation of run-off with the distributed model was the Generalized Likelihood Uncertainty Estimation (GLUE), proposed by Beven and Binley (1992). This methodology recognises that many different combinations of model parameters can lead to results, which are acceptable representations of the available observations. Therefore 150 Monte Carlo simulations were running on the model in order to create an ensemble corresponding to 100 years discharge. In the figure 4 shows the Gaussian distribution of input parameters. The selected parameters for this analysis and its limits are presented in Table 1. The result of uncertainty analysis is shown in the figure5.

Table 1 Parameters included in the uncertainty analysis

PARAMETER	MIN	MAX	DESCRIPTION	PROCESS
Alpha_Bf	0.1	0.25	Base flow alpha factor [days]	Underground
Cn2	-1	-15	SCD runoff curve number for moisture condition II	Precipitation
Surlag	0	10	Surlag lag coefficient	Precipitation
Sol_AWC	0.01	0.2	Soil available water storage capacity [mm H2O / mm soil]	Soil
CH_K2	0	50	Effective hydraulic conductivity in the main channel [mm/h]	Chanel

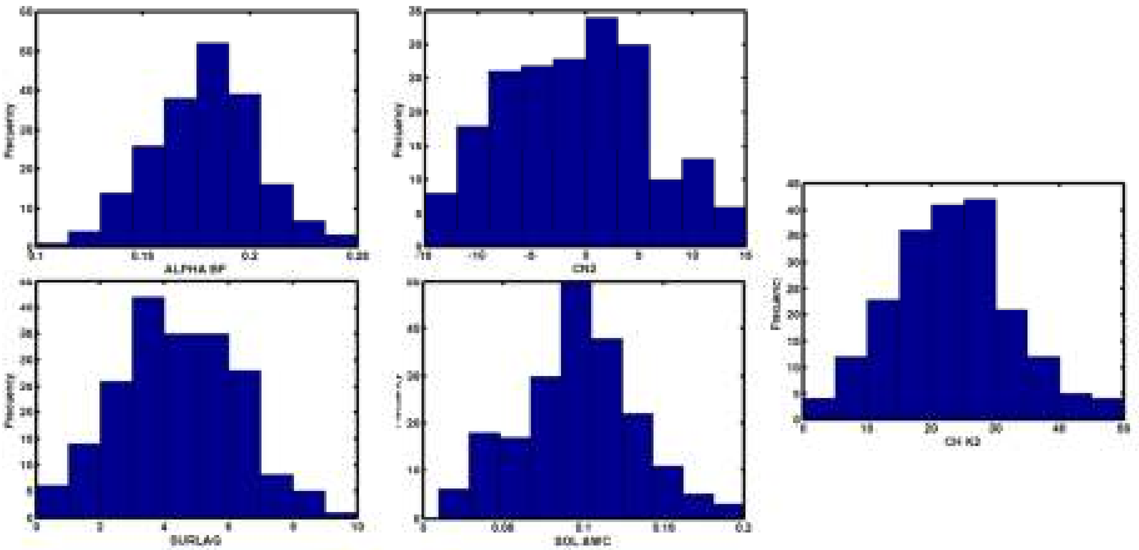

Figure 4. Histograms of marginal distributions of the aggregate parameters

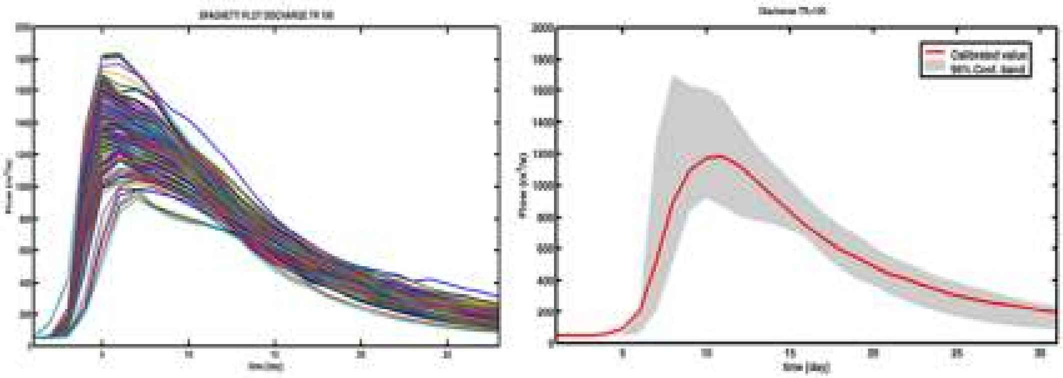

Figure 5. a) Spaghetti from Monte Carlo simulations; b) Uncertanty boundary 95% confidence band

3.2. Hydraulical modelling

The second step in the cascade modelling is the hydraulic modelling. In this study, we used the two-dimensional hydrodynamic model MIKE 21 FM developed by DHI (Danish Institute Hydrulic). This model solves the shallow water equations using a flexible meshing type and it can be used for riverine, coastal and estuarine environments.

In order to reduce the uncertainties in this step this study employs field measured river discharges, bathymetry, water levels and velocities. In addition, LiDAR data is utilised to establish an accurate representation of the topography in the study region The utility of this approach allows the setup and validation of the 2D model, which can then be used for the determination of flood maps in the Tonalá River floodplain under different hydrodynamic conditions. The figure 6 shows the architecture of the hydrodynamic model.

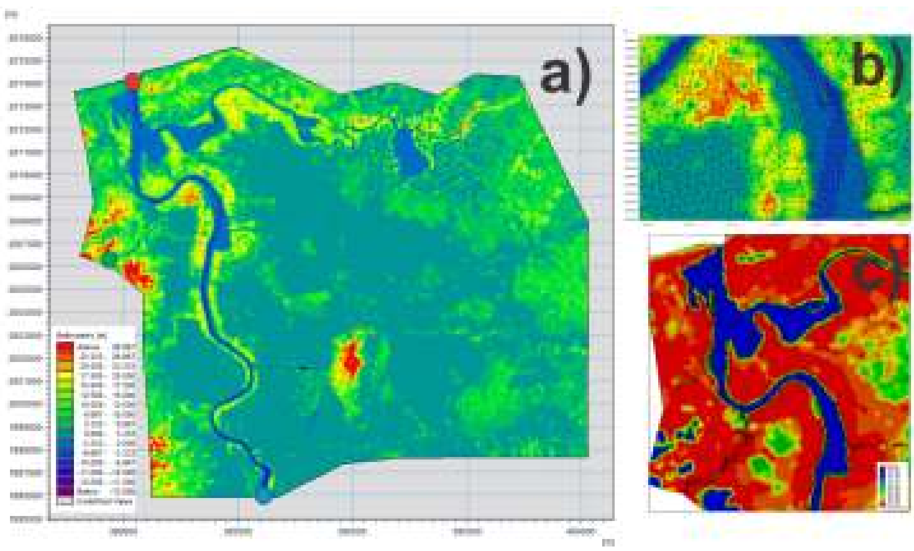

Figure 6 a) Numerical domain with contour elevations in meters and boundary conditions. b) Mesh resolution (flexible mesh); c) Variable roughness in the domain.

The numerical domain in the Figure 4a shows the boundary conditions in coloured circles. The blue dot represents the input of design hydrograph for Tonala river, the green dot is the entrance of the river Agua Dulce and the red dot represents the location of the Tonala's river mouth. Different hydrographs of the ensemble are employed as input boundary conditions for the 2D hydrodynamic model set-up in order to propagate the hydrological uncertainty in the prediction of flood extent.

3.3. Hazard estimation

The analysis of the flood hazard, requires the identification of levels associated with maximum depth hazard and travel speed of the event. Following the guidelines of the Department of Environment, UK (DEFRA, 2005), the flood hazard can define following the expression:

$$HR = d\left(v + n\right) + DF \qquad [1]$$

Where, HR = The level of flood hazard.; D = water depth (m); v = speed flow; DF = debris factor (0, 0.5, 1 depending on the probability that the debris involved in the threat);n = A constant of 0.5.

The ranges of intensity of the threat are divided into 5 categories, very low, low, medium, high and very high. In Table 2 the description of the categories of intensity associated threat levels shown.

Table 2. Flood hazard scale in the Tonala river

Hazard level		Range	Description
	Very Low	<0.5	Flood zones in shallow waters with backwaters
	Low	0.51-0.75	Flood zones in shallow waters with low velocity
	Medium	0.75- 1.25	Flood zones in medium depth water with normally velocity
	High	1.25– 2.0	Flood zones with high depth water and / or high speed causing high damage
	Very high	>2.0	Flood zones with high depth water and / or high speed causing extreme damage

3.4 Vulnerability estimation

Recognizing that the relationship of the factors that make up vulnerability, determine the degree of impairment of the system before the flood, the level of vulnerability is obtained based on the Vulnerability Index Flood (IVI) proposed (Luers et al., 2003). This rating is determined by the relative level of fragility of the system to a threat, multiplied by the level of exposure to which it is exposed. The general formula is given by:

$$FVI = \frac{flood\ susceptibility}{relative\ fragility\ threshold\ x\ \text{level}\exp osition} \qquad [2]$$

Exposition

The flood-prone areas in the physical context, are defined as the area near the river that is inundated or saturated when the water elevation is twice the maximum bankfull depth (Rosgen, 2002). In this work we calculated the level of exposition based on a physiographic analysis of cumulative distance route modified Fernandez et al., (2012). It is assumed that a flood is produced by the cost of water to reach a given elevation, the exposition level is estimated through the cumulative cost less distance to the river channel based on geomorphological terrain conditions (slope, elevation, and land use).

$$CC\left\{ff, SD, Hf, Vf\right\} \qquad [3]$$

ff is the friction factor of the surface, *SD* is the slope distance *Hf* and Vf and the vertical and horizontal forces. The minimum cost cumulative index can define following the expression:

$$LCCI = \frac{CLCR_{\min}}{CLCR_{\max}} \cdot n \qquad [4]$$

Susceptibility

The fragility or susceptibility of a system is a measure of how the sensitivity of an element in front (Messner and Meyer, 2006). This level of sensitivity can be analysed from different fields, ranking from the physical, social, economic, ecological and cultural. In the study area, the susceptibility assessment is performed through the analysis of the conditions of these systems that make it susceptible to flooding. The methodologies used to determine the fragility of these parameters are described below.

- **Social fragility:** is determined by the social index flood susceptibility (SFVI) proposed by Tapsell et al. (2002). This index estimates the flood potential impact in each social group based the summarized of four components: Population, age, health and financial situation.

$$Population\_index = LN\left(1+\frac{population\_scale}{Total\_scale}\right) \quad [5]$$

$$Health\_index = LN\left(1+\frac{disabled\_Pob}{Total\_PobDisb}\right) \quad [6]$$

$$Financial\_index = LN\left(1+\left(\frac{P.\_unemployed}{EAP}+\frac{\text{VPH\_No\_Accommodation}}{\text{Total\_VPH\_NA}}\right)/2\right) \quad [7]$$

- **Physical, economic and ecological fragility:** Based on the evolution of vulnerability by Wisner et al., (2004), within a pressure-release model (PAR), vulnerability is the result of a chain of internal and external factors of the systems, which evaluated against an opposing force (the threat) lead to disaster. In the evolution of vulnerability, the first two phases (the root causes and dynamic pressures) determine the fragility of the system, and the third phase (unsafe conditions) provides the potential for exposure to the flood level. Based on this approach, Physical, economic and ecological fragility is determined through underling factors and dynamic pressures. The first one is composed by level of complexity, social and economic importance. In the second one is analized the state and economic value of the system, the coping capacity and adaptability level. All items are evaluated on a scale from 1 to 5.

3.5. Flood Risk analysis

The last step consisted in determinate the flood risk in the Tonala basin. Based on State -Pressure - response model (SPR), the risk is represented from the perspective of cause and effect, where interrelate three factors: the pressure (the threat), the state (system vulnerability) and response (risk). According to the above, the relationship between these three parameters is given by the following equation:

$$\text{Risk }(t) = f\left(\text{Hazard }(t)\ x\ \text{ Vulnerability}\right) \quad [8]$$

4. RESULTS

4.1 Hazard analysis

After modelling the design ensemble the cascade models, the figure 7 provide the result of probabilist hazard in the boundary conditions of the discharge, the left panel shows the minimum boundary and the right panel describe the maximum boundary corresponding to 100 years design discharge.

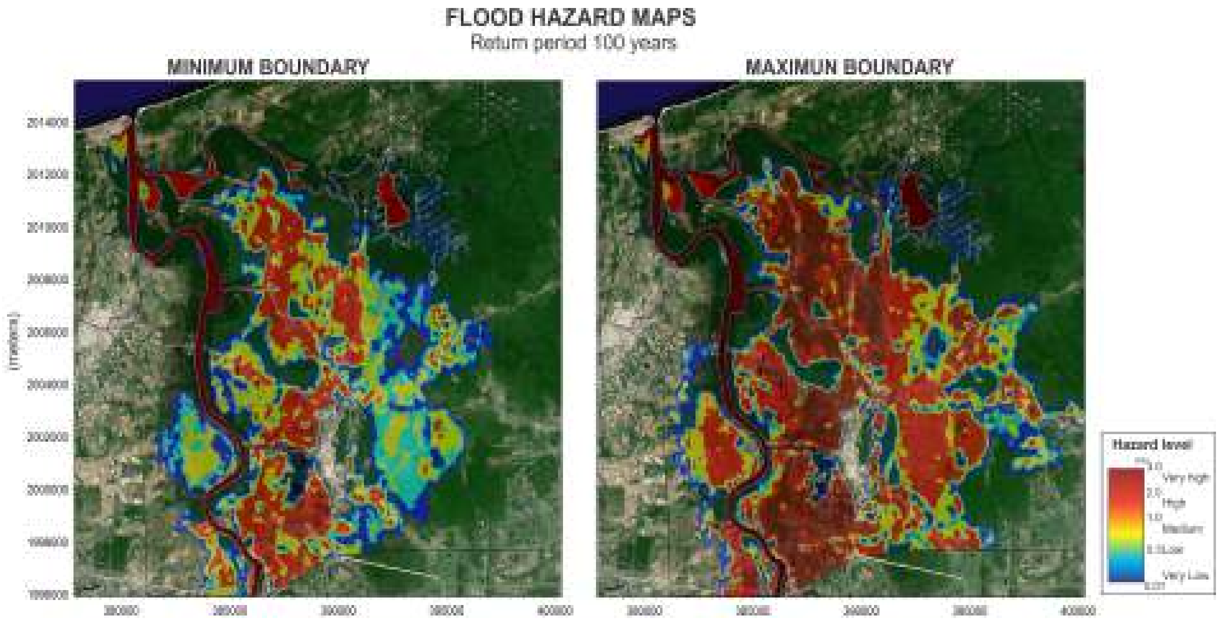

Figure 7. Flood Hazard maps in uncertainty boundary conditions

According to the results, hydraulic behaviour of the river overflows a lot of water on the plain, flooding most of the lower areas of the basin. At the minimum boundary, the highest level is between 2.5 and 3 meters, the most affected regions, near the town of La Venta and the oil infrastructure of the eastern basin. On the other hand, in the maximum boundary the floodplain is around 3 to 3.5 meters deep, affected areas of economic importance such as the suburbs near the town of La Venta and oil production areas. The systems most affected in this scenario are the urban and rural road systems and areas of oil production.

4.2 Vulnerability estimation

In the figure 8 maps of vulnerability to social, economic for social, physical, economic and ecological vulnerability is shown. This approach, analysed the level of vulnerability of the study area, depending on the characteristics of the systems that make it susceptible, and is unable to cope with the adverse effects of flooding. As for maps, vulnerability threat scenarios were constructed based on five levels of vulnerability, based on the assessment of fragility within the range of the systems analysed and the degree of exposure that are subject.

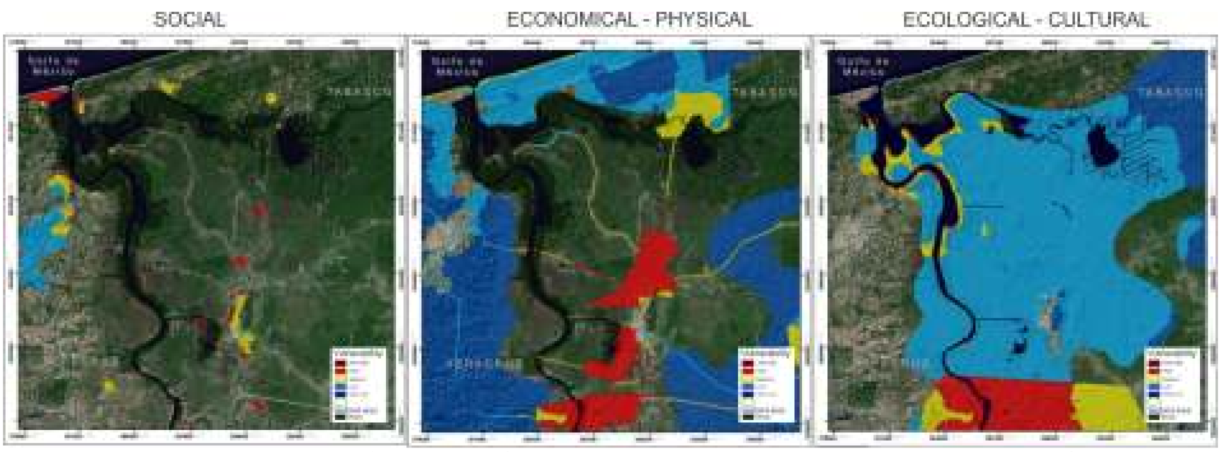

Figure 8. Vulnerability flood maps (social, economic-physical and ecological-cultural)

The overall basin has a natural vulnerability to flood events. This vulnerability is due to the particular terrain, such as its lower slopes, low topographic elevation and terrain composed mostly of areas pluvio-lacustrine and marsh plain. In the physical-economic, given their high fragility, those areas with high vulnerability are the areas of oil extraction and some systems of primary roads and driving. For the eco-cultural environment, the biggest vulnerabilities are in priority areas for conservation of biodiversity and some coastal areas of mangrove areas.

4.3 Flood risk analysis

In the figure 9 we can see the risk map the boundary conditions of the ensemble acoording with a 100 years period return discharge.

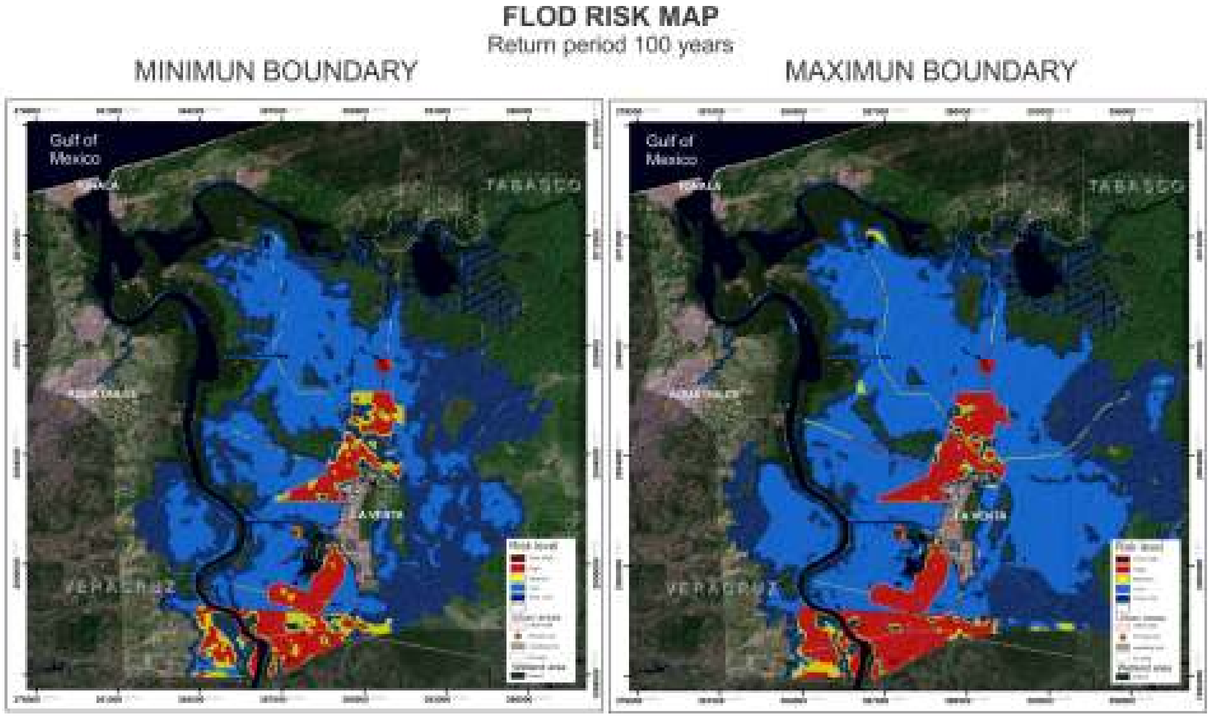

Figure 9. Flood risk map in uncertainty boundary conditions

The distribution of risk in the Tonala River basin under a probabilistic design approach affects mostly the eastern part of the lower basin of the Tonala River. The most affected areas were the systems of oil exploitation and priority places for biodiversity conservation. As for the risk in the population, the most affected localities are concentrated in the periphery area of the municipality La Venta in Tabasco. For primary and secondary road infrastructure risk level for all scenarios is between medium and high. In mangrove areas, forest, and agricultural areas, both temporary agriculture as cultivated pastures have a low level of risk. The figure 10 presents a description the level of risk in each item analised in with a deterministic approach.

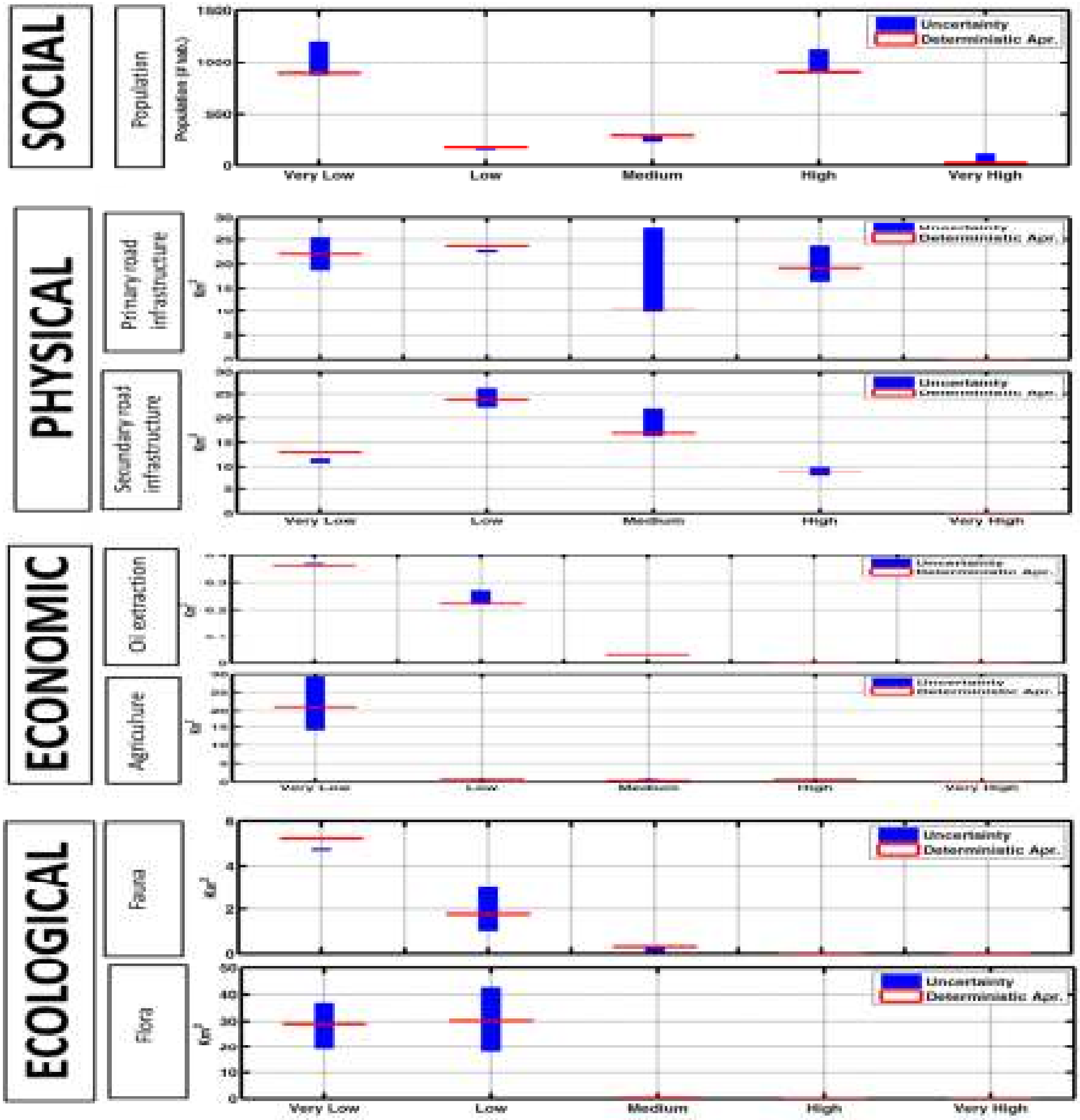

Figure 10. Risk analysis divided by social, physical and ecological item

5. CONCLUSIONS

In the hazard modelling, the distribution of flood flooding northeast takes most of the lowland areas in the basin. Under the conditions given by minimum scenario, the threat levels are low to high with a higher intensity affecting the middle region of the basin. Furthermore, in the maximum level, flood hazard levels are medium to high, with a higher proportion of high intensities. Notably, the systems that have greater involvement are the areas of oil exploration and areas of municipal and state interconnection. In urban areas of the basin are the damages in the border areas of the municipality of La Venta in Tabasco.

The geomorphological characteristics of the basin and its geographical location, make the study area present a natural vulnerability to flooding. This vulnerability is enhanced by the level of intrinsic fragility of the systems before the flood. As the level of vulnerability, projecting systems in relation to their high degree of vulnerability are the areas of oil extraction and some types of road infrastructure in the case of the physical and economic systems. In the case of social systems, peripheral areas of the municipality of La Venta, and the ecological and cultural systems, terrestrial priority areas for biodiversity conservation and some coastal mangrove areas.

The risk assessed under probabilistic approach could identify the most affected areas in extreme floods. In this context, areas that have a higher risk of flooding are the areas of oil extraction and terrestrial priority areas for biodiversity conservation. With respect to the estimated risk of the population, the analysis identified that urban areas have a greater involvement with the flooding are the rural towns located on the outskirts of La Venta.

6. REFERENCES

DHI, (2011). MIKE 21 FM Flow model, Scientific documentation. DHI Group, Horslhome

Levy, J. K., & Hall, J. (2005). Advances in flood risk management under uncertainty. Stochastic Environmental Research and Risk Assessment, 19 (6), 375-377.

Jha, A. K., Bloch, R., & Lamond, J. (2012). Cities and flooding: a guide to integrated urban flood risk management for the 21st century: World Bank Publications.

Aparicio Mijares, F.J. (1999). Fundamentos de hidrología se superficie. Mexico, Ed. Limusa, 303 pp

Plate, E. J. (2002). Flood risk and flood management. Journal of Hydrology, 267 (1), 2-11.

Hall, J., & Penning-Rowsell, E. C. (2011). 1 Setting the Scene for Flood Risk Management. Flood risk science and management, 1.

Pedrozo-Acuña, A., Ruiz de Alegria-Arzaburu, A., Mariño-Tapia, I., Enriquez, C., & González Villareal, F. (2012). Factors controlling flooding at the Tonalá river mouth (Mexico). Journal of Flood Risk Management, 5 (3), 226-244.

Schumann, A. H. (2011). Introduction–Hydrological Aspects of Risk Management Flood Risk Assessment and Management (pp. 1-10): Springer.

Comisión Nacional del Agua CONAGUA (2012) Libro Blanco CONAGUA-OI Programa Integral Hídrico de Tabasco (PIHT). México DF

Fuentes, O.A., De Luna F., Cruz, J.A., Sánchez, J.A., Morales, H.L., Hernández, D.A., Eb, J.E., Morales, A., (2010). Revisión Hidráulica mediante simulación matemática del flujo en los ríos Tonalá, Zanapa, Blasillo y Naranjeño. Capítulo 2 - Plan Hídrico Integral de Tabasco Tercera Etapa Informe Final. Instituto de 475 Ingeniería, UNAM

Arnold, J. G., Srinivasan, R., Muttiah, R. S., & Williams, J. R. (1998). Large area hydrologic modelling and assessment part I: Model development1. JAWRA Journal of the American Water Resources Association, 34 (1), 73-89.

Pedrozo-Acuña, A., Rodríguez-Rincón, J.P., Arganis-Juárez, M., Domínguez-Mora, R. and González Villareal, F.J. (2013), Estimation of probabilistic flood inundation maps for an extreme event: Pánuco River, México. Journal of Flood Risk Management. doi: 10.1111/jfr3.12067

Jing Yang, Peter Reichert, K.C. Abbaspour, Jun Xia, Hong Yang, (2008) Comparing uncertainty analysis techniques for a SWAT application to the Chaohe Basin in China, Journal of Hydrology, Volume 358, Issues 1–2, 30 August 2008, Pages 1-23, ISSN 0022-1694, http://dx.doi.org/10.1016/j.jhydrol.2008.05.012.

McKay, M., Beckman, R., & Conover, W. (2000). A comparison of three methods for selecting values of input variables in the analysis of output from a computer code. Technometrics, 42 (1), 55-61.

Beven K.J. & Binley A. The future of distributed models: model calibration and uncertainty prediction. Hydrol Process 1992, 6, 276–298.

Luers, A. L., Lobell, D. B., Sklar, L. S., Addams, C. L., & Matson, P. A. (2003). A method for quantifying vulnerability, applied to the agricultural system of the Yaqui Valley, Mexico. Global Environmental Change, 13 (4), 255-267

Rosgen, D. L. (2002). Applied River Morphology. Second Edition. Wildland Hydrology. Pagosa Springs, Colorado.

Fernández, D., Barquín, J., Álvarez-Cabria, M., & Peñas, F. (2012). Quantifying the performance of automated GIS-based geomorphological approaches for riparian zone delineation using digital elevation models. Hydrology and Earth System Sciences, 16 (10), 3851-3862.

Messner, F., & Meyer, V. (2006). Flood damage, vulnerability and risk perception–challenges for flood damage research: Springer.

Tapsell, S. M., Penning-Rowsell, E. C., Tunstall, S. M., & Wilson, T. (2002). Vulnerability to flooding: health and social dimensions. Philosophical Transactions of the Royal Society of London. Series A: Mathematical, Physical and Engineering Sciences, 360 (1796), 1511-1525.

Wisner, B. (2004). At risk: natural hazards, people's vulnerability and disasters: Psychology Press.

DEFRA, (2005). Making space for water: Taking forward a new Government strategy for flood and coastal erosion risk management in England