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HYDRODYNAMIC MODELLING OF A LARGE RIVER AND FLOODPLAIN: USUMACINTA, MEXICO

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ABSTRACT: In recent years (2008 and 2011), catastrophic flood events due to heavy rainfall periods were observed in the Usumacinta river, the largest river basin in Mexico. This work provides better decision making criteria designed to consider some of the uncertainties in the results. For such purpose, we use numerical tools, integrated high-quality field measurements such as hydrologic and hydraulic observations and LiDAR data. For validation purposes, satellite images from the RadarSAT mission were used and compared to inundation area simulations from a distributed hydrological model and a quasi 2D hydrodynamic model. The good agreement between observed and modelled discharge and inundation areas showed that high quality input data in parsimonious hydrologic and hydrodynamic modelling tools can improve flood assessment in large river basins.

Key Words: Usumacinta River, hydrological uncertainty, large-scale modelling, flood map

1. INTRODUCTION

Flooding is the most common and damaging natural hazard faced by society and current anthropogenic climate change suggest that flooding threats could increase, due to potential higher sea levels and more intense cyclonic weather systems and extreme precipitation events. The frequency, distribution and causes of floods over the last thirty years has been analysed and reported by the Dartmouth flood observatory, and an increase in the number of floods per year has been observed since the 1980s (D.F.O., 2011) whereas in Mexico, rising costs due to flooding have been estimated over the last 10 years (FONDEN, 2012) (Figure 1). Flood modelling are a key component for risk assessment and decision making purposes and in recent years there has been an increasing demand for large scale flood modelling studies, primarily aiming to understand flood risks caused by climatic variability and land use changes.

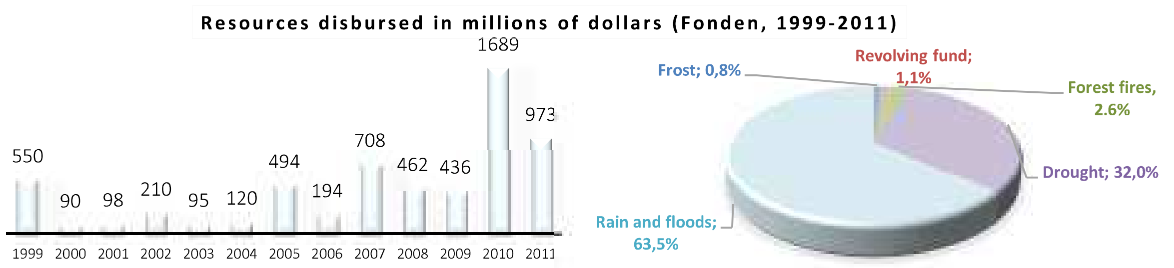

Figure 1: Left: Expenses in infrastructure recovery due to catastrophic events per year year (FONDEN, 2012)..Right: percentage of costs associated to the type of disaster.

Recent advances in remote sensing techniques have improved the capacity to simulate, calibrate and validate hydrological and hydrodynamic models. Over the last decade, new and higher accuracy topography data products such as the Digital Elevation Models (DEM) have been generated from remote sensing tools such as the Shuttle Radar Topography Mission (SRTM) (Rabus *et al.*, 2003; Farr *et al.*, 2007) or the Laser Imaging Detection and Ranging (LiDAR) (Trigg *et al.* (2009) showed that the use of highly spatial resolution terrain data can substantially improve flood extension estimates. Despite a better representation of floods using distributed hydrological and hydraulic models, uncertainty in the model parameters and the existence of unknown processes that are intrinsic to each river basin need to be taking into account using uncertainty estimation frameworks (e.g. Beven & Binley, 1992).

Most of the large-scale hydrological models are conceptual models with a minimal physical basis. However, some of these models aim at describing the role of different vegetation and soil types on the streamflow generation processes and on water and energy budgets of the basin. These features can be found in models such as VIC (Liang *et al.*, 1994), LASCAM (Viney *et al.*, 2000), TOPKAPI model (Liu & Todini, 2002) and IBIS–THMB (Coe *et al.*, 2008). However, the hydrodynamic simulation of large floodplains may require large datasets, computational requirements and numeric instabilities (Bates & De Roo, 2000; Verwey *et al.*, 2007; Werner, 2004) and a 1D hydrodynamic model is a more suitable method with respect to 2D and 3D hydrodynamic models. Additionally, flood generation processes in some large river basins may take weeks or months before reaching peak flows, which considerably increase the computational requirements due to an increase of model grid elements and longer simulation periods. Moreover, floods with durations ranging between several weeks to a few months require estimates of evapotranspiration rates (Wilson *et al.*, 2007).

The objective of this work is to provide an example of integrating remotely sensed data such as LiDAR and satellite images RadarSAT with simple hydrological and hydrodynamic modelling tools in the foremost hydrological basin of Mexico, the Usumacinta river basin.

2. STUDY SITE

The Usumacinta river basin is located in the Southeastern and Northern regions of Mexico and Guatemala, respectively. The lithological formation of riverbanks and soil in the basin and, the sinuosity of the river channels with prominent meanders enhance substantial sediment transport. Before reaching the Gulf of Mexico, the river bifurcates into two principal rivers, the first one identified as the Palizada river that discharges in the Terminos Lagoon, and a second one known as the San Pedro-San Pablo river which discharges directly to the sea. The mean annual discharge at the San Pedro gauging station is approximately 5,000 m^3/s with peak discharge values reaching values close to ~10,000 m^3/s (CONAGUA, 2008). In this region, coastal tides are in a microtidal regime (with a mean range of spring tides of 0.6 m) and low amplitude waves (mean Hs <1 m). The tidal storm in the region varies from 0.1 m to 0.3 m (during intense rain events this can slow down the drainage capacity of the floodplain). The average temperature in the downstream part of the Usumacinta basin ranges between 24-28 °C, with a climate influenced by an intense rain season (July to December), in combination with the occurrence of hurricanes and storms coming from the Gulf of Mexico. The relative humidity varies between 80 and 90% and the sky cloudiness is high throughout the year. The region has one of the highest average precipitation rates in Mexico, averaging 2000 to 3000 mm/year. The region of study consists primarily of the Usumacinta River (downstream from the Boca del Cerro gauging station until its discharge point to the Gulf of Mexico), and its main tributaries (Figure 2).

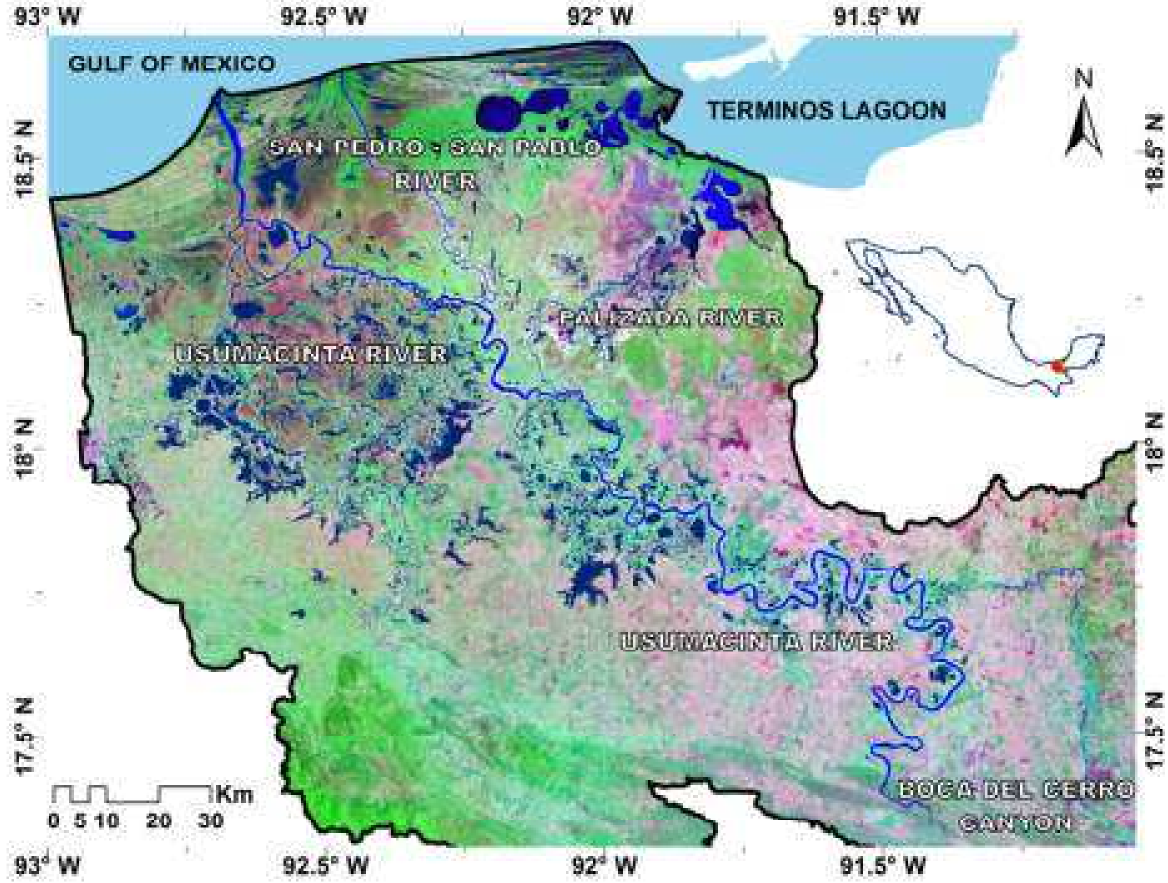

Figure 2: Map showing the downstream part of the Usumacinta river basin.

2.1 Flood events

In 2008 and 2011, severe flood events seriously affected the productive, social and productive sectors located in the lower Usumacinta river basin. For both events, flood extension was captured by the Spectrometer Moderate Resolution Imaging (MODIS) product from the satellites Terra EOS AM and Aqua EOS PM and the RadarSat satellite (Figure 3). During the 2011 event, flooding was caused by the overflowing of the Usumacinta river, due to the Tropical Storm Rina that originated in the coast of Central America and became a hurricane on October 25. The heavy rains in the region enhanced the severity of flooding across El Salvador, Costa Rica, Honduras, Guatemala, Nicaragua and Mexico. Point-rainfall rates of 260 mm/day were recorded at the Boca del Cerro station with cumulative rainfall between October 19 and October 21 close to 810 mm.

Analysis and records by the National Water Commission suggest that an overcome of five centimeters above the Extraordinary Water Level (EWL) in the Usumacinta River could lead to extensive flooding areas. The official EWL in the Usumacinta River is 21.35 m.a.s.l while during the event of 2011 the EWL reached 21.52 meters and 21.57 in 2008. The critical scale or Ordinary Water Level (OWL) is 19.21 m.a.s.l.

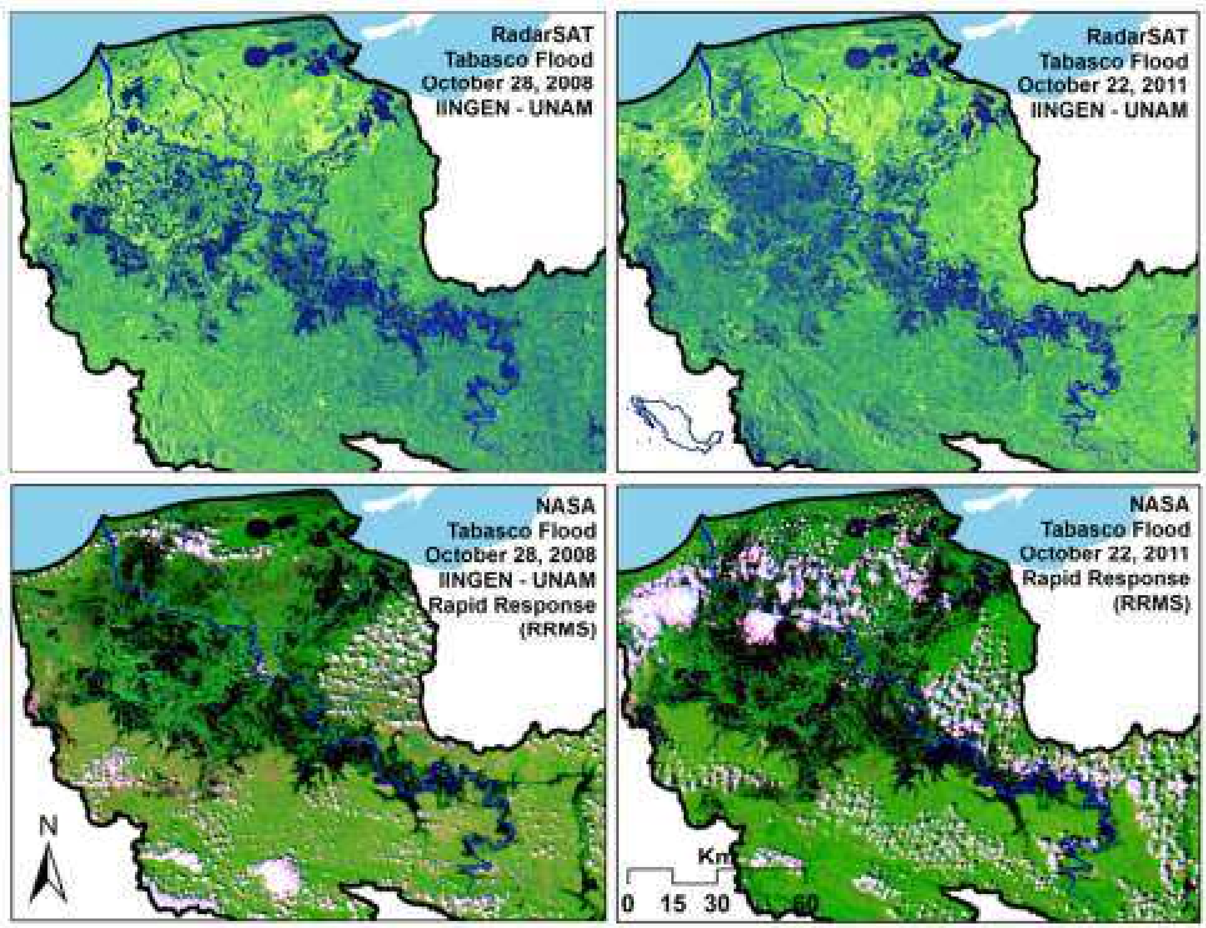

Figure 3: Satellite (top) and radar (bottom) images for the flood events in 2008 and 2011. Flooded areas detected by Radarsat (in blue) and MODIS (in black).

3. METHODOLOGY

In this work, the study area considered 15 sub-basins with a total surface of 45,443 km^2. The possibility of using a two-dimensional model that solves the shallow water equations was discarded, due to the requirements of higher computing power. Therefore, the methodology consisted in a one-dimensional model that allowed the analysis of inundation areas in large river basins. Although it is known that the selection of this tool can induce errors in the calculation of flood areas, the uncertainty due to simplified calculation is reduced with the use of high resolution data. Both RadarSAT and MODIS images were used to compare flood events in 2008 and 2011, showing clear differences in flooded areas and the variability of the response time of the river basin. The hydrological simulation was performed with a distributed parameter model (Dominguez *et al.*, 2008) and the hydrodynamic component with the HEC-RAS software. The output hydrographs of the model were used as boundary conditions for HEC-RAS.

This work used a Digital Elevation Model (DEM) constructed using data from laser altimetry (LiDAR). Overall, the quality and accuracy of LiDAR depends primarily on flying height (between 200 m to 600 m) and scan angle (10° to 75°). Surveys providing up to 12 points per square meter were obtained with resulting meshes between 0.2 m to 0.5 m and a vertical accuracy of about ± 0.1m (INEGI, 2008). The points generated by the LiDAR were corrected in the riverbeds using cross-sectional surveys acquired during a field campaign. Rainfall data were obtained from the CLICOM and CONABIO climatological databases. The simulation period covers most of the rainfall season of 2008, from August until November. For uncertainty assessment purposes, the GLUE methodology (Beven & Binley, 1992) was implemented in the Usumacinta river basin (**Figure 4**) where hydrograph uncertainty was associated for a single storm event with different initial conditions of the river basin. A sensitivity analysis of the hydrological model consisted in assigning weights to different model parameters such as the Scale Factor and Loss by Scale Factor (values ranging between 0.10 and 1.00) whereas other parameters such as the retaining potential were given a weight from 0.10 until 5.0. Finally, combinations of these weights were used to generate one hundred hydrographs.

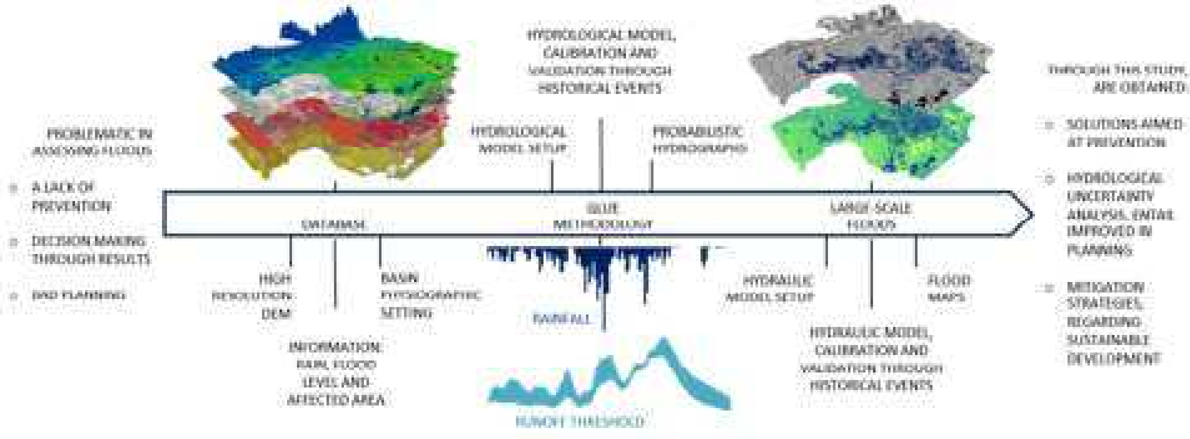

Figure 4: Framework for flood estimation with its associated uncertainty and occurrence probability.

The floodplain of the Usumacinta river basin has mild slopes and therefore the subcritical regime is dominant. In contrast, in the upstream parts of the river basin, near the input boundary condition in the Boca del Cerro canyon, slopes are significant, however the slope of the river bed is not large enough to generate flows in supercritical regime. The two main principal bifurcations, the Palizada river which discharge towards the Terminos Lagoon and the San Pedro - San Pablo river which discharge towards the Gulf of Mexico, have smaller slopes than the Usumacinta River, so flows generally follow a subcritical regime so the hydraulic regime across the river network is mainly subcritical during the initial conditions. The hydrodynamic model was performed along the Usumacinta, Palizada and San Pedro-San Pablo streams and their respective floodplains. The 2008 flood event was used for calibration purposes whereas validation was performed on the 2011 event. The peak flow reached in both events was above 8500 m3/s. Roughness across the stream was estimated according to the vegetation on the banks and the sediment composition on the channel. The average Manning coefficient was assumed as n=0.095 for the channel and n=0.200 for the right and left floodplain banks. Finally, the probability of the minimum and maximum impact of the extreme hydrometeorological event associated to hydrological uncertainty was estimated.

4. METHODOLOGY

The different inputs in the hydrodynamic model predicted a wide range of overflowing conditions in the floodplain and consequently flood area estimates that were validated by RADAR images in the 2008 and 2011 flood events. Additional information from the local and federal water agencies was also useful for validation purposes. The results for calibration and validation of the hydrodynamic model are shown in Figure 5 and Figure 6, respectively.

Data measured Upstream river	Drought season	Minimum Water Level, Meters		Rainy season	Maximum Water Level, Meters	
	Streamflow, m³/s	CONAGUA	MODEL 1D	Streamflow, m³/s	CONAGUA	MODEL 1D
Usumacinta	1052	12.58	12.46	4979	19.21	19.19
San Pedro - San Pablo	65	1.10	1.00	650	3.01	3.21
Palizada	158	1.58	1.32	438	4.98	4.58

Checkpoint	Percentage error	
	Drought	Rainy
Usumacinta	1.0%	0.1%
San Pedro - San Pablo	9.1%	6.6%
Palizada	16.5%	8.0%

Figure 5: Comparison between in situ observed and estimated water levels by the 1D hydrodynamic, both correspond to the upstream end for each river. Differences between simulations and observation vary from 0.02 to 0.40 m (during the rainy season) and from 0.10 to 0.26 m (during the dry season). The most visible differences were in the Palizada river followed by the San Pedro-San Pablo river.

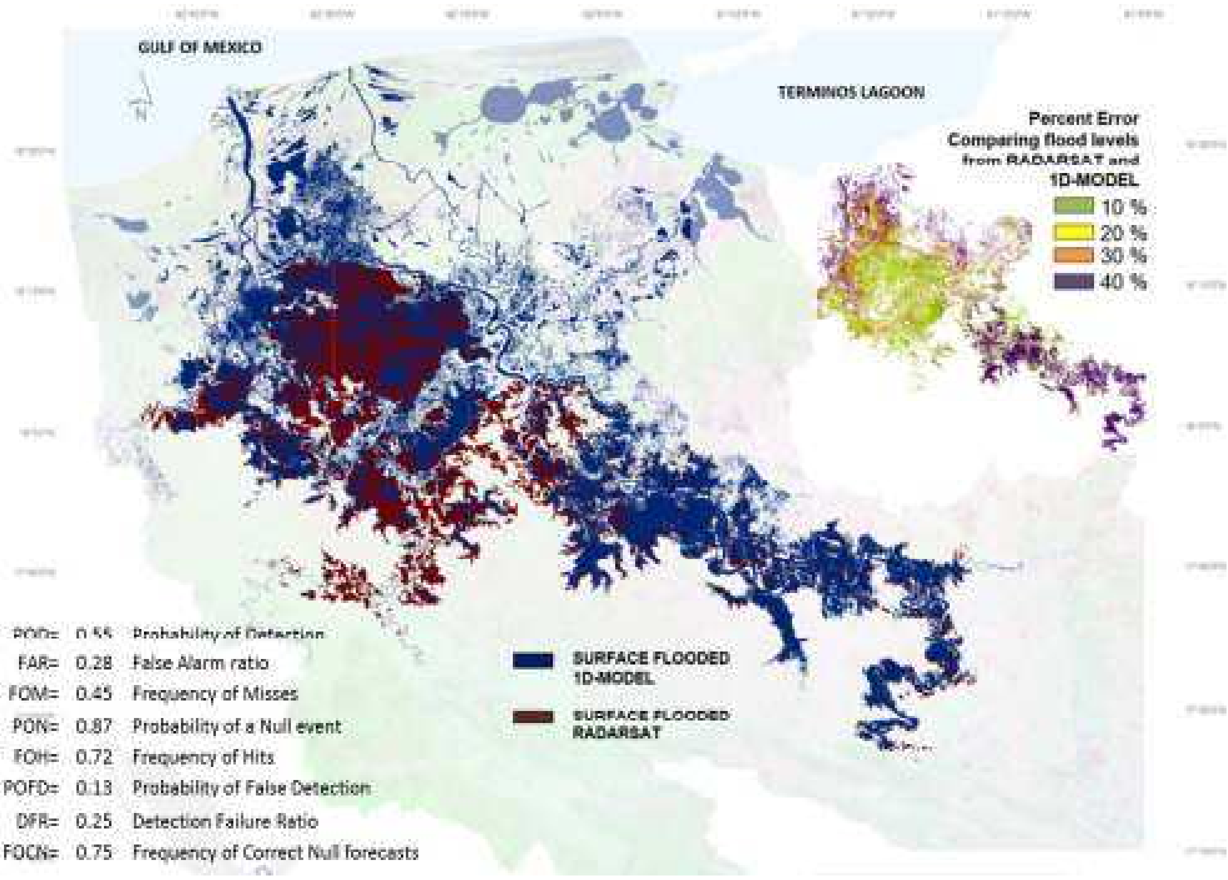

Figure 6: Modeling results for the 2011 flood event. The error between the radar (flodded area=3,940 km²) and the model (flodded area=5,041 km²) was close to 22%, however the error decreases to 5% for the middle and upper regions. Further error metrics (POD, FAR, FOM, PON, FOH, POFD, DFR, FOCN) for the whole study area are shown.

The 1D numerical model employed in this study simplified the main physical processes needed to detect and assimilate inundated areas on a floodplain. Figure 7 shows the inundation maps estimated from the probabilistic hydrographs. Three representative flood maps allow a qualitative assessment for a certain threshold in confidence. Moreover, the flooded areas observed with remote sensing tools determined the magnitude and probability of occurrence in a single map. The most affected area identified by the model were located mainly in the middle and lower parts of the Usumacinta River. Differences between flooded areas, using probabilistic hydrographs, indicate that the uncertainty in hydrological models is likely to propagate to the hydrodynamic model.

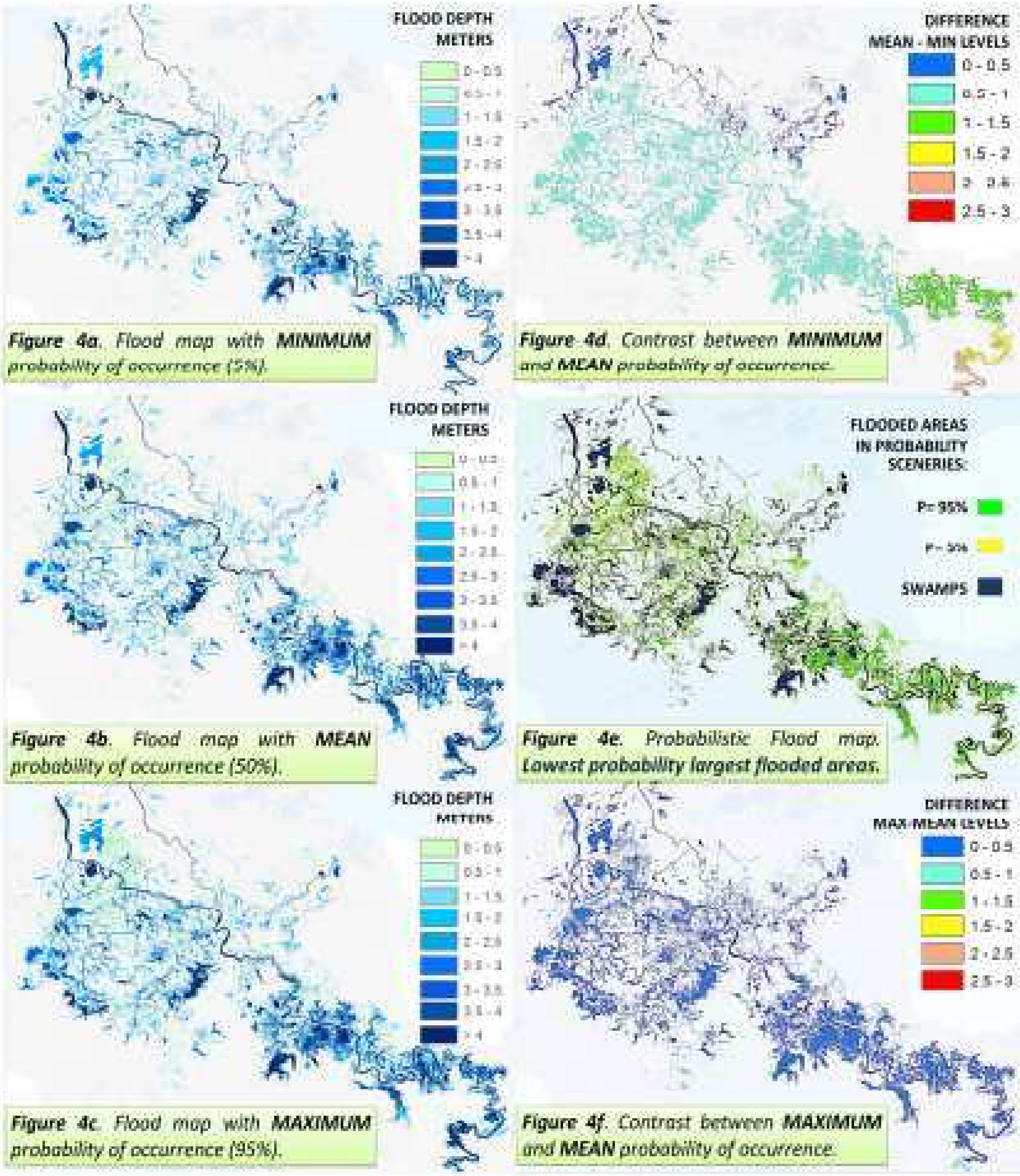

Figure 7: Estimated probabilistic flood maps: In the top-left panel with a probability of 95%, in the middle-left panel with a probability of 50% and in the lower-left panel with a probability of occurrence of 5%. Similarly, in the upper-right panel shows the contrast between 95% and 50% estimations, the lower-right panel shows the contrast between 5% and 50%, (differences are higher in the upstream region), and finally the middle-right panel, shows the magnitude in areas with a specific probability associated occurrence (5% in yellow) and (95% in green).

However, it should be noted that there are other sources of uncertainty associated with flood modeling, which can strongly affect the results such as the geometry simplified in the system (e.g. flood defense structures), the possibility of a failure in the infrastructure (levees and banks), physical characteristics of the basin (e.g. roughness), and the simplification and limitations of the available model to fully represent the physical processes (e.g. the surface and sub-surface flow, flood generation mechanisms).

5. OUTLOOK AND CONCLUSION

The proposed methodology used in this study proved to be an effective modelling approach for estimating water depths and flooding areas on large basins such as the Usumacinta river basin. It is also the first time that a probabilistic flood assessment is applied in Mexico.

One of the main purposes was to assess the hydrological uncertainty by varying the initial conditions of the hydrological model, mainly infiltration and evaporation rates as well as land use classification. It was found that much of the uncertainty comes from the upper part of the Usumacinta river basin. One of the main explanations is that the hydrological response is confined to the main river channel, which allows higher variability of water levels for different initial conditions. Flooded areas with an error of 5% were found in the upper basin in contrast to more than 20% in lower basin areas mainly due to simplified physical process in numerical modelling. Although the error is relatively higher than expected such error values are acceptable for engineering purposes. Finally, it is important to highlight that there are several additional sources of uncertainty in flood modeling process such as deforestation and erosion processes.

6. ACKNOWLEDGEMENTS

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