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Use of Lidar Data in Floodplain Risk Management Planning: The Experience of Tabasco 2007 Flood

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1. Introduction

Floodplains along rivers are vulnerable and suffer frequent socio-economical losses as consequence of large rainfall events. The risk of flooding is function of several factors such as: climate, the material that makes up the banks of the stream, the channel slope and the topography. The risk of floodplains is increased as a result of the human tendency to use the river land to cope with community demands. As the river plains are synonymous with fertile soils with high phreatic levels, their transformation into arable areas or into urban areas are guaranteed to produce an economical input improving human life. This situation makes flood less important since the benefits produced outweigh the damage; sometimes damage could be reduced or mitigated by constructing barriers. The actual problem is when the flooding generates devastation and the benefits are minimised. This is a situation that could be present at any moment through the development of the region (Maza and Franco, 1997). This is the case for many of the watersheds in the Gulf of Mexico including the Grijalva Basin, one of the largest in Mexico, which suffered severe flooding in 2007 affecting almost 70 % of the Tabasco state. As a consequence around one million residents lost their homes and the economic impact was calculated in millions of pesos.

The modification of the river landscape is determinant because it alters the natural condition of the area dredging water bodies, change drainage, building impermeable surfaces and constructing barriers. These modifications make it difficult to contain the water in the river channel when prolonged heavy rains take place as is the case in recent times, where flooding becomes more frequent, extreme, damaging and costly (Werritty, 2006).

A frequent problem is that floodplains lose their capability to preserve the hydraulic conditions to prevent floods and to function as areas to support ecosystems. In general, floodplains provide important habitats for plants and animals, and also these areas can retain water, reduce the flow velocity of a river and minimise erosion reducing the flood impact downstream (Moss and Monstadt, 2008). However, it is not enough to study the water movement in the watershed in order to determine the amount of water arriving to the river channel and to be transported during the flood event. It is also necessary to know the dynamics of the river and to determine the spatial-temporal distribution of flow as well as

the water level reached in the floodplains (Stabel and Löffler, 2003). The latter is addressed through the use of flood maps (if they exist) but most of them are theoretical predictions. Other maps are gathered using remote sensing data obtained by tracking the movement of the water on the land. However, it is difficult to find a direct relation between ground elevation and the highest expected river level.

The research reported in this chapter presents a contribution to calculate water levels and flooding maps using Geographic Information Systems (GIS) to combine existing datasets, water elevation survey data and hydrological models. There is a major emphasis to use high accuracy elevation data to model and map a particular flood event (past or future), to assess the risk of flooding in a particular region (Jones, 2004; Jones et al., 1998). LiDAR (Light Detection And Ranging) technology has the ability to produce accurate elevation data throughout the flood plain, in particular flat areas with slopes of less than 50 cm per kilometre as is the case of the coastal flatplains in Tabasco. LiDAR data allows a better calibration of hydrological models, to map the flood risk and water levels helping decision makers to cope with an emergency and to implement strategies after the event (Filin, 2003; Webster & Stiff, 2008).

2. Gathering topographic data by Digital Elevation Models

As floodplains are neither static nor stable, one needs to consider at least three aspects related to the land surface characteristic to describe a flood: (a) topography, (b) geomorphology, particularly when unconsolidated fluvial deposits are the base material, and (c) hydrology and the extent of recurring floods (DRD, 1991). These three aspects require the acquisition of different sources of information that in the case of geographic data is quite difficult to achieve using traditional terrestrial surveys and photogrammetry due to time consuming and spatial constraints (Lijian et al., 2008). Thus, there is a need to know the dynamics of the river and to determine the spatial-temporal distribution of flow. The use of remote sensing techniques has demonstrated to be an efficient tool to map the flood extent (Horritt & Bates, 2002; Jensen, 2000). These maps have been used to validate 1D or 2D flood models; however it is not enough to study the water movement in the watershed. It is also necessary to know the water level reached in the floodplains in order to determine the amount of water arriving to the river channel and to be transported during the flood event. In this case, the use of 3D information is a better option since it offers: river depths, river surface and banks topography, vegetation height, hydraulic structures and identifies different objects present in the river channel (Mohammadzadeh & Valadan Zoej, 2008). One alternative to acquire altimetry measures as well as identifying land surfaces features is the time-of-light information from a LiDAR system mounted on air- or- space based platforms.

2.1 LiDAR data

LiDAR data can acquire high precision and density elevation data of terrain surface since this technology involves laser altimeters (i.e. Nd:YAG laser or pulsed gallium-arsenide diode laser), a Global Positioning System (GPS) as a position reference to track the aircraft trajectory, and an Inertial Measurement Unit (IMU) as the main component of Inertial Navigation System (INS) to calculate the position, orientation, and velocity of a moving object without external references (Webster & Dias, 2006a). Thus, knowing the angle and the

absolute position of the instruments it is possible to establish the location (x,y,z) of the laser pulse destination precisely and accurately obtain a real representation of the ground.
The LiDAR aircraft flew at 500 m to 1 km above the surface, thus the accuracy of the laser altimeters is around a few centimetres in range (Weitkamp, 2005; Raber et al., 2007). The use of illumination with visible light from artificial sources has been used for active optical detection of objects considering relative distance values. These distance values can be determined measuring the transit time of radiation from the source to the object and back. This means that when a short pulse of radiation is transmitted in a medium, the radiation scattered from an object is going to be sensed as a function of the distance of the object at the surface. Of course the sensed signal is not going to have the same length as the transmitted pulse, but it will be extended in time (Weitkamp, 2005). This technique is also suitable for microwaves and sound sources and time-resolving detection systems. LiDAR has sensors for visible (λ= 400 – 700 nm), ultraviolet (λ= 225 – 400 nm) and infrared (λ= 700 – 1200 nm) wavelengths. For this reason, LiDAR not only provides elevation data but also provides information on pressure, temperature, turbulence and wind for gases in the upper, middle and low atmosphere, and can be used to determine hydrospheric and land use parameters (oil slicks, phytoplankton, water depth, turbidity, type of land use, health of vegetation, tree-stem diameters, biomass, and leaf area index, amongst others).
The extraction of topographic parameters using LiDAR gives advantages compared with other techniques such as photogrammetry since the high density data acquired avoids loss information. Also, it is not influenced by the shadow angle of the sun and it is not dependent on the ground control since it can gather a huge quantity of control points.
The high vertical accuracy of LiDAR enables the production of Digital Elevation Models (DEM), Digital Surface Models (DSM) and a Digital Orthophoto map (DOM) with high resolution and precision at a low cost compared with traditional techniques (Lijian et al., 2008)
Despite the high accuracy of DEM, it is important to identify the errors associated with the LiDAR data in order to reduce them (Raber et al. 2007; Webster & Dias, 2006a). The errors can be associated with several causes, some of them are related to the system (characteristics of the platform and laser) and conditions (terrain characteristics, vegetation and atmospheric conditions) (Filin, 2001). Also, Raber (2006) noticed the influence of the land cover and slope of the surface. To solve this Cobby et al. (2001) proposed a segmentation method that was tested by Raber et al. (2002) finding that the vertical accuracy is improved. Other errors are associated with the interpolation method and the data model utilised to create the DEM (Hodgson & Bresnahan, 2004). In order to reduce the systematic error, Webster et al. (2006b) suggested to perform an independent validation. In fact LiDAR processing data includes several steps such as: (a) data collection, (b) data pre-treatment, (c) filter and classification of point cloud, (d) fusion and application, and (e) ground-object extraction and modelling.

3. River and floodplain and the 2007 flooding

The present case study is based on the analysis of the Grijalva River Basin flooding in 2007, affecting almost all of Tabasco state resulting in enormous socio-economical losses.

3.1 Grijalva River Basin: characteristics

The Grijalva River Basin (GRB) is one of the largest basins in Mexico, low-lying in the Tabasco state at the Villahermosa city, and in the river delta at the Gulf of Mexico. The side branches of the Grijalva River have high runoff percentages (20%) associated with their medium permeability with little vegetation or low permeability with dense vegetation. The Grijalva River is born in the Chiapas state changing its name to Mezclapa after the Malpaso dam, to recover its name after it crosses Villahermosa city to its end at the Gulf of Mexico.

The Grijalva River is a mature river crossing Tabasco; an alluvial plain that made it to divagate generating broad plains, wide flows and meanders. Also, it has been divided over time creating two of the most important branches of the Carrizal River in 1881, and the Samaria River in 1932. Other important side branches of the Grijalva coming from the Chiapas Mountain Chain are the Pichucalco, Puyacatengo, Teapa and the La Sierra rivers (figure 1). The Grijalva River's total length is approximately 640 km and in its main branch is the country's fourth largest hydroelectric plants in the Chiapas state (GET, 2008; INEGI, 2000).

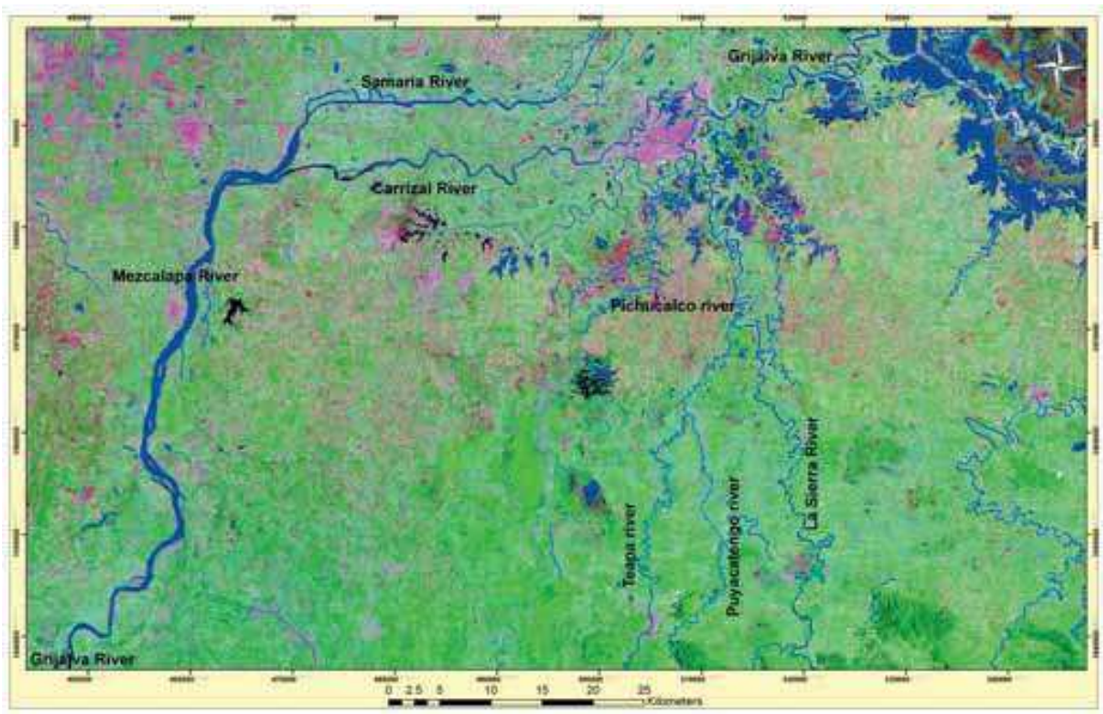


Fig. 1. The Grijalva River and tributaries around Villahermosa city, Tabasco. Landsat TM image from 28/03/2001

Tabasco is divided into two physiographical regions: Llanura Costera del Golfo Sur (Coastal plain at the south Gulf) covering almost all the state (94%) with the Sierras de Chiapas and Guatemala (Chiapas and Guatemala mountain chain) covering the remaining 6%. The main characteristics of the coastal plains are a gradual sedimentation area refilled with detritus material and eroded zones with low elevations (less than 60m), the majority related to small subtracted dominated sand and limestone highland rivers. This made the zone a source of

important lacustrine, palustrine and litoral deposits linked to extended floodplains, abandon streams and coastal lagoons.
The climate is warm humid subtropical with maritime influence. The mean annual temperature is between 24 to 28°C with a maximum and minimum mean annual temperature of 28-30 °C in May and 21-25 °C in January, respectively. The rainy season is from June to October with a mean annual precipitation in the coast of 1,500 mm with a gradual increment to the intercontinental zones till 5,000 mm. Two rainfall peaks are present, one in June with 220 mm, and the other in September with 348 mm; some authors consider another peak in October with 370 mm. This generates a cloudy atmosphere with a relative humidity around 80 to 86%. These mean annual values are a result of the extensive plains that commonly produce air masses from the sea that bring the major contribution to precipitation (INEGI, 2000).

3.2 Protection along the Grijalva River

The economic activity in Tabasco (mainly petroleum and agropecuary industries) expanded a rapid growth of most cities, the most important one being Villahermosa, capital of the state. This city is bordered by the Grijalva River (Carrizal, Mezcalapa and de La Sierra tributaries) and is quite close to the Gulf of Mexico giving at it an important role. Originally, Villahermosa was located in highland rivers surrounded by undisturbed rain forest and water bodies. However, the rapid growth of population changed the physiography of the city by dredging water bodies, modifying the course of the rivers and removing the vegetation from the surface to build urban areas (figure 2) (Oropeza, 2004).



Fig. 2. (a) City of Villahermosa in 2003 (Google image 15/03/2003) and (b) proposal for the growth population for Villahermosa after mid 2007 (PEDUT, 2007)

As Villahermosa was developed along the Carrizal, Mezcalapa and de La Sierra Rivers the risk of flooding is at its greatest in events of prolonged heavy rainfall. In order to protect the city from floods the water regime was disrupted constructing technical structures such as levees, barriers, dykes, roads, etc. In this manner, after the 1955 flooding barriers were constructed along the Samaria River, and the Malpaso and La Angostura dams were built to regulate runoff and reduce the risk of flooding in Villahermosa (Maza, 1997). Years later, the development of the transport communication system in the state and, particularly, in Villahermosa made it possible to construct levees and barrages, change of the river flow and

dredging of the rivers. Thus there was a dramatic change in the dynamics of the Grijalva River (GET, 2008) increasing the flood risk since the water levels overpass the channel and the levees act as retainers of water.

In 1997, Maza studied the hydraulic conditions in the Grijalva-Usumacinta Basin and attending to the socioeconomic development in the region he proposed several alternatives to protect against flooding. These actions were reviewed after the 1999 flood. This was an extreme event with approximately a 20-year return period that affected the Tabasco state with loss of human lives, houses and an impact on the economy. Some of the proposal considered the restitution of channels, the use of lagoons and swamps for regulation, and the improvement of current infrastructure (dams and barriers constructed along the rivers Carrizal and Grijalva in the Villahermosa city). Some tasks were done, but others were unfinished and others were unattended. In particular, for La Sierra River it was evident that hydraulic measures were not taken along the river maintaining its unregulated character. This was the reason that in the summer and autumn of 2007, several precipitation events registered along the Gulf of Mexico decreased the free water surface in the rivers, overtopping them in zones with instable soils or where the barriers failed.

3.3 The greatest flood in Tabasco 2007

In the summer and autumn of 2007, several precipitation events were registered along the Gulf of Mexico. The majority of this rain was related to 37 tropical depressions and 3 cold fronts but also it was rain due to the hurricane Dean (August 22nd) and Noel (October 28th). Exceptionally strong rainfalls took place on three periods: (a) October 10-11 associated with the cold front No.2 plus a low pressure event below Guatemala, (b) October 22-24 associated with the cold front No.4 located in Tabasco and Chiapas, and (c) October 28-30 associated with a cold air mass in the southeast of the Gulf of Mexico plus the cold front No.4 and the Tropical storm Noel (GET, 2008). After the strong rainfalls in the upper and middle GRB (specifically in the Ocotepect town in the Chiapas Mountain Chain) with 4000 mm of accumulated rainfall in 24 hours, the increase of the water levels in the river system and dams generated by the end of October and the beginning of November, caused severe flooding, which impacted 70% of the Tabasco state in Mexico, covering all urban and plain areas. In particular, the Villahermosa capital city of the Tabasco state was covered by water in around 80% of its territory due to the flooding of the Carrizal and Grijalva rivers that go through the city, and also by rivers coming from mountain areas, in the border between Tabasco and Chiapas, such as La Sierra and Pichucalco. As a result, the economic effect was huge as thousands of residential and non-residential properties were destroyed, and jobs, crops, animals, and infrastructure were lost. The total volume of overflow was around 1,800 million of m^3 for a return period of 100 years (Domínguez et al., 2009).

Different causes have been given for this disaster for example the failure of the protection system (levees), thousands of inhabitants allocated in the river divagation areas as a result of the rapid population growth, and modifications in the river flow, amongst others. On one side, as Tabasco was an alluvial plain with highland rivers, the risk of inundation was lower. However, most of the low-lying alluvial plains have been filled to allow urban developments. In consequence, the floodplain area has been increased over a long time. As floodplains are areas subject to inundation by lateral overflow water from rivers with which they are associated (Tockner and Stanford, 2002), the effect of its increment is more

significant, particularly the greatest flooding in 2007 with a 100 year return period event (figure 3).

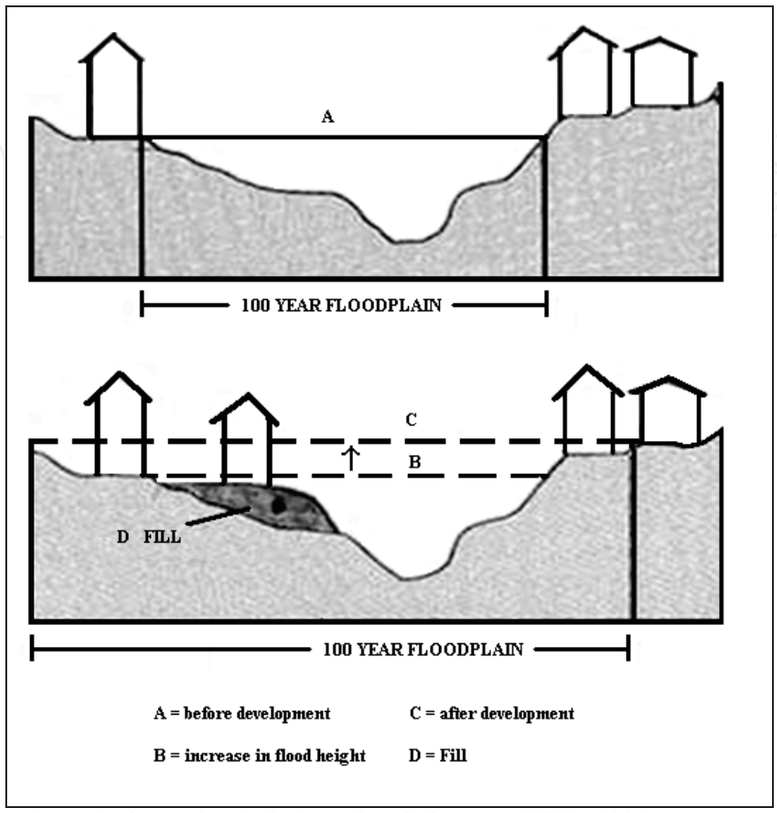


Fig. 3. Cross section of a hypothetical river flood. Source: DRD, 1991

On the other side, the hydraulic failure related to the levees could not only be explained by the design (overtopping and foundation), since there were sections that were not constructed due to financial or political reasons allowing water to pass to the urban areas. Analysing the information available and using satellite images (Landsat TM and Spot 5) it was observed that some barriers were constructed into two seasonal lagoons at the south of Villahermosa that theoretically will be the natural drainage systems to regulate the amount of water coming from the upper areas. As a consequence of the natural drainage system to the lagoons together with overtopping the banks of the rivers or the top level of levees, the water levels of the lagoons increased considerably since the reduction of the water discharge demanded more time to be drained to the Gulf of Mexico. This magnified the flooding condition in the city of Villahermosa, which was underwater for weeks (figure 4).

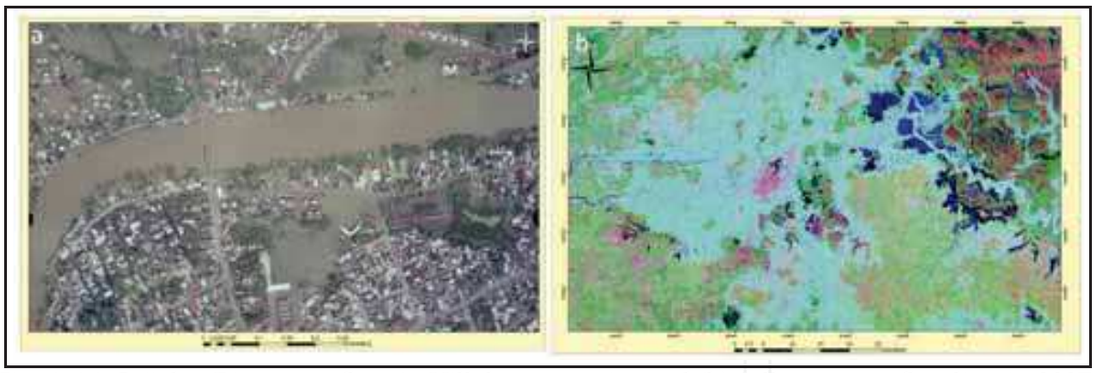


Fig. 4. (a) Grijalva River overflow in Villahermosa city and (b) full coverage flooding in 2007.

As result of the inundated areas that were under water for weeks and in some cases for months, soils were highly saturated and during the rainy season in 2008, a flood again occurred with fewer consequences but still with an impact on the economy.

4. Materials and methodology

The project used high-accuracy elevation data from LiDAR to get topographic information of the flat areas that led to an improvement in the estimation of flood risk, the extent and depth of the water and to plan efficient protective structures along the Grijalva River. Three types of data were used: (a) DEM obtained by LiDAR data, (b) field surveyed three dimension data for unchanged sites, water levels and maximum water levels during the flooding in 2007 and 2008, and (c) ancillary data to integrate the GIS to provide the information to map the water levels and flood risk.

4.1 DEM from LiDAR Data

The LiDAR data were acquired for all the Tabasco state between April-May 2008 and these are being processed by the National Institute of Statistics and Geography (INEGI, 2008). Figure 5 shows a DEM and DSM generated with 10% of the data processed by the INEGI in March 2009. The procedure followed by the INEGI (2008) started adjusting the three dimension cloud points with intensity values according to the National Active Geodetic Network (RGNA) using the GPS mounted in the aircraft and the ground station. Next, there is an altimetry adjustment to obtain a correction factor to be applied to the cloud of points. After this adjustment, a semi-automatic classification and depuration of inconsistencies was performed in order to obtain the terrain information and to generate the DEM. The DEM was created from the surface classification giving a regular horizontal spacing of 1m between each altitude measure. It was provided in binary datasets with a text file with auxiliary data such as model dimension, type of data, cartographic projection, datum and metadata. The geodesic elevation was transformed to orthometric elevations using the Mexican Gravimetric Geoid (GGM05).

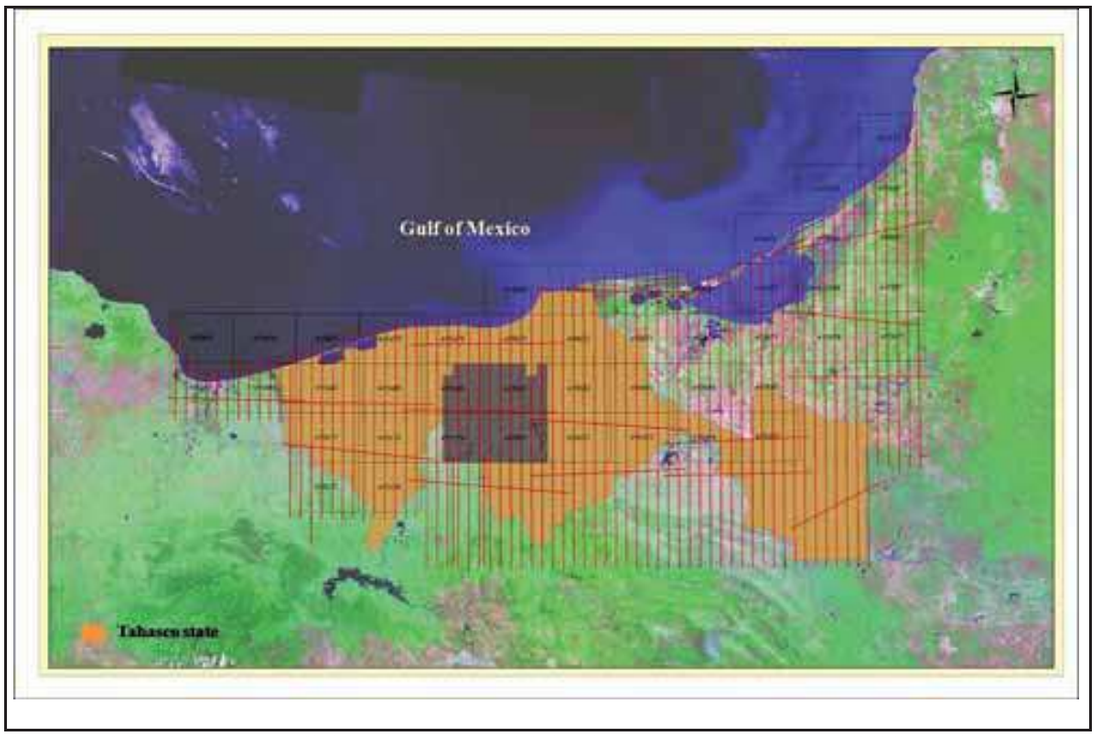


Fig. 5. LiDAR data available from the flight between April-May 2008 and the DEM processed by the INEGI (2008)

The LiDAR data files available for the INEGI were delivered in LAS format (Schukman, 2003) and they were processed using the Lidar Analyst and then the 3D Analyst in ESRI ArcGis 9.2™ to generate a grid structure where each cell provides a mean elevation in a two dimensional array. The point data were interpolated to 1m size of the cell from Kriging; in this case because of the flat topography the re-sampling was done to 0.25 m. After the interpolation, it was the DEM and DSM were visualised, and the Surface Analyst (Spatial Analyst) was applied to generate the contour lines. An advantage was the ability to take into account the DSM and DEM in the project, thus road, bridges, barriers, levees, and dykes could be identified among other features.

Additionally, the LiDAR DEM made it possible to plot the water movement using vectors that show the water direction according to the topographic features. Thus, the 25 cm grid cell permitted identification of the effect of the barriers in the lagoons since the water instead of flowing downstream was retained and the flood waters were overtopping the top level of the levees that protect Villahermosa (figure 6).

Flow movement paths in Figure 6 were plotted with the Golden Software Surfer 8.0 for both DEM and DSM it was very interesting to observe the water movement changes with and without protective barriers.

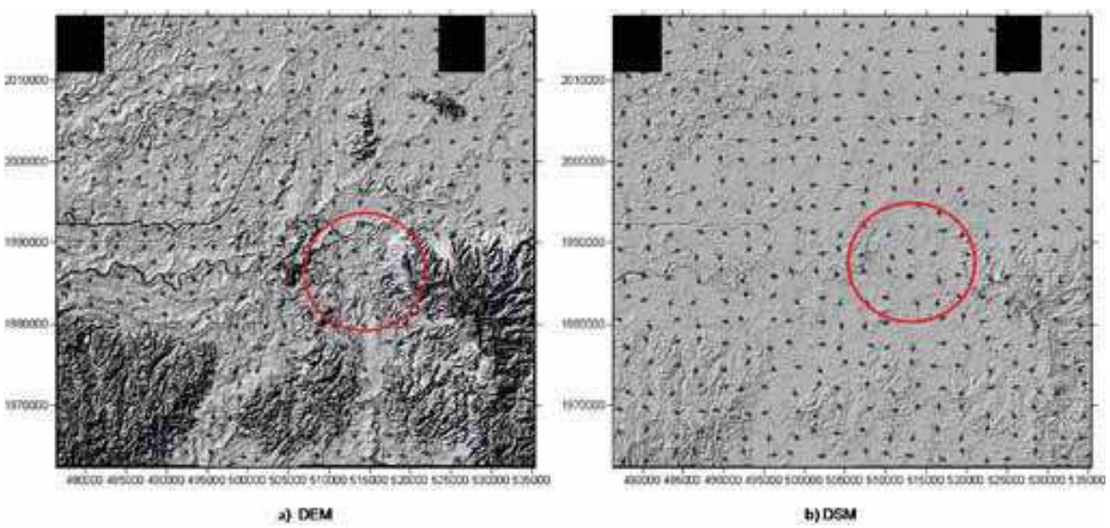


Fig. 6. Flow pattern at the southeast of Villahermosa with (DSM) and without (DEM) the protective barriers against flood. The area in red corresponds to the airport barriers

4.2 Field survey data

The field survey data was obtained during October and November 2008 using differential GPS. Two differential GPS were used: (a) Pathfinder® ProXH™ Trimble with Zephir antenna to deliver a decimetre accuracy of 20 cm post-processing (Trimble, 2008), and (b) SF-2040G integrated GPS/StarFire™ receiver from NavCom with decimetre accuracy (less than 10 cm after post-processing). The NavCom antenna has a tri-band design with an integral ground plane to track GPS, SBAS and StarFire™ satellites (NAVCOM, 2008). The surveyed points were post-processed utilising a first order geodetic control monument located in the INEGI headquarters at Villahermosa, Tabasco, to adjust the GPS position according to the registers obtained in the GPS-NAVSTAR system.

The information collected are points that refer to an altitude, water levels in rivers and lagoons and to the maximum water levels reached in the 2007 and 2008 floods (figure 7). The 2008 flood was less severe than the 2007 flood but as the soil was still saturated the inundation also had a significant impact in the region. It was not possible to have direct measurements of the water levels in 2007, but some marks were still visible on trees in November 2008. For the 2008 flood the water levels measured with the GPS (NavCom) showed a nearly consistent height of 3.0 m above sea level compared with the mean 7 m reached in 2007.

The importance of taking account of the terrain altitude and water level survey points was to identify possible alternatives to restore the floodplain and recover their natural drainage. The collected points correspond to different land covers (i.e. pavement, grass, shrub, bare soil).

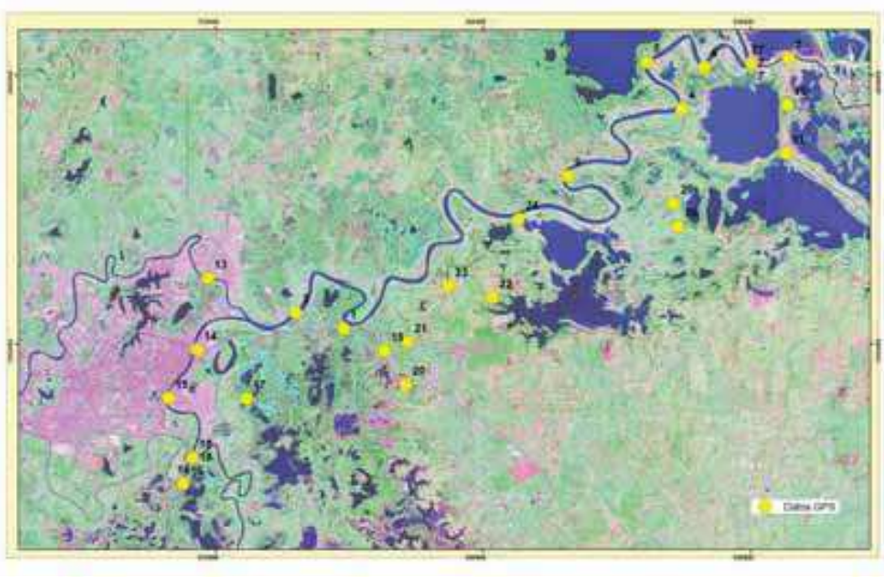


Fig. 7. GPS ground control points

Additionally, cross-sections and runoff gauged data were available for five river subbasins: Tacotalpa-La Sierra-Grijalva, Puyacatengo, Teapa, Pichucalco and Carrizal. This information was used to model the 2007 flooding in a Bi-dimensional programme to obtain the water flow in plains (Fuentes et al., 2008). In order to feed the DEM into the hydrologic model, and the accuracy of the DEM resolution was reduced from 1m to 100 m size grid cell. Although, Tamiru-Haile & Rientjes (2005) pointed out that this reduction could result in a loss of terrain information as is illustrated in figure 8.

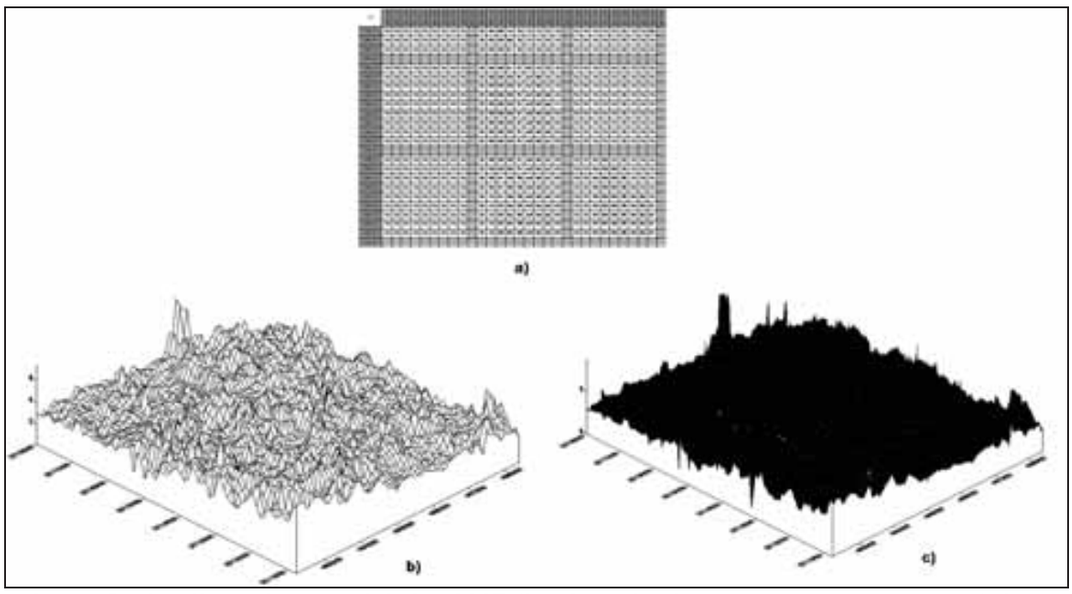


Fig.8. (a) Grid cell used to model the 2007 flood, and schematic representation of the size grid cell for (b) 100m and (c) 10m.

5. GIS system

Tamiru-Haile & Rientjes (2005) pointed out that data required for floodplain modelling needs to be analysed, calibrated and verified. This comparison was done in a GIS that is an important tool to capture, store, retrieve, analyse and display georeferenced information in an efficient way. The information in a GIS comes from different databases that are managed to generate new information, which can be displayed in a map or text file for a specific purpose. GIS has been demonstrated to be useful to establish the flood extent and the inundation patterns (DRD, 1991). An important advantage is that the GIS systems can provide information covering spatial and temporal variations. In this case additional to the baseline information (precipitation, floodplain limits, stream flow, etc.), other information related to the flooding effects, DEM and control points were plotted to map not only the flood extent but also the water levels. It also defines those areas with great inundation risk and possible alternatives by identifying a natural drainage relieve.

Thus, the LiDAR data were compared using the GPS surveyed points. Figure 9 shows the 25 control points used to compare the altitude terrain and water depth values with the LiDAR contour lines at the 2007 and 2008 flood (table 1). The control points were located in pavement roads, bare soil and vegetation (grass, shrubs).



Fig. 9. Control points from GPS NavCom (yellow points) and curve levels obtained from LiDAR spaced 0.25 m (red lines)

ID	Site	Y	X	Cota_NavCom	Wlriver	Wllagoon	MWL2007	MLW2008
1	Zapotes 2	18.00344737	-92.86025974	8.135	4.38			
2	Sandy	18.23583052	-92.66792833	1.512		1.04		
3	Porvenir	18.00878829	-92.87709476	4.906	2.673			
4	Aztlan pto1	18.07729126	-92.74075388	2.984	1.864	1.624		
5	Aztlan pto2	18.09308265	-92.75298726	2.606	1.982	1.602		
6	Grijalva-Corcho	18.09148697	-92.73264987	2.636	1.999	1.864		
7	Boca de Aztlan	18.09254211	-92.71610197	2.527	1.927			
8	Chilapilla River	18.09439884	-92.70301897	2.419	1.908	1.846		
9	Juan	18.05470363	-92.78099945	3.16	2.202			
10	Grijalva pto7	18.07867476	-92.70327103	2.195	1.908			
11	El Cuy	18.06221855	-92.70388467	1.894	1.742	1.732		2.312
12	Brigde La Pigua 2	18.02041803	-92.90815669	5.816	2.816			
13	Bridge Grijalva1	17.99634156	-92.91183319	5.216	2.673			
15	Bridge Grijalva 3	17.98000875	-92.92200179	5.491	2.689		7.317	
16	Mezcalapa-Pichucalco (Pich)	17.95126038	-92.91668256	3.33	2.614			
17	Bordo gaviotas	17.97986419	-92.89443397	3.262		2.788		
18	Conf sierra-grijal (Grij)	17.96003023	-92.91344147	5.237	3.252			
19	Zapotes 1	17.99593865	-92.8457946	3.72	2.349			
20	Potreros Bordo Aeropuerto	17.98458333	-92.83833051	2.462	2.19			
21	Bordo aeropuerto	17.99895294	-92.83758883	2.581		2.327		3.407
22	Lopez Portillo	18.01384817	-92.80752779	2.526		2.007		
23	Lagoon Sn Julian	18.01772961	-92.82322041	1.998		1.926		3.776
24	Sn Julian-Ejido Gonzalez	18.04027172	-92.79818079	3.943		2.205		4.06
25	La piedad	18.04560432	-92.74357392	1.773		1.442		2.182
26	Majagual	18.03774539	-92.74202915	1.704		1.486		2.256
	WLriver: water level for river; Wllagoon: Water level for lagoon;							
	MWL2007: Maximum water level reached in 2007; MWL2008: Maximum water level reached in 2008							

Table 1. NavCom GPS control points surveyed in the study area

Generally, to determine the risk of flood a 100 year return period is modelled, in the Tabasco flooding this theoretical situation was real, thus the flood zone extent was mapped and the statistical and hydrological model confirmed the magnitude and the extent of the flooding (Fuentes et al., 2009). The statistical analysis also considered flood events for 1-year, 2-years, 5-year, 10-year, 20-year, 50-year, 100-year, 200-year, 500-year, 1000-year, 2000-year, 5000-year and 10000-year floodplain (Domínguez et al., 2009). Figure 10B shows the extent of the 2007 flood combining a Spot image from November 6th 2007 (maximum water level reached) with contour lines every 1m. As one can observe the maximum mean water level was 7m but in some sites it was even more as dependent upon the topography of the zone (highlands or low-laying zones). In order to compare and to plot the magnitude of the 2007 flood, the 1999 flood was illustrated where a maximum water level was 4m although in some places it was of 5 m (Figure 10A).

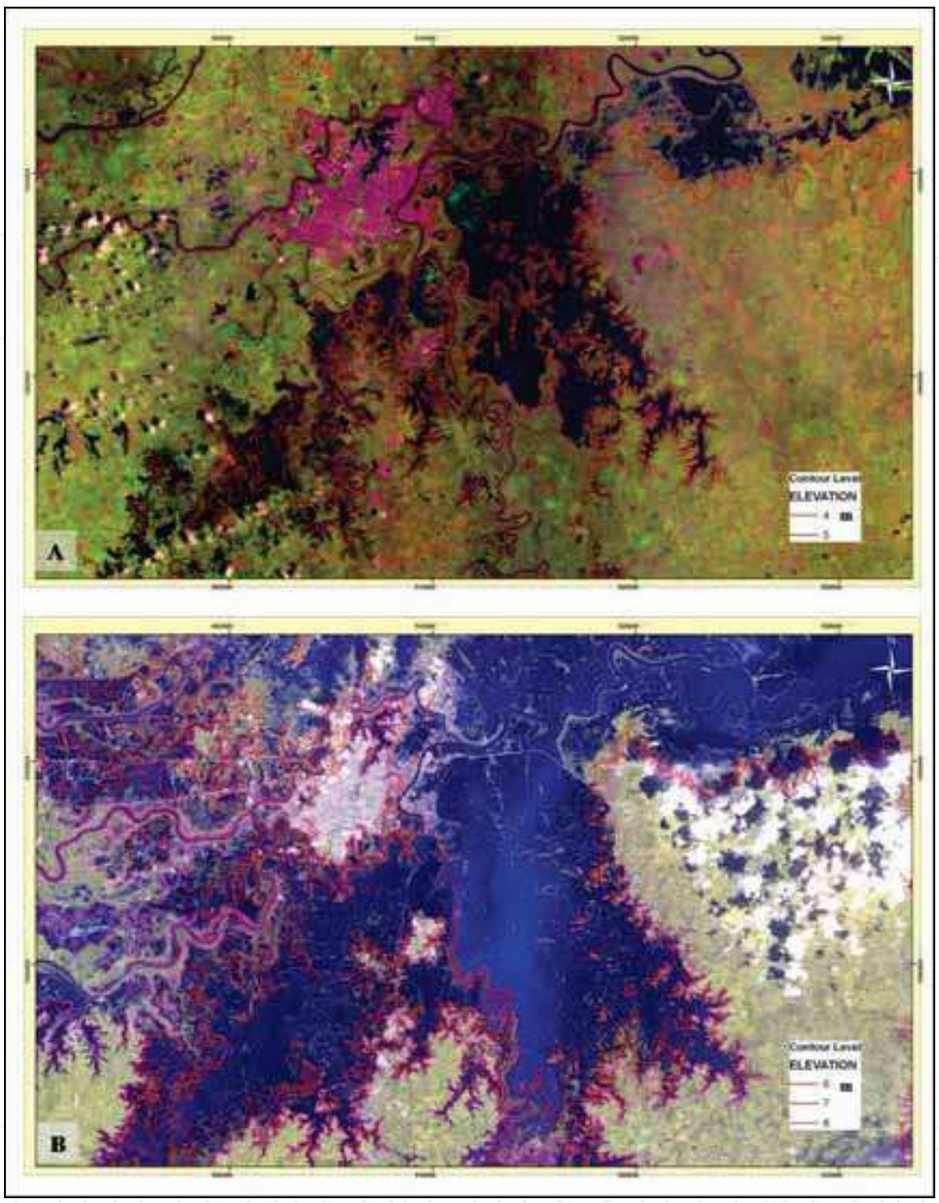


Fig. 10. Maximum water level reached during the flood events of (A) 1999

6. Results

6.1 Comparison between GPS and LiDAR

An initial comparison was carried out to see if the contour line represents the features at the borders of the area covered by the DEM. As expected they match very well due to the high accuracy of the LiDAR DEM.

The next comparison considered the surveyed points obtained with the NavCom GPS (see Table 1) and the elevations at the same x and y coordinates using LiDAR DEM. Webster & Dias (2006) proposed a method to valdate LiDAR data against GPS data. They proposed to

consider a radius less than 5 m around the GPS point covering an area with similar characteristics. Although, the available control points were very few to carry out a rigorous analysis comparison with the LiDAR DEM. They give a clear idea of the possible causes of variation. Webster et al. (2006b) noticed that a systematic pattern could be observed due to the limited precision of the laser ranging system and the motion of the aircraft. In this case the information related to the aircraft and the acquisition procedure were not available, thus the points delivered in LAS or text format georeferenced were used to generate the DEM and DSM directly.

Horizontal values from LiDAR proved to have an accuracy less than 1 cm. However, for elevation values, one found that for points located close to bridges the root mean square error (RMSE) was ± 1.75m being the largest error observed. Two very clear examples are point 1 (Zapotes 2, figure 11a) where GPS indicates a height of 8.135m and the LiDAR DEM shows a height of 4.5m, and point 15 (Bridge Grijalva 3) where GPS indicates a height of 5.491m and the LiDAR DEM shows a height of 4m. However, using the DSM the RMSE was reduced to ± 0.55m since vegetation, structural constructions and bridges were present. For point 1 DSM was 7.5 m and for point 15 it was 5.0m.

For those points located at the river bank (in November it was bare soil but surrounded by dense canopy, figure 11b) the RMSE was ±0.6m, this was because in some areas sediment deposits were observed after the flooding mainly related to human intervention to create grazing zones. The best example is point 8 (Chilapilla River), which through the years has been converted into grazing land losing completely its floodplain. After the 2007 flooding people did not agree to dredge the river and opposite to this they refilled the undermined areas by flood.

Finally, a third type of area showed a RMSE of 0.±0.297m. These areas correspond to flat areas attached to a lagoon such as San Julian point (figure 11c). In these areas the differences between height LiDAR and GPS were from 2 to 44 cm with an average of 0.11m and standard deviation of 0.30m.

Webster & Dias (2006) determined that the radium for validation is a function of the land cover. Also, they considered that the vertical accuracy of LiDAR needs to be within an average of 30 cm and for the GPS of 15 cm.

Although the NavCom GPS values were used in the study, the ones obtained using the PROXH GPS had a similar accuracy with average differences about 15% that the NavCom.

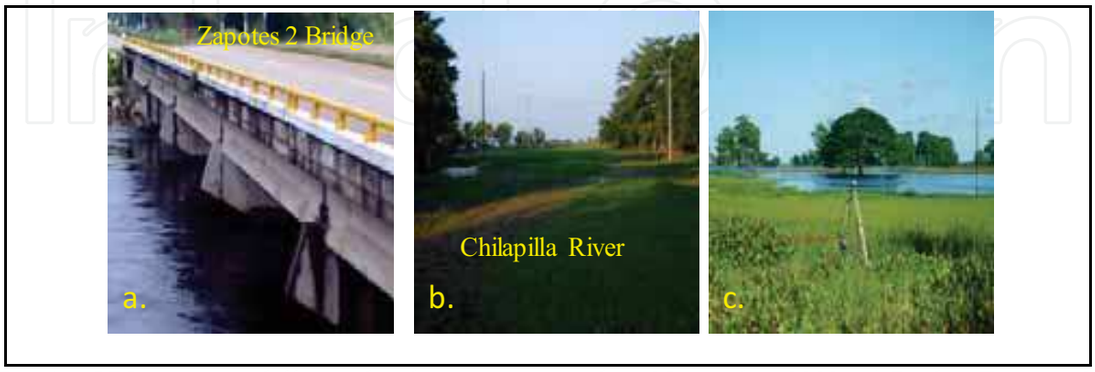


Fig. 11. GPS points at different land types surveyed on November 2008. (a) Bridge Zapotes 2, (b) Chilapilla River now a grazing area, and (c) San Julian lagoon, GPS located in an extense of grass area

6.2 Water levels for flood extent

Analysing the water levels recorded the maximum height observed was at the Carrizal River bank in Villahermosa with a height of 7.3m and the minimum was observed in the lagoons area at the northeast of Villahermosa with a height of 2.2m. This confirm the water level registered at the Gaviotas hydrometric station in the Carrizal River which maximum value was 7.81m and the average was 5.42m with a flow of 1,772 $m^3 \cdot s^{-1}$. Also in the Carrizal River, the Porvenir station registered a maximum water level of 6.67m and the González station registered a maximum of 10.20m (average of 8.77m) and a flow of 1,191 $m^3 \cdot s^{-1}$. The Pueblo Nuevo hydrometric station in La Sierra River registered a maximum water level of 8.40m (average of 7.49m) with a flow of 1,092 $m^3 \cdot s^{-1}$ (Fuentes et al., 2008). The maximum and minimum water levels as a function of the topography are significant to determine precisely the contour line at which the flood was extended during the 2007 flood and also during the 2008 flood. The contour line observed by GIS matched very well with the flood extent obtained by running the hydrological model (Fuentes et al., 2008). Figure 12 shows the impact of the water extent over Villahermosa and surrounding areas combining the contour lines from LiDAR DEM and water levels measured in the field. The progress of the flood considers a 20 years return period event such as the one in 1999 until a 100 years return period as the one in 2007. Finally, the figure shows the comparison with the 2D hydrological model result showing a close match.

The most evident fact was that the levees had the opposite effect to providing a protective action since they favoured water retains that extended flood along the original floodplain divagation. In order to avoid a similar flood several actions need to be done to regulate water flow coming from the mountain's rivers and to protect Villahermosa and its surroundings by generating better discharge conditions from the lagoons located at the south and southeast of Villahermosa.

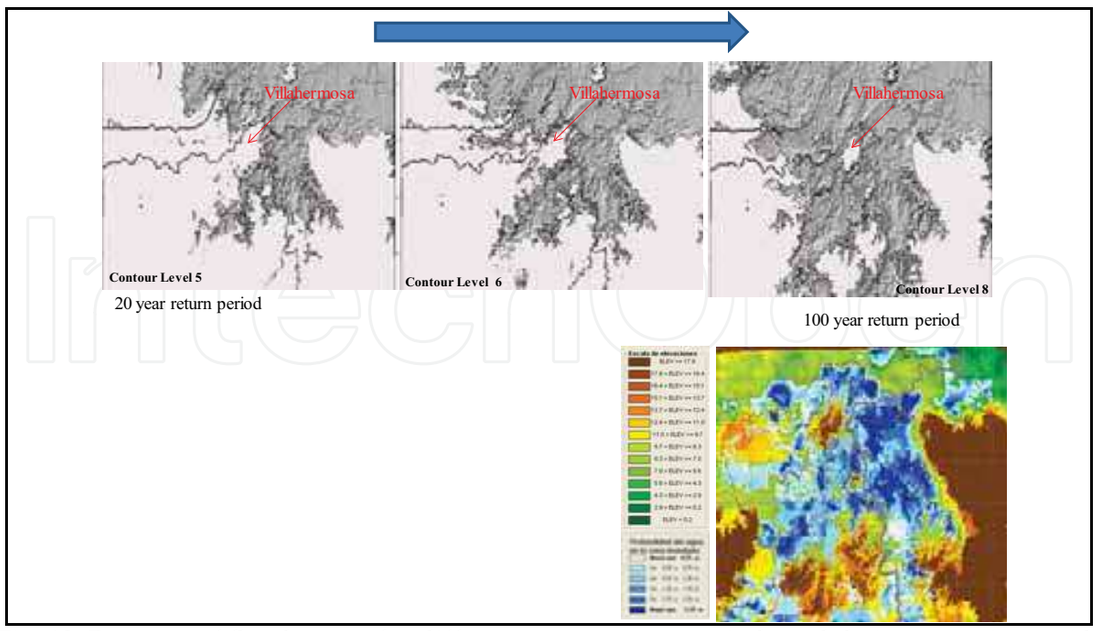


Fig. 12. Progress of flood extent for different storm return periods and their comparison with the 2D hydrological model prediction.

Figure 13 shows the floodplain risk associated with a rainfall with a return period of 100 years in the alluvial plain in Villahermosa and surroundings. As one can observe they are a low-lying area with slopes less than 50cm, thus the lateral overflow in the river can easily inundate a vast region characterised by a low-lying land.

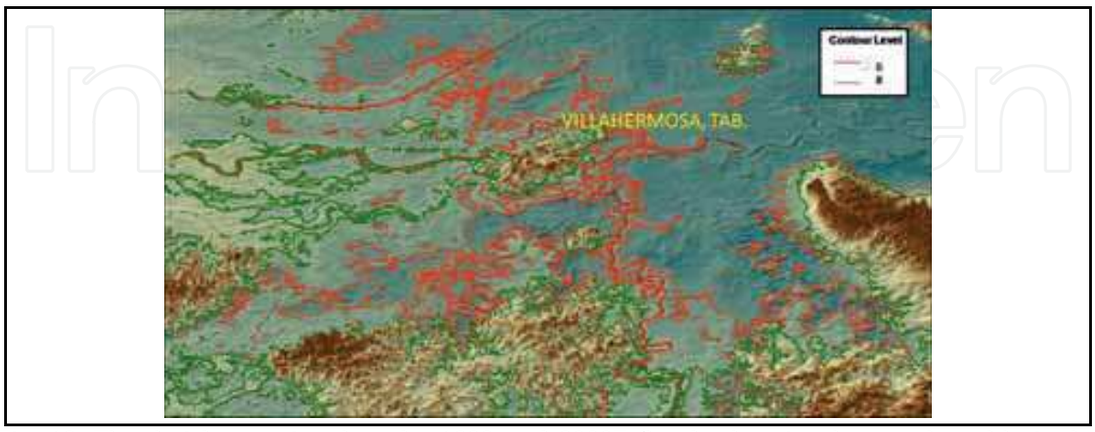


Fig. 13. Flood risk associated to the 1999 and 20007 floods showing how vulnerable is the Villahermosa city

7. Conclusion

Combining existent datasets, hydrological models, results and measured data in the field together in a GIS provide an effectively tool to analyse a flood event and to map not only water extent but also water levels to identify highly vulnerable areas. The high resolution LiDAR data is an important source of information to achieve an accurate representation of the surface making it possible to map those areas under risk in a 3D geospatial distribution.
As Webster and Dias (2006) proposed an independent validation of the LiDAR data is an important step to be considered in order to identify errors associated with this dataset. Unfortunately, a flight report was not available thus an analysis associated to the system and conditions of the flight was not possible. Nevertheless, a comparative test was carried out with limited GPS surveyed data points but sufficient to observe some trends. Here the comparison between LiDAR data and GPS surveyed values offered interesting results since some differences were mainly associated with the land cover and topography aspects. In this sense, the less representative data was obtained for those points located in bridges and levees opposite to the control points attached to lagoons with grass extent lands where heights were very similar. Although in the first case, the DSM can represent the actual height accurately, it is important to consider the representiveness of the information extracted from the LiDAR DEM.
Some authors reported a vertical accuracy for LiDAR DEM of 15 cm, in this case a grid cell of 25 cm size proves the information necessary to ensure a better distribution of the water extent and levels reached during the flooding. Also, even if the grid cell resolution was reduced with a consequent loss of information to apply to the hydrological model, the grid cell was enough to represent accurately features that traditional DEMs with a 30 m resolution could not cope with. This provides better and more information related to the origin, development and effects of the flood.

One important aspect was that a 100 year return period event was plotted allowing the analysis of a real situation and not a hypothetical one. The 2007 flood in Tabasco showed that the state and, in particular, the Villahermosa city, is a region subject to flooding as a result of several human actions that reduced significantly the original floodplain zone. Thus different actions need to be done at the upper, middle and low Grijalva River Basin in order to protect effectively the whole area.

Further research considers using a flexible grid cell to extract information every 0.25m instead of reducing the grid cell resolution. This requires a lot of data and processing time but the benefits are higher due to the accuracy of the x,y,z LiDAR data. Mapping the flood, one can identify those elements that failed. The critical one is to recognise the necessity to recover the floodplains that have been highly degraded through generation of urban or agricultural areas. By identifying the river status and its lateral connectivity, better protective systems can be proposed to recover the natural functions and process of the floodplains.

8. Acknowledgments

This project was founded by the National Water Commission. The LiDAR data was provided by the sponsor. With thanks to MSc. Víctor Franco, who reviewed the paper for comments.

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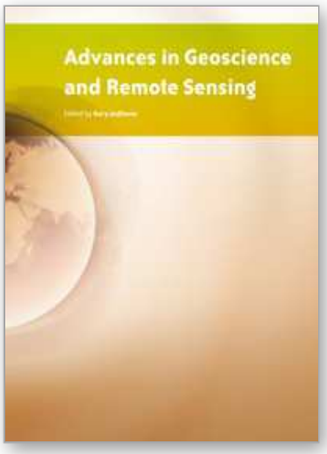
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Advances in Geoscience and Remote Sensing

Edited by Gary Jedlovec

ISBN 978-953-307-005-6

Hard cover, 742 pages

Publisher InTech

Published online 01, October, 2009

Published in print edition October, 2009

Remote sensing is the acquisition of information of an object or phenomenon, by the use of either recording or real-time sensing device(s), that is not in physical or intimate contact with the object (such as by way of aircraft, spacecraft, satellite, buoy, or ship). In practice, remote sensing is the stand-off collection through the use of a variety of devices for gathering information on a given object or area. Human existence is dependent on our ability to understand, utilize, manage and maintain the environment we live in - Geoscience is the science that seeks to achieve these goals. This book is a collection of contributions from world-class scientists, engineers and educators engaged in the fields of geoscience and remote sensing.

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