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Estimation of probabilistic flood inundation maps for an extreme event: Pánuco River, México

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Extreme event; flood management; flood map; floodplain; fluvial flood; tropical storm; uncertainty.

Abstract

This investigation evaluates the effects of hydrological uncertainty in the results of flood extent estimates during the incidence of a tropical storm. For this, the methodology is comprised of field measurements, elevation data, a distributed hydrological model and a standard two-dimensional numerical model. Uncertainty is considered in the distributed hydrological model through the estimation of possible hydrographs from precipitation data registered during the incidence of an extreme event. The characterisation of the run-off by multiple possibilities opens the door to a probabilistic estimation of flood maps, enabling the consideration of hydrological uncertainties and their propagation to an estimated flood extension. It is shown that during the incidence of the tropical storm Arlene, the estimated flooded area is similar to what was registered by satellite imagery. Although the methodology does not consider all the uncertainties that may be involved in the determination of a flooded area, it is reflected that it favours the preventive action in the generation of flood management strategies. The selected approach is a first iteration in the production of a fully quantified approach to the analysis of flood risk, especially where there are doubts about how the catchment responds to a given extreme precipitation event.

Introduction

Flooding is a natural phenomenon that generates devastation and economic losses all around the world. According to the statistical review presented by the Centre for Research on the Epidemiology of Disasters, flooding in 2010 affected 178 million people (Guha-Sapir *et al*., 2012). Recent studies have recognised that floods are the most frequent among all natural disasters (e.g. Dawson *et al*., 2009). In the last century based on International Strategy for Disaster Reduction statistical analysis, the total numbers of hydrometeorological events was 7486.

In 2007, the devastating consequences of the floods in Tabasco, Mexico were covered by the press worldwide. In 2009, the wettest November since records in the UK led to flooding across much of northern Britain and Ireland. As a result of this catastrophe, four people lost their lives. In 2011, destructive floods were recorded in Australia (Queensland) and again in Tabasco, Mexico. These flood events observed in developed and developing nations alike highlight the necessity to generate a better understanding on what causes extreme flooding events and how we can better manage flood risk. Moreover, the process of flood risk evaluation and management contains a great deal of uncertainty, which in turn is ascribed to the limitations in the current body of knowledge (e.g. Beven, 2008; Harvey *et al*., 2012). To overcome these restrictions, some efforts have been focused on the utilisation of measured precipitation data to determine the probability of occurrence of a given flood (e.g. Goppert *et al*., 1998). Although the utilisation of measured precipitation data in a study restricts the level of uncertainty in the results, it should be noted that there are also a number of unknowns associated to the idealisation of hydrological processes (e.g. from measured precipitation to a given run-off). The uncertainties in the hydrological model parameters are due to the inability to uniquely identify the best parameter set for a region (Shrestha and Solomatine, 2008). For instance, there remain limits to the detail that can be represented in a hydrological model, and there is a problem in the definition of fixed bulk parameters that comprise more complex processes varying both in time and space (Beven, 2001).

The problematic situation of having a forecast without reporting confidence limits highlights the importance of generating better and more reliable flood management strategies. Thus, it is necessary to somehow consider and inform how current limitations in the knowledge affect a given forecast (Demeritt *et al.*, 2007; Bao *et al.*, 2011). It is anticipated that a better communication of results will reinforce the disaster prevention process.

On the other hand, it has been increasingly recognised that floodplain inundation modelling plays a key role in the generation of these strategies (Horritt and Bates, 2001; Neal *et al.*, 2012). Thus, being able to reproduce the spatial inundation patterns through mathematical models provides a valuable tool to water management as well as the effects of human interventions such as embankments, dykes and dredging projects (e.g. Pedrozo-Acuña *et al.*, 2012a). However, inundation modelling in lowland rivers is a complex process and requires an accurate representation of the fluvial processes as well as the hydrological inflows into the reach (Stewart *et al.*, 1999). Moreover, uncertainties associated to the hydrodynamic model calibration process can have a significant influence on flood inundation predictions (Hall *et al.*, 2005). As pointed out by Romanowicz and Beven (2003), there are plenty sources of error in the inundation modelling process to cast some doubt on the certainty of calibrated parameters. These are associated to inaccuracies generated by different origins, from a nonrealistic representation of the floodplain geometry to a limited representation of the inflow hydrograph, not to mention the numerical approximations inherent in solutions of the flow equations. Therefore, it is anticipated that quantification of these uncertainties and their propagation through to modelling process is of great importance (Xuan *et al.*, 2009). Current approaches to flood mapping indicate that in order to produce a scientifically justifiable flood map, the most physically realistic model should be utilised. However, as pointed out by Di Baldassarre *et al.* (2010), given the amount of uncertainty involved in the determination of design events (e.g. 1-in-100 year flood) even using these models, it is desirable to visualise flood hazard as a probability. It has been acknowledged that flood maps that inform the uncertainty contained in the reproduction of a particular event would be less likely to be wrong and would be of great use for the implementation of an improved risk-based decision-making process (Beven *et al.*, 2011). Indeed, the work presented by Neal *et al.* (2013) represents a good example of the uncertainty quantification in flood risk mapping. They utilised a block-bootstrapping technique for the generation of 100 scenarios of an event, which were used as forcing conditions of a hydraulic model based on the inertial wave. Their results indicated that uncertainty in estimates of inundation probability was significant, and the confidence intervals in risk estimates were larger than expected.

In flood events associated to large rivers with alluvial plains, the main concern is the determination of the wide lateral extent of inundated areas. This is precisely the case of the lower Pánuco river basin in Mexico, which in 2011 registered a severe flood produced by the incidence of a tropical storm over the catchment. Previous studies on the area have looked at the hydrologic and geomorphic characteristics of this system (Hudson and Colditz, 2003), but to the best of the authors knowledge, there is still a need for a better characterisation of the hydrological flows and the possible flooding consequences in the floodplain. In particular, a key aspect that needs attention is the evaluation of hydrological uncertainties in the determination of a given run-off, and how these are transmitted to the definition of a flooded area.

Within this context, the main aim of this work is to evaluate the uncertainty in the reproduction of an observed flood event along the lower course of the Pánuco River. For this, real precipitation data associated to this event will be used to determine an ensemble of possible discharges with a rainfall run-off model. The resulting hydrographs will be utilised in a two-dimensional (2D) hydrodynamic model to derive different flood maps enabling the estimation of uncertainty bounds to a model prediction. This is done in order to generate better flood management strategies in this region. The proposed investigation follows an integrated approach presented by Pedrozo-Acuña *et al.* (2012a, b) and Rodríguez-Rincón *et al.* (2012), which considers the combination of a high-quality precipitation data of the catchment, a distributed hydrological model and a validated standard 2D numerical model. Uncertainty is considered in the hydrological model through the estimation of possible hydrographs from observed precipitation data, which enables the derivation of a number of possible hydrographs that could represent the observed run-off. The characterisation of the run-off by multiple possibilities opens the door to a probabilistic estimation of flood maps, which in turn allows the evaluation of uncertainty propagation to the estimated flood maps (Beven *et al.*, 2011). As pointed out by Rayner *et al.* (2005), a probabilistic output allows for the improvement of current flood risk management strategies by, for example, limiting the generation of false alarms and false negatives. This represents a step forward towards an improvement on the generation of better social communication of the risk to the affected communities, which is anticipated to enable long-term planning for flood damage reduction to downstream communities located in the affected floodplains (Popescu *et al.*, 2010).

This paper is organised as follows, *Study area and flood event* provides a description of the study area and the extreme event that is investigated; Section *Methodology* presents a description of the numerical approach comprised by field measurements and models of rainfall-runoff and hydrodynamics, this includes the setup of both models. Section *Results* presents the hydrodynamic results using the derived ensembles computed with the hydrologic model. Finally, conclusions and future work are summarised.

Study area and flood event

Study area

The Pánuco river basin is one of the most important hydrological regions in Mexico because of both its territorial extension (96 989 km^2) and the annual run-off volume (20 329 hm^3). The whole catchment comprises parts of the Mexican states of San Luis Potosí, Veracruz, Zacatecas, Guanajuato, Tlaxcala, Estado de México and Mexico City, and given its size, it has been divided in two subregions: the higher Pánuco basin and the lower Pánuco basin.

In recent years, the study area has been subjected to severe floods (e.g. 1955, 1990, 1993, 1999, 2003, 2007 and 2011) causing serious devastation. The high level of investment after the occurrence of these disasters emphasises the high vulnerability of the region to flooding.

The annual discharge regime for the Rio Pánuco replicates the regional precipitation pattern for eastern Mexico with low values during the dry season defined from late October through April. In contrast, both precipitation and discharge considerably increase with the onset of summer trade winds in June. The maximum flow in the river is often associated with the increase in tropical cyclone activity within the Gulf of Mexico (e.g. September). To give an example of the size of the extreme discharges that can be drained in this river during the event of 1993, the estimated flow was 5836 m^3/s (Pedrozo-Acuña *et al.* 2011).

The study site is a low lying area of ~900 km^2 comprised by the lower Pánuco basin, which starts at the confluence of the Rio Moctezuma and Rio Tampaón (see Figure 1). From this point, this natural watercourse flows into the Gulf of Mexico, where it defines the boundary between the states of Veracruz and Tamaulipas with a total length of approximately 120 km. As pointed out by Hudson and Colditz (2003), this region provides an excellent opportunity to undertake flood delineation studies. Additionally, close to Pánuco's river mouth, the hydraulics of the system are complicated by the interaction with another important fluvial system that comes from the north of Tamaulipas. This river, named Tamesí, has also a large hydraulic capacity with an estimated discharge of 2387 m^3/s for the 1993 event. Notably, this system is comprised by a set of lagoons that serve as a sheltered zone to mitigate the effects of overflow in this river. Additionally, there are several rural and some urban locations along both sides of the river and river mouth: the towns of Pánuco, Ebano, Pueblo Viejo in Veracruz, and Tampico and Altamira in Tamaulipas. In addition, the port is populated with industrial facilities of the national oil company (PEMEX). Thus, severe floods cause large socio-economical damage along this region. Because of the observed increase in extreme floods in the last decade, there is a clear need to increase the level of understanding on what causes extreme flooding events and how we can better manage flood risk.

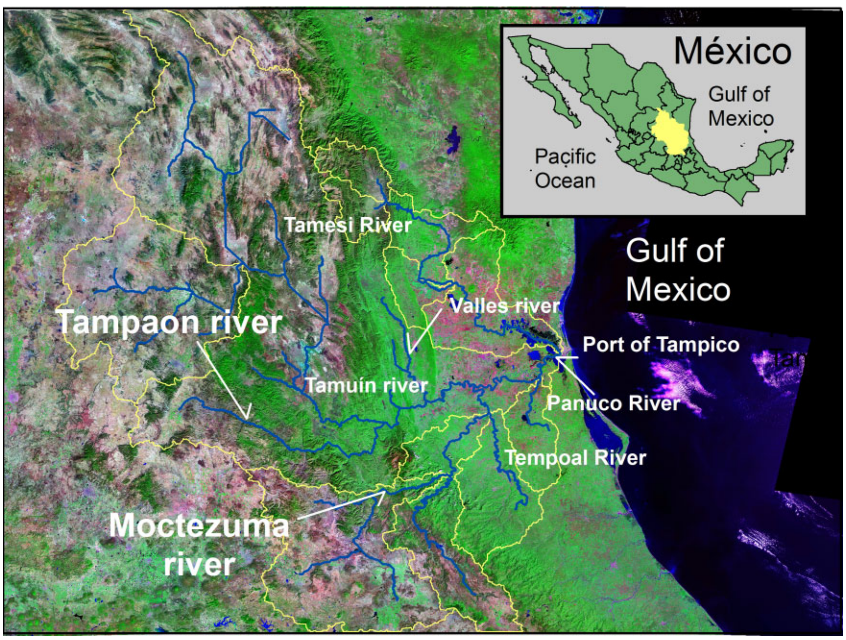

Figure 1 Location of the Pánuco river basin in relation to the Gulf of Mexico and within México.

Tropical Storm Arlene 2011

In 2011, severe flooding was produced in the lower Pánuco basin by the incidence of the tropical storm Arlene, which was recorded from the 1st to the 3rd of July. The incidence of this natural phenomenon serves as a good example of the level of exposure to flooding of this region. Severe flooding was registered during and after the occurrence of the tropical storm. Figure 2 illustrates a series of satellite images of the study area at different times before and after the incidence of the tropical storm, where the size of the inundation area is clearly reported (NASA/GSFC, 2012, Rapid Response). Moreover, the resulting precipitation from the incidence of this storm was recorded by several gauging stations of the National Water Commission (CONAGUA) at the locations illustrated in both panels of Figure 3. According to the meteorological report of the Federal Commission of Electricity, on the 28th of June, Arlene, the first tropical storm of the 2011 season, was generated 340 km to the northeast of Veracruz in the Gulf of Mexico, with an initial reported velocity of 15 km/h. On June 29th, the storm was located 180 km from the coast with maximum wind speed of 100 km/h. The maximum daily cumulated rainfall was 113.2 mm in the Port of Tampico and 150 mm in Huatusco, Veracruz. The tropical storm touched ground on the 30th of June, producing torrential rainfall in an area that comprise the lower basin of the Pánuco river located in the states of Tamaulipas, Veracruz, Hidalgo, Nuevo León y San Luis Potosí (CFE, 2011). The registered maximum cumulated rainfall in 24 h was 348.8 mm in Tamesí, Tamaulipas and 231 mm in Pánuco, Veracruz, two locations that are directly related to the lower Pánuco basin. The persistency and magnitude of the rainfall triggered an extreme flood that left several damages to the region.

On the other hand, while rain gauges provide a direct measurement of rainfall at the land surface, it should be noted that these data are also exposed to different sources of uncertainties. These are ascribed to the quantification of the spatial variability of rainfall (Yilmaz *et al.*, 2005; Morin *et al.*, 2006) and errors in the mechanical operation or in the ability of the tipping bucket to catch the rainfall in the device, preventing raindrops from entering the gauge (Molini *et al.*, 2005). Because these behaviours affect the conveyance of rain into the gauge body, they result in underestimation of the true rainfall by the gauge. These sources of error are important for quantifying rainfall accumulations over long times, but as pointed out by Molini *et al.* (2005), they have limited influence on rainfall intensity estimates, such as those used in this study. It should be noted that weather radars provide high-resolution rainfall measure-

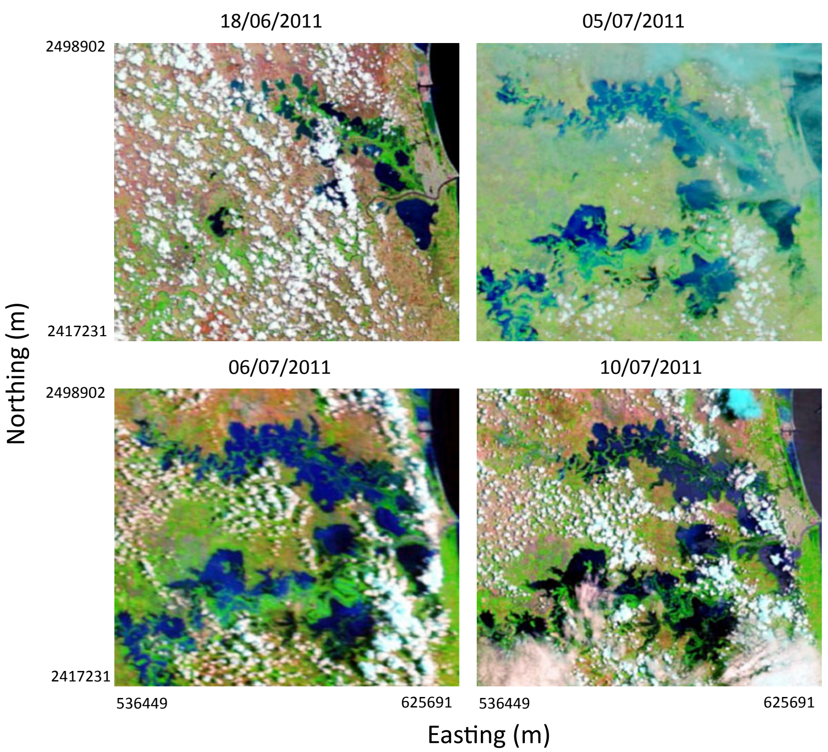

Figure 2 Satellite images of the 2011 extreme flood event in the lower Pánuco basin during the incidence of tropical storm Arlene (NASA/GSFC, Rapid Response).

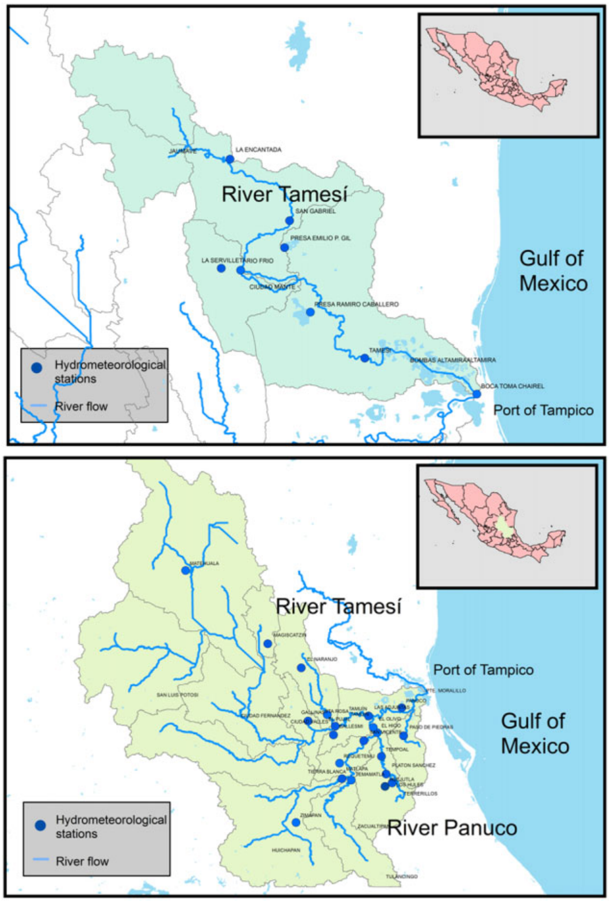

Figure 3 Subcatchment definition for both rivers and location of gauging stations (blue dots). Top panel: Tamesí basin; bottom panel: Pánuco basin.

ments in space and time (e.g. Reichel *et al.*, 2009), and therefore, they can be potentially very valuable for flood forecasting and inundation modelling. However, in the case of study, this information was not available.

In this investigation, the characterisation of this event will be carried out through the application of an integrated methodology, comprised by combination of a high-quality precipitation data, a distributed hydrological model and a validated standard 2D numerical model. Therefore, the purpose is not only to reproduce the event by means of the methodology but also to study the impact of hydrological uncertainties on the identification of flood prone areas.

For clarity, the system is divided in two subcatchments which separate the flow for each river, Pánuco and Tamesí. The division in this manner will aid to define the hydrographs for each river that will serve as boundary conditions of the flood inundation model utilised in this study. The hydrologic characteristics in combination with the physiographic features of the lower basin, flat lands and mild slopes, increase the susceptibility of the region to floods.

Methodology

The integrated approach used in this study is comprised by field measurements of precipitation for a flood event, bathymetry and elevation data, a distributed hydrological model and standard 2D numerical modelling. The precipitation data were collected during the incidence of tropical storm 'Arlene' by means of several automatic hydrometeorological stations installed by the National Water Commission of Mexican Government (CONAGUA). The data obtained in an hourly basis is used as input for the hydrological model.

The utilisation of precipitation data for the observed extreme event allows the generation of different run-off curves by means of a distributed hydrologic rainfall run-off model. The generation of the spaghetti plots for this event is carried out through the variation of free parameters in the hydrological model. On one hand, this procedure is designed to take into account the uncertainties associated to the hydrological model, while on the other hand, allows the determination of confidence limits to the derived run-off. The spaghetti plots are utilised as boundary conditions of the 2D hydrodynamic model, which in turn is used for the estimation of flood maps along the Pánuco river floodplain. The later is done, given the amount of recent research pointing towards the large uncertainty associated with flood extent predictions using these models (Bates *et al.*, 2004; Pappenberger *et al.*, 2006, 2007a, b). For clarity, Figure 4 presents a graphic summary of the proposed methodology.

As pointed out by several researchers, recent progress in remote sensing offers the opportunity to collect spatially distributed data rapidly and over large areas (e.g. Schultz, 1988; Bates *et al.*, 1997; Bates, 2004). Digital Elevation Models (DEM) can be derived from different remote sensors allowing the construction good representation of terrain data with different resolution and vertical accuracy depending on the instrument. For the study region, there is a lack of high-resolution data (airborne light ranging and detection data, e.g. LiDAR). In this sense and following conclusions put forward by Sanders (2007) and Prato *et al.* (2009), we employ data from the Shuttle Radar Topography Mission (SRTM). Although the SRTM has been found to underestimate elevation of high-relief and high-altitude terrain, it is also known that for flat terrain, such as the lower Pánuco river floodplain, the vertical accuracy of this DEM is improved (Berthier *et al.*, 2006; Guth, 2006).

Hydrological model

The hydrological model employed for the generation of basin hydrographs was developed by the Institute of Engineering – National Autonomous University of Mexico (Domínguez-Mora *et al.*, 2008). The numerical tool comprises a simplified grid-based distributed rainfall run-off

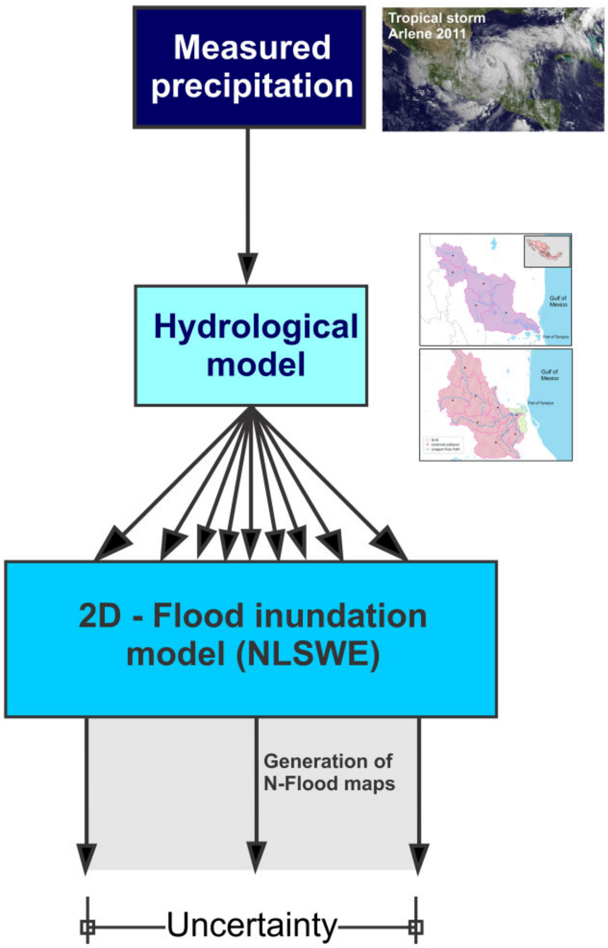

Figure 4 Flow chart of the different processes involved in the proposed methodology for the generation of probabilistic flood maps.

model, which has been developed to estimate the precipitation–run-off processes of dendritic watershed systems, and it is similar to that presented by Xuan *et al.* (2009).

The model is based on the method of the Soil Conservation Service (SCS) with a modification that allows the consideration of ground drying processes after the rain occurrence. The parameters that are necessary for the determination of a run-off curve within the catchment are the hydrologic soil group, land use, edaphology and the flow paths. Figure 5 introduces for both sub-basins Pánuco and Tamesí, the spatial definition of flow paths (left panels) and run-off curve (right panels).

There are two main assumptions that underpin the SCS curve number method. Firstly, it is assumed that for a single storm and after the start of the run-off, the ratio between actual soil retention and its maximum retention potential is equal to the ratio between direct run-off and available rainfall. Secondly, the initial infiltration is hypothesised to be a fraction of the retention potential.

Thus, the water balance equation and corresponding assumptions are expressed as follows:

$$P = P_e + I_a + F_a \tag{1}$$

$$\frac{P_e}{P_a - I_a} = \frac{F_a}{S} \tag{2}$$

$$I_a = \lambda S \tag{3}$$

where P is rainfall, P_e effective rainfall, I_a is the initial abstraction, F_a is the cumulative abstraction, S is the potential maximum soil moisture retention after the start of the run-off and λ is the scale factor of initial loss. The value of λ is related to the maximum potential infiltration in the basin.

Through the combination of Eqns (1)–(3) and expressing the initial abstraction (I_a) by 0.2*S, we have:

$$P_e = \frac{(P - 0.2S)^2}{P + 0.8S} \tag{4}$$

where, the value of S [cm] is determined by:

$$S = \frac{2450 - (25.4CN)}{CN} \tag{5}$$

CN is the run-off curve number, as defined by the Agriculture Department of the United States (USDA, 1985). Appropriated values for this parameter vary from 30 to 100, where small numbers indicate low run-off potential while larger numbers indicate an increase in run-off potential. Thus, the permeability of the soil is inversely proportional to the selected curve number. Another parameter that allows the modification of the curve number is the soil water potential given by *Fs*, following S = S**Fs*.

The model includes a parameter to reproduce the effects of evaporation on the ground saturation (F_x). This parameter is useful when the event to be reproduced lasts for several days. The computation of the run-off in the whole basin is carried out through the addition of the run-off estimated in each cell to then construct a general hydrograph (see Rodríguez-Rincón *et al.*, 2012).

Because of its size, the system is divided in two subcatchments which are aimed at representing both the precipitation and run-off for each river Tamesí and Pánuco. The data set utilised in this investigation include precipitation data recorded every 10 min from the 26th of June and end on the 7th of July. Figure 6 presents for each subcatchment the distributed precipitation estimated for these days, it is shown that rainfall intensity in the Pánuco region is persistent from 28th of June to 4th of July, while that registered in Tamesí subcatchment is more intermittent but with higher peak values.

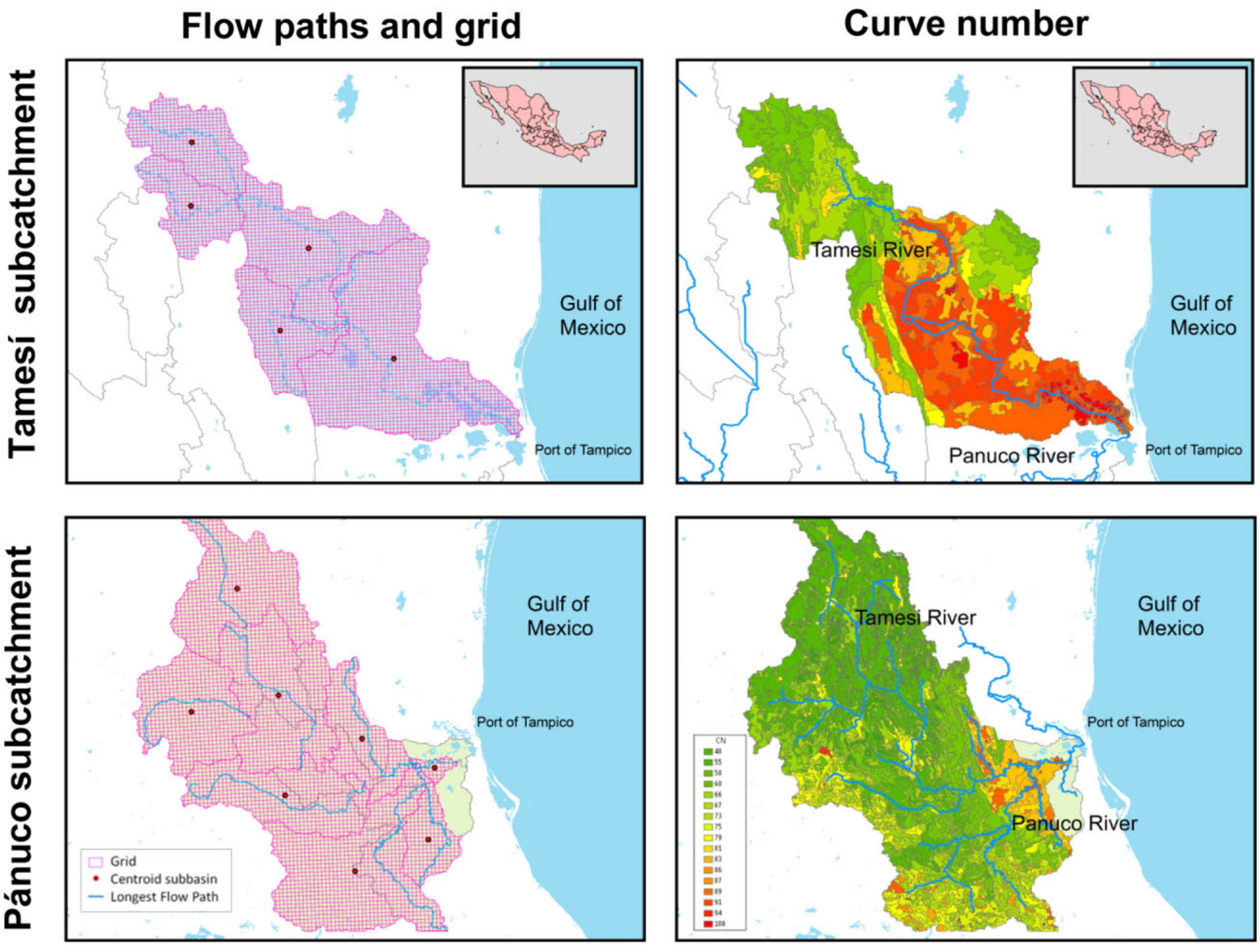

Figure 5 Input data parameters for the subcatchment characterisation within the hydrological model. Top panels: Tamesí; bottom panels: Pánuco; left panels – flow paths and grid; right panels – curve number.

Uncertainty estimation

In this investigation, there are different sources of error associated to the modelling structure that is implemented. However, it is reflected that the utilisation of a good precipitation data set reduce the errors because of input data. Therefore, focus is given to errors associated to the hydrological model set-up, and in particular, to those embedded in the model structure and its capacity to adequately describe the link of processes within the catchment during the incidence of tropical storm Arlene.

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 approach recognises that many different combinations of model parameters can lead to results, which are acceptable representations of the available observations. Therefore, in this study and making use of the concept of equifinality (Beven, 2006), the utilisation of GLUE comprises the generation of multiple runs with the hydrological model employing different parameter sets. In this form, a number of hydrographs that may represent the run-off induced by the tropical storm Arlene are generated. The selection of parameter values is carried out following Pappenberger *et al.* (2007b), retaining those runs with an acceptable model performance. The selected parameters for this analysis are related to the scale and the maximum soil retention factors, and their proposed values are presented in Table 1.

Figure 7 introduces for each subcatchment, Pánuco and Tamesí, the estimated hydrographs derived from the processing of the precipitation data registered during the incidence of the tropical storm Arlene in 2011. Top panel illustrates the estimated run-offs determined for the Pánuco River, where it is observed that the uncertainty in the flow estimation is maximum at the peak flow with bounds within the 5000 and 12 000 m^3/s. On the other hand, bottom panel shows the different estimated discharges for the Tamesí River. Notably, the peak flow for this river is smaller than that reported for the Pánuco with magnitudes between 1500 m^3/s

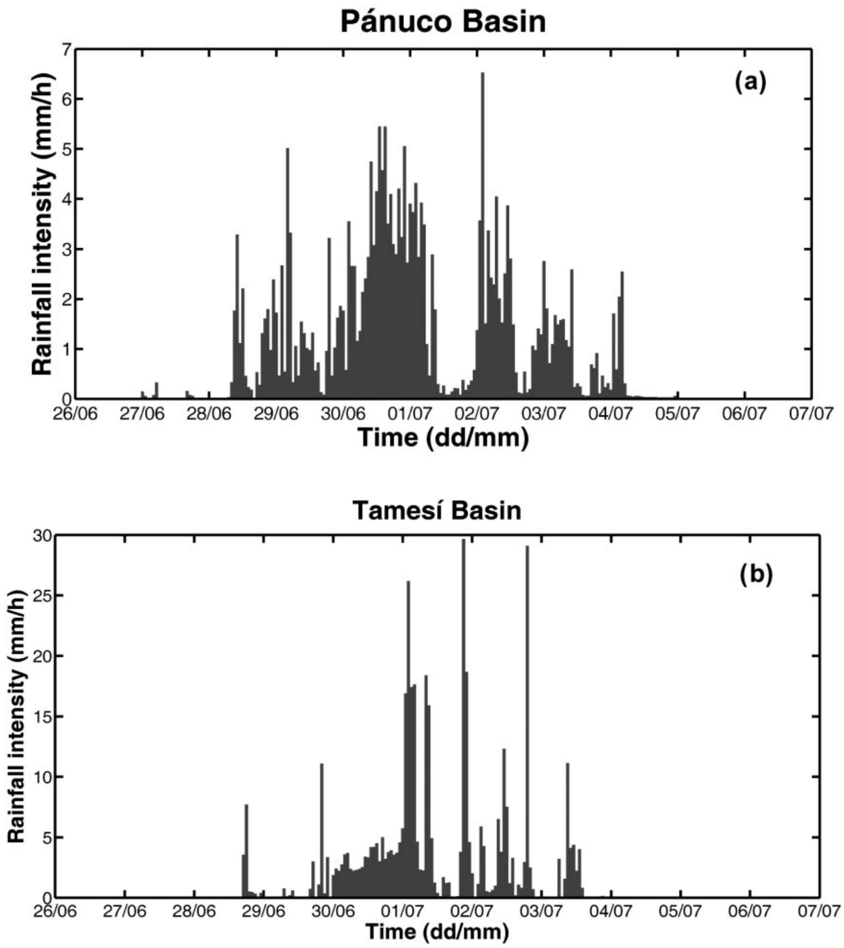

Figure 6 Hyetographs for both subcatchments in the study region (a) Pánuco river basin and (b) Tamesí river basin.

and 4000 m^3/s. The observed difference between the hydrographs for both rivers is ascribed to the lagunar system in the vicinity of the river Tamesí. In both panels, maximum and minimum envelopes are also illustrated in order to graphically determine the uncertainty bounds associated to the basin characterisation of the hydrological model (30 hydrographs were produced for each river).

The utilisation of these hydrographs enables an investigation of the propagation of these hydrological uncertainties (in the estimation of the run-off) to the results associated to flood inundation areas in the lower Pánuco river basin. The estimated run-off for both rivers are used as initial conditions for the flood inundation model for the evaluation of probabilistic flood maps for the 2011 extreme event.

Flood inundation model

The numerical tool to determine affected areas in the lower Pánuco basin during the incidence of the tropical storm Arlene is the MIKE 21 flexible mesh (FM) flow model, which solves the Reynolds-averaged 2D Navier–Stokes equations subject to the assumptions of Boussinesq and of hydrostatic pressure (http://www.dhigroup.com; DHI, 2011). The model solves the equations at the centre of each element within the domain.

The large extension of the study region ~80 km × 80 km required a numerical discretisation of the domain by means of an FM determined with elements of various sizes. The selected numerical domain is defined in a way that both, the lower reach of the Pánuco River and the Tamesí River, are included at the south and north of the domain with their corresponding flood plains. The highest mesh resolution was determined for the river stream, while the floodplain mesh was constructed through 20 subdomains each with different resolution (finest and coarser elements with a maximum area of 400 m^2 and 2500 m^2, respectively). The selected resolutions guaranteed the proper representation of the elevation in the floodplain with the utilised DEM.

The numerical model set-up requires a surface topography and bathymetry for both rivers and neighbouring lagoons, as well as definition for the surface friction coefficient to simulate flood inundation. It is acknowledged that in

Table 1 Parameters included in the uncertainty analysis

Member no.	Parameters: λ	Parameters: Fs	Parameters: Evapotranspiration Pánuco (F_x)	Parameters: Evapotranspiration Tamesí (F_x)	Q $_{peak}$ Pánuco River (m^3/s)	Q $_{peak}$ Tamesí River (m^3/s)
1	0.4	0.6	0.96	0.86	11 418.08	3715.47
2	0.4	0.8	0.96	0.86	9375.92	2876.55
3	0.4	1	0.96	0.86	8191.15	2335.62
4	0.4	1.2	0.96	0.86	7367.8	1982.93
5	0.4	1.4	0.96	0.86	6764.09	1750.91
6	0.5	1.6	0.96	0.86	6312.59	1592.65
7	0.5	0.6	0.96	0.86	10 308.31	3275.88
8	0.5	0.8	0.96	0.86	8557.15	2485.36
9	0.5	1	0.96	0.86	7446.07	2013.33
10	0.5	1.2	0.96	0.86	6665.47	1724.5
11	0.5	1.4	0.96	0.86	6138	1541.87
12	0.5	1.6	0.96	0.86	5966.7	1436.78
13	0.6	0.6	0.96	0.86	9473.97	2902.32
14	0.6	0.8	0.96	0.86	7878.67	2181.9
15	0.6	1	0.96	0.86	6797.14	1779
16	0.6	1.2	0.96	0.86	6127.46	1542.5
17	0.6	1.4	0.96	0.86	5961.73	1420.92
18	0.6	1.6	0.96	0.86	5909.22	1369.04
19	0.7	0.6	0.96	0.86	8859.84	2591.98
20	0.7	0.8	0.96	0.86	7268.21	1949.82
21	0.7	1	0.96	0.86	6242.86	1601.67
22	0.7	1.2	0.96	0.86	5975.69	1430.93
23	0.7	1.4	0.96	0.86	5910.61	1430.93
24	0.7	1.6	0.96	0.86	5874.52	1348.92
25	0.8	0.6	0.96	0.86	8284.39	2336.97
26	0.8	0.8	0.96	0.86	6688.87	1762.92
27	0.8	1	0.96	0.86	6030.14	1479.75
28	0.8	1.2	0.96	0.86	5925.76	1375.26
29	0.8	1.4	0.96	0.86	5877.69	1349.13
30	0.8	1.6	0.96	0.86	5851.69	1347.69

the flood modelling process, the treatment of both topography and surface friction represent sources of uncertainties. However, in this study, focus is given to the hydrologic uncertainties in the rainfall run-off model of the tropical storm and as such, topographic and friction representation uncertainties are treated in a deterministic way. Bathymetric data for both rivers and lagoons were provided by the National Water Commission and the authority in charge of the Port of Tampico, while topographic data were derived from the SRTM DEM. On the other hand, it is recognised that in river floodplains, the hydraulic resistance may be conceptually divided into several zones and the level of detail at which this process can be represented is dependent on the scale of the simulation and the available data used for characterising the floodplain (Mason *et al.*, 2003). However, because of the difficulty in justifying the roughness parameterisation along the floodplain and following conclusions by Pedrozo-Acuña *et al.* (2012b), whom showed that the inundation extent does not change significantly when varying the Manning number for the floodplain and the river channel, we define a value of $n = 0.04125$ m$^{1/3}$/s for the floodplain, while for the river channel, a constant value of $n = 0.03125$ m$^{1/3}$/s is utilised. It should be noted that the inundation extent to be generated through the forcing of different hydrographs will be contrasted against the available satellite images of the event.

Model boundary conditions

An overview of the selected numerical domain is presented in Figure 8, where the three set boundary conditions are identified: (1) an input hydrograph is set at the Pánuco river entrance (blue dot), (2) at the Tamesí river entrance (green dot) and (3) Pánuco's river mouth (red dot). The location of the first boundary condition is at the south of the domain where the lower Pánuco river starts; the second boundary is placed at the north of the domain at the entrance of the Tamesí river, and the third boundary defines the temporal variations of water level at Pánuco's river mouth, which in this study are determined in terms of the astronomical tide, plus the storm surge water level registered during the incidence of the tropical storm.

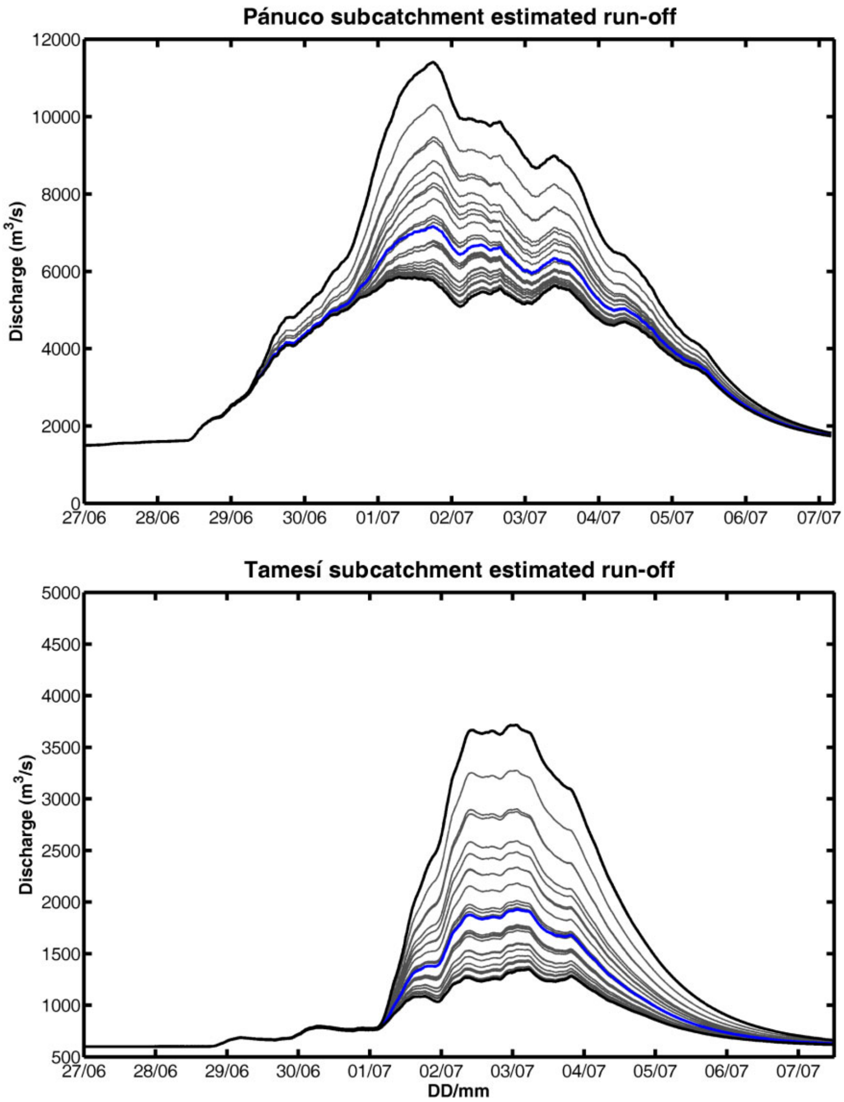

Figure 7 Hydrographs with uncertainty bounds (maximum and minimum) estimated for both subcatchments Pánuco and Tamesí.

For the characterisation of the tropical storm Arlene, the numerical model set-up is fixed apart from the definition of input boundary conditions for the river flows (Pánuco and Tamesí). For these, the spaghetti plots determined for both rivers are used in the definition of input discharges. The purpose of this is to evaluate for a known extreme event (tropical storm Arlene), the propagation of hydrological uncertainties from the determination of a given run-off to the results in terms of flood extent.

The different hydrographs are employed as input boundary conditions for the 2D hydrodynamic model set-up. For the definition of probabilities for a given run-off within the ensemble of both rivers, we determined the use of equal probability in both streams, which gave as a result pairs of hydrographs for both Pánuco and Tamesí with the same probability within the ensemble. In this way, the procedure will allow the generation of valuable information on the effects of hydrological uncertainties in the prediction of flood extent.

Results

The model results generated for the incidence of tropical storm Arlene enabled the determination of probabilistic flood maps for this event. We utilised the 30 hydrographs generated for both rivers. For each of these numerical runs, a flood map is obtained and the affected area is estimated. The comparison against the satellite imagery is carried out at two different time steps during the incidence of the event on the 6th of July 2011 and closer to the passage of the whole hydrograph on the 10th of July 2011. Although it is known that the application of visible imagery to flood mapping could be hampered by cloud cover during floods, in this case,

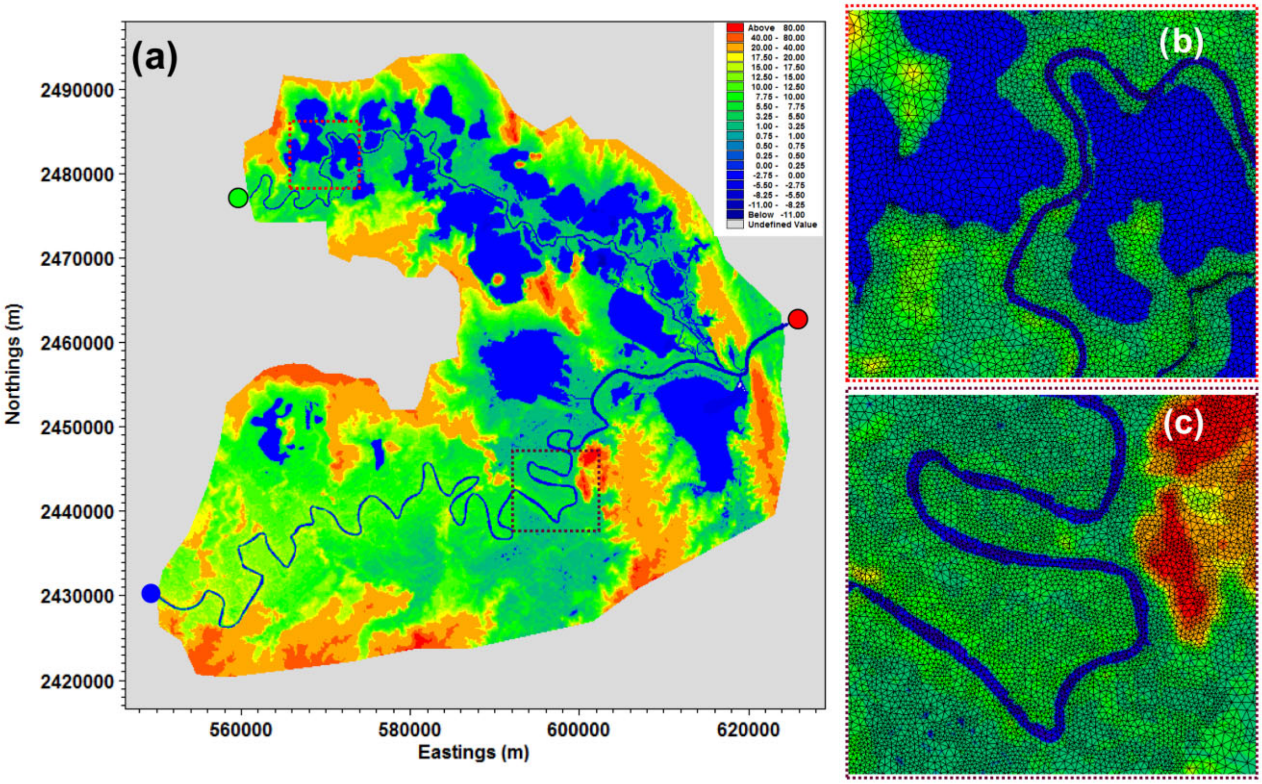

Figure 8 Numerical domain with contour elevations in meters and boundary conditions. Pánuco river: blue dot; Tamesí river: green dot; Pánuco river mouth: red dot (panel a) and two zooming details of the selected model discretisation (b – Pánuco river; c – Tamesí river) (flexible mesh).

the improved weather conditions few days after the passage of the tropical storm made available the use of optical imagery. As pointed out by Schumann *et al.* (2009), a possible alternative to flood mapping during bad weather conditions is given by the use of radar imagery.

Figure 9 presents the comparison of resulting flood maps for the 6th of July 2011 against the satellite image acquired for that date. Notably, the estimated flooded area is well represented by the proposed methodology, and the observed pattern of affected areas is found to be similar to that reproduced by the envelope of all realisations. Permanent bodies of water, such as rivers and lagoons, are illustrated in the results with a dark blue colour; this is done to show in a clearer way the probabilities of inundation from a given flood scenario. A detailed observation of the probabilities of flooded areas indicate that the highest likelihood of inundation is manly associated to both margins of the Pánuco River. Indeed, these regions are reported flooded in the satellite image in panel (a). Additionally, only high probabilities are reported at the south of the numerical domain, on the right bank of the river Pánuco. In contrast, the left bank of the river reports areas with less probability of inundation for this event. Especially in the body of water known as Marland lagoon (bottom left corner), at this location, several probability envelopes are identified within the range between 10% and 50% likelihood of occurrence. The region close to the lagoon appears flooded in the satellite image; this fact illustrates the advantages of generating a probabilistic estimate of an affected area, a region that is reported with a probability of inundation of 50% may well result flooded during the real emergency. This type of information paves the road towards the generation of better flood management strategies for this river, enabling for example, better emergency planning through the design of evacuation routes.

On the other hand, the probabilities of inundation reported for the river Tamesí are mainly located in the region of the upper part of the river, which indeed appears flooded in the satellite image. Notably, the adverse effects of the flooding in this region produced by the incidence of the tropical storm Arlene were concentrated on the river Pánuco.

It should be noted that the methodology utilised in this study contains more uncertainties that were not considered in the generation of a flood extent map. However, the comparison of the flood extent obtained from this analysis, against that observed in the satellite image, provides confidence in the selected approach. It is reflected that within the current body of the knowledge, bounded with a great deal of

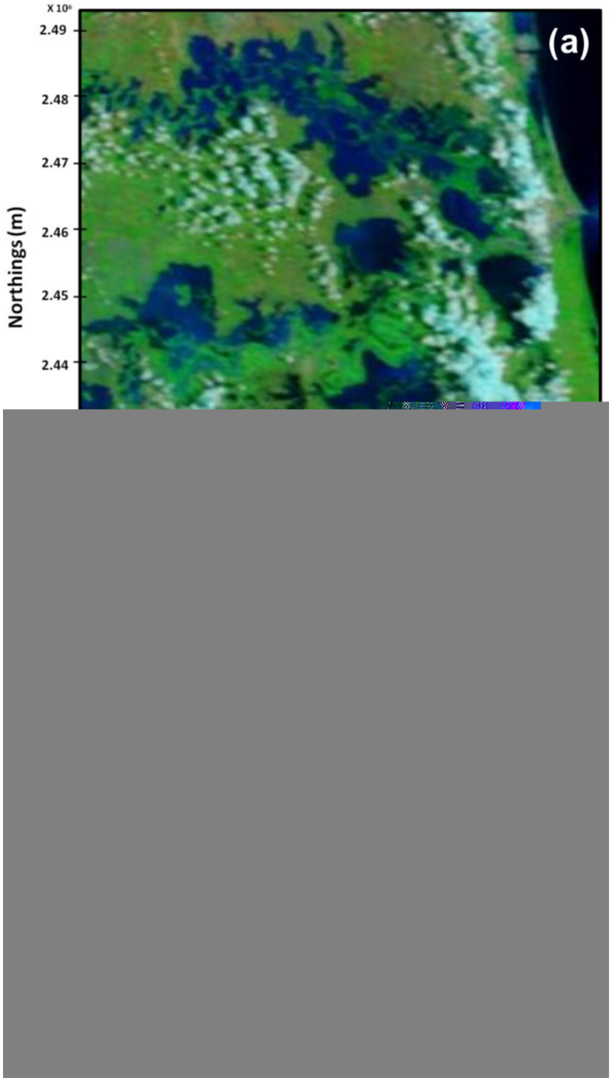

Figure 9 Satellite image of the inundation extent in the lower Pánuco river basin registered for the 6th of July 2011 (panel a) and probability of inundation estimated with the methodology (panel b).

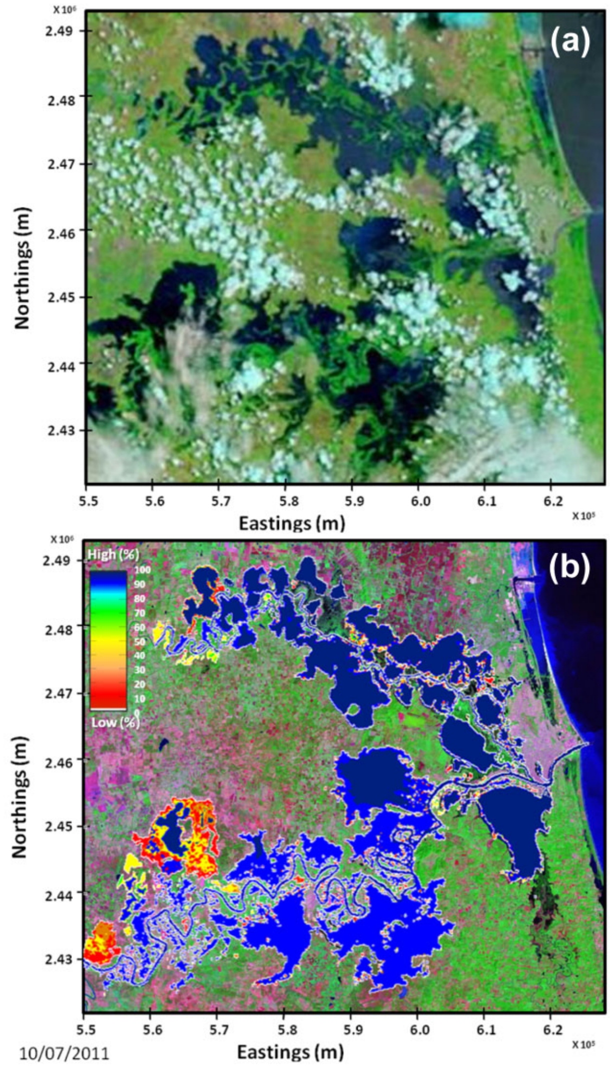

Figure 10 Satellite image of the inundation extent in the lower Pánuco river basin registered for the 10th of July 2011 (panel a) and probability of inundation estimated with the methodology (panel b).

uncertainty, naturally led us into precautionary and robust approaches as a consequence of acknowledging these deeper uncertainties. In the case of flood inundation modelling, a possible response to such level of uncertainty is to adopt the 'precautionary principle' (European Environment Agency, 2001). This is to favour the preventive action in the production of methodologies that evaluate flood extension with some level of confidence, without waiting for firm scientific evidence to determine a clear-cut answer of affected areas. It is reflected that it is better to evaluate the propagation of hydrological uncertainties in the rainfall run-off estimation and to inform their effect on the determination of an affected area, than continuing promoting the deterministic prediction of such events. As Stirling (2007) points out, precaution arises as part of the risk assessment rather than being part of risk management.

In order to analyse the temporal evolution of the flood inundation probabilities, Figure 10 presents the comparison of the satellite image against calculated results of inundated area for the 10th of July 2011. This date is selected as it comprises the final stage of the tropical storm incidence on the system, in other words when some drainage of both rivers is observed. Again, the observed pattern of affected areas in the satellite image is found to be similar to that reproduced by the envelope of all realisations. In the region close to the river mouth, some drainage of the excess volume of water is identified. However, the probabilities of flood

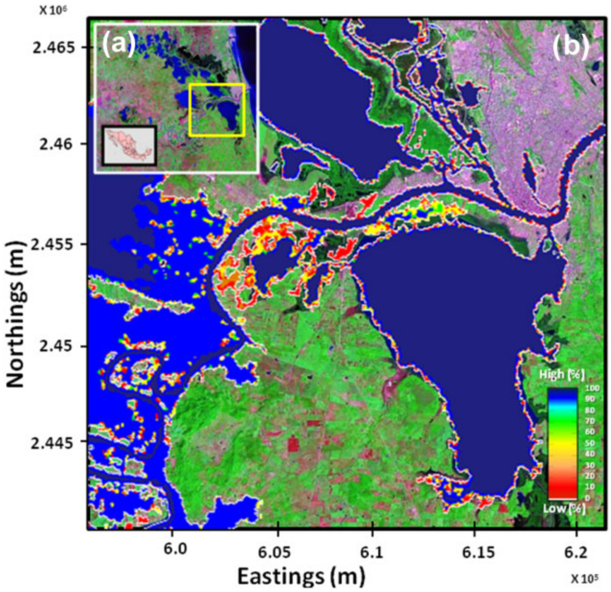

Figure 11 Zoom to the probability of inundation for the 6th of July during the incidence of the tropical storm Arlene in the region close to the junction of both rivers Pánuco and Tamesí (panel a – location of the area within the system; panel b – result).

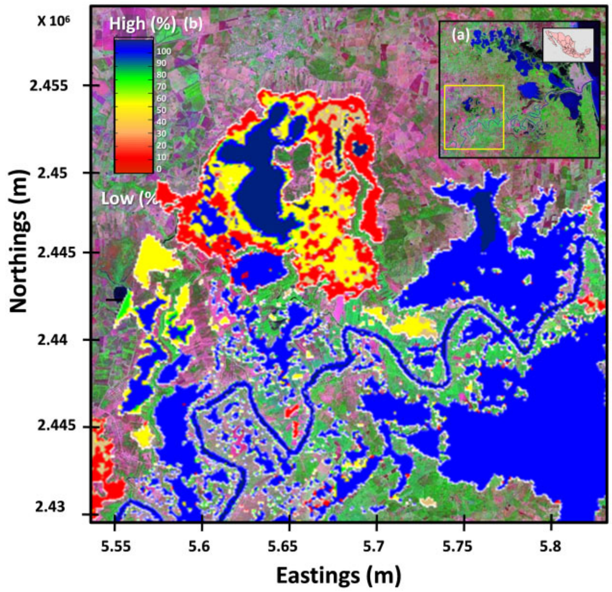

Figure 12 Zoom to the probability of inundation for the 6th of July during the incidence of the tropical storm Arlene in the region close to input boundary for the Pánuco river (panel a – location of the area within the system; panel b – result).

inundation indicate a similar story to that shown in Figure 9, with highest likelihood of inundation in both margins of the Pánuco River. Moreover, these areas along the Pánuco River appear completely inundated in the satellite image reported in panel (a) of Figure 10. The observed probabilities in the Tamesí River and Marland lagoon are conserved.

Figures 11 and 12 illustrate for the results of the 6th of July 2011, a zoom of the results to the regions of the system where flood inundation probabilities present a clear variation. These are the Marland lagoon and the confluence of both rivers Pánuco and Tamesí. Figure 11 shows results close to the Marland lagoon, where an evident difference in estimated flood inundation probabilities is depicted. The comparison against the size of the real inundation reported in panel (a) of Figure 9 indicates that the methodology is able to inform the level of exposure of this region with some likelihood. Figure 12 displays the results for the area located in the vicinity of the confluence of both rivers (Pánuco and Tamesí), where some probabilities of inundation are associated with small villages located at the Pánuco's river banks.

The observed comparisons at the selected times during the incidence of tropical storm Arlene provide confidence in the performance of the selected methodology. The purpose of these numerical experiments is the enhancement of the understanding of how hydrologic uncertainties are transported and can be represented in a flood extent estimation exercise during the occurrence of extreme conditions. The combination of field and elevation data with a distributed hydrologic model and a standard 2D model is robust enough to represent the real consequences observed during the passage of a tropical storm. It is anticipated that the use of these pieces of information are crucial for a better management of the consequences associated to this type of events. In particular, the selected approach can be seen as a first iteration in the production of a fully quantified approach to the analysis of flood risk, which arises from the consideration of hydrological uncertainty, where there are doubts about how the earth system works or its current state (e.g. soil saturation), which in turn produces increased uncertainty about what may happen in the future and what actions might be appropriate now.

Conclusions

The present study represents an effort to evaluate the effects of the hydrological uncertainty in the results of flood extent estimates observed during the incidence of a tropical storm in a major river of México. For this, the methodology was comprised of field measurements, elevation from an SRTM data source, a distributed hydrological model and a standard 2D numerical model. Uncertainty was considered in the distributed hydrological model through the estimation of possible hydrographs from precipitation data, registered during the incidence of an extreme event. This enabled the derivation of a number of possible hydrographs that could represent the expected run-off for this precipitation event. The resulting hydrographs were utilised in a 2D hydrodynamic model to derive different flood maps enabling the estimation of uncertainty bounds to a model prediction of flood inundation. The characterisation of the run-off by multiple possibilities opened the door to a probabilistic estimation of flood maps, which in turn allows the evaluation of uncertainty propagation to the estimated flood maps. This represents a step forward towards an improvement on the generation of better social communication of the risk to the affected communities, which is anticipated to enable long-term planning for flood damage reduction to downstream communities located in the affected floodplains.

It was shown that the estimated flooded area by the proposed methodology at two different stages of the event were similar to those observed in the satellite imagery. Results indicate that highest probabilities of inundation are associated to both margins of the Pánuco River. This fact illustrates the advantages of generating a probabilistic estimate of a flooded area by the incidence of an extreme event. The ability to provide a probabilistic estimate of inundation between 30% and 50% to both, decision makers and the society, opens the door for a better management of these events. For example, by changing when to issue an alert; from a binary flag (flooded versus not flooded) to a probability of affectation, which represents the embedded uncertainty in the estimates. This type of information paves the road towards the generation of better flood management strategies for this river, enabling for example, better emergency planning through the design of evacuation routes.

In accordance with observations during the incidence of the tropical storm Arlene in 2011, high probabilities of inundation for this event were shown to be associated to the river Pánuco instead of the other stream known as Tamesí. These results provide confidence in the selected approach for the estimation of probabilities of inundation.

On the other hand, it should be noted that the approach taken here is exposed to more uncertainties that were not considered in this investigation. However, in order to response to such level of uncertainty, we adopt the 'precautionary principle' by favouring preventive action in producing methodologies that evaluate flood extension with some level of confidence, without waiting for firm scientific evidence to determine a clear-cut answer for the identification of affected areas.

In particular, the selected approach which considers hydrological uncertainty can be seen as a first iteration in the production of a fully quantified approach to the analysis of flood risk, especially where there are doubts about how the catchments react to a given precipitation event (e.g. initial state, soil saturation), which in turn produces increased uncertainty about what may happen in the future and what actions might be appropriate now. This promotes the inclusion of this type of methodologies as part of the risk assessment rather than being part of risk management.

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