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

ENSEMBLE PREDICTION OF FLOOD MAPS UNDER UNCERTAIN CONDITIONS

J. P. Rodriguez-Rincón[1], A. Pedrozo-Acuña[1], R. Domínguez-Mora[1]
1. *Institute of Engineering, National Autonomous University of México*

ABSTRACT: Hydro-meteorological hazards can have cascading effects and far-reaching implications on water security, with political, social, economic and environmental consequences. Millions of people worldwide are forcibly displaced as a result of natural disasters, creating political tensions and social needs to support them. These events observed in developed and developing nations alike, highlight the necessity to generate a better understanding on what causes them and how we can better manage and reduce the 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. Thus, it is necessary to somehow consider and inform how current limitations in the knowledge affect a given prediction.

Having this in mind, the work in this paper develops a cascade modelling approach for the generation of more reliable and useful flood maps. This involves the use of a Numerical Weather Model, a rainfall-runoff model and a 2D hydrodynamic model. Uncertainty is considered in both the meteorological and hydrological models through the estimation of ensemble precipitation scenarios and spaghetti plots. The characterisation of the runoff by multiple possibilities, opens the door to a probabilistic estimation of affected areas, which in turn allows the evaluation of uncertainty propagation to an estimated flood map. The methodology is enriched with the use of field data of high quality, comprised by data from a field campaign, automatic gauging stations and LiDAR data for an accurate representation of topographic elevation. The presented approach is useful for both, the reduction of epistemic uncertainties and the generation of flood management strategies through probabilistic flood maps. The approach is applied to a region with a high precipitation rate in Mexico, expecting that generated results would be useful in the design of more effective flood management strategies.

Key Words: uncertainty, flood risk, ensemble, flood map, model cascade

1. INTRODUCTION

It has been internationally acknowledged that both coastal and fluvial floods remain the most frequent and devastating natural hazards. Recently, the evaluation of flood risks has been receiving a great deal of attention due to the increment in the number of extreme flood events registered around the world (EM-DAT, 2011). The incorporation of ensemble prediction systems (EPS) whose outputs provide the most important basis for a probabilistic approach to weather forecasting is considered useful for the accurate generation of day-to-week flood forecasts, in all time scales.

In hydrology, the utilisation of meteorological ensemble forecasts has paved the road towards a new approach to the forecast of extreme events. Their use has enabled the consideration and study of epistemic uncertainties when determining a certain level of precipitation and flood (Bartholmes and Todini, 2005; Cloke and Pappenberger, 2008). Indeed, ensemble forecasting studies of precipitation have revealed the presence of important sources of uncertainty (Bukovsky and Karoly 2009; Liguori et al. 2012). Some of these sources of uncertainty have been identified and include: model choice, initial and/or boundary conditions, and any number of physics packages including cumulus parameterization, microphysics and planetary boundary layer (PBL) parameterization. Despite this, it has been acknowledged that an ensemble forecasting approach provides an improvement of the skill when comparing with an individual deterministic one. The ensemble forecasting method aims to predict the probability of future events as accurately as possible, in addition it provides a measure of the forecast uncertainty and reliability (Cloke et al. 2013).

For operational flood forecasting purposes, coupling hydro-meteorological prediction systems with hydrological and hydraulic models has been the object of recent research (Pappenberger et al., 2011; Demeritt et al., 2010). While such integrated flood forecasting schemes have drawn the interest for decision makers, inherent uncertainties in the predictive models usually can lead to false flood alerts or inefficiently predict potential flood areas. However, as prediction systems become more complex there is also an increasing need for a more rigorous and structured guidance of what actions to take in specific situations and how to interpret forecasts best (Zappa et al., 2013; Demeritt et al., 2013; Pappenberger et al., 2013).

The purpose of this investigation is to study the propagation of epistemic uncertainties from the meteorological model to a given flood map. For this, we utilize a cascade modelling approach comprised by a Numerical Weather Prediction Model (NWP), a rainfall-runoff model and a standard 2D hydrodynamic model in combination with high-quality data (LiDAR, satellite imagery, precipitation). Uncertainty is considered in the meteorological model (Weather Research and Forecasting model) using a multi-physics ensemble technique considering sixteen parameterization schemes for an extreme event registered in Mexico in 2013.

2. CASE STUDY

Figure 1 presents the selected study region in Mexico, where the left panel shows the location within the southern part of the country and the right panel illustrates a zoom to the affected area, where the most intense precipitation was concentrated (Pedrozo-Acuña et al., accepted). The rivers that produced the extreme flood are identified as La Sabana and Papagayo, in the vicinity of the coastal lagoon known as Tres Palos.

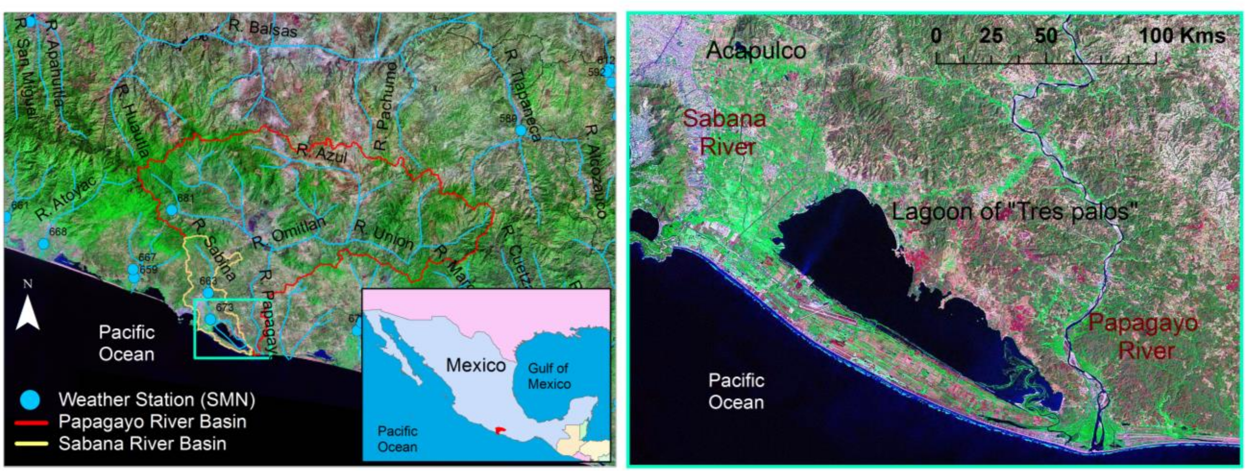

Figure 1: Study area localization in Mexico (left) and area most affected by the floods in September 2013, Acapulco-Diamante (right).

On the other hand, left panel of Figure 2 illustrates the main meteorological forcing of this event which was linked to the simultaneous incidence of two tropical storms along both Pacific and Atlantic basins. This Figure shows the tracks of both storms as they travelled over Mexican territory, the star represents the spatial location of both phenomena at the time of the picture was taken (15/09/2014). Very high precipitation rates were recorded (~800mm in two days) due to both events, Tropical Storm Manuel in the Pacific and Hurricane Ingrid (category 1) in the Gulf of Mexico. Both phenomena made multiple landfalls between the 13th and 20th of September. Right panels of Figure 2 show photographs of the registered impacts and damage to property and infrastructure.

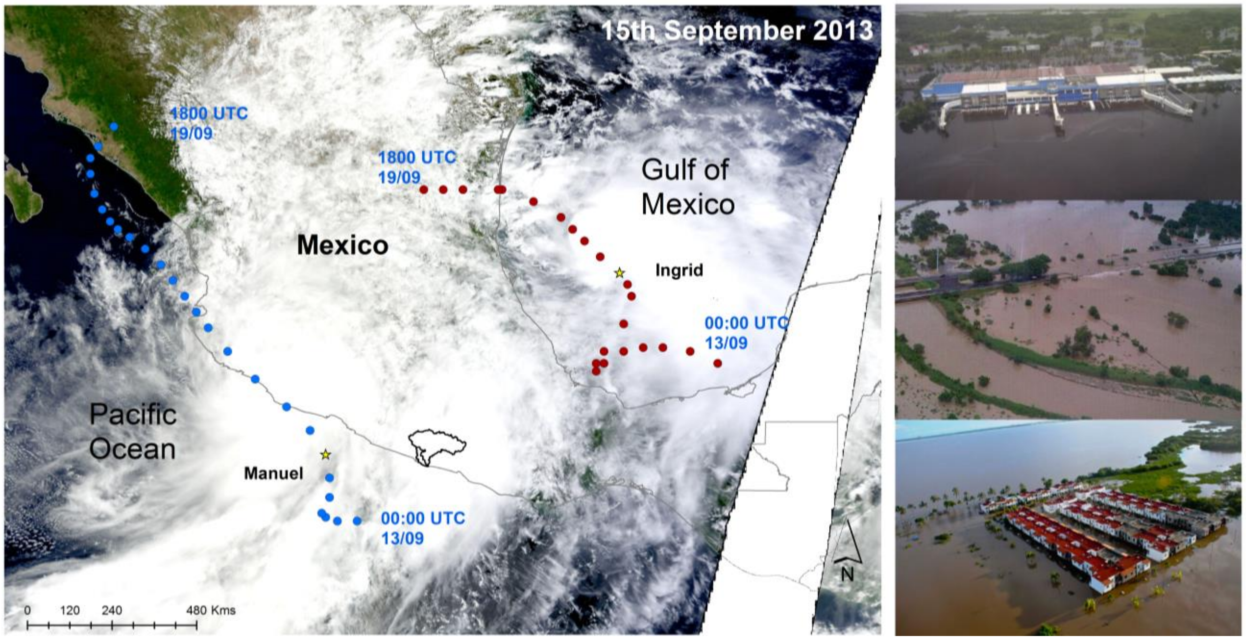

Figure 2: (Left) Satellite image of the 15th of September 2013 during the simultaneous occurrence of two tropical cyclones in Mexico (NASA Worldview). (Right) Affectations induced by the overflow of La Sabana River in the urban zone Acapulco-Diamante.

3. METHODOLOGY

The integrated approach used in this study is composed by the regional meteorological model known as WRF, a distributed hydrological code (MPE) and a standard 2D numerical model for the flood map estimation. Figure 3 shows the flow chart of the methodology used in this study. This process-based approach aims to replicate the connected system through a cascade of models representing the precipitation regime, the rainfall-runoff response of the Papagayo and La Sabana river basin and the behavior of the inundation in the floodplain. Uncertainty is considered in the WRF model using a multi-physics ensemble technique of twelve different parameterization schemes.

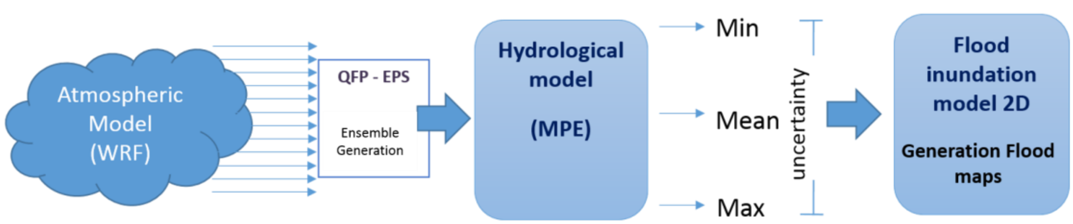

Figure 3: Flow chart of the different processes involved in the proposed methodology for the generation of probabilistic flood maps.

3.1 Meteorological model

In this study, we employ the Weather Research and Forecasting (WRF) modelling system to simulate the state of the atmosphere in order to obtain a prediction of precipitation associated to the meteorological phenomena (Skamarock et al. 2008). This numerical tool is a numerical weather prediction and atmospheric simulation system designed for operational forecasting, atmospheric research, and dynamical downscaling of Global Climate Models.

In order to capture the whole precipitation event, the simulation time period is defined from the 12th September 2013 to the 20th September 2013. For the definition of initial and boundary conditions we use data from NCEP Global Final Analysis (FNL) with a time interval of 6 hours.

The spatial domain comprises the whole Mexico as well as a part of Central America, covered with a 20-km horizontal grid spacing in the coarse domain and a finer nested domain of 4-km resolution (Fig. 4). In the vertical dimension, 28 unevenly spaced sigma levels were selected. The precipitation forecasts were compared against observations of precipitation from the National Weather Service in Mexico.

Left panel in Figure 4 illustrates for one of the simulations, the cumulative precipitation calculated by the meteorological model from the 12th to the 20th of September 2013, while right panels illustrate the model (green line) – data (gray line) comparison at some gauging stations within the region. It is observed that the model is indeed reproducing what was measured.

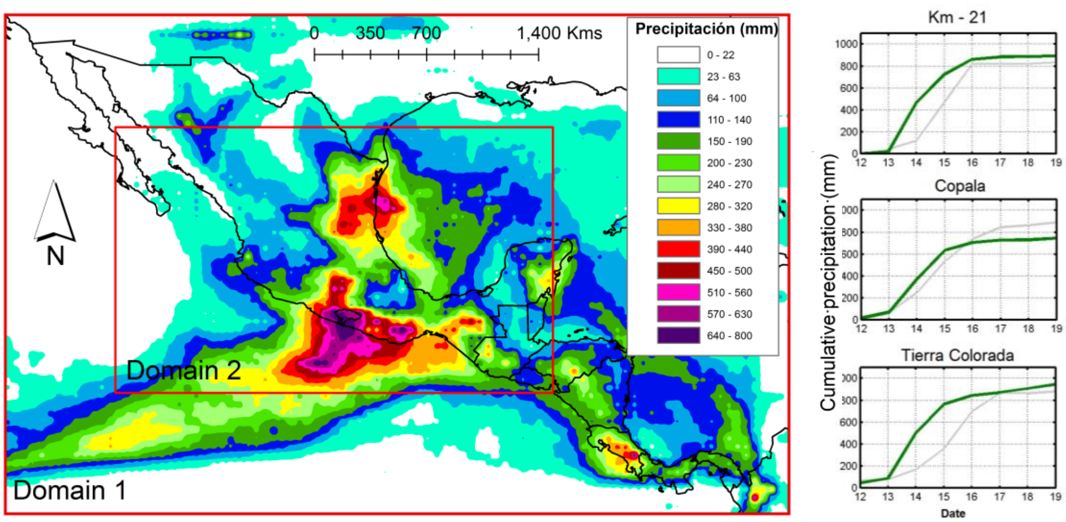

Figure 4: a) Cumulative precipitation map estimated by the WRF model and nested domains; b) Comparison of daily hyetographs b) Km21 Station; c) Copala station; and d) Tierra Colorada station (green lines – model results (Ensemble member 2); gray lines – measurements).

It should be borne in mind that it is well known that precipitation fields derived from this model may vary depending on the multi-physics parameterization that is selected. Therefore, we generate an ensemble of different precipitation fields for the event. This is done by means of a multi-physics technique proposed by Bukovsky and Karoly (2009). The ensemble is comprised of 16 different members constructed according to the selections of parameterizations reported in Table 1. It is shown that different model configurations are chosen to create the ensemble considering changes in convection, and surface layer physics parameterization schemes, generating plausible and realistic prediction of precipitation. The selection of the optimal combination of physics parameterizations was made following considerations put forward by the UCAR, as reported by Wang et al. (2010) and Jankov et al. (2005).

Table 1 Combinations of the WRF model Version 3.2 parameterizations selected to generate the ensemble prediction system.

Ensemble member	Micro-Physics	surface layer physics	Cumulus physics	Feedback/sst_update
1	WSM5	5-Layer TDM	Kain-Fritsch Eta	off/off
2	WSM5	5-Layer TDM	Kain-Fritsch Eta	off/on
3	WSM5	5-Layer TDM	Kain-Fritsch Eta	on/off
4	WSM5	5-Layer TDM	Kain-Fritsch Eta	on/on
5	WSM5	5-Layer TDM	Betts-Miller-Janjic	on/on
6	WSM5	Noah	Kain-Fritsch Eta	off/off
7	WSM5	Noah	Kain-Fritsch Eta	off/on
8	WSM5	Noah	Kain-Fritsch Eta	on/off
9	WSM5	Noah	Betts-Miller-Janjic	off/off
10	WSM5	Noah	Betts-Miller-Janjic	off/on
11	WSM5	Noah	Betts-Miller-Janjic	on/on
12	Thompson	5-Layer TDM	Kain-Fritsch Eta	on/off
13	Thompson	5-Layer TDM	Kain-Fritsch Eta	on/on
14	Thompson	Noah	Kain-Fritsch Eta	off/off
15	Thompson	Noah	Kain-Fritsch Eta	off/on
16	Thompson	Noah	Kain-Fritsch Eta	on/off

Figure 5 illustrates the 16 cumulative precipitation fields resulting from all simulations and for the simulation period between the 12^{th} and the 20th of September 2013. It is shown that clear differences arise in the southern region of Mexico, where the maximum precipitation was detected.

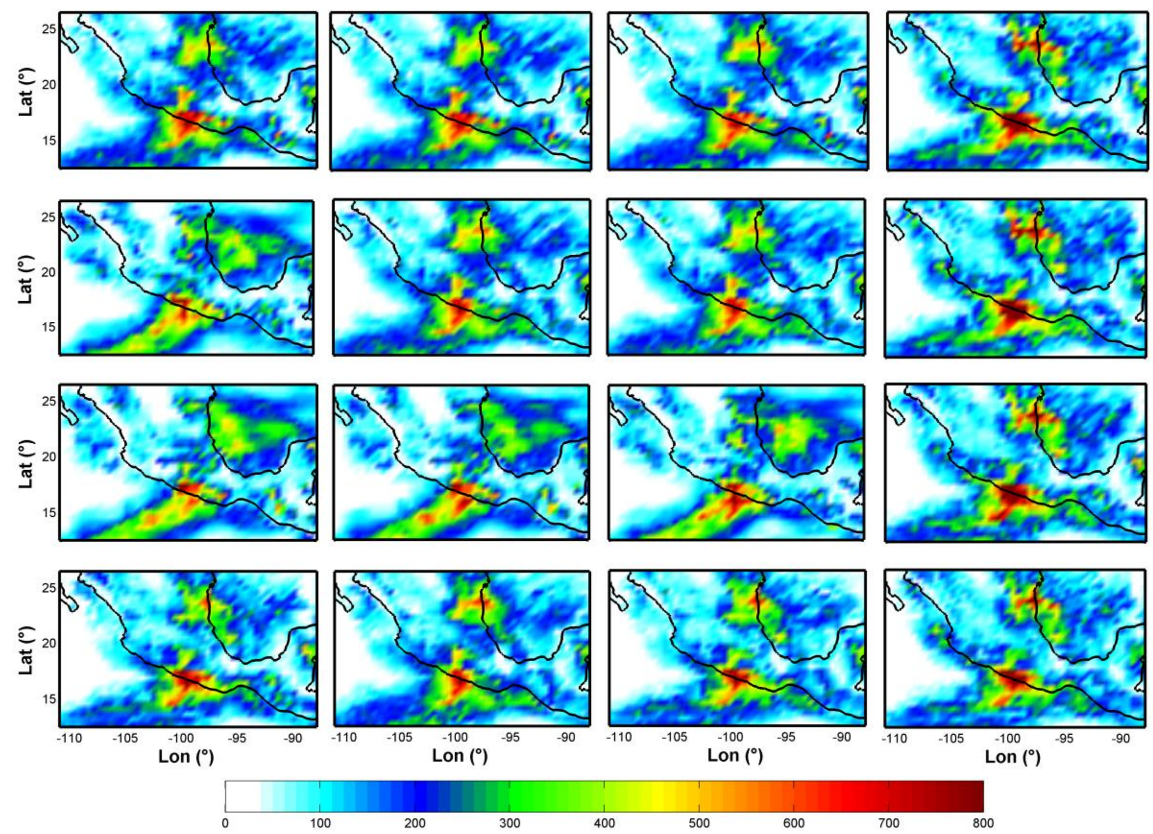

Figure 5: Cumulative precipitation fields for the 16 WRF ensemble members (mm).

Ensemble climate simulations have become a common practice in order to provide a metric of the uncertainty associated with climate predictions. There are several methods to generate these ensembles that can be broadly classified into three groups: initial (and/or boundary) condition perturbations, perturbation of physical parameters (physics ensemble) and the use of many different climate models (multi-model ensemble). Within the WRF modelling system, the use of different parameterizations allows the creation of an ensemble that limits the uncertainty in the predictions.

Figure 6 shows the daily cumulative precipitation over both river catchments (La Sabana and Papagayo) compared with measurements of weather stations. The uncertainty is represented in these plots by the spread that is registered in all the members of the physics ensemble. In both basins it is shown that the cumulative rainfall is within the uncertainty bounds of the modelled precipitation. Indeed, the cumulative recorded rainfall is well represented by the mean of all the ensemble members of the event, represented by the green line.

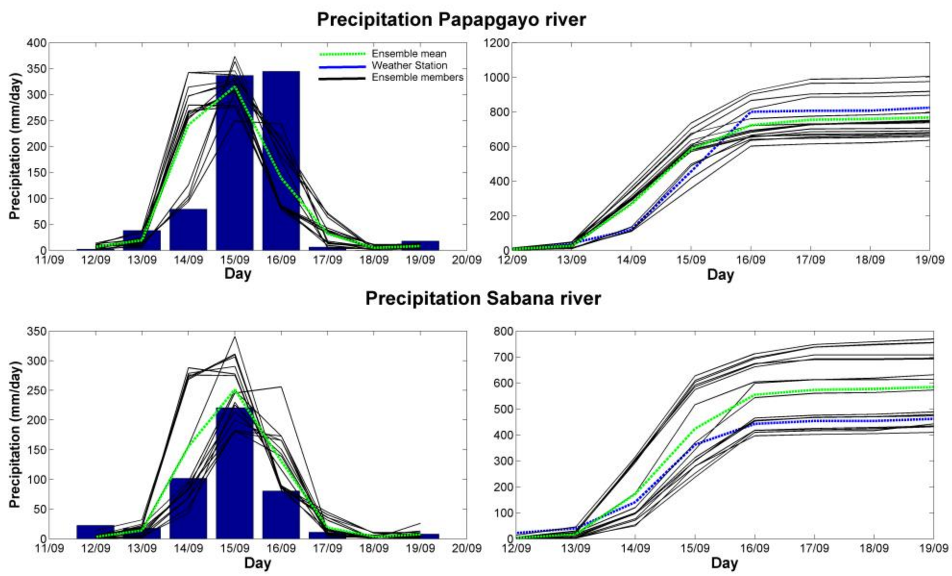

Figure 6: Comparison of cumulative precipitation WRF members vs Measurements.

3.1 Hydrologic model

The hydrological model employed for the generation of basin hydrographs was developed by the Institute of Engineering - UNAM (Domínguez-Mora et al. 2008). The numerical tool comprises a simplified grid-based distributed rainfall–runoff model, which has been developed to estimate the precipitation-runoff 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 runoff curve within the catchment are the hydrologic soil group, land use, edaphology and the flow paths. 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 runoff, the ratio between actual soil retention and its maximum retention potential is equal to the ratio between direct runoff and available rainfall. Secondly, the initial infiltration is hypothesised to be a fraction of the retention potential.

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 runoff in the whole basin is carried out through the addition of the runoff estimated in each cell to then construct a general hydrograph. The selection of the model is based on the success of this tool in other regions of Mexico (Rodríguez-Rincón et al. 2012, Pedrozo-Acuña et al 2013).

The input rainfall is given by the model results of each WRF ensemble members. In this way, we are able to propagate the meteorological uncertainty to the estimation of the runoff. For this, the parameters in the hydrologic model are fixed in the 16 simulations, which enables the generation of a spaghetti plot with different hydrographs for this extreme event. Figure 7 shows for both rivers the estimated hydrographs associated to the 16 WRF members, left panel illustrates those associated to the Papagayo river, while right panel shows those corresponding to La Sabana River. Notably, it is shown that the peak discharge in the Papagayo river is one order of magnitude bigger than that registered in La Sabana river. However, the largest flood damages in the region were registered in the latter.

Observed differences in the peak discharge computed for both rivers, are associated to the propagation of meteorological uncertainty from the estimation of a precipitation field with WRF to the estimation of a possible hydrograph. Despite the observed uncertainty in the peak discharge of both rivers, estimated values are in accordance to those determined from a post event survey.

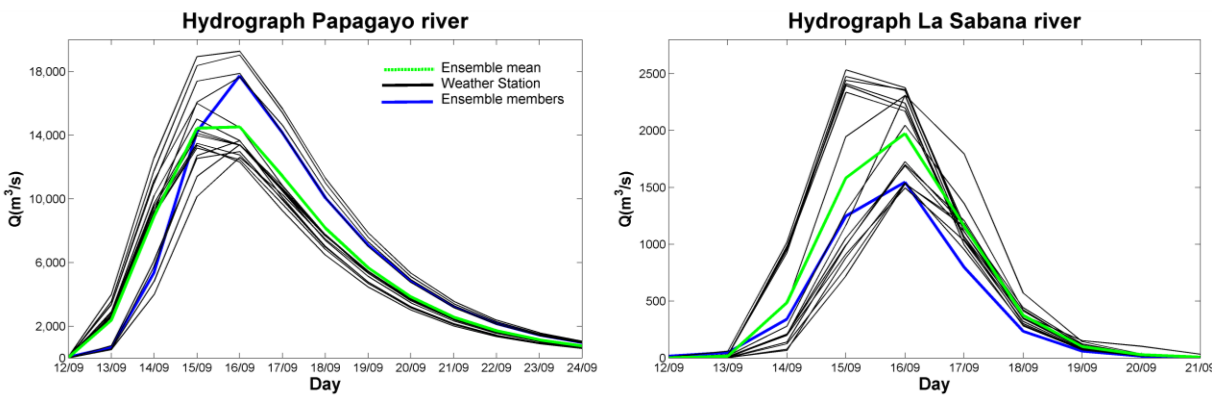

Figure 7: Hydrographs with uncertainty bounds (ensemble) estimated for both sub-catchments Papagayo and La Sabana.

3.2 **Flood inundation model**

The numerical tool to determine affected areas in the study area is the MIKE 21 flexible mesh (FM) flow model, which solves the Reynolds-averaged two-dimensional Navier–Stokes equations subject to the assumptions of Boussinesq and of hydrostatic pressure (DHI, 2014). The model solves the equations at the centre of each element within the domain. The computational mesh is represented by triangular elements of different size, five boundary conditions are considered: where the input hydrograph will be set in La Sabana River; 2) where the input hydrograph will be set in Papagayo River; there are defined through temporal evolution of the hydrographs estimated for both streams 3) at La Sabana´s river-mouth; 4) at Papagayo´s river-mouth; and 5) at the connection of the lagoon with the Pacific Ocean.

The numerical model setup 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 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 propagation of meteorological uncertainties to the flood map and as such, topographic and friction representation uncertainties are treated in a deterministic way. Bathymetric data for both rivers and lagoons was provided by the National Water Comission, while topographic data was derived from a LiDAR dataset.

For clarity, right panel of Figure 7 shows the superposition of three different flood maps, illustrated by the different tones of blue, which are derived from the ensemble members that are associated to the maximum, mean and minimum discharge in both rivers. For comparison the right panel incorporates the infrared satellite image corresponding to the 18th of September 2013, where it is evident that most of the area close to La Sabana River is heavily flooded.

Results in this figure, clearly indicate that for the same event there is a difference in the size of flood extent estimation from each ensemble member. Therefore, it is demonstrated that meteorological uncertainties in the estimation of precipitation, do propagate to estimation of an affected area by the event. For example, in the case of the maximum discharge, the flood extent identified by the hydrodynamic model comprises areas that do not appear flooded in the satellite imagery of the event (right panel). Notably, the difference between the flood extent estimated from the mean and the minimum envelope of the ensemble is minimal.

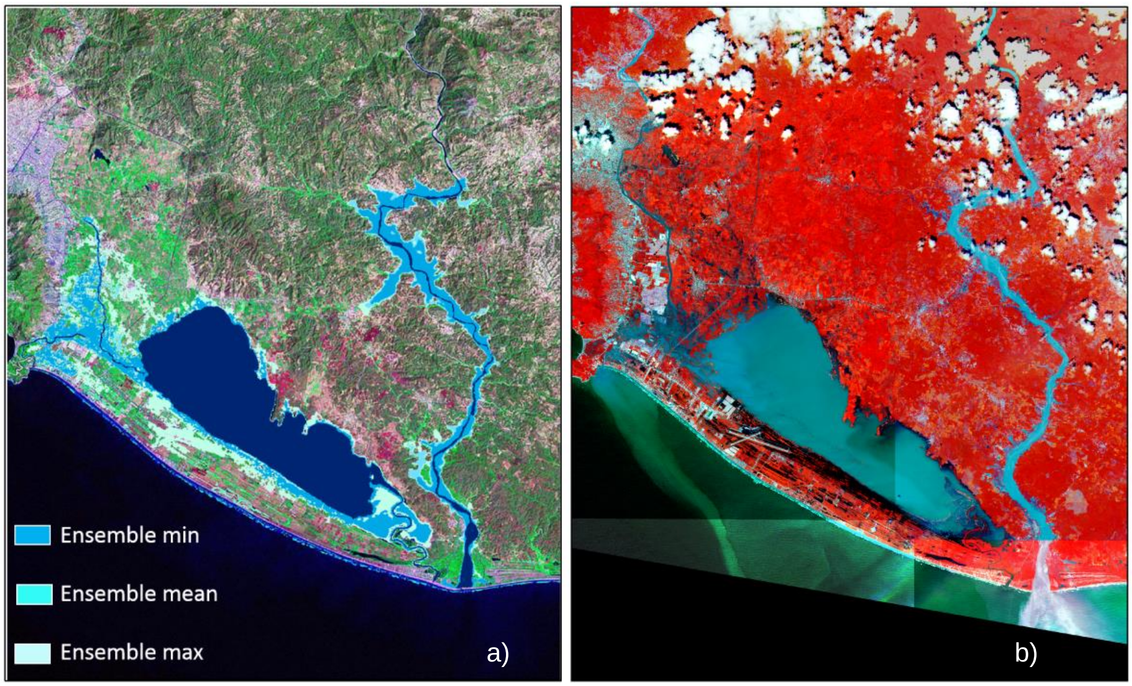

Figure 7: a) Flood maps estimated after the peak flow has entered the system, for maximum, minimum and mean hydrograph; b) Infrared satellite image of the flooded area in Acapulco-Diamante.

4. DISCUSSION AND CONCLUSIONS

The aim of this study was to generate a modeling framework that enabled a careful assessment of the error propagation, from a meteorological prediction to an estimated flooded area. For this, we introduced a cascade modelling approach to flooding, where different stages and scales of the event were incorporated (e.g Pedrozo-Acuña et al. 2013).

Uncertainty was considered in the meteorological model using a multi-physicis ensemble technique for the precipitation of an extreme event observed in 2013. Resulting precipitation fields were employed as numerical model inputs for a hydrological model with fixed parameters, enabling the generation of 16 hydrographs that represented the uncertainty propagation from the cloud to the stream flow.

For this case, it was shown that the meteorological uncertainty do propagates to the flood map. Specifically, differences were observed in the size of the affected area, which further confirm the great need of having a probabilistic framework for flood estimation. Additionally, affected areas identified with satellite imagery were in accordance to those obtained with this approach. Hence, highlighting its usefulness.

Although the integrated methodology here utilised is designed to reduce and constrain the uncertainties, it should be noted that there additional sources of uncertainties in the flood inundation modelling process, which could also be significant. Results indicate that the proposed numerical framework could be utilised as a robust alternative for the characterisation of extreme events in poorly gauged basins.

5. REFERENCES

Bartholmes and Todini: 2005: "Coupling meteorological and hydrological models for flood forecasting" *Hydrology Earth System Sciences*, 9, 333-346, doi:10.5194/hess-9-333-2005.

Bukovsky, M. S. and D. J. Karoly, 2009: "Precipitation simulations using WRF as a nested regional climate model" *Journal of Applied Meteorology and Climatology*, 48:10, 2152-2159.

Cloke, H. L. and Pappenberger, F., 2008: "Evaluating forecasts of extreme events for hydrological applications: an approach for screening unfamiliar performance measures" *Meteorological Applications*, 15(1), 181–197.

Cloke, H. L., Wetterhall, F., He, Y., Freer, J. E. and Pappenberger, F. 2013: "Modelling climate impact on floods with ensemble climate projections" *Quarterly Journal of the Royal Meteorological Society*, 139 (671 part B). pp. 282-297. doi: 10.1002/qj.1998

Demeritt, D., Nobert, S., Cloke, H., and Pappenberger, F., 2010: "Challenges in communicating and 5 using ensembles in operational flood forecasting" *Meteorological Applications*, 17, 209–222.

Demeritt, D., Nobert, S., Cloke, H. L., and Pappenberger, F. 2013: "The European Flood Alert System and the communication, perception, and use of ensemble predictions for operational flood risk management" *Hydrological Processes*, 27, 147–157, doi:10.1002/hyp.9419.

Domínguez M. R., Esquivel G. G., Mendez A. B., Mendoza R. A., Arganis J. M. L., Carrizosa E. E., 2008: *Manual del Modelo para pronóstico de escurrimiento*. Instituto de Ingeniería. Universidad Nacional Autónoma de México, D.F., México. ISBN 978-607-2-00316-3.

EM-DAT., 2011: *OFDA/CRED. International Disaster Database*, Universite Catholique de Louvain, Brussels, http://www.cred.be/emdat.

Jankov I., Gallus W.A., Segal M., Shaw B., Koch S.E., 2005: "The Impact of Different WRF Model Physical Parameterizations and Their Interactions on Warm Season MCS Rainfall" *Weather and Forecasting*, 20, 1048–1060. doi: http://dx.doi.org/10.1175/WAF888.1

Liguori S., Rico-Ramirez M.A., Schellart A. and Saul A. 2012: "Using probabilistic radar rainfall nowcasts and NWP forecasts for flow prediction in urban catchments" *Atmospheric Research*, 103, pp. 80 – 95.

López-Espinoza E. D., Zavala-Hidalgo J., and Gómez-Ramos O., 2012: "Weather forecast sensitivity to changes in urban land covers using the WRF model for central México" *Atmósfera*, 127-154.

Pappenberger F., Thielen J., and del Medico M. 2011: "The impact of weather forecast improvements on large scale hydrology: analysing a decade of forecasts of the European flood alert system" *Hydrological Processes*, 25, 1091–1113, doi:10.1002/hyp.7772.

Pappenberger F., Stephens E., Thielen J., Salamon P., Demeritt D., van Andel S. J., Wetterhall F., and Alfieri L. 2013: "Visualising probabilistic flood forecast information: expert preferences and perceptions of best practice in uncertainty communication” *Hydrological Processes*, 27, 132–146, doi:10.1002/hyp.9253.

Pedrozo-Acuña A., Breña-Naranjo J.A. and Domínguez-Mora R. accepted: “The hydrological setting of the 2013 floods in Mexico” *Weather*, Wiley and Sons.

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

Rodríguez-Rincón J.P., Breña-Naranjo J.A. and Pedrozo-Acuña A. 2014: “Uncertainty propagation in a hydro-meteorological approach: from the cloud to the flood map” 11th International Conference on Hydroinformatics, New York, USA, August 17-23, 2014.

Rodríguez-Rincón J.P., Pedrozo-Acuña A., Domínguez-Mora R., Reeve D.E. and Cluckie, I. 2012: “Probabilistic estimation of flood maps: An ensemble approach” FloodRisk2012: The 2nd European Conference on FLOODrisk Management, Rotterdam, The Netherlands, November 20-22, 2012.

Skamarock W.C., Klemp J.B., Dudhia J., Gill D.O., Barker D.M., Duda M.G., Huang X.-Y., Wang W. and Powers, J.G. 2008: *A description of the Advanced Research WRF version3.* NCAR Technical Note NCAR/TN475+STR, Boulder, USA.

Wang W., Bruyere C., Duda M., Dudhia J., Gill D., Lin H. C., and Mandel J., 2010: *ARW version 3 modeling system user’s guide. Mesoscale & Miscroscale Meteorology Division.* National Center for Atmospheric Research (July 2010), http://www. mmm. ucar. edu/wrf/users/docs/user_guide_V3/ARWUsersGuideV3. pdf, Boulder, USA.

Xuan Y., Cluckie I.D. and Wang Y. 2009: “Uncertainty analysis of hydrological ensemble forecasts in a distributed model utilising short-range rainfall precipitation” *Hydrology Earth System Science*, 13, 293–303, doi:10.5194/hess-13-293-2009.

Zappa M., Fundel F., and Jaun S. 2013: “A “Peak-Box” approach for supporting interpretation and verification of operational ensemble peak-flow forecasts”, *Hydrological Processes*, 27, 117–131, doi:10.1002/hyp.9521.