International Conference on Hydroinformatics

2014

Flood Risk From Extreme Events In Mexico

Adrián Pedrozo-Acuña

Pamela Iskra Mejía-Estrada

Juan Pablo Rodríguez-Rincón

Ramón Domínguez Mora

Fernando Jorge González-Villareal

11th International Conference on Hydroinformatics
HIC 2014, New York City, USA

FLOOD RISK FROM EXTREME EVENTS IN MEXICO

ADRIÁN PEDROZO-ACUÑA (1), P. ISKRA MEJÍA-ESTRADA (1), JUAN P. RODRÍGUEZ-RINCÓN (1), RAMÓN DOMÍNGUEZ-MORA (1), FERNANDO J. GONZÁLEZ-VILLAREAL (1)
(1): Institute of Engineering, National Autonomous University of México, Av. Universidad 3000, Mexico City, D.F. 04510, Mexico

Flooding is the most common and damaging natural hazard faced by civilization, and flooding threats are likely to increase given current climate change predictions that suggest more intense hurricanes and precipitation. In September 2013, severe flooding was registered in Mexico as a result of the rare simultaneous incidence of two tropical storms. In order to study the causes of this event, a cascade modelling approach comprised by meteorological, hydrological and hydrodynamic models is implemented. This approach enabled the assessment of the interaction of natural flows with urban infrastructure and planning in this region. It is shown land use changes have significantly increased the observed flood impacts during this event. Results highlight the importance of land-use planning as a key measure to reduce flood risk in Mexico.

INTRODUCTION

Flooding is a natural phenomenon which 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 (CRED), flooding in 2010 affected 178 million people (Guha-Sapir et al., [5]). Therefore is no surprise that all over the world, the implementation in practice of an explicitly risk-based approach to flood management has been stimulated by severe floods, for example in New Orleans (2005), on the Danube (2006), in Tabasco, Mexico (2007) and in England (2013). The severity of these events has underlined the upward trend in vulnerability to flooding (Munich Re Group, [7]).

However, as pointed out by Sayers et al. [8] the definition of flood risk is very diverse, with a range available meanings in use, often adapted to a particular need of decision-makers. The common ground observed in all definitions is that they think of risk as the combination of the chance of a particular event, with the impact that the event would cause if it occurred. Hence, it has two components: the chance (or probability) of an event occurring and the impact (or consequence) associated with that event.

Hall [6] highlighted the main challenges associated to the generation of a risk-based approach to flooding, amongst these he listed the natural variability of forcing (e.g. rainfall), the feedback between load and response, the spatial interaction within the system and the complex and uncertain processes that must be accommodated.

Flood risk is strongly dependent on the interaction between changes in the hydrological cycle and the human development. In consequence, it is of great interest to take preventive action through the communication of uncertain research results to decision makers. Recent events around the world indicate that a better communication between researchers, decision makers and society is pivotal for the generation of a successful disaster risk reduction strategy.

Mexico is no exception to the global trend, and flooding is currently the major and costly natural hazard, its geographical location make the country highly vulnerable to the strike of landfalling tropical cyclones along both Pacific and Atlantic basins (Pedrozo-Acuña et al. [10]). Recently, in September 2013, México suffered the simultaneous incidence of two tropical storms, Tropical Storm Manuel in the Pacific and Hurricane Ingrid in the Gulf of Mexico, made multiple landfalls between the 13th and 20th of September (Pedrozo-Acuña et al. [9]). Both systems affected 77% of Mexican territory with heavy rainfall producing landslides and severe flooding.

In order to study the causes of this disaster, an integrated methodology to estimate flood risk is utilised, see for example Rodríguez-Rincon et al. [12]. Uncertainties in the results are taken into account through the implementation of a cascade modelling approach, comprised by meteorological, hydrological and hydrodynamic models. These numerical tools are set up with field measurements (e.g. precipitation and bathymetry), and elevation data from a LiDAR-based DEM, enabling the representation and reconstruction of the whole event (from the cloud to the river). This approach enables the assessment of the interaction of natural flows with urban infrastructure and planning in this region.

This paper is organised as follows, the section Study area provides information with regards to the region and the meteorological conditions that generated the flood event; Methodology presents a description of the numerical approach comprised by numerical models of meteorology, rainfall-runoff and hydrodynamics. Model setup and results introduce the validation and results of this investigation. Finally, conclusions and future work are summarised in the last section.

STUDY AREA

The simultaneous occurrence of tropical storms Ingrid and Manuel, provides a crucial setting to the hydrological conditions observed during September 2013 across Mexico. According to Pedrozo-Acuña et al. [9] the most intense precipitation (due to tropical storm Manuel) was concentrated along the Southern Pacific coast of Mexico, where the touristic resort of Acapulco-Diamante is located (~700mm/48hrs).

Figure 1a presents the satellite image corresponding to the 15th of September when the most intense rainfall was registered in the southern coast of Mexico. The image shows tropical Storm Manuel in the Pacific and Hurricane Ingrid (category 1) in the Gulf of Mexico. The hydro-meteorological event left more than 45,000 homes damaged or destroyed and 192 human losses (AON Benfield, [1]).

The impacts associated to the incidence of this hydro-meteorological event are illustrated in Figure 1b, which displays an infrared satellite image of the region corresponding to the 18th of September, along with several photographs of the flooding. The satellite image corresponds to a date three days after the passage of the peak discharge in the rivers. It is shown that the severity of the affectations induced by the overflow of La Sabana river, is of great importance. The hydrologic setting of the region is quite complex as comprises two main streams (La Sabana and Papagayo) and a coastal lagoon (Tres Palos).

The 2013 floods in Mexico, were extreme, but according to Pedrozo-Acuña et al. [9] these were not statistically rare. In contrast, the registered impacts and damage to property or vital infrastructure, clearly determined the extreme of the hydro-meteorological event. On the other hand, this event demonstrated the complicated interaction between an environmental forcing and urban planning.

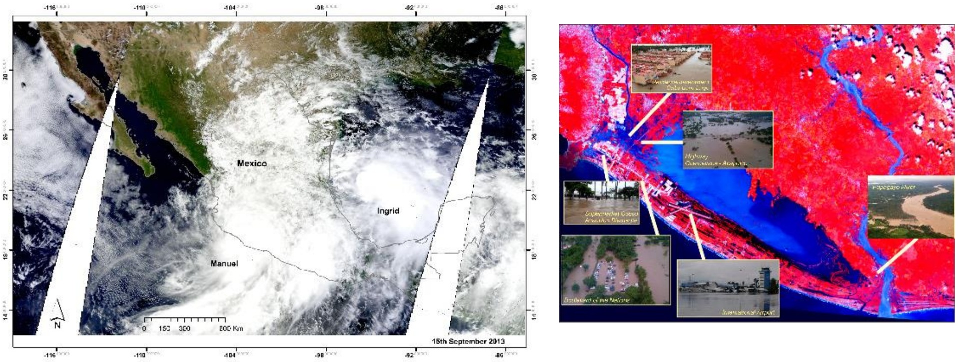

Fig 1. a) Satellite image of the 15th of September 2013 during the simultaneous occurrence of two tropical cyclones in Mexico (NASA Worldview), Manuel and Ingrid; b) Infrared satellite image identifying the flooded area on the 18th of September 2013 in Acapulco-Diamante.

This is clearly illustrated in Figure 2, where top row shows the localization of Acapulco-Diamante within Mexico (panel a) along with the observed impacts by the 18th of September 2013 (panel b). Middle and bottom rows of the same figure illustrate the temporal evolution of urban areas within La Sabana river floodplain. It is shown that between the years 2002 and 2013, the economic growth of the region was predominant in the determination of new land-use practices (i.e. more urbanization), which resulted in an increment of negative impacts after the incidence of the 2013 event. Indeed, one of the most important lessons learnt from the 2013 event, is the urgent need for a better understanding of the link between land management and the observed impacts of flooding.

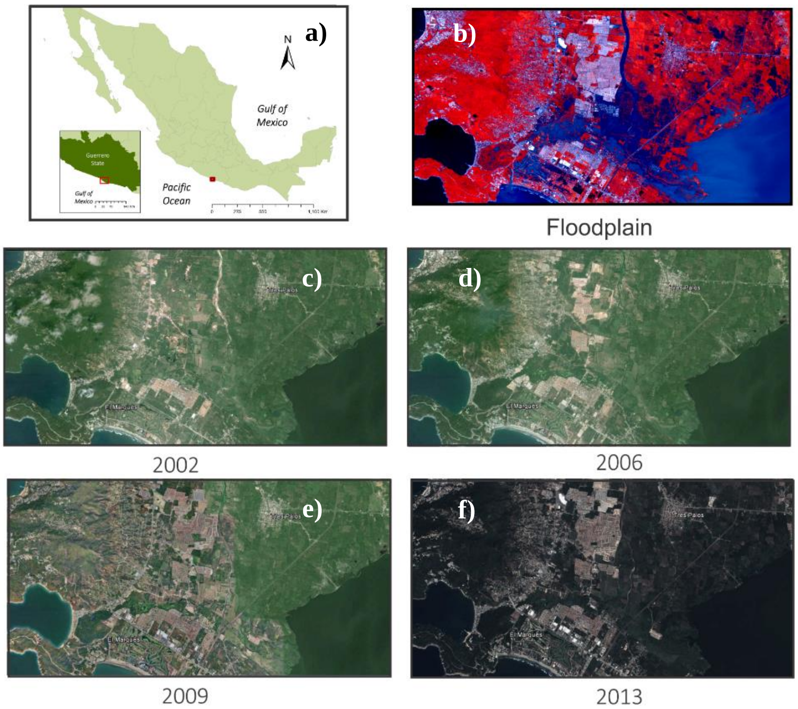

Fig 2. a) Study area localization in Mexico; b) Flooded area identified by infrared satellite imagery of the 18th September 2013; (c-f) Temporal evolution of urban development registered in Acapulco-Diamante during the 2002-2013 decade.

METHODOLOGY

The integrated approach used in this study is comprised by a cascade modelling of the entire flooding process, which includes a meteorological model (Weather Research and Forecasting, WRF), a distributed hydrologic model for the rain-runoff estimation (Domínguez-Mora et al. [3]), topographic elevation from a LiDAR data source and a standard 2D numerical modelling for the flood map estimation.

Meteorological model

The starting point is therefore comprised of the numerical reproduction of the weather conditions observed from the 12th to the 20th of September 2013. In this study, the Weather Research and Forecasting (WRF) modelling system is utilised to resolve the dynamics over high-resolution grids. The Advanced Research core of the Weather Research and Forecasting (WRF) model Version 3.2 is implemented. The WRF model is a next-generation mesoscale numerical weather prediction and data assimilation system, and is thoroughly detailed by Skamarock et al. [13]. For this study the model is carried out by means of two nested domains covering the entire country (See Figure 3a) and with a vertical discretisation comprised of 28 unevenly spaced sigma levels. The optimal combination of physics parametrisations was made with reference to those described by members of the University Corporation for Atmospheric Research (UCAR) (Wang et al. [15], Efstathiou et al. [4] Bukovsky and Karoly [2]). In order to set up the initial and boundary conditions of the simulation, data from the NCEP Global Final Analysis (FNL) at 6-hour intervals was used, simulations were initialized at 0000 UTC 14 September 2013, with a duration of 48 h.

On the other hand, panel b) of Figure 3 shows an example of the cumulative precipitation calculated by the meteorological model for those days when the precipitation was more intense (from the 14th to the 16th of September 2013). Notably, the southern Pacific region of the country, where Acapulco-Diamante is located, is enclosed by the highest precipitation values. The cumulative rainfall registered in this region is close to the 700mm in 2 days, which is similar to that registered by several gauging stations.

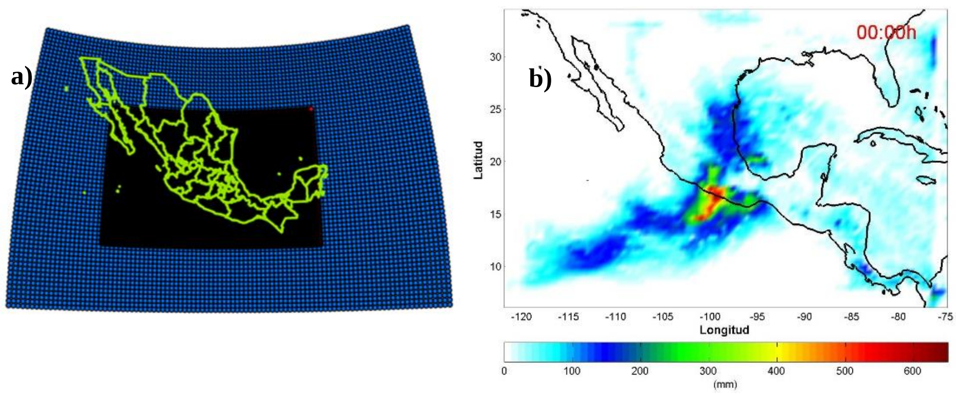

Fig 3. a) Nested domains in WRF blue area indicates the low resolution domain (19 km) and black area is the nested domain of (4 km); b) Cumulative rainfall from the 14th - 16th September 2013.

For the verification of results from the meteorological model, Figure 4 presents results comparing cumulative values of precipitation derived from the WRF model with daily observations from a number of locations around the Southern Pacific region of Mexico, where precipitation was most intense. Cumulative precipitation derived from the WRF is shown to be reliable at capturing those observed by the gauging stations. This comparison suggest that WRF significantly reproduces the meteorological phenomena, being able to capture the precipitation during the storm period. In summary, we consider that good results have been achieved with the WRF model. In addition, the output precipitation fields are of a temporal and spatial scale suitable for input into the distributed hydrologic models.

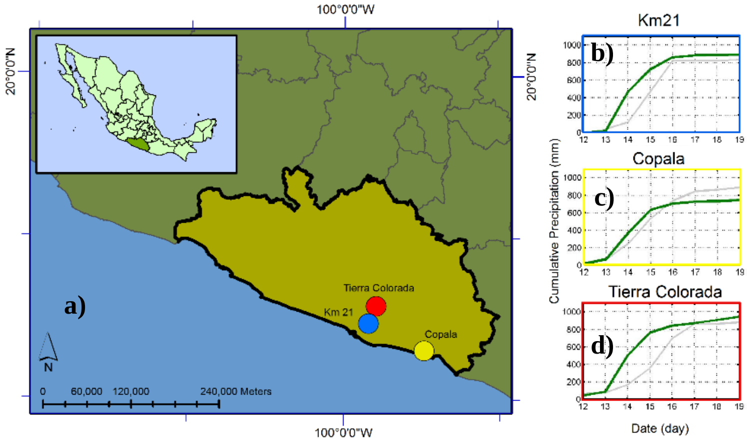

Fig 4. a) Localisation of gauging stations used for model validation; Comparison of cumulative precipitation from the 12th to the 19th of September 2013 at: a) Km21 Station; b) Copala station; and c) Tierra Colorada station (green lines – model results; gray lines – measurements).

Hydrological model

The hydrological model employed for the generation of basin hydrographs comprises a simplified grid-based distributed rainfall–runoff model, which has been developed to estimate the precipitation-runoff processes of dendritic water-shed systems (Domínguez et al. [3]). The model is based on the method of the Soil Conservation Service (SCS) (USDA, [14]) with a modification that enables the consideration of ground drying processes after the rain occurrence. The input parameters to determine a runoff curve are the hydrologic soil group, land use, edaphology and flow paths within the catchment.

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.

Figure 5 introduces the hydrographs computed in both basins within the study area (see Figure 1b). One corresponds to La Sabana river, which produced the largest flood impacts on urban areas and the Papagayo river to the East of Tres Palos lagoon.

Complementary, a post-flood survey was carried out by members of the Hydraulic Department of the Institute of Engineering at the National University of Mexico. This activity involved an identification of watermarks in the region, in order to reconstruct the peak flow value for the event (Pedrozo-Acuña et al. [9]). The best estimate of discharge through the Sabana River was of the order of 1000 – 1300 m3s-1. It is shown that the peak flow of La Sabana river is indeed in this order of magnitude. This enables the use of these hydrographs for an investigation of the affected areas after the passage of this hydro-meterological event.

Notably, the peak discharge of Papagayo river (East of Tres Palos lagoon) is larger than that registered in La Sabana (West of Tres Palos lagoon). However, there were more houses and commercial properties damaged alongside La Sabana, in comparison to those registered in Papagayo. This may be ascribed to a better hydraulic efficiency of the latter stream, which is indeed discharging the excess volume of water to the sea.

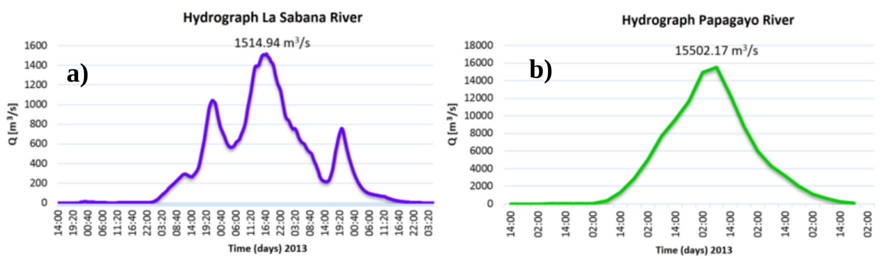

Fig 5. a) Estimated hydrograph for La Sabana River; b) Estimated hydrograph for Papagayo River.

Hydrodynamic model

The hydrodynamic model solves the Reynolds-averaged two-dimensional Navier–Stokes equations subject to the assumptions of Boussinesq and of hydrostatic pressure (http://www.dhigroup.com; DHI, 2014). The numerical discretisation of the study region is carried out considering both rivers, La Sabana and Papagayo, as well as their interaction with the coastal lagoon, Tres Palos (See Figure 6a). The computational mesh is presented in Figure 6a, where the five boundary conditions are considered: 1) where the input hydrograph will be set in La Sabana River (blue dot); 2) where the input hydrograph will be set in Papagayo River (green dot); 3) at La Sabana´s river-mouth (yellow dot); 4) at Papagayo´s river-mouth (orange dot); and 5) at the connection of the lagoon with the Pacific Ocean (red dot). The first two boundaries are defined through temporal evolution of the hydrographs estimated for both streams; while the rivermouths are determined as a temporal function of the induced water level by astronomical tide.

A bathymetric survey was carried out in both rivers as well as in Tres Palos lagoon, while the topography was defined through a LiDAR derived Digital Elevation Model with a spatial resolution of 5m, which ensures both accuracy and detail of the ground surface (See Fig. 6b).

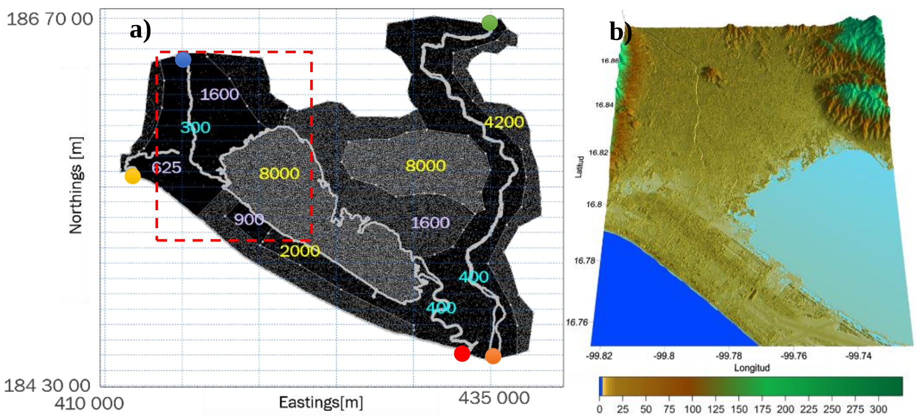

Fig 6. a) Illustration of the computational mesh utilised (numbers represent the maximum allowable area for an element within the region); b) LiDAR data (5m resolution) utilised for the definition of the topography.

Figure 7 presents the estimated flood map for the hydro-meteorological event registered in September 2013. Left panel shows the affected area as identified by satellite imagery while right panel introduces the results for the cascade modelling approach. Although there are some differences in the affected areas estimated by the numerical approach, it is interesting to note that the affected areas are properly identified, despite the non-linear flow processes occurring when a river goes out of bank.

Results shown provide a clear indication of the observed consequences associated to this event. It should be noted, that differences observed in this approach may be ascribed to uncertainties in the hydrological model to determine the discharge in both rivers.

Fig 7. a) Infrared satellite image of the flooded area in Acapulco-Diamante; b) Numerical result of flooded area.

CONCLUSIONS

The purpose of the investigation is to generate a numerical framework that enables an assessment of flooding impacts produced by an extreme event, from the cloud to the flood map. For this, we introduce a cascade modelling approach to flooding, where different stages and scales of the event are implemented. It comprises the integration of a cascade of models: meteorological, hydrological and hydrodynamic.

Despite the uncertainties in each interlinked model, and the uncertainty propagation from meteorological model to hydrological and hydrodynamic models, the outputs of the interlinked ensemble modelling framework are in accord with the reality of a recent flooding observed in Acapulco, Mexico.

On the other hand, it is recognised that large uncertainty exists in the magnitude, time and location of maximum peak discharge. Therefore, it is important to include the uncertainty estimate, as well as the error propagation within the framework when estimating a flooded area (Rodriguez-Rincón et al. [11]).

The September 2013 event discussed here was a significant event for the southern region of Mexico, however the impacts were clearly amplified by land-use changes resulting from economic growth of the region. The approach developed in this study is generic and is currently being utilised to estimate the flood and damage at other sites in Mexico. In view of the magnitude and ubiquity of the hydro-climatic change now under way, understanding the complexities of the interrelationships of natural and social domains is vital. On the other hand it is demonstrated that land-use changes in Acapulco have had a significant role in the increment of flood impacts during this event. This highlights the importance of land-use planning as a key measure to reduce flood risk in Mexico.

ACKNOWLEDGEMENTS

We are indebted to the Mexican Government, in particular to Secretaría de Hacienda y Crédito Público and Secretaría de Gobernación for the LiDAR data of Acapulco-Diamante utilised in this study, provided to the Institute of Engineering UNAM, under the project "Sistema de Cuantificación de Pérdidas, Control de Recursos y Análisis de Riesgos para el FONDEN (2012)".

REFERENCES

[1] Aon Benfield. September 2013 Global Catastrophe Recap Report. Impact Forecasting LLC, Aon Benfield, 2013: Chicago, IL.

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

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

[4] Efstathiou, G.A., Zoumakis, N.M., Melas, D., Lolis, C.J., Kassomenos, P. Sensitivity of WRF to Boundary Layer Parameterizations in Simulating a Heavy Rainfall Event using Different Microphysical Schemes. Effect on Large-Scale Processes. *Atmospheric Research*, Vol. 132-133, October-November 2013, 125-143pp.

[5] Guha-Sapir D, Vos F, Below R, with Ponserre S. *Annual Disaster Statistical Review 2011: The Numbers and Trends*. Brussels: CRED; (2012).

[6] Hall, J.W., Flood Risk Management: Decision Making Under Uncertainty. In: *Applied Uncertainty Analysis for Flood Risk Management*. Edited by: Keith Beven and Jim Hall, World Scientific (2014).

[7] Munich Re Group. *Natural Catastrophes 2006: Analyses, Assessments, Positions*, (2007), Munich.

[8] Sayers, P.B., Hall, J.W. and Meadowcroft, I.C. Towards risk-based flood hazard management in the UK, *Civil Eng*., (2002). 150, 36–42.

[9] Pedrozo-Acuña, A., Breña-Naranjo, J.A., Domínguez-Mora, R. The hydrological setting of the 2013 floods in Mexico. *subjudice*

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

[11] Rodríguez-Rincón, J.P., Breña-Naranjo, J.A., Pedrozo-Acuña, A., Uncertainty propagation in a hydro-meteorological approach: from the cloud to the flood map. *11th International Conference on Hydroinformatics*, 2014.

[12] Rodríguez-Rincón, J.P., Pedrozo-Acuña, A., Domínguez Mora, R., Reeve, D.E., Cluckie, I. Probabilistic estimation of flood maps: An ensemble approach. *FloodRisk2012, The 2nd European Conference on FLOODrisk Management*. (2012).

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

[14] USDA-SCS. *National Engineering Handbook*, Section 4 - Hydrology. Washington, D.C.: USDA-SCS, 1985.

[15] Wang, W., Bruyere, C., Duda, M., Dudhia, J., Gill, D., Lin, H. C., & Mandel, J.. *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.