ADVANCES IN FLOOD RISK ASSESSMENTS FOR DATA-LIMITED CHANGING ENVIRONMENTS

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ABSTRACT: Developing countries have a recognized increasing need for reliable flood risk assessment and demand novel approaches due to the complex and evolving nature of hydrological and socio-economic conditions, limited availability of data, and, in some cases, lack of permanent inter-institutional collaborative arrangements for the assessment of flood risk. In the framework of the Probabilistic Risk Assessment Program at The World Bank, advances have been made in the development of methodologies that allow the estimation of flood risk considering these challenges. The application of one of these methodologies was carried out in the City of Boquete in Panama, where complex orographic, geological, hydrologic and hydrodynamic conditions dominate. In particular, the Caldera River, which crosses Boquete, causes frequent flooding in the urban area of the city. At the same time, the Caldera River Basin is one of the most important economic areas of the region because of its high natural, agricultural and touristic value. The results of the analysis show the need to continue investing in simplified approaches to meet data availability and computer capabilities conditions as well as the value of considering uncertainty into flood risk assessment. The analysis also acknowledges the need to further examine a balanced approach that also integrates additional robust and advanced tools to appropriately take into account the complexity of flood hazard assessment. The Boquete project had the involvement and participation of national and local government agencies in charge of water resources management and engineering, including potential users of the results generated. Therefore, this experience also sought to identify and define collaborative approaches that would lead to the adequate application and communication of risk information and the sustainability of flood risk assessments in Panama.

Key Words: Probabilistic Flood Risk, Hazard, Vulnerability

1. INTRODUCTION

The Probabilistic Risk Assessment (CAPRA) Program at The World Bank supports the generation and application of disaster risk information to development programs and policies (Ramirez Cortes et. al, 2010). The Program focuses on building the capacity of sector government agencies, academic institutions, private companies and others in Latin America to design and perform probabilistic disaster risk assessments due to different hazards, including earthquakes, floods, and hurricanes, and integrate the generated information into decision-making processes to reduce risk (The World Bank, 2014). These projects are led and implemented by local organizations. The role of the Bank along this process, here referred to as technical assistance projects (TAP), are to work with local organizations to design the risk assessments based on the local context, expert institutions, their capacity, and data availability, and to provide targeted advisory services and customized trainings—the Bank primary role has been to fuel these processes throughout the region. Organizations in Costa Rica, El Salvador, Panama, Peru and other countries have partnered with the Bank and enjoyed this type of strategic support. Specifically in Panama, the Bank participated in the process of establishing and providing technical assistance to an interdisciplinary team formed to conduct a probabilistic seismic risk assessment in the city of David (Ministerio de Vivienda y Ordenamiento Territorial et al. 2012) After its completion, this engagement opened an opportunity to pilot the Program's flood risk assessment technical framework in an area within Boquete, Panama. Prior to this new activity in Panama, the Bank had not been involved in a flood risk assessment using the new TAP framework. This, along with the fact that no inter-institutional arrangements existed in Panama then, was taken into account in the design of the TAP on flood risk assessment for Boquete.

As means to enhance knowledge exchange by technical experts within the region, the CAPRA Program encourages the use of common technical language. Risk encompasses the combination of the probability of an event and its negative consequences (UNISDR, 2009). Consequences may be defined as expected losses resulting from the interaction between hazards and vulnerability (UNISDR, 2009) (Birkmann, 2006). Vulnerability of exposed assets may be characterized using vulnerability functions, which establish a correlation between hazard intensity and damage ratio. Given that a vulnerability function, in reality, describes a set of exposed assets of similar physical characteristics, the function is represented by two curves: the mean damage ratio and a standard deviation. Exposed assets are the group of elements, such as buildings, infrastructure and population that may be affected by the occurrence of a natural phenomenon (MIVIOT et al., 2012). While considering occupancy levels of buildings is important for decision making, the Program only accounts for physical elements into probabilistic risk assessments. Occupancy levels are then incorporated into the decision-making phase, along with the generated risk information and other criteria. Komatina and Branisavljević (2005) use equation 1 to measure risk in terms of annual average loss (AAL).

$$R=\int_0^1 S(P)dP \qquad 1$$

S corresponds to the expected consequences from flood events of annual probability of occurrence P. Given the relationships between hazard, asset exposure and vulnerability of assets to that hazard, each with its own uncertainty, risk is here defined as a function of these variables, and not as their product.

To account for these uncertainties, the Program proposes a probabilistic approach. Flood risk studies have traditionally focused on producing deterministic results (Domeneghetti et al., 2013). The assessment and mapping of flood risk involves many different sources of uncertainty (Beven et. al, 2010), including estimates of flow characteristics, terrain data, water surface elements (Merwade et al., 2001) and other model parameters. Similarly, vulnerability assessment carries uncertainties related to the structural response of exposed elements to different flood hazard intensities. Considering complex social, economic, behavioral, institutional and political aspects exacerbates the level of uncertainty in risk assessments. This leads to regard flood risk assessments, as much as risk evaluations due to other natural hazards, to have several sources of uncertainty that propagate through the analysis (Pappenberger, 2006). As a result, critical aspects of flood risk assessments include developing a good understanding of the uncertainty associated with the various input variables (Merwade et al., 2001) and fully evaluate the identified uncertainties using probabilistic methods. The main objective of a probabilistic risk assessment is to account for the uncertainty of both the variability of the natural processes that cause flooding and the uncertainty involved in the modeling process (epistemic uncertainty) in order to obtain results expressed through probability distributions that can be used to make informed decisions. Risk assessments that are accompanied by an indication of the reliability of results are a strong basis for decision making (Apel et. al, 2008).

2. TECHNICAL METHOD

The methodology applied is illustrated in Figure 1. The analysis is carried out using the software modules of the CAPRA Platform: ERN-Rain, ERN-Flood, ERN-Vulnerability and CAPRA-GIS (The World Bank, 2014).

ERN-Rain creates a set of stochastic storms, which are constructed on the basis of the Precipitation-Area-Duration-Frequency (PADF) curves for the analyzed watershed. The PADF curves describe the relationship among the maximum average precipitation, the area over which this precipitation occurs, the duration of the precipitation and its frequency of occurrence (Mijares, 1994). While these curves can be constructed for several durations, in cases where only daily precipitation is available, the PADF curves could be generated for 24 hours durations. From the PADF curves, ERN-Rain constructs a set of elliptical storms using the variation of the geometrical characteristics and centers of the storm, storing the resulting stack of raster layers in a single file with .AME extension that is used as input to ERN-Flood.

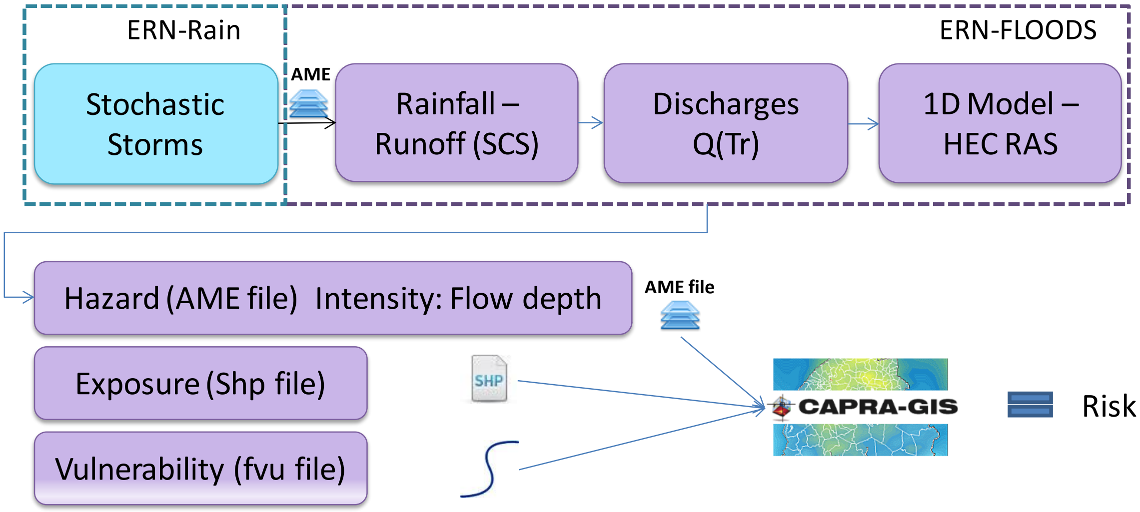


Figure 1: Technical Framework

In order to obtain a set of discharges from the set of stochastic storms, ERN-Flood uses the curve number method to determine the runoff (Soil Conservation Service 1986) and a triangular unit hydrograph (Mockus, 1957). Once obtained, the set of discharges are used as upstream boundary conditions for a model developed in the software Hydrologic Engineering Centers River Analysis System (HEC-RAS) (Brunner, 2010) of the area under analysis. ERN-Flood constructs the HEC-RAS flow data file and subsequently runs HEC-RAS automatically in steady flow mode under the following particular conditions: only one discharge upstream is allowed as boundary condition in the model and no structures are allowed in the model. ERN-Flood reads the results form HEC-RAS and interpolates the flow depths creating a stack of raster layers—each corresponding to a discharge scenario obtained from each stochastic storm, compiling them into single file in .AME format. It is worth noting that during the execution of ERN-Flood, the user is asked to provide a coefficient of variation based on experience to be used in each scenario to characterize the results probabilistically. Using this coefficient of variation, each output is transformed into a normal probability distribution, where the flow depth obtained from HEC-RAS constitutes the mean value, and the product of the mean by the coefficient of variation constitutes the standard deviation. These probability distributions represent uncertainties from data, model structure and parameters.

To analyze exposure, a shape file is needed that may contain data on number of floors, main construction material, replacement cost and other values that would help determine the asset vulnerability and potential losses. Proxy values are often used when data is scarce. These may be based on asset area, replacement cost per square meter, known typical construction types in given sectors of the study zones, and field surveys, among others. The level of use of proxies will have an impact on the definition of direct applications of the risk results at the end of the analysis. Assets are then grouped according to physical characteristics such that the vulnerability of each group (construction types) could be broadly described by a vulnerability function. A one-to-many relationship is established between vulnerability functions and exposed assets. ERN-Vulnerability has a library of vulnerability functions for select construction types often found in the region (ERN América Latina, 2009).

CAPRA-GIS then integrates the hazard assessment .AME file, the exposure shape file—updated with a field to map each asset to a vulnerability function, a set of vulnerability functions in .fvu format, and a .dat file that links the vulnerability function names used in the exposure database and the .fvu file names to estimate risk.

3. PILOT PROJECT IN PANAMA

3.1. Description of the Study Area

The Caldera River Watershed is located in the Chiriquí Province in the southwest of Panama (Figure 2). Its area is 143.3 km^2, ranging from 675 to 3,302 m above sea level (Arosemena 2010)(Arosemena, 2010) and representing 7.5% of the total area of the Chiriquí River Basin. The hazard assessment addressed a 4.8 km reach of the Caldera River located in the Municipality of Boquete and was limited to the floodplains with existing topographic data. The Caldera River Watershed has two well-defined seasons: a rainy season from May to November and a dry season from December to April with a mean annual precipitation of 3,466 mm. The main population center in the watershed is the Boquete district with a population of 22,400 inhabitants.

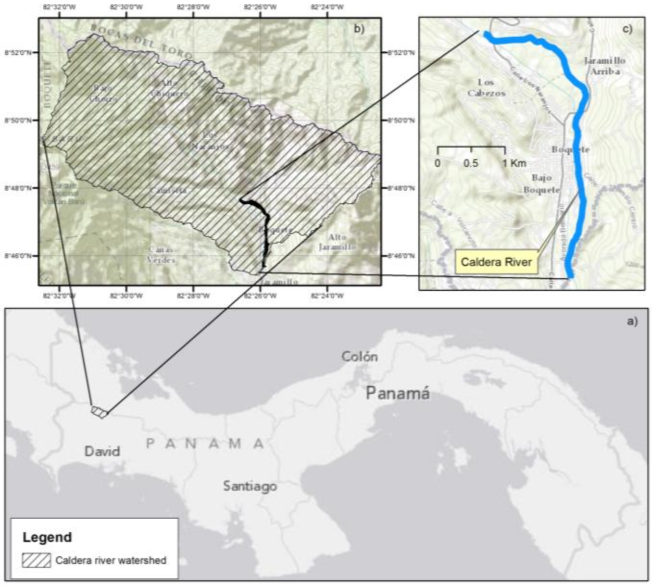


Figure 2: Location of the Study Area: (a) Location of the Caldera River Watershed in Panama, (b) Zoom of the Caldera River Watershed, and (c) River Reach under Analysis

The Caldera River Watershed is of high importance to Panama. The high fertility volcanic soils contribute to highly developed agriculture with 72% of the population working on agricultural labor (Arosemena, 2010). Approximately 37% of the surface of the watershed corresponds to forests (Arosemena, 2010) and the upper watershed of the Caldera River belongs to the Barú Volcano National Park. Volcanic structures from the quaternary Pleistocene and the tertiary Miocene can be found in that area (Sánchez and González, 2009). The lower watershed, on the other hand, is formed by flat and slightly hilly terrain corresponding to alluvial deposits from the quaternary, lahars from the quaternary and tertiary and volcanic structures (Sánchez and González, 2009).

The Caldera River is characterized by a torrential behavior and sediment-laden floods (Bolaños and Cuevas 1995) This implies that detailed studies on the hydrogeomorphic processes of the watershed should consider the possibility of hyperconcentrated flows and debris flows. However, for the probabilistic flood risk assessment, the assumption of clear water flows was used to simplify the hydrodynamics and to facilitate the understanding of the basics of probabilistic flood risk assessment through the use of simple models. Flooding has been the cause of several emergencies in the watershed. From 1969 to 2010, ten major floods have affected the urban area of Boquete causing casualties and significant economic losses. Flooding has been progressively worsened due to the disorganized interventions in the watershed generating erosion and sediment problems (Bolaños and Cuevas 1995). Flood risk has increased in the last decades due to the lack of planning and the urban development of the flood plains.

3.2. Data

National and local institutions participated in the compilation of the data used for the analysis. No additional data surveys were carried out except for the exposure data collected in the field to validate and complement cadastral information of the study area. Daily precipitation data of the study area was collected from the Empresa de Transmisión Eléctrica (ETESA), with most stations having data from 1980. The main source of uncertainty for the pilot project was considered to be the variability in rainfall conditions. The only available topographic data corresponded to a survey carried out in 2009 by a private firm for the construction of levees and dredging of the river channel in the urban area, which included cross sections of the river and topography in part of the floodplain. Updated conditions of the river could not be assessed. As previously stated, the analysis was limited to the area covered by the survey, and not the complete floodplain. Given the limited scope of the analysis and the demonstrative objective of the pilot, the coefficient of variation was assumed to be 0.4 per the expert recommendation of the developers of ERN-Flood, who had conducted several similar assessments during the development of the software. The selection for the coefficient requires further investigation and a sensitivity analysis.

The exposure analysis was based on data provided by the Instituto Nacional de Estadística y Censo (INEC), corresponding to the Census and cadastral data of the municipality dated 2010, including geo-referenced location of buildings, number of floors, construction materials, number of inhabitants, connectivity to public utility services, average household income, and ownership of vehicle and home appliances. To complement these data, an inventory of exposed elements was carried out in the field. Replacement values were obtained using as proxy household income and prices per square meter provided by previous studies in the study area (MIVIOT et al., 2012).

Using construction material and number of floors, three construction types were determined: (a) wooden houses with one floor - W1, (b) brick houses with one floor - M1, and (c) brick houses with two floors – M2. Since there was no data on food damage in the study area that allows for the construction of tailored vulnerability functions, available literature (Reese and Ramsay, 2010) on flood vulnerability and the library included in the software ERN-Vulnerability served to create a catalogue of functions for this study.

4. ANALYSIS AND DISCUSSION OF RESULTS

4.1. Hazard Assessment

The PADF curves generated are shown in Figure 3-a. On the basis of these curves, 250 storms were simulated for each return period. One of these is shown in Figure 3-b.

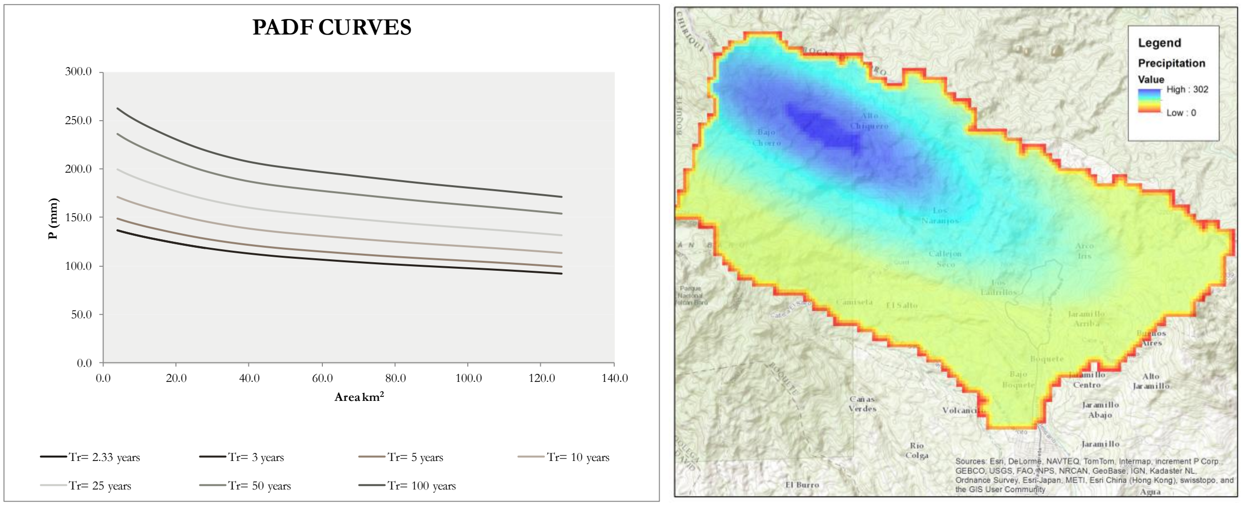


Figure 3: (a) PADF Curves. (b) Example of Elliptical Storm for a Return Period of 100 Years

The simplification of the precipitation scenarios through the use of the PADF and the elliptical storms shows several implications in the analysis. Given the mountainous terrain, the precipitation is dominated by the orography with the Barú volcano as the main feature. In consequence, elliptical storms may not represent adequately the expected precipitation spatial distribution. Furthermore, the current capabilities of the software ERN-Rain do not allow locating the center of the storm, preferentially in areas where the probability of occurrence is high since the location of the stochastic storm is randomly sampled over the study area. Therefore, the precipitation analysis carried out under these assumptions is adequate for preliminary assessment but their validity must be evaluated carefully for each case. Unfortunately, no data for validation was available for the case study. A stack of raster layers of stochastic storms was prepared and used to develop the hydrodynamic model of the study reach. Figure 4 shows the HEC-RAS model generated. The manning coefficient used for the main channel is 0.05 and 0.1 for the flood plains according to (Bolaños and Cuevas 1995).

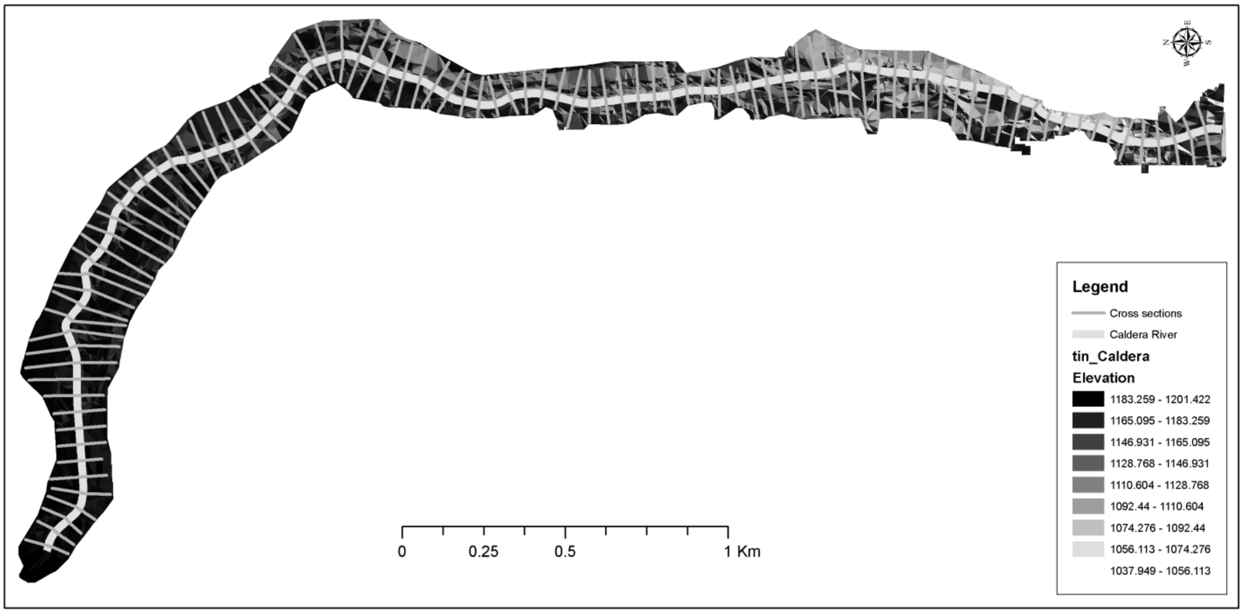


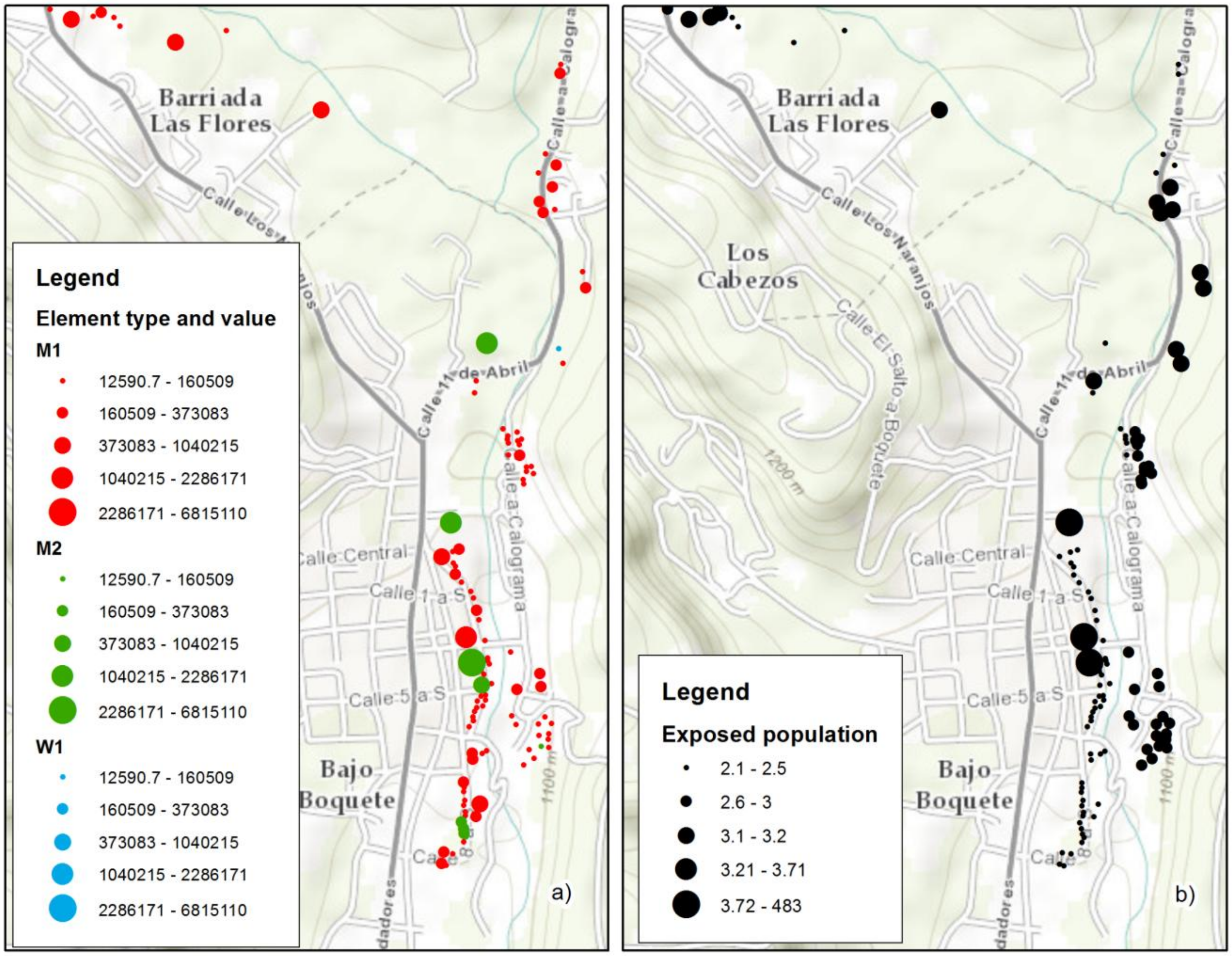
Figure 4. HEC-RAS Model

Once the inputs were correctly obtained, ERN-Flood was used to generate the .AME file, where each raster contains the intensity in terms of the flood depth of each stochastic storm scenario. 1500 scenarios were generated in total. In a first stage, the triangular unit hydrograph is generated. For the case of the Caldera River the resulting hydrograph corresponds to a time of concentration of 1.15 hours and a base time of 3.36 hours.

Due to the limitation of ERN-Flood to consider the influence of levees in the flood extent interpolation procedure, the use of this software module leads to an overestimation of the flood extent under conditions of no failure of the levees. This overestimation is larger for small return periods. A further source of overestimation corresponds to the limitation of the software to use only one discharge in the reach of analysis, this implies that the discharge in the 4.8 kilometer reach had to be considered constant. This assumption also leads to the over estimation of flooded areas in the upstream portion of the reach before the discharge of the tributaries of the lower basin of the Caldera River.

4.2. Exposure Analysis

Data from the Census, the municipal cadaster and field visit resulted in a classification of the buildings located in the area of study according to construction type, the estimation of a value for each exposed element and the identification of population exposed. The spatial distribution of the results is shown in Figure 5.



Service Layer Credits: Sources: Esri, DeLorme, NAVTEQ, TomTom, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, and the GIS User Community

Figure 5. (a) Spatial Distribution of Type and Value of Exposed Elements (in Panamanian Balboas B/.). (b) Spatial Distribution of the Number of Persons Exposed.

4.3. Vulnerability Assessment

The four classifications of exposed elements were assigned vulnerability functions shown in Figure 6. The blue line represents the variation of the intensity (given in terms of flow depth) with the expected percentage of damage. The red line represents the standard deviation.

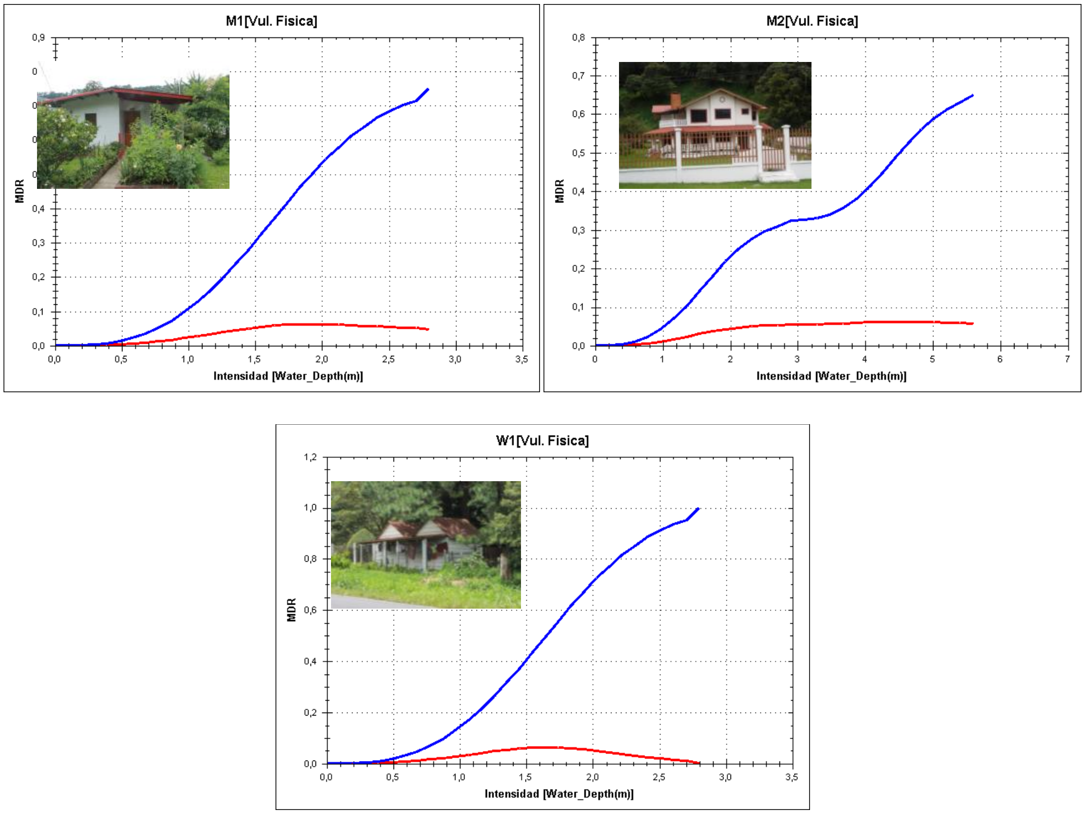
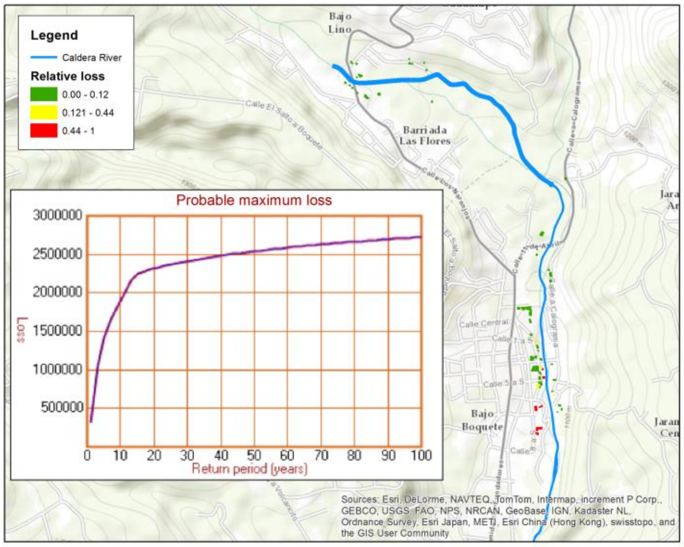


Figure 6. Vulnerability Functions

4.4. Risk Assessment

The resulting probable maximum loss (PML) curve is shown in Figure 7. As observed, maximum losses increase rapidly for events of return periods of 15 years or less.



Sources: Esri, DeLorme, NAVTEQ, TomTom, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, and the GIS User Community

Figure 7. Risk Results

The high loss for low return periods implies that the exposed elements are located mostly in areas frequently flooded; this is, in the floodplain of the river. The spatial distribution of the relative loss (AAL divided by the total replacement value of the exposed element) is shown Figure 7. The exposed elements with the highest relative loss are located in the south of the river reach.

One of the main assumptions of the hazard assessment in ERN-Flood is that no levees are constructed in the river; therefore, overflow of the river is simulated by ERN-Flood for low return periods. Figure 8 shows the flood extent obtained directly from HEC-RAS using the tool RAS Mapper (Brunner, 2010) and the extent interpolated by ERN-Flood for the return period of 10 years. The comparison of both results illustrates de difference when levees are considered. The flood extent for return periods less than 50 years show small or no flooded areas in the south zone of the reach when levees are considered, while the results interpolated by ERN-Flood show broad flooded areas in the same zone even for return periods of 2.33 years. These conditions influence the results since in the south zone of the reach the majority of the exposed elements are located. The wide impact of low return period floods obtained by ERN-Flood leads to high losses for low return periods and the identification of scenarios of return periods of 2.33 to 3 years as critical. These are scenarios that contribute the most to the AAL.

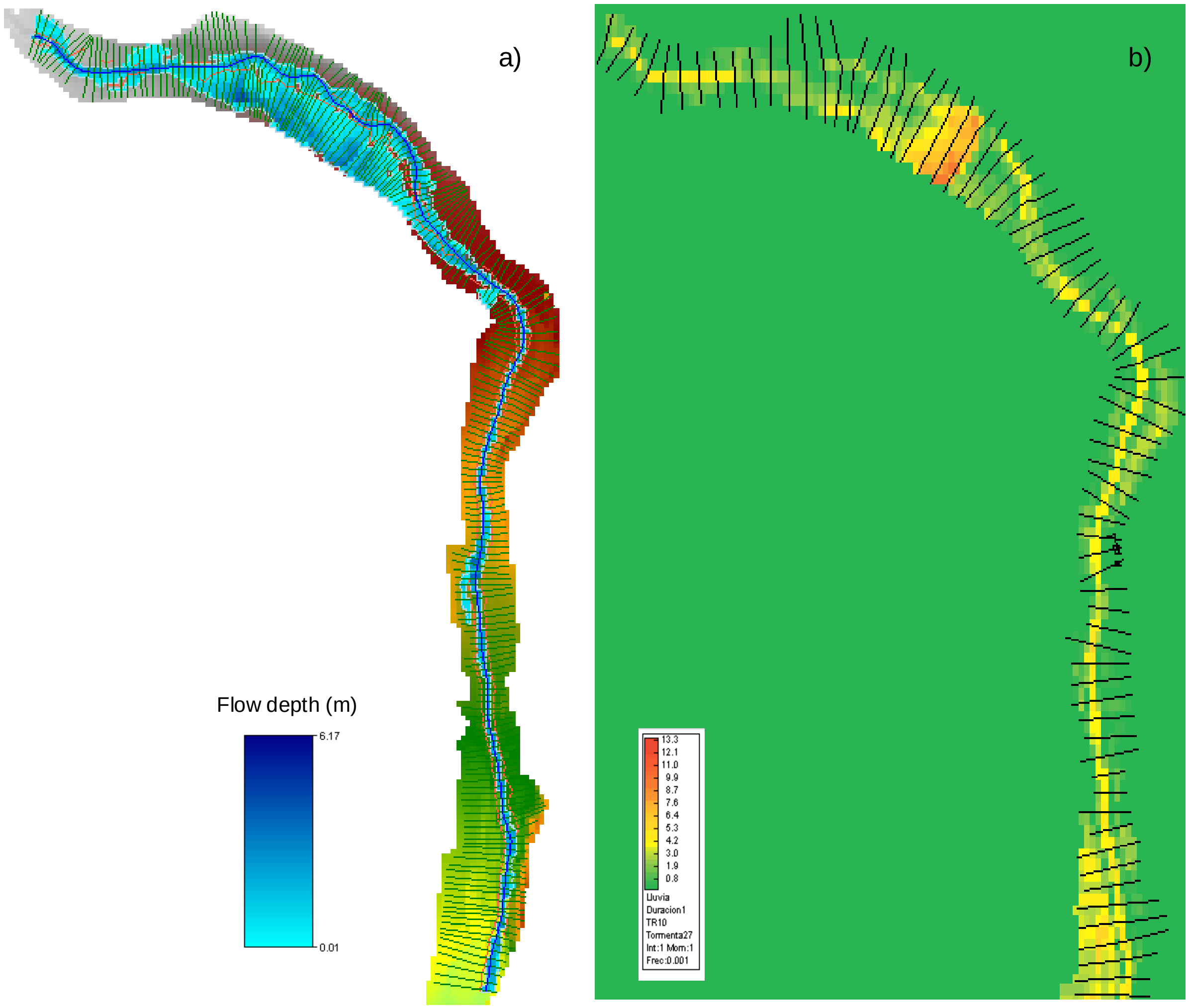


Figure 8. Flood Extent for a Return Period of 10 years: a) Results from HEC-RAS using RAS Mapper, b) Results Interpolated by ERN-Flood

If levees are considered in the risk estimation, no losses would be generated for low return periods. The results obtained using ERN-Flood are useful for a rapid assessment, but have a limited use for flood risk management and require careful interpretation.

From the analysis carried out with CAPRA-GIS, the AAL corresponds to B/. 1,036,393, corresponding to 5.3% of the total replacement value of the exposed elements (B/. 19,490,256).

4.5. Diffusion of Results and Discussion with Flood Risk Management Authorities

Given the simplified and demonstrative scope of the risk assessment exercise, the main objective of the process was focused on the discussion of results with the national and local flood risk management authorities—many of whom participated in the data collection process and project definition—about the importance of the generation of flood risk information and their application into decision-making process.

The probabilistic approach represents a novel procedure for many practitioners; therefore, a clear understanding of the concepts and simplification of the problem to be addressed in the study was important in the early stages of capacity building. In this case, the set of uncertainties involved in the flood hazard assessment is reduced to the variation of storm characteristics, which is source normally most familiar to hydrologists. Nonetheless, along the discussion process, several sources of uncertainty were pointed out and recognized as important to be carefully considered in future analyses. The discussion about uncertainty leads to the acknowledgment that data collection is crucial for reliable risk-based decision-making information. The analysis was useful to identify priorities for data collection and detailed flood risk assessments as well as possible strategies for the study area. Some of the next steps discussed include (a) developing a plan to sustainably generate flood risk information, leveraging the newly-established inter-institutional group knowing the variety of data required for the analysis, background of professionals needed and involved institutions, (b) installing additional hydrometeorological instrumentation to improve data, (c) implementing early warning systems, and (d) working closely with universities to advance the practice in Panama.

5. CONCLUSIONS

Probabilistic risk assessment tools developed under the CAPRA Program framework were used in a case study to carry out a flood risk assessment in a 4.8 km river reach in Boquete, Panama. Due to the early stage of development of the tools, the results of the analysis are aimed at demonstrating the potentiality of probabilistic flood risk assessment and do not constitute a detailed assessment. The probabilistic information obtained through the analysis allowed Panamanian institutions to consider the role that they play in flood risk management. The complexity of the analysis even if the most simplified models are used, leads to the acknowledgement that flood risk requires the contribution of diverse government institutions and the participation of local authorities to be effective.

The preliminary probabilistic flood risk assessment carried out in the case study showed to be useful to define priorities for detailed studies and to highlight the need to reduce uncertainties. The latter is consider one of the most important contributions of the approach, since the clear visualization of the dominant sources of uncertainty allows flood risk management authorities to allocate efforts to develop better models and to effectively plan data collection aimed at the reduction of uncertainty. The need for organized and readily available data as well as systematic, standardized and reliable risk information calls for strong inter-institutional arrangements and clear role definition, so effective risk management strategies can be put in place.

The current limitations of the hazard assessment modules call for enhancements in the procedures. A reliable estimate of hazard is a crucial input for the risk calculation. Simplification of models is in general needed for probabilistic flood hazard assessment; however a balance must be obtained between simplification and reliability. The models included in the current hazard assessment modules of the CAPRA Platform imply simplifications that are not always applicable in the flood risk studies. Then, further developments shall be aimed at leveraging existing advanced models commonly used by practitioners to generate hazard inputs for CAPRA-GIS. In this way, the model that is most convenient for each study case can be applied. Regarding vulnerability, an urgent need for reliable databases is evidenced, in order to construct more reliable vulnerability curves adapted to the particular conditions of each location.

6. ACKNOWLEDGEMENTS

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