NUMERICAL MODELING AND COLLABORATIVE FLOOD RISK MAPS: PEÑÓN DE LOS BAÑOS, VENUSTIANO CARRANZA, MEXICO CITY, MEXICO

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ABSTRACT

The foundation for a fruitful prevention policy should be a probabilistic study of the natural phenomenon occurrence, along with an estimate of the short- and long-term damages it could cause. This probabilistic study can be used to provide the relevant authorities with the necessary data to define possible risk scenarios and, at the same time, allow a sustainable territorial planning. Peñón de los Baños is in the borough of Venustiano Carranza. It has a perimeter of 6,180 m (20,275 ft) and an area of 1.59 km^2 (392.9 acres). It is a zone where ponding often occurs during wet season on a yearly basis. However, this problem has not been mitigated despite its recurrence. The purpose of this paper is to show the results of a numerical simulation model, by referencing a collaborative flood risk map made by the community and the academy. From an engineering point of view, efforts were made to make a numerical simulation model that could be used to support flood predictions as per data provided by the population (streets where water is perceived to run and ponding zones). Iber is a two-dimensional mathematical model for the simulation of flows in rivers and estuaries, it is promoted by the Center for Hydrographic Studies of CEDEX, and it was used to get scenarios and to be able to prevent floods. The coincidence of routes (streets where water runs) and flooding zones, as provided by the community, could be contrasted with the results of the numerical model to provide feedback and possible solutions that would mitigate this problem.

Keywords: risk, flood, models, Iber, community.

1 INTRODUCTION

In general, there is a need to carry out studies on the assessment of the vulnerability and risk to which places with recurring floods are subject. As part of this assessment, several factors need to be taken into account such as: vulnerability, with respect to risk, and periods of return and especially exposure to that risk, with respect to rainfall. As part of the studies focused on floods, the scientific community has developed research studies related to the problem by creating analysis models to understand the cause and provide possible solutions.

As part of the research, numerical simulation models and other models have been developed. These simulation and forecast models provide useful information to foresee – depending on rainfall – the evacuation of populations in order to avoid flooding. To this end, developing risk maps locally and micro-locally is important to help the population to mitigate the problem.

To develop risk maps, it is important to take into account people's collaboration, since, in the case of floods, these people are the ones who observe the problem and know which are the most floodable areas and streets, and where the water runs during the rainy season.

This article shows the process of making a map of flood risk in a low-income neighborhood (Peñón de los Baños), in collaboration with the population. This map then works as a basis for picking up data again and implementing a numerical model (Iber), which provides us with possible flood scenarios that help propose possible solutions in the prevention stage.

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2 RISK MAPS

Risk maps are required for the flood prevention stage [1]. For an efficient flood risk assessment, the study area is related to a given time. To this end, historical records and data on both rainfall and flooding are required to make hydrological and simulation models. In addition to geomorphological topographic analysis of the analyzed recurrent flooding area, it is worth mentioning that the more accurate the topographic data, the more accurate the numerical simulation model. Risk maps help long-term forecasting, as well as urban planning of fast-growing urban areas [2].

According to Kron [3], risk should be considered as the result of a hazard and its consequences. This means that the frequency and extent of a flood, as well as its consequences, can be analyzed by using flood risk as a basis. The purpose of risk maps is to show the result of calculating and visualizing the probability of occurrence of an event, as well as its extent, and damages that such an event may cause.

The creation of risk maps is based on the estimation – through statistical models or hydrological methods – of discharge rates in correspondence with specific return periods. Flood levels are estimated by using 1-D or 2-D hydrodynamic models. Finally, flooded areas are obtained by coupling water levels with digital elevation models (DEM).

Risk maps are made by combining information related to the hazard in a study area (causes and consequences). This also help estimate material and economic losses quantitatively in case of no prevention. Methods implemented to develop risk maps have currently evolved and are more accurate due to numerical and simulation models.

According to Bonasia and Lucatello [4], epistemic uncertainties have been reduced, which has improved numerical techniques, while random errors in field measurements have been overcome by introducing detailed statistical studies on historical rainfall and flood data, as well as studies on the effects of DEM properties (vertical and horizontal resolution) on flood models. In many cases, satellite imagery, when available, sharply reduces error due to uncertainty of topographic data.

Models based on numerical data are being used effectively for flooding problems, e.g., “Machine learning models are data-driven techniques that can be used for prediction purposes, with minimal entries, on the basis of historical data” [4]. This technique has been applied for short- and long-term prediction and represents a prediction method with a high level of accuracy. New models of hybrid neural networks have been developed based on ensemble empirical mode decomposition (EEMD) and discrete wavelet transform (DWT) to predict flow from rainfall [5]. Advances have been made in daily rain-runoff simulation by using hybrid machine learning models such as least-squares support-vector regression (LSSRV) and extreme machine learning (ELM) [6].

At the beginning of the year 2000, independent governmental organizations worldwide became concerned about the problem of flooding and financed projects for developing risk maps of affected areas, especially when floods are recurrent, with the aim of managing and mitigating the risk. Approaches already taken are based on the effectiveness of studying the probability of flood occurrence in order to reduce it and, consequently, reduce the damage it may cause. In some programs, government institutions use flood maps in different ways, e.g., informing the public and the decision-making bodies and providing guidance in the implementation of rescue and reconstruction operations. Or, for instance, these maps have been found in emergency plans to be a concrete basis in the use of hazard and risk maps.

Several countries in Europe and the U.S. have developed awareness and information campaigns in which online flood maps have been created and are available for consultation by people. This type of tool is essential for population living in flood-prone areas, as it describes the hazard and its impact and, consequently, provides the elements to protect themselves and face the risk responsibly.

3 IBER MODEL

Iber is a numerical simulation model for the processes of environmental and unstable flow in turbulent free surface in river hydraulics [7]. Iber application ranges cover river hydrodynamics, dam failure simulation, flood zone assessment, sediment transport calculation, and wave flow in estuaries.

According to Bonasia and Lucatello [4], Iber has three main computer modules: a hydrodynamic module, a turbulence module, and a sediment transport module. All of them work on an unstructured mesh of finite volume formed by triangular or quadrilateral elements. The hydrodynamic module, which forms Iber basis, solves two-dimensional equations of shallow waters averaged in depth (Saint-Venant 2D Equations). The turbulent module allows the inclusion of turbulent stresses in the hydrodynamic calculation, thus allowing its use for different turbulent models for shallow waters in different degrees of complexity. The latest Iber version also includes a parabolic model, a mixing length model, and a k-ε model. The sediment transport module solves the bed load and suspended turbulent load transport equations, based on the evolution of bed sediment mass balance.

The Iber model works with two boundaries: one is wall-type closed and others are open through which water enters and comes out for calculation. In closed boundaries, a free-slip or wall-friction condition may be provided. As for open boundaries, alternatives are considered depending on the hydraulic regime.

It has two boundaries: some for inlet and others for outlet. In inlet boundaries, water flow rate is set and flow direction is taken as perpendicular to the boundary. In outlet boundaries, a water sheet level is proposed in case of a subcritical regime, whereas no conditions need be proposed if the regime is supercritical. In outlet boundaries, the possibility of introducing a rating curve defining the relationship between the water sheet size and the specific flow rate drained at each point of the boundary is also considered.

Internal conditions are used to model hydraulic structures such as gates, landfills or bridges being under load.

Shallow water equations and k-ε model equations are solved by using the finite volume method for unstructured two-dimensional meshes. Numerical schemes used in Iber are particularly suitable for modeling regime changes and dry–wet fronts (flood fronts).

4 NUMERICAL SIMULATION MODEL FOR PEÑÓN DE LOS BAÑOS (IBER) IN COLLABORATION WITH THE COMMUNITY: RESULTS AND ANALYSIS

Our case study is the town of Peñón de los Baños. This town has an area of 1.59 km^2 (392.9 acres) and is in the borough of Venustiano Carranza, in Mexico City, which has an area of 33.42 km^2 (8,258.26 acres). This represents 2.24% of the total area of Mexico City. To the north of the borough, there stands a structure of 2,290 m.a.s.l. which pertains to what is referred to as Peñón de los Baños.

Peñón de los Baños is an area that experiences ponding and flooding year after year in some points. In 2019, fieldwork to identify ponding and flooding points, as well as monitoring water levels, was proposed, but due to the COVID-19 pandemic that reached Mexico that same year, fieldwork could not be carried out.

However, we chose to continue with the research by proposing new strategies for data collection. To do this, taking into account that it is a town, we contacted chroniclers and people directly affected by floods.

Initially, we conducted semi-structured telephone interviews recorded with the participants' consent. Interviews consisted of 71 questions (about 40 minutes of sound recording) to know the causes of floods (causes included the hypothesis that floods are caused by water coming down from the hill). As it was not possible for us to go to the place, the inhabitants (seven town representatives) provided in the same interviews house location and water level both in the street and in the house during rainy season.

In these interviews, they also provided information about the streets where people perceived that water flowed the most during the rain (this information later was useful to define water flow routing for Iber). Regarding this information, we developed collaborative maps, which were shown to participants in Zoom meetings to feed back into the map and listen to suggestions.

5 ROAD LAYOUT

Once the case study is chosen, road layout is necessary to make the model. In this case, the road layout was drawn in AutoCAD including blocks, streets, and primary and secondary avenues. Urban amenities – such as gas stations, market, cemetery, clinics, hotels, green areas, parks, churches, cultural center, and schools – are also drawn. Churches, cultural center, and schools are important, as they can serve as shelters at a certain time. As for litter, locating the points where it accumulates is important, as it blocks both water flow and storm drains during the rainy season. Fig. 1 was made with the information obtained.

Figure 1: Road layout, drains, and trees in Peñón de los Baños.

6 DRAINS AND TREES LOCALIZATION

The population says, in the semi-structured interviews, that dry leaves fallen from trees during the rainy season clog drains. Locating trees was necessary to confirm whether there are really many dry leaves. In the case of storm drains, identifying the type of sewerage in the town is important. We observed that in the streets where floods occur the most, sewers have round hatches and storm drain inlets. There are drainage driveway grates along the road pavement only in the streets near the Oceanía subway station, although they are the most affected by flooding in spite of this fact. Fig. 1 shows road layout, drains, and trees.

7 DEFINING ZONES BY LEVELS

With the information provided by the population during semi-structured interviews about flood streets and water levels, we developed a collaborative map (Fig. 2) that demarcates three zones with different levels of flooding. Zone 1, where Esterlinas Street is located, with levels up to 1.20 m; Zone 2, on the side of the municipal market of Pensador Mexicano Street, with levels up to 1.00 m; and Zone 3, in front of the Niño Quemado park, with levels up to 50 cm.

Figure 2: Flood zones, routes, and water flows in Peñón de los Baños.

8 WATER FLOW ROUTING

As a result of the interviews, we identified six routes (Fig. 2). The population perceives that in these routes water comes down from the Peñón de los Baños hill, and that in the rainy season these streets serve as streams, causing floods. Iber simulation model works using routes detected as routes of water flow inlets and outlets.

9 CUTS

We need to know the topography of the place to run the model. It is worth mentioning that the more accurate and better defined the topography (contour lines), the better the simulation. Topographical surveying with drones is recommended since accuracy is greater than INEGI's resolution (5 m). These cuts and profiles are made along the routes (streets where water runs more intensely), to know the slopes and levels along them.

10 TYPOLOGY

The model requires knowing the place climate and vegetation, since vegetation provides a percentage of the amount of water that can be filtered into the soil and the amount of water going to the lower area of Peñón de los Baños.

- Climate: Semi-arid temperate, i.e., an annual average temperature of 16°C.
- Soil type: Clay, sandy layers, artificial soils, basaltic material.
- Vegetation: Trees, ash, eucalyptus, jacaranda, Peruvian peppertrees, roses, and grass.

11 RAINFALL DATA

Rainfall data are collected from the nearest station, in this case in San Juan de Aragón. Higher annual rainfall on a day from 1979 to 2016 was recorded for return periods, as shown in Table 1, respectively.

Table 1: Return periods.

Tr		Mm
5	P5	18.0910442
25	P25	23.5707347
50	P50	25.930709
100	P100	28.2906832
500	P500	33.7703738

12 CALCULATING HYETOGRAPHS

Calculation is made of the maximum probable precipitation from which precipitation intensity in mm/h is obtained. Then, the required linear regressions are made by following the return period and the power regression that will work together with all the previous ones. To obtain the rainfall intensity, the maximum probable precipitation (mm) is correlated to duration time (see Fig. 3).

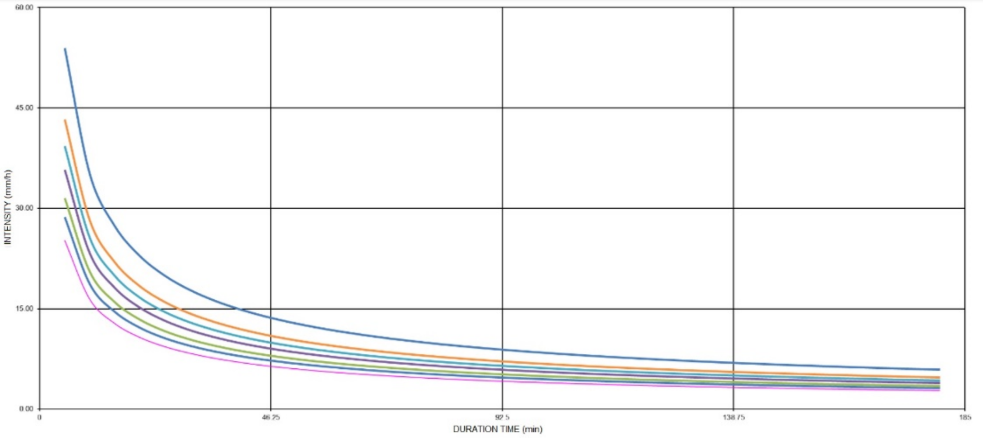

Figure 3: Result of hyetographs.

Hyetographs were used for simulations, in correspondence with return periods of Tr = 5–500 years. The higher the return period, the heavier the rain. Lower return periods do not generate any critical flood levels. Levels of 10–50 cm are verified when Tr > 100 years.

13 IBER SIMULATION MODEL

Hyetographs obtained are introduced by proposing the use enough simulation time for the current to occur on the routes. The mesh outlet boundary condition is landfill-type, and the outlet condition is that all mesh elements were dry.

14 RESULTS AND ANALYSIS

Draft evolution in one of the critical streets (see Fig. 4).

- Return period: Tr = 500 years
- Rainfall duration: 6 hours.
- A maximum draft of 30 cm is reached after > 6 hours. Water level begins to exceed 10 cm 1 hour after rain has started.

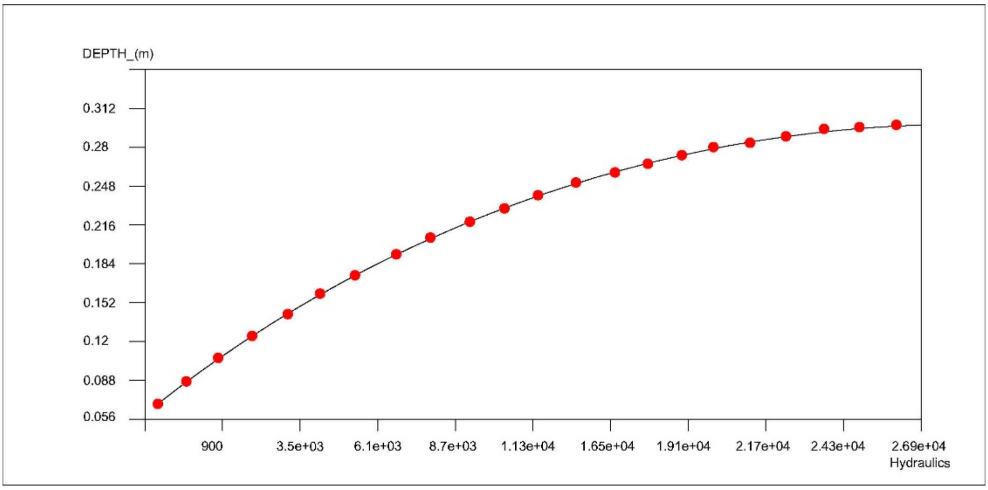

Figure 4: Draft evolution in one of the critical streets.

- Return period: Tr = 500 years (see Fig. 5).
- Rainfall duration: 6 hours.
- The variation in the volumetric flow rate from the hill to the street is very low. This means that the hill does not influence the increase in flood levels down the hill.

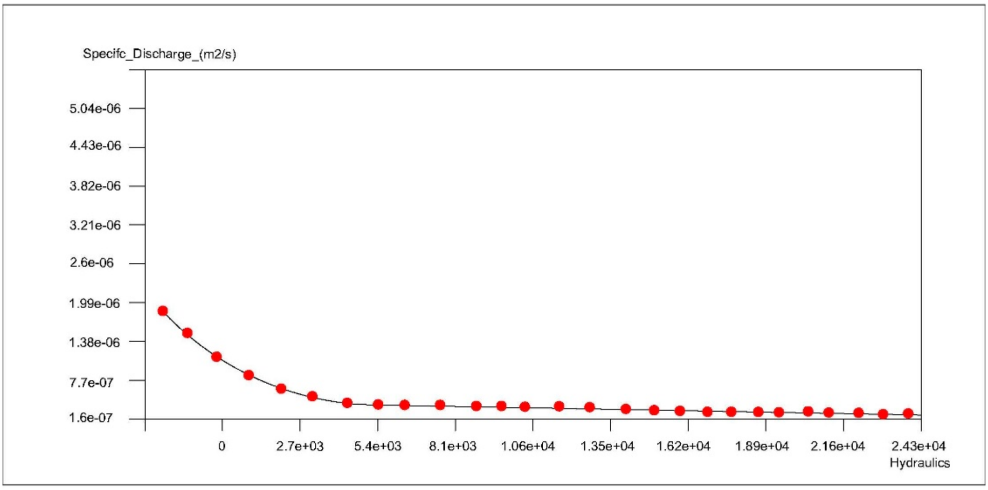

Figure 5: Return period: Tr = 500 years in a rainfall of 6 hours.

- Return period: Tr = 500 years (see Fig. 6).
- Rainfall duration: 24 hours.
- After 24 hours, flood levels > 50 cm are reached.

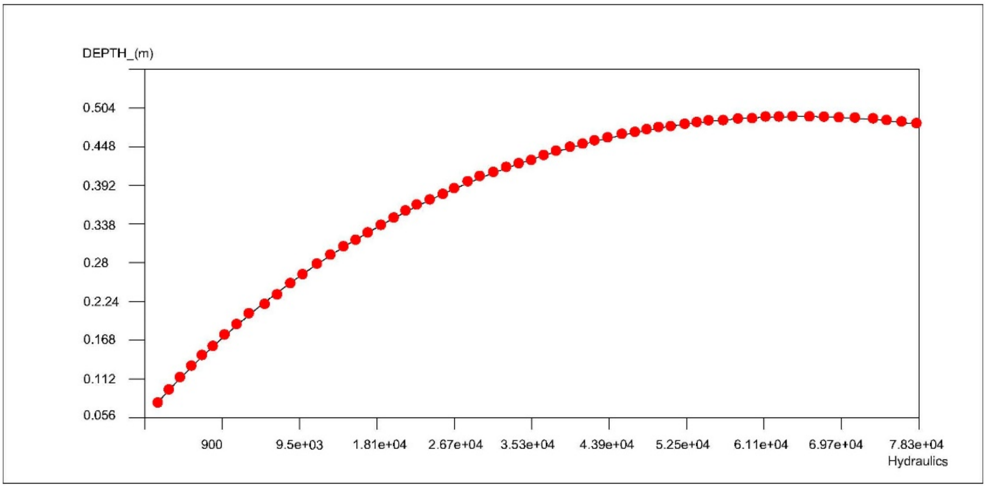

Figure 6: Return period: Tr = 500 years in a rainfall of 24 hours.

Considering these results, the water flow from the hill to Soles Street, which intersects Norte 184 Street and Esterlinas Street in Zone 1, is found to be very low with a constant rain of 6 hours. So, this flow rate does not cause flooding. In case of an atypical precipitation event, flow rate reaches 10 cm after 1 hour and up to 30 cm after 6 hours. It is only after 24 hours, that the level increases to 50 cm.

This invalidates the population's hypothesis that floods are caused by rainwater coming down from the hill. However, the results of the model show a need to improve drainage capacity and flow reorientation to alternate streets, since piping becomes clogged at any given time (see Fig. 7).

(a) (b)

Figure 7: Flow rates in Route 3. (a) Volumetric flow rate in section 420; and (b) Volumetric flow rate in section 1800.

In spite of not being included in any route, the model shows that at any given time, especially with an unusual heavy rain, Hermosillo Street also carries a considerable amount of rainwater and, where it intersects Route 3, rainwater going down to Zone 1 gathers and causes flooding.

15 CONCLUSION

Risk maps are a very important tool nationwide to prevent risks. For floods, these maps help identify the most vulnerable areas. However, existing maps are of relatively large areas.

Risk maps at the local level (community) are important because they can be used for accuracy on the phenomenon studied. While it is true that there are numerical models for flood modeling, which require quantitative data such as maximum and minimum rainfall records, as well as topographical surveys, among others, sometimes it is difficult to access certain information, since it belongs to the government.

Collaborative (population inclusion) maps can be used for accuracy in the phenomenon, as people living in specific areas perceive and know accurately how floods occur, and also keep their rainfall and water level records. Hence, it is important to make collaborative maps with the community that can be used as a basis for implementing flood models locally.

The information provided by the community shows specific flooding points, as well as levels reached during the time it takes for water to rise depending on rainfall extent. In addition, information about the streets where rainwater flows more intensely can only be provided by inhabitants because they see and live the problem.

In times of pandemic, using technology such as WhatsApp networks, video calls, and virtual meetings will be greatly helpful to maintain communication with the population and make collaborative maps that, in turn, feed back information.

The results of the flood model, taking into consideration the community's participation and using hard data on rainfall, confirm that critical zones brought up by the population really come to have the highest levels of flood during the rainy season. However, the hypothesis that floods are caused by water runoff from the hill is not the only one because, according to the model, other causes influence floods, such as the capacity of drainage infrastructure, its maintenance, and even litter.

At governmental level, risk maps should be made locally, taking into account the population's collaboration that, together with the implementation of flood models, can give better and accurate results in the maps that help understand the causes and problems in a certain region in order to mitigate and prevent the problems.

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