# Dam break simulation by means of a high-resolution algorithm applied to La Parota Dam, Guerrero, Mexico

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## Abstract

In this paper a dam break simulation of "La Parota" hydroelectric powerplant project, in the State of Guerrero, Mexico is presented by means of the CARPA system which is based in a 2D WAF-TVD (Weighted Average Flux – Total Variation Diminishing) high-resolution finite volume numerical scheme. With the obtained results it is possible to draw maps depicting the water depth, velocity and affected zones, which have proved very useful for civil protection purposes.

**Keywords:** Dam break, CARPA, 2D free surface model, finite volumes

## Introduction

The Papagayo River basin is located in the State of Guerrero, Mexico; it is the most important basin of the Costa Chica hydrological region because it collects water from the Omitlán, Azul or Petaquillas and Papagayo rivers and outflows into the Pacific Ocean (Fuentes *et al.*, 2005). The hydroelectric project "La Parota" of the *Comisión Federal de Electricidad* (CFE), will be located across the Papagayo River at a distance of 28 kilometers in a straight line to the northeast of Acapulco Bay; from the embankment dam to its mouth the river length is of almost 40 km. Its geographical coordinates are 16° 56' 03 latitude N and 99° 37' 32" longitude W (Figure 1).

In such basin three gage stations operate: *Agua Salada*, *El Puente* and *La Parota*; the maximum instantaneous flow rate estimated in the latter station during the whole historical record was equal to 11,653 $m^3/s$. Such flow rate corresponds to a scale record of 16.06 m and it happened on September 26, 1967. The flow rate was not measured but it was rather deducted by means of extrapolations from an elevation-flow rate curve supported by measured data corresponding to lower elevations. The minimum instantaneous flow rate becomes zero due to the operation of La Venta Dam, located 35 km upstream from the station. The embankment of the dam will be of the rockfill type with clay core and concrete facing; it will reach an elevation of 180.5 meters above mean sea level with an average height of 155 m and slopes of 1.5:1.

The State of Guerrero lies at a highly seismic zone in the country; therefore, an important study to be considered prior to the beginning of the project is the possible embankment dam breach as well as the hydraulic analysis of the eventual flood wave propagation, so as to be able to estimate depths reached, flow velocities, and elapsed times for the purpose of identifying possible flood plains and towns likely to be affected by such phenomenon.

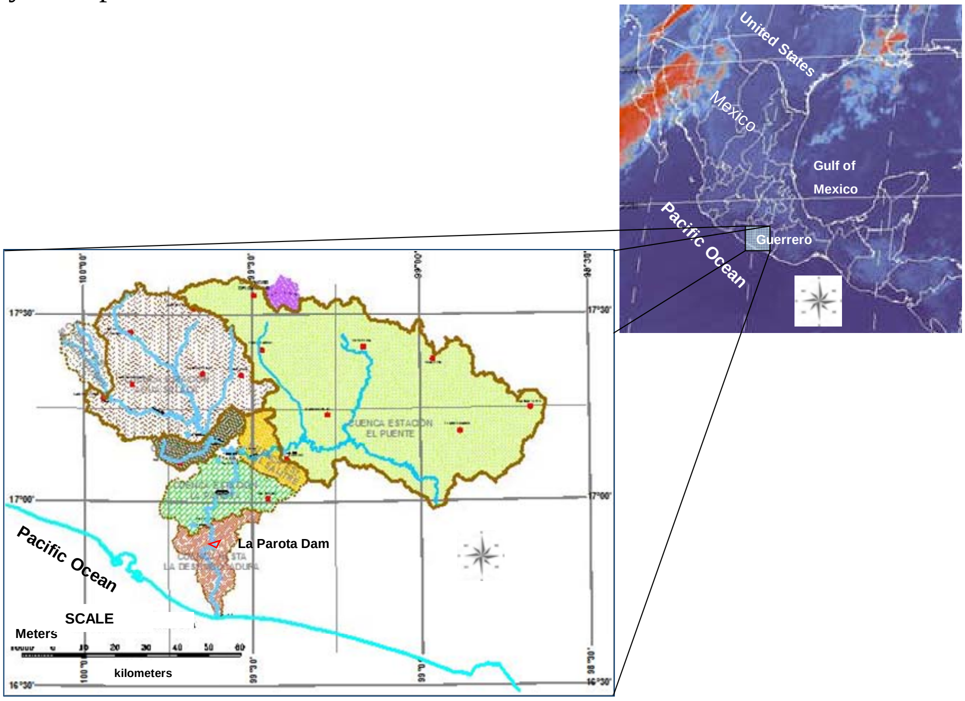


**Figure 1. Papagayo River basin**

Two aspects that must be taken into account for the mathematical simulation of this kind of river flows are, in the one hand, the application of flow simulation models in rivers and in their flood plains, which should consider the steep hydraulic profile and the regime types that could occur, and on the other hand, the accurate degree of approximation to the real phenomenon. Hydraulic modeling is usually complex due to the flow changes from slow to rapid from one reach of the river to the next, during the analysis, because of geometry variations of the river channel, steep slope zones followed by very flat bottom zones, etc. This situation implies the use of high-resolution numerical schemes to be able to take into account such variations in the flow condition.

In various parts of the world schemes have been developed and applied to simulate free surface flood propagation wave in one and two dimensions; such is the case of finite differences and finite volumes schemes. Additionally, laboratory models has been built to perform simulations of the flood wave propagation using small scale prototypes of natural rivers, prismatic channels, etc. For example, Chinnarasri *et al*. (2004) did experimental studies to estimate the breach width, breach time and peak flow through the breach, during a dike break considering the construction materials and these variables were taken into account to determine the evacuation time of people located downstream from the dike, prior to its collapse; Michaud *et al*. (2005) proposed to apply a GIS to estimate and mitigate the possible damages due to a dam break event in Hawaii reservoirs; Nguyen *et al*. (2006) successfully validated a 2D superficial water model by using a UFVM (unstructured finite volumes method) applied to several cases, among them a total and a partial idealized dam breach problem. Studies about this topic have also been done in Germany, France, Belgium, etc.; the importance of this topic of flood wave propagation is such, that its discussion and presentations on conferences, symposia and water related events are quite often made on separate technical sessions different from those on open channel flow; in Mexico studies about this topic are scarce.

**Methodology**

Saint Venant equations, in their conservative form, as used in 2D free surface flow analysis can be written as:

$$\frac{\partial}{\partial t}\overline{U} + \nabla\overline{F} = \overline{H} \qquad (1)$$

In equation 1:

$$\overline{U} = \begin{bmatrix} h \\ hu \\ hv \end{bmatrix}; \ \overline{F} = \begin{bmatrix} hu & hv \\ hu^2 + g\frac{h^2}{2} & huv \\ huv & hv^2 + g\frac{h^2}{2} \end{bmatrix}; \ \overline{H} = \begin{bmatrix} 0 \\ gh(S_{0x} - S_{fx}) \\ gh(S_{0y} - S_{fy}) \end{bmatrix} \qquad (2)$$

where $\overline{U}$ is the flow variables vector, $\overline{F}$ is the flow tensor and $\overline{H}$ is an independent term or source term. The first term in equation 1 represents the temporal local variation of the hydrological variables of mass and momentum; the second term stands for the spatial variation of the flux of those quantities; the independent term represents the gain or loss of mass and momentum in time of a differential volume which moves with the flow. Since the mass is a constant in the problem, the first component of the independent variables vector is equal to zero. Those equations are valid for flows with small vertical velocities, smooth bottom slopes and when horizontal dimensions predominate over the vertical ones. Saint Venant equations constitute a quasi-linear, non homogeneous, hyperbolic partial differential equations system with an independent term.

In this paper the finite volume method is applied and it has proved to be very useful to develop high resolution schemes in two dimensions. The finite volumes method (Figure 2) allow the partition of the domain into irregular regions and therefore it is adapted to the contours and the equations can be applied in their integral form

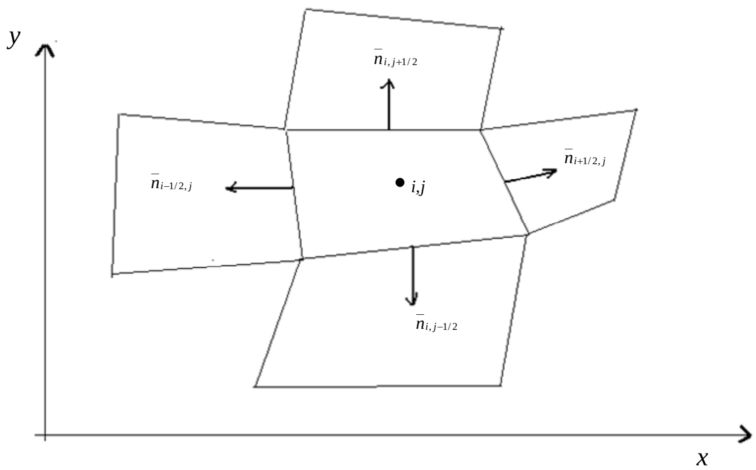


**Figure 2. Two-dimensional domain represented in finite volumes**

Integrating the Saint Venant equations on a finite volume the numerical scheme can be written as:

$$U_i^{n+1} = U_i^n - \frac{\Delta t}{V_i}\sum_{k=1}^{N_l}(\overline{F}^*_{w_k}\,\overline{n}_{w_k})dS_{w_k} + \Delta t H_i \qquad (3)$$

In equation 3 the numerical flow expression $F^*_{w_k}$, as a function of the values assumed by the variables in adjacent elements, marks the difference among numerical schemes. The numerical algorithm used by the CARPA program is based on the WAF-TDV scheme and it can be understood as an extension of the Lax-Wendroff scheme, or as an extension of second order precision of the Roe scheme as well. (Bladé, 2005; Bladé and Gómez, 2006). The Riemann solver of Roe approximates the jump of the numerical flux across a boundary as:

$$\overline{F}(\overline{U}_i) - \overline{F}(\overline{U}_j) = \tilde{A}(\overline{U}_i - \overline{U}_j) \qquad (4)$$

being $\tilde{A}$ an approximation to the Jacobian of $\overline{F}$ at the finite volumes values.

The expression of the numerical flux is therefore:

$$\overline{F}^*_{w_k}\overline{n}_{w_k} = \frac{1}{2}(\overline{F}_i + \overline{F}_j)\overline{n}_{w_k} - \frac{1}{2}\left(\sum_{l=1}^{3}\tilde{\alpha}_l\varphi_l(1-\psi_l(1-\left|\tilde{\lambda}_k\frac{\Delta t}{\Delta x}\right|))\tilde{e}_l\right)_{w_k} \qquad (5)$$

where $\tilde{\alpha}_l$ are the Roe averages of the wave strengths, $\tilde{\lambda}_l$ are the eigenvalues of $\tilde{A}$ and $\tilde{e}_l$ are its eigenvectors, $\varphi_l$ is the Harten and Hyman entropy fix for $\tilde{\lambda}_l$ as presented by Toro (1997) and $\psi_l$ is the Minmod flux limiter. The scheme is explicit, so the Courant's condition must be satisfied:

$$\Delta t \le \min\left(\frac{l}{\sqrt{2}\left|\sqrt{u^2+v^2}+c\right|}\right) \qquad (6)$$

where $l$ is the length of the side of an element, $u$ and $v$ are the velocity components and $c = \sqrt{gh}$ is the wave celerity.

**CARPA program in a GiD environment**

The algorithm explained before was codified in FORTRAN by Bladé and Gómez (Bladé, 2005; Bladé and Gómez, 2006), in the CARPA program (High-Resolution Calculation of Flood Propagation that means in Spanish: *Cálculo en Alta Resolución de Propagación de Avenidas*).

The GiD software (www.gidhome.com) allows in a preprocessing stage the creation of structured and non structured meshes with various geometries, for example rectangular, triangular or a combination of them; they can be created by the user or from imported digital ground surface models with grid format or also with a *tin* format but converted into a shape file (.shp) previously obtained from a GIS or from CAD files as *dxf* files, etc. In the GiD environment the problemtype called RAMFLOOD is selected and it allows to import or to create a digital ground surface model; once such model is developed, boundary conditions (or contours) are provided for an analysis which can be 1D or 2D or a combination of both. Initial conditions are assigned and the mesh data (it is very important to specify if it is a 1D or a 2D problem) as well as roughness values and Manning roughness coefficients (*n*) (more than one coefficient can be assigned depending on the type of soil) are also supplied..The input data are provided and the calculation is performed (CARPA processing). After the calculations are completed a post-process file is created which in a GiD environment allows the creation of maps showing water depths, flow velocities, specific flows, topography, etc. Also shape (shp), or *jpg* or *tif* files can be imported as background images to produce estimates of potential effects to towns, railroads, crops, etc. in flood plains.

## Application

### Input data

Since no detailed topography of the site under study is available, a digital ground elevation model from the Mexican Republic downloaded from the website of the *Instituto Nacional de Estadística, Geografía e Informática* (INEGI) was considered; with a scale 1:50,000 in zones different from the river channel and in some parts of its banks; for the river channel itself and along a distance of about 1 km in both banks, points based on bathymetric studies made by CFE along the river channel were considered. Both models were integrated into a grid format, with cells measuring 50 x 50 m, using Arc View software and from them two digital ground surface models in *tin* format were created, assuming a tolerance smaller than or equal to 0.75 m as well as a more refined model with a tolerance smaller than or equal to 0.5 m. Subsequently, in arc map environment, the *tin* file with the largest tolerance was converted into a shape file, which was in turn fitted trying to cover a convenient distance along both river banks (it was intended to guaranty the analysis from possible effects of flood damages by considering two kilometers on both banks of the river); such file was the one imported by GiD (Figure 3). Using this shape file a structured mesh was created in GiD, with the same number of elements of the *tin* file in the shape format Surfaces regarded as large were partitioned into triangles until the desired mesh was achieved. In addition, a satellite image of the Papagayo River, extending from the dam site to the mouth was obtained from GoogleEarth software in *tif* format which was geo-referenced using a *twf* file (Figure 4); it was used as background image, as an aid to assign initial and contour conditions.

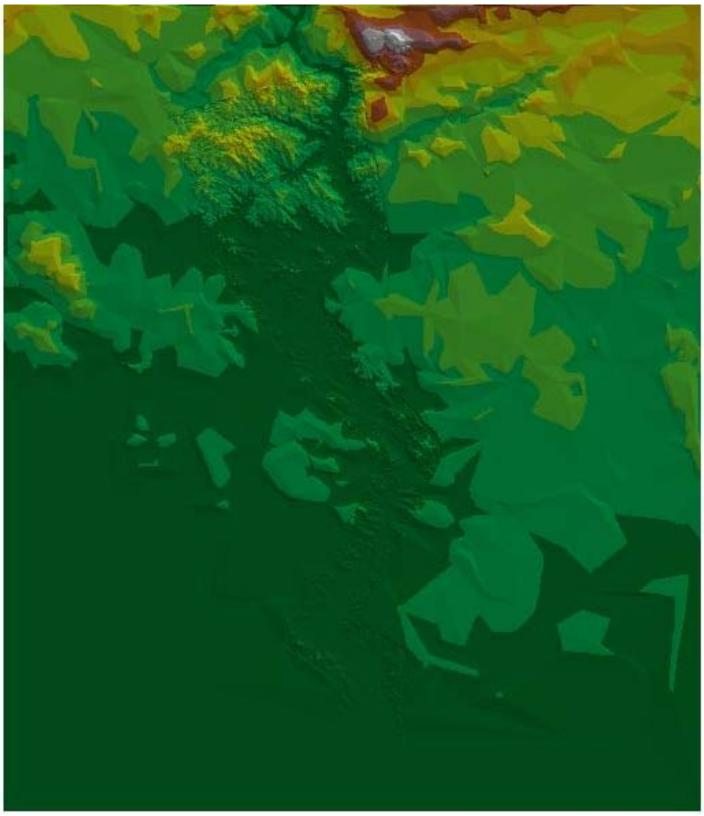

**Figure 3. Digital ground surface model (*tin* file, tol. $\leq$ 0.5 m)**


**Figure 4. Satellite  image of the Papagayo River, State of Guerrero, Mexico**

As initial conditions, the whole region under study (downstream from the dam site) was considered dry after assuming that the breach could be induced by seismic events; for the inlet contour conditions a hydrograph generated under the hypothesis of a rectangular breach varying in time was used, having a maximum width of 120 m and a final embankment height of 30 m. This hydrograph was simplified by considering only a few points, including the peak flow of approximately 264,000 $m^3/s$, a base time close to 39,600 s (about 11 hours) and a base flow rate of 30 $m^3/s$ (Figure 5); data of the hydrograph are expressed per unit width.

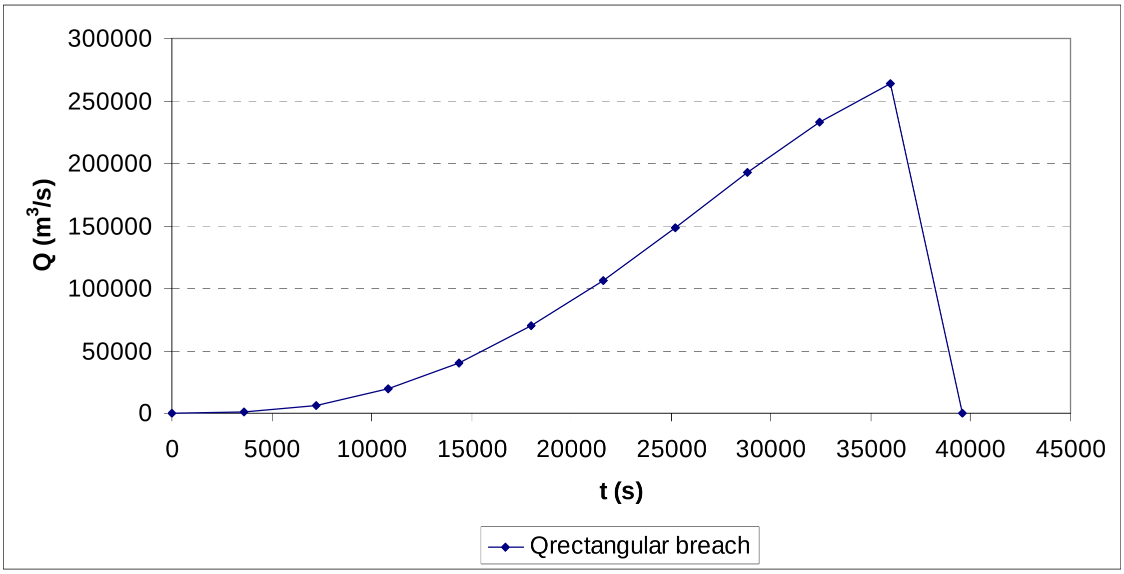


**Figure 5. Breach outlet hydrograph (assuming a rectangular shape)**

As contour discharge a weir-type outlet was considered , assuming a weir coefficient of 3 (somewhat smaller than the critical value) and a hydraulic head equal to zero by taking into account the river channel topography when it reaches the sea. An average roughness Manning coefficient of 0.035 was used in the whole region being studied. To fulfill Courant's condition, an initial value of $\Delta t$ equal to one second was assumed. The CARPA program makes the corresponding fitting to such time increase to comply with such condition. In the first trial a printing time of the results equal to 900 s was considered as well as a maximum calculation time of 46,800 seconds.

The information provided by the first trial made it possible to redefine the mesh dimensions for the final trial that was performed with a subtler *tin* file (for a tolerance smaller than or equal to 0.5 m); the dry elements were no longer considered and the possible affected zones in nearby towns were expanded, by taking into account registries of the maximum water depth determined in that trial; the need to review the ground surface topography reported was also identified in terms of the water flow behavior.

With the new mesh the final trial was performed, establishing initial and boundary conditions similar to those used in the first trial. The final calculation time was set after 90,000 seconds; the results are shown below.

## Results and discussion

The simulated hydrograph, with a peak flow rate of about 264,000 $m^3/s$ and an approximate base time of 11 hours (39,600 s), corresponds to a volume spilled through the breach of approximately 3895 million cubic meters if a unit flow rate is assumed;

the unit peak flow rate would be equal to 2186 $m^3/(s.m)$ which corresponds to a unit volume of 32.26 million $m^3/m$. The inflow and outflow hydrographs for the problem domain taken as a whole are presented in Figure 6.

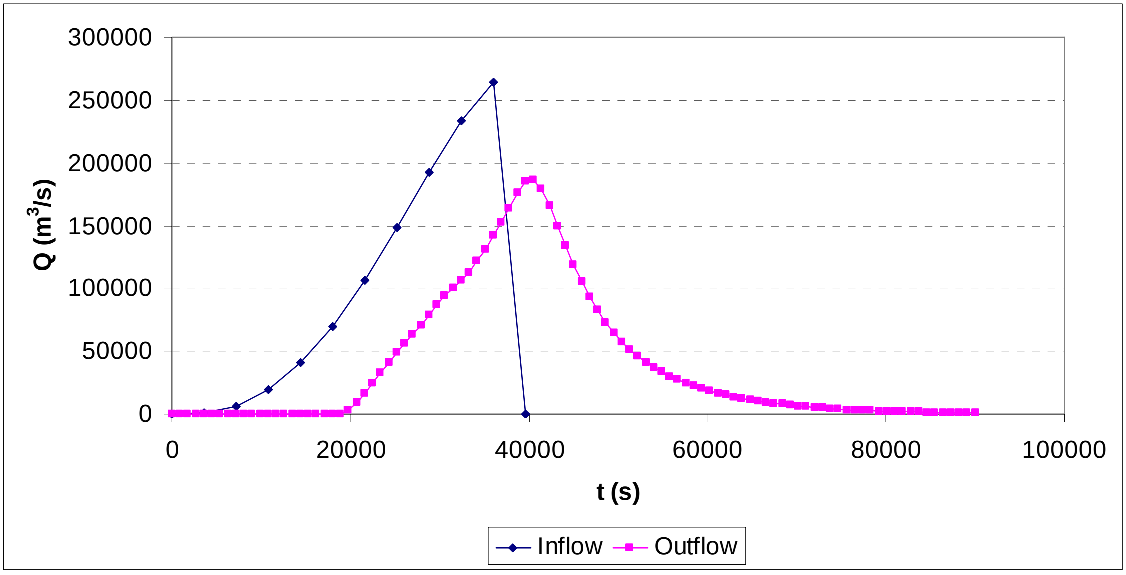


**Figure 6. Flow rate variation in the problem domain**

According to Figure 6, the estimated time for the discharge of the volume of water flowing through the breach at the assigned outlet contours is of about 5.5 hours (19,800 s). The peak outflow is equal to 186,329 $m^3/s$, i.e. an attenuation in the peak flow of 77,671 $m^3/s$. The volume under the outflow hydrograph is of about 3557 million cubic meters; therefore, a volume of 338 million cubic meters is temporally impounded in the affected zones (distributed inside the main river channel and in the flood plains).

With the flood wave propagation simulation of the hydrograph due to the eventual dam break of La Parota Dam, the following parameters were determined, among others: water surface elevations, water depth, velocity and specific flow rate, every 900 s; in particular, determinations of the peak values of water depth and velocity were made and maps were plotted such as those shown in Figures 7 and 8, which allow an estimate of the flood risk in towns and places close to the river.

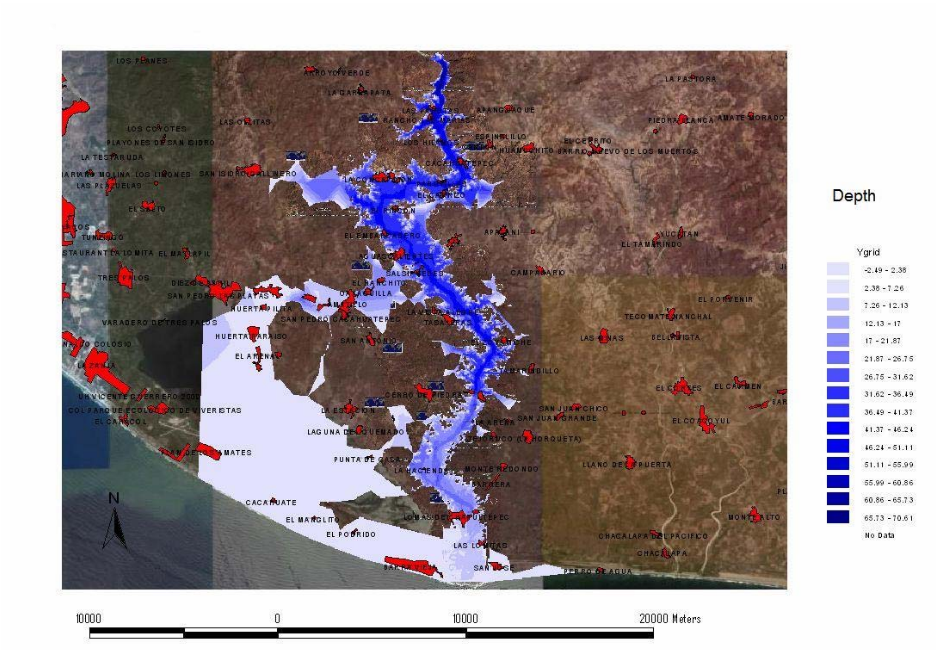


**Figure 7. Risk map of maximum water depths. Dam break simulation of La Parota Dam, State of Guerrero, Mexico**

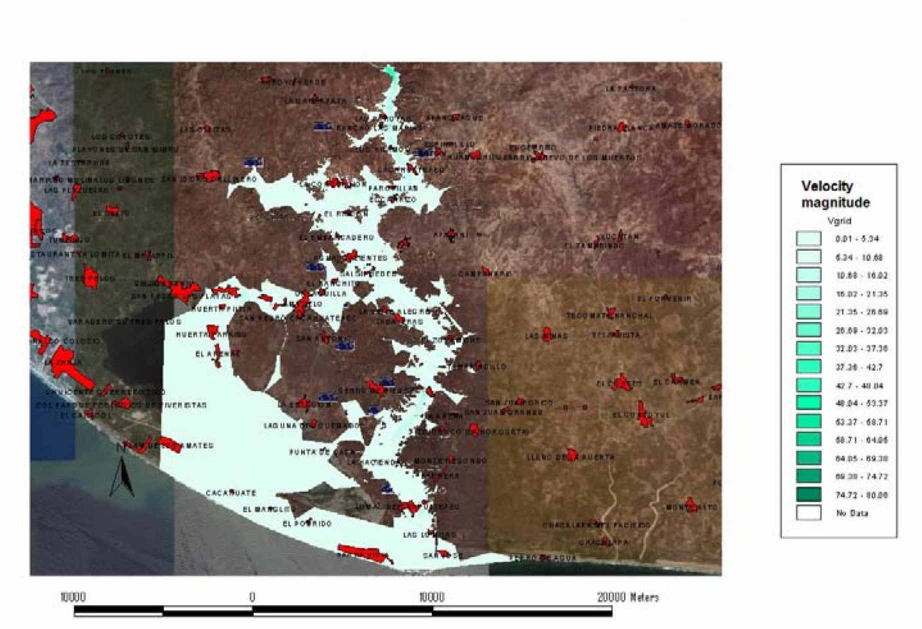


**Figure 8. Risk map of maximum water velocities. Dam break simulation of La Parota Dam, State of Guerrero, Mexico**

The consequences of the huge volume that could be discharged, under the assumed dam break conditions would represent 36 affected towns, with maximum water depths of about 52 m in high elevation areas and maximum water velocities of about 18 m/s (65 km/h) in the flooded areas; that gives an idea of the magnitude of the disaster when such type of events occur.

## Conclusions

With the 2D free surface flow model CARPA an estimate was made of the flood wave propagation along a river channel and its flood plains due to the eventual breach of La Parota embankment dam in the State of Guerrero, Mexico. With the obtained results it was possible to prepare risk flood maps of possible zones affected by potential major floods, as well as an estimate of maximum possible flow velocities. By comparison with an operative hydrograph, with the reservoir at its maximum water operating level, under a flood with 10,000 years of return period and considering the flood period, it was possible to forecast that the behavior of the flood wave during an event of such magnitude could be catastrophic for the areas adjacent to the river channel.

With the maps thus obtained it is feasible to develop early warning systems to allow the timely evacuation of people from possible affected sites; this represents a useful tool for civil protection agencies.

Although the CARPA model has been validated in other practical cases of river hydraulics, it is advisable to corroborate it through laboratory testing by building a dam breach model and simulating the shape of the flood propagation wave so as to be able to validate the results described herein.

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