Numerical Simulation of Hydrodynamic Conditions in Rivers Facing Extreme Events Due to the "El Niño" Phenomenon

Gabriela Alvarez, Alvaro Moreno, Emanuel Guzmán, and Sissi Santos

Abstract Disasters caused by floods are increasingly common around the world, such as the case in the western part of North and South America, due to the presence of the "El Niño" phenomenon, which causes an increase in rainfall and flow rates of the rivers causing floods. For this reason, this present work has carried a numerical simulation of flooding in the face of extreme events such as "El Niño," with the purpose of validating a hydrodynamic model that subsequently allows to predict the magnitude of a future event, for this, hydrological data of average flows and instantaneous maximums over a period of 40 years has been used. The hydrological information was processed using the Gumbel method to obtain simulation flows for return periods of 2, 5, 10, 50, 100 and 500 years. As a result, an approximation of 75% of the model was obtained in comparison with the historical event. Additionally, an increase of 103% in water elevation was found for discharge with a return period of 500 years, compared with the event of March 27, 2017, which represents a discharge with a return period of 36 years.

Keywords Flood · Hydraulics · "el niño" phenomenon

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1 Introduction

Floods caused by river overflows are recurring problems worldwide and are related to increased rainfall, structural failures in dams or protection structures, as well as the occurrence of extreme phenomena such as the "El Niño" phenomenon (FEN). It affects the western part of North and South America, causing large economic and human losses. Facing this situation, the authorities carry out contingency plans to mitigate the negative impacts caused by these phenomena.

Several studies and investigations have been carried out in order to study the floods and prevent the disasters they cause [1–13], one of the techniques used for this is hydraulic modeling where programs such as IBER [5], HEC-RAS [13], FLO2D [11], among others are used.

In order to develop the modeling, it is common to use digital terrain elevation models (DEM) to characterize the topographic configuration of the study area. The DEM is a computational representation of the triangular irregular networks (TIN) of the surface that can be obtained from satellites that take images obtaining from horizontal (x, y) and vertical (z) vectors in such a way that it generates the digital terrain models with different resolutions [14, 15]. From the DEM obtained, TINs are created, which are a necessary requirement for hydraulic simulation, since from this it is possible to generate the mesh that covers the study area, the river cross-sections, among others [6]. A joint work of data collected in the field and a digital model facilitates and enriches the information extracted from the satellite at the time of the extraction of cross-sectional sections of the river for 1D or 1D/2D modeling [16–18]. The hydrological data (rain, river or both) implemented in the models help determine flood plains that occur around the river or within the study basin. For the calibration of the generated model, it is possible to make use of statistical parameters that start from physical properties of the place or the digital calibration is carried out, which consists in the comparison of models of different satellites to obtain the best available model with the least possible error and closely related [10, 16]. On the other hand, to carry out the validation of the model there are different studies that compare the numerical models obtained in a combination of the digital elevation models and the hydraulic information of historically observed events, comparing mainly their physical differences. Maswood & Hossan [14] use the comparison of the bathymetry water levels of the flooded days and the numeric values obtained, while Abdul Kadir [1] compares the longitudinal profiles observed with the numerical ones, and in the key points are compared to verify if they have a significant difference. In addition, Surwase [17] compares flood plains by changing roughness parameters, proving that for a higher Manning n value, an increase in the flood area will be generated.

Therefore, the use of numerical modeling is an important tool since it allows evaluating real and hypothetical scenarios, considering return periods of up to 500 years, which allow obtaining extreme events and assessing and identifying the most vulnerable areas to flood risks, which allows competent authorities to prepare management plans for these risks. The present investigation provides a hydrodynamic model in

HEC-RAS applied in Peru, to simulate possible future extreme events caused by "El Niño" phenomenon.

2 Area of Interest

The study area is located in the northern part of Perú, in the department of Piura and includes the section between the Los Ejidos dam to the Bolognesi Bridge (Fig. 1). Likewise, other bridges are shown within the study area, such as the Andrés Avelino Cáceres Bridge, Eguiguren Bridge, Sánchez Cerro Bridge, and San Miguel Suspension Bridge, being its distribution with downstream direction.

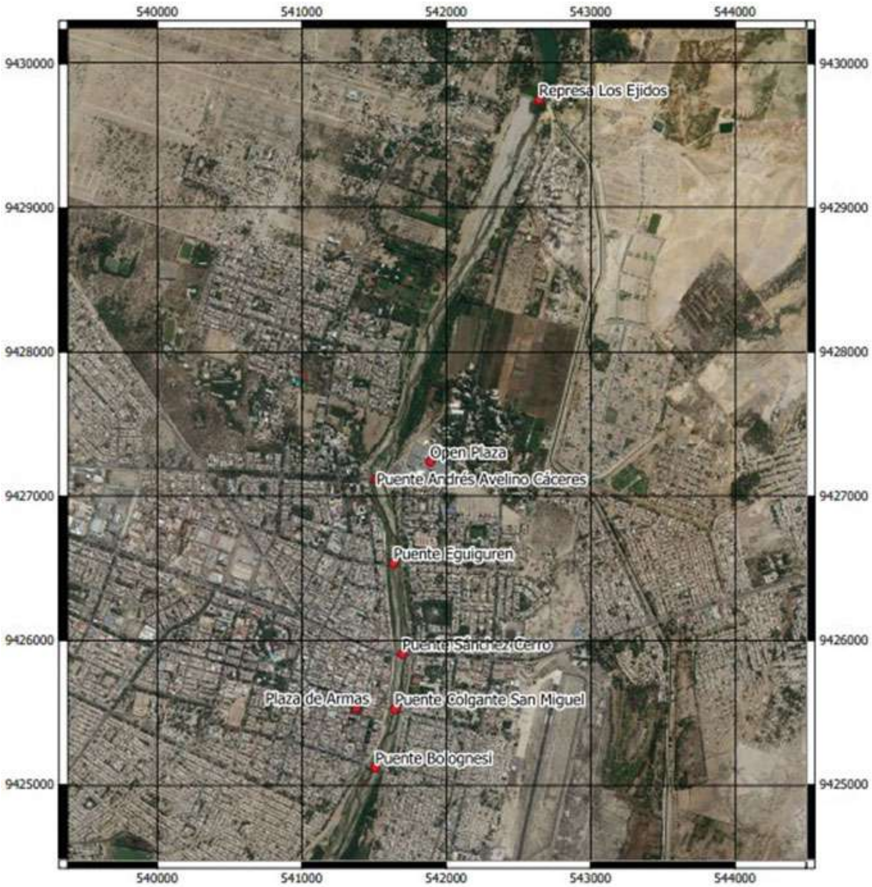

Fig. 1 Study section from Los Ejidos dam to Bolognesi Bridge

The district of Castilla and the district of Piura represent a part of the urban area of Piura. In these areas, there are homes, schools, parks, etc. Points of importance due to flooding are places such as the main square of Piura and the open plaza of Piura due to its proximity to the river.

The Sánchez Cerro Bridge hydrometric station is administered by the National Water Authority (ANA) [4] and is in the district of Miraflores, at a height of 34 m.a.s.l in the coordinates of latitude = 05° 11′37.15″, longitude = 80° 37′24.39″. The station records average normal flow conditions of 752.6 m^3/s, while in extreme events it reaches 4424.0 m^3/s. In the structure of the Sánchez Cerro Bridge, its cross-section supports a maximum avenue of 2000 m^3 before overflowing; this flow is recorded and usually exceeded when natural phenomena such as the "El Niño" phenomenon occur.

3 Methodology

The work began with the collection of data from different official institutions such ANA [4], Regional Emergency Operations Center of Piura (COER-PIURA) [3] and the Special Project Chira-Piura (PECHP) [12], from where the information of maximum daily, daily average and hourly discharged was obtained. For the morphological characterization of the area, information has been used on a digital terrain elevation model (DEM), obtained from the SPOT-7 satellite, with a resolution of 6 × 6 m, which was collected from National Aerospace Research and Development Commission (CONIDA) [2]. DEM has been processed, the land data and the corresponding cross-sections of the river were obtained and exported to HEC-RAS for simulation.

For the generation of the model, after adding the input data in the HEC-RAS, in the geometry section, the mesh was defined according to the DEM resolution. Also, the upstream edge conditions were defined, where the hydrograph corresponding to the date and time of the event was entered, while the average slope of the river in the study area was placed downstream.

Subsequently, the values of Manning n were chosen according to the river's characteristics as observed in the study area, since it is a coefficient that represents the roughness of the riverbed and was used to calibrate the model, also, when modifying that parameter, it will change substantially the results of the model. To have a better fit, the calculation intervals of the model were determined according to the Courant stability criterion, which is indicated in the HEC -RAS 5.0.7 manual. The hydrodynamic simulation was visualized in RAS Mapper, and the validation was carried out by means of a comparison of the flood area with the high-resolution digital image of the same date and time selected. Finally, an extreme flood event was modeled with the data obtained of discharge for 500 years of the return period, where the flooded area is visualized, and this allowed to generate control and prevention plans in the vulnerability area to these disasters. This methodology was adapted according to Surwase for the respective purposes [17]. The extremes discharge values were obtained using Gumbel Distribution, which passed the Kolmogorov-Smirnov test to verify that it has a normal distribution, and the flows for the return periods of 10, 20, 50, 100 and 500 years.

4 Simulations

The DEM for the required study area was adjusted and modified since it has elevation data. For the study, the contour lines were extracted at an interval of every 3 m to provide the necessary precision for the model. The contours achieved to consider the topography of the terrain, from them a tin (irregular triangulation networks) was created, showing the different elevations in the area. Then, the cross-sections were created, following the axis alignment and the defined river limits. The terrain geometry was entered in the HEC-RAS in the "RAS Mapper" window to display the respective elevations. In the "Geometric Data" window, the calculation mesh within the flood area was defined, which must contain a cell size that conforms to the DEM resolution for best results. Different boundary conditions were considered for the calculation mesh, for example, for the upstream the respective input hydrograph was entered and for the downstream, the slope of the land was entered, which was 1.2%. Finally, for the calculations of computation interval, the cell parameters and speed of the unsteady flow for different levels of river water with a Courant coefficient equal to 1 were considered, according to the equations defined in the HEC-RAS Manual 5.0.7.

Simulations were developed for the event of March 27, 2017, date that a flood event was reported due to the FEN, in this stage, it was proceeded to calibrate the model and validate with a satellite image. In the second stage, an extreme event was modeled for the discharge rate obtained for a return period of 500 years, so the flood hazard area was obtained.

4.1 Event Simulation: FEN March 27th, 2017

For the simulation, a Manning roughness coefficient of 0.035 was considered as roughness for dredged material with short grass and some weeds [7] and the hydrogram of March 27th from 00:00 h until 21:00 h taken from the Ejidos dam (Table 1; Fig. 2).

The modeling result for March 27th, 2017 (Fig. 3b) shows a flooded area of 3.18 km^2, where two mainly affected areas such as the main square and the Open Plaza Shopping Center are observed due to its large audience attendance.

Figure 2 shows the difference between (a) the observed flood, by calculating the Normal Differential of Water Index NDWI index, obtained from the Sentinel-2 satellite, image from April 4th, 2017 and (b) the modeled flood of the DEM obtained from CONIDA. For the main square, the observed event and the modeling have an area of 0.98 km^2 and 0.74 km^2, respectively, this represents an approximation of 75.5%. Also, for the Open Plaza, the observed event and the modeling have an area of 0.30 km^2 and 0.23 km^2, respectively, this represents an approximation of 79.31%. In addition, results were obtained from the depths and average speeds in areas such as the open plaza Piura, the main square, Sánchez Cero Bridge and Bolognesi Bridge, which are consistent with the historical information of the "Niño Costero" phenomenon of the year 2017 (FEN Costero 2017) (Table 2).

Table 1 Hourly discharge of March 27th, 2017 at the Ejido dam station. *Source* COER [8]

Ejidos dam					
Time	Flow m^3/s	Time	Flow m^3/s	Time	Flow m^3/s
00:00	2270	08:00	3095	16:00	3133
01:00	2325	09:00	3095	17:00	3076
02:00	2396	10:00	3264	18:00	3035
03:00	2501	11:00	3378	19:00	3005
04:00	2574	12:00	3468	20:00	2923
05:00	2864	13:00	3264	21:00	2850
06:00	2895	14:00	3216		
07:00	3016	15:00	3174		

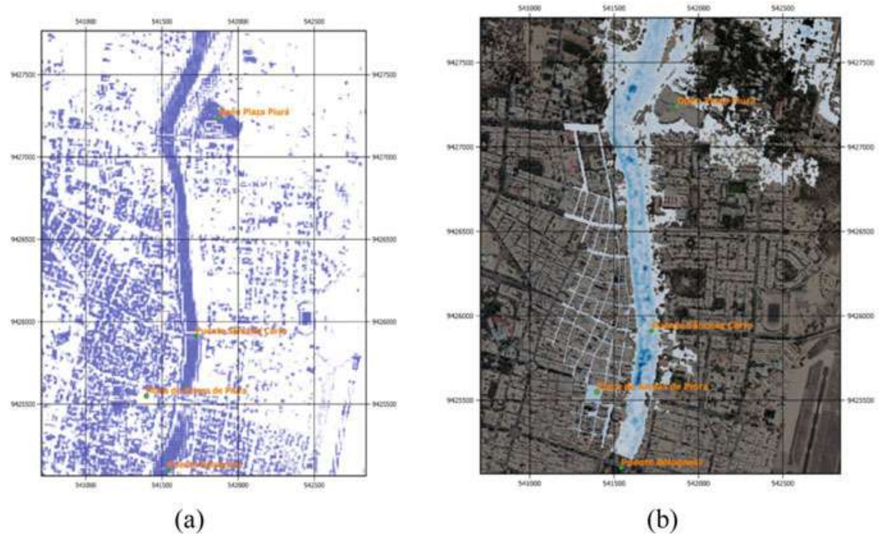

Fig. 2 **a** Flood observed by the SENTINEL-2 satellite for April 4th, 2017 [9]. **b** The simulated flood of March 27th, 2017

For calibration, adjustments were made to both the digital elevation model and the roughness coefficients, so that the results of the flood are more in line with reality, for the calibration of our model. For this, several simulations of the scenario of March 27th, 2017 (FEN Costero 2017) are carried out, verifying that the information about water levels is consistent with what happened historically.

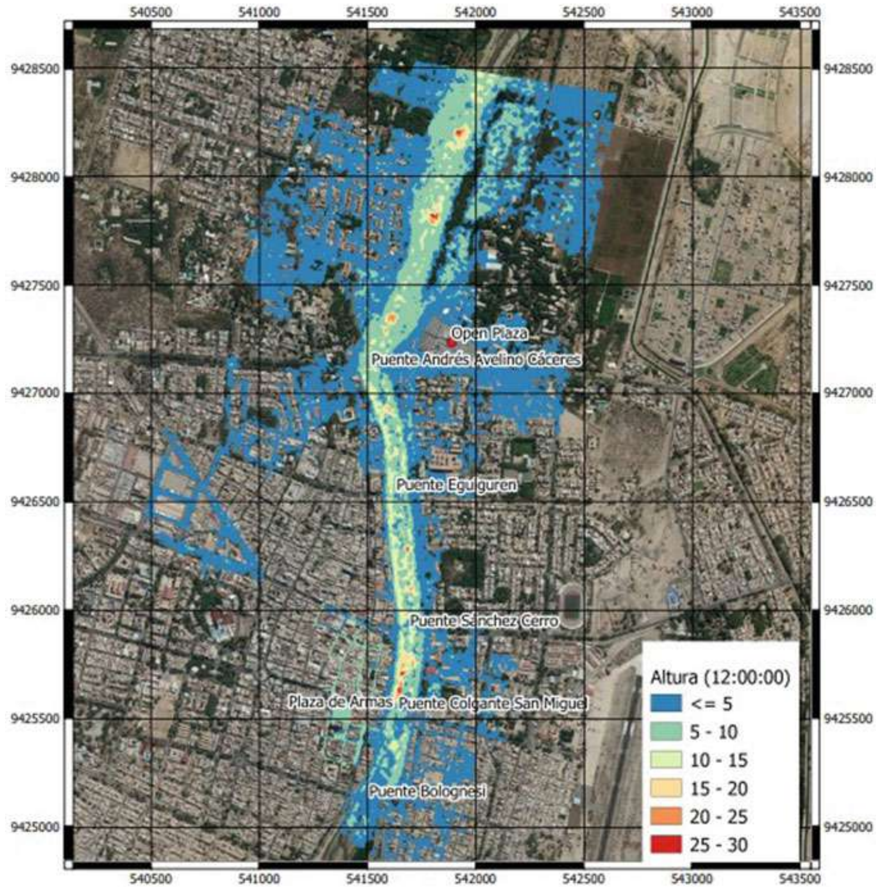

Fig. 3 Flood simulation of the city of Piura for discharge with a return period of 500 years

Table 2 Results of depth and speed obtained from modeling in HEC-RAS

Location	Depth (m)	Speed (m/s)
Open Plaza Piura	2.57	1.26
Main square	1.80	0.099
Sánchez Cerro bridge	3.10	4.25
Bolognesi bridge	2.18	9.90

Table 3 Extremes discharge obtained for different return periods

T (years)	Q (m^3/s)
10	2335.29
20	2950.13
50	3745.97
100	4342.34
500	5720.47

Table 4 Depth and speed for discharge for the return period of 500 years

Location	Depth (m)	Speed (m/s)
Open Plaza Piura	3.55	2.42
Main square	4.72	1.54
Sánchez Cerro bridge	7.37	10.20
Bolognesi bridge	3.80	11.75

4.2 Extreme Event Simulation with a 500 Year of the Return Period

To achieve the extreme event with a return period of 500 years, the distribution of Extreme Values Type I of the maximum instantaneous discharge of the Chira-Piura project was made from 1971 until 2017 when the last El Niño phenomenon occurred. Once the probability of exceedance for this distribution was realized, the flows were calculated for the return periods of 10, 20, 50, 100 and 500 years. To do this, the flows were obtained as shown in Table 3.

Then, the modeling of the extreme event was performed for a 500-year return period, where an increase in the extent of the flood could be seen (Fig. 3). The results of the depths and speeds with a flow rate for the return period of 500 years are presented in Table 4.

5 Results

The simulation performed with HEC-RAS shows an accuracy between 75.5 and 76.67% respect Sentinel Satellite image for April 4th, 2017. For 500 years of the return period, water levels show a significant increase of 103% respect the last FEN 2017, it will generate a greater impact on vulnerable areas and the population.

The simulation carried out for the extreme event provides data on the most affected areas to be damaged by flooding, thus to mitigate the impact of this situation is necessary to develop a contingency, that involves building hydraulic protection structures, dredging plans for water depth that can control these effects.

Water surface elevation (WSE) vary along the stretch of the Piura River, obtaining values between 55 and 63 m.a.s.l (0–15 m water depth), due to the geometry of its channel and the discharge obtained and simulated for a return period of 500 years. The highest WSE found were located by the Open Plaza Piura, being an average of 61 m.a.s.l, since it is upstream and the riverbed was narrower and while going downstream the channel decreases.

The velocity found for a 500-year return period event would vary between 0 and 4 m/s in public places such as sidewalks, streets, the main square, open plaza, etc., and the velocity would increase in the riverbed becoming values between 10 and 17 m/s as in the Sanchez Cerro Bridge and Bolognesi Bridge which predicted speeds of 10.2 and 11.75 m/s, respectively.

6 Conclusions

The main contribution of the work is to make a model as close as possible to the events that occurred historically. As a result of the investigation, a model with a 75% approximation to the facts was obtained, in this way, simulations can be carried out for possible future extreme events of different return periods, as can be done in the simulation for 500 years, where an increase of the flood area of 80% was obtained in comparison with a simulation for 10 years, which represents a normal condition of the river. Also, based on the results of this study, once the most vulnerable areas are found, risk maps and contingency plans will be developed, such as the implementation of riverine defense structures to mitigate the economic and human impact caused by floods.

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