Flood Risk Management due to Climate Variability in Catamayo-Chira Binational Basin

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ABSTRACT: The current issue in the basin focuses on a process of climate change with a clear trend of increasing humidity, with larger and more intense rainfall therefore higher runoff, shortening return periods of extreme events. The operation of hydraulic structures, such as the principal: Poechos Reservoir, affected by sedimentation, especially in very wet years where there are increasingly more likely opportunities for events of magnitude greater, is faced with the difficult problem of considerable excess water discharges, increasing the risk of flooding in the areas located downstream threatening the social and economic infrastructure. Based on hydrometeorological analysis have been developed isohyets maps and 3D surfaces to assess the spatial distribution of rainfall with altitude, considering temporary scenarios with El Niño phenomenon and without it to see the weather patterns of the basin, considering also humidity levels. An analysis of maximum flood and traffic simulation downloads in the basin, using various programs like HEC plataforms and GIS processes, Risk assessment is given through the analysis of probability of extreme events, for different volumes and expected levels of the reservoir. An estimate of damage, according to recent census records, after work, it is necessary to design and establish an action plan for the emergence and identification of possible flooded areas, improving the existing density, especially in sections of high population density and also achieving optimal emergency mobilization. It is necessary a network of weather stations and especially in gauging the confluence of the tributaries of the Chira to understand and manage water resources and extreme events, within a comprehensive hydro-meteorological early warning.

KEY WORDS: Binational Basin, Flood, Climate Variability, Risk Management, Dam operation

1 INTRODUCTION

The Catamayo-Chira basin occupies 17,199.18 km^2 between Ecuadorian and Peruvian territory, the latter to a greater extent, in the department of Piura. Starting at the confluence of the rivers Catamayo and Macara, the river takes the name of Chira. Downstream receives inputs from tributaries and streams that are activated in wet seasons. Floods have intensity in a defined space and time, caused by the dynamics of the earth, where no man intervenes, cannot avoid acting as a lateral overflow of river water in times of heavy rainfall. The risk lies downstream of the dam, in the valley of the Chira River to the Pacific Ocean. It has made an analysis according to hydrometeorological and topographical information collected by institutions of Peru and Ecuador observing the behavior and trend of wet years in the basin, implying greater avenues in the Chira River and the possible evacuation of large flows through the dam Poechos at occurrence of extreme avenues and with the support of numerical simulation models for flood routing in the river. The basin is under climatic incidences both the Pacific and the Atlantic watershed. Both wet and dry years, rainfall, runoff and therefore, abound in the flood season, between the months of February to May, concentrating in March and April, the rest of the year without heavy precipitation, runoff descending to minimum values, while in the high rainfall throughout the year with higher rainfall from January to May.

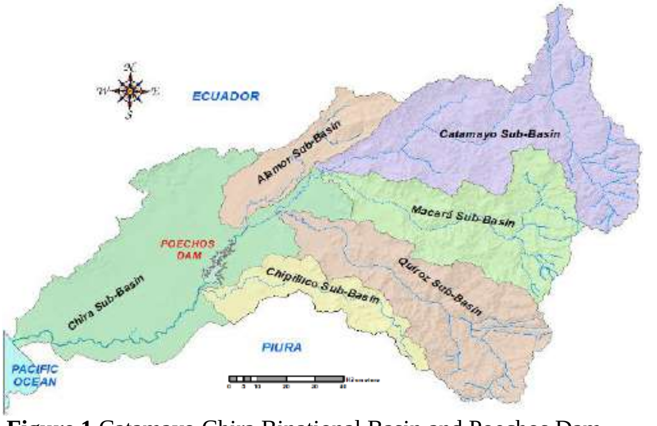

Figure 1 Catamayo Chira Binational Basin and Poechos Dam

2 STUDY METHODS

Throughout this research we study the behavior and climate variability in the basin, evaluating the possible evacuation of discharges during extraordinary events in Poechos dam, now reduced to half of its storage by sedimentation, quantifying the damage that could occur in the Chira river Valley flood, in order to contribute and discuss measures in risk management from the technical, economic, social and sustainable point of view. Meteorological and hydrological history available was analyzed, regionalizing and climatic variables describing its territory, with projections for future years. It is important to highlight the impact of climate changes and recent El Niño events (1982-83 and 1997-98). With the development of research will see the role of regulation and flood control by Poechos Dam, which was not designed for this latter function, and operation of structures associated with current capabilities giving control to projected maximum floods from hydraulic, topographical and sedimentological available data, presenting hydraulic and economic analysis for possible effects on the Chira valley.

The reservoir, with a maximum level of 103.00 m in operation on the project dimensions, formed by damming the river Chira with Poechos, 48 m in height, became operational from July 1976. An important aspect to consider in this context is the Poechos Dam operation should be subject to strict rules made simulations intended to minimize potential flood damage. In years where rainfall intensifies, considerable excess water is discharged to maintain the safety of the dam, preventing flooding and ensuring, at the same time that the reservoir is filled at the end of the season until the maximum normal operation of 103.00 m.

Poechos was designed strictly for storage and regulation, however, has not been considered in the design, the dam has fulfilled and fulfills an important role in the lamination and flood control Chira River, mitigating the risk to flooding. Throughout the Chira, to the Pacific Ocean, are located in the valley about 31 towns belonging to the provinces of Sullana Piura and Paita, positioning on different levels with economic infrastructure such as irrigation works and road, being affected by large runoff and flooding in the case of any extra downloads. Placing ourselves in the year 1998, year in which was presented the phenomenon "El Niño" in Peru, the annual average flow of the river Chira was 484.28 m^3/s, with a maximum of 3,050.00 m^3/s (March) and a minimum of 25.80 m^3/s (October), values obtained Sullana Bridge station (station representative for this research), indicating an exceptional year, generating flooding and considerable damage mainly by scouring sludge material, rocks and logs that are highly erosion in the floods that occurred in villages and low-lying areas of the valley. The study reach extends from the dam (KM 0+000) to the area "La Bocana" (km 95+000) (Fig. 2), the characteristics of the river in that section are variable, its effective width ranges from 300 to 900 m

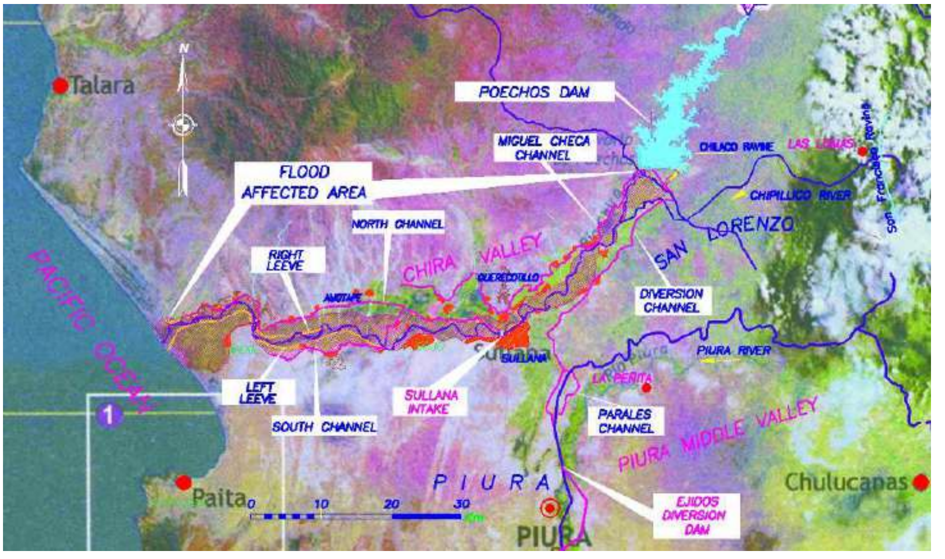

Figure 2 Chira River valley in flood risk (Yellow: Dikes, Purple: Flooded areas)

The basic information for hydrologic and hydraulic analysis is based on studies and measurements made by the Project Chira-Piura, Piura Regional Government and organizations like the INEI, SENAMHI and INAMHI (Ecuador) in the basin with data recorded from 1937 to the 2011. The change in the weather conditions show clear tendency to increase with higher intensity rainfall therefore transport liquid and solid runoff over its territory, decreasing return periods of extreme events. The reservoir will be at risk Poechos to download large volumes that can affect the Chira River valley and cause flooding, injuries on many economic and social sectors in the population. As for weather stations in Catamayo sub basin (Ecuador) are seven 12 stations, 3 stations to Macara (Ecuador and Peru), 5 sub stations for Alamor (Ecuador) for the sub Quiroz (Peru) 3 stations and from Chira sub basin (Peru) to the Pacific Ocean are five 5 stations. They have average monthly precipitation series of up to 48 years. Isohyets maps were developed and three-dimensional maps based on geostatistical Kriging interpolation for normal years and El Niño. The graph shows the distribution multiyear upward territorial precipitation with altitude, which changes in El Niño years with higher rainfall in the middle of the basin (Fig. 3)

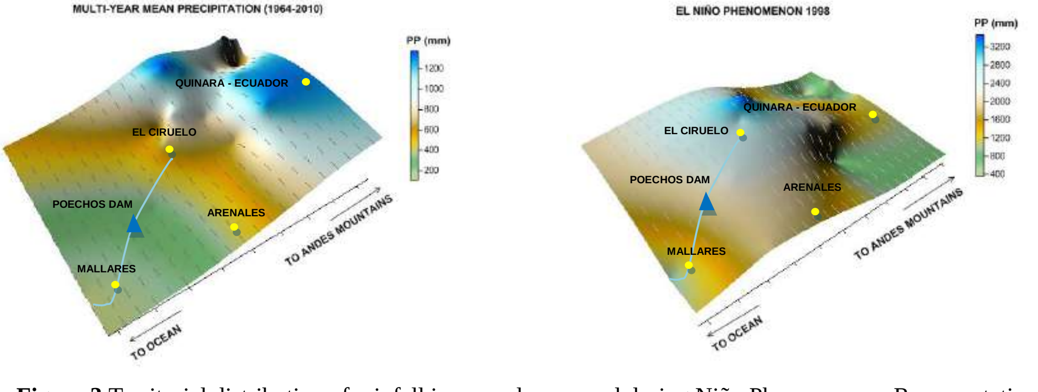

Figure 3 Territorial distribution of rainfall in normal years and during Niño Phenomenom. Representative Hydrometeorological stations in yellow

The power of events like El Niño is characterized by the value of a SOI (South Oscillation Index) which we show in Figure 4, provided by the National Oceanic and Atmospheric Administration (NOAA). It must also relocate the El Niño in the context of the possibility of climate variability.

Many experts agree think the hypothesis of global climate warming on the planet, if so would run the risk of very strong Niño phenomena more frequent.

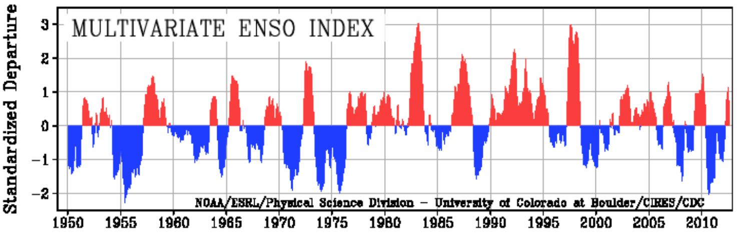

Figure 4 Surface temperature standardized anomaly of Eastern Pacific Ocean (Red area> El Niño Phenomenom, blue area>La Niña Phenomenom)

Basin is climatically regionalized for a greater understanding of hydrological and meteorological behavior, considering spatial variability of physiographic and hydrologic features. With full regionalization inspects existing information, trying to estimate hydrological variables in places lacking data where existing or insufficient quantity or quality. This technique allows better explore specific samples and, consequently, improve the estimates of the variables; verify consistency of hydrological series, identify the lack of observation posts, etc. The technique of Index Avenue, used to regionalize was proposed by Dalrymple (1960), which states get rainfall or peak flows for a return period of 2.33 years as a function of geographical coordinates and compared with rainfall or average annual maximum discharge obtained by frequency distribution adjustment. In our case the methodology is reliable with a correlation between the Real and the Regionalized than 94.00%.

In order to obtain four future scenarios were defined Climatically Homogeneous regions (Fig. 5). To check if they are homogeneous even in cases that are not geographically, multidimensional strokes method by Andrews (1972) was used, performing multiple regressions between precipitation values for each station and its geographic coordinates, defining more based conceptual whether or not the regions are homogeneous. In this binational basin we face the difficulty of not having the necessary hydrometeorological information, in quantity and quality, in order to estimate the flow rates to study the waterworks as Poechos dam. In the sub information is not relevant for a proper hydrological study. Using mapping regionalization hydrological reduces time that takes hydrological studies, ensuring high reliability in the estimation of the design variable associated with a given recurrence period.

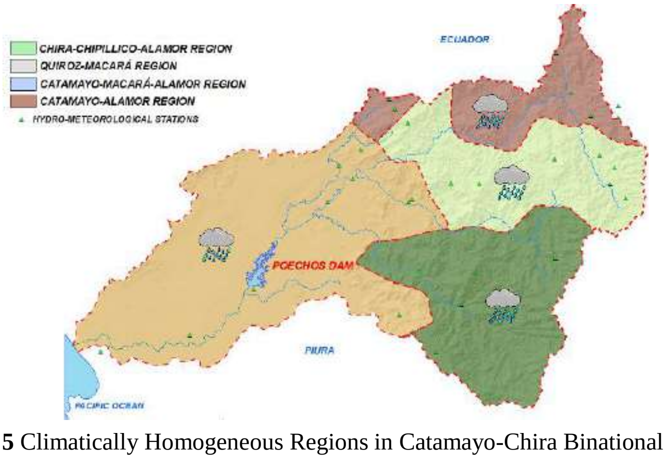

Figure 5 Climatically Homogeneous Regions in Catamayo-Chira Binational Basin

Orange region is the largest, but in turn require a greater number of stations arranged for further study. In this region has Sullana Bridge hydrological station. If we analyze the rainfall for each station, we define the kurtosis as a measure that indicates the degree of presence of observations very far from the mean, taking a measurement of the deviation. If annual rainfall is a moderate dispersion variable and many kurtosis, the rain will be relatively stable performance year after year, with no major ups and downs but, exceptionally, years with rainfall produce very different from the usual: either very dry years, or extremely rainy years. Noting the maximum monthly rainfall records each season in two phases, with a before and after El Niño phenomena. In almost all of the stations has decreased kurtosis, showing that there is interannual variability in rainfall, and therefore wet years (rainfall) will not be seen as "exceptional" or "unexpected", but occur more frequently compared to past. In the upper basin (Ecuador) specifically in the region Catamayo-Alamor rainfall decreases in size over the years (negative trend), the opposite occurs in the middle and lower basin where we have a progressive increase, therefore the basin is undergoing a process of climate change with a tendency to wet seasons.

RESULTS AND DISCUSSION

Field Investigations

There was a visit to the dam to update the knowledge of the state of discharge works gathering information, and also observed the evacuation channel spillways (Figure 6), as Chilaco creek , who was with dense vegetation, and the Chira River channel for possible flood zones, crop areas and marginal strips. Were inspected side income streams and live the reservoir and Chira River channel and hydrological and meteorological stations installed in the Peruvian sector.


Figure 6 Emergency spillway (fuse dams) and spillway with gates in Poechos dam

Before the 1983 El Niño phenomenon, the annual volume of sediment is presented within the expected levels in the design, ie between 6-8 MCM / year. In extreme events sedimentation volume averaged 75.0 MCM / year. Performed after the last measurement (September 2011) of sediment through a bathymetric, reservoir capacity has decreased 52.79% representing 467.19 MMC (Figure 7), of the 885MCM initial operating volume, this means that the current available volume is 417.8 MCM. It is important to know the process of sedimentation in the reservoir Poechos because it affects the "expected volumes" rolling reducing its capacity to floods as calculated in the simulation transiting the Chira River channel.

From the start the operation of the reservoir has been governed under different rules of operation, which have been in effect at different times but considered only as a storage reservoir of water to be refilled as soon as possible, without considering that this could cause serious problems downstream flooding due to the discharge of excess water. The rules of operation are in three types of as extraordinary hydrological year (1982/83-1997/98), wet (1998/99-2001/02), normal and very dry. If we take the pattern generated extraordinary events of El Niño causes (Table 1) shows that the highest average daily maximum flow occurs in the month of April 1983, after being produced in the previous month's most monthly precipitation in the middle and upper basins, downstream Poechos higher rainfall occurred.

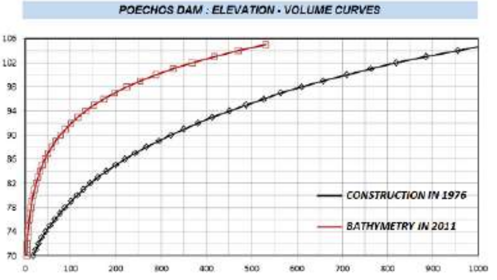

Figure 7 Bathymetry Survey in 2011 and Great storage Changes in Poechos Dam

It is also noted that the average daily maximum flow Poechos falls from May 1983 to be significantly reduced precipitation in the middle and upper basin. Finally, during El Niño 1982-83 average daily peak flows were influenced by high rainfall in middle basin, especially in the homogeneous region Chira-Chipillico Alamor, since in the upper basin are precipitation runoff and therefore small, which have a lesser role. Also, that occurred in the lower basin the highest monthly rainfall between March and June. In the other years without El Niño peak flows also occurred daily mean significant magnitude, but only for 1 month a year, contrary to what happened in years with El Niño phenomenon which occurred during 6-7 months a year

Table 1. Rainfall and Maximum flows in the Basin during El Niño Phenomenon

Year	**Month**	**Monthly Precipitation**			**Poechos Maximun daily Dischargue (m^3/s)**
		Upper Basin	**Middle Basin**	**Lower Basin**	
1982	**November**	150	30	0	82
	December	300	150	20	589
1983	**January**	380	400	350	1726
	February	150	250	150	1679
	March	450	350	550	2059
	April	250	550	650	2469
	May	50	400	500	1770
	June	-	150	300	1693
	July	-			316

With the variability has on the magnitude of precipitation and peak flows in the basins of Chira, it is interpreted that there is no simultaneity of the joint occurrence of rainfall events affecting critical operation Poechos discharge system. It is emphasized that exceptional events are independent in minor and major sub-basins, given the different geomorphology and surface coverage, so it is concluded that not apply the sum of the maximum flow, eg to the Chira Chipillico for an analysis of maximum flooding in the Chira Valley. Basic information about daily and instantaneous peak flows the river Chira was obtained by Sullana Bridge hydrometric station for the period 1937-1975. In 1976 with the construction of the dam began recording at the entrance of the Reservoir during the period 1976-1997. From 1998 to date inflow dischargues are calculated indirectly through dischargue structures, water levels in the reservoir and evaporation because "Ardilla" hydrometric station, located at the tail of the dam, was destroyed during El Niño Phenomenon in 1998. The determination of maximum avenues was made by HYFRAN hydrologic model that allow notably statistical analysis of extreme events, using tests of homogeneity, independence of the series and analysis with 15 theoretical frequency distributions. In contrast to results of previous studies, the Pearson distribution is adopted. The density and probability distribution function is defined as:

$$f(x) = \frac{1}{\alpha_1 \Gamma(\beta_1)} \left[\frac{x - \partial_1}{\alpha_1} \right]^{\beta_1 - 1} e^{-\frac{x-\partial_1}{\alpha_1}} \qquad F(x) = \frac{1}{\Gamma(\beta_1)\alpha_1} \int e^{-(\frac{x-\partial_1}{\alpha_1})} (\frac{x - \partial_1}{\alpha_1})^{\beta-1} dx$$

Where: λ1, β1 and δ1 are the parameters of the distribution and (β1) is the Gamma function.

The contribution of the basin downstream of the dam is not negligible, though not decisive from the point of maximum flows, distinguishing the streams of Chipillico and Saman. For calculation of time of concentration and other factors, the contributions of side streams, given the different geomorphology and surface coverage have no effect on the flow of the Rio Chira, which should be considered for analysis. Discharges have been evaluated considering the Dam operation in three critical maximum discharge capacity of the spillway gate, physics 6150 m^3/s, 2500 m^3/sec 5500 operating m^3/ s emergency because of possible damage to the stilling basin downstream. Regarding the emergency spillway peak discharges were determined levels of each fuse dam crests: 105.00, 105.30, 105.60 and 105.90 m, each of the four dams reach their physical ability when:

-The reservoir water level exceeds the crest level of each fuse dam in 0.30 m, or

-In case this level is not reached after one hour of operation.

The goal includes assessing maximum income avenues to the reservoir with flow rates up to 15,500 m^3/s and the incidence of these events both the magnitude of the storage volume as the initial level or "hold" water. If we analyze the operation in very extreme events and emergency spillway, the fully activated extensive damage would occur and the destruction of almost all works located in the valley of the Chira River, so it is necessary to propose measures to avoid or reduce the minimum possible negative effects of such an eventuality. To consider the problem of sedimentation was simulated in addition to the initial working volume (885 MCM) and the current volume for comparison of the effect of reservoir operation loss to laminate avenues. The mathematical model is in solution, in real time, considering the continuity equation follows from the equation shown with finite variables:

$$0.5(Q_i + Q_{i-1} - q_{i-1})\Delta t + V_{i-1} = V_i + 0.5 q_i \Delta t$$

$D_t = t_i - t_{i-1}$

Q_{i-1}/Q_i: Inflow at the start and end of the time interval.

q_{i-1} / q_i: Outflow at the start and end of time interval.

V_{i-1}/V_i: reservoir volume at the start and end of the time interval.

D_t: Time interval.

Whereas, in general, the volume of the reservoir and discharge are functions of the water level, the solution of the above equation is relatively easy by means of the iterative method. The downloads for the spillways has been done within the framework of the proposed operating rules for storage volumes between 190 and 417.8 MMC, considered for the simulations and evaluations. To set the rules has been carried out the simulation of the operation time of the reservoir in real time to the period of March 25 to April 18, 1998 (Figure 8) that, according to the simulation results of 2002, it be the most critical period for the operation of said reservoir for all the time since its commissioning in 1976, aiming not to exceed the maximum of the normal operation of 103.00 m.

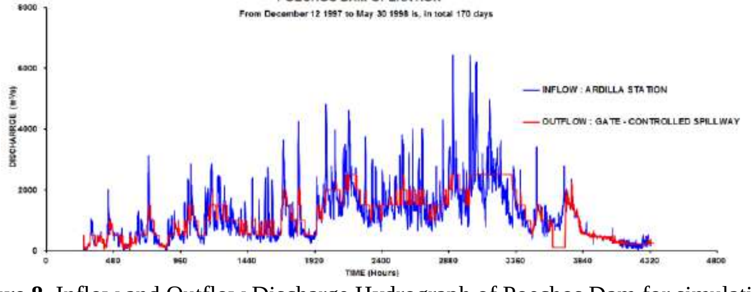

Figure 8. Inflow and Outflow Discharge Hydrograph of Poechos Dam for simulations

The flow routing has been considered two phases: Based on the mathematical model of rolling and flood retention, calculated peak discharges varying inflow discharges and volume expected levels, and the other phase, associating potential floods with the probability of their occurrence, has assessed the risks, ie. return periods. Activation of the emergency spillway and evaluation of critical inflow floods and peak discharges was performed within the framework of the rules of operation and have located four stages covering different limitations on the use of maximum capacity of the structures controlled relief of the reservoir. 1) Stage A, Within which peak discharges are generated different levels of the reservoir to wait between 98.00 and 103.00 m levels, according to the magnitude of the storage volume to maximum operating level 2)Stage B extends its validity on all reservoir storage volumes, considering the operational capacity of the spillway gates.3) With stage C is considered physical capacity spillway gates installed.4) In stage D enters the frame of the emergency spillway capacity of 2,500 gates m3 / s, with two sub-stages: D1, limited to a height of 104.00 m and D2, to the maximum level possible for the entry and passage through Reservoir Avenue with the maximum flow of 15,550 m3 / s 10,000-year return period. The unit hydrograph typical Avenue entrance to the reservoir, which comes from the evaluation of the hydrograph of the Probable Maximum Flood (PMF) for the simulation of gradually varied flow, steady and unsteady, between the dam and the Pacific Ocean was necessary to form mathematical models from the Dam to Ocean Pacific and from Chilaco Creek to Chipillico River and finally to its confluence with Chira River.

Topographic surveys conducted in Chira riverbed until today have been improved using ASTER-GDEM digital elevation model (Figure 9) which provides accuracy of up to 20 m, surveying corroborated. With this new model were extended cross sections to cover the entire valley. The LANDSAT satellite imagery and Google Earth allowed seeing Chira current stream . By treating "Tiff" image files and others with Geographic information systems and derivatives (ARCGIS, HEC-GeoRAS) we can establish the sections of the river in order to work with HEC-RAS model.

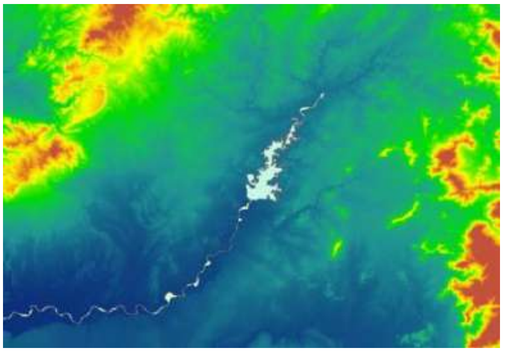

Figure 9. ASTER GDEM model in the study area

According to the morphology of the river Chira and other waterways leading inherent reservoir discharges to the Pacific Ocean, variable section and no permanent flow simulation and evaluation of hydraulic variables was carried out by through computerized software package HEC-RAS (River Analysis System) by U.S. Army Corps of Engineers, Hydrologic Engineering Center, Version 4.0, 2003, (Figure 10) developed precisely for this type of simulations. Following the recommendations of The Spanish National Committee on Large Dams, only considered significant incidence of obstruction in the wave when simultaneously presented the following two circumstances: 1) Represents a significant obstruction, which, expressed as area ratio and total clogged pierced channel is over 20%. 2) The obstruction creates a temporary reservoir relative magnitude importantly, that with respect to the volume wave dam failure, more than 5%. Not occur if any of these circumstances, be established, in general, the hydraulic regime regardless of their existence.

Finally, the mathematical model for the entire Chira River between the dam and the Pacific Ocean Poechos of 91.91 km was applied to four sections of the river Chira. Mathematical model of the first section, between the dam and diversion dam Poechos Sullana, of 33.59 km long, with 52 cross sections. The second section, between the diversion dam and the town Sullana Macara, of 20.03 km long, with 29 cross sections. The third section, between Macará and Arenal town , of 21.65 km long, with 33 cross sections. Fourth section, between El Arenal town and the Pacific, of 16.64 km long, with 29 cross sections. Finally there is a important zone, between the emergency spillway and the river's confluence with the Chira Chipillico of 5.29 km with 18 sections. The boundary conditions for the first tranche of the mathematical model between Poechos dam and Sullana diversion dam are set to start in Poechos with discharge hydrographs (Figure 11) and controlled relief with dam operation, generated based on the simulation of rolling flood and its termination in accordance Sullana diversion dam rating curve.

For subsequent sections, the discharges hydrograph previous section is regarded as the boundary condition at the start of the section, while the termination is considered rating curves in steady flow simulation for different flow therefore considered 5,812 m3/s as the capacity limit levee has been simulated in two scenarios: with and without these, considering them destroyed and washed. The simulation traffic from other large-scale discharges has been carried out within the framework of levees warrant completely destroyed as the respective cases.

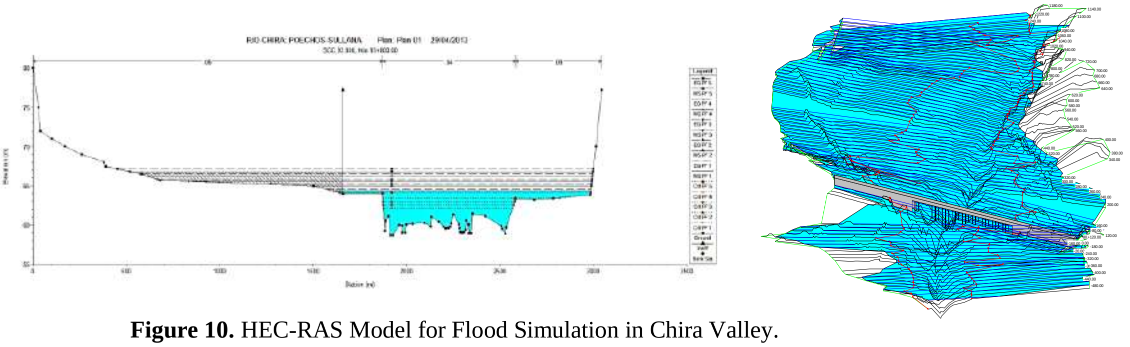

Figure 10. HEC-RAS Model for Flood Simulation in Chira Valley.

The decrease in reservoir storage volume due to sedimentation, virtually no effect on the passage of the avenue of 10,000 years, with the maximum flow of 15,550 m3 / s, keeping in all cases the maximum levels. According to the analysis and simulations estimated the total damage value based on simulations evaluating conditions to social infrastructure, economic infrastructure and agriculture in particular, for being the first important economic activity that is impacted within the area of influence.

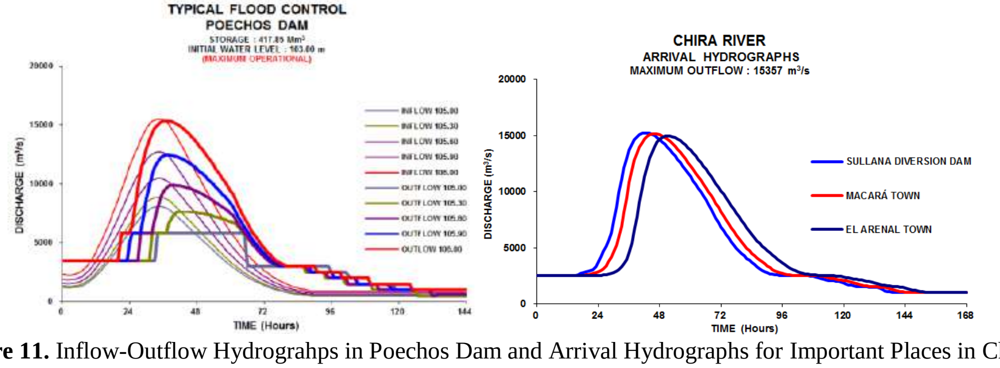

Figure 11. Inflow-Outflow Hydrograhps in Poechos Dam and Arrival Hydrographs for Important Places in Chira Valley

According to the simulations and the related capacity channels, generate substantial flooding throughout the Chira valley downstream of the dam to the Pacific Ocean, causing extensive damage to both agricultural areas and infrastructure in the valley, especially in the former located on the banks and in the bed of the Chira such as bridges, levees and riparian protection works and the diversion dam Sullana, among others. The flood maps were projected on the National Geographic Institute (IGN), cadastral maps and according to the definition of Chira River marginal strip (Figure 12). According to 2007 census in Perú and delineation of marginal strips, there are a total of 396.215 inhabitants of the provinces of Paita and Sullana, detailing population densities and crop areas, among others. Total damage has been estimated value based on simulations evaluating conditions to social infrastructure, economic infrastructure and agriculture in particular, being the first important economic activity that is impacted within the area of influence. Given the valuation of damage likely effect of floods, it has established a best-fit relation of the data that defines a polynomial trend of the value of the damage. Citing potential damage from a flood hypothesis generated by a discharge with return period 100 years, would affect 15 towns of the provinces with 3,514 Sullana Paita and inhabitants, 5530.45 hectares of agricultural land among others. The total value of the damages that would produce a phenomenon of this type amounts to over U.S. $ 143'200, 100 approximately.

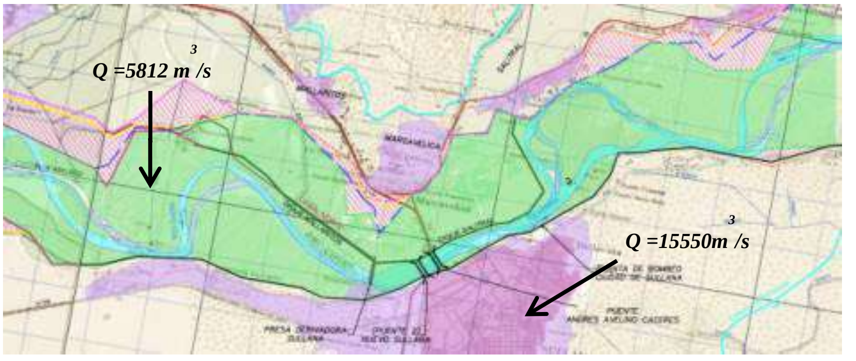

Fig 12. Potential Flooded Areas in Sullana City due to Critic Discharges in Poechos Dam (Chira River in sky-blue)

CONCLUSIONS

The binational Catamayo-Chira basin has a trend of climate variability with wetter seasons trend intensified in the middle and lower basin, and therefore higher runoff, leading to Poechos Reservoir is at risk of operating at events sheet ends and wide avenues with current issues that has accelerated sedimentation. The magnitude of the losses caused by a flood event at a given time point is determined by the total value of damage, the fact that happens or not determines a situation of uncertainty and reflects the risk of damage expressed by the probability of occurrence . The main damage identified, quantified and valued consist of social infrastructure (equipment of population centers, housing and basic equipment of households), economic (agricultural and non-agricultural land, road infrastructure and irrigation infrastructure) and economic activities in flood areas, where agriculture is of primary importance.

With this research remains to conceive, design and establish emergency programs aimed at protecting populations inhabiting areas at risk of flooding which can collect national and international experiences. Signaling is essential and flood zoning and setting milestones materializing with the areas of safety and security or protection. Investment costs, operation and maintenance of alternative solutions should not exceed the estimated damage values according to probability of occurrence of rare events whose return periods are shortening. A system of early warning and monitoring in the basin is needed through a line located according to hydrometeorological network regionalization made to detail what happens in the basin hydrology and meteorology. It has made a proposal to the government on these two key points.

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