PREDICTING FLOOD HAZARD AREAS: A SWAT AND HEC-RAS SIMULATIONS CONDUCTED IN AGUAN RIVER BASIN OF HONDURAS, CENTRAL AMERICA

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ABSTRACT

Honduras is located in the Caribbean basin where hurricanes represent a constant natural threat to human lives and physical infrastructure. Hydrological monitoring is considered as an effective tool to respond to high flood events by preventing and mitigating damages. The purpose of this study was to conduct and perform hydrological modeling to determine areas prone to be flooded during high rainfall events in the Aguán river basin, Central Honduras.
The methodology involved: hydroclimatic data base building, a detailed Digital Elevation Model (DEM), a land use cover, based on a LandSat-satellite imagery, and a soil map of the basin. With all this data, the SWAT model (Soil and Water Assessment Tool) was used to predict discharge values. These discharge values were used, along with the DEM, to predict flood hazard areas in the Aguán river basin floodplains. This procedure was made using the HEC-RAS model (Hydrological Engineering Center-River Analysis System).
Finals results show the exact location of areas with high, moderate and low risk to be flooded at specific high flood events. The results also provided the location of critical areas, so that an early warning system can be located. Additionally, as a part of this study, valuable information was provided to at-risk residents about how to prevent and mitigate the effect of flood-related damages in low land areas of the Aguán basin.

INTRODUCTION

Honduras is relatively well rich in natural resources and they seem to be, at least for the near future, the primary source that drives economic growth. Natural resource-related sectors represent a significant percentage of the gross domestic product (GDP). Further, Honduras' wealth of ecosystems and biodiversity places it in the middle of the Central American Biological Corridor and connects it with the Mesoamerican Coral Reef System, both of inestimable value nationally and within the continent. However, this natural resource wealth and potential are under increasing human and natural pressures that will further undermine the economy, impoverishing the people and region as a whole.

Honduras also has abundant water resources. The average precipitation rate is 2,000 mm per year and this rainfall produces significant runoff from watersheds (Government of Honduras 1991). Two major river systems drain from the central highlands to both the Caribbean sea (eight river basins) and to the Pacific Ocean (two river basins) (Gutierrez 1992). Since Honduras is a narrow strip of land, rivers run from the continental divide (2,000 meters above sea level) to the lowlands in the Pacific and Carribean coasts in very short distances. As a result, rivers are typically steep, enclosed in v-shaped valleys, and possess dendritic drainage patterns. An impermeable, semi-compacted soil layer underlies a thin soil surface which increases the risk of flash floods during the rainy season (Hargreaves 1992). Approximately 75 percent of the country has slopes steeper than 15 percent and the country experiences a highly seasonal rainfall pattern and a tendency towards extreme storm events. In addition, current land use, resource exploitation practices, and related population impacts, pose major obstacles. Under these conditions, economic activities and human well-being are tied to unhealthy and unsustainably-managed watersheds and river basins.

Around 73 percent of land in Honduras is suitable for forestry production or perennial cultivation, with only 23 percent of Honduran soils designated as suitable for agriculture and livestock (COHDEFOR 1996). In real terms, however, only 50 percent of the land is currently is forested and the balance is under agricultural production and other uses. Deforestation due to: inappropriate farming, grazing, forestry and other resource extraction practices, driven in part by poverty, ignorance, inadequate policies or enforcement safeguards, or inadequate market incentives have resulted in significant soil degradation and accelerated erosion rates, especially since Hurricane Mitch. The water attenuation and retention capacity of the soils and vegetation has been reduced, resulting in increased flash floods and landslides. Sedimentation blocks streams, degrading water quality and further increasing the threat of flooding.

Purpose and Need

In the last decades the frequency and intensity of hurricanes have doubled in the Caribbean basin. In October of 1998, Hurricane Mitch hit Honduras taking more than 11,000 lives and millions in infrastructure damages. Ninety percent of the bridges were damaged and one quarter of the population was directly affected (Hubb and Inbar, 2002). At the Aguan river basin, the town of Santa Rosa de Aguan, located at the river basin outlet, almost disappeared. The country was not prepared to mitigate a natural disaster of that scale. Since that time, however, Honduras recognized its vulnerability to these phenomena and has been establishing emergency operations centers throughout the country to avoid that kind of destruction. Another important point that became very clear during Hurricane Mitch was the inseparable link between emergency preparedness and sustainable natural resources planning. Much of the loss of life was a result of: landslides from unstable, saturated or eroded hillsides; an inundation of flood water on low-land areas where people setup homesteads; and a lack of communication of where the dangers and safe places could be found during, and immediately after the hurricane hit. Projections indicate growing problems of endemic flooding, landslides, severe shortages of drinking water, scarcity, and contamination of water for productive uses. Honduras sees the need to address disaster preparedness and mitigation along with natural resources management.

This study consists of assessing the river flow patterns for the Aguan river basin (Figure 1). River flow modelling was conducted using SWAT (Soil and Water Assessment Tool), a computer-based program developed by University of Texas. Then, discharge values were used, along with the DEM, to predict flood hazard areas along the river basin's floodplains. This procedure was made using the HEC-RAS model (Hydrological Engineering Center-River Analysis System).

Based on the result of this study, the government agencies and disaster relief NGO's are directing efforts to relocate human settlements, high-value crops, place emergency response systems and increase people awareness.

Characterization of Honduras

Honduras is located in the center of the Central American isthmus, between 13° and 16° latitude North and 83° and 89.5° longitude West (Figure 1). It has an area of 112,088 square kilometers (Annis 1993).

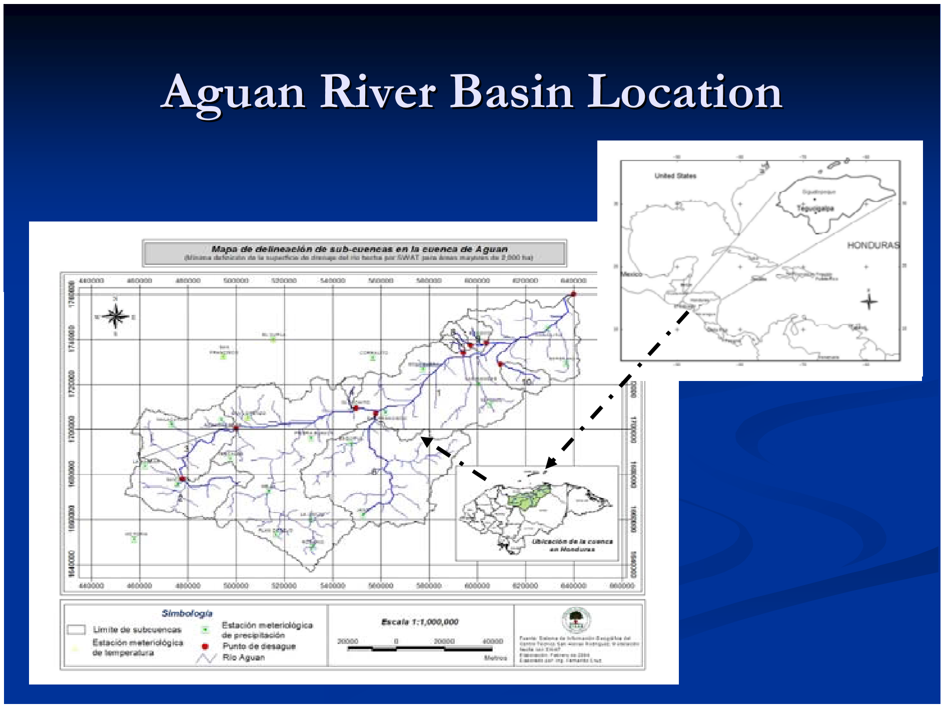

Figure 1. Location of Honduras. The Aguan river basin is located in the Northern portion of Honduras.

The Study Area

This study was conducted in the Aguan river basin (Figure 1), located to the southwestern of the town of Trujillo, Honduras. The area is mountainous with elevations ranging from 0 to 2,000 m above sea level. Rainfall in the valleys is approximately 2500 mm per year, while upland forest-covered areas receive an annual average of 2000 mm (Hargreaves 1992).

The study area is located within the North Coast Corridor, the core of which includes the coastal watersheds between La Ceiba and Trujillo (all or parts of some 15 municipalities, some 50,000 people), is characterized by rich, regionally significant, and threatened biodiversity. It has high potential for tourism and other natural resource-based enterprise development, and suffers conflicting demands – industrial and urban growth – on its resources. This population is entirely rural and the vast majority lives below the poverty limit. Great efforts are being done by the government agencies to provide safe water to downstream users and improve living standard conditions of the upstream residents.

Poor management of land and water resources is significant, and the area is highly vulnerable to the impacts of natural disasters, at the same time that intact natural systems provide significant protection against extreme events (Annis 1993). This geographic area includes eight existing and one proposed parks and protected areas. An integrated "ridge-to-reef" approach to natural resources management is required to improve land and water management, decrease pressure on protected areas and critical biological resources, and mitigate against natural disaster impacts.

METHODOLOGY

The methodology started with the data collection process. This consisted of obtaining a current land use cover. A land use map, generated for the area, was made using a 2000 Landsat image and Arc View ver. 3.2 (Howard 2000; Alexander and Millington, 2000). The field data collection consisted of using GPS to validate the obtained land use covers.

The soil and climate data bases were built using local data from government agencies and previous studies. Both were transformed and edited to be used as input files for the SWAT model. A portable digital flowmeter Flowmate Model 2000 was used for flowstream measurements. Rain gauges data was collected from all 5 authomatic weather stations distributed all over the studied watershed.

The most consuming time part was to build the Digital Elevation Model (DEM) for the river basin delta. The DEM was prepared for the town of Santa Rosa de Aguán (136.10 Km^2) and an additional are of the Aguan river basin (40.54 Km^2). The method consisted of extracting the MDT main features using digital photogrammetic procedures embedded in the OrthoBASE Pro® software (ERDAS 2003). This technology allows creating digital stereoscopic pairs from different sensors. We used panchromatic aerial photos, scale 1-40,000. Nine points from the primary triangulation network were acquired using a Primary Ortho Rectification procedure.

Aerial photos were digitized with high resolution (1016 dpi) to detect a minimal differential area of 0.0004 ha. A total 0f 49 Ground Control Points (GCP) were chosen in the field and located in the aerial photos. Latter, these GCP were used in the triangulation process. Vegetation, water bodies and other terrain features were subtracted to obtain a more accurate DEM. Contour curves (20-meter) were digitized from the rest of the basin to complete a DEM for the entire area (Lillesan and Kiefer, 2000) (Figure 2).

Further, the data bases containing: land use, soils, and climate data were adapted with field data and information collected from local agencies. In order to predict streamflow patterns under different scenarios, SWAT simulations were ran using the soil, climate, DEM and land use data.

With the complete DEM, flood plains and channel geometry features were mapped using ArcView and the extensions: HEC-GEORAS and 3D Analyst (Figure 2). River flow direction was also determined to further use it as a model input variable.

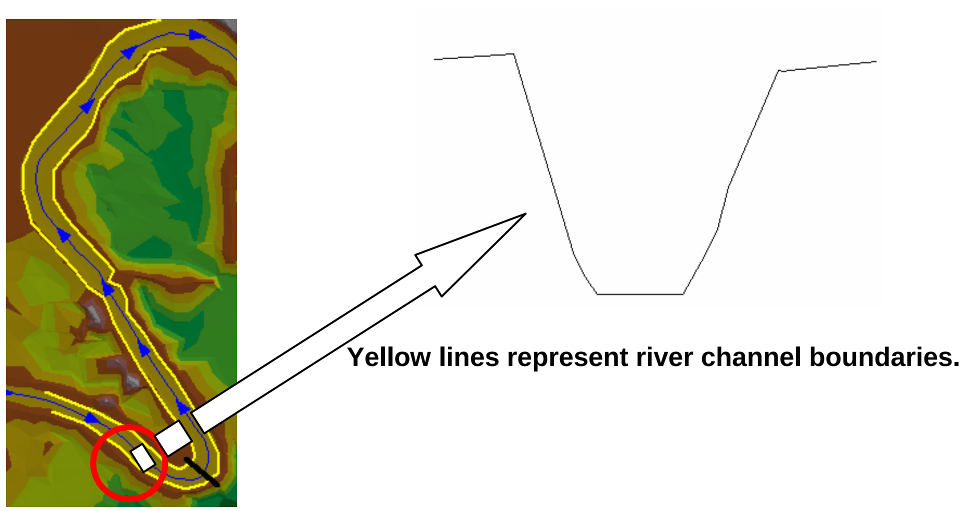

Figure 2. Mapping river channel features from the Digital Elevation Model, DEM, Aguan River basin, Honduras.

Cross sections are perpendicular lines to the flow direction. Their width varies depending upon channel geometry and floodplain configuration. These cross sections were calculated for the valley floodplains subjected to frequent inundation events (Figure 3).

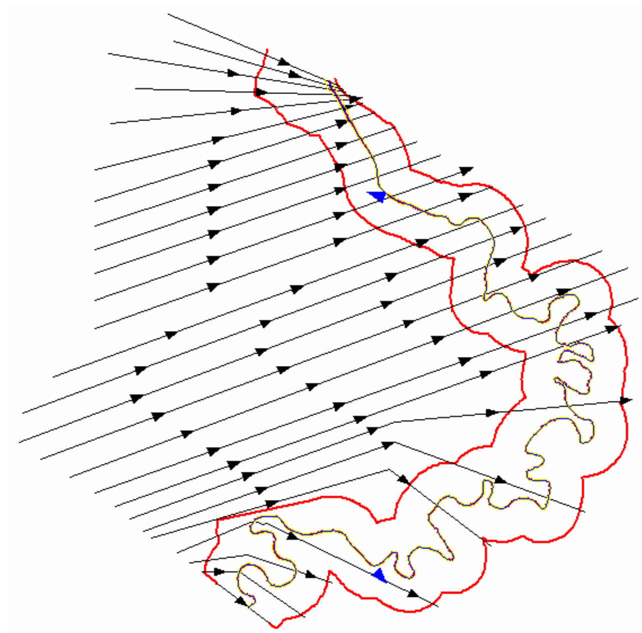

Figure 3. Mapping cross sections at the river channel, Aguan River basin, Honduras.

Information from channel geometry and SWAT-generated discharges values were used to generate HEC-RAS channel flows. HEC is a very sophisticated computer program to model water surface profiles from corresponding discharge values. The HEC-RAS model calculates water surface elevations at all locations of interest for given values. It uses Bernoulli equation (1) for subcritical flow at each cross section (Bedient and Huber, 2002):

$$WS_2 + \frac{\alpha_2 V_2^2}{2g} = WS_1 + \frac{\alpha_1 V_1^2}{2g} + h_e \qquad \text{(Eq. 1)}$$

where:

$WS_1, WS_2 =$ Elevation of water surface at each cross section

$V_1, V_2 =$ Mean velocity

$\alpha_1, \alpha_2 =$ Velocity coefficient

$g =$ Gravitational constant

$h_e =$ Energy head loss

All data were analyzed and processed using the software and procedures above mentioned. Water surface elevations predicted with HEC-RAS were used as input to generate the flood area coverages. This information allowed us to visualize (spatially) where the high hazard areas might be located.

As a last step, a vulnerability analysis workshop was conducted in a set of community meetings, in which at-risk resident expressed their opinions on what they though it represented a risk for their lives. In natural disaster terms, *vulnerability* represents the susceptibility of the human beings who are exposed to the threat (floods, in this case) and it is usually associated with socio-economic vales (USAID, 2001; Hubp and Inbar, 2002). Around 90 families were interviewed in the workshop, following CATIE methodology (CATIE, 2003).

RESULTS AND DISCUSSION

The photo interpretation process allows us to detect where the Santa Rosa de Aguan population was located, its proximity to the river meandering system and to the Caribbean Sea. Figure 3 shows the location of these three features and also how the cross sections were delineated in the terrain to further be modeled with the hydrological models. We also used this image as the starting point to develop the DEM of the area.

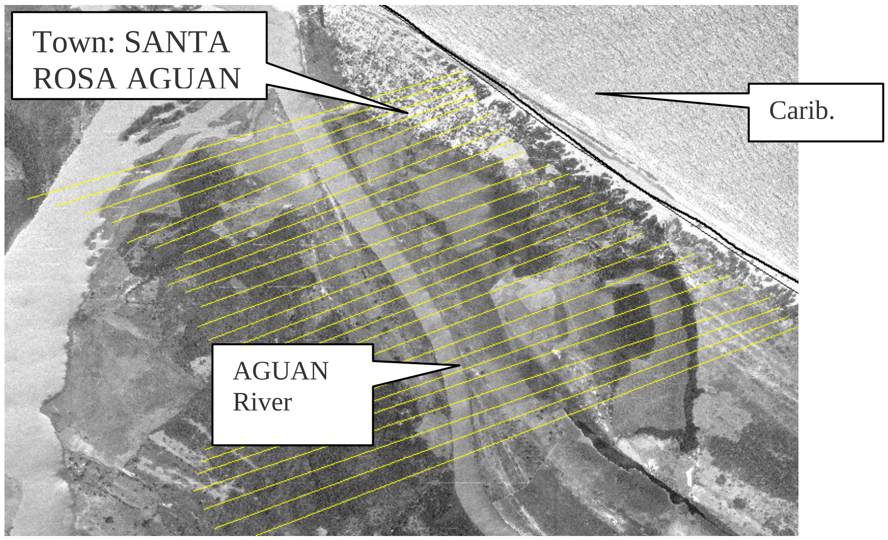

Figure 3. Aerial photo showing the Town of Santa Rosa de Aguan, Aguan River and the Caribbean Sea Aguan River basin, Honduras.

Digital Elevation Model, DEM

The developed DEM showed great precision in the majority of the area of the studied basin, however, in some areas such as: urban and riparian zones, its precision decreased due to: texture, brightness and the triangulation process of the aerial photos. These photo features affected the stereo-visualization of the photo pairs and consequently, affected the precision of the DEM (Fig. 4).

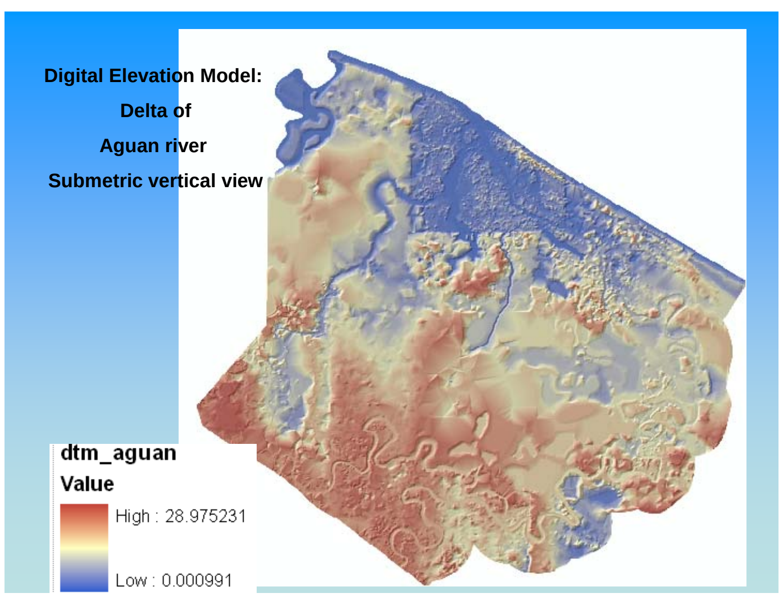

Figure 4. Digital Elevation Model, DEM, for the delta of Aguan River, Honduras.

SWAT Simulations

Figure 5 depicts how the predicted discharge (Q) values (35 values) behave with the observed discharge values (Q) (35 observations). In general, SWAT predictions were relatively close to the observed values. SWAT showed some increases that corresponded to some slight variations in the observed values (Fig. 5).

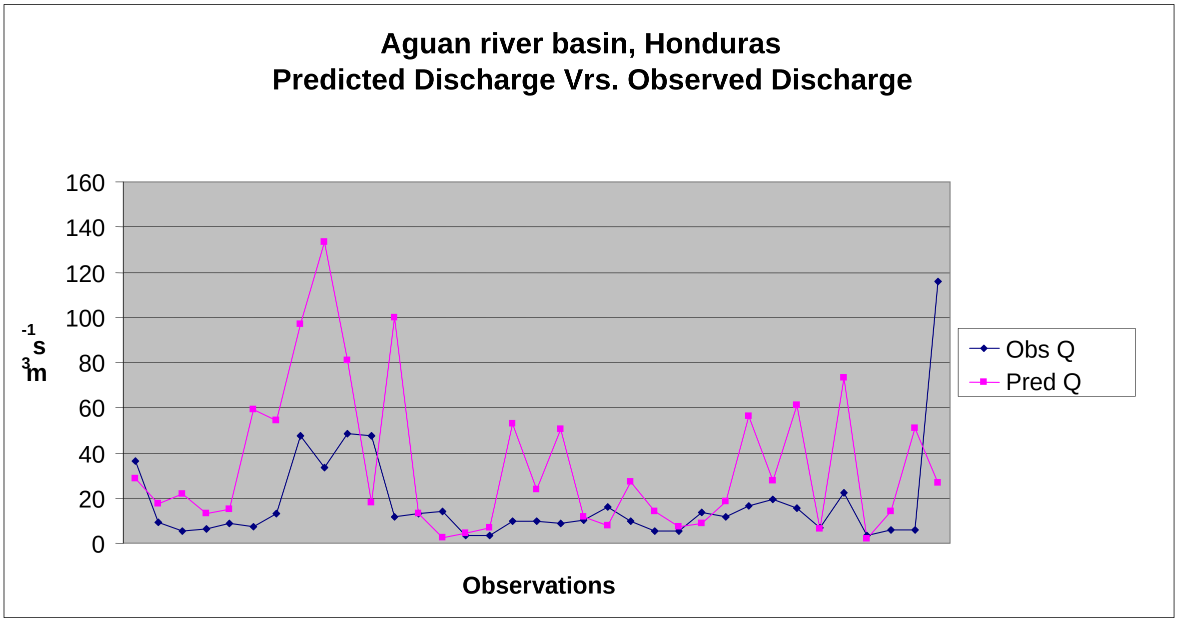

Figure 5. SWAT predicted streamflows versus observed flows from the Aguan river basin, Honduras.

The Q values estimated by SWAT slightly over predicted the real Q values; however, we noticed that as the quality of the input data improved, the model would adjust better to the real-observed values. We also noticed that if we subdivide the whole watershed in sub-watershed-small portions, the precision of the model improved. In other words, the model worked better for small areas with better data. All these consideration were taken into account by the time these Q values were input into the HEC-RAS model.

HEC-RAS Simulations in Hypothetical Scenarios

HEC-RAS model was able to predict annual flood events with high precision. Most of its precision was attributed to the DEM precision. Figure 6 illustrates a segment of the river passing by the Santa Rosa town (left). It shows the simulated flow under normal conditions. To the right, the figure shows the simulated flow under a 50-year recurrence interval flow, which correspond at the Q value for hurricane Micth. It also shows how the high risk area is flooded by the event.

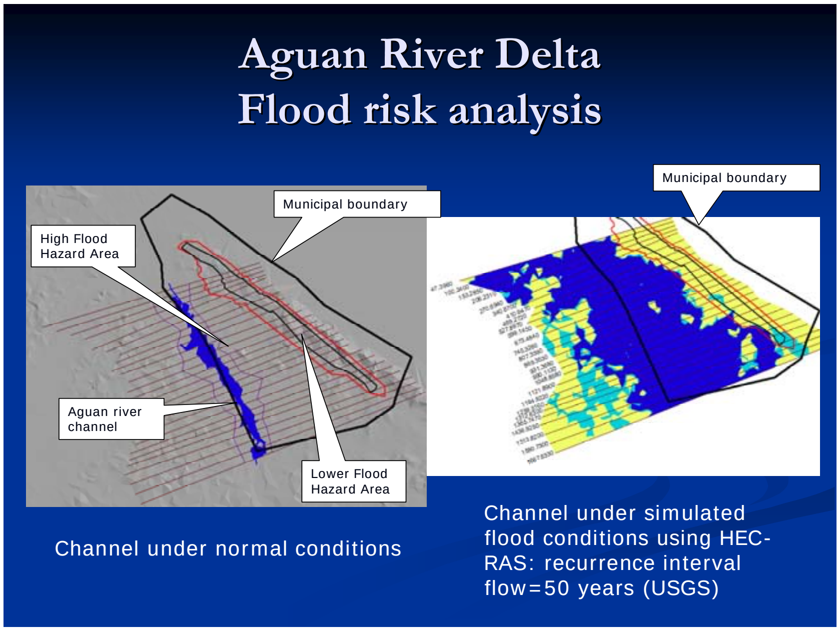

Figure 6. HEC-RAS simulations for the Aguan river delta, including the town of Santa Rosa de Aguan, Aguan river basin, Honduras.

Discharge values between 2,410 and 4,265 m^3/s were able to flood the flood plain adjacent to the town of Santa Rosa. This data coincided with the opinion of the town residents who were affected by the recent flood events. The high water mark for the Hurricane Mitch-simulated flow (1,063m^3/s) was validated by the residents (Fig. 7).

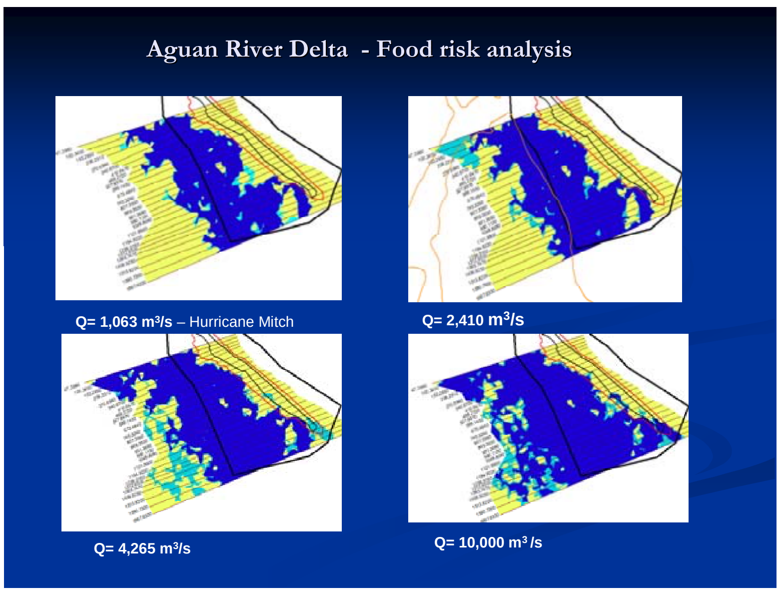

Figure 7. HEC-RAS simulations for the Aguan river delta for Q values of 1,063, 2,410 and 4,265, and 10,000 m^3/s, Aguan river basin, Honduras.

Simulations were ran with the following discharge (Q) values: 0.01 (normal conditions), 3.5m^3/s, 7.7m^3/s, 10m^3/s, 50m^3/s, 100m^3/s, 1,063m^3/s (Q value for hurricane Mitch), 2,410m^3/s, 4,265m^3/s and 10,000m^3/s. All simulated discharges were mapped. Figure 7 shows a comparison among the 1,063m^3/s (Q value for hurricane Mitch), 2,410m^3/s, 4,265m^3/s and 10,000m^3/s discharge values.

Notice that flooding starts to occur earlier in the flooding events (Q lower than 1,000 m^3/s), then as the water level rises, it tends to inundate the oppose side of the river, and not the town. It also shows that even under an extreme event of 10,000m^3/s, there is a middle area of the town that cannot be reached by the waters. It is important to mention that a catastrophic event of 10,000m^3/s might occur given the dimension of the basin and the proximity to the Caribbean sea, where a reverse flow might occur. HEC-RAS does not take into account this reverse flow.

Along the river valley, the most important city is Tocoa, a town of 30,000 people. HEC-RAS provided us some insights of how the Aguan River might affect the urban developments in an event of the magnitude of Hurricane Mitch (50 year recurrence interval event). Figure 8 illustrates the different depths at which water might go in such event. Maximum water elevations can reach up to 3 meter height.

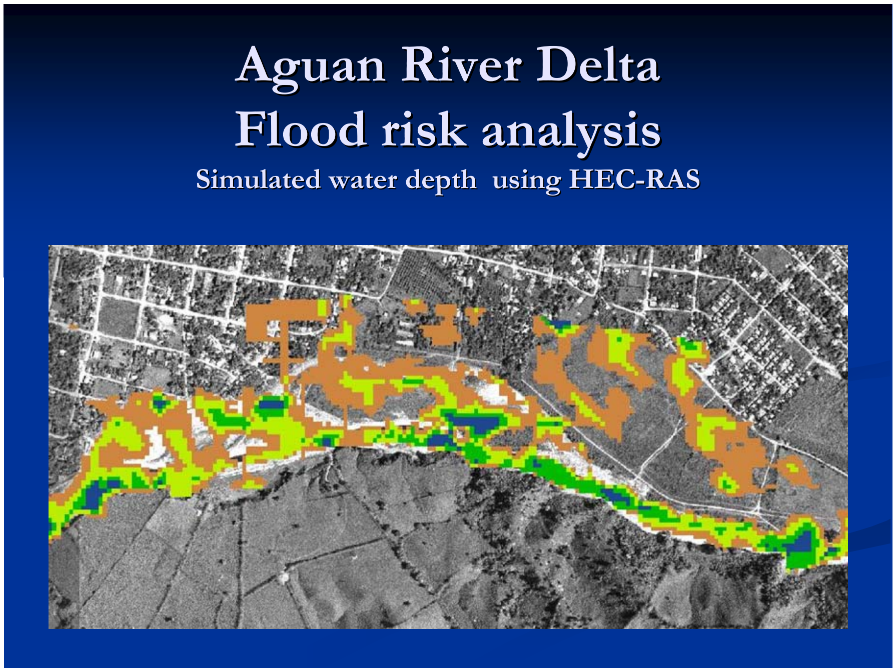

Figure 8. HEC-RAS simulated flows for a 50 year recurrence interval flow, close to an urban settlement (Tocoa) in the Aguan river basin. Orange color indicates a water depth of up to 1 meter, light green=1-2 m, green=2-3 m, and blue deeper than 3 meters.

Vulnerability Analysis with the Communities

Results showed that the overall vulnerability of the municipality of Santa Rosa was from moderate to high. Around 91 families were identified that were at risk, from which 57 resulted at high risk and 34 are at medium risk. The variables that most increase their vulnerability were: education level, economic status and presence of children and elderly at each household. The most vulnerable neighborhoods of Santa Rosa de Aguan were: El Hormiguero, Barra de Aguán, and Hacienda Manatí, and Creek.

CONCLUSION

SWAT proved to be a powerful tool for modelling streamflow patterns in Honduras. The predicted stream values (SWAT outcomes) and one-year field measurements were compared and a small disparity was observed. SWAT helped to understand the complex tropical hydrology. In a simple way, stream flow in most watersheds represents that part of the precipitation that is not evaporated nor lost by transpiration. Streamflow is usually divided in storm flow and base flow. The first one, obviously, is affected by the amount of precipitation fell in a period of time. The second: baseflow is very important in tropical areas. The surface flow or overland flow provides water only to the stormflow during the rainy season.

This paper provides an insight of how the HEC-RAS model can be a useful tool for providing important information about river flow fluctuations affected by extreme rainfall events. Future studies are needed to evaluate with more detail each land management practice. Work is still in progress to improve HEC-RAS data bases to Honduran-tropical conditions.

ACKNOWLEDGEMENTS

We acknowledge the contributions of Mr. Fernando J. Cruz and Abner J. Jimenez for their outstanding contributions in the SWAT and HEC modeling, respectively. Ms. Alma Duarte conducted the workshops in the communities to validate the flood risk maps; we appreciate enormously her contributions to this study.

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