# STRUCTURAL COUNTERMEASURES PROPOSAL FOR FLOOD DISASTER MANAGEMENT IN THE SULA VALLEY, HONDURAS

**CABALLERO FIGUEROA Eduardo Jose*** **MEE23715**

**Supervisors: Dr. MIYAMOTO Mamoru****
**Dr. NAITO Kensuke*****
**Dr. Badri Bhakta Shrestha******
**Prof. HIBINO Naohiko*******

## ABSTRACT

Recurring floods in the economically and socially vital Sula Valley of Honduras have caused substantial infrastructure damage and disrupted local livelihoods. This quantitative study developed a comprehensive flood mitigation strategy by analyzing historical precipitation data and employing the Rainfall-Runoff-Inundation (RRI) model. Frequency analysis revealed the 1998 rain event as the highest, with 2 to 10-year return periods. The calibrated and validated RRI model simulated 40- to 200-year flood scenarios, finding that peak discharges for the 50-, 100-, 150-, and 200-year cases exceeded the overflooding threshold at the Santiago Station, suggesting significant flooding.
To mitigate the risk, the study proposes constructing a new dam at a suitable 8,628 km2 upstream location, alongside the existing Francisco Morazan Hydroelectric Dam, using a constant-volume discharge method to manage overflooding for the 50- to 200-year return period events. Cost-benefit analysis showed that dams targeting higher return periods (100-, 150-, 200-year) provide greater overall benefits, despite higher upfront costs. The findings indicate that the proposed dam construction is economically feasible and effective in enhancing the Sula Valley's resilience against extreme rainfall events, providing a framework applicable to other flood-prone regions.

**Keywords:** *Flood Mitigation, Feasible Structural Countermeasures, Hydrological–Hydraulic Modeling, Flood Risk Assessment, Numerical Simulations*

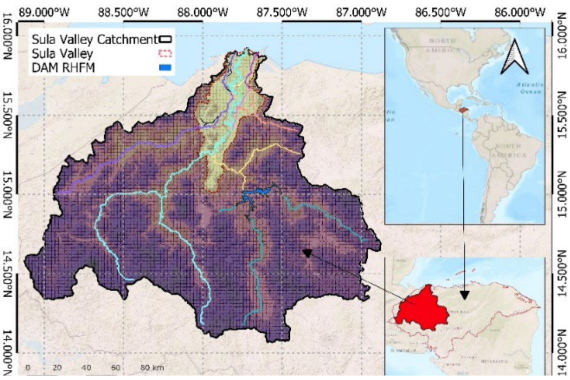



**Figure 1. Sula Valley location and catchment features**

## INTRODUCTION

Honduras is highly vulnerable to floods, particularly in the Sula Valley region, which is a critical economic hub that generates over 60% of the gross domain product (GDP) of the nation. The susceptibility of the region to flooding triggered by tropical storms and hurricanes has led to significant disruptions in industry, transportation, and agriculture, causing substantial economic losses.
The Sula Valley (red dotted area in **Figure 1**) is a 2,400 km$^2$ alluvial plain encompassing the Chamelecon and Ulua River basins, accounting for nearly a quarter of the total land area of Honduras. This concentration of economic activity makes the region a vital driver of the nation's GDP, but also heightens its vulnerability to water-related hazards. Honduras has experienced 53 major disaster events between 1990 and 2024, resulting in thousands of deaths, injuries, and affecting millions of people. The

* Civil Engineer, Project Coordinator for Sula Valley Study and Development Center (Water Related Disaster Management Office) for the Infrastructure and Transport Secretary of Honduras
** Associate Professor, Senior Researcher, ICHARM, PWRI
*** Senior Researcher, ICHARM, PWRI
**** Research Specialist, ICHARM, PWRI
***** GRIPS Professor

catastrophic impacts of Hurricanes Eta and Iota in 2020 highlighted the inadequacy of the existing flood control infrastructure in the Sula Valley in managing the increased discharge and intensity of extreme weather events. Despite the devastation, no substantial improvements have been made to river systems or flood control measures in the region. This gap in the effectiveness of current flood management strategies underscores the urgent need for comprehensive research and development of robust countermeasures tailored to the Sula Valley's specific challenges, crucial for safeguarding the socioeconomic wellbeing and enhancing the region's resilience to water-related disasters.

## THEORY AND METHODOLOGY

The methodology section of this study presents a multistage approach (refer to **Figure 2**) for analyzing precipitation patterns and developing a countermeasure proposal to mitigate flood risk in the study area.

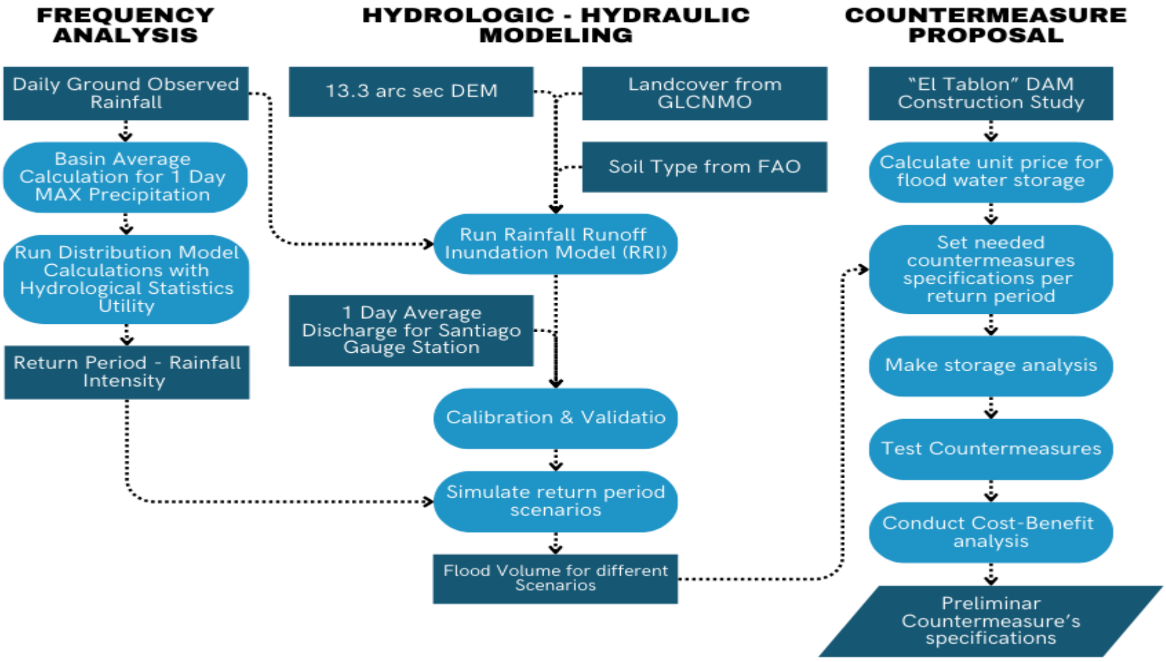



**Figure 2. Methodology of the study with flow chart**

### Frequency Analysis

Daily records of rainfall were collected from 53 monitoring stations operated by SERNA (Natural Resources Secretary of Honduras) and CENAOS (Atmospheric, Oceanographic, and Seismic Study Centre), between 1990 and 2017. These data were processed to calculate 1-day annual maximum basin average rainfall by conducting the frequency analysis using the “Hydrologic Statistic Tool” developed by the Japan Institute of Country-ology and Engineering, and referring the manual translated to English by the International Centre for Water Hazard and Risk Management (ICHARM). This tool compared the results of 16 different probability distribution models and selected the best fit based on the standard least-squares criterion and jackknife error. A log-normal distribution was chosen as the most suitable model for the study area. The output of this analysis provided the return periods and rainfall intensity for each return period.

### Hydrologic–Hydraulic Modeling

The rainfall runoff inundation (RRI) model, created by ICHARM, employs a two-dimensional diffusive wave approximation and considers the infiltration effect on plain low-land and hilly areas (Sayama et al., 2012, 2015a, 2015b)[1], which is well-suited to the characteristics of the study area. The model is capable of simulating rainfall and runoff interactions simultaneously, the reason why it was used in this research.

The RRI model was calibrated for a 2015 rain event and validated with a 2014 rain event, using MERIT Hydro digital elevation model (DEM), Global Land Cover Map, and Digital Soil Map by Food and Agriculture Organization (FAO). The performance of the model was evaluated using the Nash-Sutcliffe efficiency (NSE) and Percent Bias (PBias) criteria.

### Countermeasure Proposal

A calibrated and validated hydrologic-hydraulic model was used to simulate various return period scenarios (40, 50, 100, 150, and 200 years) based on the frequency analysis results. The overflooding volume was then calculated using 2,600 $m^3/s$[2] as the threshold for overflow at the Santiago Station on the Ulua River. Countermeasures were proposed for the calculated volume with the idea of preventing flood in the Sula Valley in case of having a 50-, 100-, 150-, or 200-year return period rainfall. The effectiveness of each of these structures was quantified through a cost-benefit analysis.

## DATA

The data were obtained from several sources. Daily precipitation records were collected from 53 monitoring stations operated by the Natural Resources Secretary of Honduras and the Atmospheric, Oceanographic and Seismic Study Centre of Honduras, from 1990 to 2017. Additionally, daily averaged discharge data were obtained from the Santiago Water Level Gauge, which is also operated and provided by SERNA. Precipitation and discharge data were used for the hydrologic–hydraulic modeling and analysis.

Furthermore, digital elevation model data was obtained from MERIT HYDRO in 3 arc seconds of special resolution but upscaled to 13.3 arc seconds, land cover data from the Global Land Cover by National Mapping Organizations, and soil type data from the Digital Soil Map of the World by Food and Agriculture Organization, to support the development and calibration of the hydrologic-hydraulic model. Furthermore, to conduct the cost analysis, measures and costs from "El Tablon-Multipurpose Dam[3]" project were gathered to replicate the dam structure for a project cost calculation. Then to conduct the benefit analysis, a damage assessment from the previous disaster of ETA and IOTA[4] in 2020.

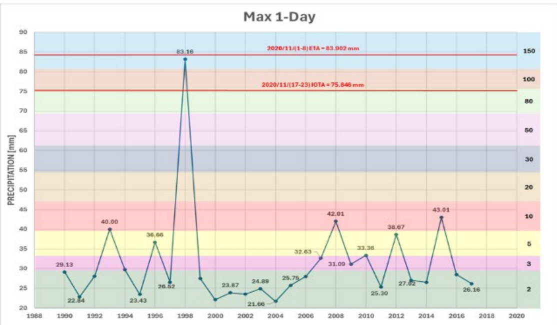



**Figure 3. 1-day annual maximum rainfall (1990-2017)**

## RESULTS AND DISCUSSION

**Frequency Analysis.** As shown in Figure 3, 1-day annual maximum rainfall data were used to perform frequency analysis employing the Hydrological Statistical Utility software. The 1998 rain event had the highest precipitation for this period, with 18 years having a 2-year return period, 3 years having a 3-year return period, 3 years having a 5-year return period, and 3 years having a 10-year return period.

---

[1] Extracted from Rainfall-Runoff-Inundation (RRI) Model User's manual; from Online version in PWRI's Website.

[2] Discharge for Inundation threshold based on analysis of observational data for Santiago Water Gauge and field survey by CABALLERO FIGUEROA Eduardo José for Julia Storm in September 2022.

[3] From *Extreme-flood control operation of dams in Japan* by Ryota Nakamura, and Yukihiro Shimatani in 2021

[4] Made by Inter-American Development Bank and (BID) the Economic Commission for Latin America and the Caribbean in "Effect and Impact Evaluation for ETA and IOTA storms in Honduras"

**Model Calibration & Validation.** From the 1-day annual maximum rainfall frequency analysis of the 2015 rain event, 10 years return period was chosen to calibrate the RRI model. After obtaining parameters that best fitted with the catchment characteristics, an NSE value of 0.90% was obtained with a PBias value of -1.7%, indicating that the simulated hydrograph was slightly overestimated. Both NSE and PBias were good values to validate the model. For validation, the 2014 rainfall event was considered because of dam data availability. The obtained NSE value of 0.78, is considered good, and the PBias of -19.03%, is also within the acceptable range[5].

**Countermeasure Proposal.** Using the calculated multiplication factor, the 40-, 50-, 100-, 150-, and 200-year return period cases were selected to analyze them. After running the model for each extreme rainfall case, the overflooding volume was calculated, showing in the results that the 50-, 100-, 150-, and 200-year return period cases presented high amount of overflooding water as seen in Table 1. When the model was run, it was consider that the existing dam would release only the power generation discharge, which was in average 74.40 $m^3/s$ for the simulation period, in other words, the upstream flow was controllled by the existing dam and its discharge was not representative for the Santiago Station hydrograph. These two facts leaded to select another dam as countermeasure. The location of the proposed dam was selected considering topographical and hydrological characteristics, and then it was tested. The simulation results in Table 2 shows that through the conditios set in the dam to control the outflow, the peak in Santiago Station was reduced under the 2,600 $m^3/s$ overflooding threshold because the discharge was successfully controlled (see results in Figure 4) by the proposed dam (see dam in Figure 5).

**Table 1. Overflooding volume in Santiago Sation for Return Period flood scenarios**

| Return Periods | Overflooding Volume [$m^3$] | Peak without CM [$m^3/s$] |
|---|---|---|
| 40 | 0 | 2,595.09 |
| 50 | 19,673,276.00 | 2,815.39 |
| 100 | 139,512,670.00 | 3,456.35 |
| 150 | 281,454,080.00 | 3,860.61 |
| 200 | 416,121,410.00 | 4,141.17 |

**Table 2. Countermeasure application simulation result**

| Return Periods | Dam max storage [$m^3$] | Dam Q start [$m^3/s$] | Peak in Santiago Station [$m^3/s$] |
|---|---|---|---|
| 50 | 229,203,008.00 | 1,800.00 | 2,113.41 |
| 100 | 744,534,504.00 | 1,750.00 | 2,338.60 |
| 150 | 1,038,952,267.00 | 1,700.00 | 2,505.60 |
| 200 | 1,406,042,231.00 | 1,600.00 | 2,582.51 |

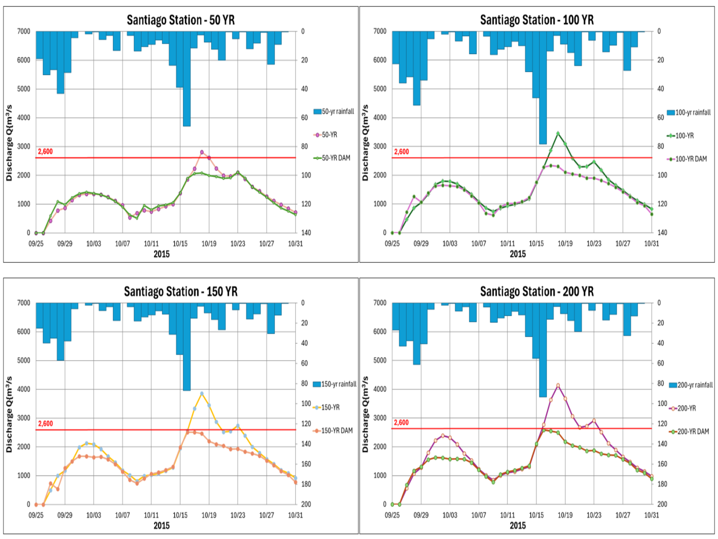



**Figure 4. Simulation result of dam effect in Santiago Station**

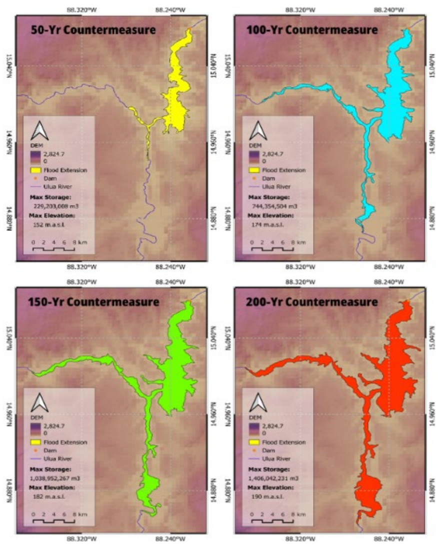
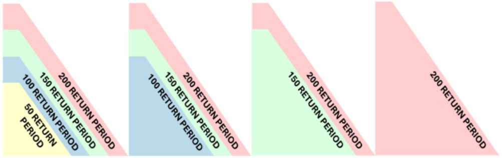



**Figure 5. Dam flood storage extent for 50-, 100-, 150-, 200- year return period scenarios**

[5] Acceptance parameters from Model Evaluation Guidelines for Systematic Quantification of Accuracy in Watershed Simulations by D. N. Moriasi, et. Al., 2007. Published by American Society of Agricultural and Biological Engineers.

**Cost-benefit Analysis.** To confirm the feasibility of constructing dams as countermeasures for the Sula Valley, a cost-benefit analysis was conducted. Using data from the "El Tablon Multi-Purpose Dam" project, the construction costs of the proposed dams were calculated. This included estimating the concrete quantity and flood extent for each dam's return period case, allowing the project cost to be determined. The analysis aimed to identify the most cost-effective approach to mitigating flood risks in the region.




| CASES | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| 50-YR | $166,208,463 | --------- | --------- | --------- |
| 100-YR | $100,226,989 | $266,435,452.00 | --------- | --------- |
| 150-YR | $42,922,923 | $42,922,923.00 | $309,358,375.00 | --------- |
| 200-YR | $40,353,773 | $40,353,773.00 | $40,353,773.00 | $349,712,148.00 |

**Figure 5. Dam construction cost analysis in four construction**

To analyze construction costs, four cases were considered:

1. Building a 50-year dam first, then upgrading to 100-, 150-, and 200-year capacities.
2. Building a 100-year dam first, then upgrading to 150- and 200-year capacities.
3. Building a 150-year dam first, then upgrading to 200-year capacity.
4. Constructing a 200-year dam directly.

To calculate damage without countermeasures, a report on the previous Eta and Iota disasters was used. These had a 150-year return period rainfall and caused $2,104.66 million in losses in the Sula Valley. It was assumed that a future 150-year event would cause similar disaster-level damage.

**Table 3. Estimated loss calculation for each return period case**

| Return Periods [Years] | ETA & IOTA Damage [Mil. USD] | Overflooding Volume for Design Flood [$m^3$] | Multipliying Factor 150 YR ref | Estimated Annual Damage (Benefit) [Mil. USD / Year] |
|---|---|---|---|---|
| 200 | | 416,121,410.00 | 1.48 | $15.56 |
| 150 | $2,104.66 | 281,454,080.00 | 1.00 | $14.03 |
| 100 | | 139,512,670.00 | 0.50 | $10.43 |
| 50 | | 19,673,276.00 | 0.07 | $2.94 |

Using the previous considerations, the cost analysis was conducted for different cases (see Table 3) based on the construction of the dam for each return period scenario. Firstly, the estimated loss for each return period case was calculated, where using the overflooding volume at the Santiago Station, a multiplying factor to expand the damage was calculated. In this sense the estimated loss is directly proportional to the overflooding volume of each return period case. Having calculated the estimated loss for each return period case, the cost analysis was individually conducted for each case.

**Table 4. Case 1: Cost-benefit analysis of a 50-Year Return Period Dam**

| Extreme rainfall in Return Periods [Years] | Estimated Annual Damage (Benefit) [Mil. USD / Year] | Benefit having 50-year RP Dam constructed [Mil. USD / Year] | Real Loss with 50-year Dam construction [Mil. USD / Year] | Loss reduction with 50-year Dam construction |
|---|---|---|---|---|
| 200 | $15.56 | 2.94 | 12.62 | 19% |
| 150 | $14.03 | 2.94 | 11.09 | 21% |
| 100 | $10.43 | 2.94 | 7.49 | 28% |
| 50 | $2.94 | 2.94 | 0.00 | 100% |

By constructing the 50-year return period dam, which has an estimated price of $166.21 million, a 50-year return period extreme event can be fully addressed. Additionally, if an extreme rainfall event with a higher return period were to occur, the potential damage in the Sula Valley would be reduced by ratios considered and presented in Table 4.

**Table 5. Case 2: Cost-benefit analysis of a 100-Year Return Period Dam**

| Extreme rainfall in Return Periods [Years] | Estimated Annual Damage (Benefit) [Mil. USD / Year] | Benefit having 100-year RP Dam constructed [Mil. USD / Year] | Real Loss with 100-year Dam construction [Mil. USD / Year] | Loss reduction with 100-year Dam construction |
|---|---|---|---|---|
| 200 | $15.56 | 10.43 | 5.13 | 67% |
| 150 | $14.03 | 10.43 | 3.60 | 74% |
| 100 | $10.43 | 10.43 | 0.00 | 100% |
| 50 | $2.94 | 2.94 | 0.00 | 100% |

Constructing a 100-year return period dam with an estimated $266.44 million cost would provide significant benefits. It would prevent damage from 100-year and lower return period events, and greatly reduce potential losses if extreme rainfall exceeds the 100-year threshold, as shown in Table 5.

**Table 6. Case 3: Cost-benefit analysis of a 150-Year Return Period Dam**

| Extreme rainfall in Return Periods [Years] | Estimated Annual Damage (Benefit) [Mil. USD / Year] | Benefit having 150-year RP Dam constructed [Mil. USD / Year] | Real Loss with 150-year Dam construction [Mil. USD / Year] | Loss reduction with 150-year Dam construction |
|---|---|---|---|---|
| 200 | $15.56 | 14.03 | 1.53 | 90% |
| 150 | $14.03 | 14.03 | 0.00 | 100% |
| 100 | $10.43 | 10.43 | 0.00 | 100% |
| 50 | $2.94 | 2.94 | 0.00 | 100% |

Constructing a 150-year return period dam at an estimated $309.36 million would fully protect the region against events up to 150-year return periods. Even in a 200-year event, the dam would address 90% of potential damages, as shown in the data presented in Table 6.

**Table 7. Case 4: Cost-benefit analysis of a 200-Year Return Period Dam**

| Extreme rainfall in Return Periods [Years] | Estimated Annual Damage (Benefit) [Mil. USD / Year] | Benefit having 200-year RP Dam constructed [Mil. USD / Year] | Real Loss with 200-year Dam construction [Mil. USD / Year] | Loss reduction with 200-year Dam construction |
|---|---|---|---|---|
| 200 | $15.56 | 15.56 | 0.00 | 100% |
| 150 | $14.03 | 14.03 | 0.00 | 100% |
| 100 | $10.43 | 10.43 | 0.00 | 100% |
| 50 | $2.94 | 2.94 | 0.00 | 100% |

Constructing a 200-year return period dam at $349.71 million would fully protect against 200-year and lower return period events, preventing all associated damages as shown in the data presented in Table 7. This provides significant benefits compared to the potential losses without such a dam.

## CONCLUSSIONS & RECOMMENDATIONS

The findings of this study highlight the pressing need for the Sula Valley region to invest in robust and resilient flood mitigation infrastructure. The analysis has clearly demonstrated the vulnerabilities of the existing drainage system, which leaves the area exposed to devastating impacts from extreme rainfall events. However, proactive construction of flood control measures, such as dams with return periods of 100 years or more, could dramatically reduce the potential losses. Looking to the future, the increasing frequency and severity of extreme weather events driven by climate change means the Sula Valley must be prepared to withstand an evolving range of hydrological risks. Recommendations include constructing a 100-year or more flood control dam, implementing an early warning system, strengthening land use regulations, launching a public awareness campaign, establishing a rigorous monitoring and maintenance program, and regularly updating hydrological models and flood risk assessments.

## ACKNOWLEDGEMENTS

I express my sincere appreciation to my research supervisors, Professors MIYAMOTO Mamoru, Dr. NAITO Kensuke, and Dr. SHRESTHA Badri for their invaluable guidance, expert advice, and unwavering support throughout this research. I am especially grateful for the encouragement provided by my supervisors, which motivated me to overcome the challenges I encountered during this study.

## REFERENCES

*Sayama, T.* Rainfall-Runoff-Inundation (RRI) Model

*Japan Institute of country-ology and Engineering (JICE) & International Centre for Water Hazard and Risk Management (ICHARM) under the auspices of UNESCO, Public Works Research Institute (PWRI) and CTI Engineering Co., Ltd.* Hydrological Statistics Utility

*CONSORCIO CINSA-SNC-LAVALIN.* Review and Update of the Feasibility Study for the Construction of the El Tablon Multi-Purpose Dam.