CLIMATE AND DISASTER RISK ASSESSMENT USING HYDROLOGICAL MODELING AND FREQUENCY ANALYSIS APPROACHES FOR MUNICIPALITIES IN THE TAGO RIVER BASIN, PHILIPPINES

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ABSTRACT

The hazard potential of the Philippines shaped by its location and archipelagic geography, has led to various types of hydrometeorological hazards, including floods, landslides, storm surges, sea-level rise, and drought. These catastrophic phenomena shifted the country's disaster management to a proactive approach by mandating local authorities to mainstream disaster risks and climate change in local development plans. This entails the utilization of a tool called the Climate and Disaster Risk Assessment (CDRA), a systematic process of factoring climate and disaster risk into development plans and programs. This study aims to provide recommendations for the enhancement of CDRA by incorporating the rainfall-runoff-inundation model and frequency analysis approaches. Data on the current climate and future periods of climate change for the Tago River Basin were utilized to produce the design rainfall for the 2-, 30-, and 100-year return periods. In this study, simulated design rainfall for current and future climate scenarios were used to quantitatively assess risk and generate exposure maps for the Municipalities of San Miguel and Tago. The results of this study demonstrate that integrating hydrological modeling and frequency analysis can be a valuable tool for a detailed and realistic approach to risk assessment at the local level. This provides a solid foundation for making well-informed decisions that prioritize risk reduction and resilience-building measures.

Keywords: *climate, disaster, risk assessment, hydrological modeling, frequency analysis*

INTRODUCTION

Between 1980 and 2020, storms and floods were among the most frequently occurring disasters in the Philippines (WorldBank,2021). It led to numerous deaths and damage to property and livelihoods, severely affecting the country's economy and society. To pacify the recurring loss of lives and damage, the country enacted Republic Act No. 10121 or the Philippine Disaster Risk Reduction and Management Act of 2010 which mandates a proactive approach towards climate change adaptation (CCA) and disaster risk reduction (DRR). This highlights the importance of mainstreaming DRR and CCA into development processes such as local plans, budgets, and policies. (PDRRM Act, 2010). Integral to mainstreaming is the utilization of the Climate and Disaster Risk Assessment (CDRA) tool, a systematic process designed to assess the risks and vulnerabilities associated with various exposed elements (Figure 1). It addresses multi-hazard coverage focusing on extreme weather conditions and historically worst-case scenarios. Utilizing these severe but infrequent hazard occurrences as the sole basis for planning tends to overlook common scenarios, such as ordinary-rainfall (monsoons and low pressure) causing floods. Therefore, this study aims to provide recommendations for the improvement of CDRA using

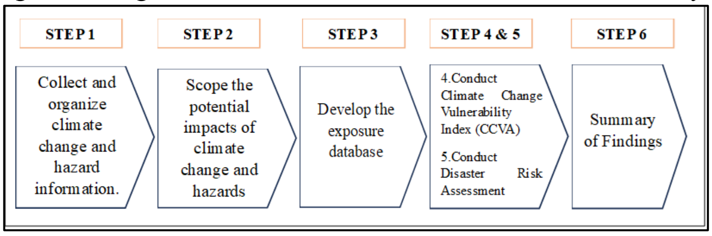

Figure 1. Climate and Disaster Risk Assessment process

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rainfall-runoff-inundation (RRI) model and frequency analysis.

The Tago River Basin located on the island of Mindanao, Philippines (Figure 2), is one of the flood-prone areas in the province with a catchment area of approximately 1,448 km^2 and is inhabited by 81,640 individuals. Utilizing the basin's exposure profile and input data, this study employed an RRI model to simulate flood inundation using the design rainfall for current and future climates based on frequency analysis. The results were extracted to develop flood scenarios, determine exposure, and quantify risks.

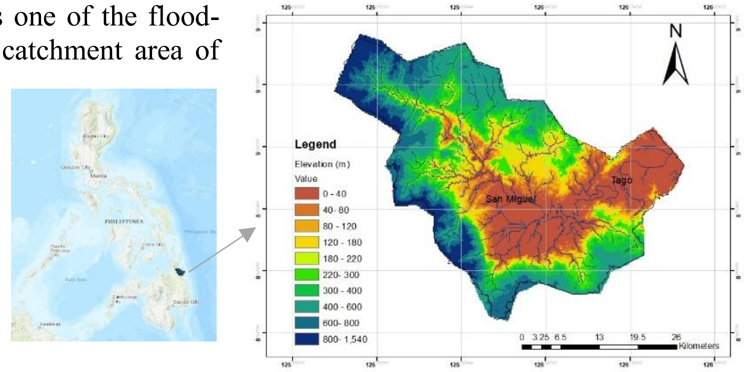

Figure 2. Location and elevation map of Tago River Basin

THEORY AND METHODOLOGY

The methodology used in this study was categorized into five parts, as shown in Figure 3.

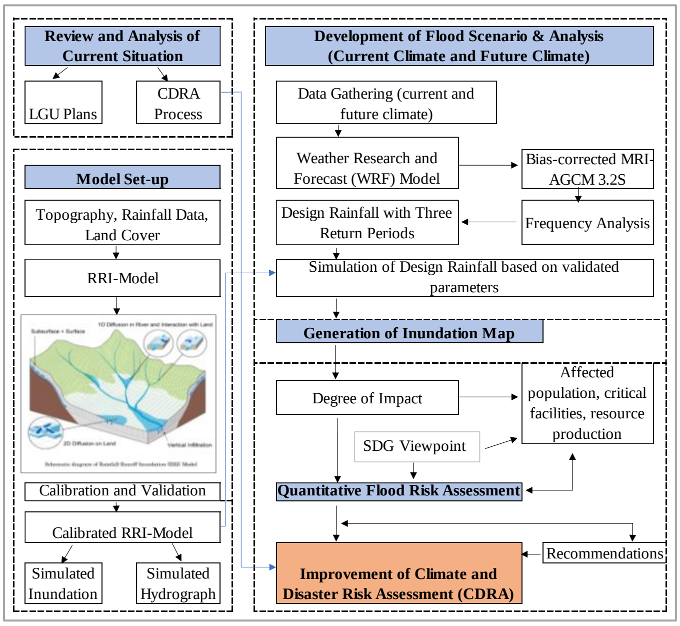

Figure 3. Methodology employed in this study.

A. Review and Analysis of the Current Situation

The situational analysis in this study consisted of two aspects- existing local government plans and the CDRA process. The Comprehensive Land Use Plans (CLUP) and DRR-CCA plans of two municipalities (San Miguel and Tago) were evaluated based on their contents and the integration of climate and disaster risks. Th CDRA process was assessed according to the methodologies employed to identify risks and incorporate climate change data. The results of this review and analysis have led to succeeding research methodologies.

B. Model Set-up

The RRI model used in this study is a two-dimensional model capable of simulating rainfall-runoff and flood inundation simultaneously. A schematic of the model is presented in Fig. 3 (Sayama, 2017).

The model was calibrated typhoon Seniang in 2014 which caused the worst flooding, and was validated for the flood events caused by typhoons Marce in 2016 and Onyok in 2015. Processes include comparison of simulated and observed discharge, comparison of simulated inundation map and flood hazard map of actual flood events, and verification of data based on model efficiency criteria (e.g., coefficient of determination r^2, and Nash-Sutcliffe Efficiency).

C. Development of Flood Scenario and Analysis for Current and Future Climate

Flood scenarios were simulated using current and future climate precipitation data derived from the general circulation model (GCM). The initial selection of return periods was based on historical rainfall data and flood events. This includes identifying the rainfall that causes annual floods, the worst past flood events, and the possibility of extreme flooding caused by heavy rainfall. In this study, three return periods were selected for the design rainfall: 2-, 30- and 100-year return periods, respectively. Flood inundation extent and depth were extracted from the RRI-simulated design rainfall for three different return periods of the current and future climate.

D. Generation of the Inundation Map

Inundation maps for both current and future climates were compared and categorized based on flood depths (in meters): 0-0.2, 0.2-0.5, 0.5-1.0, 1.0-2.0, 2.0-3.0, and 3.0-maximum depth. The inundation areas for the most affected municipalities, San Miguel and Tago, were extracted and analyzed.

E. Quantitative Flood Risk Assessment

In this study, the identified exposure elements were population, critical facilities, and resource production or croplands. Spatial locations of these exposed elements were overlayed with inundation map using a GIS tool. The baseline inundation for estimating the affected population and critical facilities was flood depth >0.5 m. Resource production (cropland) exposure was categorized according to the stages of the rice crop. A flood depth > 0.2 m was considered the minimum threshold depth for crop damage for the vegetative stage, and >0.5 m for the maturity stage. An additional correlation with the Sustainable Development Goals (SDG) was also incorporated in the risk and damage assessment such as affected poor families, inundated schools and hospitals, and inundated croplands.

DATA

Data	Description	Source
Topographic Data	200m x 200m grid size Digital Elevation Model (DEM) derived from Interferometric Synthethic Aperture Radar (IFSAR)	National Mapping and Resource Information Authority (NAMRIA)
Landcover Data	2020 Land Cover data on 12 land cover categories, generated from 2019 Sentinel 2 (10-m resolution) satellite imagery	NAMRIA
Rainfall Data	Hourly Global Satellite Mapping of Precipitation (GSMaP) Near Real-Time (NRT) version 6	Japan Aerospace Exploration Agency-Earth Observation Research Center (JAXA/EORC)
	Daily ground rainfall data (mm) at Hinatuan Synoptic Station	Philippines Atmospheric, Geophysical and Astronomical Services Administration (PAGASA)
Discharge data	Hourly water level data at Cabtic Bridge Water Level Monitoring System	Department of Science and Technology-Advanced Science and Technology Institute (DOST-ASTI)
	Discharge conversion through rating curve equation (Q = 245.83H - 1374.2)	University of the Philippines and Caraga State University (Paringit et.el, 2017).
Current and Future Climate precipitation	Meteorological Research Institute Atmospheric General Circulation Model (MRI-AGCM3.2S), a super high-resolution data of 20-km grid size. Data of basin average of an annual maximum rainfall for the year 1979 to 2003 for current climate, and 2075 to 2099 for future climate.	ICHARM

RESULTS AND DISCUSSION

A. Calibration and Validation of Model

Figure 4 presents a comparison between the calculated discharges and the observed discharges for both the calibration and validation cases. In both cases, the model's performance fell within an acceptable range (Table 1).

Table 1. Model efficiency criteria results

Efficiency criteria	Seniang 2014 (a)	Marce 2016 (b)	Onyok 2015 (c)	Acceptable range
NSE	0.45	0.57	0.73	0-1.0
r^2	0.86	0.60	0.78	≥0.5

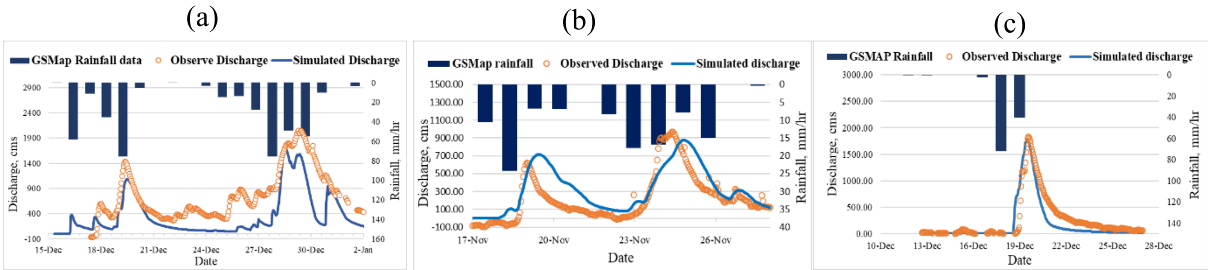

Figure 4. Observed and simulated discharges at Cabtic Bridge station for calibration using (a) Seniang 2014, and validation using (b) Marce 2016, (c) Onyok 2015

B. Development of Flood Scenario and Analysis

The flood frequency analysis was carried out using a 1-day annual maximum rainfall of 25 years based on the Gumbel and GEV probability distribution methods. Results of the frequency analysis were assessed using efficiency criteria such as Root Mean Square Error (RMSE) and r^2. The current climate has an RMSE of 3.84 and r^2 of 0.945 for the Gumbel distribution, and an RMSE of 2.88 and r^2 of 0.989 for the GEV distribution. For the future climate, Gumbel has an RMSE of 5.37 and r^2 of 0.969, while GEV has an RMSE of 5.85 and r^2 of 0.952. Based on the foregoing data, Gumbel had the best fit for the rainfall data; therefore, the Gumbel 1-day maximum rainfall for the three different return periods was employed. Results of the converted rainfall were then utilized as inputs in the RRI-model to generate flood scenarios, as shown in Table 2.

Table 2. Conversion factors used to calculate rainfall of different return periods.

Return Period	Gumbel, mm/day	Current Climate	Gumbel, mm/day	Future Climate
Peak rainfall date of the period		(Jan. 1990)		(Feb. 2089)
Selected original rainfall		183.67		294.31
2-year	119.50	0.65	138.10	0.47
30-year	197.10	1.07	261.40	0.88
100-year	228.30	1.24	311.10	1.06

C. Generation of Inundation Maps

Figure 5 shows a basin-wide inundation map for different return periods. Based on this illustration, central and downstream areas are mostly inundated with significant increases in flood depth and extent for the 30 and 100-year return periods in the future climate compared with the current climate. Primarily, overflows in the river and its tributaries caused flooding in many areas of the basin especially in low-lying areas.

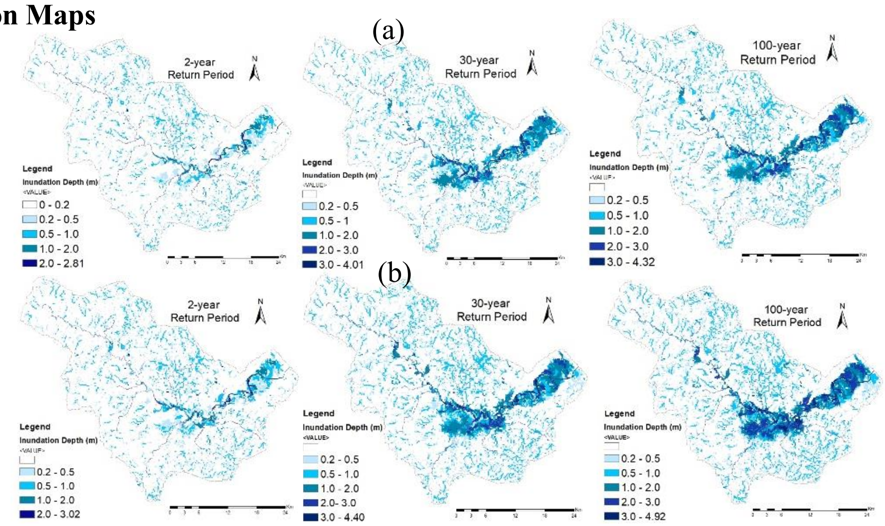

Figure 5. Inundation map of Tago River Basin for current (a) and future (b) climate.

D. Quantitative Flood Risk Assessment

In this study, the risks associated with each exposed element were assessed using a GIS tool and available data. Specifically, the exposed population and critical facilities in flood-prone areas were quantified in the Municipality of Tago as the downstream area with more inundated barangays. Additionally, exposure to resource production, particularly cropland, was computed in the Municipality of San Miguel, the highest rice-producing town in the province.

Table 3. Number of barangays per risk level of population in Municipality of Tago

	CURRENT CLIMATE			FUTURE CLIMATE		
Risk Level	2-year	30-year	100-year	2-year	30-year	100-year
Very High	5	12	13	5	11	15
High	6	5	4	6	6	2
Moderate	1	1	1	5	1	1
Low	12	6	6	8	6	6

Under the current climate with a flood depth greater than 0.5 meters, 10% of the total municipal population will be affected by a 2-year flood, 26% by a 30-year flood, and 29% by a 100-year flood (Figure 6a). The future climate will affect 10% of the population by a 2-year flood, 27% by a 30-year, and 31% by a 100-year flood (Figure 6b). The number of affected poor families was calculated using the 31% poverty incidence data of the municipality, thereby correlating with SDG Goal 1.

Table 3 illustrates the risk level of population per barangay based on exposure to flood depth >0.5 m. Very High means >20%, High means >10-<20%, Moderate means >5-<10%, and Low means ≤5% of the total barangay population is affected. For critical facilities, 7 out of 18 schools designated as evacuation centers during disasters will be at risk of inundation by 30- and 100-year floods; one has a higher risk of being inundated by a 2-year flood. Ten out of the 24 health centers will be flooded by 30- and 100-year flood, while two health centers will be frequently inundated by a 2-year flood (Figure 6c and 6d). Based on the foregoing data, inundated schools and health centers are identified linking to safety of schools as evacuation centers during disasters and access to health centers. Hence, correlating to SDGs 3 and 4.

Table 4. Cropland exposed value

Return Period	Affected cropland (in ha) with flood depth > 0.2m	Vegetative Stage (Million PhP)	Affected cropland (in ha) with flood depth > 0.5m	Maturity Stage (Million PhP)
CURRENT CLIMATE				
2-year	516.51	41.3	211.44	16.1
30-year	4,774.28	381.9	4,180.60	317.7
100-year	6,843.85	547.8	5,093.56	387.1
FUTURE CLIMATE				
2-year	3,822.42	305.8	1,739.08	132.1
30-year	7,562.19	605.0	5,797.21	440.6
100-year	8,557.58	684.6	6,693.27	508.7

Figures 6 (e,f) show a total of 15, 396.33 hectares are considered agricultural zones where the majority of crops planted is rice. Based on Table 4, with 1-day continuous rainfall produced by a design rainfall, the municipality will incur higher values of exposure in cropland in the vegetative stage than in the maturity stage. One reason is the extent of the area covered by inundation >0.2 m flood depth and its impact to the early stage of the rice crop. Data on the exposed value of crops are associated with food security, impact on livelihood and income losses linking to SDGs 1 and 2.

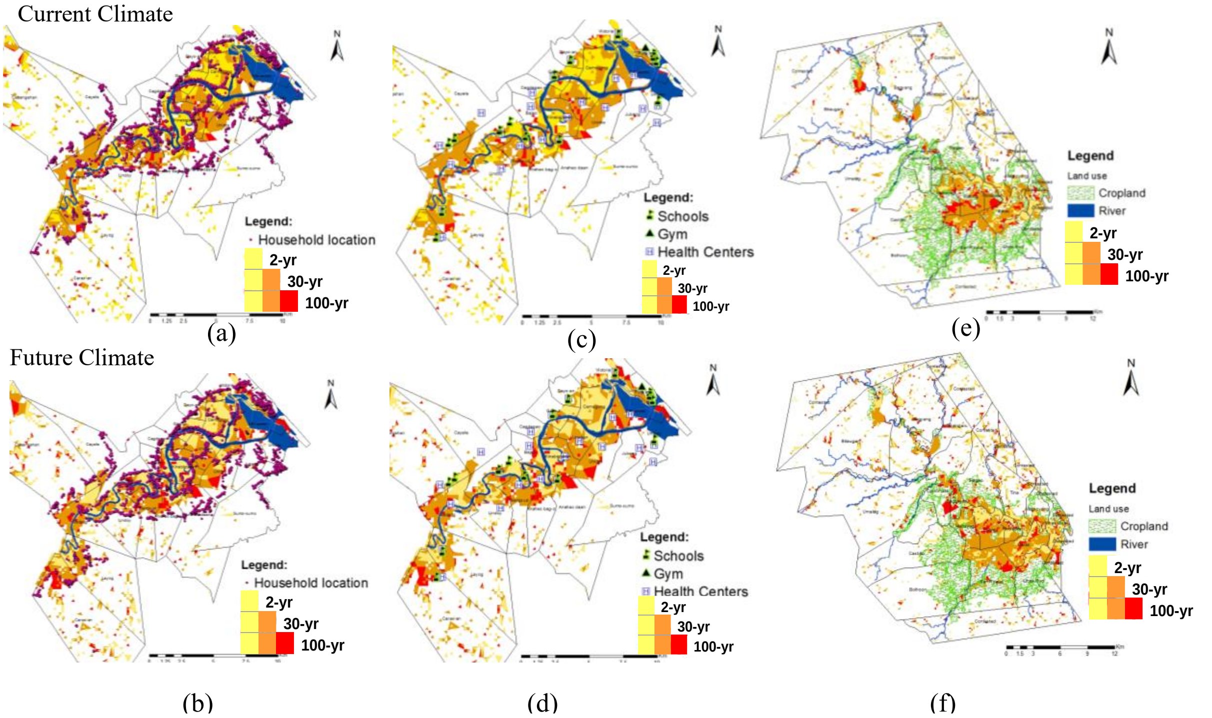

Figure 6. Inundation exposure of population(a,b), critical facilities (c,d) for Municipality of Tago; and cropland (e,f) for Municipality of San Miguel, under current and future climates

CONCLUSION AND RECOMMENDATION

The primary objective of this research is to enhance the effectiveness of the CDRA tool by implementing a more intricate and realistic approach to risk assessment with the utilization of the RRI-model and frequency analysis. The application of this study to Tago River Basin revealed that future climate under climate change will significantly increase the inundation extent as well as affected population, facilities, and croplands. Risk calculation to exposed elements vary depending on the available data of a local government. The use of design rainfall is particularly dependent on the period employed in the frequency analysis. Possible consequences in the near future climate data could also be explored.

For national facilitators and technical providers of CDRA, this study suggests methodologies and recommendations that will be helpful for future consideration. Consultations among stakeholders and LGU functionaries are necessary to gather ideas and feedback on the applicability to the local level.

CDRA Major Steps	Existing sub-process	Recommendations for improvement of CDRA
Step 1: Collect and organize climate change and hazard information	Qualitative likelihood of occurrence Worst-case scenario basis	The probability of occurrence will be based on frequency analysis to understand past flood events and predict future floods. It is recommended to categorize flood scenarios into three return periods. Designation of return periods will be based on the results of frequency analysis and recurrence of floods (i.e. for this study, 2-, 30-, and 100-yr). The chosen return periods will be used for design rainfall, considering both current climate and future climate. Both will be simulated using Rainfall Run-off Inundation (RRI) model. Results of the simulation will be utilized, i.e. for the current climate for step 5: DRA; and future climate for step 4: CCVA.
Step 4: Climate Change Vulnerability Assessment (CCVA) and Step 5: Disaster Risk Assessment	Exposure based on a 100-year flood hazard map Calculation of exposure based on one scenario only	Utilizing design rainfall with three different return periods, inundation maps will be generated for both climate scenarios. Inundation map will be the basis in measuring flood extent and flood depth using GIS tool. For exposure calculation, additional considerations may be recommended, as follows: 1. Population Exposure- consideration of the height of the dwelling as part of the factors for exposure, that is for instance in this study, greater than 0.5 m flood depth was considered for computing the exposed population. 2. Resource Production (cropland)- additional consideration may be given to crop stages at the time of flood- vegetative stage, and maturity stage. Each with different calculations on exposed values. A more realistic approach to foreseeing loss or damage to agricultural products. Moreover, consideration to flood depth based on crop stage may be helpful for the improvement of CDRA. For each exposed element, inclusion and correlation with the SDG viewpoint are proposed. Results of the quantitative assessment will be utilized to determine the impact of each goal and develop interventions in attaining the SDGs.
Overall		The initial stage of the CDRA will comprise the gathering of historical flood events, topographic data, and rainfall data as input for the RRI model. This time LGU personnel will be the end-user of simulating the model. With the absence of ground data, LGUs may refer to satellite data such as GSMap data, Google Earth Engine, and MODIS.

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