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Integrating GIS-AHP and HEC-RAS for Flood Risk Indexing and Floodplain Mapping in Bagac, Bataan, Philippines

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A B S T R A C T

Floods pose a growing threat to low-lying coastal communities in the Philippines, yet local risk assessments remain limited. This study presents a comprehensive framework combining Geographic Information Systems (GIS), the Analytical Hierarchy Process (AHP), and the Hydrologic Engineering Center's River Analysis System (HEC-RAS) to produce both a spatially explicit Flood Risk Index (FRI) and detailed floodplain extents for Bagac, Bataan. The FRI synthesizes four core dimensions—hazard, exposure, vulnerability, and coping capacity—through seven indicators, including seasonal precipitation, digital elevation, land cover, population density, household count, medical personnel distribution, and existing mitigation infrastructure. Pairwise comparisons in AHP yielded weightings that were applied in QGIS to classify the municipality into five risk tiers, from Very Low to Very High. In parallel, a 1-D unsteady flow simulation in HEC-RAS, validated against historical flood records, delineated inundation depths and extents for the 25-, 50-, 100-year return periods. The resulting maps reveal critical hotspots along the coastal plain and riparian corridors, pinpointing communities and infrastructure most susceptible to flooding. These outputs offer decision-makers a robust toolset for land-use planning, early-warning system design, zoning regulation, and targeted mitigation investments. By integrating multi-criteria risk scoring with hydraulic modeling, this workflow advances localized flood resilience planning and can be readily adapted to other Philippine municipalities facing similar climate-driven challenges.

1. INTRODUCTION

Flooding stands as one of the most destructive and recurrent natural hazards globally, inflicting substantial impacts on human lives, infrastructure, agriculture, and economic activities. The frequency and severity of flood events have experienced a notable increase over recent decades, attributed to climate change, rapid urbanization, deforestation, and improper land-use practices [1]. As per the Intergovernmental Panel on Climate Change (IPCC), climate-induced increments in precipitation intensity and extreme weather events have intensified hydro-meteorological hazards, particularly in vulnerable coastal and developing nations [2]. Flood disasters pose a significant threat in Southeast Asian countries, where densely populated areas, inadequate drainage systems, and evolving watershed conditions contribute to heightened flood susceptibility.

The Philippines is one of the most susceptible countries to hydro-meteorological disasters due to its geographical position along the Western Pacific typhoon belt. The country experiences an average of approximately 20 tropical cyclones annually, with several of these events resulting in severe flooding, landslides, and storm surges. Flood hazards in the Philippines have become increasingly frequent and damaging due to intensified monsoon rainfall, watershed degradation, and rapid urban expansion [3]. In numerous provinces, flooding has become a recurring environmental and socio-economic issue that disrupts transportation systems, damages infrastructure, affects livelihoods, and endangers community safety.

Bagac, a vulnerable municipality situated in the province of Bataan, Central Luzon, presents a unique topographic configuration. Positioned on the western side of the Bataan Peninsula, Bagac is characterized by mountainous terrain in the east and coastal lowlands facing the West Philippine Sea in the west. This geographical arrangement establishes a watershed-to-coastal drainage system that amplifies runoff concentration during periods of heavy rainfall. Several river systems, including the Umagol, Tiis, and Caybobo rivers, traverse the municipality and ultimately discharge into Bagac Bay. This riverine drainage system contributes to riverine flooding during intense precipitation events and typhoon activity.

Bagac, spanning approximately 23,120 hectares, is administratively subdivided into fourteen barangays. Coastal barangays, including Pag-asa, Quinawan, and Paysawan, are particularly vulnerable to coastal inundation and storm surges. In contrast, inland communities face the risk of fluvial flooding due to river overflow and insufficient drainage capacity. The municipality's flood susceptibility is further exacerbated by deforestation, land-use conversion, sedimentation, and unregulated development in proximity to waterways. These factors diminish infiltration and elevate surface runoff, thereby intensifying flood risks in both upland and low-lying regions.

Recent flooding events in the municipality underscore the escalating vulnerability of Bagac to hydro-meteorological hazards. During the southwest monsoon, exacerbated by Typhoon Carina in 2024, flooding incidents were reported in several barangays, including Barangay Ibis. These events underscore the imperative for updated and scientifically sound flood hazard assessments to facilitate disaster preparedness, land-use planning, and infrastructure management. Despite the recurrent occurrence of flooding, comprehensive and current flood risk maps for Bagac remain limited. Existing flood assessments frequently lack the integration of recent topographic, hydrological, and socio-environmental datasets, thereby diminishing their efficacy for local planning and decision-making.

Advancements in geospatial technologies and hydrological modeling have facilitated more comprehensive flood risk assessment methodologies. Geographic Information Systems (GIS) are extensively utilized for spatial analysis and hazard mapping due to their ability to integrate multiple flood-related parameters, including elevation, slope, rainfall, drainage density, land use, and proximity to river systems. Concurrently, the Analytic Hierarchy Process (AHP), developed by Thomas L. Saaty, offers a structured multi-criteria decision-making approach for assigning relative importance to flood-contributing factors [4]. The integration of GIS and AHP has been extensively applied in flood susceptibility mapping studies due to its capacity to incorporate both quantitative and expert-based evaluations.

In the Philippine context, [3] employed GIS-based multi-criteria analysis utilizing AHP to identify flood-prone areas in Davao Oriental. Their findings demonstrated that the integration of rainfall, elevation, slope, drainage density, and population exposure significantly enhanced the accuracy of flood risk assessment. Similarly, [5] employed GIS, HEC-HMS, and HEC-RAS to generate flood hazard maps in the Gingoog River Basin in Mindanao. Their research highlighted the utility of hydrologic and hydraulic modeling in floodplain delineation and the development of early warning systems. Studies that integrate GIS and hydraulic models have demonstrated that combining spatial analysis with flood simulation yields more reliable flood hazard characterization and supports evidence-based disaster risk reduction planning.

Hydraulic modeling through HEC-RAS has emerged as a pivotal tool in flood inundation analysis. It facilitates the simulation of river flow dynamics, water surface elevation, flood depth, and floodplain extent under diverse rainfall and discharge scenarios. When integrated with Geographic Information Systems (GIS), HEC-RAS enhances the visualization and spatial interpretation of flood hazards, rendering it highly valuable for local government planning and risk mitigation. Consequently, the integration of GIS, Analytic Hierarchy Process (AHP), and HEC-RAS provides a robust framework for identifying flood-prone areas and assessing flood risks in vulnerable communities.

Considering the escalating flood vulnerability of Bagac and the constrained availability of up-to-date flood risk assessments, this study endeavors to establish an integrated flood risk mapping framework employing GIS spatial analysis, AHP-based multi-criteria evaluation, and HEC-RAS hydraulic modeling. Specifically, the study aims to produce flood susceptibility and floodplain maps and develop a flood risk index that can facilitate disaster risk reduction and management initiatives, land-use planning, infrastructure development, and climate adaptation strategies within the municipality. The study's findings are anticipated to contribute to evidence-based planning and enhance local resilience against hydro-meteorological hazards.

2. METHODOLOGY

2.1 Data Acquisition and Preprocessing

Rainfall data (2014–2019) were obtained from Philsensor's Automated Rain Gauge Network, which provided temporal rainfall intensity and frequency across the municipality. Topographic data, including slope and elevation, were sourced from the Mines and Geosciences Bureau (MGB), while land cover classification was derived from Sentinel-2 satellite imagery processed using supervised classification.

Socio-economic datasets were provided by the Municipal Planning and Development Office (MPDO) and included updated information on population density, number of households, health personnel distribution, and location of evacuation centers. Infrastructure data included flood protection walls, canals, and other mitigation assets.

2.2 Analytical Hierarchy Process (AHP)

The AHP involved pairwise comparisons of the selected indicators under four major categories: hazard (H), exposure (E), vulnerability (V), and coping capacity (C). Criteria included distance to the nearest discharge channel (H1), total annual precipitation (H2), number of households (E1), population density (E2), elevation (V1), number of medical personnel (C1), and existing flood mitigation infrastructure (C2).

The normalized judgment matrices were constructed and analyzed using Saaty's method [4], producing a Consistency Index (CI) and Consistency Ratio (CR) to validate reliability. The final weights for each factor were computed and applied to the spatial layers:

$$CR = CI / RI \tag{1}$$

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{2}$$

Where λmax is the principal eigenvalue, n is the number of indicators, and RI is the Random Index. A CR below 0.10 confirmed acceptable consistency.

2.3 GIS Weighted Overlay and Risk Classification

The raster calculator and overlay function were employed to spatially map the various levels of flood risk in QGIS after the flood risk was calculated using equation 3.

$$\text{Risk} = H + E + V - C \quad (3)$$

Wherein: H = hazard, E = exposure, V = vulnerability, C = coping capacity.

Listed in Equations 4 to 7 where α, β, γ, δ = global weight for hazard, exposure, vulnerability, and coping capacity, respectively; and ai, bi, ci, di = local weights for hazard, exposure, vulnerability, and coping capacity, respectively.

$$H = \alpha\,(a_1(H_1) + a_2H_2) \quad (4)$$

$$E = \beta\,(b_1E_1 + b_2E_2) \quad (5)$$

$$V = \gamma\,(c_1V_1) \quad (6)$$

$$C = \delta\,(d_1C_1 + d_2C_2) \quad (7)$$

To verify the accuracy of this study, the generated flood risk and floodplain maps were evaluated with historical flood data obtained from the MDRRMO. The evaluation was assessed whether the identified high-risk areas correspond with the locations affected by past flooding events. Additionally, field validation involved visiting areas susceptible to flooding to examine terrain characteristics, infrastructure, and other factors that support the model's predictions.

Each raster layer was standardized using min-max normalization and reclassified on a scale of 1 (low) to 5 (high). The weighted sum overlay tool was used to aggregate indicator scores into a final Flood Risk Index (FRI) map. The resulting index was classified into five categories—Very Low, Low, Moderate, High, and Very High—based on quantile classification.

2.4 HEC-RAS Hydraulic Modeling

Floodplain mapping and simulation are necessary for land and water resources management, flood management, and forecasting. For the 2-D flow area of the basin, the computational time interval for the model is 5 minutes for the flood event, with cell sizes 30m x 30m used for analysis. This study used the rainfall return period from PAGASA's synoptic station in Apalit, Pampanga, which includes a 25-yr, 50-yr, and 100-yr return period.

Hydraulic modeling was performed using Hydrologic Engineering Center River Analysis System (HEC-RAS v6.6). Geometry data including cross-sections, riverbanks, and flow paths were extracted from the Digital Elevation Model using HEC-RAS. The hydraulic model simulated unsteady flows for the 25-year, 50-year and 100-year rainfall return periods.

3. RESULTS AND DISCUSSION

3.1 Computation of AHP Pairwise Matrix and Consistency Ratio

Table 1 presents the pairwise comparison matrix for the flood risk criteria based on expert judgments. The calculated priorities show coping capacity (0.529) as the most influential factor in determining flood risk, followed by hazard (0.195), vulnerability (0.176), and exposure (0.099). Coping capacity is the highest priority in the flood risk index, which means that the ability of each barangay to respond to and recover from floods reduces the overall risk. The CR of the indicators is 0.095 which indicates that the integrated experts' judgment is consistent since the CR value is less than 0.10.

Table 1. Weights for global, local, and indicator derived from the AHP analysis.

Criteria	Indicator	Global weight (%)	Local weight	Indicator weight
Hazard	H_1	$\alpha = 0.195$	$a_1 = 0.789$	0.1540
	H_2		$a_2 = 0.211$	0.0412
Exposure	E_1	$\beta = 0.099$	$b_1 = 0.10$	0.0099
	E_2		$b_2 = 0.90$	0.0891
Vulnerability	V_1	$\gamma = 0.176$	$c_1 = 1$	0.176
Coping Capacity	C_1	$\delta = 0.529$	$d_1 = 0.1$	0.0529
	C_2		$d_1 = 0.9$	0.4761

This result is consistent with findings by [6], who emphasized the importance of local capacities in shaping risk outcomes in the Philippines. Conversely, local study such as [7] focused more on hazard, exposure, and vulnerability, aligning with the traditional hazard-based approach. The results of this study diverge by quantifying the value of preparedness and adaptive systems, reinforcing UNDRR's emphasis on capacity-building as a core aspect of disaster resilience. These weights suggest a paradigm shift in flood risk prioritization, where resilience-building and response capabilities are valued more than the physical and social threat itself.

3.2 Flood Risk Index Map

Figures 1 to 4 presents the generated flood criteria maps for this study. The hazard map of the municipality corroborated the correlation between geographic features and flood susceptibility. Based on figure 1, the four barangays demonstrate exceptionally high susceptibility to flood hazards, five barangays exhibit a high susceptibility to flood hazards, and five out of fourteen barangays possess a moderate susceptibility to flood hazards. These findings align with [8], who also emphasized the heightened flood hazard in riverine and coastal barangays.

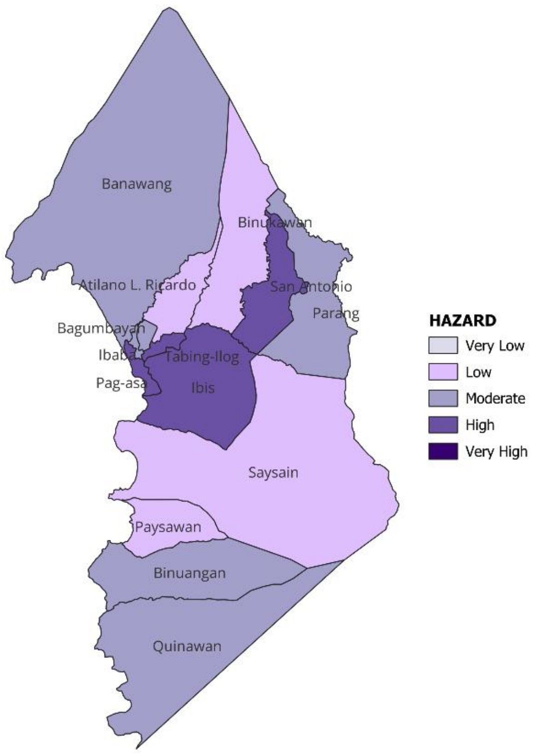

Fig. 1. Flood Hazard Map.

The generated flood exposure map, figure 2, for this study accurately depicted the flood exposure levels of the barangays within the Bagac municipality. The map revealed that the barangays of Bagumabayan, Pag-asa, and Tabing Ilog experienced elevated flood exposure. Conversely, the remaining barangays exhibited moderate flood exposure levels. Notably, the high-exposure barangays have been designated for targeted preparedness interventions, particularly in the areas of evacuation planning and emergency services. This map serves as a valuable decision-making tool for the Local Government Unit (LGU) of Bagac, facilitating the implementation of mitigation strategies and the efficient allocation of resources for effective flood risk planning.

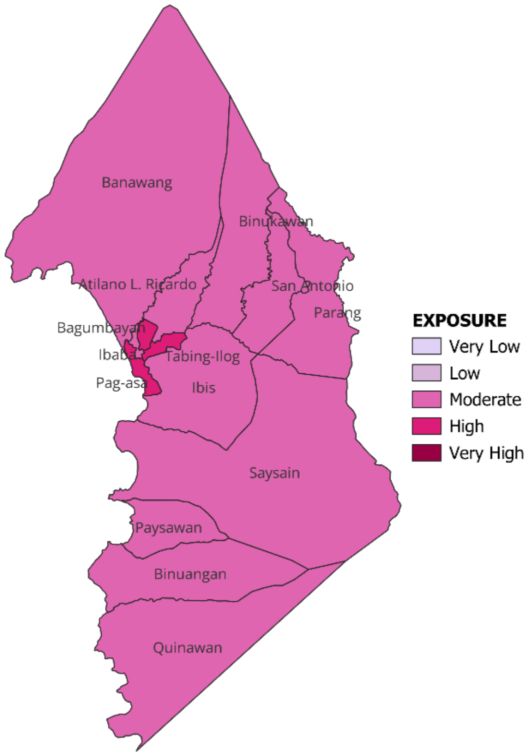

Fig. 2. Flood Exposure Map.

The vulnerability map in figure 3 indicated that the majority of barangays are moderately susceptible to flooding. Experts suggest that barangays with moderate flood vulnerability are at heightened risk during intense rainfall events and should be prioritized for mitigation strategies. These findings are consistent with those of [7], who discovered a strong inverse correlation between elevation and flood vulnerability in low-lying rural areas.

Lastly, the coping capacity as seen in figure 4 varies significantly across barangays. Barangays such as Ban-awang, Pag-asa, Parang, and Saysain exhibit high coping scores due to the presence of a greater number of medical personnel and consistent flood mitigation infrastructure.

Conversely, Binuangan, Binukawan, Paysawan, and Quinawan lag in these areas due to their low coping capacity for floods. The remaining barangays demonstrate a moderate level of coping capacity for flood events. Experts recommend that barangays with very low to moderate coping capacity should implement flood mitigation strategies to enhance their ability to cope with or recover from floods. The findings align with the framework established by [6], which emphasizes that physical infrastructure must be complemented by local institutional and healthcare capacity to be effective. This spatial differentiation provides valuable insights for Local Government Units (LGUs): barangays with low coping capacity but high hazard/exposure values should be prioritized for resource allocation.

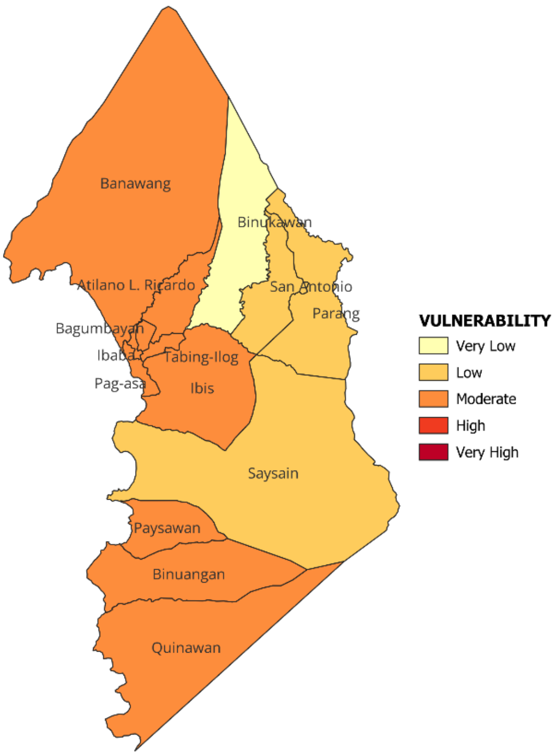

Fig. 3. Flood Vulnerability Map.

The Flood Risk Index Map in figure 5 highlights Pag-asa as the barangay with a very high flood risk level. Conversely, the barangays of Bagumbayan, Ibaba, and Tabing-Ilog are classified as having a high flood risk level. This was attributed to their proximity to rivers and coastal areas, low elevation, and limited medical and infrastructural capacity. This map also indicates that the barangays of Binukawan and Saysain have a low flood risk level, while the remaining barangays are categorized with a moderate level of flood risk.

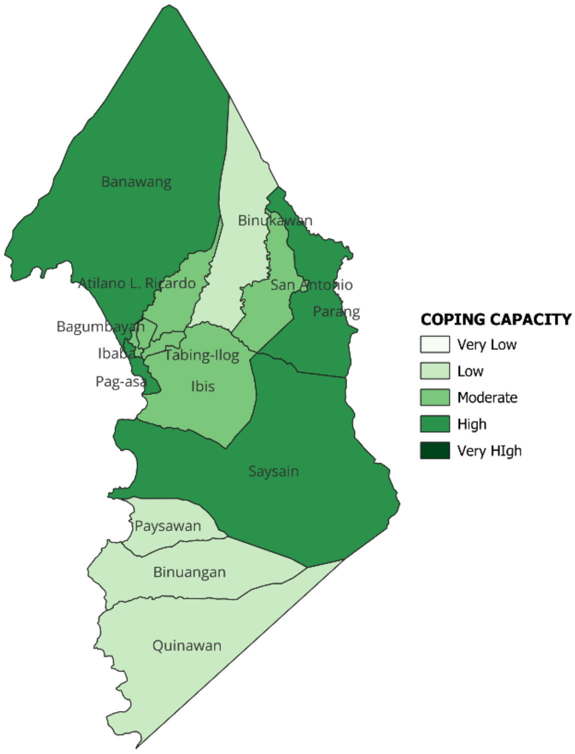

Fig. 4. Flood Coping Capacity Map.

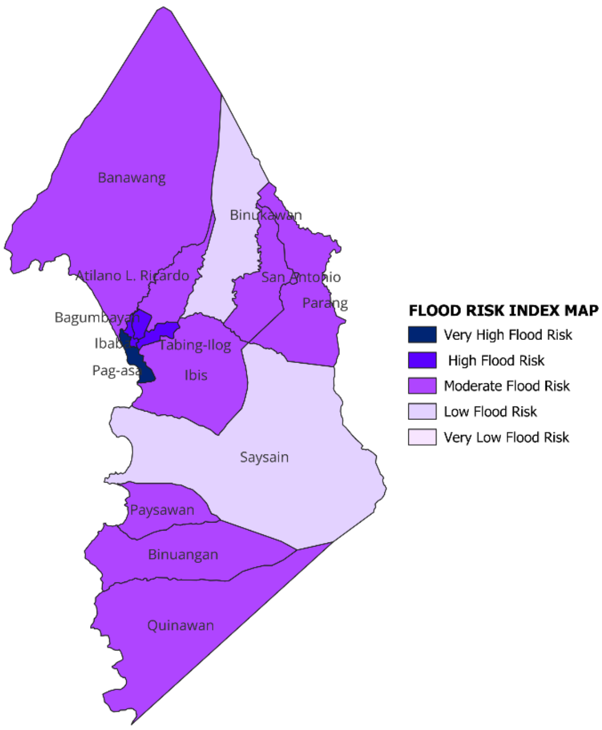

Fig. 5. Flood Risk Index Map.

This flood risk map can assist decision-makers in policymaking, land-use planning, developing guidelines and countermeasures and flood disaster insurance. One concrete example would be assessing the adequacy of each barangay's available evacuation centers and flood mitigation structures.

Areas classified under Very High Risk must have enough evacuation centers to accommodate affected residents. Additionally, the developed risk map can be used to identify the impacts of flooding on several sectors, such as the education sector, the medical sector, and the private sector [8]. The developed flood risk map can also be used to appropriately assist government stakeholders in prioritizing budget and type of countermeasure, either structural or non-structural. [9] emphasized that understanding large-scale patterns in flood hazards and flood risk should be done with an appreciation of the limitations of the underlying datasets, methods, and models used.

3.3 Floodplain Map

Figure 6 shows the exported maximum floodplain maps from HEC-RAS to QGIS. Floodplain simulations provide insight into the depth and velocity of potential floods. The three return periods simulation in HEC-RAS have almost the same results, except for the minimal difference in the velocity and depth of the floodplain. The figure shows consistent flooding in barangays located in coastal areas, rivers, and barangays with low elevations. These floodplain maps support the results of the flood risk index and validate its accuracy. Moreover, they offer crucial evidence for zoning, infrastructure placement, and emergency route design.

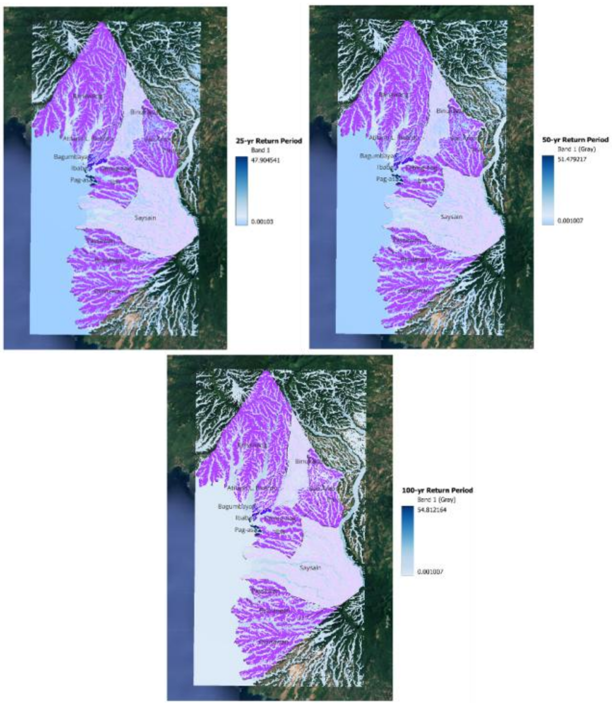

Fig. 6. Exported Floodplain Maps from HEC-RAS to QGIS (25-yr, 50-yr, and 100-yr return period).

4. CONCLUSION AND RECOMMENDATION

The study effectively produced comprehensive flood risk and floodplain maps for Bagac, Bataan by integrating GIS, AHP, and HEC-RAS, offering a powerful tool for planners and decision-makers to conduct in-depth flood risk assessments. The developed flood risk indexing system incorporated hazard, exposure, vulnerability, and coping capacity, providing a multi-dimensional and robust framework for identifying and evaluating flood-prone areas.

This study presents flood risk index and floodplain maps as essential resources for stakeholders such as citizens, local governments, Community Emergency Response Teams (CERT), urban planners, infrastructure developers, and researchers. With the aid of this study, the integration of multiple tools offers a scalable and replicable approach that can be modified for other flood-prone areas in the Philippines.

To incorporate the created flood risk maps into local land-use planning infrastructure development and disaster preparedness efforts, the municipal government of Bagac should formally adopt and implement them. It is recommended that to maintain the relevance of these maps, they should be updated every 3 to 5 years to reflect environmental and developmental changes. Enhancing community involvement through regional training initiatives will also enable locals to better comprehend and address flood hazards.

Furthermore, it is advised to carry out flood mitigation projects that give coping capacity top priority to successfully lower the risk of flooding. By adding socioeconomic indicators and high-resolution real-time data the approach will be extended to nearby municipalities improving flood risk management. Flood risk assessments will be considerably enhanced by this all-encompassing strategy. Encouraging interdisciplinary cooperation and incorporating flood risk data into regional building codes and policies will also advance resilient urban planning which will ultimately guarantee the community's long-term safety and well-being.

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