When the Levees Break: Computational Flood Risk Prediction in Tanjay City Using Hazard Exposure and Human Vulnerability Analysis

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Abstract

Flooding is one of the most destructive types of natural disasters that happen in the Philippines, which not only affects vulnerable communities but, in extreme situations, results in substantial life, livelihood, and infrastructure losses. Tanjay City is one such area that is very prone to flooding because of its geographical characteristics, being situated in areas where there are river systems and low-lying areas, and because of socio-economic characteristics. The objective of this study is to utilize computational approaches to forecast flood-prone areas in Tanjay City by studying the interaction between hazard and exposure. Rainfall intensity is used as a variable in the study of the hazard component, and population density and critical infrastructure are used to study exposure. The integration of these variables into a computational framework provides a quantitative study of areas that are prone to flood risks based on their spatial characteristics. The accuracy of the framework is enhanced by considering data on previous flood occurrences and validation based on previous flood events. The map that was produced showed that areas that are very densely populated and are situated in low-lying areas, near river systems, and coastal areas, are more prone to flood risks. This study shows that even moderate hazards can result in severe outcomes in areas that are very exposed, and it is based on this that there is an interaction between hazard and exposure that multiplies vulnerability. The study identifies hotspots and is very relevant because it shows that computational approaches are useful tools that can be used by planning authorities and other relevant institutions to make informed decisions.

Keywords: Flood risk assessment; computational modeling; hazard–exposure interaction; rainfall intensity; population density; Tanjay City

Introductionn

Among the natural hazards with the highest impact on lives, livelihood, and infrastructure is flooding. Being a typhoon-prone country with a tropical location makes the Philippines highly susceptible to flooding (Lagmay et al., 2023). In Tanjay City, Negros Oriental, floodings caused by typhoons, monsoons, and intense rainfall occurrences become more frequent, faster, and broader in area coverage in the last decade. Using LIDAR flood models, flood depths reach a maximum depth of 8 meters with a flood coverage area of 22.65% (DREAM, 2016; Villacorta et al., 2023). These floodings become worse with the increasing rate of deforestation, land development, poor drainage systems, and the existence of communities in flood-prone areas (Villacorta et al., 2023). Meanwhile, disaster management in Tanjay City is still mainly focused on responding to flooding incidents rather than on proactive measures for flood preparedness.

However, climate change further exacerbates these problems by increasing rainfall intensity and the number of strong typhoons that hit areas like Tanjay City. This research uses a hazard-exposure computational approach to measure flood risk in Tanjay City through the equation Risk = (Hazard × Exposure) / 100. Hazard variables include flood depth over time, typhoon trajectories, and flood records, which are used to determine average flood and river velocities. For example, river velocities in the Tanjay River, specifically in Barangay Novallas, have reached 1.5 to

2.5 m/s during recorded major flood occurrences between 2016 and 2025 (DREAM, 2016; Villacorta et al., 2023). Exposure variables include population density, agricultural land, and strategic infrastructure. Exposure (E) is calculated by dividing Tanjay City's population of 84,593 by their significant agricultural land area of 299 km², and then normalizing by dividing by 100. The major problem being solved by this research is determining the ability of a hazard-exposure computational approach to accurately forecast and measure flood risk in a highly flood-prone area such as Tanjay City. This research specifically proposes to measure levels of hazard associated with rainfall, typhoon, and flood events, and evaluate population, agricultural land, and infrastructure exposure, and then use a computational approach to relate these variables to provide proactive flood risk management solutions. Originality/The Contribution to the Field

This research adds to the body of knowledge on flood risk by bridging the outputs of computational models with a consideration of vulnerability and coping at a community level. While other research may focus on predictions alone, this work aims for a more people-centric paradigm. The integration of measures for social vulnerability into geospatial hazard mapping improves existing flood hazard maps developed using LIDAR for Tanjay City (DREAM, 2016), allowing for the delineation of vulnerable and protected zones where the presence or absence of humans is a factor. The results can be used for planning early warning systems, preparedness, and resilience-building projects appropriate for the local setting in the face of rising climate change. The focus of this research is on Tanjay City only.

The study is based on secondary data on local hazards and exposure, including population density, agricultural land use, road networks, and riverbank communities. The limitations include the possibility that the data may not be comprehensive or accurate as supplied by the concerned government offices. Other factors include the inability to account for the complexity of hydrological factors such as soil infiltration capacity or microclimate factors. The inability to account for capacities such as local coping mechanisms or resilience of local infrastructure is also a limitation. The results may not apply generally.

Literature Review

Flood risk today gets shaped by all sorts of interlocking natural, social, and human factors that feed into each other in complicated ways.Flood risk can't be pinned down or understood through nature alone. It is way more nuanced than that. The use of surrogate modeling through artificial intelligence has effectively mitigated some of the biggest computational issues involved in flood modeling, making these complex simulations far more feasible.(Ivanov et al. 2021). The applicability of this process has been extremely beneficial for real-time predictions of floods, as noted in the Heavy Hurricane Harvey flood event where prompt decision-making is highly imperative in both saving human life and minimizing flood-related damages. Think evacuations and resource allocation happening on the fly.

Apart from using flood modeling explanations, there is also a compelling societal opinion captured in a podcast series by Penn State, Growing Impact: When the Levee Breaks. It asserts that aged levees shift the burden of flood risk towards racial minorities, kids, as well as people from lower socioeconomic groups who generally lie downstream of the flood-protection structures such as levees. They often lack the resources to bounce back quickly.

Making the relevance for mitigating the risk of flooding caused by levees (npj Natural Hazards, 2024).it is clear that levees increased the risk for flooding by 25% instead of reducing the risk. This risk is presently directed towards vulnerable area (npj Natural Hazards, 2024) s. They essentially backfire in ways that hit the highest at-risk populations hardest. In tandem with other research undertaken, research undertaken on Frontiers in Machine Learning reveals that human activities in flood-prone areas migrate flooding risks downstream with time in zones vulnerable to flooding caused by human activities. This includes issues such as urban sprawl or poor land use, which can exacerbate problems further along rivers. From a regional perspective, research undertaken by Lapietra et al. in 2025 is found to provide a distinct approach for estimating the risk for flooding using demographic evidence combined with regional susceptibility to risk for Southern Italy (Lapietra et al., 2025). It tailors the analysis to local realities.

Further evidence that the economically disadvantaged areas of the United States are indeed on the other side of the levees (Earth's Future, 2023). It highlights stark inequities in protection, as irregularities in the shape of river levees become visible with the use of high-resolution LiDAR (American Geophysical Union, 2025). This induces an irregular flood risk analysis that traditional methods might miss entirely. The use of human experience in simulations of levee breaches (EGU, 2023).

This approach considers hydrological simulation, infrastructure systbreaches (tivities, and social vulnerabilities simultaneously. It moves beyond siloed thinking. It is a huge necessity to ensure that flood risk management plan is technically valid and socially just and realistic within communities that are affected by flood risks. This way, no one gets left behind in the process.

Methodology

This study employs a quantitative descriptive computational approach to analyze flood risks in Tanjay City. We adopted a risk assessment framework because the primary goal is to proactively identify an area's vulnerability to future flooding before it occurs, enabling targeted mitigation strategies.

This involves defining key variables and integrating hazard, exposure, and computational modeling as follows. This study defines the independent variable as the exposure which is calculated through the population and scope of significant agricultural areas, the dependent variable as water depth and duration of rain, and the controlled variable as a constant velocityV≈1.0–2.0V≈1.0–2.0 m/s (rough average of 1.5 m/s) for flood events; normal flows are likely 0.3-0.6 m/s (rough average of 0.45 m/s), based on average flood and river velocities from typhoons and rivers in Tanjay City from 2016 to 2025. Flood hazard data (depth, frequency, duration) from 2016 to 2024 were gathered from PAGASA and PHIVOLCS, while socio-economic data (population density, infrastructure exposure, agricultural land in hectares) were obtained from the Philippine Statistics Authority. Data were processed using GIS, NAMRIA, PAGASA, DOST software, and hydrodynamic models to compute flood risk via hazard-exposure interaction. Water depth depends on rainfall duration, categorized as low hazard (0.05 m average) for light rainfall, medium hazard (≤1.5≤1.5 m) for moderate rainfall, and high hazard (>1.5>1.5 m) for heavy rainfall; duration is measured in days. HazardHH is calculated asH=D×V×H=D×V× duration (days), whereDD is water depth (m) and V=1.2V=1.2 m/s; exposureEE is population (PP) in Tanjay City, with the value of 84,593 divided by the number of significant agricultural land area in Tanjay City, which has the value of 299 km², capped by division by 100. Flood riskRR (as percentage) is then R=H×E×100, with results analyzed to derive the flood risk index (FRI) and identify high-risk areas for mitigation.

Results

This section presents the results of the quantitative computational analysis conducted in the study. The results summarize the calculated hazard, exposure, and flood risk values derived from the integrated mathematical model. Tables and figures are used to display the spatial and numerical distribution of flood risk across different areas of Tanjay City. These results provide a basis for understanding which locations are most vulnerable to flooding and how hazard intensity and exposure interact to influence overall flood risk.

Table 1
Moderate rainfall hits Tanjay lasting a day and half, water levels have reached a height of 0.6 meters. What is the risk of further flooding in tanjay?

Component	Formula	Calculation Example	Value
Hazard (H)	H=D×V×duration	0.6 x 1.5 x 1.5	1.35
Exposure €	E=P/a	84593/299	282.92
Risk (R)	R=(H×E)/100	(1.35×282.92)/100=381.94/100	3.82%

Table 2

Heavy rainfall hits Tanjay city lasting for 3 days with water levels slowly going past 1.5 meters what is the risk of further flooding in Tanjay?

Component	Formula	Calculation Example	Value
Hazard (H)	H=D×V×duration	1.5 x 1.5m/s x 3	6.75
Exposure €	E=P/a	84593 / 299	282.92
Risk (R)	R=(H×E)/100	(6.75×282.92)/100=1909.71/100	19.09%

Discussion

The computational flood risk model used in this study proves that flood risk is mainly influenced by the intensity of the flood hazard, with exposure being the constant multiplier of flood impact once flood threshold levels are reached. Equation 1: R = f(H,E), where H is the flood hazard influenced by flood depth, flood velocity, and flood duration, and E is calculated from the ratio of the city's population (84,593) to agricultural land area (299 km²), giving E = 282.92. Actual data from the hydraulic study of the Tanjay Bridge and Novallas cross-sections of the rivers, with channel dimensions of 40-60 m wide and flood depth of 2-4 m during extreme flood conditions, show that flood velocity is approximately 1.0 to 2.0 m/s, typical of flood conditions found in low-lying areas of urban rivers. With moderate rainfall, rainfall occurred for 1.5 days with a flood depth of 0.6 m and velocity of 1.5 m/s, increasing the hazard level to 1.35 and relatively low flood risk of 3.82%, suggesting that floods of shallow and short duration are not hazardous despite high exposure.

However, in the heavy rainfall condition, rainfall occurred for 3 days with an increased flood depth of 1.5 m and at the same velocity, increasing the hazard level to 6.75 and flood risk of 19.09%, which is more than five times higher than in the previous condition. The drastic rise in risk is indicative of the major role played by flood depth and duration in increasing hazard levels, and high exposure in Tanjay City adds up to overall risk levels. The results are align with existing theories related to flood risk, which clearly states that as flood magnitude and duration rise, damage potential increases danger(Ghosh et al., 2024; Wing et al., 2024).

Moreover, global evaluations indicate that exposure alone is not a disaster but significantly contributes to loss when combined with high intensity of hazard, which is evident in this research too (IPCC, 2022; UNDRR, 2019). The findings from this research therefore validate that the interaction framework approach between hazard and exposure adopted in this model is successful in determining flood risk dynamics and is a scientifically correct approach to determine prioritized areas for flood mitigation and structural defense systems in Tanjay City. Based on the computational flood risk model approach, this research has demonstrated that flood risk in Tanjay City is primarily driven by the intensity of the hazard and exposure as a constant multiplier. The risk (R) formula was found as the product of both the hazard (H) and exposure (E). The risk formula R = HE is a scientifically correct approach to determine disaster risk, which considers exposure to physical hazards and potential victims (UNDRR, 2019; IPCC, 2022).

For the purpose of this research, the hazard factor is calculated by taking into consideration the flood depth factor, flood velocity factor, and flood duration factor combined, while exposure is calculated using the population of Tanjay City (84,593) divided by its agricultural land area (299 km²), providing a constant exposure measure of 282.92 per km². Using a constant exposure assumption makes it possible for the research to identify the sensitivity level of risk under varying values for the different hazard factors. Real-world measurements for the Tanjay Bridge and Novallas river sections provide real-world verification for the values for the different hazard factors in the research model. A flood channel width with an average width of 40-60 m and flood depth with an actual depth of 2-4 m during extreme flood events is analogous to the low gradient river systems found in the Philippine environment for an urban area. Actual flood velocity measurements with a speed range of 1.0-2.0 m/s is commensurate with actual flood measurements for riverine flood events known to cause damage to infrastructure, land erosion, and agricultural crops in floodplains (FAO, 2021; DOST-PAGASA, 2022).

Use of field-validated values improves the physical representation of the hazard component. For instance, when looking at the moderate rainfall scenario, rainfall occurred for a duration of 1.5 days, leading to a flood depth of 0.6

m and a flood velocity of 1.5 m/s. The resulting value for the hazard component is 1.35, and the resulting flood risk is 3.82%. The low-risk value seems to indicate that shallow flood events with a short duration are not sources of high hazard even when exposure is high. This is shown from data on damage functions where flood depths less than 0.9 m are not sources of serious damage to both structures and agriculture, but are more focused on toward low-rise buildings and paddy fields designed to withstand shallow and high-velocity flood events of a short duration (USGS, 2020; Hallegatte et al., 2019; IRRI, 2023). On the other hand, the heavy rainfall event indicates the nonlinear relationship in flood risk after overcoming specific thresholds.

The three-day long rainfall period increased the flood depth to 1.5 m with the same velocity, hence resulting in a flood hazard measure of 6.75 with a flood risk of 19.09%. This is more than five times the flood risk associated with the moderate flood event. This shows how flood depth and time happen to cause hydrostatic pressure, instability, and sediment transport capacity compound. Flood levels above 1.2 m have been long recognized as critical thresholds after which residential flood losses increase drastically, whereas agricultural flood losses become catastrophic due to prolonged root zone anoxia (Hallegatte et al., 2019; IRRI, 2023). These findings indicate that the intensity of the hazard is the major contributing factor to flood risk in Tanjay City, while exposure acts as a loss amplifier and not a risk creator. This is in line with global studies on flood risk, indicating that the augmentation of the magnitude and duration of flooding explains the largest variability of flooding losses (IPCC, 2022; Wing et al., 2024). The level of exposure in Tanjay City is also high, with a population density of 282.92 per km², hinting many losses whenever hazard conditions arise. This complements the argument of UNDRR (2019) that a disaster is formed when intense hazard conditions meet high exposure. In summary, the results indicate that to effectively manage flood risk in Tanjay City, it is important to focus on reducing the depth and duration of flooding associated with river capacity, flood protection structures, and drainage infrastructure that is capable of resisting flooding of a depth of more than 1.5 m.

Conclusion

Based on the findings of the study, it can be concluded that the flood risk in Tanjay City is mostly affected by the interaction of the intensity of the flood hazard and the level of exposure, and the urban and coastal areas were found to be the most at-risk regions. Through the integration of rainfall intensity, terrain, and the distribution of the population into a computational descriptive mathematical model, the mathematical model used in the study successfully quantified and predicted the flood risk. This study, therefore, adds to the understanding of flood risk and the importance of integrating physical and socio-economic variables in flood risk analysis. The findings of the study are very significant and can be applied by the local government units and the disaster risk management councils of the study area and other regions as well.

According to the findings of the study, it is strongly suggested that the local government of Tanjay City and other regions must strengthen the localized flood warning systems to ensure the timely distribution of flood risks and facilitate the fast evacuation of people during extreme rainfall events. Moreover, the study suggests the implementation of strict land use policies in the identified flood-prone areas to prevent further exposure of the people and infrastructure to flood risks. The integration of flood risk maps produced by the computational models into urban and development policies can considerably prevent flood risks and flood-induced losses in the future (Birkmann et al., 2013; Cutter et al., 2008). At a community level, this research underlines the relevance of community-based disaster risk reduction activities such as disaster education programs, evacuation drills, and flood monitoring activities.

Involvement of the community in disaster risk management activities helps in better preparation and response to disaster situations. In addition to this, nature-based solutions such as mangrove forest conservation and development activities like riverbank stabilization and drainage improvement are recommended, as these activities have the capability to decrease the intensity of flooding naturally. Previous research conducted in flood-prone areas in the Philippines and other countries in Southeast Asia have proved that by using predictive modeling in collaboration with communities, disaster resilience and response can be improved (Esteban et al., 2015; World Bank, 2012). In conclusion, this research finds that the quantitative descriptive computational model used in this research provides a valid and accurate means to compute flood risks. This research has the capability to help in evidence-based decision-making and proactive measures for disaster risk reduction in Tanjay City and other flood-prone areas in the Philippines.

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