Assessment on Flood Hazard of Different Return Periods in Mueang Phrae District, Phrae Province, Thailand

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Abstract

Floodings occur frequently in Phrae Province, Thailand, particularly in Mueang Phrae District, which locates within the upper Yom River Basin. The Yom River is a major tributary of the Yom River Basin which significantly influences flood runoff of the River Basin. The recent floods in 2024 caused substantial damages to infrastructure, agriculture, and communities, underscoring the need for effective flood management. This study assesses flood hazards in Mueang Phrae District by evaluating flood-affected areas at different return periods of 2, 5, 10, 25, 50, 100, and 500 years. Hydrodynamic modeling was conducted using the well-known HEC-RAS model developed by the U.S. Army Corps of Engineers, along with topographic data, river cross-sections, and historical daily water level data. Both model calibration and validation demonstrated high model performance, with Coefficient of Determination (R^2) values of 0.95 and 0.87, Nash-Sutcliffe Efficiency (NSE) of 0.95 and 0.87, Percent Bias (PBIAS) of 1.10% and -1.60%, Mean Absolute Error (MAE) of 0.01 and 0.33, and Root Mean Square Errors (RMSE) of 0.28 and 0.38 for the flood periods during 2000-2011 and 2012-2023. Flood hazard maps were created to identify flood-prone areas for each return period, covering the following extents: 4.23, 5.86, 7.35, 8.06, 9.48, 10.51, and 11.80 km^2 for the 2, 5, 10, 25, 50, 100, and 500 years, respectively. These areas were classified into five hazard levels: very low, low, medium, high, and very high according to the flood damages. The findings contribute to a better understanding of flood hazards in Mueang Phrae District and provide valuable insights for flood disaster adaptation measures, preparedness, and enhancing community resilience to future floods.

Keywords: Floods, Hazard Assessment, Return Periods, Phrae, Yom River Basin, Adaptation Measures

1. Introduction

Flooding in Mueang Phrae District, located in Phrae Province, Thailand, has long been a frequency issue, resulting in significant losses and damages, particularly in the sub-districts of Nai Wiang, Tha Kham, Thung Hong, Na Chak, Mueang Mo, Wang Hong, Mae Lai, Mae Kham Mi, Mae Yom, Thung Kwao, Pa Maet, and Wang Thong. Positioned within the upper Yom River Basin, Mueang Phrae is highly susceptible to flood events due to the Yom River role as a major tributary [1-2]. In recent years, flood event of 2024 has caused widespread destruction to infrastructure, agricultural land, and local communities across all eight districts of Phrae Province, affecting approximately 13,982 households. These events underscore the urgent need for effective flood management strategies to safeguard local development, the economy, and resident well-being. The vulnerability of Mueang Phrae to flooding, combined with increasing climate variability, necessitates comprehensive flood hazard assessments to inform and guide targeted mitigation efforts [3].

Flood hazard assessment plays a significant role in understanding and managing flood risks by identifying vulnerable areas and forecasting potential flood characteristics over time [4]. Through assessing the likelihood of floods occurring at different return periods, this can design appropriated flood management strategies, allocate resources effectively, and implement preventive measures [5]. Additionally, flood adaptation measures such as land use planning, and agricultural adjustments can significantly reduce flood impacts. Modifying crop choices in flood-prone areas [6], for instance, can help maintain agricultural productivity during periods of inundation, while strategic zoning and flood resilience planning can help protect urban areas from flood damage [7].

The objective of this study is to develop comprehensive flood hazard maps for Mueang Phrae District, evaluating different return periods (2, 5, 10, 25, 50, 100, and 500 years) to increase understand the spatial distribution of flood hazard. In addition, the study aims to explore flood adaptation strategies, including the introduction of flood-resistant crops for paddy fields. By focusing on potential hazard areas within flood-prone areas and effective adaptation measure, the findings of this study contribute to flood disaster preparedness, assist in guiding policy development, and promote community resilience against future flood events.

2. Study area and data collection

2.1 Description of study area

The study area is located in the upper Yom River Basin, which is a major river in the northern region of Thailand. The Yom River originates in the Khun Yuam Mountain in Phi Pan Nam Range in Pong and Chiang Muan district, Phayao province, where it begins at an elevation of over 180-360 meters above sea level [8]. The river flows southward for approximately 735 kilometers, passing through various districts before merging with the Nan River. The upper Yom River Basin is characterized by diverse topography, including steep mountains, rolling hills, and expansive lowlands, which significantly affect the regional hydrological behavior and flood dynamics. The region experiences a tropical climate, with distinct wet and dry seasons. The average annual rainfall is about 1,225.3 millimeters, with the majority of rainfall occurring during the monsoon season from May to October. These climatic and geographical factors contribute to the frequent flooding in Mueang Phrae District, particularly during the peak of the wet season, when the river is prone to overflowing [1].

Mueang Phrae District is located along the Yom River in Phrae Province, making the area highly susceptible to flooding events. The district is situated in the central part of the province, where the Yom River flows through lowland areas. Mueang Phrae is divided into 20 administrative sub-districts, each with varying levels of exposure to flood risks, depending on proximity to the river and topographical characteristics. As shown in Fig. 1, the district layout and relationship to the river make certain sub-districts particularly vulnerable to seasonal flooding, especially during heavy rainfall in the wet season.

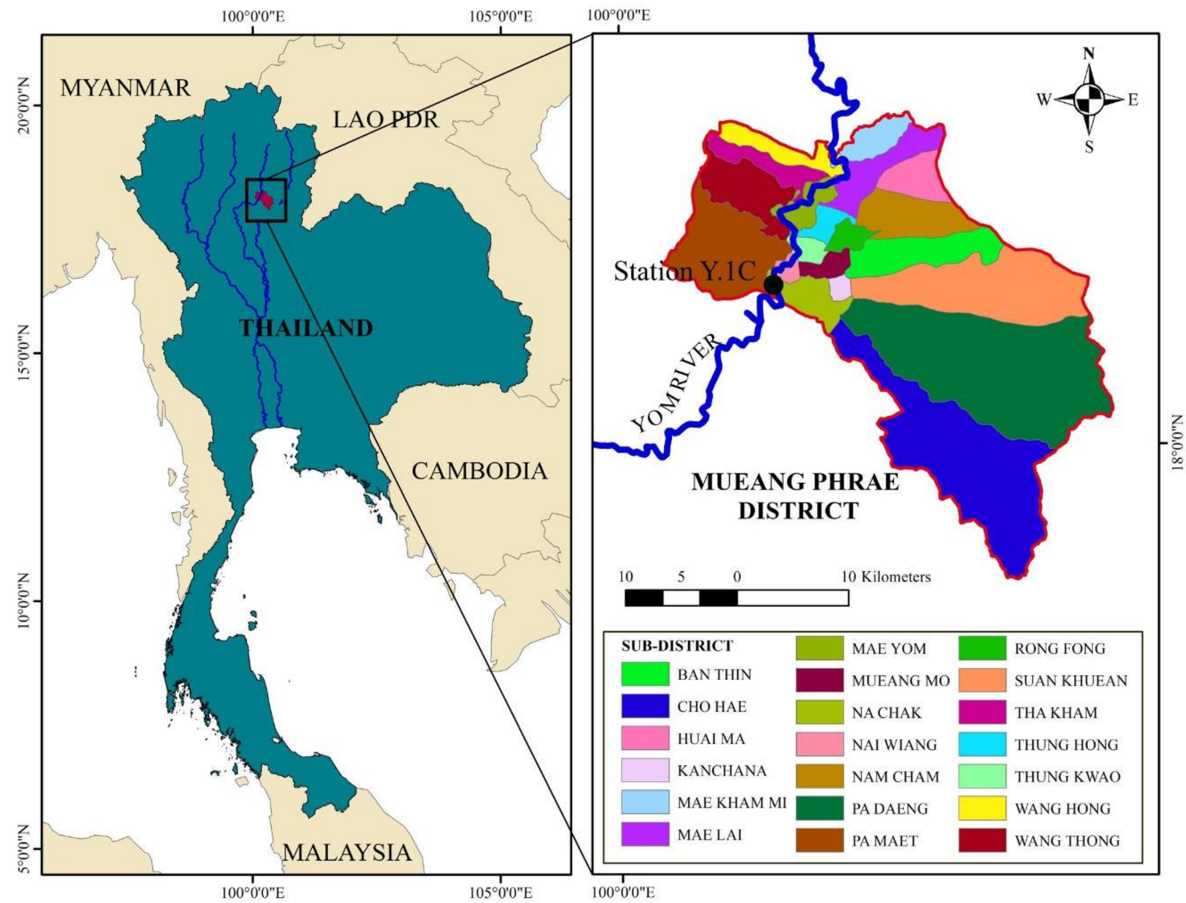


Fig. 1 The location of Mueang Phrae District and Sub-District

The land use in the study area is diverse, reflecting both agricultural, forest, build-up area, water body and miscellaneous land types. The majority of the agricultural land is used for agriculture, with paddy fields covering 119.51 km^2, which is the dominant land use in the district [1]. It is approximately 84% for sticky rice and 16% for jasmine rice. Additionally, there are 22.92 km^2 of field crops and 38.55 km^2 of perennial crops, contributing to the agricultural economy. Orchard areas cover 12.17 km^2 while horticulture and swidden cultivation make up smaller areas of 0.39 and 1.09 km^2, respectively. Other agricultural uses include aquacultural lands and pasture/farmhouses, which cover 0.27 and 0.85 km^2. Forest land is the largest land use category, covering 485.18 km^2, followed by miscellaneous land at 14.45 km^2. Urban and built-up areas, which include residential and commercial zones, cover 61.02 km^2, while water bodies, such as rivers and lakes, cover 10.17 km^2 as shown in Fig.2.

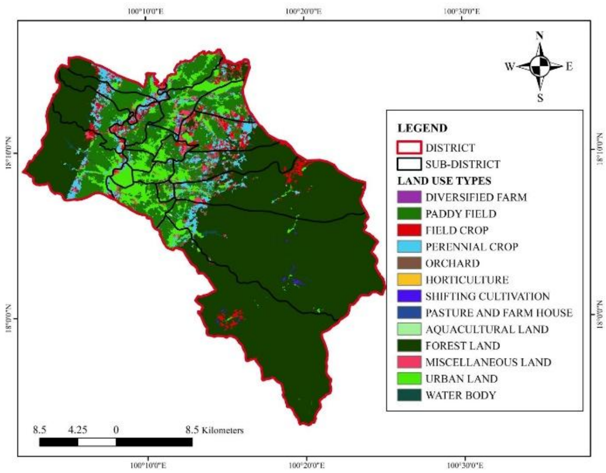


Fig. 2 Land use map of Mueang Phrae District with various land use types in 2020

2.2 Data collection

For the hydrodynamic modeling using the HEC-RAS model, several types of input data were collected to accurately simulate flood conditions in Mueang Phrae District. The primary data sources included a Digital Elevation Model (DEM), four river cross-sections, river and floodplain roughness coefficients, and daily river discharge and water level data from 2000 to 2023, obtained from the Royal Irrigation Department (RID). For the assessment of flood adaptation measures, land use data from 2020, provided by the Land Development Department (LDD), were used to evaluate the suitability of various flood resilience strategies.

3. Methodology

3.1 Hydrodynamic Modeling (HEC-RAS)

HEC-RAS (US Army Corps of Engineers, 2016) is a widely recognized and reliable software tool used for simulating river hydraulics and floodplain inundation. It is designed to model both steady and unsteady flow conditions, providing critical outputs such as water surface profiles, flow velocities, and flood extents [9-10]. The model is highly flexible, capable of simulating various flow scenarios, including those corresponding to different return periods, and can handle complex river systems with diverse cross-sectional geometries.

HEC-RAS supports both one-dimensional (1D) and two-dimensional (2D) hydrodynamic modeling. The 2D modeling feature allows for more detailed representation of floodplain dynamics by simulating flow in multiple directions across a grid-based computational domain. Unlike 1D models that rely on cross-sections to represent flow conditions, 2D models solve the full shallow water equations (Saint-Venant equations) over a mesh of computational cells, capturing complex flow behaviors such as flow divergence, overtopping, and interactions with terrain features [11]. By simulating realistic flood scenarios with 2D modeling approaches, HEC-RAS provides valuable insights into flood dynamics, aiding in the development of effective flood mitigation strategies.

3.1.1 Model setup

The setup of the HEC-RAS model begins with defining the river network, including delineating reaches and establishing cross-sections that accurately represent the river geometry [11]. Flow data, such as discharge or stage hydrographs, are specified at upstream boundaries, along with boundary conditions such as water surface elevations. To model flow resistance, roughness coefficients (Manning's n) are assigned to each cross-section, accounting for factors like riverbed material and land cover. These input parameters are defined, the model simulates the movement of water through the river system, calculating critical hydraulic parameters such as daily water surface elevations, daily flow velocities, and daily discharge at various points along the river. This process allows for a detailed understanding of flow dynamics and flood behavior within the study area.

3.1.2 Mode performance

Model performance is evaluated by comparing simulated results with daily observed water level data using several statistical parameters. The Coefficient of Determination (R^2) measures the proportion of variance in the observed data explained by the model, with values closer to 1 indicating a better fit. The Nash-Sutcliffe Efficiency (NSE) evaluates the model ability to predict observed data, with values closer to 1 reflecting high predictive accuracy. The Percent Bias (PBIAS) quantifies the average tendency of the model to overestimate or underestimate observed values, with values near zero indicating minimal bias. The Mean Absolute Error (MAE) calculates the average of the absolute differences between simulated and observed water levels, while the Root Mean Square Error (RMSE) provides a measure of error magnitude, where lower values indicate better model performance. Calibration and validation are carried out using observed water level data from different periods (2000–2011 and 2012–2023) to ensure the model reliability in simulating flood events and accurately representing real-world conditions.

3.2 Flood hazard classification

Flood hazard classification is based on simulated maximum daily flood depth (in meters) and duration (in days) obtained from the HEC-RAS model [12-13]. However, this study did not consider flood velocity, as its impact is less significant compared to flood depth and duration. Flood depth is categorized into five hazard levels, taking into account the average height of people across different age groups, houses and buildings. These classifications were developed by referring to the concept of the flood hazard mapping manual in Japan [14-15]. For built-up areas, the classifications are as follows: very low or affecting about 0-20% of people (0–0.40 meters), low or affecting about 21-40% (0.41–0.80 meters), medium or affecting about 41-60% (0.81–1.20 meters), high or affecting about 61-80% (1.21–1.60 meters), and very high or affecting about 81-100% (greater than 1.60 meters). For agricultural areas, the classifications are: very low or affecting about 0-20% of rice crops (0–0.35 meters), low or affecting about 21-40% (0.36–0.70 meters), medium or affecting about 41-60% (0.71–1.05 meters), high or affecting about 61-80% (1.06–1.40 meters), and very high or affecting about 81-100% (greater than 1.40 meters), based on the height of rice plants during the vegetative, reproductive, and maturity stages [16], as shown in Table 1. These flood depth categories are based on their impact on the average height of local residents (approximately 1.66 meters during 2022-2025) [17]. For rice plants, the majority is glutinous rice (RD6) (approximately 1.54 meters height) and jasmine rice (Khao Dawk Mali 105: KDML105) (approximately 1.40 meters height) [18].

For flood duration, hazard levels are similarly classified into five categories. In built-up areas, flood duration is defined as very low (0–1 days), low (1–3 days), medium (3–5 days), high (5–8 days), and very high (greater than 8 days). These classifications were developed based on the flood hazard classification concept in terms of flood duration [19]. In agricultural areas, the classifications are very low (0–1 days), low (1–3 days), medium (3–7 days), high (7–14 days), and very high (greater than 14 days), considering the flood tolerance duration of rice [16]. The classification of flood duration for built-up areas is based on historical flood events in Mueang Phrae Municipality, where recorded flood durations ranged from a minimum of 1 day (observed in 2000, 2005, 2010, and 2014) to a maximum of 8 days (observed in 2011) [20]. These values were determined by analyzing overflow durations at the river cross-section near hydrological station Y.1C. For agricultural areas, the flood duration classification is based on the threshold at which rice crops experience total damage, which occurs after 14 days (or two weeks) of continuous submergence [21].

This classification system is essential for identifying areas with varying degrees of flood hazard and assessing the potential risks to both build-up and agricultural areas.

Table 1 Flood hazard classification from flood depth and duration

Flood Hazard Level	Build up Area	Agricultural Area	Flood Hazard Index (FHI_i)
Flood Depth (meters)			FHI_D
Very Low Hazard	0-0.40	0-0.35	1
Low Hazard	0.41-0.80	0.36-0.70	2
Medium Hazard	0.81-1.2	0.71-1.05	3
High Hazard	1.21-1.60	1.05-1.40	4
Very High Hazard	Over 1.60	Over 1.40	5
Flood Duration (Days)			FHI_T
Very Low Hazard	0-1	0-1	1
Low Hazard	1-3	1-3	2
Medium Hazard	3-5	3-7	3
High Hazard	5-8	7-14	4
Very High Hazard	Over 8	Over 14	5

However, the flood hazard index (FHI) can be calculated from flood depth and duration with weighting factors as shown in Eq. (1). The weight factor was analyzed by using Analytic Hierarchy Process (AHP) [4-22].

$$FHI = w_D FHI_D + w_T FHI_T \tag{1}$$

FHI is flood hazard index, FHI_D is flood hazard index of flood depth, FHI_T is flood hazard index of flood duration, w_D and w_T are weighting factors of flood depth and duration, respectively.

4. Results and discussions

4.1 Calibration and validation of hydrodynamic model

The HEC-RAS model was set up using manning roughness coefficient (n) values of 0.035 for the river and 0.050 for the floodplain, reflecting flow resistance based on riverbed material and vegetation. Calibration and validation were performed with observed water level data from two separate periods: 2000-2011 for calibration and 2012-2023 for validation, as shown in Fig. 3. The figure shows a similar trend between observed and simulated peak flow water levels for most periods. However, discrepancies were observed in low flow water levels during 2009 and 2015–2023.

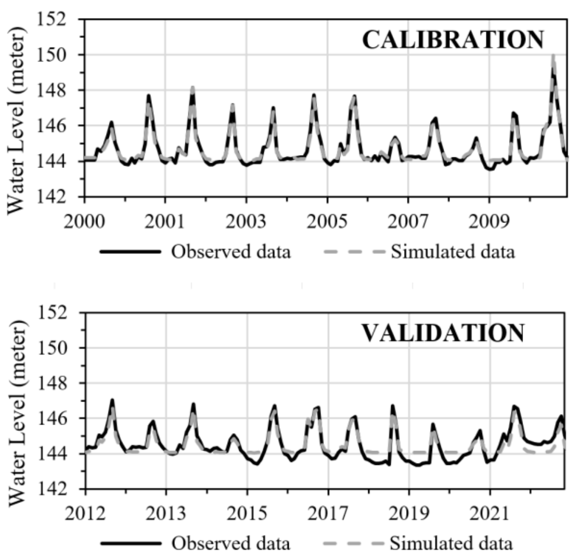


Fig. 3 The result of HEC-RAS model for calibration (2000-2011) and validation (2012-2023)

During calibration, the model showed excellent performance, with R^2 at 0.95, NSE at 0.95, and PBIAS at 1.1%, indicating a high degree of accuracy with minimal overestimation. The MAE was 0.01 meters, and the RMSE was 0.28 meters, both suggesting very precise predictions. For validation, the model maintained strong performance, with R^2 at 0.87, NSE at 0.87, and PBIAS at -1.6%, indicating good accuracy with slight underestimation. The MAE was 0.33 meters, and RMSE was 0.38 meters, demonstrating reliable predictive capabilities. Overall, the calibration and validation results confirm that the HEC-RAS model accurately simulates flood conditions, providing robust and reliable flood predictions across both periods as shown in Table 2.

Table 2 Model performance for HEC-RAS model

Times	R^2	NSE	PBIAS	MAE (meter)	RMSE (meter)
Calibration (2000-2011)	0.95	0.95	1.10	0.01	0.28
Validation (2012-2023)	0.87	0.87	-1.60	0.33	0.38

4.2 Flood inundation

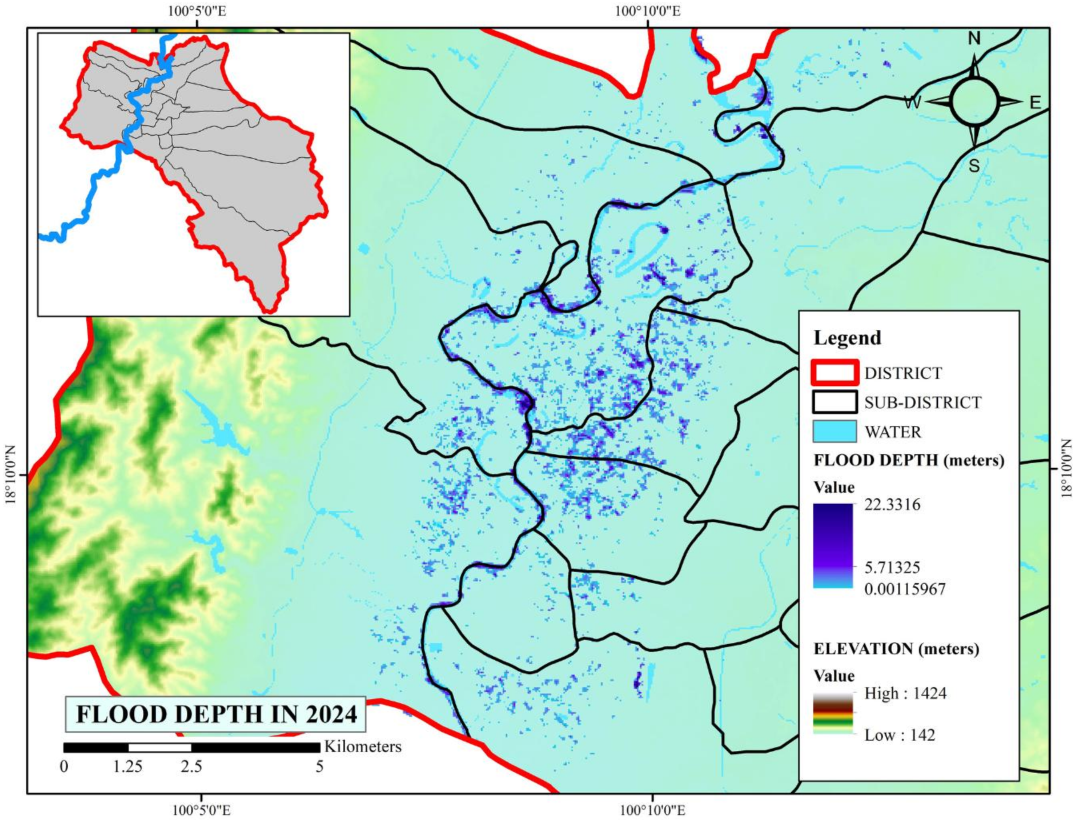
Flood inundation was simulated using the HEC-HMS model with 2024 water discharge data. The results indicate a total flooded area of 13.87 km², accounting for 1.81% of the total area in Mueang Phrae District, as shown in Fig. 4. The figure categorizes flooding into two key characteristics: flood depth (measured in meters) and flood duration (measured in days). The most significant flooding occurred in the Mae Yom, Thung Hong, and Thung Kwao sub-districts, which are particularly vulnerable due to their proximity to the Yom River. These areas experienced the great flood extents, emphasizing the need for targeted flood management strategies to mitigate risks in these high-exposure zones.

The findings from the HEC-HMS model provide valuable insights for future flood mitigations in the district, helping to develop more effective strategies for reducing flood impacts and enhancing resilience.

4.3 Weighting factors using Analytic Hierarchy Process (AHP) techniques

The weights of the Flood Hazard Index on depth (FHI_D) and Flood Hazard Index on duration (FHI_T) were determined using the AHP based on interviews with local residents in Mueang Phrae Municipality and agricultural areas. The results indicate that flood depth has a greater impact on local communities compared to flood duration. Similarly, in agricultural areas, where rice is the dominant crop, flood depth was found to have a more significant effect than flood duration.

Table 3 presents the pairwise comparison matrix, which has been normalized by ensuring that the sum of each column equals 1 [23]. The calculated weights for flood depth and flood duration are approximately 0.75 and 0.25, respectively, as shown



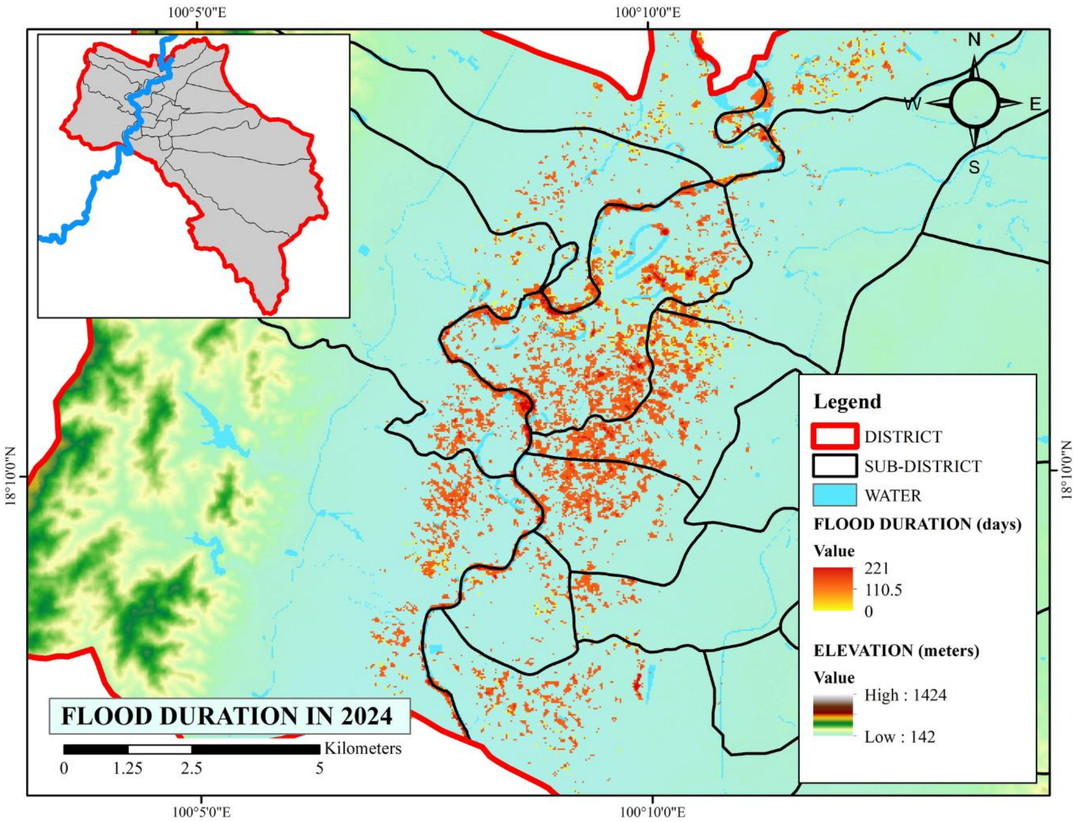


Fig. 4 Flood depth and duration maps of Mueang Phrae District in 2024

in Table 4. These weights follow the weight identification concept from a previous study on flood hazard assessment in Quang Nam, Vietnam, which assigned weights of 0.71 to flood depth and 0.29 to flood duration [24]. The weights were validated by confirming that their sum equals 1.

Additionally, consistency parameters including the eigenvalue, consistency ratio, and consistency index were used to verify the weighting results. The eigenvalue must be equal to the total number of hazard parameters, while the consistency ratio and consistency index should be close to zero [25]. The findings of this study confirm that the eigenvalue is equal to the number of hazard parameters, and the consistency ratio and consistency index are very close to zero, indicating a reliable weighting assessment.

Table 3 Pairwise comparison matrix of FHI_D and FHI_T

Parameters	FHI_D	FHI_T
FHI_D	1	3
FHI_T	1/3	1

Table 4 The normalized weight of FHI_D and FHI_T

Parameters	FHI_D	FHI_T	Weight (W_i)
FHI_D	3/4	3/4	0.75
FHI_T	1/4	1/4	0.25
sum	1.00	1.00	1.00

4.4 Flood hazard analysis with different return periods

The flood hazard areas for various return periods were estimated to be 4.23, 5.86, 7.35, 8.06, 9.48, 10.51, and 11.80 km², corresponding to 0.55%, 0.76%, 0.96%, 1.05%, 1.24%, 1.37%, and 1.54% of the total area (about 766.89 km^2) for the 2, 5, 10, 25, 50, 100, and 500 year return periods, respectively, as shown in Table 5 and Fig. 5.

For the hazard analysis, the 2-year return period, representing the lowest level of flood hazard, revealed the following flood-affected areas: 0.00 km² (Very Low), 0.15 and 0.67 km² (Low), 0.10 and 0.08 km² (Medium), 0.24 and 0.45 km² (High), and 0.60 and 1.94 km² (Very High) for built-up and agricultural areas, respectively. The highest proportion of flood damage was observed in the Mae Yom, Thung Hong, and Thung Kwao sub-districts, while Wang Hong, Wang Thong, Pa Maet, Nai Wiang, Tha Kham, Mae Lai, Mae Kham Mi, Mueang Mo, and Na Chak sub-districts experienced relatively minor flood impacts.

For the 500 year return period, the flood hazard areas expanded significantly, with the following distribution: 0.00 km² (Very Low), 0.27 and 0.68 km² (Low), 0.40 and 0.62 km² (Medium), 0.31 and 1.41 km² (High), and 1.96 and 6.15 km² (Very High) for built-up and agricultural areas, respectively. In this scenario, the Mae Yom, Thung Hong, and Thung Kwao sub-districts, along with additional areas, exhibited significantly higher flood hazard proportions. Conversely, the Ban Thin, Huai Ma, Nam Cham, Suan Khuean, Pa Daeng, Cho Hae, Kanchana, and Rong Fong sub-districts remained unaffected across all return periods, from the 2-year to the 500 year events, due to their high ground elevation and far distance from the Yom River. Table 5 presents a detailed comparison of the 2, 5, 10, 25, 50, 100 and 500 year return periods, illustrating the progressive shifts in flood hazard levels. These results provide a comprehensive understanding of the varying flood risks over different return periods, highlighting the regions most vulnerable to future flood events. As the return period increases, the extent of flood-prone areas expands, with a greater number of regions classified under higher hazard levels, particularly in the very high flood hazard zone.

Table 5 Flood hazard level for build-up and agricultural areas with different return periods (2, 5, 10, 25, 50, 100 and 500 years) (km^2)

Return period (years)	Build-Up Area (km^2)						Agricultural Area (km^2)					
	Very low	Low	Medium	High	Very high	Total	Very low	Low	Medium	High	Very high	Total
2	0.00	0.15	0.10	0.24	0.60	1.09	0.00	0.67	0.08	0.45	1.94	3.14
5	0.00	0.16	0.20	0.22	0.95	1.53	0.00	0.54	0.18	0.90	2.71	4.33
10	0.00	0.37	0.18	0.15	1.20	1.90	0.00	0.76	0.85	0.18	3.66	5.45
25	0.00	0.19	0.35	0.19	1.34	2.07	0.00	0.45	0.51	1.05	3.98	5.99
50	0.00	0.36	0.20	0.37	1.42	2.35	0.00	1.16	0.39	0.80	4.78	7.13
100	0.00	0.49	0.19	0.29	1.63	2.60	0.00	1.18	0.91	0.30	5.52	7.91
500	0.00	0.27	0.40	0.31	1.96	2.94	0.00	0.68	0.62	1.41	6.15	8.86

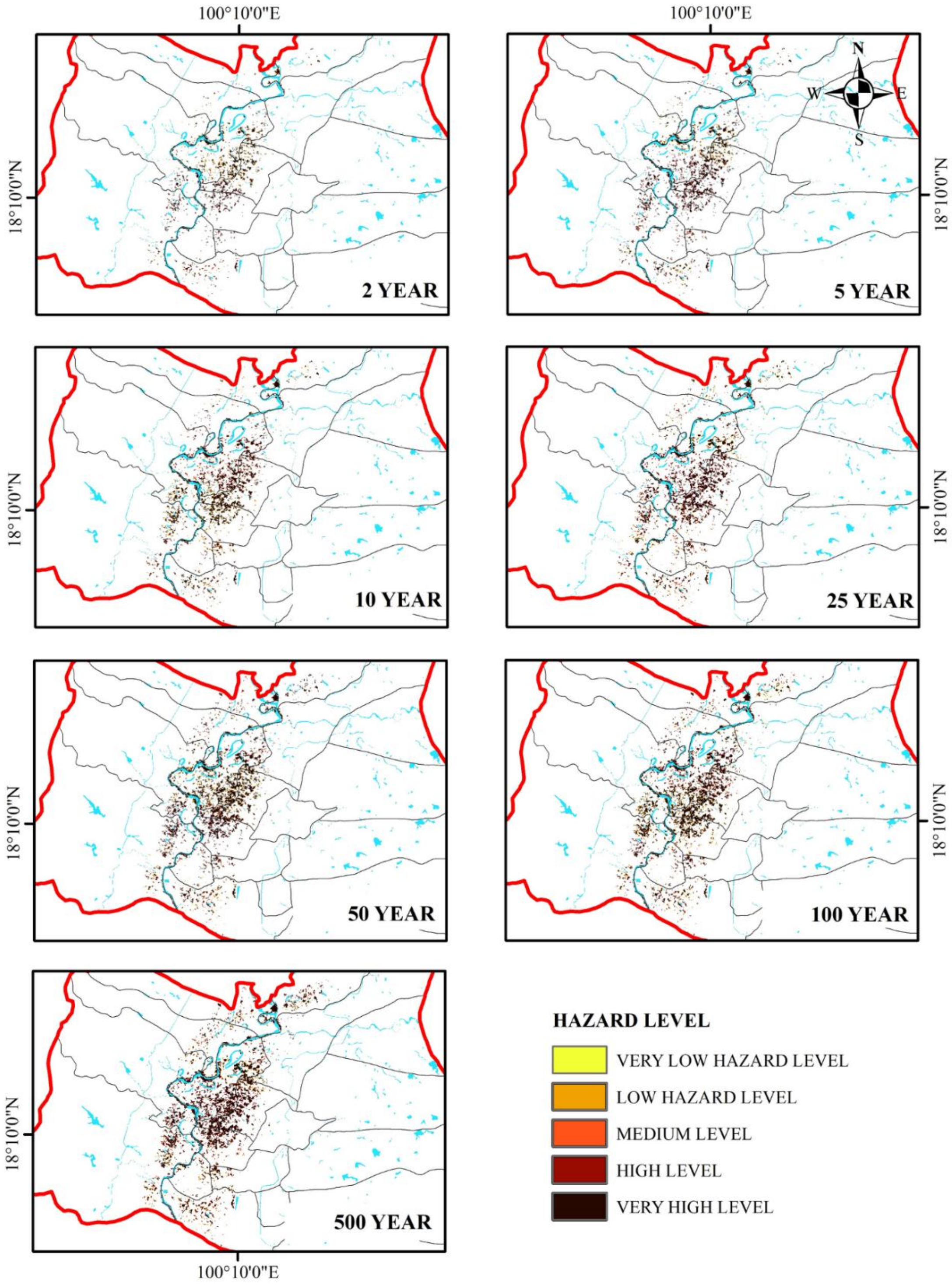


Fig. 5 Flood hazard maps for 2, 5, 25, 50, 100, and 500 years return periods, respectively

4.5 Flood adaptation measures

Flood adaptation measures are essential for mitigating the impacts of flooding and enhancing resilience, particularly in flood-prone areas such as Mueang Phrae District. One major strategy to strengthen flood resilience in agriculture, particularly rice cultivation, is the adoption of flood-resistant crops. The build-up areas were insignificantly flooded due to higher ground elevation. Therefore, flood drainage improvement to mitigate flooding is recommended.

Flood-resistant crops play a crucial role in minimizing crop losses in flood-prone agricultural areas by withstanding prolonged submergence. For instance, flood-resistant rice varieties and water-tolerant vegetables can be introduced in sub-districts such as Mae Yom and Thung Hong. These measures can reduce the affected agricultural areas classified as very low to high hazard levels by approximately 0.96, 1.31, 1.42, 1.58, 1.87, 1.92, and 2.20 km², corresponding to 30.57%, 30.25%, 26.06%, 26.38%, 26.23%, 24.27%, and 24.83% of the total affected agricultural area for return periods of 2, 5, 10, 25, 50, 100, and 500 years, as presented in Table 6. However, areas classified as very high hazard levels are unlikely to be protected by flood-resistant rice varieties, as both flood depth and duration exceed 1.40 meters and 14 days (or two weeks), which typically result in total crop failure.

Rice fields in these areas are frequently impacted by flooding, necessitating adaptive strategies to mitigate agricultural losses. Approximately 84% of the cultivated rice in this region is sticky rice (glutinous rice), while the remaining 16% consists of jasmine rice. A viable alternative for sticky rice cultivation is the Hom Naka glutinous rice variety (Oryza sativa L.), developed by the Rice Gene Discovery and Utilization Research Unit at the National Center for Genetic Engineering and Biotechnology (BIOTEC) in collaboration with Kasetsart University [26]. This variety can survive submergence for one to two weeks without significant yield loss. By adopting flood-tolerant crops, farmers can mitigate economic losses, maintain agricultural productivity, and enhance food security.

Another effective approach is switching from prevailing jasmine rice (KDML105) to the RD51 variety, a flood-tolerant alternative. The RD51 variety, also known as RGDU99003-1012-B-2-6-B, is a photoperiod-sensitive cultivar that grows to an average height of approximately 155 cm [15]. Developed by the Rice Department under the Ministry of Agriculture and Cooperatives of Thailand, this variety exhibits superior physical and chemical grain qualities. Notably, it can withstand sudden flooding during its vegetative growth stage for up to 12 days and recover effectively, yielding up to 82% more than jasmine rice (KDML105) variety after submergence. However, a limitation of this study is the lack of consideration for flood velocity, which can significantly impact rice crops (rice falling). Additionally, the analysis does not account for flood protection measures for both structural (e.g., levees, floodwalls) and non-structural (e.g., early warning systems, land use planning) that could help protect paddy fields and mitigate crop damage in the study area.

Furthermore, implementing diversified farming practices that incorporate a variety of flood-tolerant species can minimize crop risks during flood events, ensuring more stable agricultural outputs over time.

Table 6 Computed flood-affected paddy field areas (km²) and corresponding percentages of total flood agricultural hazard areas in Mueang Phrae District for different return periods (2, 5, 10, 25, 50, 100, and 500 years)

Flood hazard levels	Return period (year)						
	2	5	10	25	50	100	500
Very low	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)
Low	0.53 (16.88)	0.42 (9.70)	0.62 (11.38)	0.37 (6.18)	0.89 (12.48)	1.00 (12.64)	0.56 (6.32)
Medium	0.06 (1.91)	0.14 (3.23)	0.65 (11.93)	0.40 (6.68)	0.33 (4.63)	0.67 (8.47)	0.53 (5.98)
High	0.37 (11.78)	0.75 (17.32)	0.15 (2.75)	0.81 (13.52)	0.65 (9.12)	0.25 (3.16)	1.11 (12.53)
Very High	1.55 (49.36)	2.17 (50.12)	2.95 (54.13)	3.21 (53.59)	3.80 (53.30)	4.40 (55.63)	4.92 (55.53)
Total	2.51 (79.93)	3.48 (80.37)	4.37 (80.19)	4.79 (79.97)	5.67 (79.53)	6.32 (79.90)	7.12 (80.36)

Agricultural mitigation measures will play a crucial role in enhancing Mueang Phrae District's resilience to flooding. These measures not only reduce the immediate impacts of flood events but also contribute to the long-term sustainability of urban and rural communities. As climate change continues to increase the frequency and intensity of extreme weather events, the adoption of comprehensive adaptation strategies will become increasingly vital for minimizing future flood hazards.

5. Conclusion

This study evaluated flood hazards in Mueang Phrae District, Phrae Province, Thailand, using the HEC-RAS model to simulate flood scenarios across various return periods (2, 5, 10, 25, 50, 100, and 500 years). The model demonstrated strong calibration and validation performance, with high R^2 and NSE values (0.95 and 0.87, respectively) and low PBIAS, MAE, and RMSE values. These results confirm the model reliability in predicting flood behavior and provide a robust foundation for understanding flood hazards in the study area, contributing to the development of effective flood management strategies.

The flood hazard analysis revealed several levels of maximum daily flood depth and duration throughout the district, with the affected areas increasing as the return period lengthened. For the 2-year return period, flood-prone areas were primarily concentrated in the very high hazard zones, particularly in sub-districts such as Mae Yom, Thung Hong, and Thung Kwao. Under the 500 year return period scenario, these high-hazard zones expanded significantly. In contrast, sub-districts like Ban Thin, Huai Ma, and Nam Cham showed no flood damage across all return periods, highlighting the need for location-specific flood management interventions.

The analysis of flood adaptation measures emphasized the importance of integrating agricultural strategy. Flood-resistant crops such as flood-tolerant rice varieties like the Hom Naka glutinous rice variety (Oryza sativa L.) and RD51 (RGDU99003-1012-B-2-6-B) offer a promising solution for mitigating flood impacts in frequently affected sub-districts such as Mae Yom and Thung Hong. Promoting these crops, along with flood-tolerant vegetables could reduce the affected area approximately from 0.96 to 2.20 km², or from 24.27% to 30.57%, across varying return periods. Additionally, implementing diversified farming systems that incorporate multiple flood-tolerant species can strengthen resilience, minimize economic losses, and promote sustainable agricultural practices. For build-up areas, in which flooding was not significantly, flood drainage improvement is recommended as mitigation measures.

The findings of this study are crucial for establishing flood management policies and ensuring the long-term sustainability of agricultural and urban systems in Mueang Phrae District. By adopting adaptive strategy such as promoting flood-resistant crops, the district can significantly improve capacity to manage future flood hazards, particularly in light of increasing uncertainties posed by climate change. These measures not only mitigate the immediate effects of flooding but also enhance long-term resilience, safeguarding local communities and the economy.

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