

FLOOD MITIGATION STRATEGIES IN UBON RATCHATHANI AND SISAKET PROVINCES: A STUDY USING MIKE FLOOD MODELLING

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Abstract

The provinces of Ubon Ratchathani and Sisaket experienced severe flood events in 1938, 1978, 2002, and notably in 2019, when widespread flooding occurred in late August. A comprehensive study using MIKE FLOOD modelling was conducted to consider the causes of flooding in these areas and explore potential flood prevention measures. The results highlighted the crucial role of changes in upstream water discharge in triggering extensive flooding. It was found that water inflow from the upstream basin was a primary factor contributing to major flood incidents in both provinces. The study demonstrated that river dredging could reduce flood-prone areas in Sisaket by 52.38%, while its impact in Ubon Ratchathani was predicted to be minimal. The diversion of water from the upstream basin could reduce flooded areas by a minimum of 43.81% to a maximum of 49.83%, showing that strategic water diversion could contribute to flood mitigation efforts. Moreover, eight runoff stations within the upper basin of the study area were also found to be vital for effective flood warning systems. Effective flood mitigation in the area requires a combination of upstream water flow management, strategic dredging, and robust flood warning systems. The insights gained from this study can inform future flood prevention and management strategies to reduce the vulnerability of these regions to destructive flood events.

Keywords: Flood mitigation; MIKE FLOOD; Non-Structural measurement; Structural measurement

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Introduction

Flooding is a complex natural phenomenon that has been a recurrent concern throughout human history. It is a pervasive global issue that carries important implications for society, infrastructure, and the environment (Maura, 2018). Understanding the intricacies of flooding is essential for devising effective measures to mitigate its effects. Flooding events are the culmination of interacting processes that are studied across multiple scientific domains. Meteorological factors, such as intense or prolonged rainfall, can overwhelm the infiltration capacity of soils, leading to overland flow and riverine flooding. Hydrological processes, including the rate and volume of water discharge from a catchment area, as well as the capacity of river channels, significantly influence the severity and extent of flooding. Geomorphological factors, such as topography, slope gradients, and the presence of natural levees, also play a critical role in determining flood vulnerability. A comprehensive understanding of these interrelated factors is paramount for accurate flood prediction and effective mitigation strategies. By incorporating these diverse influences into flood risk assessments, more effective management strategies can be developed to safeguard communities from the destructive impacts of fluvial flooding. (Lechowska, 2018; Feloni *et al.*, 2022)

The impacts of flooding are multifaceted and encompass diverse sectors. Societal consequences include displacement, loss of life, damage to property, and disruptions to essential services. Infrastructure, including transportation networks, utilities, and public facilities, is susceptible to extensive flood damage (Kang *et al.*, 2009). Flooding can also result in environmental degradation, such as soil erosion, water pollution, and ecosystem disruption (Januriyadi *et al.*, 2020). In addition, significant economic repercussions are felt through damage to critical infrastructure and reduced agricultural yields, which can disrupt global food supply chains and trade relationships (Minea and Zaharia, 2011). Mitigating the impact of flooding involves a combination of structural and non-structural measures and only by combining both can communities develop a comprehensive and effective flood mitigation strategy. This multifaceted approach not only reduces the risk and severity of flooding but also helps communities recover more quickly and efficiently when floods do occur (Schnabl *et al.*, 2014; Kundzewicz, 2002).

Our ability to understand, predict, and manage the complex dynamics of flooding has been expanded by the use of mathematical modelling,

which now plays a crucial role in the formulation and optimization of flood management strategies. The integration of Geographic Information Systems and high-resolution topographic data into mathematical modelling has led to significant advancements in flood forecasting (Krzywoszańska *et al.*, 2019). These technologies provide valuable input data and improve the accuracy of models by capturing terrain variations, land use, and land cover changes. Furthermore, the use of real-time monitoring data, such as river gauges, enhances the precision of flood forecasts (Vijendra *et al.*, 2023). Mathematical models are indispensable for the design and assessment of flood protection structures such as levees and dams, enabling the evaluation of their effectiveness under various scenarios. Moreover, mathematical modelling can create a virtual testing platform for flood management strategies, allowing for experimentation and optimization of designs prior to the allocation of resources to real-world projects. This approach not only conserves time and financial resources but also enhances the robustness and efficacy of flood protection measures, thereby ensuring better protection for communities against the devastating impacts of floods. (Davydov *et al.*, 2018; Schreider *et al.*, 2000; Mohammadtaghi *et al.*, 2021)

Two areas of Thailand frequently impacted by flooding are Ubon Ratchathani and Sisaket Provinces. Located at the downstream ends of two major rivers, the Mun and Chi, the terrain predominantly features shallow undulating plains. The central area is the floodplain of the Mun River, and the Dongrak Mountains form a natural southern boundary. This topography, combined with heavy upstream rainfall, often results in significant flooding of the lower plains and riverbanks (Tsumita *et al.*, 2021; Kosa *et al.*, 2023). Flood prevention measures in this area are critical. Research has recommended both structural measures, such as flood barriers, two-story houses for communities, and water diversion, and non-structural measures, including water level monitoring, evacuation warnings, and community training on water data awareness. Furthermore, the creation of integrated short-, medium-, and long-term flood prevention plans is essential. However, it is important to note that these recommendations, derived from in-depth interviews and analyses of historical flood data, lack mathematical modelling to demonstrate the effectiveness of each measure in reducing damage in specific areas (Kikuchi *et al.*, 2019; Liengjindathaworn *et al.*, 2020; Phongnairat and Nophaket, 2020; Boonreang *et al.*, 2022).

Flood protection modelling is a multifaceted process that serves as a cornerstone of attempts to mitigate the destructive consequences of flooding. The foremost objective of the proposed modelling approach is to meticulously analyze the various causes of flooding. This entails an exhaustive examination of the complex interplay of meteorological, hydrological, and geomorphological factors. This understanding is essential for crafting effective mitigation strategies. The second objective involves the development and simulation of comprehensive mathematical models. These models encompass both structural and non-structural measures designed to prevent and ameliorate the impacts of flooding. The third and equally critical objective involves an in-depth analysis of the effects of proposed flood prevention measures. This comprehensive framework can equip decision-makers, policymakers, and flood management authorities with the knowledge and tools necessary to formulate resilient and sustainable flood protection plans tailored to the challenges presented by flooding events in specific regions.

Description of the study area

The provinces of Ubon Ratchathani and Sisaket, located in the northeastern region of Thailand, confront recurring inundation challenges. The principal contributing factors are their low-lying terrain, proximity to the Mun River, and the influence of seasonal monsoons. During the rainy season, the area experiences substantial precipitation, resulting in elevated water levels in the Mun River and its tributaries. The inadequacy of local drainage systems compounds the situation. The recurrent flooding episodes in the provinces are therefore the result of the interplay between natural and infrastructural elements (Kikuchi *et al.*, 2019).

Historically, Ubon Ratchathani and Sisaket Provinces experienced significant flood events in 1938, 1978, 2002, and 2019. The 2019 flood event was notably severe, causing economic damages exceeding 1 billion THB. (Tsumita *et al.*, 2021). The event was characterized by a confluence of factors. Early August witnessed the convergence of Storm Podul, Storm Kajiki, and runoff from upstream provinces, resulting in the accumulation of a substantial volume of water (Kosa *et al.*, 2023). This accumulation culminated in widespread flooding in late August, with Ubon Ratchathani and Sisaket bearing the brunt of the inundation (Phongnairat and Nophaket, 2020). The amount of

rainfall within a single week equaled more than half of the total annual rainfall (Boonreang, 2019). Notably, flooding from the upper Mun River basin coincided with flood discharge into the Chi River, subsequently flowing into Ubon Ratchathani. On September 12, 2019, the water level at the M7 runoff station reached 115.88 meters mean sea level (msl), surpassing the levels recorded during the catastrophic flood of 2002. The river burst its banks, submerging homes and causing considerable distress to the local population.

The research area extends from the downstream section of the Rasi Salai Dam to the Mekong River, encompassing the entirety of Ubon Ratchathani Province and a portion of Sisaket Province. These provinces are situated in the far eastern reaches of Thailand and share borders with the neighboring countries of Laos and Cambodia. The study area included all 25 districts and 219 sub-districts of Ubon Ratchathani Province, and 7 districts and 84 sub-districts of Sisaket Province, as shown in Table 1. The region is characterized by a diverse topography, with the western segments of both provinces marked by hilly and mountainous terrain, prominently featuring the Phanom Dong Rak mountain range. In contrast, the eastern areas, in proximity to the Mekong River, predominantly consist of plains and lowlands. Notably, the Mun River, a significant watercourse, runs through both provinces, eventually merging with the Mekong River near the eastern boundary of Ubon Ratchathani Province. The Mun River receives contributions from various tributary rivers, including the Chi River, Lam Sebai, Lam Sebok, Lam Dom Yai, Lam Dom Noi, Huay Samran, and Huay Kha Lung, which form an intricate hydrological network (Figure 1).

Table 1. List of studied districts in Ubon Ratchathani and Sisaket Provinces

Code	District	Code	District
UB-1	Muang Ubon Ratchathani	UB-17	Samrong
UB-2	Si Muang Mai	UB-18	Don Motdaeng
UB-3	Khong Chiam	UB-19	Sirinthon
UB-4	Khuang Nai	UB-20	Thung Si Udom
UB-5	Khemrat	UB-21	Nayia
UB-6	Det Udom	UB-22	Natan
UB-7	Nachaluai	UB-23	Lao Sua Kok
UB-8	Nam Yun	UB-24	Sawang
			Wirawong
UB-9	Buntharik	UB-25	Nam Khun
UB-10	Trakan Phutphon	SK-1	Muang Sisaket
UB-11	Kut Khao Pun	SK-2	Yang Chumnoi
UB-12	Muang Samsip	SK-3	Kanthararom
UB-13	Warin Chamrap	SK-4	Rasi Salai
UB-14	Phibunmangsan	SK-5	Uthumphon
			Phisai
UB-15	Tansum	SK-6	Non Khun
UB-16	Pho Sai	SK-7	Nam Kiang

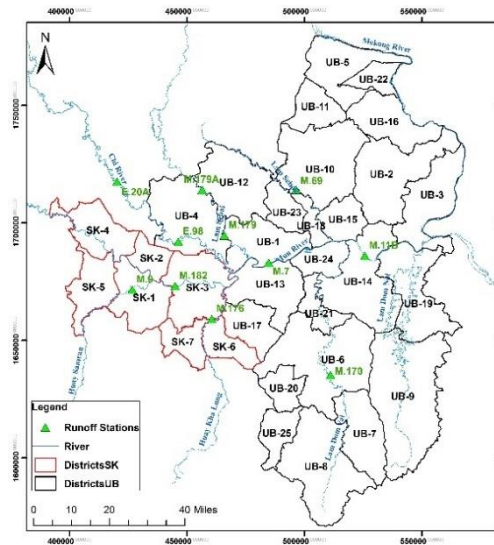


Figure 1. The boundaries of districts and positions of river dams in the study area

Materials and Methods

The methodology employed in this study, presented schematically in Figure 2, provides a structured

framework for potential flood mitigation strategies aimed at reducing flood-affected areas in Ubon Ratchathani and Sisaket Provinces through a combination of structural and non-structural measures.

Spatial and temporal dataset

MIKE FLOOD modelling was employed to accurately simulate and analyze flood events. The spatial and temporal input data comprised rainfall data, water levels, flow rates, evaporation rates, river cross-sections, channel widths, riverbed elevations, land use, and Digital Elevation Models (DEM). The input time series data included daily rainfall, water level, flow rate, and evaporation data from 1989 to 2018. Rainfall and evaporation data were collected from the Thai Meteorological Department or TMD (28 stations), while water level and flow rate data were collected from the Royal Irrigation Department, or RID (11 runoff stations). River cross-sections, channel widths, and riverbed elevations in the Mun River system were collected from 373 cross-sections surveyed by the RID (11 cross-sections at runoff stations) and by this project (362 cross-sections). The locations of all cross-section surveys, runoff stations, and TMD

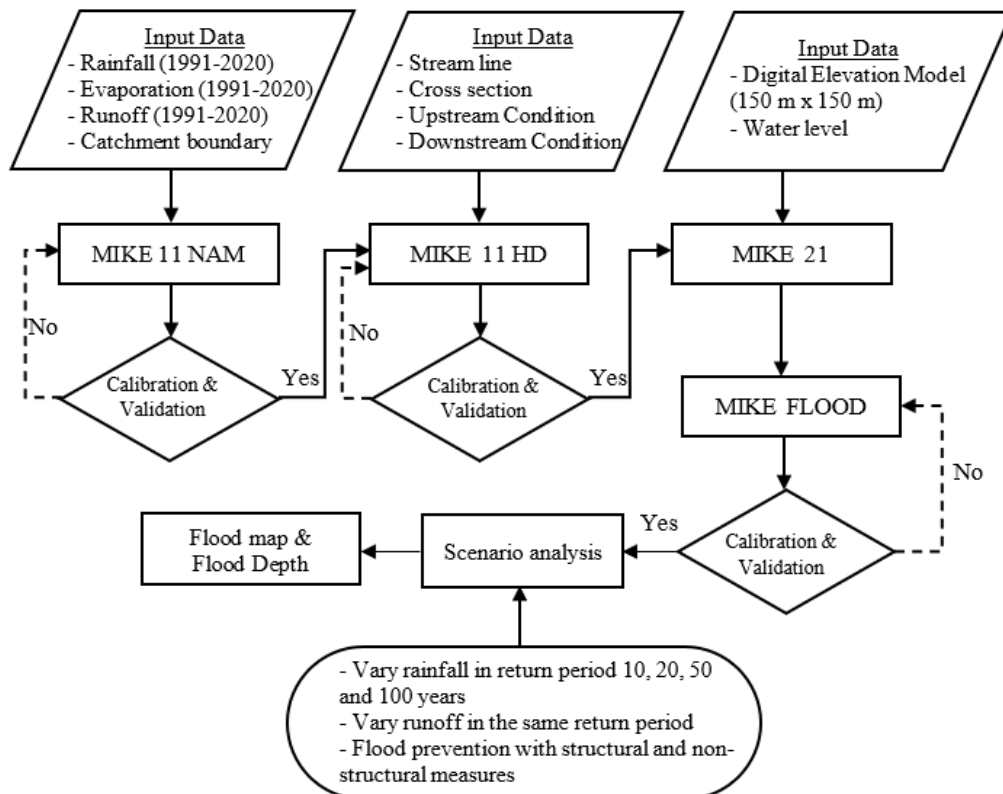


Figure 2. Workflow for MIKE FLOOD modelling in this study

stations are presented in Figure 3. DEMs were topographical maps of areas measuring 150 m × 150 m and were used as input data for 2D overland flow modelling, which is supported by the Land Development Department (LDD).

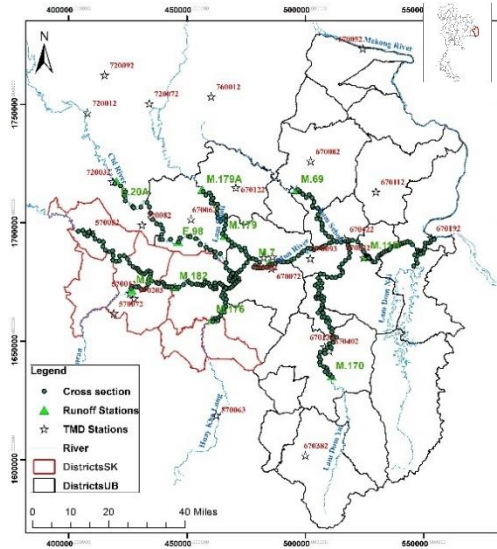


Figure 3. The locations of TMD stations, runoff stations, and cross-section surveys

MIKE11 NAM Modelling

MIKE 11 NAM, MIKE 11 HD and MIKE 21 are sub-models that output data into MIKE FLOOD to generate flood maps. MIKE11 NAM is a mathematical hydrological model that converts rainfall into runoff volumes, explained in a simple quantitative manner, using the characteristics of the land area of the hydrological cycle (Refsgaard and Knudsen, 1997; Agrawal and Desmukh, 2016). The MIKE11 NAM model can be characterized as a deterministic, lumped, conceptual model with moderate input data requirements (Danish Hydraulic Institute, 2007a, Teshome *et al.*, 2020). To simulate outputs, nine model parameters of physical watershed data must be calibrated: maximum water content in surface storage (U_{max}), the maximum water content in root zone storage (L_{max}), an overland flow runoff coefficient (CQOF), a time constant for routing interflow (CKIF), a time constant for routing overland flow ($CK_{1,2}$), a root zone threshold value for overland flow (TOF), a root zone threshold value for inflow (TIF), a root zone threshold value for GW recharge (TG), and a time constant for routing base flow (CK_{BF}) (Danish Hydraulic Institute, 2007b).

MIKE11 NAM simulates the rainfall-runoff process by continuously accounting for the surface storage and lower zone storage due to a shortage of groundwater data. When the surface storage is

exceeded, or when $U > U_{max}$, the excess water (P_N) gives rise to overland flow and infiltration (Danish Hydraulic Institute, 2007c). The QOF indicates the part of P_N that contributes to overland flow. It is assumed to be proportional to P_N and to vary linearly with the relative soil moisture content, L/L_{max} , of the lower zone storage, as follows :

$$QOF = \begin{cases} CQOF \frac{L/L_{max} - TOF}{1 - TOF} P_N & \text{for } L/L_{max} > TOF \\ 0 & \text{for } L/L_{max} \leq TOF \end{cases} \quad (1)$$

where $0 \leq CQOF \leq 1$ and $0 \leq TOF \leq 1$. The proportion of P_N which does not run off as overland flow infiltrates into the lower zone storage. A portion, ΔL , of the water available for infiltration ($P_N - QOF$) is assumed to increase the moisture content L in the lower zone storage. Moreover, the infiltrating moisture, G , that is remaining, is assumed to percolate deeper. The interflow contribution, QIF, is proportional to U and varies with the relative moisture content of the lower zone storage as follows:

$$QIF = \begin{cases} (CKIF)^{-1} \frac{L/L_{max} - TIF}{1 - TIF} & \text{for } L/L_{max} > TIF \\ 0 & \text{for } L/L_{max} \leq TIF \end{cases} \quad (2)$$

where CKIF is the time constant for interflow, and TIF is the lower zone threshold value for interflow ($0 \leq TIF \leq 1$) (Abbott and Ionescu, 1967).

MIKE 11 HD Modelling

MIKE 11 HD is a hydrodynamic model used to simulate water flow and water levels in rivers, considering factors such as bathymetry and river cross-sections. It uses advanced numerical methods to accurately simulate the hydrodynamic behavior of water bodies. The model can explain sub-critical as well as super-critical flow conditions through a numerical scheme which adapts according to the local flow condition or in time and space. The formulations can be applied to looped networks and quasi-two-dimensional flow simulations on flood plains (Danish Hydraulic Institute, 2017a).

The principal calculation of the hydrodynamic sub-model based on unsteady non-uniform flow is the 1D flow Saint-Venant Equation, in which the flow rate (Q) and water level (H) can be calculated as functions of time and distance as follows (Teshome *et al.*, 2020):

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = q \quad (3)$$

$$\frac{\partial Q}{\partial t} + \frac{\partial \left(\alpha \frac{Q^2}{A} \right)}{\partial x} = gA \frac{\partial h}{\partial x} + \frac{gQ|Q|}{C^2 AR} = 0 \quad (4)$$

where Q is the discharge, A is the flowing area, q is lateral flow, h is the stage above datum, C is the Chezy resistance coefficient, R is the hydraulic or resistance radius, and α is the momentum distribution coefficient.

MIKE21 Modelling

MIKE21 computes water depth over a floodplain based on the shear stress or resistance to flow. The values can be selected as either a Chezy number or a Manning's n number. Manning's n number has been applied in this study because more resistance data is available.

The hydrodynamic (HD) model in the MIKE 21 Flow Model is a general numerical modelling system for the simulation of water level and flow in lakes, estuaries, bays, coastal areas, and seas. It simulates unsteady two-dimensional flow in monolayer (vertical homogeneous) fluids and has been applied in many studies. MIKE 21 HD makes use of a so-called Alternating Direction Implicit (ADI) technique to integrate the equations for continuity and momentum conservation in the space and time domain. The solution of these two equations is based on an implicit finite difference scheme. (Danish Hydraulic Institute, 2019). The obtained equation matrices for each direction and each individual grid line are resolved by a Double Sweep (DS) algorithm (Brown Hill Keswick Creek Stormwater Project, 2016; Danish Hydraulic Institute, 2017b). Q-points are placed midway between neighboring h-points and at structures, while h-points are located at cross-sections, or at equidistant intervals in between if the distance between cross-sections is greater than maximum dx . The discharge is then defined by convention as positive in the positive x direction or increasing chainage.

MIKE FLOOD Medelling

MIKE FLOOD modelling integrates MIKE 11 and MIKE 21 into a single, dynamically coupled modelling system. MIKE 11 is a quasi-1dimensional unsteady flow modelling tool that has been used before in the study area to model the flow in the Mun River section. Previously, the Mun River MIKE 11 model was linked laterally to MIKE 21 to represent spilling from the river to the floodplain and drainage back into the river (Jens, 1997). The input data from the left and the right banks of the river were coupled to MIKE 21. The software simulates the variation in water level and flow on a rectangular grid generated from input topographic data, ground surface resistance coefficients, and hydrographic boundary conditions. For this study, lateral links were utilized

to simulate flow between the MIKE11 river model and the MIKE21 floodplain model. Lateral links enabled a string of MIKE 21 elements to be linked to a Mun River model in MIKE11, and allowed the transfer of flow between MIKE 11 datapoints that represent computed water levels and MIKE21 90 m floodplain grid cells. The selection of the grid size involved a trade-off between run-time and accuracy. The smaller the grid the more accurate but the longer the run time. (Madsen, 2000)

Calibration and Validation

The phases of calibration and validation are foundational and indispensable elements in the development and enhancement of dependable and precise simulations (Nicolas *et al.*, 2020). The dataset employed for calibration and validation must encompass critical parameters, including water levels, flow rates, and flood extent. Reliable forecasts from MIKE11 NAM, MIKE11 HD, and MIKE FLOOD modelling depend on the quality, precision, and spatial fidelity of the input data. The calibration process for this study incorporated graphical and numerical metrics for performance evaluation. The comparison between the simulated and observed hydrographs was subjected to meticulous graphical assessment, while the numerical metrics included the overall water balance error (Teshome *et al.*, 2020). This error is ascertained by calculating the difference between the average simulated and observed discharge, thus quantifying the precision and reliability of the model (Morisa *et al.*, 2007).

For the effective calibration and validation of the MIKE11 NAM model, a specific set of nine pivotal model parameters was defined (Table 2). The performance evaluations were based on coefficients of determination (R^2) and the water balance errors (%WBL), the results of which are presented in Table 3. These outcomes demonstrated R^2 values exceeding 0.5, indicative of a commendable level of agreement, while %WBL values fell within the range of $\pm 25\%$, further underscoring the fidelity of the model.

Table 2. The values of nine model parameters for MIKE11 NAM

Runoff Station	Calibration		Validation	
	R^2	WBL (%)	R^2	WBL (%)
M.9	0.83	-1.0	0.80	-14.5
M.69	0.83	-9.2	0.86	-0.7
M.170	0.81	0.0	0.74	-6.9
M.176	0.77	23.7	0.71	22.7
M.179A	0.61	-18.9	0.79	-14.8

Table 3. Results of calibration and validation for MIKE 11-HD at each runoff station

Station	Data	Calibration		Validation	
		R ²	NSE	R ²	NSE
M.182	Flow rate	0.99	0.93	0.98	0.96
	Water level	0.97	0.87	0.97	0.87
M.7	Flow rate	0.98	0.95	0.99	0.98
	Water level	0.98	0.96	0.99	0.99
M.11B	Flow rate	0.98	0.94	0.99	0.97
	Water level	0.98	0.94	0.99	0.95

In the context of MIKE FLOOD, the confusion matrix method was used to compare the flood area generated by the model and the flood area derived from satellite images by the Space Technology Development Agency (GISTDA). The comparison revealed that 90.6% of the areas overlapped. This degree of similarity signified a robust level of agreement between the flood areas predicted by the model and those observed in the satellite images.

Flood Causation and Remediation Medelling Scenario

The calibrated and validated MIKE FLOOD model provided a robust and reliable platform for this study. To fulfill the study objectives, the following series of simulations was devised and analyzed.

Scenario 1: Identifying the Root Causes of Flooding

In this scenario, the primary focus was the principal causes of flooding in Ubon Ratchathani and Sisaket Provinces. The investigation primarily hinged on the role of rainfall and runoff. Data from 2016 provided a baseline, representing normal conditions with typical rainfall and flooding patterns. During this year, a floodplain area of 214.54 km² was observed. Subsequently, rainfall and runoff data corresponding to return periods of 10, 20, 50, and 100 years were introduced into the MIKE FLOOD model. The inclusion of four return periods facilitated an analysis of the disparate trends in flooding.

Scenario 2: Flood Mitigation through Structural Measures

This scenario encompassed two distinct sub-scenarios, each aimed at assessing the efficacy of various measures for flood protection.

- **Scenario 2.1: River Dredging**

This scenario took into consideration both major and secondary rivers. The aim of dredging was to smooth out the slope of the river bottom. If a point within the river exhibited a steeper slope than the preceding and following points, it was

considered for dredging. The principal river under consideration was the Mun River, and secondary rivers included the Chi, Huai Samran, Lam Say Bai, and Lam Sebok. The upper section of the Mun River, located in Sisaket Province, could require dredging. Similarly, specific segments of the secondary rivers could also require dredging for flood protection.

- **Scenario 2.2: Upstream Water Diversion**

This scenario involved excavating channels to mitigate flooding downstream by diverting water from upstream runoff stations. The selection of critical upstream runoff stations, pivotal for flood management, was determined by considering the discharge characteristics during 30 years of daily simulations. The key runoff stations were M5, M9, E20A, M179, M69, M170, and E98, which are all instrumental for flood warnings.

Five distinct levels of diversion from the upstream stations were applied, each releasing a different proportion of discharge at the onset of flooding. The five levels were as follows:

Level 1: Diverting 10% of discharge at the onset of flooding.

Level 2: Diverting 20% of discharge at the onset of flooding.

Level 3: Diverting 30% of discharge at the onset of flooding.

Level 4: Diverting 40% of discharge at the onset of flooding.

Level 5: Diverting 50% of discharge at the onset of flooding.

These scenarios enabled the assessment of variations and trends in flooding areas under different conditions and levels of water diversion, as illustrated in Table 4.

Table 4. Case study of diverting water from upstream runoff stations

Runoff station	Diverted discharge in each case (m ³ /s)				
	1	2	3	4	5
M5	104.4	208.9	313.3	417.8	522.3
M9	22.11	44.23	66.34	88.46	110.5
E20A	114.0	228.1	342.1	456.2	570.2
M179	30.19	60.38	90.57	120.7	150.9
M69	29.09	58.18	87.27	116.3	145.4
M170	30.36	60.72	91.08	121.4	151.8
E98	82.06	164.1	246.1	328.2	410.2

Scenario 3: Non-structural Measures: Flood warning

Issuing timely warnings before the occurrence of flooding is essential to allow sufficient time to prepare for flooding. The analysis of water levels and discharges in the main river channels where flooding begins is particularly crucial. In this study, water levels and discharges were measured at runoff stations M.5, M.9, M.182, M.7, M.170, M.179,

E.20A, and E.98 to determine initial water levels and flow rates at the onset of flooding events. These analyses were conducted based on the results of flood inundation modelling generated in the various scenarios outlined above.

Results and Discussion

Flood Cause Analysis

The simulation based on Scenario 1 was aimed at generating models that showed the impacts of varying rainfall intensities on river water levels that are already very high (using data from 2016) and how the extent of flooding in the study area could be affected. The findings indicated that the volume of rainfall within the study area was not the primary cause of flooding. The observed flood areas at the return periods of 10, 20, 50, and 100 years measured 206.03, 214.54, 228.31, and 259.76 km², respectively. Compared to the 10-year return period, the flood areas increased by only 4.13% at the 20-year return period, 10.81% at the 50-year return period, and 26.08% at the 100-year return period (Figures 4 and 5).

Using the MIKE FLOOD model, the simulated flood areas based on runoff data at return periods of 10, 20, 50, and 100 years were 487.59, 696.55, 696.55, and 944.57 km², respectively. The flood area at the 100-year return period was twice as large as the flood area at the 10-year return period (Figures 6 and 7). At different return periods, the flood areas extended from downstream of the Rasi Salai dam to the mouth of the Mun River, including the Chi River and tributaries flowing into the Mun River. Heavy flooding affected areas in Muang Sisaket, Kanthararom, and Muang Ubon Ratchathani districts, as well as parts of Warin Chamrap district in Ubon Ratchathani Province. Furthermore, it was significant that the change in water discharge from the upstream areas played a crucial role in causing extensive flooding in Ubon Ratchathani Province, as the flood areas resulting from variations in water discharge were 57.75%, 69.20%, 72.74%, and 72.50% larger, respectively. These significant differences indicated that water discharge from upstream areas was a primary contributing factor to flooding in Ubon Ratchathani Province. The findings of this study differed from those of Phongnairat and Nophaket (2020), who conducted a literature review and identified the causes of flooding as generally attributable to four factors: 1) topographical conditions, 2) urban planning, 3) dam construction, and 4) seasonal storms. However, these factors were discussed in a broad context without the application of mathematical modelling for a more precise analysis.

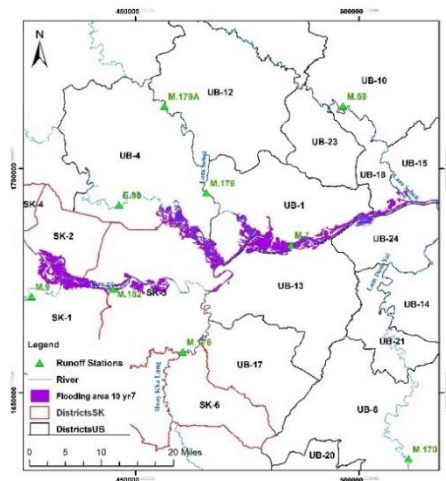


Figure 4. Flooded areas caused by rain at a 10-year return period

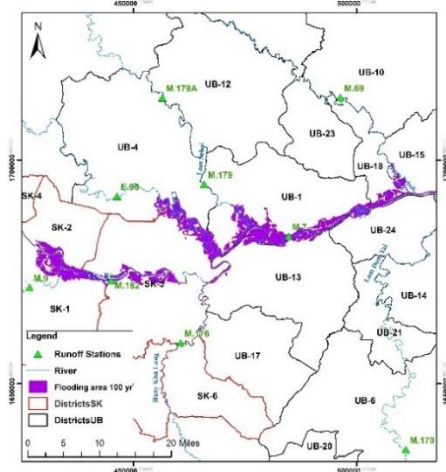


Figure 5. Flooded areas caused by rain at a 100-year return period

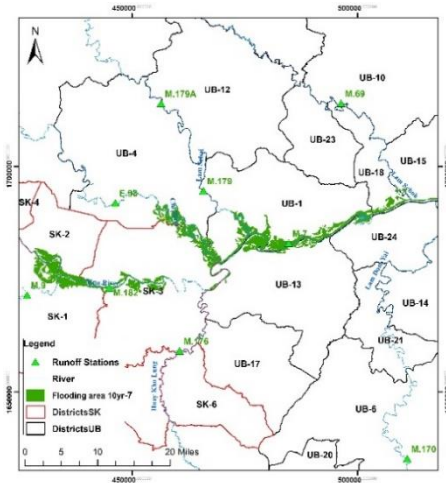


Figure 6. Flooded areas caused by runoff at a 10-year return period

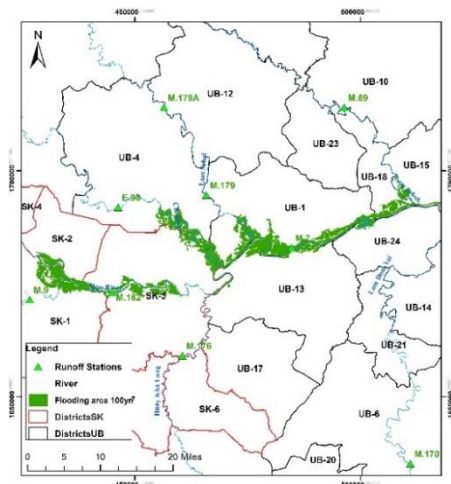


Figure 7. Flooded areas caused by runoff at a return period of 100 years

Evaluation of Reduction Measures for Areas of Flooding

In scenario 2.1, the dredging of main and secondary rivers was based on water level data collected along the Mun River, Chi River, Huai Samran, Huai Khyung, Lam Sebay, Lam Dom Sebay, Lam Dom Yai, and Lam Dom Noi Rivers. The trends of water level data were plotted, and river cross-sections with water levels above the trend line were identified as suitable for dredging.

The analysis of water level data for dredging in the main and secondary rivers revealed a major section of the Mun River that could require dredging, primarily within Sisaket Province. For the Chi, Huai Samran, Lam Sebay, and Lam Sebay Rivers, only minor sections could require dredging. However, no substantial need was indicated for dredging the Huai Khyung, Lam Dom Yai, and Lam Dom Noi Rivers.

Furthermore, taking the results of the water level analysis for dredging into the MIKE FLOOD model for assessing the impact on flooding, it was predicted that the flood-prone areas in Sisaket Province decreased from 84.91 square kilometers (in the case of a 20-year flood event) to 40.31 square kilometers after dredging. This represents a significant reduction of 52.38%. In contrast, the change in flood-prone areas in Ubon Ratchathani Province was minimal. Therefore, river dredging based on water level data could be an effective measure for reducing flood-prone areas in Sisaket Province.

Since the topography in the vicinity of Kaeng Saphue, which is located downstream of station M.11B, acts as a pseudo-dam, a significant amount of water cannot be rapidly discharged. Dredging Kaeng Saphue can enhance the floodwater discharge capacity by improving drainage.

The analytical premise in MIKE FLOOD modelling is that the water level in the Mun River at the Kaeng Saphue location should be equal to the water level throughout the entire river.

The modelling of Scenario 1 predicted that the flood-prone area decreased from 214.538 square kilometers in the case of a 20-year flood event to 176.693 square kilometers when river dredging was performed. This represented a 17.64% reduction of the flood-prone area. However, it should be noted that certain sub-districts and districts could still be affected by flooding, but with reduced depths of flooding. Only one area, Jik Tong Sub-district in Talsum District, Ubon Ratchathani Province, could remain free from flooding. Due to the steady flow nature of the modelling and the constant rainfall input data for a 20-year return period, predicting the specific timing of the flood event was not feasible.

It is imperative to conduct an in-depth study that considers the advantages and disadvantages in all dimensions, with active involvement from local communities, as the practical implications of river dredging are critical.

In Scenario 2.2, following the diversion of water from upstream runoff stations, a notable reduction was forecast in the flooded area from 214.5 km² (in the 20-year return period) to 120.56 (43.81%), 116.06 (45.90%), 111.24 (48.15%), 108.74 (49.31%), and 107.64 km² (49.83%) for Levels 1 to 5, respectively.

Several sub-districts, which were initially susceptible to flooding, could be spared from inundation. These include:

1. Pho and Phonkwao Sub-districts in Muang Sisaket District, Sisaket Province
2. Non-Sang, Du, and Bua Noi Sub-districts in Kanthararom District, Sisaket Province.
3. Yang Chum Yai and Lin Fa Yang Sub-districts in Chum Noi District, Sisaket Province.

Furthermore, sub-districts that could experience a substantial reduction in flooded areas, exceeding 30%, were:

1. Chaeramae, Kham Yai, Nong Khon, and Nong Bo Sub-districts in Muang Ubon Ratchathani, Ubon Ratchathani Province.
2. Khamnamsaep, Tha Lat, Bung Mai, Bung Wai, Warin Chamrap, and Nong Kin Pel Sub-districts in Warin Chamrap District, Ubon Ratchathani Province.
3. Tha Chang Sub-district in Sawang Veerawong District, Ubon Ratchathani Province.

Despite the reduction in flooded areas, it is worth noting that Phibunmangsahan Sub-district, downstream of Ubon Ratchathani, could maintain a

consistent flood intensity. Kaeng Saphue is located within the Sub-district. Consequently, floodwaters that traverse Phibunmangsan Sub-district ultimately find their way to Pak Mun Dam and into the Mekong River.

Discussion

Ubon Ratchathani and Sisaket Provinces have suffered large areas of flooding due to the volume of water coming from upstream areas. The runoff stations strategically positioned within the upper basin of the study area assume a pivotal role in flood monitoring and warning systems. These stations include M.5, M.9, M.182, M.7, M.170, M.179, E.20A, and E.98, which serve as vital components of the flood prediction and warning infrastructure.

M.5, located at the uppermost stretch of the Mun River, operates as an initial flood warning station, issuing timely alerts for potential flood events. The progression of floodwaters downstream toward the M.7 station significantly impacts floodplains within densely populated urban areas, giving rise to extensive economic and social repercussions.

Of particular significance, runoff stations E.20A, M.179, M.69, and M.170 are strategically situated upstream from the respective That Noi Dam, Lamsebai Dam, Lam Sebok Dam, and Lam Dome Dam. During periods of heightened water volume, the effective management of water within these dams becomes imperative. The primary objective entails maximizing water retention within the dam reservoirs. However, it is equally crucial to ensure that the water levels and flow rates at E.20A, M.179, M.69, and M.170 runoff stations consistently remain below the thresholds that would trigger flooding.

In the event of elevated water levels and discharge, appropriate measures should be implemented to facilitate the gradual release of excess water. This would involve directing the surplus water toward E.98 and M.7, thereby

maintaining water levels and flow rates well within the safe limits that preclude the onset of flooding. Table 5 presents the water levels and flow rates at each hydrological station designated as a potential flood warning station. This data could immediately be applied in scenarios where a flood warning system has yet to be established, as well as in cases where such a system is already in place.

The study of flood impacts should be conducted from both spatial and temporal perspectives, covering a large area and requiring daily meteorological and hydrological data that span at least 30 consecutive years. Therefore, mathematical modelling should be employed as the primary tool in flood studies. Here, MIKE FLOOD modelling identified that flooding in Ubon Ratchathani and Sisaket Provinces was primarily caused by upstream water inflows. The model also provided precise information on the extent of flooding in specific sub-districts. Additionally, MIKE FLOOD modelling was used to simulate various potential scenarios, showing how affected areas might change with different flood conditions. The input data for the model is crucial; for example, the resolution of the DEM grid cell should be 5×5 m for urban areas and 30×30 m or 150×150 m for other areas. The cross-sectional data of river channels should be the most recent for the year of study to ensure the model closely reflects actual conditions, with a minimum distance of 10 km between cross-sections. Field surveys and land use maps remain important for the model due to the need to assign Manning's coefficients based on ground cover and land use characteristics.

Given the limitations of this study in terms of climate change, environmental, ecological, and social impact assessments, changes in groundwater during flooding, and the feasibility of implementing both structural and non-structural flood prevention measures, further studies on these topics are necessary to increase the reach of the research.

Conclusions

The predominant factor responsible for flooding in the provinces of Ubon Ratchathani and Sisaket is the influx of upstream runoff. Implementing measures to alleviate flooding, such as the dredging of primary and secondary river channels could potentially reduce flood-prone areas by up to 52.38%. Additionally, the diversion of water from upstream runoff stations could yield significant reductions in inundated areas. In the context of a 20-year return period, these reductions could range

Table 5. Flood threshold water levels and flow rates

Runoff station	Water level (m.+msl)	Discharge (m ³ /s)
M.5	118.42	1044.64
M.9	119.35	221.14
M.182	115.42	1121.01
M.7	112.00	2300.00
M.170	131.42	303.61
M.179	113.00	301.90
E.20A	121.94	1140.53
E.98	116.41	820.57

from 43.81% to 49.83%, depending on the amount of water diverted. Furthermore, the findings of this study hold promise for assessing the feasibility of implementing real-time flood warning systems at water-level monitoring stations. Of noteworthy significance in the present context are stations M.5, M.9, M.182, M.7, M.170, E.20A, and E.98.

The Royal Irrigation Department and the Department of Water Resources should be the primary agencies responsible for implementing both structural and non-structural measures proposed in this study. This recommendation reflects the fact that the flood-affected areas fall within both irrigated and non-irrigated zones, and these agencies possess a high level of readiness and capability. Therefore, if the proposed measures were implemented according to these findings, it is expected that the damage in the mentioned sub-districts could be significantly mitigated.

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