

APPLICATION OF NUMERICAL MODELING AND GIS FOR SIMULATING INUNDATION UNDER DAM FAILURE SCENARIOS

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Abstract

Dam failure and unsafe dam reservoirs cause extremely serious flooding and affecting the environment and ecosystem in the downstream area. The study applied numerical modelling (MIKE 11, MIKE 21, MIKE FLOOD) combined with GIS technology to simulate flooding due to the collapse of Dong Be reservoir, Thanh Hoa, Vietnam, with flood scenarios of frequency $P=1.5\%$ and $P=0.5\%$. The study calibrated and validated the MIKE FLOOD model for two historic flood events in 2010 and 2017. Assessment results show that they were relatively consistent with flood trace survey data. Inundation results in two scenarios show that the inundation area with the $P=0.5\%$ scenario tends to increase compared to the $P=1.5\%$ scenario. The evaluation of simulation results for flooding under two scenarios, when overlaid with administrative, population, and construction layers, will help assess the impact of dam failure and establish its consequences.

Keywords:

Numerical Modelling;
 GIS Technology;
 Inundation;
 Dam Failure.

1 Introduction

Dams, constructed as artificial barriers in watercourses, serve a crucial role by creating reservoirs for various purposes, including agricultural production, energy generation, daily life, flood control, and social activities [1]. Safeguarding the integrity of water reservoirs is a paramount concern for countries due to the significance of water resources. In China, densely populated areas heavily depend on reservoirs, with up to 51% of the population relying on them as their primary source of drinking water Zhanga et al. [2]. Despite the evident advantages of water reservoirs, there is an inherent risk of incidents, sometimes resulting in disasters, as observed in different countries globally by Williamson [3]. Dam failures can lead to downstream floods, impacting human lives and the economy and causing significant harm to the environment and ecosystems. Meimei et al. [4] quantified the environmental impact factors of dam failures through expert interviews, integrating them into comprehensive environmental impact indicators. The research emphasized noticeable changes in the natural environment and the reservoir's ecological conditions following dam failure.

In a comprehensive analysis, Peng and Zhang [5] utilized Bayesian networks to assess the potential downstream human impact during dam failures. Their research delineated strategic recommendations regarding the optimal timing for evacuating residents from vulnerable zones, grounded in meticulous evaluations of flood-related financial repercussions, human life valuations, and associated evacuation costs. Building upon this foundation, Zhang, Xu, Liu, and Peng [6] introduced a structured theoretical framework for Dam Yielding Emergency Management (DYDEM). This framework integrates geological, hydrological, and socio-economic variables affected by downstream flood dynamics, facilitating informed decisions concerning the timely evacuation of populations from jeopardized regions. Furthermore, Li et al. [7] underscored the profound downstream ramifications of dam failures, with human casualties representing the gravest outcome. Their research elucidates the multifaceted factors influencing human fatalities attributable to dam failures. Concurrently, a plethora of studies have employed sophisticated modelling methodologies, including (HEC-RAS [8]-[11], MIKE 21 [12], NWS-DAMBRK [13]-[14], NWSFLDWAV [15]-[16], SPH [17]-[18], MIKE FLOOD [19]-[20]) to

simulate dam failure scenarios and rigorously evaluate flood risks and inundation vulnerabilities within downstream regions.

In the context of Vietnam's water infrastructure, data from the Directorate of Water Resources (2022) [21] delineates the existence of 592 reservoir dams and 6,750 irrigation reservoirs currently in operational status. These comprise four strategically pivotal reservoirs, 888 large reservoirs, 1,633 medium-scale reservoirs, and 4,225 small reservoirs [22]. These facilities can store an estimated 14.5 billion cubic meters of water, with distribution spanning 45 of the nation's 63 provinces. The classification of these reservoirs varies based on their designated functionality, encompassing both irrigation-specific and combined hydroelectric-irrigation purposes. Regardless of their categorization, construction materials for these infrastructures predominantly encompass combinations of earth, rock, and concrete. Notably, most of these reservoirs in Vietnam undertake multifaceted roles, including but not limited to water provisioning, flood mitigation, hydraulic regulation, power generation, and tourism facilitation. The genesis of dam construction within Vietnam can be traced back to the initial decades of the 20th century, characterized by nascent technological constraints.

Consequently, a significant proportion of these structures approach a lifespan of 50 to 70 years, thereby accentuating inherent safety vulnerabilities. This investigation focuses on the risks pertinent to medium-scale and smaller reservoirs within the North Central region, exemplified by the Dong Be reservoir in Thanh Hoa. The ramifications of dam failure within this geographical purview are both expansive and instantaneous, engendering significant implications for densely populated locales replete with pivotal infrastructural, economic, and transportation facets. Additionally, the Central Coast region of Vietnam is increasingly beset by inclement meteorological phenomena characterized by erratic and intensified precipitation and inundation events. This scenario is exacerbated by the proliferation of numerous dispersed reservoirs, many of which languish in states of infrastructural degradation due to fiscal constraints hindering routine maintenance, thereby amplifying associated risk parameters. Examinations predicated upon statistical compilations from the Dam Safety Department of the Ministry of Agriculture and Rural Development delineated by the General Department of Irrigation (2022) elucidate a disconcerting trend. The timeframe spanning 2010 to the contemporary era has witnessed 71 discrete incidents about dam and reservoir vulnerabilities, with the zenith observed in 2017, registering 23 consequential events. Notably, the preliminary nine-month period of 2019 manifested 11 such critical incidents, underscoring an exigent imperative to reevaluate and fortify dam safety and management paradigms holistically.

Many research endeavours focusing on dam safety have been conducted, predominantly employing simulation methodologies to assess scenarios of dam failures resulting in downstream flooding. The investigation into dam failure scenarios entails spatial-temporal rupture simulations, hydraulic flow computations through the breach, and simulations to delineate flood extents and inundation durations downstream. Lan et al. [23] constructed flood inundation maps predicated upon simulations revealing that within three hours post-incident, the maximum inundation depth, predominantly exceeding 5 meters, encompassed approximately 50% of the affected area. By the six-hour mark, the inundation encompassed a vast expanse affecting 55 communes across three districts, aggregating to an area of 345 km². This catastrophe submerged approximately 47,940 households and impacted 375,395 inhabitants, constituting approximately 12% of the directly affected population as of 2008. Nghi [24] meticulously evaluated risk factors associated with the cascade reservoir system on the Da River in the event of dam failures, employing hydraulic models for assessment. The outcomes of this assessment serve as foundational knowledge for policymakers, planners, and operational researchers to devise prudent management strategies for the cascade reservoirs on the Da River while ensuring the safety of the downstream populace residing along the Red River. Chanh and Ly [25] leveraged the MIKE model to develop flood inundation maps for potential dam failure scenarios and emergency water releases. This initiative aims to bolster flood warning systems and risk mitigation strategies, thereby minimizing adverse impacts on downstream regions, including the Dinh Binh reservoir. Dat et al. [26] studied numerical models (1D and 2D of MIKE FLOOD models) to simulate the downstream flood of the Tra Khuc - Song Ve River basin, including the breakdown of DakDrinh, the biggest dam in the basin.

According to an exhaustive review of previous scholarly investigations, the predominant methodology employed for assessing downstream flood implications arising from dam failures has consistently centred around the utilization of 1-2-3D modelling methodologies. The study initiative has selected the MIKE modelling suite, incorporating the MIKE 11, MIKE 21, and MIKE FLOOD modules, to simulate inundation scenarios resulting from two distinct dam failure events. The study objectives were: (1) To establish a coupled mesh domain in 1D and 2D to simulate the hydraulic regime in the

downstream area; (2) To use the coupled 1D and 2D MIKE FLOOD model to calculate the depth of the inundation and flow velocity flow during and after the dam failure.

2 Materials and methods

2.1 Description of study site

The Dong Be reservoir is approximately 40 km southwest of Thanh Hoa City, within the administrative boundaries of three communes: Phuong Nghi and Xuan Du in Nhu Thanh District and Trieu Thanh in Trieu Son District. Its geographical coordinates are 19°47' North Latitude and 105°30' East Longitude. The primary function of the Dong Be reservoir is to provide potable water and irrigation services to approximately 225.0 hectares of agricultural land spanning two communes: Trieu Thanh and Hop Thanh in Trieu Son District and Xuan Du in Nhu Thanh District. Initially constructed in 1989 as a seasonal regulating reservoir, significant refurbishments and safety upgrades were undertaken in 2007 under the WB8 dam safety enhancement project, culminating in its operational readiness by 2020. The reservoir is a sizable, seasonal regulating facility categorized as Grade III. Its catchment area spans 9.4 km², with a designed flood level ($P = 1.5\%$) set at 40.71 meters and a verified flood level ($P = 0.5\%$) at 40.88 meters. The total storage capacity of the reservoir stands at 1.974×10^6 m³, with a usable storage volume amounting to 1.892×10^6 m³.

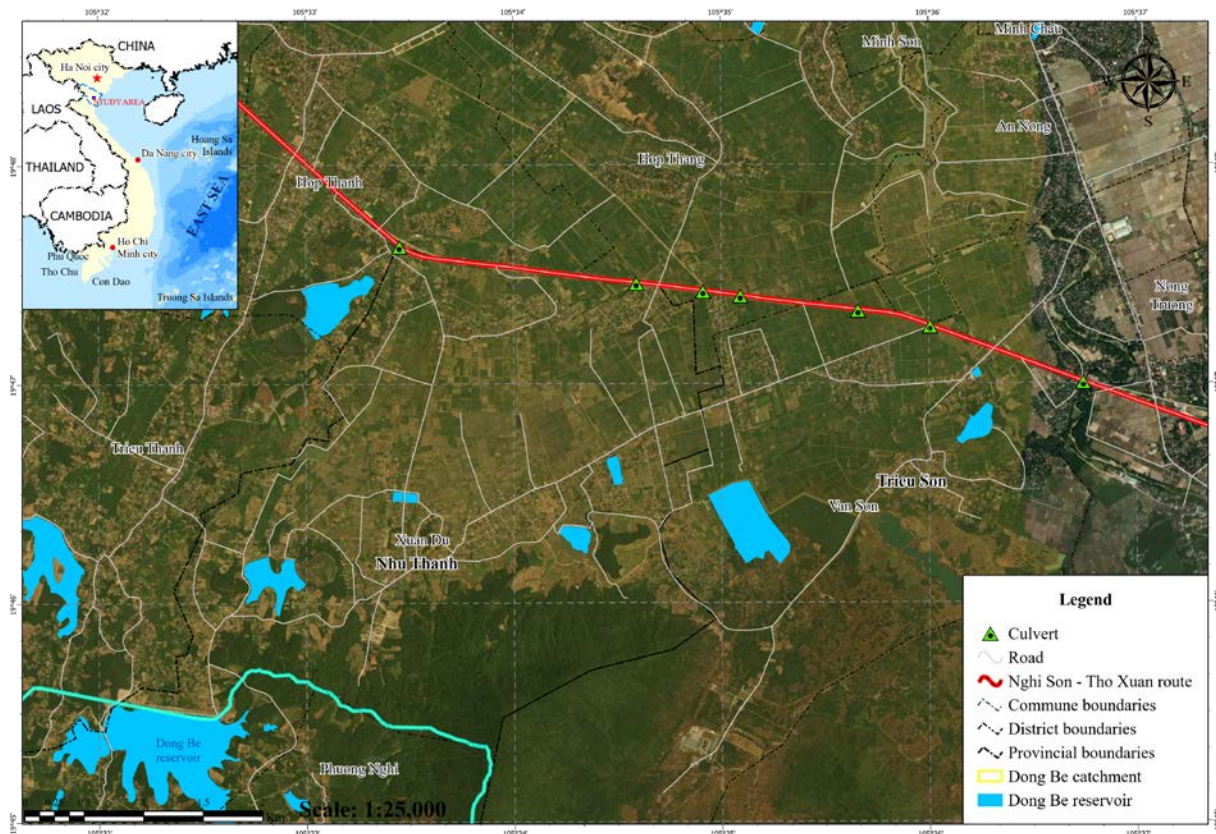


Fig. 1: Location of study site.

+ Main Dam Specifications: The main dam has a length (L_d) of 798.6 meters, a crest width (B_d) of 5.0 meters, and an elevation of the dam's crest height of +42.30 meters. Additionally, the Parapet Wall the dam stands at an elevation of +42.80 meters; maximum dam height is 10.95m. The upstream slope (upper) has a slope coefficient (m_u) of 2.75, while the downstream slope (lower) possesses a slope coefficient (m_n) of 2.5.

+ Auxiliary Dam Specifications: The auxiliary dam measures 390.8 meters long (L_d) with a crest width (B_d) of 3.5 meters. The elevation of the dam's crest height is set at +42.30 meters; maximum dam height is 5.70m. The upstream and downstream slopes have a slope coefficient (m) of 2.5 and are vegetated with grass to provide protection.

+ Spillway specifications: The spillway operates as a free overflow spillway. Its width, known as the spillway width (B_{tr}), measures 50.0 meters, and the elevation of the spillway crest height is set at +39.40 meters. The design discharge flow rate, denoted as Q_{TK} ($P = 1.5\%$), is $120.57 \text{ m}^3/\text{s}$. The checked discharge, Q_{KT} ($P = 0.5\%$), is $143.54 \text{ m}^3/\text{s}$. Furthermore, the extreme maximum flow rate (Probable Maximum Flood, PMF) is recorded at Q ($P = 0.01\%$) = $259.29 \text{ m}^3/\text{s}$.

The Song Chu Joint Stock Company manages the reservoir. The research area encompasses four communes: Phuong Nghi and Xuan Du in Nhu Thanh District and Trieu Thanh and Hop Thanh in Trieu Son District, Thanh Hoa Province. The total natural land area of all four communes amounts to 7,103.68 hectares. This includes 1,813.02 hectares of agricultural land, 3,051.94 hectares of forested land, 107.46 hectares dedicated to aquaculture, and 682.86 hectares of residential land. The combined population of these four communes is 24,716 individuals.

2.2 Methodology

The study used a modelling approach using the MIKE 11, MIKE 21, and MIKE FLOOD software to simulate the flooding process resulting from dam failures under two distinct scenarios: (1) Dam failure due to spillway overflow caused by a 1.5% annual probability flood event combined with corresponding downstream rainfall; (2) Dam failure resulting from spillway overflow due to a 0.5% annual probability flood event in conjunction with corresponding downstream rainfall. GIS technology is utilized to visualize the simulation results derived from the model, focusing on the maximum inundation depth (H_{max}) at various frequencies and the maximum flow velocity (V_{max}). The study framework structure is illustrated in Fig. 2.

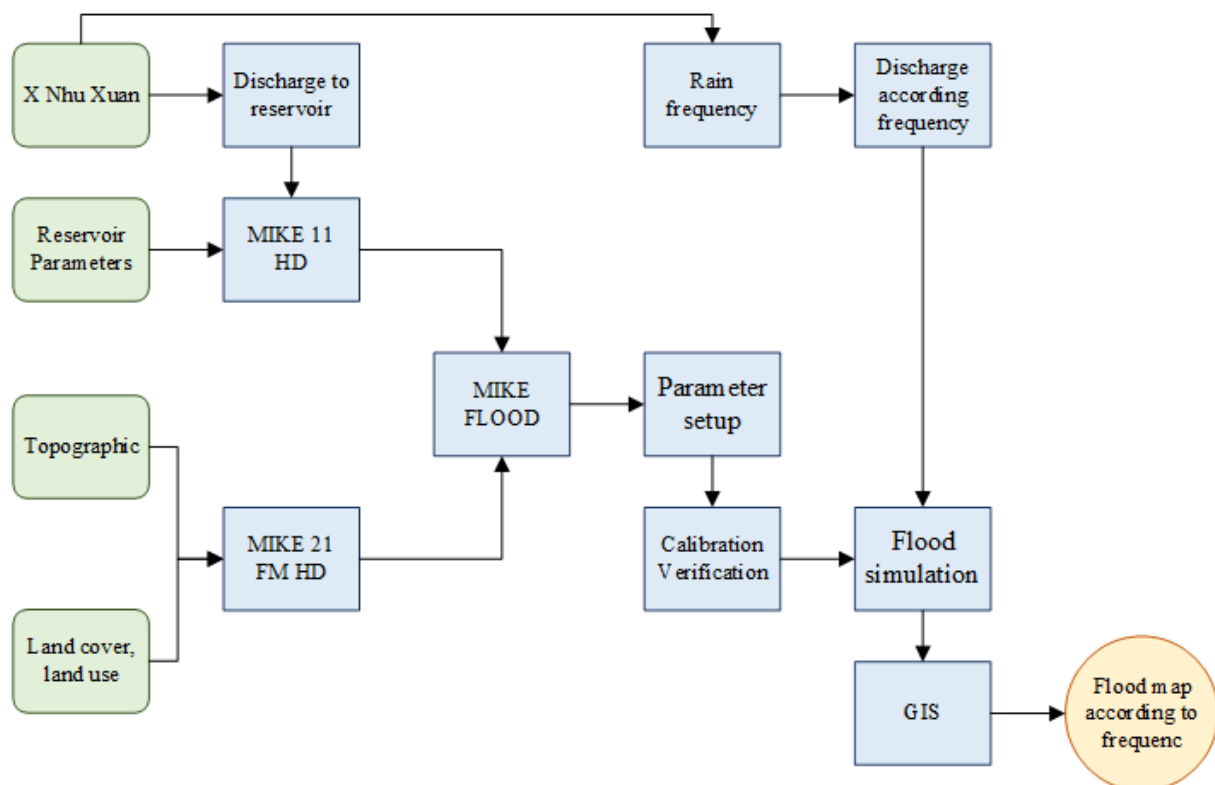


Fig. 2: Flowchart of study structure.

2.2.1 Establish of MIKE 11, MIKE 21, MIKE FLOOD models

a) Establish hydraulic MIKE 11 model

The downstream vicinity of the Dong Be reservoir predominantly comprises agricultural lands and residential structures. Concurrently, the Khe Rao canal is the principal drainage conduit during flood discharge events from the reservoir. Informed by comprehensive field surveys, geospatial assessments, and consultations with local inhabitants residing downstream, insights were garnered concerning the inundation levels and flow dynamics during reservoir discharge cycles. The report integrates advanced remote sensing techniques and GIS applications. Specifically, the MIKE 11 model was employed to

digitize and analyze the flow trajectory of the Khe Rao canal, commencing from the primary dam of the Dong Be reservoir and extending toward the proximity of the Tho Xuan airport thoroughfare.

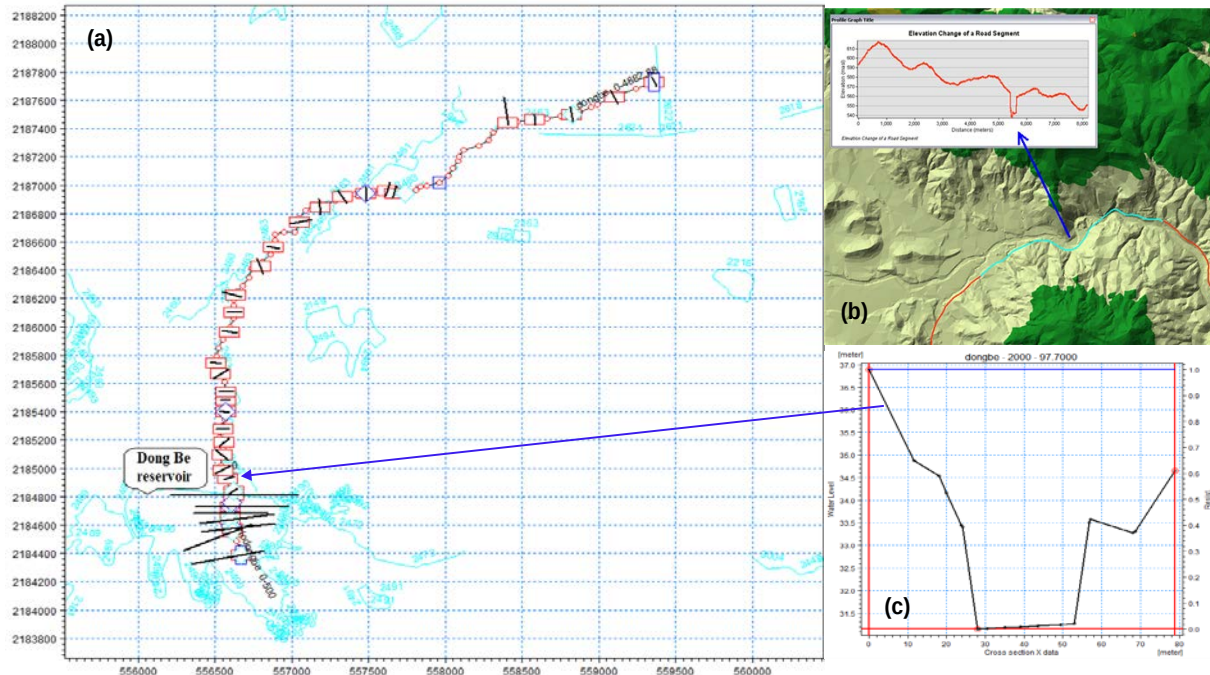


Fig. 3: (a) Digitizing the Khe Rao canal in the MIKE 11 model; (b) The Profile Graph Tool was employed to interpolate the elevation profiles; (c) Establishing the cross-section in MIKE 11.

The study has established 29 cross-sections for the downstream reservoir model, with an average distance between each cross-section of 180 meters (Figs. 3a, 3a). Additionally, the terrain of the downstream dam area undergoes significant variations due to the alternating areas of paddy fields, flower cultivation, and residential houses. Therefore, the study utilized topographic survey data and integrated ArcGIS 10 with the Profile Graph Tool to interpolate and supplement areas with significant terrain variations where actual data was lacking. After interpolation, the elevation data of the terrain was exported for input into the MIKE 11 model (Fig. 3b).

The upper boundary: Delineating the upstream limit, is characterized by the temporal flow discharge across the entirety of the cross-sectional profile during the computational interval ($Q \sim t$). The positioning of this boundary is contingent upon the specific simulation scenario under consideration.

To elucidate: In a simulation scenario where the dam remains intact, the upper boundary is strategically positioned immediately downstream of the dam structure. Conversely, within a simulation framework depicting a dam failure, the upper boundary is distinctly positioned upstream, anterior to the dam's reservoir.

The downstream boundary is determined using the $Q \sim h$ relationship from the river cross-sectional profile due to the need for empirical water level data in that reservoir section.

Furthermore, inflow from the intermediate catchment area notably influences downstream inundation during rainfall. The report uses topographic data and river networks to define this catchment boundary for the simulated river section (Fig. 4).

The upper boundary models regulated flows and dam failure scenarios in the Dong Be reservoir simulation. The lower boundary uses the $Q \sim h$ relationship at the simulated river's end. The intermediate boundary represents downstream rainfall contributions. During dam failure simulations, the report models flow from the reservoir's upper part downstream under a free-flow scenario.

Initial conditions for the model: At the Dong Be reservoir location, the initial conditions for the simulation scenarios will be set at a normal water level of 39.4 meters.

Hydraulic parameters in the model are derived from topographical surveys and downstream area data, incorporating Manning's roughness coefficient from referenced documentation [27]. The hydraulic values for the Dong Be reservoir area range between 0.03 to 0.04.

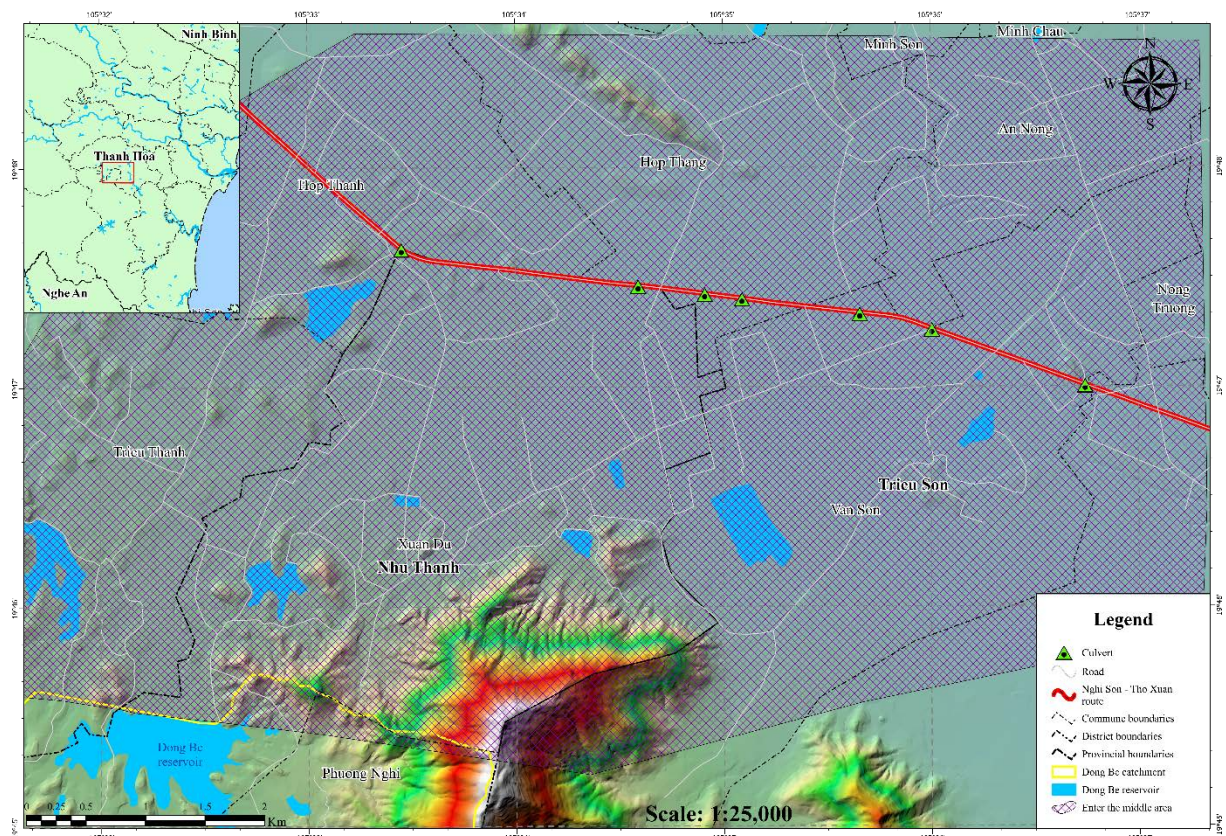


Fig. 4: The boundary delineating the intermediate catchment area for the simulated river section.

b) Establish hydraulic MIKE 21 model

The computational domain is constructed based on the following criteria: Gridlines must closely adhere to rigid boundaries and downstream boundaries; Detailed grids are essential at locations such as rivers, reservoirs, channels, and streams; Given the rugged and complex terrain that varies both vertically and horizontally at specific sites, the computational grids must be meticulously detailed. Nevertheless, an increase in grid granularity directly correlates with a heightened computational burden within the model. In alignment with the stipulated criteria for a grid system, the computational domain is systematically partitioned into distinct regions characterized by varying grid dimensions (Figs. 5a, 5b).

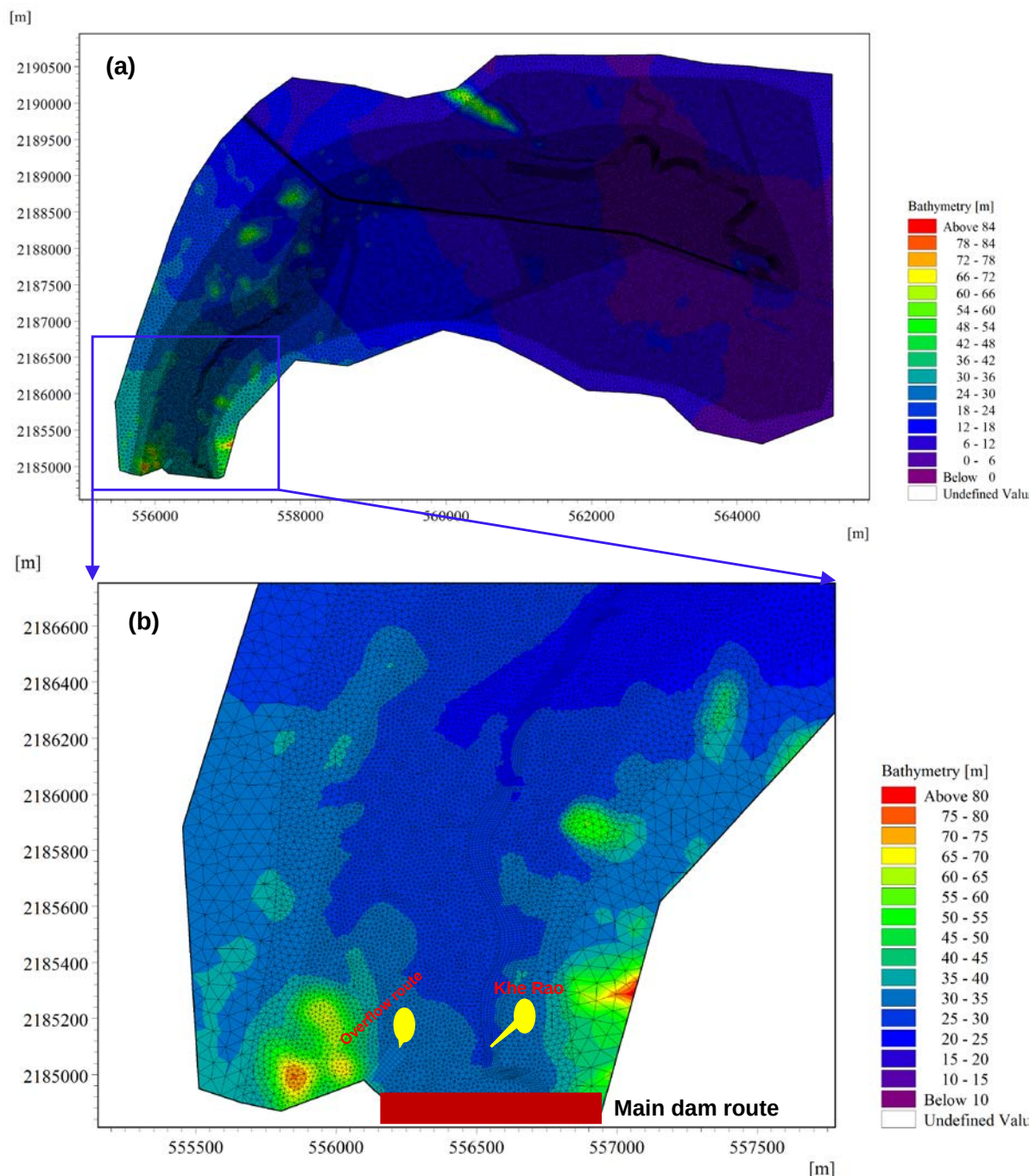


Fig. 5: (a) Establishment of the topographical grid for the downstream area of the Dong Be reservoir; (b) Detailed refinement of the computational grid for the Khe Rao area and spillway alignment.

Terrain analysis: Beyond river cross-section measurements, the report integrates 1:10,000 scale topographic maps from Vietnam's National Center for Surveying and Mapping. After processing with ArcGIS, this elevation data will serve as input for the two-dimensional MIKE 21 FM model, establishing a mesh terrain representation. Each terrain point will determine the elevation of its corresponding grid cell. The study compares the data it with three-dimensional representations from Google Earth to achieve precise topographical interpolation results. This rigorous comparison examines features such as hills, mountains, rivers, cultivated fields, reservoirs, lakes, and expressways. This verification process aims to ensure that the simulated flood modelling aligns meticulously with real-world conditions. Enclosed are select visual representations after the interpolation, computational analysis, and rigorous verification of the terrain (Fig. 6).

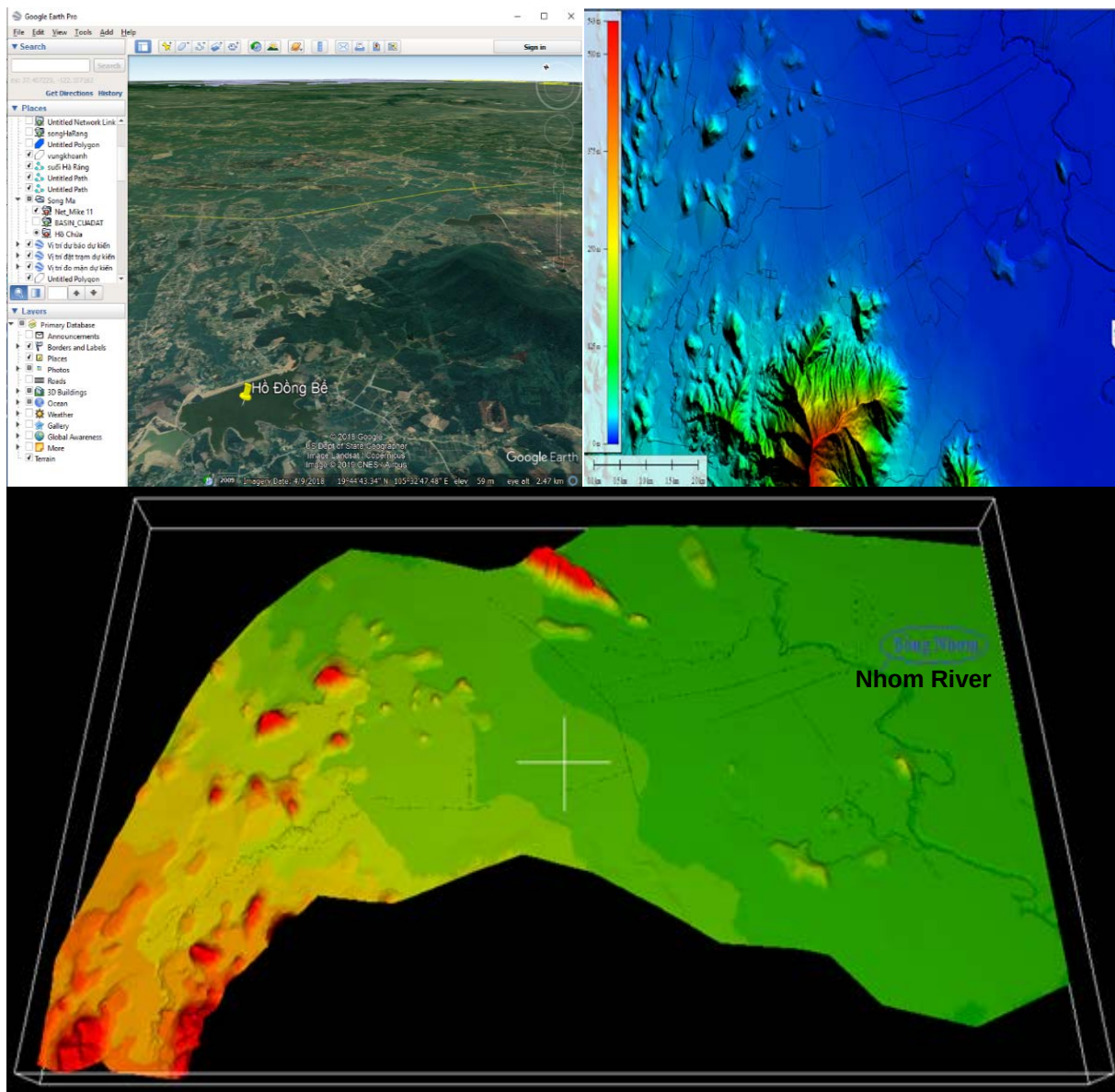


Fig. 6: The interpolated terrain results for the downstream area of Dong Be reservoir, constructed using MIKE 21.

Boundary conditions: Within the framework of the two-dimensional model, the delineation of boundaries encompasses both an upper and lower boundary analogous to the one-dimensional paradigm. Specifically, the upper boundary delineates the discharge emanating from the lake, while the lower boundary demarcates the water elevation at the designated location of the Nhom River. Furthermore, beyond discharge and water elevation constraints, the MIKE 21 FM model integrates precipitation parameters tailored to align with the frequency of flow scenarios computed for each distinct computational instance.

Initial conditions: In a two-dimensional model, the initial conditions are analogous to a one-dimensional one. These conditions are contingent upon specific scenarios corresponding to varying water levels or discharge rates.

Hydraulic parameters: Manning's roughness coefficient is a crucial factor in hydraulic calculations, particularly sensitive during hydraulic result calibration. In 2D hydraulic simulations for floodplains, this coefficient exhibits nuanced variations based on soil type, land use, and ground cover. For example: Sparse grass areas: 0.025-0.035, unvegetated land: 0.02-0.04, asphalt roads: 0.011, concrete roads: 0.012, gravel roads: 0.024. Based on research and soil-specific data for the watershed, a Manning's coefficient range of 0.03-0.05 has been established for the downstream area of Dong Be reservoir. This range ensures an accurate representation of hydraulic characteristics in the simulation (Fig. 7).

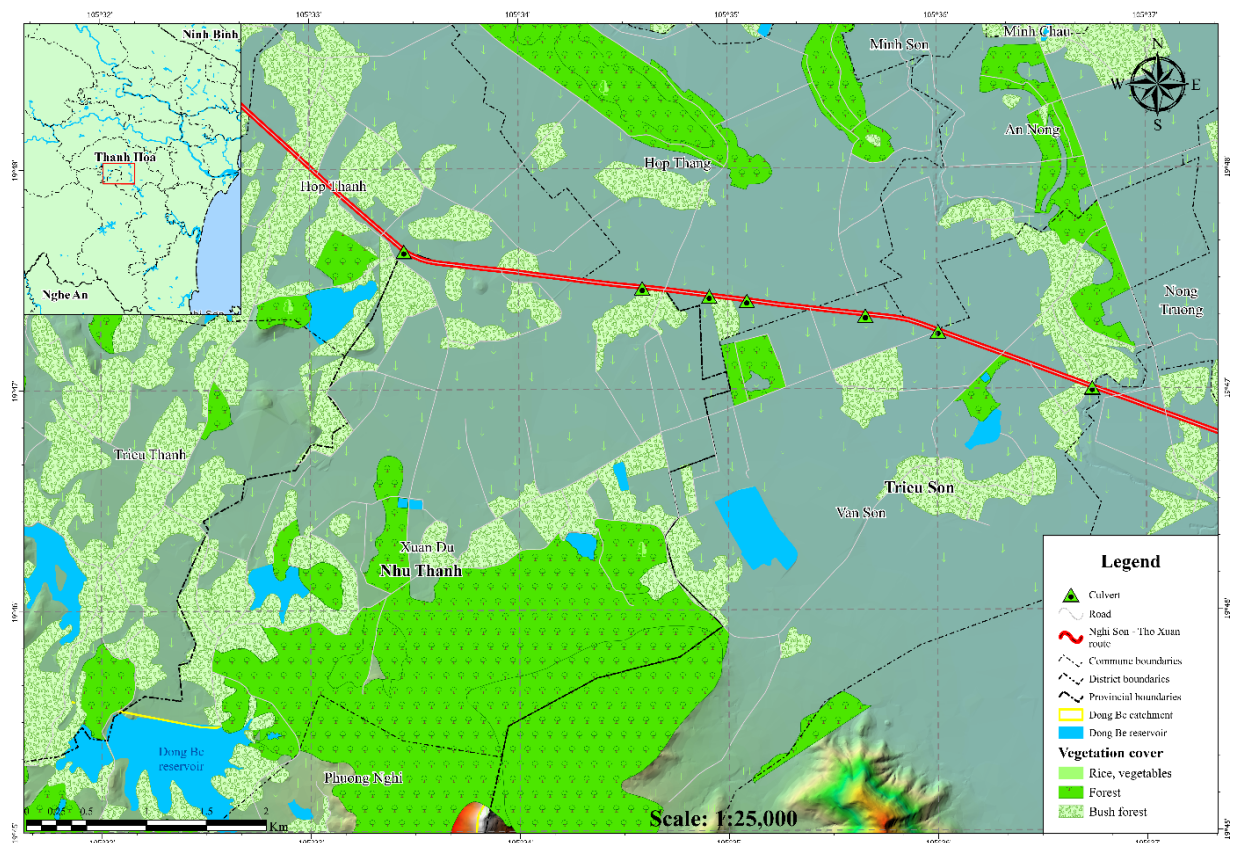


Fig. 7: Land cover map of the study area.

c) Establish of MIKE FLOOD model

The MIKE FLOOD model integrates the MIKE 11 and MIKE 21 FM models. River branches in MIKE 11 align with both banks in MIKE 21 FM, termed as branch connections. Culverts in MIKE 11 are linked via standardized structures to the MIKE 21FM topography. The MIKE 11 and MIKE 21 models have defined the input boundaries. Consistency between the two models concerning simulation duration and computational time steps is maintained (Fig. 8).

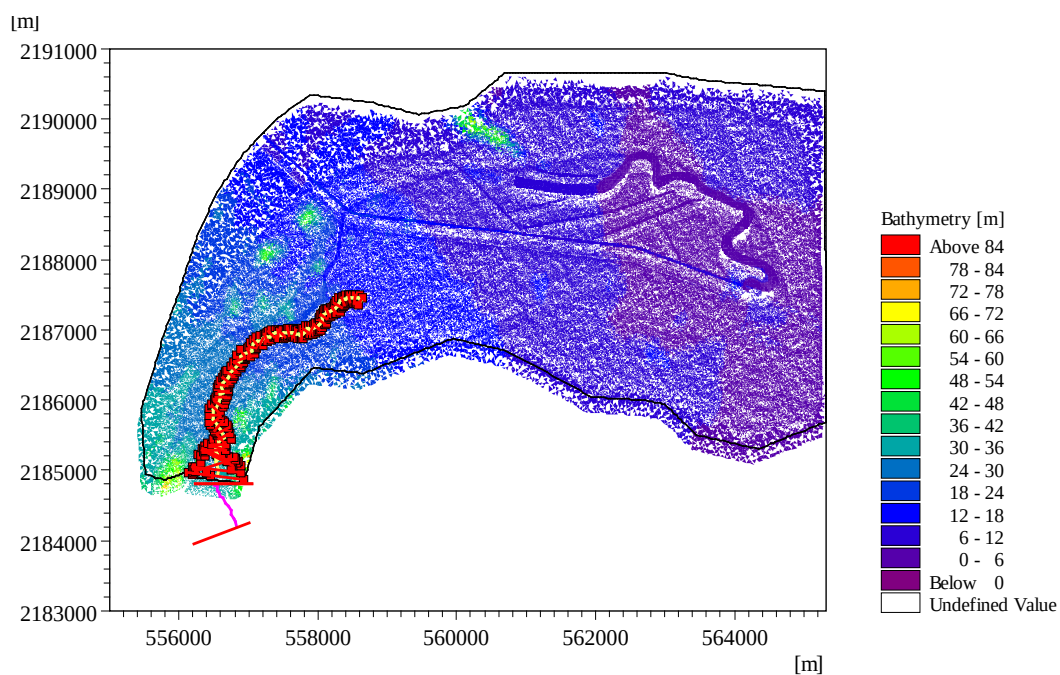


Fig. 8: Establishment MIKE FLOOD model.

2.3 Dam failure scenarios

The study establishes a hypothetical worst-case scenario in the context of Dong Be reservoir, which features an earthen primary dam. This scenario suggests that the dam would rupture entirely should the water level within the lake exceed the dam's crest elevation. The anticipated initial point of breach is identified at the dam's crest, taking on a trapezoidal configuration (Fig. 9). The methodology to assess this potential breach encompasses a detailed computation of erosion parameters. These parameters consider the inherent material properties of the dam construction, along with hydrological factors such as particle diameter, specific weight, and porosity, etc.

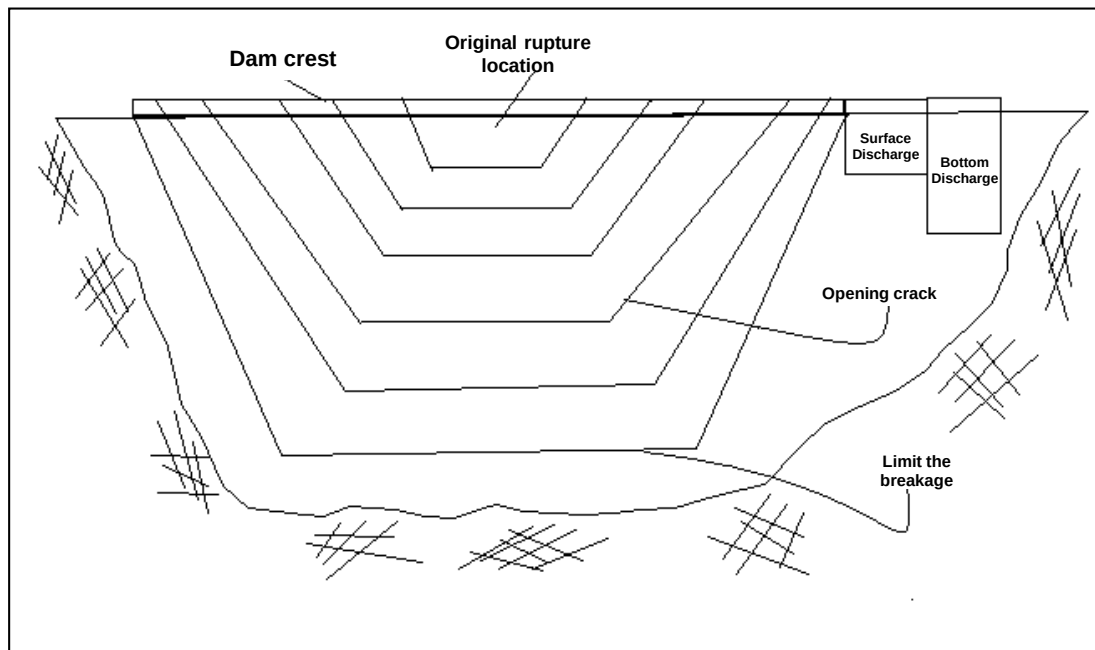


Fig. 9: A formal and clearer description of the fracture's location and its development mechanism.

a) Scenario 1: The dam breaks due to an overflow incident caused by a flood designed to a frequency of $P=1.5\%$ and corresponding downstream rain frequency (Fig. 10).

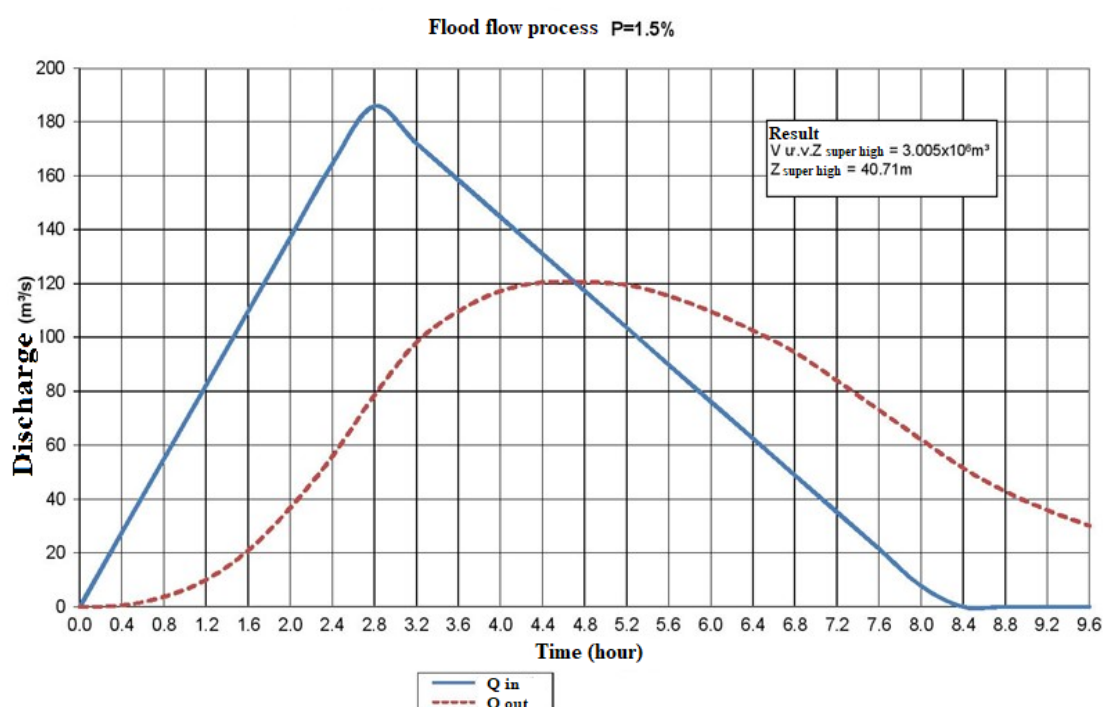


Fig. 10: The inflow and outflow processes with a frequency of $P = 1.5\%$.

- b) Scenario 2: The dam breaks due to an overflow incident caused by a test flood designed to a frequency of $P = 0.5\%$ and corresponding downstream rain frequency (Fig. 11).

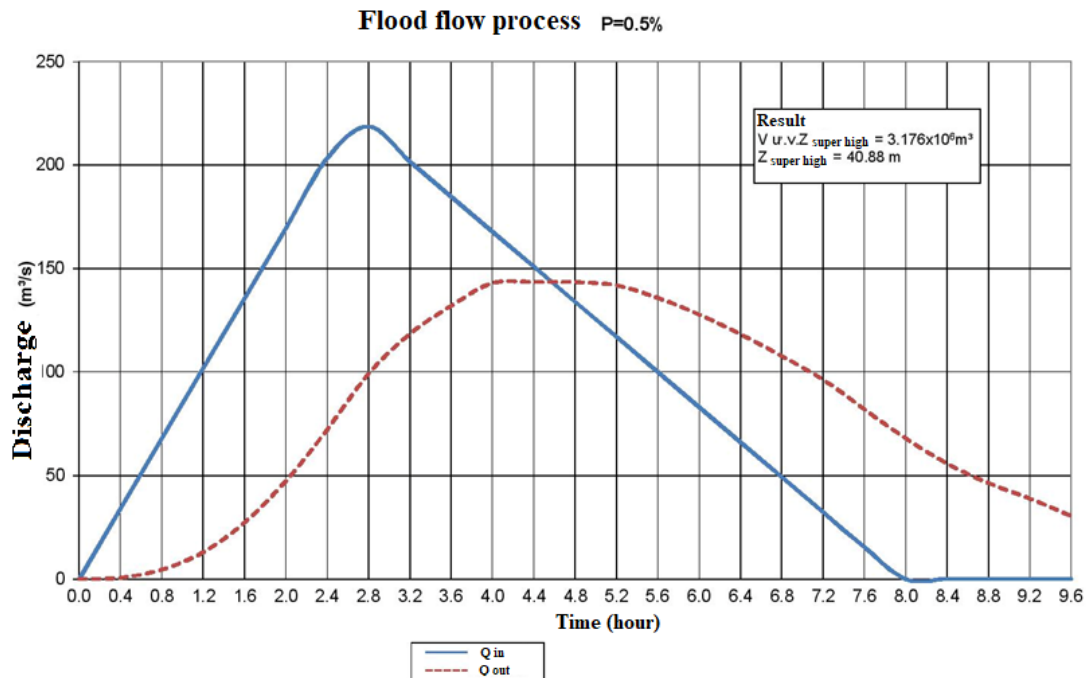


Fig. 11: The inflow and outflow processes with a frequency of $P = 0.5\%$.

Note: $Z_{\text{super high}}$ is the highest water level appears in the reservoir when the design flood occurs in the basin; $V \sim Z_{\text{super high}}$ is the reservoir capacity corresponds to the highest water level.

3 Results and discussion

3.1 Calibration and validation of MIKE FLOOD model

A one-dimensional hydraulic model has been established for the Rao Khe segment, spanning from the primary dam of the Dong Be reservoir to proximate the national thoroughfare leading to Tho Xuan airport. Concurrently, a two-dimensional hydraulic model is employed to compute hydrodynamic parameters within the floodplain regions, encompassing locales such as Trieu Thanh, Xuan Du, Hop Thanh, Hop Thang, Van Son, and An Nong. The one-two-dimensional hydraulic model has undergone rigorous calibration and validation, benchmarked against two seminal flood events. These selected inundation events are predicated upon their extensive geographical impact, substantiated by meticulous precipitation records and empirical flood survey documentation. Emphasis is accorded to recent flood occurrences proximally affecting the downstream sectors of the Dong Be reservoir. This prioritization ensures contemporary insights into topographical nuances, geomorphological attributes, precipitation patterns, and overarching climatic variations pertinent to the designated research zone, thereby facilitating the meticulous refinement and validation of the MIKE FLOOD computational model-the inflow and outflow processes with a frequency of $P = 0.5\%$.

Two pivotal flood events from 2010 and 2017 were chosen for calibrating and validating the hydraulic model. Data for flood inundation surveys were sourced from the Song Chu Joint Stock Company. The assessment compared discrepancies between simulated and observed flood elevations at six specified inundation sites, as detailed in Table 1 and Fig. 12.

Table 1: Inundation locations designated for model calibration and validation.

No	Longitude	Latitude	Place
1	105.541	19.769	The village of Hoi, located in Trieu Thanh commune, is situated 1.2 kilometers from the Dong Be dam.
2	105.542	19.772	The village of Hoi, in Trieu Thanh commune, is located 1.5 kilometers from the Dong Be dam.
3	105.561	19.787	The village of Chua, situated in Xuan Du commune, is proximate to the primary elementary school area and is located 0.6 kilometers from the Tho Xuan airport access road.
4	105.560	19.789	The village of Chua, located in Xuan Du commune, is adjacent to the elementary school district and is positioned 0.4 kilometers from the access road to Tho Xuan airport.
5	105.573	19.789	Dong Phu Hamlet, situated in Xuan Du commune, is located 0.2 kilometers from the access road to Tho Xuan airport
6	105.565	19.778	Tan Lap Hamlet, located in Xuan Du commune, is situated 1.2 kilometers from Xuan Du Secondary School

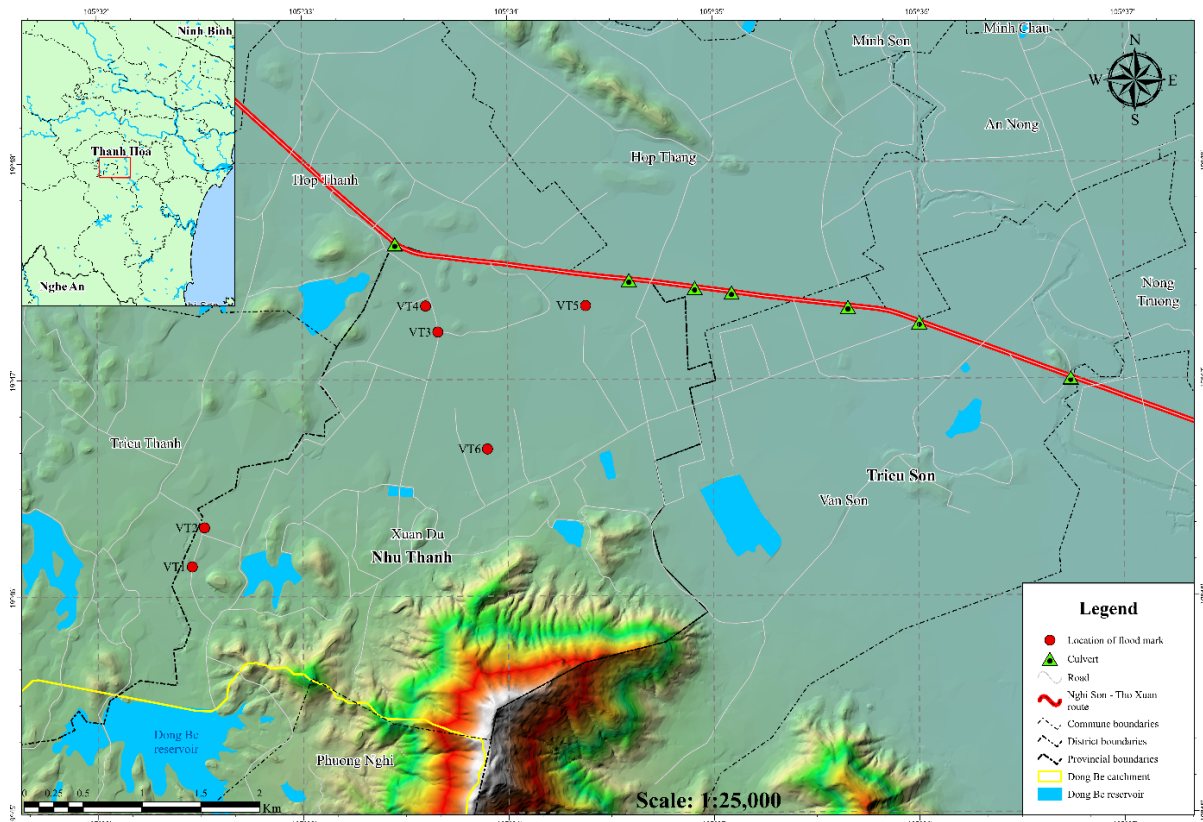


Fig. 12: Surveyed inundation locations map.

3.1.1 Results of model calibration using the 2010 flood event

The calibrated simulation results for the October 18, 2010, inundation event indicate that the water level elevations align reasonably well with the observed inundation locations. The discrepancies range from a minimum of 1.0% to a maximum of 5.5%. Based on the successful calibration, the derived parameter set can now be utilized to validate the flood event of October 11, 2017 (Table 2, Fig. 13).

Table 2: Results of the calibration for the flood event on October 17-18, 2010.

No	$H_{\max}$ simulation (m)	$H_{\max}$ observed (m)	Margin of error (%)
1	26.43	27.9	5.3
2	26.1	27.07	3.6
3	16.85	16.69	1.0
4	16.73	16.35	2.3
5	12.15	12.29	1.1
6	16.79	16.45	2.1

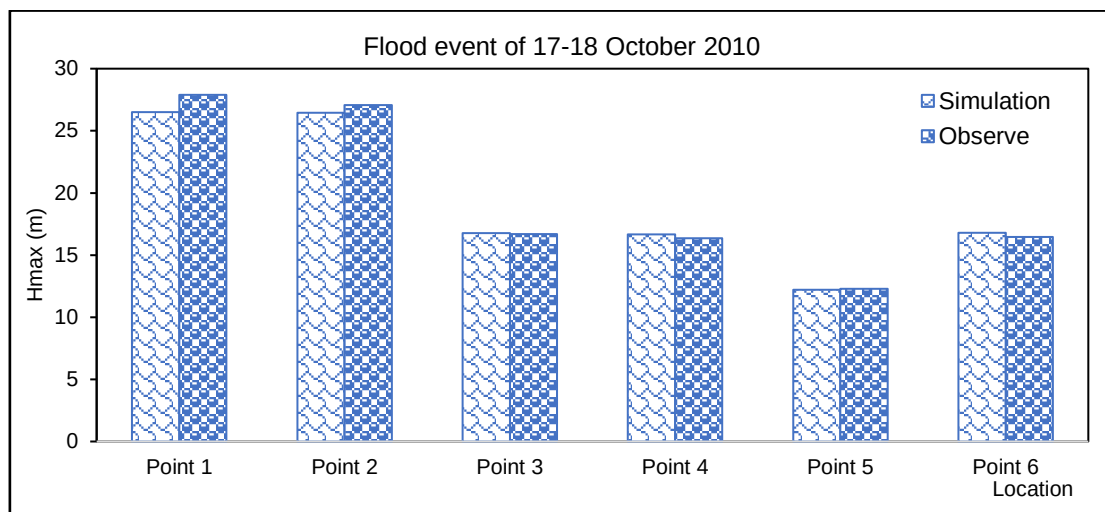


Fig.13: Calibration Results for October 17-18, 2010 floods at designated locations.

3.1.2 Validation results of the model against the 2017 flood event

Validation of the model against the October 11-13, 2017 flood event at designated locations indicates that water level simulations closely align with observed data. Discrepancies remain within permissible limits, with a minimum error of 1.5% at positions 2 and 6 and a maximum of 2.7% at location 4. Validated results are presented in Table 3, Fig. 14.

Table 3: Validation results for the October 11-13, 2017 flood event.

No	H _{max} simulation (m)	H _{max} observed (m)	Margin of error (%)
1	27.2	27.85	2.3
2	26.61	27.02	1.5
3	17.1	16.68	2.5
4	16.65	16.22	2.7
5	12.51	12.27	2.0
6	16.69	16.44	1.5

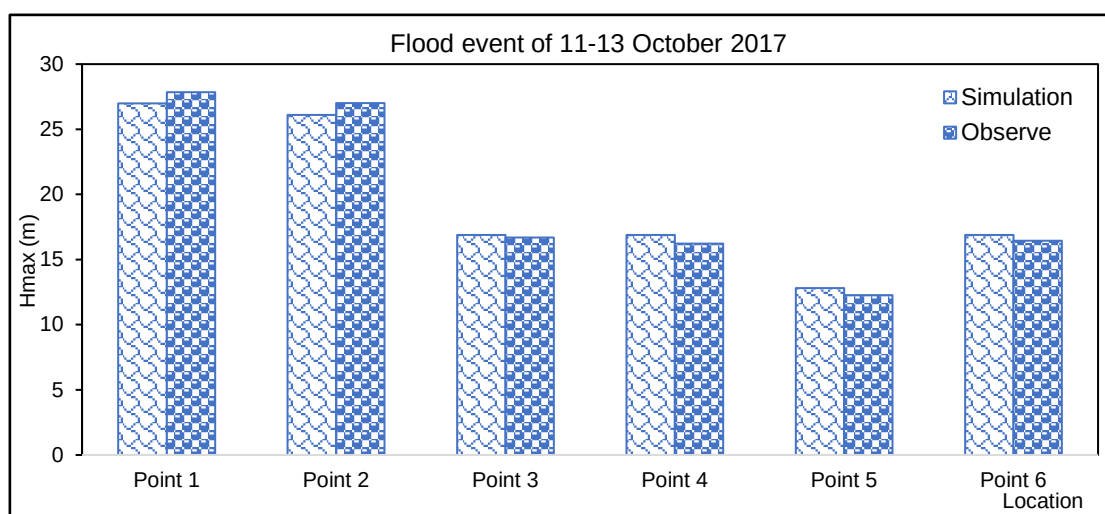


Fig. 14: Validation results for the flood event of October 11-13, 2017, at designated measured inundation locations.

The calibration and validation procedures, and the flood simulation results about the two precipitation events in the downstream vicinity of the Dong Be reservoir have demonstrated commendable accuracy and alignment. Consequently, leveraging this empirical basis, the report advances towards formulating flood inundation maps under diverse dam failure scenarios.

3.2 Results of constructing flood inundation maps based on dam failure scenarios

The dam failure simulation utilizes the MIKE 11 model, incorporating its advanced computational capabilities. Within these scenarios, it is assumed that dam failure initiates once the reservoir water level reaches the dam's crest elevation. The extent of rupture propagation hinges on erosion parameters intrinsic to the dam structure, influenced by flow rates and material characteristics. Results are succinctly illustrated in subsequent visuals (Figs. 15a-15c).

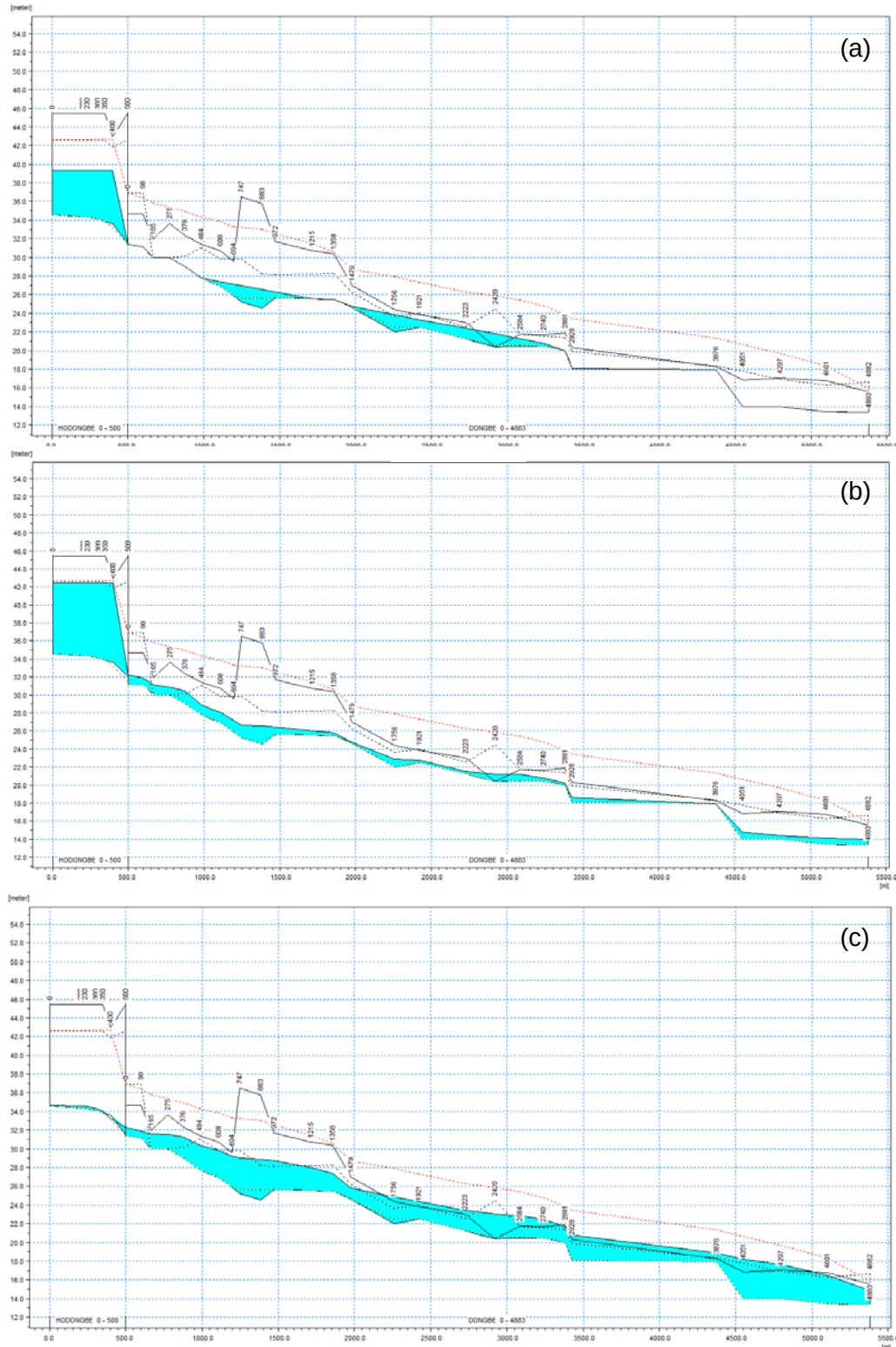


Fig. 15: (a) Initial water level before dam failure; (b) Reservoir water level at the onset of dam failure; (c) Reservoir water level following dam failure.

- In the event of dam failure resulting from overflow incidents aligned with a design flood frequency of $P = 1.5\%$ and commensurate downstream precipitation frequency, the simulation elucidates that the maximum flow rate immediately downstream of the dam achieves a magnitude of $1549 \text{ m}^3/\text{s}$.

- In the scenario where dam failure occurs due to overflow incidents aligned with a design flood frequency of $P=0.5\%$ and corresponding downstream rainfall frequency, the simulation reveals that the peak flow rate downstream of the dam reaches $1663 \text{ m}^3/\text{s}$. This maximum discharge is observed within one hour and forty-five minutes after the initiation of the breach.

Drawing upon the hydrological simulations that elucidate the discharge dynamics at the dam, this report rigorously utilizes the MIKE FLOOD model to analyze downstream flood inundation scenarios. The primary objective is to pinpoint specific areas vulnerable to inundation in a dam failure across predetermined scenarios. The ensuing sections meticulously detail the simulation results for dam failures within two delineated scenarios.

3.2.1 Scenario 1

The hydraulic simulation outcomes for the dam failure scenario, characterized by a 1.5% flood frequency, reveal significant flow velocities, and maximum flow velocity in the downstream area (Figs. 16-17). Precisely, at coordinates ($x = 556496.6$; $y = 2185277.7$), situated approximately 430 meters downstream from the principal dam, the flow velocity attains a zenith of 5.3 m/s (Fig. 18a). Concurrently, at coordinates ($x = 557032.7$; $y = 2186642.4$), positioned roughly 2200 meters downstream from the primary dam, the velocity reaches a peak of 3.27 m/s (Fig. 18b).

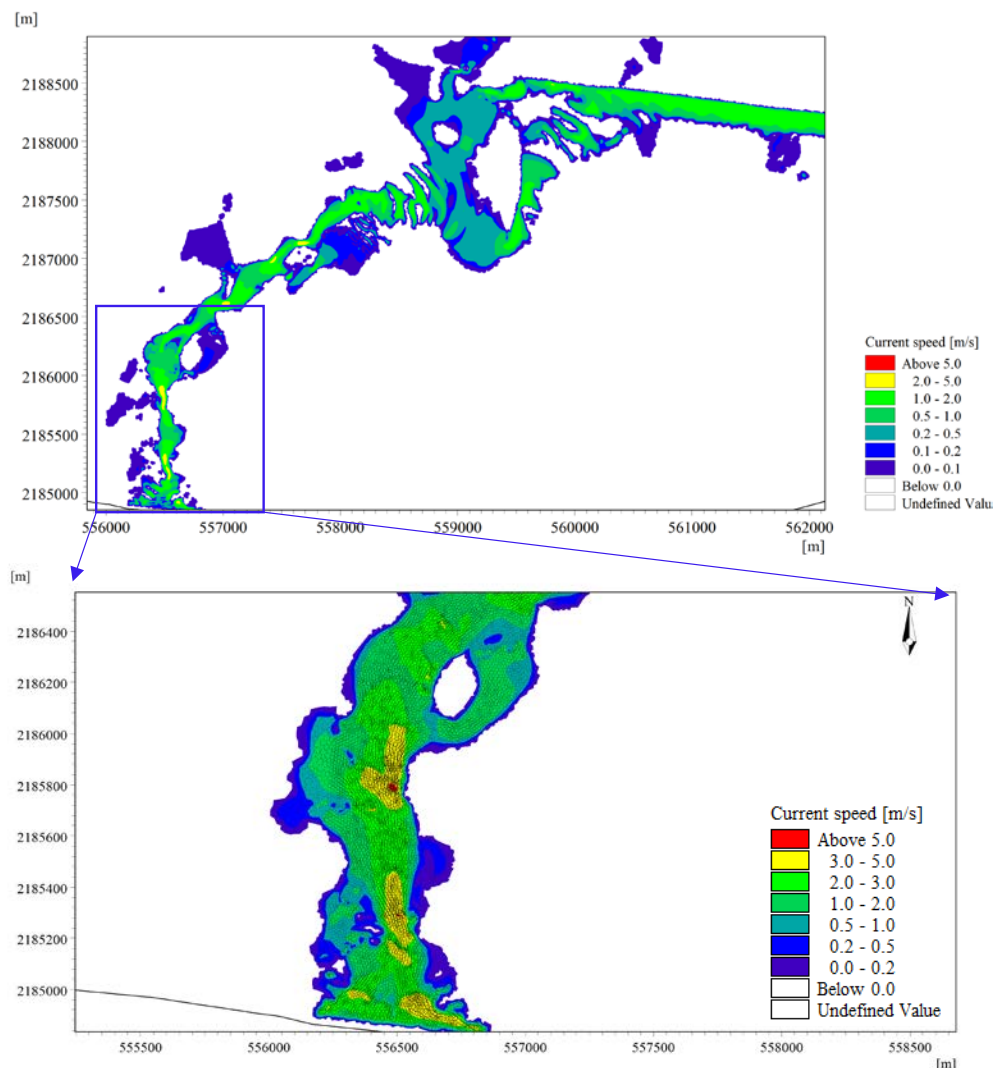


Fig. 16: Flow velocity in the downstream area of the dam for the case of dam failure due to a flood frequency of $P = 1.5\%$.

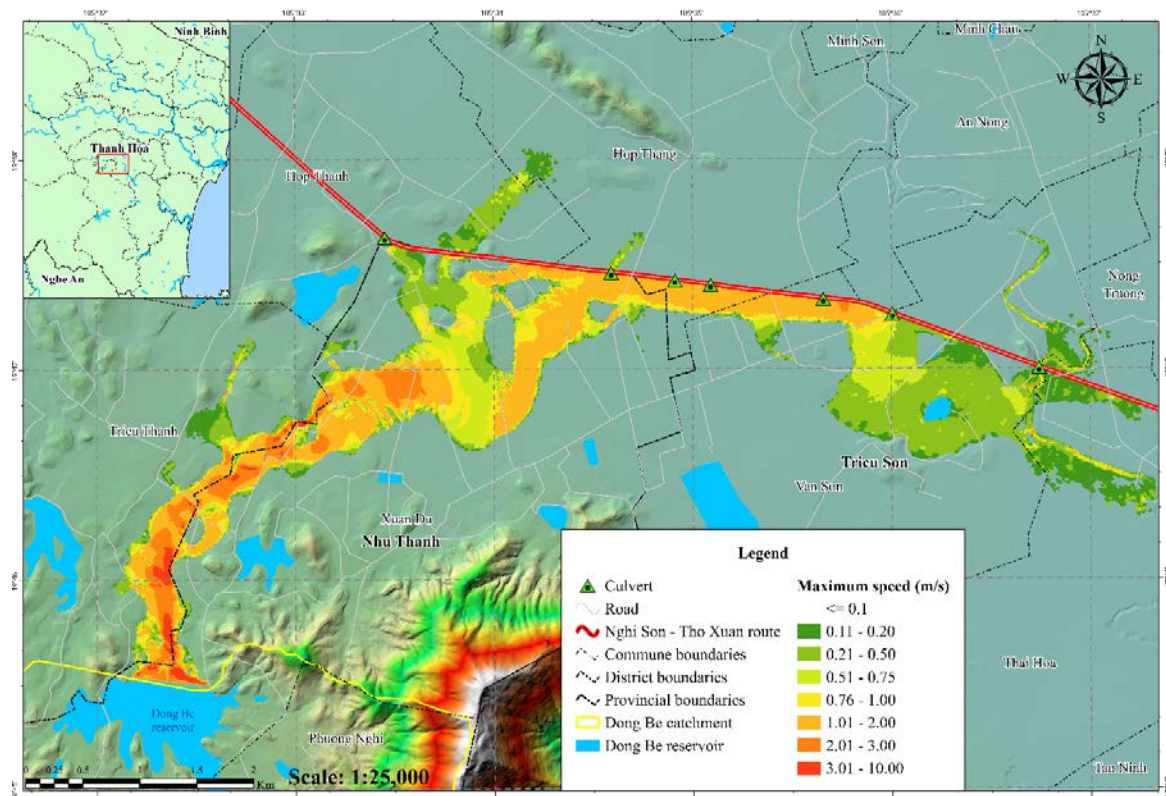


Fig. 17: Maximum flow velocity in the downstream area of the dam for the scenario of dam failure due to a flood frequency of $P = 1.5\%$.

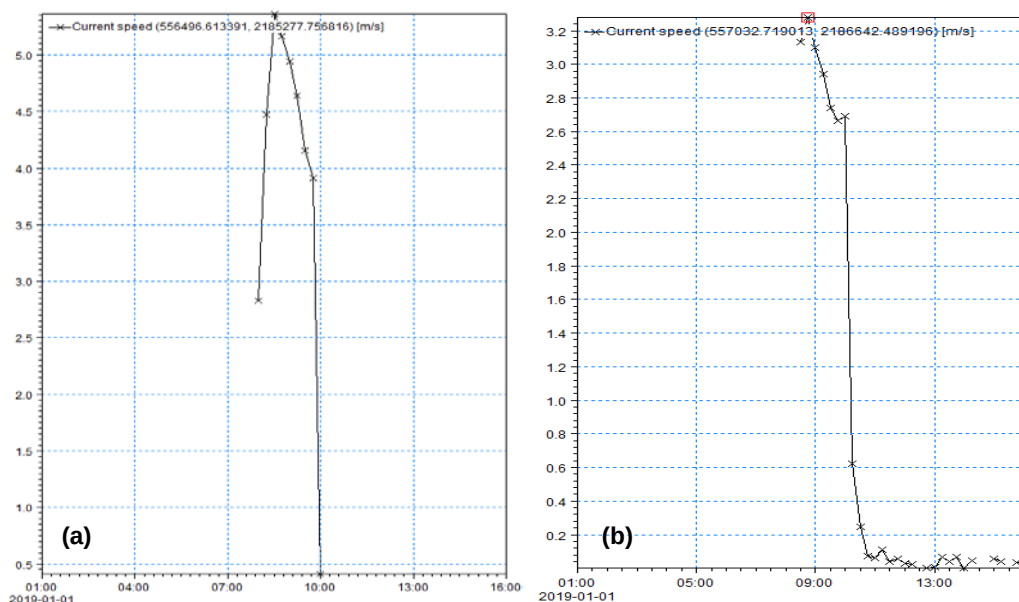


Fig. 18: (a) Flow velocity process at a location approximately 430m downstream from the main dam; (b) Flow velocity process at a location approximately 2200m downstream from the main dam.

Based on rigorous statistical analysis, the comprehensive area subject to inundation is precisely quantified at 431.46 hectares. Within this context, the Xuan Du commune emerges as the most significantly affected, encompassing 246.38 hectares, which equates to 57% of the aggregate inundation area. In juxtaposition, the Van Son commune encompasses 84.38 hectares, constituting 20% of the overarching inundation expanse. In contrast, the Hop Thanh commune exhibits the least inundation impact, with a modest 1.93 hectares, representing a nominal 0.45% of the total inundation area. A detailed exposition of these empirical findings is meticulously presented in the ensuing Table 4 and Fig. 19.

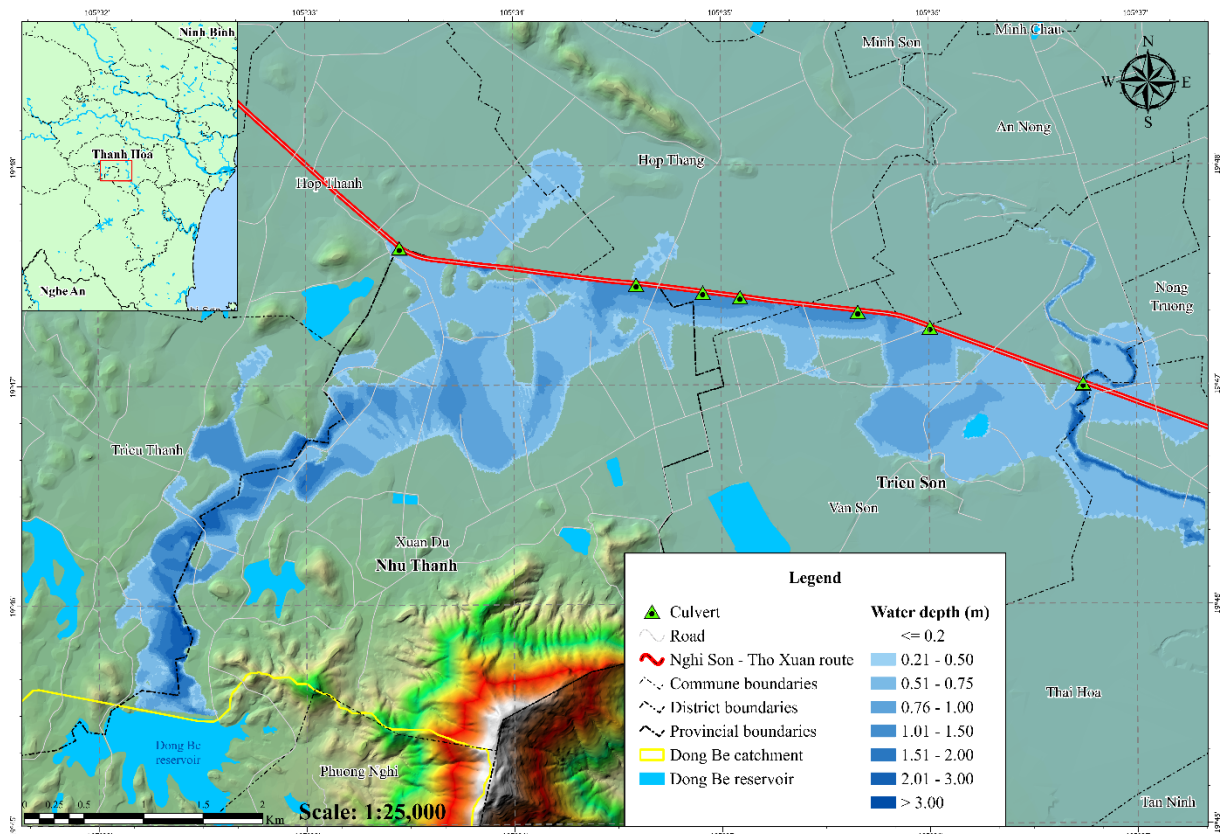


Fig. 19: Inundation map for the downstream area under scenario 1.

Table 4: Statistical overview of inundation areas for scenario 1 (Unit: hectares).

Inundation depth (m)	Xuan Du	Van Son	Thai Hoa	Tricu Thanh	Hop Thang	Hop Thanh	Nong Truong	An Nong
0.2 - 0.5	26.7	13.5	7.6	9.9	8.0	7.3	1.1	0.1
0.5 - 0.75	160.6	124.6	54.5	25.9	18.0	20.6	2.1	
0.75 - 1.0	89.9	63.0	3.4	10.2	7.2	0.01		
1.0 - 1.25	28.3	7.9	2.3	18.6	6.4			
1.25 - 1.5	11.3	2.0	1.5	11.1	1.4			
1.5 - 2.0	13.5	1.3	2.9	14.2	0.04			
2.0 - 3.0	3.5	2.4	3.1	8.4				
>3.0	0.3	0.2	0.01	1.5				
Total	334.12	214.9	75.37	99.71	41.16	27.96	3.25	0.15

In the scenario with a frequency of $P = 1.5\%$, Xuan Du commune has the largest inundation area, exceeding 300 hectares, followed by Van Son with nearly 200 hectares. Thai Hoa and Trieu Thanh communes cover over 70 and nearly 100 hectares, respectively. Hop Thang has more than 40 hectares inundated, while An Nong is the least affected, with about 0.15 hectares. Notably, Hop Thanh, Nong Truong, and An Nong experience minimal inundation, with no depths surpassing 1.0 meters.

3.2.2 Scenario 2

In the context of the simulation of the dam failure under a flood frequency of 0.5%, the findings reveal exceedingly elevated flow velocities (Figs. 20-21). At the coordinates ($x = 556496.6$; $y = 2185277.7$), situated approximately 430 meters downstream from the primary dam structure, the flow velocity attains a peak value of 5.45 m/s (Fig. 22a). Furthermore, at the coordinates ($x = 557032.7$; $y = 2186642.4$), located roughly 2200 meters downstream from the principal dam, the velocity escalates to a maximum of 3.55 m/s (Fig. 22b).

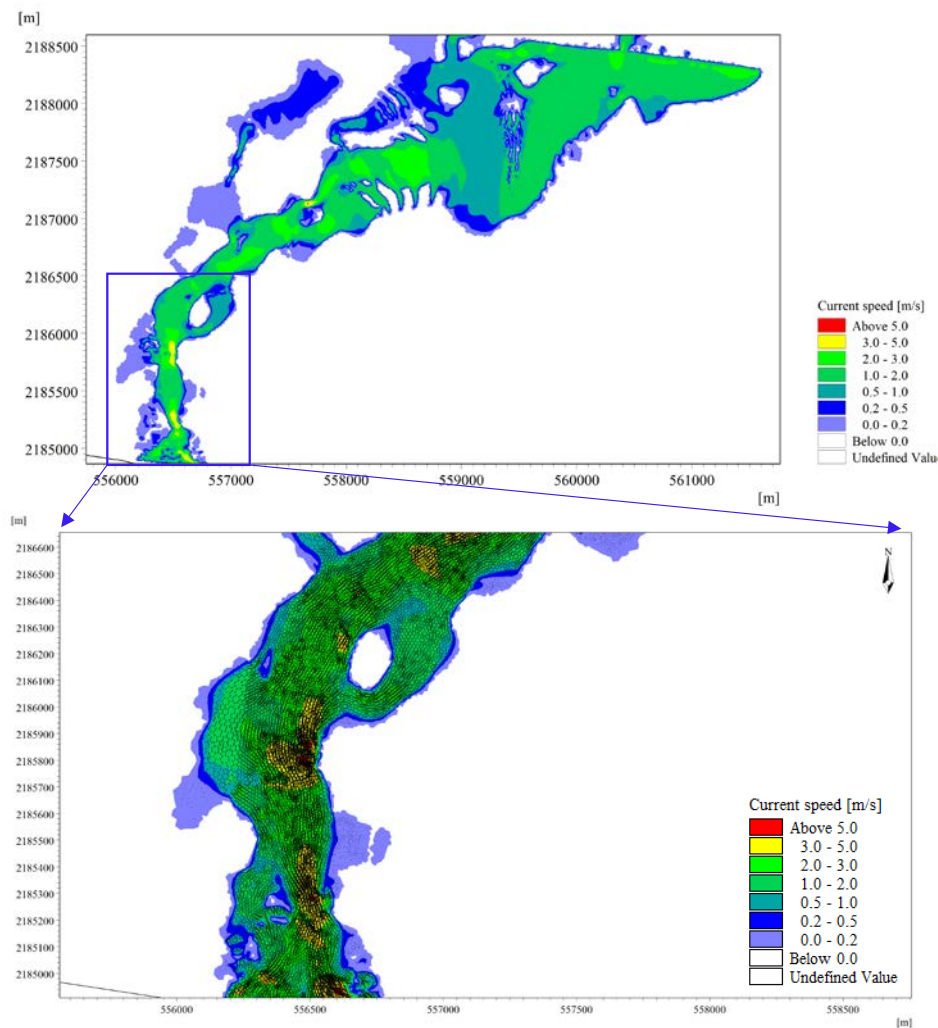


Fig. 20: Flow velocity in the downstream area of the dam for the scenario of dam failure due to a flood frequency of $P=0.5\%$.

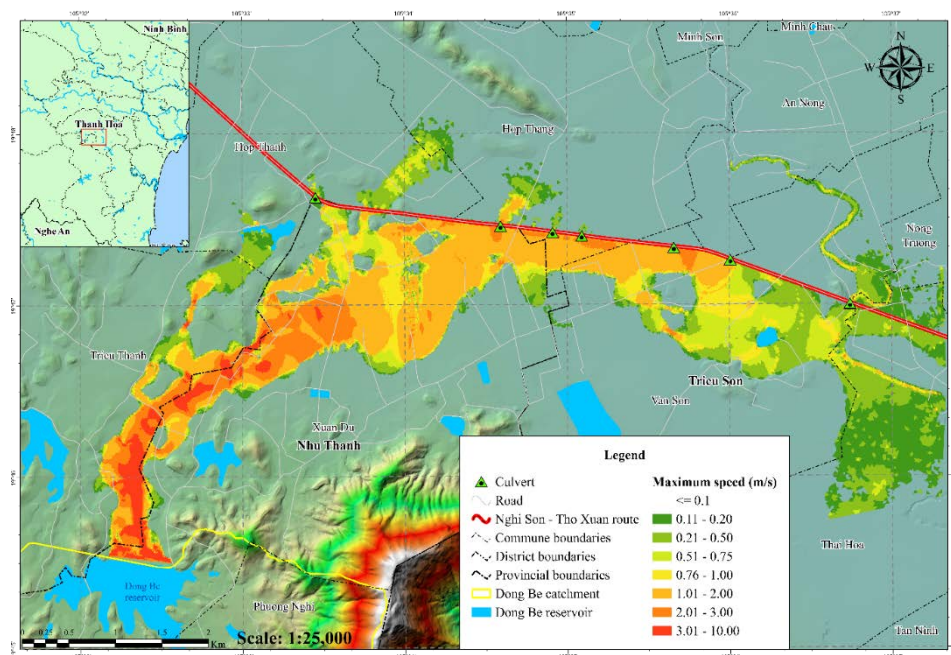


Fig. 21: The maximum flow velocity in the downstream area of the dam for the scenario of dam failure due to a flood frequency of $P=0.5\%$.

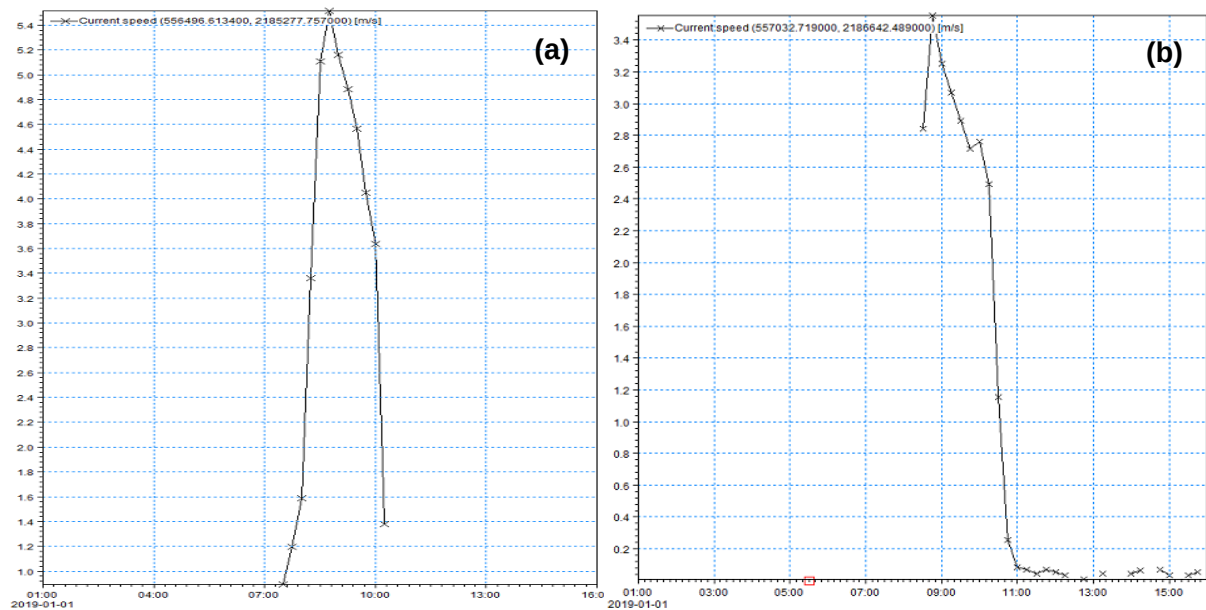


Fig. 22: (a) Flow velocity process at a location approximately 430m downstream from the main dam; (b) Flow velocity process at approximately 2200m downstream from the main dam.

Based on statistical analysis, the total inundation area measures 500.8 hectares. Xuan Du commune has the largest inundation area at 256.37 hectares (51%), followed by Van Son with 123.93 hectares (24%). In contrast, Hop Thanh has the smallest affected area at 2.88 hectares (0.45% of the total). Further details are provided in the subsequent Table 5 and Fig. 23.

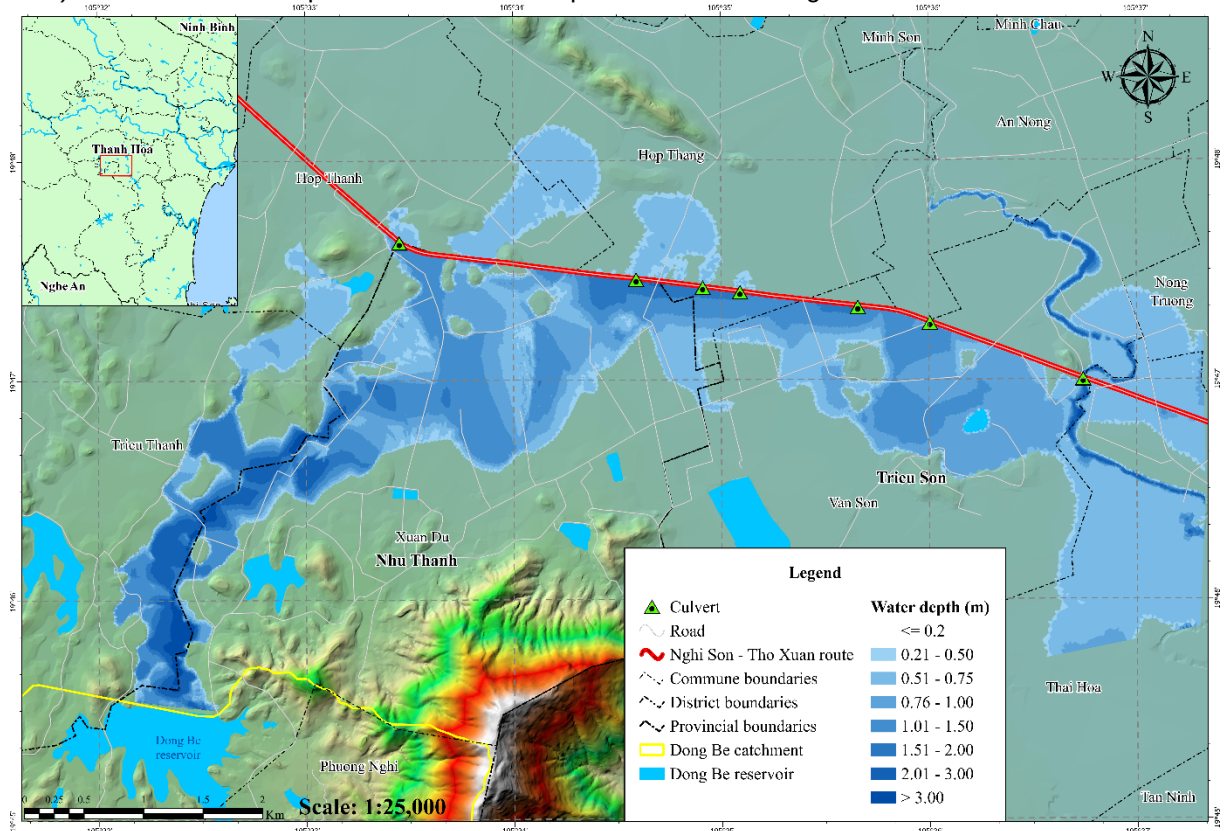


Fig. 23: Flood inundation map for the downstream area under scenario 2.

Table 5: Statistical overview of inundation areas for scenario 2 (Unit: hectares).

Inundation depth (m)	Xuan Du	Van Son	Thai Hoa	Trieu Thanh	Hop Thang	Hop Thanh	Nong Truong	An Nong
0.2 - 0.5	25.5	17.9	7.3	7.6	18.6	14.7	2.6	0.8
0.5 - 0.75	99.6	80.2	188.2	25.1	59.8	45.4	19.9	0.6
0.75 - 1.0	99.8	113.3	10.1	10.0	3.7	0.8	0.1	0.6
1.0 - 1.25	91.2	53.5	2.5	9.6	5.7	0.2		0.6
1.25 - 1.5	47.3	9.4	1.9	16.9	7.5			0.6
1.5 - 2.0	35.2	6.0	3.1	28.7	5.0			0.8
2.0 - 3.0	19.0	6.8	3.4	26.8	0.1			0.03
>3.0	2.5	0.4	0.1	8.4				
Total	420.1	287.4	216.5	133.0	100.3	61.0	22.6	4.0

In the analysis of scenario 2 with a frequency of $P = 0.5\%$, there is a notable increase in inundation area across the communes. Specifically, Xuan Du has the largest inundated area at 420.1 hectares, followed by Van Son with 287.4 hectares and Thai Hoa with 216.5 hectares. Conversely, An Nong reports the smallest affected area at approximately 4 hectares. Importantly, Hop Thanh has areas with inundation depths exceeding 1.0 meters, while An Nong records depths surpassing 2.0 meters. Overall, the extent and depth of inundation intensify across the communes in this simulation scenario.

Fig. 24 and Table 6 compare inundation areas across two simulation scenarios within the research area in scenario 2, with a $P = 0.5\%$ frequency, indicating larger inundation area than scenario 1 at $P = 1.5\%$. Both the extent and depth of inundation increase between the two scenarios. These simulation results will inform flood mapping for various dam failure scenarios. These maps will overlay administrative, demographic, and infrastructure layers to assess the socio-economic impacts downstream of the Dong Be reservoir.

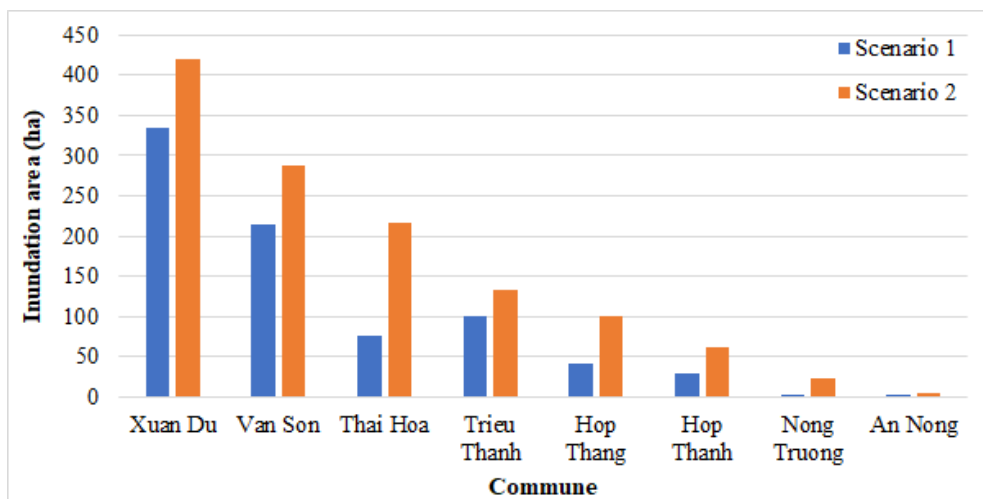


Fig. 24: Comparing the inundation area of communes between Scenario 1 and Scenario 2.

Table 6: Statistical table of inundation areas based on dam failure scenarios.

No.	Commune	Inundation area (%)	
		Scenario 1	Scenario 2
1	Xuan Du	19.15%	24.08%
2	Van Son	13.62%	18.21%
3	Thai Hoa	4.42%	12.70%
4	Trieu Thanh	9.90%	13.21%
5	Hop Thang	4.32%	10.53%
6	Hop Thanh	4.22%	9.21%
7	Nong Truong	0.60%	4.21%
8	An Nong	0.03%	0.85%

4 Conclusion

Dong Be Reservoir provides domestic water and irrigation for 225.0 hectares of agricultural land in 02 communes: Trieu Thanh, Hop Thanh, Trieu Son district and Xuan Du commune, Nhu Thanh district. Dong Be reservoir plays an important role in water supply for daily life and industry in some communes in Thanh Hoa City. However, during dam operation, there are still possible risks involved. Dam failure can have profoundly serious consequences for people and structures, affecting the environment and socio-economic development of the dam downstream area. The study has applied the MIKE numerical modelling, incorporating the MIKE 11, MIKE 21, and MIKE FLOOD modules, to simulate inundation scenarios resulting from two distinct dam failure events. This study has achieved some results as follows:

1) This study has established a coupled 1D-2D model to simulate the hydraulic regime in the downstream area.

2) This study established the coupled 1D-2D MIKE FLOOD model to simulate inundation depths and flow velocity flow during and after the dam failure scenarios ($P = 1.5\%$ and $P = 0.5\%$). The depth of inundation and the maximum flow velocities maps in the downstream area of the dam for the scenarios of dam failure will be important information for building emergency preparedness and emergency response plans.

In future work, the set of flood maps and maximum flow speed maps will be input factors in the study to assess socio-economic vulnerability in the downstream area when an incident dam failure scenario occurs.

Acknowledgement

Result in this study is a part of the Ph.D. thesis "Assessment of socio-economic vulnerability due to dam failure causing flooding in the downstream area: Case study in the North Central region", carried out by corresponding author at National Economics University.

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