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FLOOD HAZARD ASSESSMENT BY HYDRO-HYDRAULIC MODELING: A CASE STUDY IN THE VU GIA-THU BON BASIN IN VIETNAM

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Abstract. Flooding is one of the most impactful natural hazards throughout history. In the present context, it has become more and more unpredictable due to urbanization and climate change. This study develops a flood hazard map by simulating the flood event in 2007 using MIKE FLOOD software, supported by Geographic Information Systems (GIS) and the Analytic Hierarchy Process (AHP). Flood hazard is assessed based on two components: flood depth and flow velocity, and classified into five levels: Very High, High, Moderate, Low, and Very Low. The case study focuses on the Vu Gia-Thu Bon basin, the largest and most vulnerable river basin in Central of Vietnam. The results indicate that, out of a total flooded area of 405 hectares, 17% falls within the Very low flood hazard, 24% Low, 46% Moderate, 12% High, and 1% Very high. These outcomes are considered as a valuable tool for flood risk assessment in the Vu Gia-Thu Bon basin.
Keywords: flood risk, hazard, urbanization, Vu Gia-Thu Bon watershed.

1. INTRODUCTION

Vietnam is vulnerable to natural disasters, particularly floods. Influenced by a tropical monsoon climate, the country is frequently exposed to storms and floods, especially in the central region, where there is a high annual rainfall. Following the Vietnam Maritime Seach and Rescue Co-ordination Centre indicate that between 1945 and the present, Vietnam has been affected by a total of 459 tropical storms and typhoons, averaging approximately 6 to 7 events per year.

Indeed, the Vu Gia-Thu Bon basin is considered as the largest and most vulnerable basin in the Central of Vietnam when facing floods. It is the focus of numerous national and international research studies (Duong & Gourbesville, 2016; Hương et al., 2020; Pham, Luu, Dao, et al., 2021). Every year, storms and floods have caused severe losses in terms of human lives and property, while also disrupting socio-economic activities. According to (Vo & Gourbesville, 2018), the flood event in October 2009 resulted in 303 deaths, 1,308 injured persons, 9 missing persons, damage to 373,740 domiciles, 7,423 classrooms, and 158 hospitals. The total economic loss is estimated about USD

1,094 million. In comparison with the flood event in November 2007, the flood peak is recorded at the Hoi An hydrological station in 2009 was 3.20 m, whereas the flood event in October 2007 reached a higher peak of 3.28 m. Despite its greater intensity, the flood event in 2007 caused lower impacts: 47 deaths, 122 injured persons, 2 missing persons, damage to 32,580 domiciles, 296 classrooms, and 68 hospitals, with the economic loss is estimated at only USD 97.5 million. This means that flood risk must be considered in relation to people and society, not just the flood hazard.

Evidently, flood hazard constitutes the primary factor to be determined when assessing flood risk, since if there is no hazard, there is no disaster risk, even if vulnerability is very high (Hương et al., 2020). Accordingly, this study proposes an approach based on hydro-hydraulic modeling to evaluate flood hazard in the Vu Gia-Thu Bon river basin in the 2007 flood event. In most previous studies conducted in this basin, flood hazard has been assessed through the simulation of historical flood events (Duong & Gourbesville, 2016; Hương et al., 2020; Thai et al., 2023). This is considered a fundamental prerequisite for flood risk assessment.

For the above reasons, this study aims to establish flood hazard maps, using MIKE software developed by the Danish Hydraulic Institute. The Analytic Hierarchy Process (AHP) method in conjunction with Geographic Information Systems (GIS) is applied to determine the weights of contributing factors, which are subsequently integrated to generate the flood hazard map. The study is intended to provide a valuable tool for the development of flood risk maps, thereby supporting authorities in their decision-making processes.

2. MATERIALS AND METHODS

2.1. Study area

The study area is located in Central of Vietnam, where the terrain is mainly sloped from west to east. Consequently, the two main rivers of the basin, the Vu Gia and the Thu Bon, flow in similar direction: originating from the high mountains in the west, flowing through the flat plain, and eventually discharging into the East Sea via the Han and Dai estuaries. This topography characteristic is one of the primary causes of numerous floods in the deltas. Moreover, this basin river is large, covering an area of approximately 10,350 km², extending from the high mountainous ranges of the Truong Son, through semi-mountainous areas, and ultimately to the coastal plains (Fig.1). The region is characterized by a tropical monsoon climate, with high annual rainfall, of which 60% to 80% is concentrated in the rainy season from September to December. Furthermore, rainfall is unevenly distributed spatially: ranging from 3,000-4,000 mm/year in the high mountainous areas, 2,500-3,000 mm/year in the semi-mountainous zones, and 2,000-2,500 mm/year in the coastal plains.

2.2. Data collection

Data collection consists of the topography of basin river, the fluvial hydromorphology, and meteo-hydrological data of flood events in 2007 and 2009, one for calibration of the model, the other for validation.

(i) Digital Elevation Model (DEM) data were downloaded from https://www.earthdata.nasa.gov/ - the official portal of NASA's Earth Science Data Systems (ESDS) with a resolution of 12.5 × 12.5 meters.
(ii) A total of 395 cross-section profiles along 19 major rivers were provided by the Vietnam Institute of Geography.
(iii) Precipitation and evaporation measured at seven meteorological stations (Hien, Que Son, Hoi Khach, Cam Le, Thanh My, Kham Duc, Tra My).
(iv) Discharge, water level, and sea level recorded at seven hydrological stations (Hoi Khach, Thanh My, Son Tra, Nong Son, Hoi An, Cau Lau), provided by the National Center for Hydrometeorological Forecasting.

2.3. Methodology

2.3.1. Model setup

In this research, the MIKE software integrated by the Danish Hydraulic Institute (DHI) was selected due to its flexibility and its ability to simulate hydrological and hydraulic processes in both one-dimensional (1D) and two-dimensional (2D). This feature enhances the output results, making them more intuitive and easier to interpret. Moreover, MIKE software has the capability to link with GIS, enabling users to analyze flood space and to support flood risk management and decision-making. These features are mentioned in many similar studies (Duong & Gourbesville, 2016; Nguyen et al., 2021; Nguyen & Șerban, 2022).

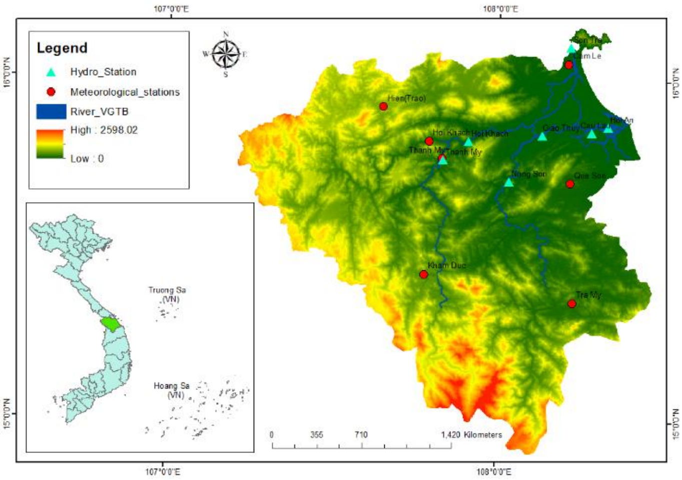

Figure 1. Location de Vu Gia-Thu Bon basin in Vietnam

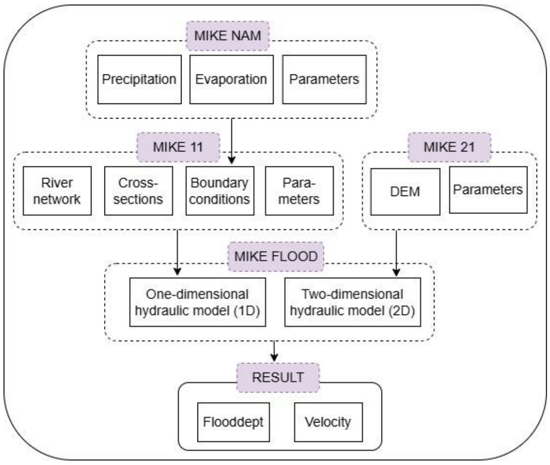

Figure 2. Simulation diagram

This study employs: (1) MIKE NAM - rainfall-runoff processes; (2) MIKE 11 - for modeling 1D river flow; (3) MIKE 21 - simulates 2D floodplain flow; (4) MIKE FLOOD - coupling MIKE 11 and MIKE 21 to represent hydrodynamic flood propagation from river to floodplains.

In the Vu Gia-Thu Bon basin, several tributaries lack discharge data. Therefore, the MIKE NAM model was established to simulate rainfall-runoff processes for the two main rivers, after which the validated parameters were applied to simulate streamflow for the sub-basins. These data were subsequently used as inputs for the MIKE 11 model. Rainfall data from seven meteorological stations were processed to determine the average precipitation for each sub-basin using the Thiessen polygon method. Evaporation data from the Tra My station were applied for the entire watershed. The outputs at tributaries such as the Bung, Kon, Tuy Loan, Ba Ren, and Ly Ly rivers were then utilized as boundary conditions for the MIKE 11 model.

MIKE 11 is established to illustrate unsteady flow in two main rivers and 17 tributaries. Model employs 395 cross-sections, Manning coefficients of each cross-section represent the friction of the rivers. Discharge data recorded at the Thanh My and Nong Son stations were considered as upstream boundary conditions for the MIKE 11 model, while inflows from the tributaries - derived from the outputs of the MIKE NAM model - were set as lateral inflow boundaries. Tidal levels observed at Son Tra and Hoi An stations are assigned to downstream boundaries at the Han and Dai estuaries. The model is built on the Saint-Venant equations, simulating water level, flow velocity, and discharge of rivers in both space and time.

An unstructured triangular mesh is built from a Digital Elevation Model (DEM) with a resolution of 12.5 × 12.5 m to illustrate the surface of terrain. Hydraulic parameters, such as the Manning coefficient, were adjusted through trial simulations in order to identify the optimal set. The model solves the two-dimensional Saint-Venant equations, allowing for the computation of water level and flow velocity variations in both spatial and temporal dimensions.

MIKE FLOOD integrates the MIKE 11 and MIKE 21 models by establishing links between rivers and their adjacent floodplains, thereby enabling the interaction of flows between rivers and floodplain areas. A time step of 5 seconds was adopted for both 1D and 2D simulations. The model outputs include shapefiles representing flood depth and flow velocity along rivers as well as across the deltas.

2.3.2. Analytical Hierarchy Process

In order to determine the weights of flood hazard components which are flood depth và flow velocity, this research applied The Analytical Hierarchy Process (AHP). This process, proposed by Thomas L. Saaty in the 1970s, is one of the Multiple Criteria Decision Making (MCDM) methods. This method based on pairwise comparisons of criteria and the quantification of ranked priorities according to expert judgment, so it depends on the subjective opinions of experts. However, numerous studies employed AHP due to its ease of use (Nguyen et al., 2021, 2023, 2024; Pham, Luu, Phong, et al., 2021). The process consists of three main steps: (i) Estimate the priority level of the criteria (table 1); (ii) Determine the weight of each criteria (table 2); (iii) Verify the Consistency Ratio (CR), if CR less than or equal to 10% can be accepted. Các bước thực hiện được chi tiết ở trong một số nghiên cứu về flood risk (Gigović et al., 2017; Luu et al., 2018; Ngọc et al., 2016; Nguyen & Şerban, 2022; Ouma & Tateishi, 2014).

Table 1. Matrix of Flood hazard

	Flooddepth	Velocity
Flooddepth	1.00	3.00
Velocity	0.33	1.00
Sum	1.33	4.00

Table 2. Normalized matrix of Flood hazard

	Flooddepth	Velocity	Weight
Flooddepth	0.75	0.75	0.75
Velocity	0.25	0.25	0.25

After verifying the Consistency Ratio is within the acceptable range, flood hazard is synthesized by a tool in Arcgis according to the following equation:

$$\text{Flood hazard} = 0.75*\text{flood depth} + 0.25*\text{velocity}$$

The output values are classified into five class: Very low, Low, Moderate, High, Very high.

2.3.3. Methodology flowchart

To ensure the applicability of the simulation results, the model must first be calibrated and then validated. (Fig. 3). Calibration process was performed using the historical flood event in 2009 (26 September - 6 October) to determine suitable parameter sets. The model was validated with the 2007 flood event (10-16 November).

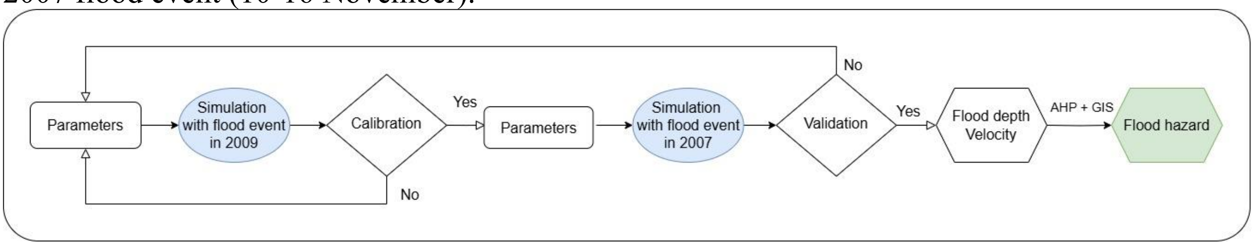

Figure 3. Methodology flowchart for Flood hazard assessment

(i) Calibration of model. Using a trial-and-error approach, the parameters of the MIKE model were calibrated by testing multiple combinations and progressively excluding unsuitable ones. This flexible calibration process enables the model to be adapted to local hydrological conditions through comparison and alignment with observed flow data recorded at available stations in the study area.

In the MIKE NAM module, seven parameters are required for calibration, including: (1) Maximum water content in surface storage (Umax); (2) Maximum water content in the root zone; (3) Overland flow runoff coefficient (CQOF); (4) Time constant for routing interflow (CKIF); (5) Time constant for routing overland flow; (6) Root zone threshold value for overland flow (TOF); and (7) Root zone threshold value for interflow (TIF).

In the MIKE 11 module, Manning's roughness coefficients were calibrated for each cross-section and along the riverbed, while in the MIKE 21 module, the coefficient was applied to represent surface flow resistance across the Vu Gia-Thu Bon basin. The parameter was adjusted within the range of 0.02 to 0.035 to account for surface conditions.

The MIKE View tool was employed to visualize the simulation results. The simulated flows were compared with observed water levels and discharges at four hydrological stations (Thanh My, Nong Son, Hoi Khach, and Cau Lau). Performance indicators, including the correlation (R^2), volume error (%), and peak error (%) are available in MIKE View to evaluate the model's accuracy and efficiency.

(ii) Validation of model. The parameter set derived from calibration (Step 1) was independently validated using a distinct flood event within the same basin to evaluate the model's generalization capacity. The flood event in November 2007 was selected. Observed data from two hydrological stations were employed to verify the model's accuracy. In cases where the model did not achieve the required performance, the parameter set was re-chosen and the process reverted to the calibration stage in step 1.

The model outputs, including flood depth and velocity, were aggregated into flood hazard maps using the Spatial Analysis Tool in ArcGIS software.

3. RESULTS AND DISCUSSION

3.1. Calibration and validation

Observed discharges at Nong Son and Thanh My station are collected in order to evaluate model's performance of MIKE NAM. A comparison between observed and simulated discharges at the Nong Son and Thanh My stations indicates that the calibrated MIKE NAM model achieved very good performance, with R^2 of 0.96 and 0.99, Volume error of -17.3% and -20.8%, and Peak error of 10.5% and -10.3%, respectively. During the validation phase, the model performance was slightly lower but still classified as very good, with R^2 of 0.9 and 0.96, Volume error of -15.8% and 16.5%, and Peak error of -2.9% and 15.9%. Figure 4, 5 presents the hydrographs of observed and simulated discharges at each station.

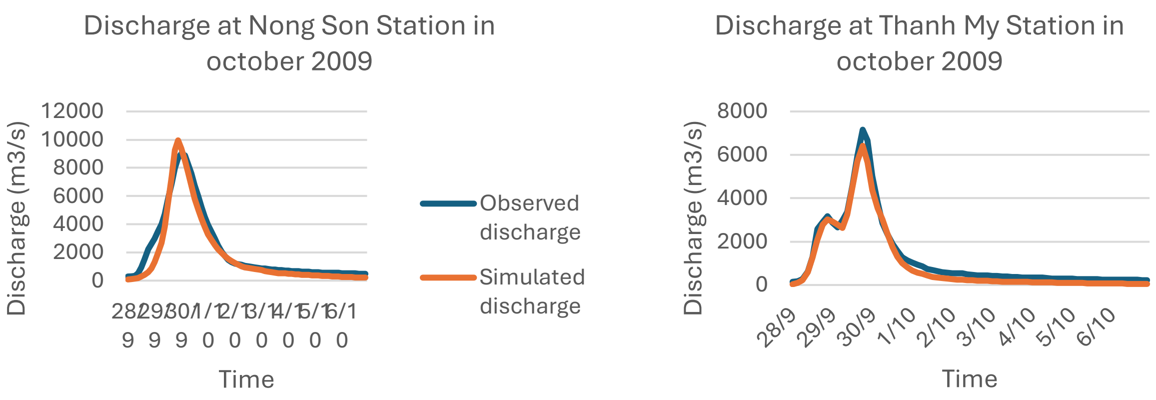

Figure 4. MIKE NAM - Calibration by flood event in 2009

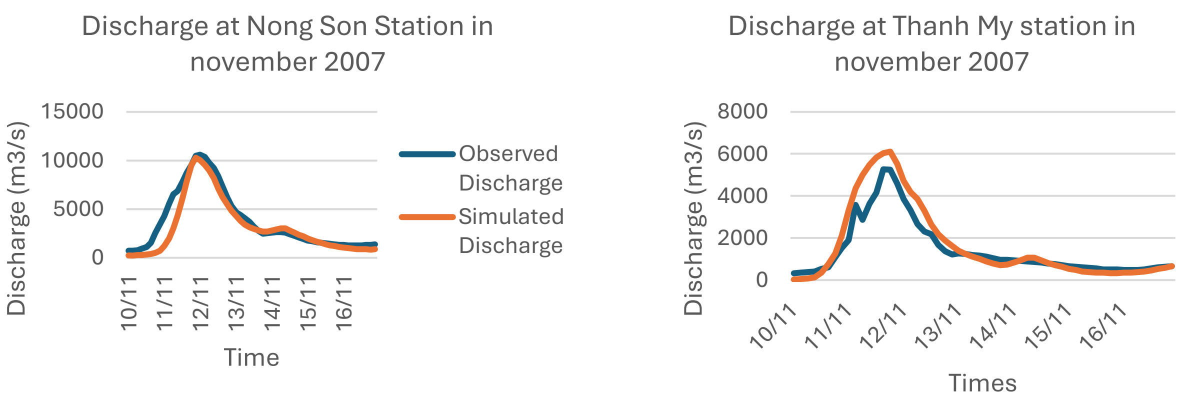

Figure 5. MIKE NAM - Validation by flood event in 2007

For the MIKE 11 model, the research uses observed water levels at the Cau Lau station (in Thu Bon river) and Hoi Khach station (in Vu Gia river) in order to assess model performance as observed discharge data were not available. The results showed high agreement between observation and simulation. During the calibration phase, the coefficient R^2 of 0.95 and 0.91, Volume error of -6.7% and -9.1%, and Peak error of 2.8% and 9.0%, respectively. During the validation phase, the coefficient R^2 of 0.94 and 0.96, Volume error of -5.7% and -2.5%, and Peak error of 5.9% and 6.4%. Figure 6, 7 presents the hydrographs of observed and simulated water level at each station.

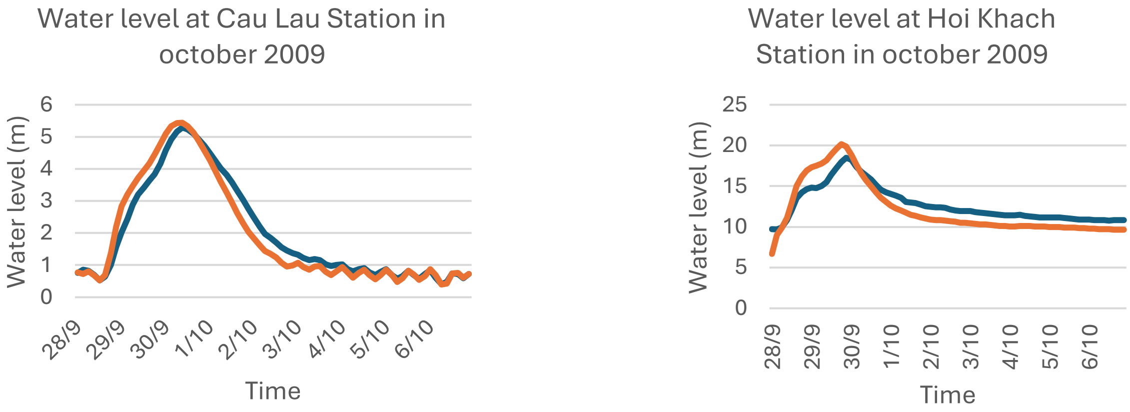

Figure 6. MIKE 11 - Calibration by flood event in 2009

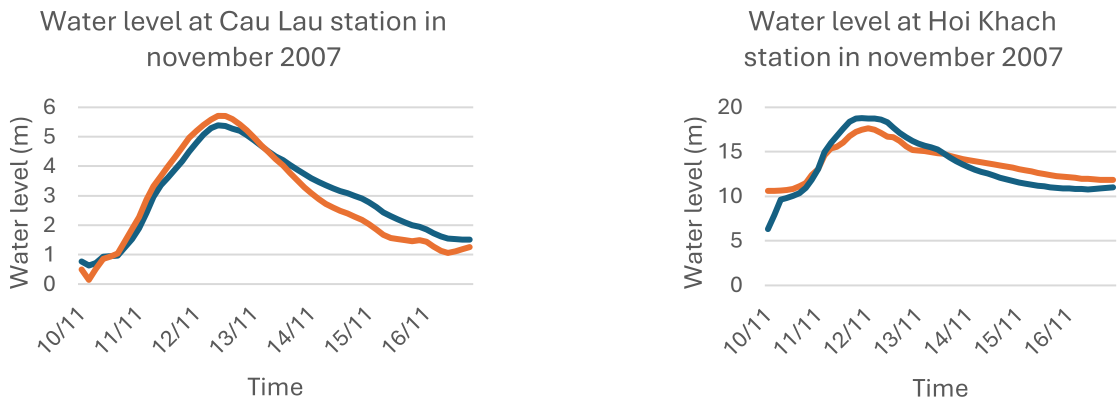

Figure 7. MIKE 11 - Validation by flood event in 2007

The results confirm the optimality of the parameters as well as the model's capability to realistically replicate observed conditions. The following section presents the simulation outcomes of flood depth and flow velocity during the flood event in 2007.

3.2. Flood dept and flow velocity

The results indicate that the flooded areas are predominantly situated in the lower plain of the Vu Gia-Thu Bon basin, including Duy Xuyen District, Hoi An City, Dai Loc District, Dien Ban District, Ngu Hanh Son District, Cam Le District, and Hoa Vang District (Figure 8). A total of 405 hectares of land are submerged, of which 9% with flood depth less than 0.5 m; 14% between 0.5-1 m; 14% between 1-1.5 m; 31% between 1.5-2.5 m; and 32% exceeding 2.5 m. This means that more than two-thirds of the flooded area is subject to water depths greater than 1.5 m, leading to severe impacts on residential zones, infrastructure, and human safety.

The areas experiencing the greatest flood depths are located along both banks of the two main rivers, the Vu Gia and Thu Bon, as well as the Quang Hue and Vinh Dien rivers. Notably, flooded areas with flood depth over 2.5m account for the highest proportion (32%). In terms of disaster prevention and response, these areas need particular attention to mitigate potential flood risk. In terms of land use planning, the findings of this study suggest areas which could be planned as flood retention corridors, wetland parks, or flood storage zones,… It is necessary to limit the expansion of residential areas towards deep flooded areas. In terms of disaster management, It is necessary to establish early warning systems for very deep flooded areas such as the East of Dai Loc district, the South of Hoi An city, and the South of Dien Ban district. For residential areas located in deep flood areas, there should be plans to evacuate people to higher areas as well as prioritize the allocation of resources for natural disaster prevention.

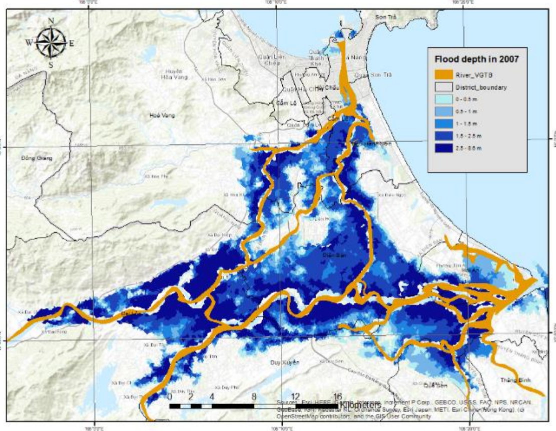

Figure 8. Flood depth

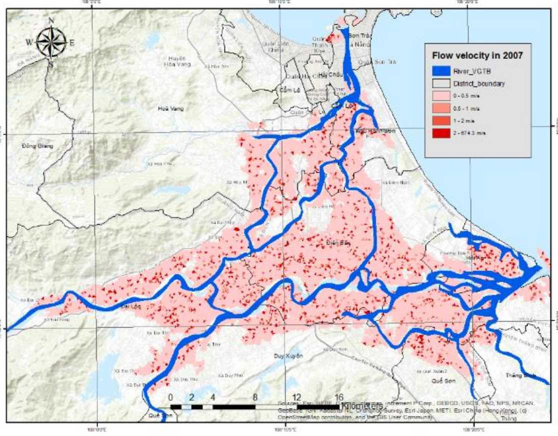

Figure 9. Flow velocity

The flow velocity map indicates that, within the total 405 ha of flooded areas, 89% is affected by flows with velocities of less than 0.5 m/s, 3% by flows between 0.5-1 m/s, 3% by flows between 1-2 m/s, and 5% by flows over 2 m/s (Figure 9). The majority of the inundated area (89%) is subjected to low flow velocities (<0.5 m/s). This suggests that the flow tend to move slowly or stagnate, which may reduce the immediate risk of structural damage but may prolong the duration of inundation. Consequently, this can exacerbate socio-economic losses and increase health risks related to waterborne diseases. Following (Smith et al., 2014), flow velocities over 2 m/s (accounting for 5% of the area) may be unsafe for both vehicles and people. Moreover, all buildings in such zones are susceptible to structural damage, some less robust buildings subject to failure.

3.3. Flood hazard map

The flood hazard map was generated by combining flood depth and flow velocity using the Raster Calculator tool in ArcGIS thông qua công thức: Flood hazard = 0.75*flood depth + 0.25*velocity. Accordingly, flood hazard was classified into five levels: very low, low, moderate, high, and very high.

The flood hazard map shows that 17% of the area falls within the very low hazard zone, 24% within the low hazard zone, 46% within the moderate hazard zone, 12% within the high hazard zone, and only 1% within the very high hazard zone. It shows that the moderate flood hazard zone accounts for nearly half of the flooded areas, predominantly agricultural land (Figure 10). This finding is important because agricultural land that is flooded for too long can also affect crop yields and food security in the region. The high flood hazard areas are primarily distributed along the Thu Bon, Quang Hue, and Vu Gia rivers. This zone is particularly vulnerable due to their proximity to major rivers where water level and flow velocities tend to be more important. Although the very high flood hazard areas account for only 1% of the total area, it should not be overlooked, as it often corresponds to critical flooded points where extreme conditions can result in substantial losses in human lives, property, and livelihoods.

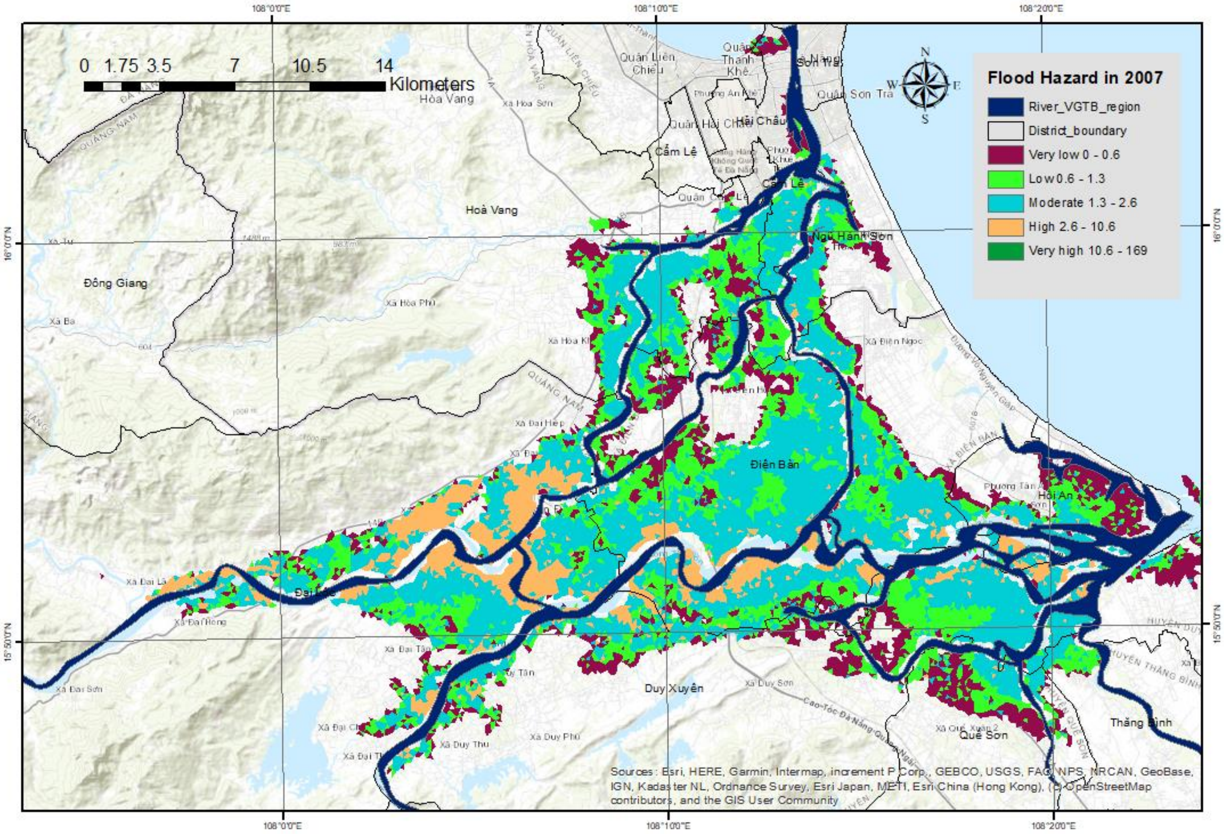

Figure 10. Flood hazard of flood event in November 2007

Overall, these findings can inform local authorities in formulating strategies as well as solutions for land use planning and disaster management. In terms of land use planning, a flood retention corridor may be proposed along high flood hazard zones, while biodiversity parks, wetlands, or flood detention areas could serve as suitable adaptive solutions. Areas classified as moderate flood hazard may be appropriate for the development of retention ponds, green spaces, or even agricultural land with flood-tolerant crops. Conversely, industrial zones, central zones and residential areas should be avoided planning in moderate, high, or very high flood hazards regions. In terms of disaster management, early warning systems should be prioritized in sensitive zones such as high and very high hazard areas. Furthermore, raising community awareness through training, evacuation drills, and education at school is essential for enhancing resilience.

4. CONCLUSION

Using the MIKE software suite, this study constructs flood hazard maps of the flood event in November 2007. Flood depth and flood velocity were integrated using the Raster Calculator tool in ArcGIS to generate flood hazard maps with five levels: Very Low, Low, Moderate, High, and Very High. Results indicate that within the Vu Gia-Thu Bon river basin, the high and very high flood hazard areas are concentrated along the Thu Bon, Quang Hue, and Vu Gia rivers; the moderate flood hazard areas are distributed in the lower plain regions, which correspond to the main population centers of Quang Nam province, including Hoi An city, Dien Ban district, the northeastern part of Duy Xuyen district, the eastern part of Dai Loc district, the southern part of Cam Le district, the western part of Ngu Hanh Son district, and the southeastern part of Hoa Vang district. Given the increasing flood hazard across the scenarios, this study provides an effective tool for land use planning and disaster management in Vietnam.

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