DEVELOPMENT OF FLOOD RISK WARNING SYSTEM FOR RIVER BASINS OF VIET NAM, CASE STUDY IN THE CAI NHA TRANG RIVER BASIN

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Abstract: *Flooding is one of the most serious natural hazards affecting river basins in Viet Nam, particularly in urban and coastal areas. This paper presents the development of a flood risk warning system for the Cai Nha Trang River Basin. In this study, flood risk is quantified based on the combination of three components: Hazard, exposure, and vulnerability. Hydrological and hydraulic models were applied to simulate flood hazards, while socio-economic and land use data were used to assess exposure and vulnerability. These layers were integrated into a WebGIS platform that allows real-time monitoring of rainfall and water levels from observation stations, and provides flood risk assessment under different rainfall and flood scenarios. The system not only visualizes the spatial distribution of risks but also supports timely warnings and decision-making. Results from the Cai Nha Trang case study suggest that the proposed approach can be an effective tool to improve preparedness and strengthen resilience in flood-prone basins of Viet Nam.*

Keywords: *Flood risk, Early warning system, Cai Nha Trang River basin.*

1. Introduction

Flooding is among the most frequent and devastating natural hazards worldwide, causing substantial losses in terms of human life and economic damage. The impacts of floods and inundation have become increasingly severe, as evidenced by statistics from the World Bank (2020), which indicate that at least 87 flood events occurred between 1990 and 2018, resulting in nearly 6,000 deaths and injuries and causing an estimated economic loss of up to USD 4.3 billion. Although floods occur worldwide, their consequences tend to be far more severe in developing countries [1], [3], [17]. These regions often experience greater losses due to limited infrastructure, insufficient early warning and response systems, and higher levels of exposure and vulnerability [2]. Addressing these disparities by strengthening flood risk management has become an increasingly urgent priority, particularly in vulnerable regions.

Among the most widely applied and effective tools for flood risk management is the development of flood warning systems (FWS) [3], [4]. These systems aim to reduce disaster impacts by providing timely information, enabling communities and authorities to take preventive or mitigative actions [4]. Over the past decades, various FWS models have been implemented globally, significantly contributing to reducing flood-related damages [5], [6]. At a global scale, probabilistic and hydrological-meteorological modeling-based FWS have been developed to provide real-time flood forecasts and early alerts, particularly for transboundary or large river basins. For example, the Global Flood Awareness System (GloFAS) is a globally-operational flood warning system that integrates numerical weather predictions with hydrological modeling to forecast potential flood events worldwide [7]. Similarly, the European Flood Awareness System (EFAS), developed by the European Commission's Joint Research Centre (JRC) in collaboration with national

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meteorological and hydrological services, aims to provide early warnings for large-scale flood events across Europe, with a particular focus on major transnational river basins [8]. In addition to global-scale systems, many countries have developed national-level FWS tailored to their specific hydrometeorological conditions and institutional frameworks. For example, Australia's Bureau of Meteorology (BoM) operates a national flood warning system that combines real-time hydrometeorological data, numerical weather predictions, and semi-distributed hydrological models. Unlike many automated systems, BoM's FWS includes expert interpretation, allowing forecasters to adjust model parameters and issue scenario-based forecasts. Warnings are disseminated through multiple platforms, with national coordination in place to support flood response [9]. The U.S. National Weather Service operates the Hydrologic Ensemble Forecast Service (HEFS), a national FWS implemented through regional River Forecast Centers [10]. HEFS produces probabilistic river flow forecasts by integrating bias-corrected weather ensembles with hydrologic and hydraulic models. Forecast outputs include probabilities of exceeding critical thresholds, aiding risk-based decision-making. Results are publicly accessible through an online platform. Several regions have taken a more localized approach by implementing flood warning system that cater specifically to basin-scale hydrology and community-based needs. A notable example is the Mekong River Commission's Flood Forecasting and Warning System (MFFS), which plays a key role in transboundary flood management across the Lower Mekong Basin [11]. Utilizing the Delft-FEWS platform developed by Deltares [12], the system generates essential water level and discharge forecasts, particularly for flood-prone areas in Laos and Cambodia, thereby supporting timely decision-making and regional coordination. At a smaller urban scale, South Korea has developed a real-time FWS for small catchments in Seoul, aimed at managing flash floods in densely populated areas [14]. The system employs ultrasonic water-level sensors and threshold-based alerts to provide timely warnings for small streams, where the response time is extremely limited. In Siberia, a pilot FWS model has been conceptualized to support flood forecasting for specific river basins, using hydrological and meteorological modeling, real-time telemetry, and integration of satellite-based remote sensing data [13]. These regional-scale initiatives reflect the growing trend of developing FWS to basin-specific characteristics, enabling more context-sensitive and responsive flood risk management.

The Intergovernmental Panel on Climate Change (IPCC) proposes a widely recognized risk framework, in which flood risk is conceptualized as the interaction between hazard, exposure, and vulnerability [15]. This framework has become foundational in both climate adaptation and disaster risk reduction literature, enabling a more holistic understanding of what drives flood impacts [16]. Designing flood warning system based on the IPCC framework allows for more effective and targeted interventions, not only by forecasting the physical occurrence of floods, but also by identifying who is at risk and why. This integrated approach is particularly relevant in developing and flood-prone regions, where high exposure and vulnerability often amplify the consequences of even moderate flood events.

Building upon this global perspective, Viet Nam represents a highly relevant case for applying an integrated flood risk framework. As a developing country, Viet Nam is particularly susceptible to the adverse impacts of flooding, due to a combination of climatic, topographic, and socio-economic factors, most notably prolonged monsoon rains, complex river systems, and rapid, unregulated urbanization. According to the World Bank (2018), approximately 930,000 people in Viet Nam are affected by flooding each year, with annual economic losses estimated at USD 2.6 billion. Given these challenges, enhancing flood risk management is a critical priority, and the development of effective, context-specific flood warning systems plays a vital role in this process.

In Viet Nam, existing flood risk management measures-such as dike systems, reservoirs, land-use regulations, and national flood warning services have played an important role in reducing direct damages. However, the warning systems have provided essential information, their operational effectiveness remains constrained. In practice, warnings are frequently characterized by limited lead time, insufficient spatial resolution, and weak institutional linkages to community-based response mechanisms. Consequently, existing early warnings often fail to deliver actionable and context-specific guidance, thereby reducing their capacity to mitigate localized vulnerabilities and to support timely at the household and community levels.

This study aims to develop a flood warning system for a specific river basin in Viet Nam using the IPCC risk framework. Based on this concept, the research seeks to not only improve flood hazard detection but also to identify and address underlying socio-environmental vulnerabilities, enabling more timely and practical early action at the local level. Importantly, the proposed system is not intended to replace existing structural measures but to complement them by enhancing the anticipatory aspect of flood risk management. This integration is particularly urgent in Viet Nam, where increasing climate extremes, coupled with rapid socio-economic change, are intensifying flood risks beyond the capacity of traditional management tools.

2. Methodology

2.1. Flood risk assessment approach

Based on the IPCC's conceptual framework [15], flood risk is typically defined as a function of three interrelated components, including hazard (H), exposure (E), and vulnerability (V):

$$Risk = f(Hazard, Exposure, Vulnerability) \quad (1)$$

Where:

● Hazard refers to the potential occurrence of a physically damaging flood event (e.g., heavy rainfall, storm surges, or river overflows), that may cause harm to people, infrastructure or the environment.

● Exposure denotes the presence of people, assets, infrastructure, or ecosystems in areas that could be adversely affected by hazardous events. High population density or concentration of critical infrastructure in flood-prone zones increases exposure.

● Vulnerability represents the degree to which those exposed are susceptible to harm and their capacity to anticipate, cope with, and recover from the impacts of disasters. This includes physical, social, economic, and institutional factors that influence resilience.

2.2. Estimation of flood risk components

In this study, the assessment of Hazard (H), Exposure, and Vulnerability is conducted at the district level, with each district denoted by j. All indicators associated with H, E, and V are therefore calculated individually for each district j, enabling a spatially evaluation of flood risk across the study area.

To ensure relevance and practical applicability, the analysis focuses on a typical historical flood year. The 2009 flood event was chosen as it recorded the highest flood magnitude in recent decades and was well-documented in terms of hydrological, meteorological, and socio-economic impact data. Frequency analysis indicates that this event corresponds to an annual exceedance probability of 1%, equivalent to a 100-year return period. All hazard, exposure, and vulnerability indicators in this study are calculated with reference to this event.

2.2.1. Hazard

In this study, flood hazard (H) refers to the integration of the probability of occurrence of a flood event (H1) and its intensity or magnitude (H2), expressed as:

$$H = H_1 \times H_2 \quad (2)$$

H_1 is set to 1.0 when the assessment is based on a historical flood event or on a scenario with an assumed occurrence. For early-warning applications, H_1 represents the forecast reliability, which takes a value between 0 and 1. H_2 is calculated using flood depth and inundation duration, which are taken from the results of hydrological-hydraulic model simulations at the commune level.

These variables are normalized to dimensionless values in the range (0-1) using the Min-Max method, yielding H_{21} and H_{22}, which is then computed as:

$$H_2 = \frac{H_{21}+H_{22}}{2} \tag{3}$$

The hazard index is determined using Equation (2), followed by the classification of hazard levels using the equal range method (Table 1).

2.2.2. Exposure and Vulnerability

In this study, the indicators used to determine exposure and vulnerability were initially refer from previous research, then subsequently modified through expert consultations to ensure local relevance. The exposure assessment considers four main aspects, including commerce, population, agriculture, and infrastructure. Vulnerability is evaluated through two primary components: Sensitivity (S) and adaptive capacity (AC). Sensitivity is represented by two key indicators, while adaptive capacity is characterized by seven indicators. Further details of the indicators are provided in Appendix 2.

Similar to Hazard, the indicators within Exposure and Vulnerability were first normalized to dimensionless values using the min-max method. Subsequently, each normalized indicator was assigned a weight using the Iyengar and Sudarshan method, to reflect its relative contribution to the E and V components. After normalization and weighting, E and V indices for each district j were calculated using the formulas below:

$$E_j = \sum_{i=1}^{NE} w_{Ei} \text{ x } E_{ij} \tag{4}$$

Where w_{Ei} are weights of exposure indicator E_i; E_{ij} is the normalized value of the i^{th} exposure indicator for district *j; NE* is a number of exposure indicators, here *NE=11* (Appendix 1).

$$S_j = \sum_{i=1}^{NS} w_{Si} \times S_{ij} \tag{5}$$

$$AC_j = \sum_{i=1}^{NA} w_{Ai} \times AC_{ij} \tag{6}$$

Where, S_{ij} and w_{Si} are the sensitivity indicator i^{th} for district *j* and its weight, respectively; AC_{ij} and w_{Ai} are the adaptive capacity indicator i^{th} for district *j* and its weight, respectively. The vulnerability to flooding is

$$V_j = S_j \times w_S + AC_j \times w_{AC} \tag{7}$$

In calculating vulnerability, the *AC* indicators were normalized in reverse. This way, higher original *AC* values (showing stronger capacity to cope with floods) become lower normalized values. The inversion makes *AC* move in the same direction as S so that higher normalized values of both indicate greater vulnerability. As a result, the "+" sign in Eq. 7 simply adds the effects of *S* and the inverted *AC* to form the overall vulnerability index.

The list of proposed exposure and vulnerability indicators is presented in Appendices 1 and 2 and the classification of their levels is provided in Table 2, using the percentile hierarchy method.

2.2.3. Risk

The flood risk index (R) for each district j was calculated using the multiplicative aggregation method, as expressed:

$$R_j = \sqrt[3]{H_j \times E_j \times V_j} \tag{8}$$

Flood risk was classified into five qualitative levels: Very Low, Low, Moderate, High, and Very High, following the classification framework stipulated in Decision No. 18/2021/QĐ-TTg of the Prime Minister of Viet Nam on natural disaster forecasting, warning, information dissemination, and disaster severity levels (Table 1). This standardized classification ensures consistency with national regulations and facilitates effective communication of flood risk levels for decision-making and emergency response planning.

Table 1. Hazard and Risk classification

Level	Thresholds	Value
1	Very low	<0.2
2	Low	0.2-0.4
3	Moderate	0.4-0.6
4	High	0.6-0.8
5	Very high	>0.8

Table 2. Exposure and Vulnerability classification

Level	Thresholds	Percentile	Exposure value	Vulnerability value
1	Very low	$<20^{th}$	0-0.085	0-0.427
2	Low	20^{th} - 39^{th}	0.085-0.117	0.427-0.475
3	Moderate	40^{th} - 59^{h}	0.117-0.159	0.475-0.499
4	High	60^{th} - 80^{th}	0.159-0.250	0.499-0.539
5	Very high	$>80^{th}$	>0.250	>0.539

2.3. Development of flood risk warning system

The flood risk warning system is developed as a comprehensive decision-support WebGIS platform that integrates real-time meteorological and hydrological data to provide continuous monitoring of current conditions (Figure 1). It incorporates hydrological to simulate flood flows under different scenarios, while also generating and displaying flood-risk classification maps that highlight vulnerable areas. By combining data visualization, modelling, and spatial analysis, the system supports timely decision-making for disaster preparedness, emergency response, and long-term flood risk management.

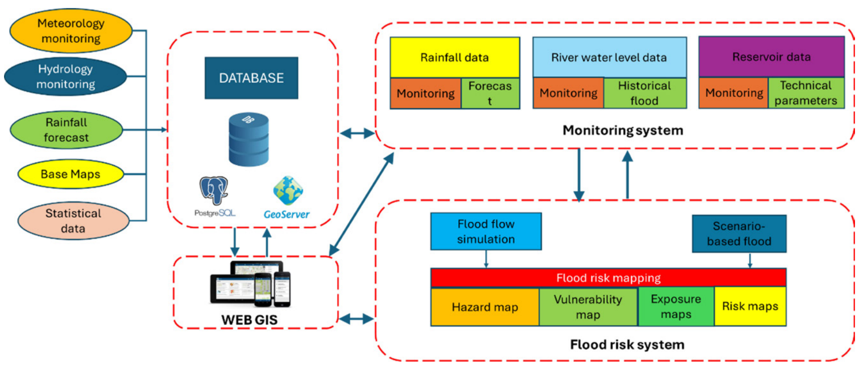

Figure 1. Architecture of the WebGIS system

The system has been developed using Web and GIS technologies, specifically Python-based Flask as the Web framework with geospatial capabilities, PostgreSQL for data storage and Geoserver for maptile management.

Python is a flexible, interpreted language that supports a wide range of applications from web development to machine learning and advanced data analytics. Its extensive ecosystem of open-source libraries enables various tasks. In addition, Python's cross-platform compatibility and support for multiple programming paradigms make it highly effective for integrating with external systems and enhancing interoperability.

Flask is a lightweight Python web framework. It is based on WSGI and uses Jinja2 for templates. Flask includes core features such as URL routing, a built-in development server, and debugging tools. It also supports building REST APIs easily.

Thanks to its extension system, Flask can integrate with many libraries to create modern web services.

PostgreSQL is an advanced open-source relational database. It focuses on standards compliance, robustness, and flexibility. Its architecture combines a strong SQL layer with a cost-based query planner and optimizer. It supports efficient indexing, rich data types, and secure role management. PostgreSQL also offers replication for high availability and many extensions, making it suitable for both small apps and large enterprise systems.

GeoServer is open-source server software for sharing and processing geospatial data. It publishes data from sources like PostGIS, Oracle Spatial, and shapefiles. Data can be served through web standards such as Web Map Service (WMS), Web Feature Service (WFS), and Web Coverage Service (WCS). GeoServer handles both raster and vector data, with flexible styling via SLD and CSS. It is widely used in fields like environmental monitoring, urban planning, and disaster management, serving as a core tool in many WebGIS platforms.

Figure 1 shows the architecture of a flood risk warning system within a WebGIS environment. The system integrates monitoring, simulation, and mapping functions. Data such as meteorological records, hydrological measurements, rainfall forecasts, base maps, and statistics are collected from the Viet Nam National Centre for Hydro-Meteorological Forecasting and open sources like GFS. These datasets are stored in a central PostgreSQL database and published through GeoServer for web access. They are organized into modules, including rainfall, river water level, and reservoir data, combining monitoring, forecasting, historical floods, and technical parameters. The database links with flood simulation models and scenario analyses to produce spatial results. The system then generates flood risk maps-covering hazard, vulnerability, exposure, and risk-which are shared on web platforms to support decision-making, early warning, and disaster management.

3. Case study and Data

3.1. Study area

The Cai River - the largest river system in Khanh Hoa province in Viet Nam (Figure 2), plays a vital role in the socio-economic development and ecological balance of the Nha Trang region. Originating from the highlands of the Dien Khanh district, the river flows approximately 75km in a Northeast direction before emptying into Nha Trang Bay in the East Sea. Its basin area covers around 2000 km² [18], encompassing diverse landscapes ranging from mountainous headwaters to coastal plains.

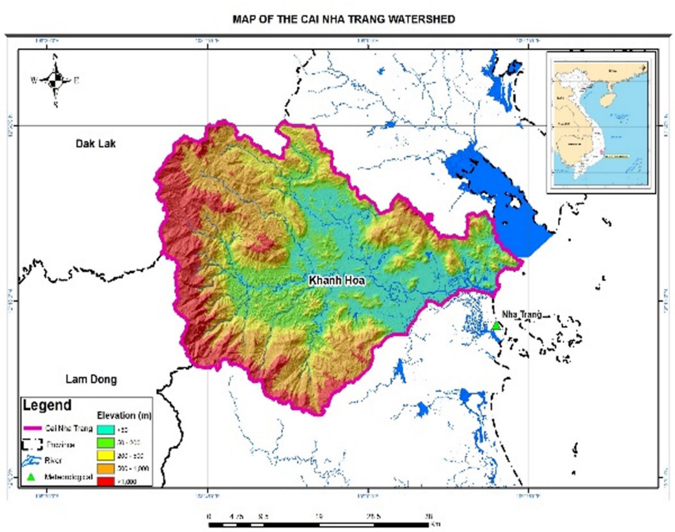

Figure 2. The Cai Nha Trang River

The flood season in the Cai River basin typically begins in September and ends in December. Flood events are primarily driven by high-intensity rainfall associated with the regional tropical monsoon climate and, at times, tropical storms or typhoons from the East Sea. Due to the basin's steep topography and relatively short river length, rainfall runoff concentrates rapidly, resulting in sudden and sharp rises in river water levels. This hydrological characteristic leads to the rapid development of floods, characterized by sudden onset and short duration, often causing severe damage to downstream communities, agricultural lands, and infrastructure.

3.2. Data

The data used in this study comprise hydrometeorological observations, socio-economic statistics, and spatial datasets.

Hourly rainfall data from the Dong Trang, Khanh Vinh, and Nha Trang stations, together with hourly evaporation data from the Nha Trang station, were used to set up the hydrological model for the November 2009 typical flood event (31 October - 7 November 2009). Discharge data at the Dong Trang station were used for hydrological model calibration, while water level data at numerous flood marks supported the calibration of the hydraulic model.

Socio-economic data at the district level were sourced from the Statistical Yearbook of Viet Nam in 2020. These include demographic, economic, agricultural, infrastructure, and other relevant indicators, serving as the basis for calculating exposure and vulnerability indices in the flood risk assessment. Field surveys were also conducted to supplement missing socio-economic information for districts where complete data were not available in the Statistical Yearbook.

The spatial datasets include a 1:10,000 topographic map of the study area, 19 cross-section data for hydraulic modeling, a digital elevation model (DEM), and various shapefiles used in the production of flood risk maps.

4. Results and discussion

4.1. Flood risk mapping in the Cai Nha Trang River Basin

For the Cai River Basin, hazards are concentrated primarily in Nha Trang City and Dien Khanh District, with 6 wards and 16 communes classified at a Very High level. In other localities within the basin, hazard levels are relatively negligible. In terms of exposure, most areas of Khanh Hoa Province are categorized as High or Very High, except for Cam Ranh City (Moderate) and Khanh Son District (Low). Vulnerability levels across the province are generally in the Moderate to High range.

Risk levels in the basin are highest in Nha Trang City and Dien Khanh District, where 8 wards and 16 communes are classified as Moderate. In the 2009 event, the peak water level at Dong Trang station reached 13.42 m, exceeding Alarm Stage III by 3.42 m and surpassing the historic 2003 flood peak by 0.08 m, corresponding to a risk level of three (Figure 3).

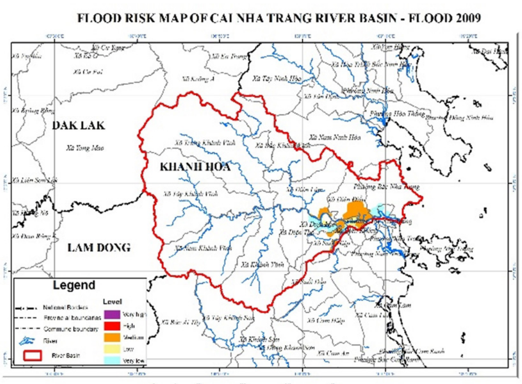

Figure 3. Flood risk map of Cai Nha Trang River basin

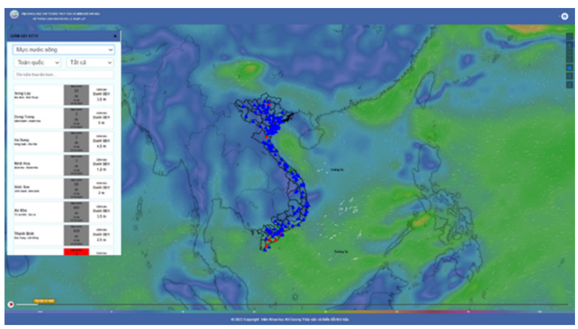

Figure 4. Interface of the flood risk warning system

The results indicate that the downstream region from Dong Trang station is classified at risk level of four, resulting from the combination of Very High hazard, Very High exposure, and High vulnerability.

4.2. Flood risk warning system

The flood risk warning system integrates a sophisticated set of functions that concentrate on two essential groups: The monitoring of meteorological and hydrological data and the flood and inundation risk warning capabilities. Together, these groups constitute the operational core of the platform, transforming environmental data into actionable knowledge for disaster preparedness and management (Figure 4).

Meteorological-Hydrological Monitoring Functions

The meteorological-hydrological monitoring group is designed as a continuous surveillance hub to bring together diverse datasets on environmental conditions and embed them within a WebGIS interface for easy visualization and analysis. Its main function is to provide users, from government agencies to local stakeholders, with the ability to access, query, and interpret both real-time and historical data on variables that drive flood and inundation dynamics. Key data types include rainfall, river water levels, reservoir storage and discharge capacity. These datasets are displayed spatially on interactive maps to ensure that information is not presented as raw figures but contextualized within the geographic reality of watersheds, river basins, and communities at risk.

Users can manipulate the data layers through multiple GIS tools. The system allows them to switch between different base maps such as satellite imagery or topographic layers and to overlay thematic layers, including rainfall station locations, water-level gauging stations, reservoirs, and vector fields of wind patterns. Functionality includes zooming, panning, and drawing selection boxes to focus on particular regions or administrative boundaries.

The monitoring group also facilitates detailed station-level analysis. By selecting a rainfall station, for example, the user can view a time series of recorded precipitation, explore color-coded intensity scales, or examine pop-up windows that summarize metadata such as station location and recorded values. Similar tools exist for water level stations, where managers can assess river fluctuations, detect peaks associated with flood events, and compare data with thresholds to determine the onset of hazardous conditions (Figure 5). Reservoir monitoring adds further depth by presenting information on water storage capacity, inflow and outflow rates. This is vital for flood management, since the behavior of reservoirs directly influences downstream inundation risk.

Beyond observation data, the module integrates forecast information. Most notably, users can access 10-day rainfall forecasts that allow the combination of short-term projections with real-time monitoring to anticipate potential flood triggers. The integration of forecasts with observed values ensures that the platform does not merely describe what has already occurred but provides forward-looking information. In practice, users can use these functions to monitor rising rainfall in an upstream basin, compare current figures with 10-day forecasts, and assess whether downstream rivers are likely to exceed safe thresholds.

The comprehensive visualization of meteorological and hydrological parameters coupled with interactive GIS functionality makes this monitoring group more than a passive repository. It is a dynamic decision-support tool enabling pattern detection, anomaly recognition, and proactive assessment of conditions. For communities and local managers, this means the ability to track storms, rainfall surges, or unusual reservoir behavior in real-time, while for national agencies it offers an integrated overview of conditions across multiple basins.

Flood and Inundation Risk Warning Functions

Whilst the monitoring group provides raw environmental intelligence, the flood and inundation risk warning group represent the translation of that intelligence into direct decision support. This module focuses on visualizing and analyzing related to flood hazards, transforming environmental signals into clear guidance on risk levels.

At its core are interactive flood risk maps, which classify hazard levels into five categories from level I to level V. These maps are spatially detailed, disaggregated down to the commune level, allowing decision-makers to identify not only which provinces or districts face risks but which specific communes are most exposed. The risk levels are represented through standardized color codes, ensuring that users can quickly grasp the severity of conditions without requiring specialized training in hydrology or GIS (Figure 6). When users click on a commune polygon, a pop-up window appears containing administrative identifiers (commune, province) and the assigned risk classification. This function enables highly localized risk communication, essential for planning evacuation routes, pre-positioning resources, or prioritizing vulnerable communities.

Complementary to risk maps and community reports, the module also integrates hazard, vulnerability, and exposure layers, combining them into comprehensive risk assessments. This reflects modern disaster risk frameworks where risk is conceptualized not just as hazard intensity but as a function of hazard, exposure, and vulnerability. By embedding these multiple dimensions, the system allows planners to ask nuanced questions: Which areas face high hazard but low vulnerability due to strong infrastructure? Which communes are moderately exposed but highly vulnerable because of socio-economic conditions? The resulting maps provide multidimensional insights that surpass simple hazard warnings.

In this system, users can define flood risk and its underlying components through two approaches: A scenario-based method and a modeling-based method (Figure 7). The scenario-based approach allows users to rapidly generate flood risk maps by selecting from predefined scenarios stored in the system's database, such as design floods with return periods of 1%, 5%, or 10%, as well as alternative reservoir operation strategies. This enables decision-makers to quickly obtain an overview of potential risk distributions under different hydrological and management conditions, providing a valuable basis for contingency planning. In contrast, the modeling-based approach integrates a hydrological model directly within the WebGIS platform to simulate flows at specified control points using rainfall forecasts as inputs. Rainfall data can either be automatically fed from the system's meteorological database or manually uploaded by users to test multiple assumptions. The simulation results are then processed to determine the most appropriate warning layers, with the platform automatically displaying the corresponding flood hazard and risk maps. By combining static scenario analysis with dynamic model-driven forecasting, the system ensures both rapid situational awareness and adaptive, data-driven decision support for flood risk management.

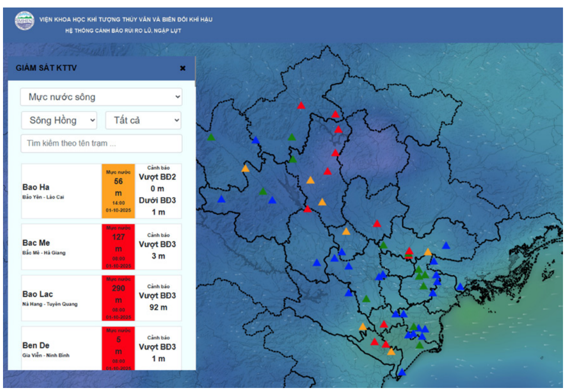

Figure 5. Displays of hydrological data

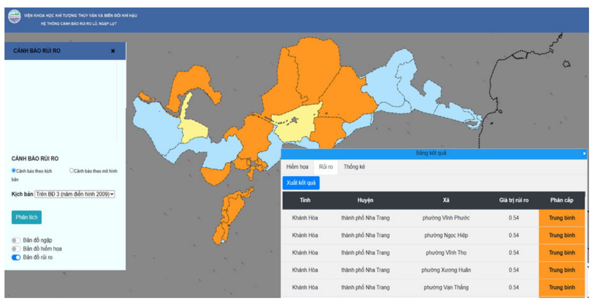

Figure 6. Display of a flood risk map

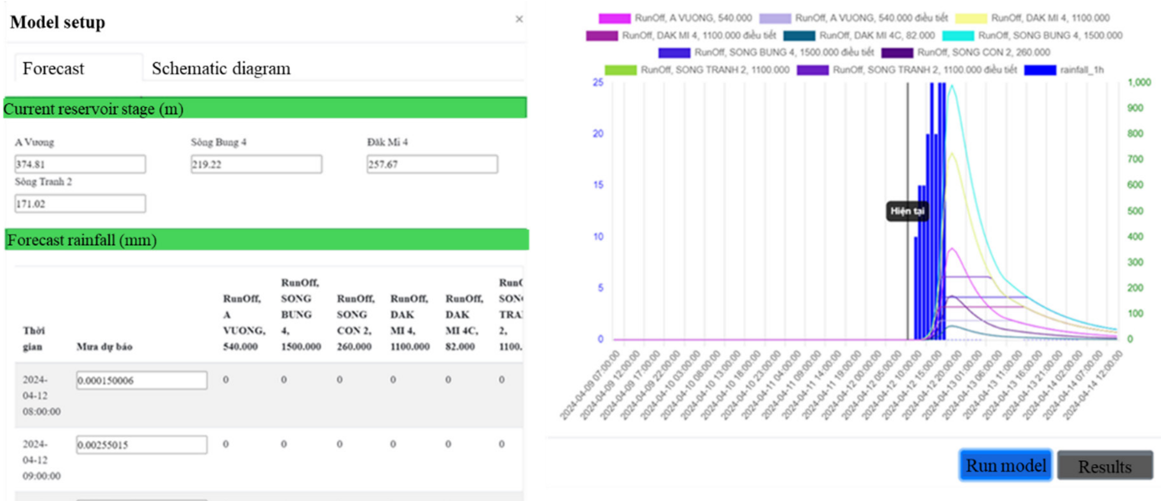

Figure 7. Flood flow modelling function

Significance and Integration of the system

The combination of the meteorological-hydrological monitoring and flood risk warning functions forms a tightly integrated ecosystem. Monitoring ensures a smooth flow of current status information, while the warning functions translate this into practical outputs for emergency management. The GIS platform serves as a bridge between users and observed rainfall data, forecasts and commune-level risk classifications.

The significance of these functions lies in their scalability and accessibility. At the national level, they provide a macro view of hydrological risks across major river basins. At the provincial or commune level, they support targeted preparedness and real-time operational decisions. This multi-scale, multi-stakeholder design strengthens resilience by guaranteeing that information is shared, validated, and acted upon across institutional boundaries.

5. Conclusions

The flood risk map for the Cai Nha Trang River basin shows that Nha Trang city and the old Dien Khanh district would be at moderate risk level when a flood as severe as flood 2009 occurs. The developed flood risk warning system for the Cai Nha Trang River Basin has proven to be a valuable tool for enhancing flood preparedness and disaster risk management. By combining real-time monitoring, modeling, and risk mapping, the system enables timely warnings and informed decision-making at both local and regional levels.

The experience gained from the Cai Nha Trang case study provides a foundation for scaling up flood risk warning systems nationwide.

Author contribution statement: *Luong Huu Dung: Generating and outlining the research; Ngo Thi Thuy: Outlining the research and developing the methodology; Chu Nguyen Ngoc Son: Simulating hydrological and hydraulic model; Luong Tuan Trung: Developing the warning system; Duong Hong Nhung: Calculating flood risk.*

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Competing interest statement: *The authors declare that this article was the work of the authors, has not been published elsewhere, has not been copied from previous research; there was no conflict of interest within the author group.*

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Appendix 1. Exposure indicators to flooding

Criteria	Indicators	Unit
People	Population	Persons
Economy	Number of businesses and economic establishments operating in the area	-
Agriculture	Agricultural land area	Ha
	Number of livestock	-
	Number of poultry	-
	Number of motorized vessels and boats exploiting marine resources	-
	Aquaculture land area	Ha
	Forest area	Ha
Infrastructure	Roads including national, provincial, and district highways	km
	Number of key projects (headquarters, schools, and medical stations)	-
	Residential land area	Ha

Appendix 2. Vulnerability indicators to flooding

Component	Criteria	Indicators	Unit
Sensitivity (S)	People	Proportion of elderly and children	%
		Proportion of disabled people	%
	Society	Unemployment rate of population aged 15 and over	%
		Proportion of poor households (multidimensional approach)	%
Adaptive capacity (AC)	Education	Proportion of high school graduates/total population	%
	Health care	Number of hospital beds/10,000 people	beds/10,000 persons
		Number of medical and pharmaceutical staff/10,000 people	staffs/10,000 persons
		Proportion of people participating in health insurance	%
	Infrastructure	Proportion of solid/semi-solid houses	%
		Total flood protection capacity of river basins	Mil. m^3
	Communication	Proportion of people using telephone/internet	%
	Economy	Average income per capita	Mil. VND
	Society	Proportion of people participating in social insurance	%
	Environment	Percentage of households using sanitary latrines	%
		Percentage of households using clean water	%