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RESEARCH ON THE DEVELOPMENT OF A METHOD FOR DETERMINING FLASH FLOOD HAZARD FOR THE NORTHERN MOUNTAINOUS REGION OF VIETNAM

Major: Hydrology

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INTRODUCTION

1. Rationale of the dissertation

Flash floods are among the most dangerous natural hazards in mountainous regions. They strike suddenly – frequently at night – and are highly destructive. In 2023 alone, two major flash floods at Mu Cang Chai (Yen Bai) and Sa Pa (Lao Cai) caused severe losses, while in 2022 as many as 310 floods and flash floods were recorded. Early warning of flash flood hazard is therefore key to reducing damage, particularly the loss of human life.

At present, several Flash Flood Guidance Systems (FFGS) – including SEAFFGS, VNOFFG and MRCFFGS – are operated in Vietnam to issue time-dependent flash flood warnings. These systems share two features: they take forecast rainfall as input, and they assess the hazard at the sub-catchment scale. Because the hazard is evaluated per sub-catchment, the internal tributaries are not resolved individually; the warnings therefore lack spatial detail and cannot pinpoint specific reaches of a given stream. This leaves a critical gap in answering the two central questions of flash flood warning – 'where' and 'when'.

Many international studies have established warning thresholds based on rainfall, discharge or water level. This dissertation, however, contends that the destructive nature of a flash flood lies in the power of the flow – the action of the flood flow on the channel and on the exposed objects – an aspect that existing thresholds do not capture explicitly. Accordingly, the

dissertation undertakes the topic 'Research on the development of a method for determining flash flood hazard for the Northern mountainous region of Vietnam', aiming to define a warning threshold grounded in stream power and, at the same time, to build a solution that computes flash flood hazard at every location in space and time.

2. Objectives of the dissertation

– To classify flash flood hazard on the basis of stream power and flow velocity, and to develop a toolset for determining flash flood hazard in space and time.

– To apply the toolset to determine flash flood hazard for a representative study catchment: the Nghia Do River catchment, Lao Cai province.

3. Research questions

– Which physical quantity of the flow characterizes the destructive power of a flash flood and can serve as the basis for a flash flood hazard classification threshold specific to the Northern mountainous region, in place of empirical thresholds based on rainfall or bankfull discharge?

– How can flash flood hazard be resolved at the point scale in space and time while still reflecting the upstream hydrological response at each location, and while achieving a computational speed suited to real-time warning operation?

– Under the scarce field-survey data typical of the Northern mountainous region, how can the hydraulic parameters (velocity, flow depth, etc.) required for the hazard threshold be estimated at locations lacking surveyed cross-sections?

4. Propositions to be defended

– Proposition 1. The hazardous nature of a flash flood is governed by the unit stream power and the flow velocity. A hazard classification threshold built on these two quantities faithfully reflects the destructive power of the flood flow, distinguishes flash floods from ordinary floods, and provides a physical explanation of why flash floods do not form at mountain summits or on large rivers.

– Proposition 2. A flash flood is the extreme outcome of the hydrological response of a specific catchment. By treating every point on the stream network as the outlet of an independent upstream catchment (the 'grid-cell catchment') and simulating the flow with a lumped hydrological model (SCS-CN coupled with the unit hydrograph) integrated into a GIS, flash flood hazard is resolved at the point scale in both space and time while still reflecting the upstream hydrological response at each location, at a computational speed suited to real-time warning operation.

– Proposition 3. The cross-sectional geometry of the small streams of the Northern mountainous region can be generalized by two characteristic indices, r and k. This allows the hydraulic parameters required for the stream power and velocity thresholds to be estimated at any

location, so that the method can be applied even to small and medium catchments that lack detailed survey data.

5. Research object and scope

– Research object: flash floods; flash flood hazard classification thresholds; flash flood hazard warning.

– Research scope: rainfall-induced flash floods (excluding debris flows, channel blockage and the associated landslide processes) in small and medium catchments of the Northern mountainous region; pilot application: the Nghia Do River catchment, Lao Cai province.

6. Research methods

Statistical analysis; remote sensing and GIS; and hydrological mathematical modelling.

7. Scientific and practical significance

Scientific significance: the study proposes stream power and flow velocity as flash flood hazard warning thresholds that reflect the true level of danger of the flood flow, and it develops a point-based approach to flash flood hazard by coupling hydrological principles with GIS techniques.

Practical significance: the scientific basis for flash flood hazard determination is a reliable reference transferable to other regions, since it relies on the intrinsic properties of the flow rather than on geographic location; the method delivers warnings in space and time at the point scale; and the approach can be applied to data-scarce areas with high reliability.

8. New contributions of the dissertation

1. Proposing a flash flood hazard classification threshold based on unit stream power and flow velocity – the first such threshold developed for the Northern mountainous region – which reflects the physical basis of the flow's destructive power and distinguishes flash floods from ordinary floods.
2. Proposing the 'grid-cell catchment' principle, whereby a lumped hydrological model is used to generate a distributed result at the point scale in space and time, combining the point-level detail of index-based methods with the physical realism of the catchment's hydrological response.
3. Generalizing the cross-sectional geometry through two indices, r and k, which enables the hydraulic parameters to be estimated and the method to be applied to small and medium catchments lacking survey data.

9. Structure of the dissertation

In addition to the Introduction, the Conclusions and Recommendations, and the Appendices, the dissertation comprises three chapters: Chapter 1 – Overview of research on flash floods; Chapter 2 – Development of the scientific basis for determining flash flood hazard in the Northern mountainous region; and Chapter 3 – Pilot application of flash flood hazard determination in space and time for the Nghia Do River catchment.

CHAPTER 1. OVERVIEW OF RESEARCH ON FLASH FLOODS

1.1. Concepts

Chapter 1 synthesizes the definitions of flash floods given by ACTIFF (2004), APFM (2006), NOAA (2010) and WMO (2009), together with those of Vietnamese researchers (Cao Dang Du & Le Bac Huynh; La Thanh Ha & Ngo Trong Thuan). The principal characteristics of a flash flood are: (1) a short duration with a large amplitude of water-level fluctuation; (2) a high flow velocity; (3) a high solids content; (4) great destructive power; and (5) an onset typically within about 6 hours. Most of these characteristics are described only **qualitatively**, which makes it difficult to identify a flash flood and to distinguish it from an ordinary flood.

1.3. Review of flash flood characteristics

With respect to flow characteristics, the dissertation examines the flow's capacity to entrain material (the relationship between unit stream power and clast size), the flash flood velocity, and the level of danger to people, vehicles and structures, thereby establishing the rationale for selecting stream power and velocity as the classification indices.

1.4. Review of flash flood hazard assessment methods

Research on flash floods follows four main directions: (1) assessment of flash flood susceptibility (AHP, FR, WOE, machine learning); (2) rainfall-based, (3) hydrologically based and (4) hydraulically based hazard assessment.

1.5. Review of flash flood hazard indices

The representative indices and thresholds reviewed include the FFPI, the DFFHI, the Critical Line (CL), EPIC, RTI, the specific peak-discharge (flood-peak modulus) index, and the Flash Flood Guidance (FFG) index underlying the FFGS.

1.7. Remaining issues for further research

The review identifies several limitations: the point-intrinsic indices (FFPI, DFFHI) neglect the upstream hydrological response and may therefore produce false alarms on summits and steep hillslopes; the Critical Line (CL) demands large historical datasets; and the FFGS, although state of the art, averages the hazard over each sub-catchment, depends on the reliability of forecast rainfall, and lacks source-code control.

Compared with the FFGS, the system proposed in this dissertation differs in three main respects: it resolves hazard on a point basis (each point being the outlet of a catchment, computed with a lumped-parameter model); its classification threshold is based on stream power and flow velocity, whereas the FFGS uses bankfull discharge; and its source code is self-developed.

On this basis, the dissertation identifies two gaps to be addressed: (i) the absence of a flash flood hazard classification threshold grounded in the physical nature of the flow (stream power, velocity) for the Northern mountainous region; and (ii) the absence of a solution that resolves flash flood hazard at the point scale in space and time.

CHAPTER 2. DEVELOPMENT OF THE SCIENTIFIC BASIS FOR DETERMINING FLASH FLOOD HAZARD IN THE NORTHERN MOUNTAINOUS REGION

2.1. Approach, research methods and techniques

The dissertation adopts the premise that a flash flood is the extreme outcome of the hydrological response of a specific catchment. Every point on the stream network is treated as the outlet of an independent upstream catchment (the 'grid-cell catchment'); the flow at each point is simulated with the SCS-CN loss method coupled to the unit hydrograph and integrated into a GIS.

Hydrological mathematical modelling (SCS-CN combined with the unit hydrograph). The SCS-CN method rests on the water-balance equation and two basic assumptions, which yield the expression for effective rainfall (direct runoff):

$$P_e = (P - I_a)^2 / (P - I_a + S) \quad (2\text{-}3)$$

$$I_a = \lambda \cdot S \quad (2\text{-}4)$$

$$S = 1000/CN - 10 \quad (2\text{-}5)$$

where P_e is the effective rainfall (direct runoff); P is the total rainfall; I_a is the initial abstraction; S is the potential maximum retention (in inches; multiply by 25.4 to convert to mm); λ is the initial-abstraction ratio; and CN is the Curve Number (derived from the hydrologic soil group and land cover). The unit peak discharge and the time to peak are given by:

$$q_p = K \cdot A \cdot P_e / T_p \quad (2\text{-}6)$$

$$K = 2 / (1 + T_r/T_p) \quad (2\text{-}7)$$

$$T_p = l^{0.8} \cdot (S + 1)^{0.7} / (1900 \cdot Y^{0.5}) \quad (2\text{-}8)$$

where q_p is the peak discharge (m^3/s); A is the catchment area (m^2); T_p is the time to peak (h); T_r is the recession time of the unit hydrograph; K is a coefficient (with $T_r/T_p = 1.67$, $K = 0.75$); l is the flow length (ft); and Y is the mean catchment slope (%). The flood hydrograph is constructed through superposition of the unit hydrograph, with baseflow separation following Eckhardt.

2.2. Determination of the flash flood hazard warning threshold

2.2.1. Flash flood hazard classification threshold

Following Bagnold, the total stream power and the unit stream power are defined as:

$$\Omega = \rho \cdot g \cdot Q \cdot S_e \quad (2\text{-}14)$$

$$\omega = \Omega / w \quad (2\text{-}15)$$

where Ω is the total stream power at the cross-section (W/m); ω is the unit stream power (W/m^2); ρ is the flow density (kg/m^3, taken as 1000 for water); g is the gravitational acceleration (≈ 9.81 m/s^2); Q is the discharge (m^3/s); S_e is the energy (hydraulic) slope (m/m); and w is the mean cross-section width (m). The formulation permits ρ to be adjusted for sediment-laden floods.

Drawing on statistics of past flash floods and on the relationship $\omega = a \cdot D^b$ between unit stream power and the size of the entrained material (boulders of 1.0–3.0 m corresponding to

1,200–4,500 W/m²), the dissertation proposes the following classification of flood levels by unit stream power:

Table 2-4. Proposed classification of flood levels based on unit stream power

Level	Description	Size of entrained material (m)	Proposed unit stream power (W/m²)
0	No flood	0.0–0.2	0–200
1	Minor flood	0.2–0.5	200–500
2	Rapid flood	0.5–1.0	500–1,200
3	Flash flood	1.0–1.5	1,200–2,000
4	Major flash flood	≥ 1.5	≥ 2,000

For the minimum threshold, the dissertation adopts a flow depth h ≥ 0.5 m and a velocity v ≥ 2.0 m/s as the condition for treating a flood as a flash flood; this is consistent with the depth × velocity product ≥ 1.0 m²/s of the Australian flood-hazard guidance. Because stream power and velocity are related but do not determine each other, the dissertation proposes a hazard classification matrix based on both quantities simultaneously:

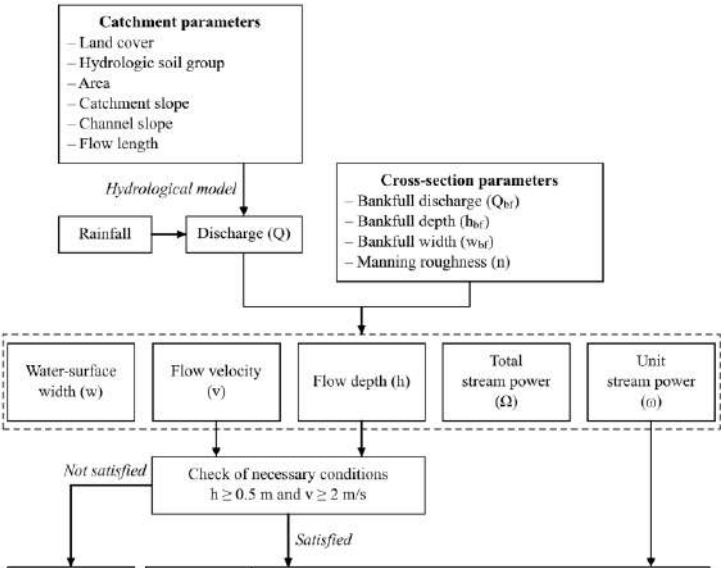
Table 2-5. Flash flood hazard classification for the Northern mountainous region

Flow velocity (m/s)	Unit stream power (W/m²)				
	< 200	200–500	500–1,200	1,200–2,000	≥ 2,000
2.0–3.0	Very low	Low	Moderate	Moderate	Moderate
3.0–5.0	Low	Moderate	Moderate	High	High
5.0–7.0	Moderate	Moderate	High	High	Very high
≥ 7.0	Moderate	High	High	Very high	Very high

Note: the column values denote the unit stream power (W/m²). Where the velocity is below 2.0 m/s or the estimated flow depth is below 0.5 m, flash flood hazard is not considered.

2.2.2. Flash flood hazard determination workflow

The determination of flash flood hazard at a point comprises four steps: (1) determining the channel slope; (2) determining the peak discharge (hydrological model); (3) determining the flow width, velocity and depth; and (4) computing the unit stream power and assigning the hazard class.



Flow velocity (m/s)	Unit stream power (W/m²)				
	< 200	200–500	500–1,200	1,200–2,000	≥ 2,000
2.0–3.0	Very low	Low	Moderate	Moderate	Moderate
3.0–5.0	Low	Moderate	Moderate	High	High
5.0–7.0	Moderate	Moderate	High	High	Very high
≥ 7.0	Moderate	High	High	Very high	Very high

Figure 2-22. Workflow for determining flash flood hazard at a single point

To estimate the hydraulic parameters at every location – where surveying all cross-sections is infeasible – the dissertation generalizes the channel geometry after Dingman using a **cross-section shape exponent r** and the **bankfull width-to-depth ratio $k = w_{bf}/h_{bf}$**:

$$h = h_{bf} \cdot (w/w_{bf})^{r} \tag{2-16}$$

Combining this with the Manning equation (taking the hydraulic radius R ≈ the mean flow depth) yields the discharge–depth and velocity relationships:

$$Q = (1/n) \cdot k \cdot S^{1/2} \cdot h_{bf}^{(1-1/r)} \cdot h^{(5/3+1/r)} \cdot (r/(r+1))^{5/3} \tag{2-22}$$

$$v = (1/n) \cdot (h \cdot r/(r+1))^{2/3} \cdot S^{1/2} \tag{2-21}$$

where n is the Manning roughness coefficient and S is the channel slope. The bankfull discharge follows the form $Q_{bf} = \alpha \cdot A^{\beta}$ (for the northern region, the coefficients derived from 34 hydrological stations are $\alpha = 3.6$ and $\beta = 0.765$; the North-East and Viet Bac region and the North-West region have their own coefficient sets), from which the bankfull depth is derived:

$$h_{bf} = [\, n \cdot Q_{bf} / (\, k \cdot S^{1/2} \cdot (r/(r+1))^{5/3} \,) \,]^{3/8} \tag{2-25}$$

Once the discharge at a location is known, it is substituted successively into Eq. (2-22) to obtain the flow depth h, into Eq. (2-21) to obtain the velocity v, and into Eq. (2-16) to obtain the width w, from which the unit stream power ω is computed for hazard classification.

Using 132 cross-sections from eight small river and stream systems of the Northern mountainous region (the Xuan Lac, Nam Cuong, Pac Ngoi, Nam Ly, Na Nhung, Ta Lung, Lung Po

and Song Bac streams), the dissertation analyses the two indices statistically. The analysis shows that r ranges from 1–7, with a mode of r = 2 (≈ 25%), a mean of 2.68 and a median of 2.0; k ranges from 1.8–53.55, with a mean of 11.3 but a median of 8.5 (a right-skewed distribution). The dissertation recommends adopting r = 2.0 and k = 8.5 (the median values) as representative indices for the Northern mountainous region under data-scarce conditions, together with a representative roughness coefficient n = 0.04.

2.3. Validation of the warning threshold against past flash floods

The classification threshold was validated against nine flash floods with complete hourly rainfall records in the Northern mountainous region (using the representative values n = 0.04, k = 8.5 and r = 2.0). Consistent with the research scope, all nine events were rainfall-induced flash floods, with no dam breach or channel blockage recorded. All events satisfy the necessary conditions (h ≥ 0.5 m; v ≥ 2 m/s), and the resulting classification is consistent with the observed character of each flood.

Table 2-13. Parameters for flash flood hazard determination of selected flood events in the Northern mountainous region (excerpt)

No.	Name	Qmax (m^3/s)	v (m/s)	ω (W/m^2)	Hazard class
1	Ban Co Muong	49.44	3.563	1,107	Moderate
2	Thon Na Pao	59.59	2.168	222	Low

No.	Name	Qmax (m^3/s)	v (m/s)	ω (W/m^2)	Hazard class
3	Thon Kim Van	72.76	4.235	1,763	High
4	Luong Son	79.93	2.493	324	Low
5	Nam Pam (2022)	192.32	5.963	4,482	Very high
6	Tram Y te xa Ho Bon	240.93	7.451	8,177	Very high
7	Nam Pam (2021)	350.57	7.238	7,273	Very high
8	Cha To	58.10	3.314	855	Moderate
9	Nam Pam (2017)	84.22	4.569	2,303	High

The events classified as 'Very high' (Ho Bon 2023 and Nam Pam 2021, with $v > 7$ m/s and $\omega > 7{,}000$ W/m^2) were all major flash floods that caused loss of life, whereas the 'Low' events (Ban Lau and Luong Son, with $\omega = 222–324$ W/m^2) were essentially inundation – confirming the suitability of the proposed classification threshold.

CHAPTER 3. PILOT APPLICATION OF FLASH FLOOD HAZARD DETERMINATION IN SPACE AND TIME FOR THE NGHIA DO RIVER CATCHMENT

3.1. The study area

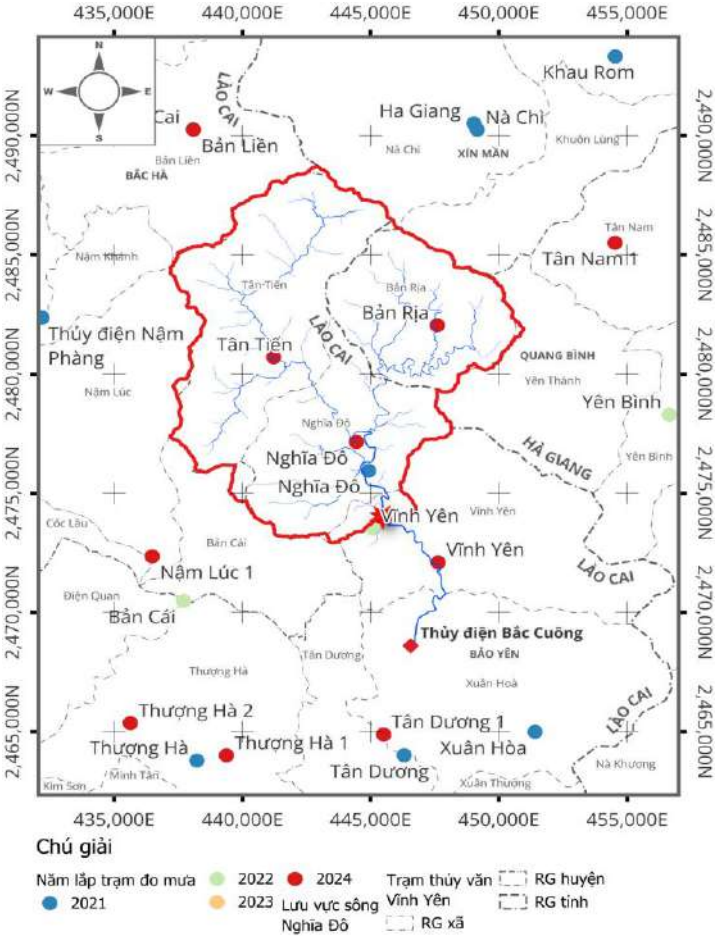


Figure 3-1. The study area and the monitoring stations

The study area is the Nghia Do River catchment, Lao Cai province, with its outlet at the Vinh Yen hydrological station. The catchment was selected because flash floods occur there frequently and because complete rainfall and discharge records are available from 2021 onwards (owing to the expanded, privately-operated rain-gauge network of Vrain and WeatherPlus). The flood of 09/09/2024, associated with the circulation of Typhoon Yagi, caused about 4 billion VND of damage within the catchment and breached the body of the Ban Ria dam.

3.2. Construction of the hydrological–GIS model based on the 'grid-cell catchment'

Through GIS analysis, every point in the study area is assigned its own values of slope, CN and other parameters; a flow-direction algorithm delineates the upstream catchment corresponding to each point (the grid-cell catchment principle). From the observed records at the Vinh Yen station, the catchment's initial-abstraction ratio was calibrated as $\lambda = 0.1$ (from the assessment of 16 recent floods), and the dimensionless unit hydrograph was reconstructed from the flood of 21/8/2022. These two parameters are applied uniformly to all grid-cell catchments within the study area.

The rainfall–runoff model for the catchment draining to the Vinh Yen station achieved a Nash–Sutcliffe efficiency (NSE) of 0.95 in calibration and 0.81 in validation (the flood of 07/9/2023); several additional events likewise confirmed the model's adequacy.

3.3. Characterization of the Nghia Do River catchment

From the surveyed cross-section at the Vinh Yen hydrological station, the cross-sectional geometry was determined in situ as $r = 2.5$ and $k = 8.72$ (measured values) and

applied uniformly to every cross-section in the study area to compute the flow depth, width and velocity. The values measured at Vinh Yen are close to the region-wide generalized values (median r = 2.0; median k = 8.5), which reinforces the reasonableness of the representative parameter set. Because observations are available for this catchment, the roughness coefficient was calibrated locally as n ≈ 0.095 (in place of the representative value n = 0.04 used for ungauged areas).

3.4. Construction of the flash flood hazard map for the 09/09/2024 event

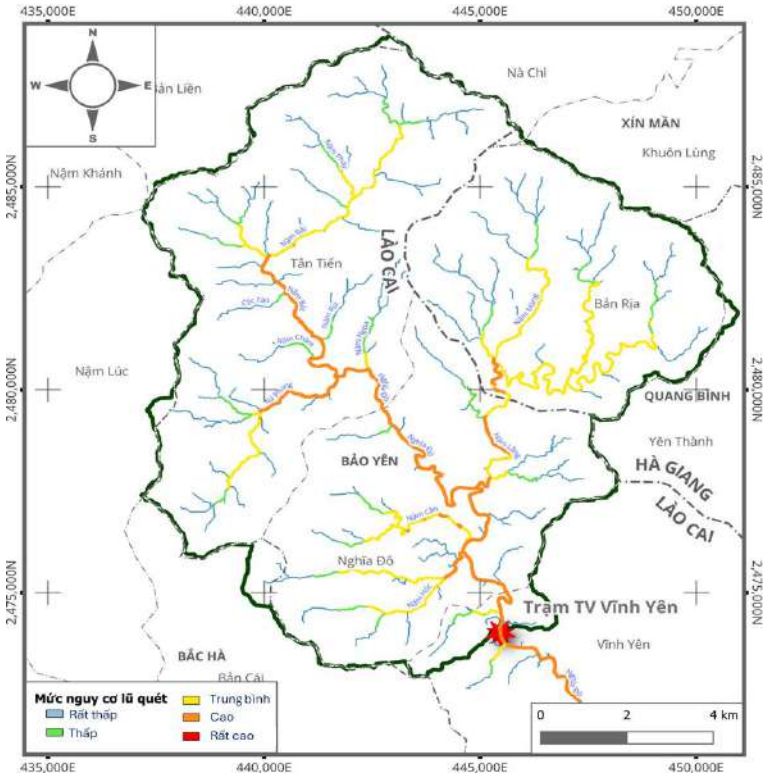


Figure 3-19. Flash flood hazard map for the 09/09/2024 event, Nghia Do stream

High flash flood hazard developed along the main Nghia Do stream (from the lower part of Tan Tien commune, through Nghia Do and Vinh Yen communes): the unit stream power ranged from 2,700–3,200 W/m², peaking at ≈ 3,900 W/m², with velocities of 3.5–4.0 m/s. Most upstream tributaries fell within the very-low and low classes because their velocities were below 2.0 m/s (flow depth below 0.5 m). No major flash flood occurred in the area (the maximum velocity reached only ≈ 4.0 m/s).

Determination of hazard over time. The dissertation simulated the hazard at hourly time steps from 01:00 to 15:00 on 09/09/2024, assuming no rainfall after each computation time. The results reveal a trade-off between reliability (the more rainfall that has already fallen, the closer the estimated discharge is to reality) and lead time (the more rainfall that has already fallen, the shorter the remaining warning time).

The most favourable combination occurred at 06:00 – when the catchment-average hourly rainfall peaked at 33.24 mm – at which point the model forecast a discharge of 428.49 m³/s with a lead time of up to 4 hours 10 minutes at the Vinh Yen station.

Table 3-12. Evolution of the projected discharge at the Vinh Yen station over time

Simulation time	Projected peak discharge (m³/s)	Time to peak	Lead time (min)
01:00 09/09	127.51	04:10 09/09	190
03:00 09/09	198.21	07:10 09/09	250
06:00 09/09	428.49	10:10 09/09	250
09:00 09/09	663.20	11:40 09/09	160
12:00 09/09	679.02	12:30 09/09	30
15:00 09/09	681.11	12:30 09/09	−150

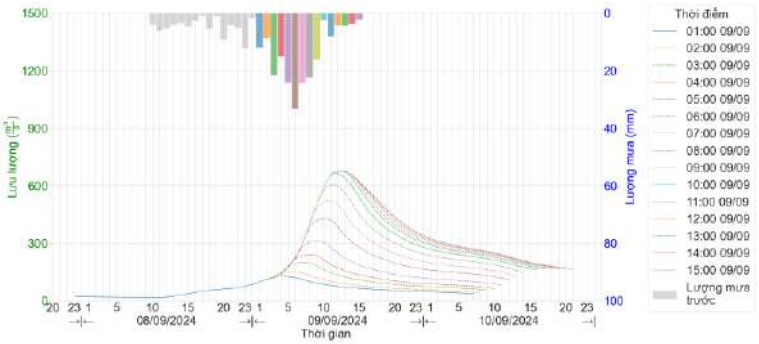


Figure 3-23. Hourly flood simulation and the forecast peak discharge at the Vinh Yen hydrological station

3.5. Development of the space–time flash flood hazard simulation tool

The dissertation developed a simulation tool comprising seven steps: acquiring rainfall → interpolating the rainfall raster → selecting simulation points → simulating rainfall–runoff → storing results (retaining peak discharges ≥ 0.1 m^3/s) → building the peak-discharge map → computing the flood parameters and building the hazard map. The tool allows the user to click any location to display the corresponding grid-cell catchment together with its full hydrological and hydraulic information. The total run time for the entire catchment (~135 km^2), from the receipt of rainfall to the delivery of the hazard map, is about 3 minutes – meeting the requirements of real-time warning operation.

3.6. Evaluation of the pilot application

Compared with recent flash flood warning studies in the same area (the FFGS-based work of Trinh Thu Phuong; the static susceptibility map of Le Nhu Nga; and the Sentinel-1 flood-extent detection of Ngo Thi Phuong Thao), the added value of this dissertation lies in its point-scale spatial resolution,

its classification basis founded on flow characteristics (stream power, velocity), and its explicit time dimension.

The pilot results show that unit stream power (ω) and velocity (v) carry complementary information and cannot be reduced to one another; the classification scale ranks the floods in an order consistent with the observed damage (the 09/09/2024 event, classed as 'High' – causing infrastructure damage but no loss of life – occupies a reasonable intermediate position between the 'Very high' and 'Low' events). The minimum velocity threshold $v \geq 2.0$ m/s acts as a screen that removes steep but shallow upstream grid cells. The tool's output serves two purposes: a map of the maximum hazard at each point (for zoning and planning) and an hourly sequence of hazard maps (for warning and response operations).

CONCLUSIONS AND RECOMMENDATIONS

1. Main results

Regarding the first objective (hazard classification and toolset development):

(1) A flash flood hazard classification threshold was established for the Northern mountainous region on the basis of unit stream power and velocity, comprising five unit-stream-power classes (< 200; 200–500; 500–1,200; 1,200–2,000; ≥ 2,000 W/m²) together with the minimum conditions $v \geq 2.0$ m/s and $h \geq 0.5$ m; the threshold was validated against nine real flash floods. The method faithfully reflects the hazardous nature of the flow and explains why flash floods do not form on summits or on large rivers.

(2) A workflow and toolset were developed to resolve flash flood hazard at the point scale following the 'grid-cell catchment' principle, with a total run time of about 3 minutes for a catchment of ~135 km².

(3) The cross-sectional geometry of the small streams of the Northern mountainous region was generalized by two characteristic indices, $r = 2.0$ and $k = 8.5$ (the medians of 132 cross-sections across eight stream systems), enabling the estimation of hydraulic parameters (velocity, flow depth, width) under data-scarce conditions.

Regarding the second objective (application to a representative catchment):

(4) The method was successfully applied to the Nghia Do River catchment: the initial-abstraction ratio was calibrated as $\lambda = 0.1$ (from 16 floods) and the in-situ cross-section parameters as $r = 2.5$ and $k = 8.72$; the rainfall–runoff model attained a Nash–Sutcliffe efficiency of 0.95 (calibration) and 0.81

(validation); and the simulation of the 09/09/2024 event yielded a flood peak of ~681 m^3/s, classed as 'High' hazard along the main Nghia Do stream, with an early-warning lead time of up to ~4 hours at the Vinh Yen hydrological station.

These results fully answer the three research questions and substantiate the three propositions defended in the dissertation: (i) unit stream power and velocity provide the physical basis for classifying flash flood hazard; (ii) the 'grid-cell catchment' principle resolves the hazard at the point scale at an operationally adequate speed; and (iii) the cross-sectional geometry generalized by r and k enables application to data-scarce catchments.

2. New contributions

1. A flash flood hazard classification threshold based on unit stream power and velocity – the first developed for the Northern mountainous region – which reflects the physical basis of the flow's destructive power and distinguishes flash floods from ordinary floods.
2. The 'grid-cell catchment' principle, whereby a lumped hydrological model produces a distributed result at the point scale in space and time – combining the point-level detail of index-based methods (FFPI, FR, MCA) with the physical realism of the catchment's hydrological response, and providing finer detail than sub-catchment-based warning systems (FFG/FFGS).
3. The generalization of the cross-sectional geometry through two indices, r and k, enabling the estimation of hydraulic parameters and the application of the method to small and medium catchments lacking survey data.

3. Limitations and recommendations

– The use of observed rainfall in the Nghia Do application keeps the warning window short and not fully suited to very small catchments (where the rainfall observation time step exceeds the catchment lag). The method is best suited to catchments with a lag greater than 1 hour; a continuous observation step (e.g. every 10 minutes) is required for optimal results.

– The assumption of no rainfall after the computation time may introduce transient errors; it is recommended to combine very-short-range (nowcast) rainfall forecasts (1–6 hours) and weather-radar data to extend the lead time. The reliability of forecast rainfall was not evaluated, so forecasts were not used in the computation; the tool already accepts forecast rainfall as an input.

– Empirical parameters (CN, roughness, cross-section data) are costly and region-specific; site-specific surveys and assessments are needed to improve reliability. The 132 cross-sections used to generalize r and k remain modest relative to the extent of the whole region.

– The SCS-CN method applies to catchments smaller than 250 km²; consequently, points on large rivers (with upstream areas exceeding 250 km²) should be handled by hydraulic simulation.

– The grid-cell catchment principle does not route the flow between points, so it does not describe the propagation of the flood wave, sediment and debris from upstream to downstream.

– The stream power is presently computed with the density of clear water (ρ = 1,000 kg/m³), so the stream power values and the corresponding hazard classes should be regarded as

a **lower bound**; a real flash flood entrains mud and boulders of higher density, so the actual stream power will be greater.

– The velocity is computed with the Manning equation, assuming uniform flow and a hydraulic radius approximately equal to the mean depth; in narrow, steep mountain streams during flash floods, the errors arising from these two assumptions have not been assessed within the scope of the dissertation.

– The hazard map represents the intensity class of the flood flow for each rainfall event; a hazard map expressed as a probability of occurrence would require computations with design rainfall of different return periods.

4. Directions for further research

– To determine the cross-sectional geometry indices (r, k) for individual regions and sub-regions nationwide, toward large-scale flash flood hazard mapping.

– To assess the reliability of forecast rainfall and recommend very-short-range forecasts (under 6 hours) for flash flood hazard computation, so as to limit false alarms.

– To incorporate the density of the mud–boulder mixture into the stream-power computation, in order to represent more completely the danger of sediment-laden flash floods.

LIST OF PUBLISHED WORKS

1. **Le Van Thin**, Tran Dinh Hoa (2023), "Methods for determining flash flood hazard", *Journal of Agriculture and Rural Development*, T9, pp. 164–172.
2. **Le Van Thin** (2023), "Analysis of selected characteristics of flash flood formation in Cha To commune, Nam Po district, Dien Bien province, July 2023", *Journal of Water Resources Science and Technology*, pp. 99–103.
3. **Le Van Thin** (2024), "A method for calibrating the initial-abstraction ratio and constructing the unit hydrograph in hydrological computation for the Bac Cuong stream catchment, Lao Cai province", *Journal of Water Resources Science and Technology*, No. 84, pp. 67–77.
4. **Thin Van Le**, Duong Cao Phan, Hoa Dinh Tran and Giap Dang Nguyen (2026), "Characterizing cross-sectional shape indices for hydraulic estimation in small mountainous streams: a case study in Northern Vietnam", *Sustainable Water Resources Management*, vol. 12, no. 1, Art. no. 3, doi: 10.1007/s40899-025-01313-5.