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Field-calibrated Hydrologic Engineering Center – River Analysis System modelling of Krueng Keureuto River flow

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Abstract: Flooding in the Krueng Keureuto Watershed, North Aceh, Indonesia, poses a recurring threat to the community and agricultural productivity. This study aims to develop a reliable hydraulic model using HEC-RAS (Hydrologic Engineering Center – River Analysis System) 6.5 to generate profiles of calibrated water levels and validated flood inundation maps at various return periods. The calibration process used hydrometric data from the Serba Jaman automatic water level recorder (AWLR) to optimise the Manning roughness coefficient. The calibration result showed an optimum Manning value of 0.08 with a simulated depth of 2.55 m and a deviation of only 5.5% from the observed data, indicating that the model is reliable. Unsteady flow simulations showed an increase in flood depth from 7.16 m (Q_2) to 10.66 m (Q_{50}), while the inundation area expanded from 379.13 ha to 940.42 ha. Spatial analysis indicated that lowland areas, specifically Tanah Luas and Paya Bakong districts, were most vulnerable, with more than 59% of the inundation area having a depth of more than two meters. These findings emphasise the need for an integrated flood mitigation strategy, combining technical infrastructure with non-structural approaches such as risk-based zoning, early warning systems, and Nature-based Solutions. Methodologically, this study highlights the crucial role of calibration and validation in hydraulic modelling to ensure the accuracy of recommended predictions to strengthen flood risk management in the Krueng Keureuto Watershed and similar watersheds.

Keywords: calibration, flood modelling, HEC-RAS 6.5, Krueng Keureuto, validation

INTRODUCTION

Flood is a natural disaster that remains a serious challenge worldwide during the rainy season (PBBI, 2025). The overflow of water to normally dry land can be caused by natural phenomena such as extreme rainfall, melting snow, or tidal waves. One common type of flooding is surface runoff flooding due to high rainfall intensity (Azmeri *et al.*, 2017; Basri *et al.*, 2022). When the soil is saturated with water, infiltration capacity decreases drastically, causing rainwater to flow directly onto the surface. This condition is often exacerbated by inadequate drainage systems, which cause water to overflow and inundate surrounding areas (Palla *et al.*, 2018; Yu *et al.*, 2023).

The Krueng Keureuto Watershed in North Aceh Regency, Indonesia, is an area frequently affected by flooding. The Krueng Keureuto River is vital for its surrounding communities, who use it for domestic and agricultural purposes. However, despite its benefits, recurring floods frequently strike this region with high intensity and devastating impacts. The recurrence of flooding along the Krueng Keureuto River is evidenced by a series of major events reported in the media. Between 2014 and 2015, floods occurred up to ten times, including an event that inundated 19 villages and 651 houses. A severe flood re-emerged in 2021 following a levee breach, resulting in two fatalities and the displacement of 32,000 residents. In early 2022, flooding expanded to 113 villages, and similar events recurred in 2023, submerging 1,737 ha of farmland and affecting 12 districts with more than 22,000 people impacted (AJNN, 2015; Setyadi, 2022; Munir, 2023; Keumalasari *et al.*, 2024). The flooding is primarily attributed to runoff from the Keureuto River, and the frequency has been increasing in recent years. It appears to increase the affected area, and the duration of inundation is prolonged (Dianto, Azmeri and Yulianur, 2024).

According to the flood control master plan from the Dinas Pengairan Aceh (2022), this area suffers the greatest and most damaging impacts in all of Aceh Province. It is crucial to conduct flood risk reduction measures, including integrated, data-driven flood modelling and mitigation planning. Various studies have shown that data-driven approaches, such as hydrological and hydraulic modelling, are effective in identifying flood-prone areas and supporting disaster management policy decisions (Muis *et al.*, 2015; Winter *et al.*, 2018).

Flood modelling often faces limitations in calibration and validation. However, the absence of proper calibration and validation would result in inaccurate flood modelling. Uncalibrated models risk providing inaccurate estimates of peak discharge and inundation area compared to actual conditions, which can lead to errors in infrastructure planning, such as overdesign or underdesign (Kumar *et al.*, 2023). The lack of validation results in models that are only valid for specific conditions and cannot be relied upon for different or future scenarios. This inaccuracy increases uncertainty in decision-making and reduces the effectiveness of flood mitigation strategies. Therefore, calibration and validation are not merely technical steps but are essential foundations for building reliable and applicable models for flood risk management (Wang *et al.*, 2023; Kuhanestani *et al.*, 2025).

Due to recurring flooding events, flood management efforts are necessary. An effort to reduce the risk and impacts of flooding is by providing information on flood conditions, including discharge, profiles of floodwater levels at specific points, and inundation areas. In response to the increasingly complex needs of flood modelling, the U.S. Army Corps of Engineers introduced the HEC-RAS (Hydrologic Engineering Center – River Analysis System) software in 1995. In its initial version, HEC-RAS only supported 1D flow modelling for both steady and unsteady conditions. As the technology advanced, HEC-RAS was updated to its latest version, which supports 2D flow modelling, and was released in 2015. In this study, HEC-RAS was selected because it is open-source and capable of performing detailed river flow simulations supported by various technical features such as calculations of discharge, depth, and flow velocity, as well as interactions with technical structures such as bridges and dams. Furthermore, the availability of hydrometric data of the study location (hydrometric posts) is a primary consideration in using the HEC-RAS application. The availability of hydrometric data allows model calibration to be optimally performed. Calibration was conducted by adjusting the Manning coefficient to obtain flow depth simulation results that best align with actual field conditions. The HEC-RAS update offers significant improvements in data processing performance, simulation accuracy, and result visualisation, allowing for more detailed analysis of surface flow patterns, sedimentation, interactions with river structures, and integration with geographic information systems (GIS). This application is an essential tool in hydraulic studies and flood mitigation (Costabile *et al.*, 2020; Ongdas *et al.*, 2020; Djafri *et al.*, 2024).

The novelty of this research lies in its ability to produce detailed information on flood levels at specific points and flood-prone areas through accurate calibration and validation techniques, thereby enabling optimal mitigation. The Keureuto Dam is located upstream, while the automatic water level recorder (AWLR) hydrometric post, is near the Serba Jaman Bridge at the downstream. Flood routing data from the Keureuto Dam served as input for upstream discharge. Hydrometric data and AWLR data were used for modelling calibration. In addition, the study location was selected due to the unavailability of discharge data at the hydrometric post, while AWLR log data were available. This situation makes the study location a potential option, as the availability of AWLR data allows for discharge conversion for each recorded water level. The discharge and water level data can then be used to determine the river flow rating curve.

MATERIALS AND METHODS

STUDY AREA

This research was conducted at the Keureuto River, which was located at the Keureuto Watershed, North Aceh Regency, Aceh Province, Indonesia. The upstream point is the Keureuto Dam and the downstream point is the Serba Jaman Bridge. Flood routing data for the Keureuto Dam were available in the upstream area of the watershed, while hydrometric measurements were collected downstream of the area. The total area of the Keureuto watershed studied was 51.615 km^2 with a river length of 21.4 km. The study location is located between coordinates 4°56'18.43"N – 97°9'27.11"E and 5°0'51.10"N – 97°14'8.50"E (Fig. 1).

DATA COLLECTION

The data used include various sources.
- Rainfall data (2009–2023) and data on the characteristics of the Krueng Keureuto Watershed, including river length and area of the studied watershed (Dinas Pengairan Aceh, 2022). These data were used to calculate flood discharge.
- Geometric data on the Krueng Keureuto River (Dinas Pengairan Aceh, 2022) as inputs for HEC-RAS (Hydrologic Engineering Center – River Analysis System), including river cross-sections and long sections.
- Data on the Alue Ubay Weir (Dinas Pengairan Aceh, 2022), located within the studied watershed, were used to input dam structure information into the HEC-RAS program.
- River roughness data (Brunner, 2010) were used to obtain the initial Manning coefficient value used in the river flow depth calibration process.

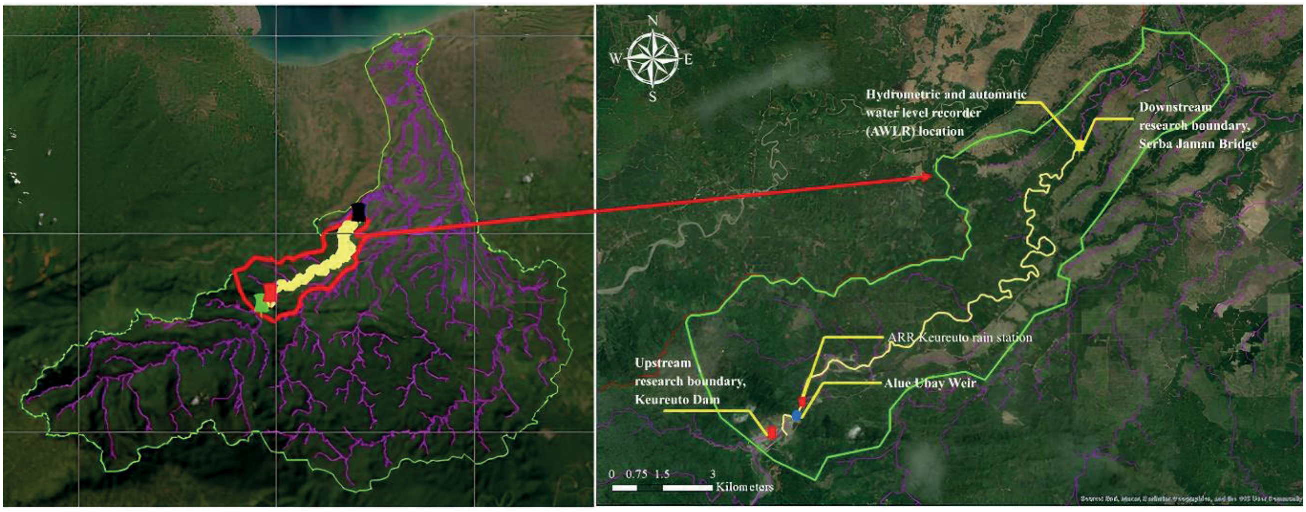

Fig. 1. Study location; ARR = automatic rainfall recorder; source: own elaboration

– Hydrometric data (Dinas Pengairan Aceh, 2022) were used for the calibration process to compare the simulated maximum river flow depth with the hydrometric maximum flow depth.
– Flood routing data (Dinas Pengairan Aceh, 2022) were used as input for discharge from the Keureuto Dam. This position also serves as the upstream boundary condition.
– Locations affected by the Krueng Keuereuto flood, obtained from various sources (Setyadi, 2022; Munir, 2023). These data were necessary to validate the flood-affected areas from the simulation.

HYDROLOGY

Hydrological analysis was conducted to understand the watershed's response to rainfall, particularly in the formation of flood discharge. Drobot *et al*. (2021) defined planned flood discharge as the maximum discharge in a river with a specific return period, which requires information on rainfall data, catchment area, and land cover. The research method used the Nakayasu unit hydrograph method, an empirical approach based on watershed characteristics, namely, watershed area and river length. All equations are available in the supplementary materials (Eqs. S1–S6). The Nakayasu method was chosen because it performs well with limited discharge data, requiring only basic morphometric parameters and effective rainfall. It is also appropriate for medium-sized tropical watersheds, where its hydrograph characteristics effectively represent rapid runoff responses. Besides that, the Nakayashu method has been used in Indonesian regulation as stated in SNI 2415:2016 concerning Procedures for Calculating Planned Flood Discharge (Badan Standarisasi Nasional, 2016). According to this method, the planned flood discharge can be obtained by correlating the unit hydrograph and effective rainfall, and subsequently adding the baseflow value calculated using the GAMA I. The equation is available in the supplementary materials (Eq. S7).

MODELLING OF HEC-RAS 6.5

The steady-flow simulation (1D simulation) was used for calibration by comparing the modelled water depth with hydrometric observations. At this stage, the discharge is assumed constant over time, allowing the analysis to focus on the agreement between the simulated and observed water-surface profiles. The unsteady-flow simulation (2D simulation) was applied to model the time-varying dynamics of flooding. Using design hydrographs for return periods Q_2–Q_{50} as inputs, the model produced temporal variations in water surface elevation, flow velocity, and inundation extent throughout the flood event.

1D SIMULATION

A 1D HEC-RAS (Hydrologic Engineering Center – River Analysis System) simulation was conducted to calibrate the simulated flow depth and field hydrometry (Ardıçlıoğlu and Kuriqi, 2019; Diedhiou *et al*., 2020). Calibration is successful if the difference between the compared parameters is less than 10% (Azmeri *et al*., 2025a). The 1D HEC-RAS simulation was carried out by creating river geometry, determining the channel scheme, cross section, Alue Ubay Weir structure, inputting upstream and downstream hydraulic data (boundary conditions), as well as discharge or water level values. It also required inputting the initial value of the Manning coefficient (n) according to channel conditions and running a steady flow simulation (Dasallas, Kim and An, 2019; Spor, Pasa and Dogan, 2025). Subsequently, a comparison between the simulated and the hydrometry flow depth is needed.

2D SIMULATION

A 2D HEC-RAS (Hydrologic Engineering Center – River Analysis System) simulation was conducted to obtain information on flood increases that occurred at the cross-section for each flood return period (Djafri *et al*., 2024; Ullah *et al*., 2024). The inundation area was also observed at locations where flood flow overtopping occurred. The 2D HEC-RAS simulation was carried out by importing the ArcGIS watershed location file into HEC-RAS, generating it, adding the Alue Ubay Weir structure, determining boundary conditions and inputting data for each boundary condition, and then running the simulation (Tonin and Paiva, 2022). After the simulation was completed, information regarding the accurate flood water level profile for the cross-section of the river under study was obtained.

RESULTS AND DISCUSSION

REGIONAL RAINFALL ANALYSIS AND DESIGN FLOOD DISCHARGE ESTIMATION

The regional rainfall analysis using the Thiessen Polygon method showed that the Keureuto automatic rainfall recorder (ARR) station influenced the occurrence of flooding at the study location. A 7-hour rainfall resulted in flooding in the Keureuto Watershed. The planned flood discharges for return periods of 2, 5, 10, 25, and 50 years were 178.4, 295.1, 363.3, 458.6, and 536.6 $m^3 \cdot s^{-1}$, respectively. In addition to being caused by rain, flood discharge was also influenced by the base flow rate of 2.63 $m^3 \cdot s^{-1}$.

MODELLING OF HEC-RAS 6.5

1D simulation

The results of the steady flow simulation depicted the relationship between hydrometric discharge and the maximum depth of river flow. The hydrometric discharge calibration is available in Figure 2. This simulation is modelled with a hydrometric discharge input of 16.42 $m^3 \cdot s^{-1}$ and an initial Manning coefficient of 0.05. Comparison of the steady flow simulation results before and after calibration is presented in Table S1. Figure 3 presents the results of the Manning roughness coefficient calibration using statistical performance models, namely: a) coefficient of determination (R^2), b) root mean square error ($RMSE$), c) mean error (ME), and d) percent bias (PBias) at the automatic water level recorder (AWLR) station.

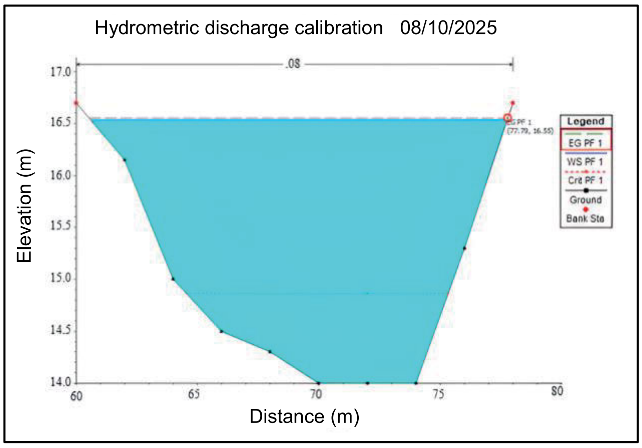

Fig. 2. Hydrometric discharge calibration; EG = energy grade line, PF = profile, WS = water surface, Crit = critical depth, Sta = station; source: own study

The calibration of the channel roughness coefficient (Manning's n) is an important stage in hydraulic modelling, because this variable directly affects the result of the flow depth and velocity simulations. The iterative approach in this study was carried out by testing the maximum n value (0.15), minimum value (0.07), and optimal calibration value (0.08), which is a good practice in developing the HEC-RAS (Hydrologic Engineering Center – River Analysis System) model. In this study, calibration was carried out by comparing the results of the steady flow simulation to the water depth data from hydrometric field observations. The results of Manning's roughness coefficient calibration using statistical performance models, shown in Figure 3. The model indicates that

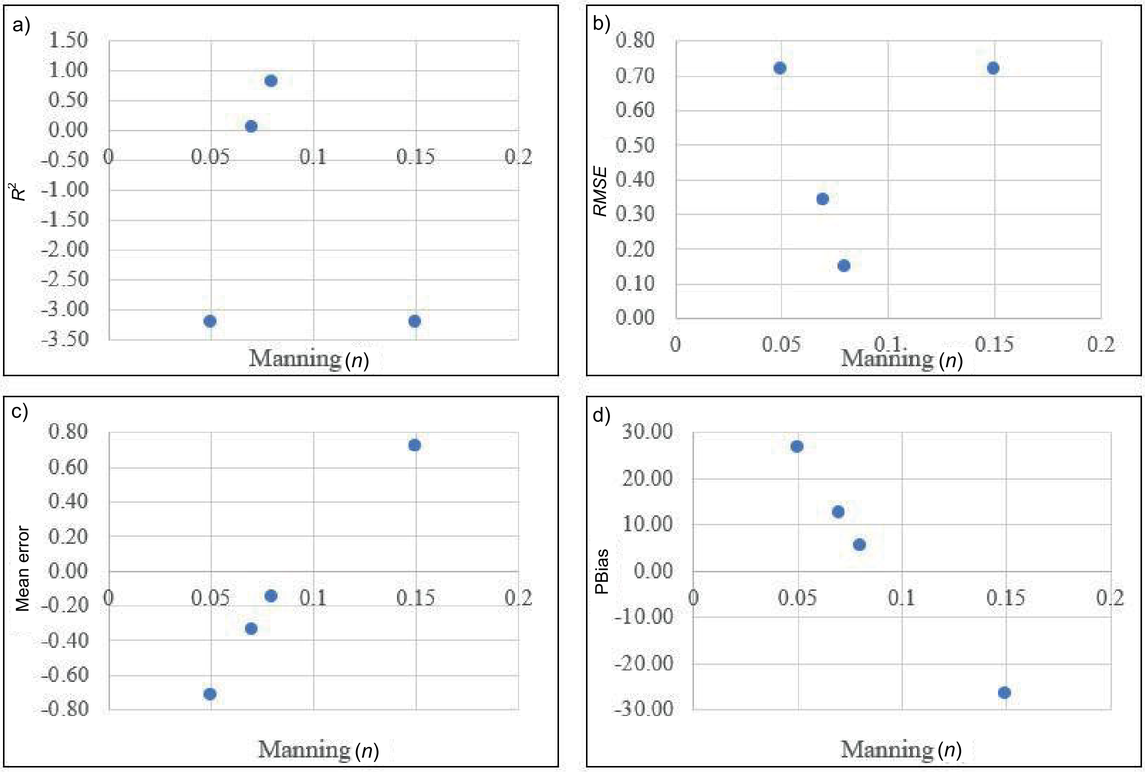

Fig. 3. The calibration of the Manning roughness coefficient (n) using statistical performance models, namely: a) coefficient of determination (R^2), b) root mean square error ($RMSE$), c) mean error, d) percent bias (PBias) at the automatic water level recorder (AWLR) station; source: own study

the optimal Manning's *n* value at this location is 0.08. This calibration result gives a flow depth of 2.55 m, with a deviation of 5.5% from the observation data of 2.7 m, indicating that the model is within acceptable calibration tolerance limits (less than 10%), as indicated by Ardıçlıoğlu and Kuriqi (2019) and Azmeri *et al.* (2025b).

The slight difference between the simulation and observations confirms the assumption that the physical characteristics of the river have been realistically represented. An *n* value that is too high will result in an overestimation of the simulated flow depth, while an *n* value that is too low will result in an underestimation of the actual depth. The simulated cross-section at the hydrometric observation location based on the calibrated Manning's value is illustrated in Figure 4.

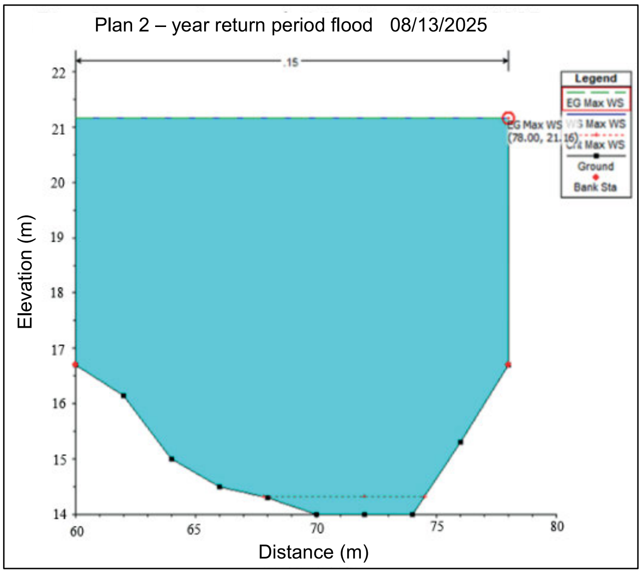

Fig. 4. The simulated cross-section based on the calibrated Manning's value; EG = energy grade line, WS = water surface, Sta = station; source: own study

The use of roughness data from Brunner (2010) as the basis for the initial *n* value demonstrates methodological consistency. However, it should be noted that river roughness values are influenced by local conditions such as riverbank vegetation, riverbed material, and the presence of hydraulic structures. Therefore, field validation and documentation of actual river conditions are essential to increase the reliability of the *n* value used. This study employs a spatially uniform Manning's *n* value in the 2D model, which represents a methodological limitation.

In the future, a multi-calibration approach based on additional observational data, such as drone data or LiDAR imagery, can be used to generate a more detailed spatial distribution of Manning values, particularly for 2D modelling that considers roughness variations across the floodplain. This approach has been proven in studies by Kim *et al.* (2026), which demonstrated improved flood modelling accuracy through a spatially variable roughness approach.

Thus, the successful Manning calibration in this study not only confirms the model's reliability for steady-state conditions but also provides a strong foundation for unsteady flow analysis and inundation maps under various flood return period scenarios.

2D simulation

One of the key features of HEC-RAS (Hydrologic Engineering Center – River Analysis System) is its ability to generate flood inundation maps using unsteady flow simulations integrated with spatial data. This simulation generates time-varying river flows, representing water level dynamics and flow distribution during flood events. Flood zones were generated using the output of the HEC-RAS 2D unsteady-flow simulation, which produced flood-depth grids for Q_2 return period (Fig. 5). Flood inundation maps for return periods of 5 years until 50 years are available in the supplementary materials (Figs. S1–S4). The maximum inundation depth, affected area, and percentage of inundation area for each depth range were also obtained (Tab. 1). These depth grids were exported to GIS for classification into three hazard categories (0–1 m, 1–2 m, and >2 m), followed by delineation to determine the extent, boundaries, and spatial expansion of inundation from Q_2 to Q_{50}. The classification and delineation results were then used to define flood-risk zones by considering flood depth, flow velocity, and the vulnerability of surrounding areas such as settlements and agricultural land. This process produced flood-zone maps that can be directly applied to risk-based spatial planning and flood-mitigation strategies.

Table 1 shows that the maximum flow depth increased with the return period, from 7.16 (Q_2) to 10.66 m (Q_{50}). This condition indicates a sensitive river hydraulic response to increases in planned flood discharge. The distribution of inundation is consistent, dominated by depths of more than 2 m (around 59–60%), while shallow inundation of less than 1 m accounts for only 19–20%. This result shows that flooding in Krueng Keureuto is not only widespread but also tends to be deep, potentially causing severe damage to infrastructure and agricultural land.

The inundation area also increased sharply from 379.13 (Q_2) to 940.42 ha (Q_{50}), with a greater non-linear expansion at high return periods. This pattern indicates that any increase in extreme rainfall intensity will significantly expand the affected area. This condition supports the finding that Tanah Luas and Paya Bakong districts were the most vulnerable areas. Therefore, these results emphasise the need for an integrated mitigation strategy, both structural (embankments, river normalisation, polders) and non-structural (risk-based zoning, early warning systems, and Nature-based Solutions (NbS)).

The distribution of flood inundation from HEC-RAS simulations for return periods of 2 years is shown in Figure 5. The results of flood modelling using HEC-RAS 6.5 on the Krueng Keureuto River indicate that a field-based calibration and validation approach is crucial in improving the reliability of hydraulic simulations. The calibrated Manning coefficient value resulted in a flow depth difference of only 5.5% compared to hydrometric observation data, which is within the model accuracy tolerance limits according to the reference (Azmeri *et al.*, 2025b). This result indicates that the developed model is highly reliable and can be used as a basis for flood mitigation planning.

Furthermore, the unsteady flow simulation results show a significant increase in maximum flow depth and inundation area as the return period increases. Inundation increased from 379.13 (Q_2) to 940.42 ha (Q_{50}), reflecting the potential for escalating disaster risks due to climate change and land use change in the study area. This phenomenon aligns with the findings of Muis *et al.* (2015), who stated that urban

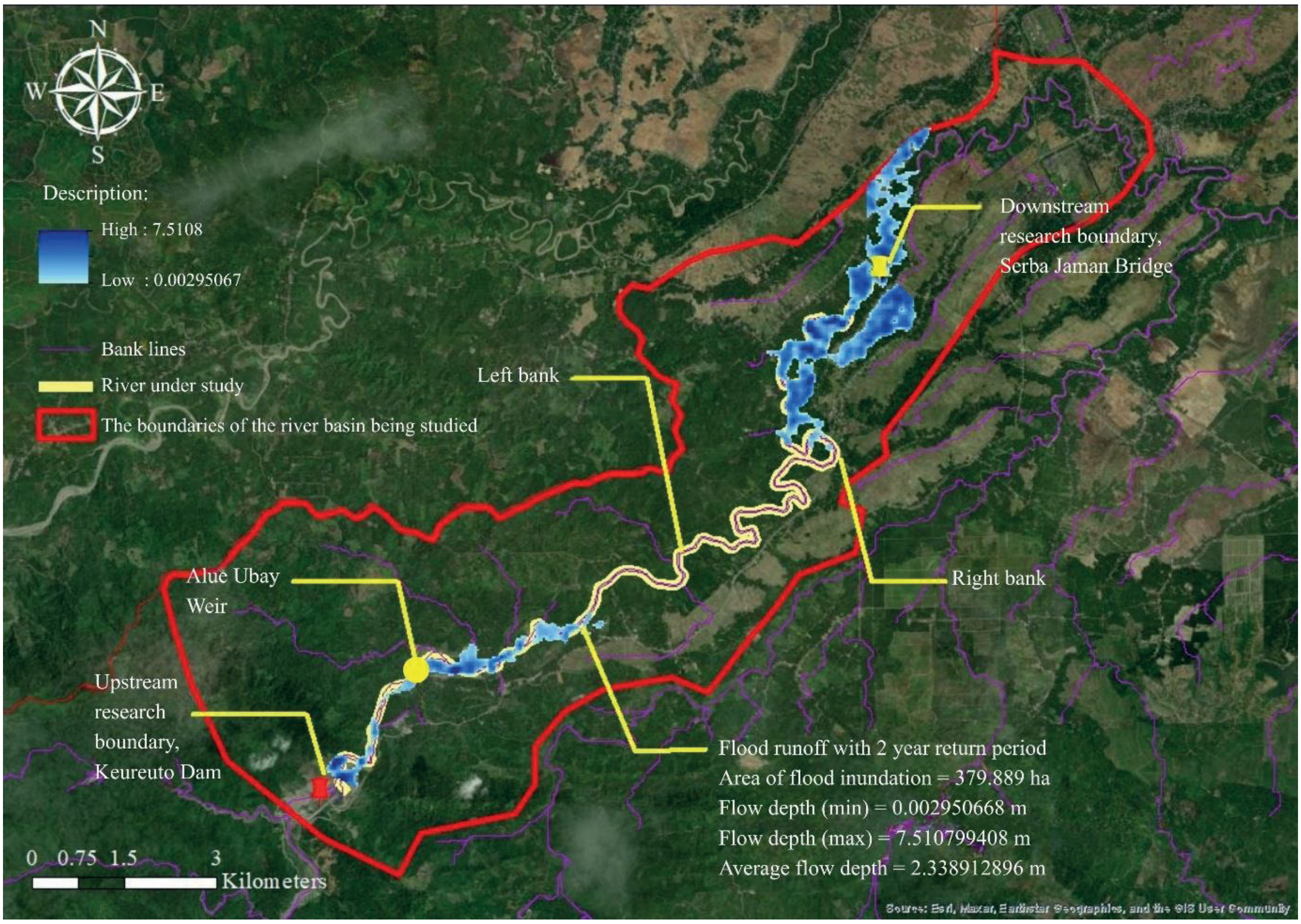

Fig. 5. Flood inundation maps for return periods of 2 years; min = minimum, max = maximum; source: own study

Table 1. Depth, inundation area, and percentage of flood area of Krueng Keureuto River

Return period (y)	Maximum depth (m)	Range of flood depth (m)	Area (ha)	Percentage (%)
2	7.16	[0; 1]	73.68	19.43
		(1; 2]	81.24	21.43
		>2	224.21	59.14
5	7.83	[0; 1]	108.77	20.01
		(1; 2]	113.05	20.80
		>2	321.69	59.19
10	8.36	[0; 1]	155.09	20.22
		(1; 2]	162.87	21.23
		>2	449.13	58.55
25	8.92	[0; 1]	167.42	20.30
		(1; 2]	165.04	20.01
		>2	492.29	59.69
50	10.66	[0; 1]	181.87	19.34
		(1; 2]	190.41	20.25
		>2	568.14	60.41

Source: own study.

expansion and land use changes directly affect flood intensity and extent.

The spatial inundation distribution indicates that lowland areas such as Tanah Luas and Paya Bakong districts are most vulnerable to river overflows. These areas are highly vulnerable to flooding due to their dense population and productive agricultural land. This situation underscores the importance of implementing risk-based zoning and adaptive spatial planning to reduce flood exposure. The finding that over 59% of the inundated area experiences water depths exceeding 2 m indicates a high-hazard condition. At these depths, horizontal evacuation becomes unsafe, as strong flood currents severely limit mobility and increase the likelihood of entrainment. Consequently, the early warning system must provide adequate lead time to facilitate timely and effective vertical evacuation to structurally safe multi-story buildings. In addition, NbS strategies, such as restoring riparian vegetation and strengthening natural drainage systems, can complement technical infrastructure.

Methodologically, the use of the Nakayasu HSS method combined with baseflow estimation using the GAMA-I approach provides representative results, especially in watersheds with limited historical discharge data. The 2D HEC-RAS simulation successfully visualised complex inundation patterns (Kim *et al.*, 2026). The accuracy of inundation prediction determines the effectiveness of evacuation plans and emergency response resource allocation. Thus, the findings of this study not only enrich the hydrological-hydraulic database of the Krueng Keureuto watershed but also provide a scientific basis for evidence-based flood disaster risk reduction strategies. These findings are supported by historical data from various news sources that record repeated flooding events in North Aceh due to the overflow of the Krueng Keureuto River, which often causes mass evacuations and disruption of community activities. Therefore, an integrated and sustainable mitigation strategy is needed to reduce the impact of future floods.

CONCLUSIONS

The results of the study demonstrate that hydraulic modelling using HEC-RAS (Hydrologic Engineering Center – River Analysis System) 6.5 with a field-based calibration and validation approach can reliably represent the actual conditions of the Krueng Keureuto River. The Manning coefficient calibration result (n = 0.08) showed a deviation of only 5.5% from the hydrometric data, confirming the model's accuracy in steady flow simulations. Unsteady flow simulations revealed that the maximum flow depth increased significantly from 7.16 (Q_2) to 10.66 m (Q_{50}), with an expansion of the inundation area from 379.13 to 940.42 ha. These findings confirm the high vulnerability of the study area to flood risk escalation, especially in Tanah Luas and Paya Bakong districts. Methodologically, the integration of the Nakayasu Synthetic Unit Hydrograph method with GAMA-I baseflow estimation proved effective under conditions of limited historical discharge data. Furthermore, spatial visualisation of inundation using 2D HEC-RAS enhances understanding of flood risk distribution, which is crucial for spatial planning, evacuation strategies, and disaster mitigation. The main contribution of this research lies in the implementation of rigorous calibration and validation, resulting in a credible and applicable flood model. The practical implication of this study's results is the need to strengthen integrated mitigation strategies through a combination of flood control infrastructure, the application of Nature-based Solutions, and evidence-based adaptive spatial planning. In the future, integration with remote sensing-based observational data and long-term climate projections is recommended to improve the reliability of flood predictions in the Krueng Keureuto Watershed and similar areas.

SUPPLEMENTARY MATERIAL

Supplementary material to this article can be found online at https://www.jwld.pl/files/Supplementary_material_69_Bantacut.pdf.

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CONFLICT OF INTERESTS

All authors declare that they have no conflict of interests.

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