Dam Break Analysis: A Case Study of the Tala Hydropower Plant Dam using HEC-RAS

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Abstract
Dam break flood is widely recognized as a low probability but a high impact event that can pose significant risks to downstream communities and critical infrastructures. Numerous studies have focused on the significance of dam break modelling for hazard assessment, risk mitigation and emergency preparedness planning. In this study, the Dam Break Analysis of the Tala Hydropower Plant (THP) involves a systematic approach combining data collection, hydraulic modeling, and risk assessment under different failure conditions. High-resolution 2.5-meter AW3D Digital Elevation Model served as the primary input dataset for the hydraulic modelling. The analysis employs the Hydrologic Engineering Centre-River Analysis System (HEC-RAS) to model three dam-failure scenarios under both extreme flood and normal reservoir conditions: One scenario represents THP dam failure caused by overtopping during the Probable Maximum Flood (PMF), while the remaining two scenarios simulate cascade failure of the Chhukha Hydropower Plant (CHP) and THP dams under sunny-day and Probable Maximum Flood conditions. The three scenarios were selected to represent probable and worst-case scenario for emergency planning and associated flood hazard study. The analysis demonstrates varying levels of flood hazard across the three simulated scenarios, with maximum breach outflows reaching 47,364.95 m^3/s, 37,469.66 m^3/s and 52,771.27 m^3/s respectively. Downstream regions including key infrastructure such as bridges, settlements, and the Tala powerhouse Main Access Tunnel are found to be at risk, with floodwaters potentially extending into the Indian plains up to approximately 66.18 km from the dam. A sensitivity analysis performed for the study indicates that the breach elevation is a critical factor influencing the magnitude and timing of flood impacts, with lower elevations leading to more severe and rapid flooding, particularly in regions closer to the dam. The flood inundation maps generated in this study highlights the need for effective dam safety management including identifying high-risk zones, early warning systems and effective emergency response planning.
Keywords: *Dam Break Analysis, Flood Inundation, HEC-RAS, Probable Maximum Flood, Sensitivity Analysis, Tala Hydropower Plant*

1 INTRODUCTION

Dams, often referred to as mega structures, play a crucial role in promoting both social and economic development by serving multiple purposes, including irrigation, water supply, flood control, recreation, and power generation (Karamma et al., 2022). Dams, complex structures subjected to various forces, can fail, and their long-standing safety does not guarantee future stability. One of the forces that induces failures on dam structures are seepage. Excessive seepage can lead to structural failure, including internal erosion at the dam foundation, known as piping failure. Additionally, dams may fail due to overtopping, resulting from inadequate emergency spillway capacity or clogged spillways (Leoul & Kassahun, 2019).

The Tala and Chhukha Hydropower Plants which are both located along the Wangchhu river, plays a pivotal role in harnessing hydroelectric potential, contributing significantly to the energy requirements of the region. Both Tala and Chhukha dam are part of the oldest Concrete gravity dam in Bhutan and holds a crucial position as a fundamental hub of infrastructure for primary hydroelectric power generation. The dams are located in a seismically active region, with the Main Central Thrust (MCT) and Main Boundary

Thrust (MBT) fault lines situated in close proximity to the study area. This necessitates careful and continuous monitoring to anticipate and address potential risks to its stability.

Thus, this study aims to conduct a thorough dam break analysis of the Tala Hydropower Plant under three critical cases. A standalone Tala dam breach analysis is evaluated under a failure caused by overtopping during the Probable Maximum Flood (PMF) while the Cascade scenario is evaluated under two pivotal cases: a sunny day failure at Full Reservoir Level (FRL) and failure caused by overtopping during the Probable Maximum Flood (PMF). For the cascade dam break scenario, the breach outflow hydrograph of Chhukha dam breach is modeled as the inflow boundary condition for the Tala Cascade dam breach analysis. This study conducted assess the risk posed to the downstream communities and infrastructure thus supporting dam safety management, emergency action planning mitigation strategies.

2 PROBLEM DESCRIPTION

The Tala dam, a vital component of the Tala Hydropower Plant, currently lacks a comprehensive dam break analysis. Despite its strategic importance, no such analysis has been conducted to date. The absence of a dam break analysis poses a significant challenge, as it hinders the ability to assess the specific risks associated with different failure scenarios. Understanding the potential impacts on downstream infrastructure and communities is crucial for informed decision-making, risk mitigation, and the development of effective emergency response strategies.

3 STUDY AREA AND FEATURES OF THE DAMS

Both Tala and Chhukha Hydropower Plant are run of the river hydroelectric scheme and are the oldest power plants of DGPC located in south-west of Bhutan. 1020MW Tala Hydropower Plant which is the biggest running Plant under Druk Green Power Corporation had its commercial operation in 2006-2007 while 336MW Chhukha Hydropower Plant was commissioned in September, 1988.

Both the power plant utilizes the Wangchhu (Raidak) River, a major perennial river system of Bhutan, with a design head of 819 meters for Tala Hydropower Plant and 435 meters for Chhukha Hydropower Plant. The distance between the two dams is approximately 12, 507meteres and the location of the dams are shown in Fig. 1. Table 1 shows the salient features of the dams.

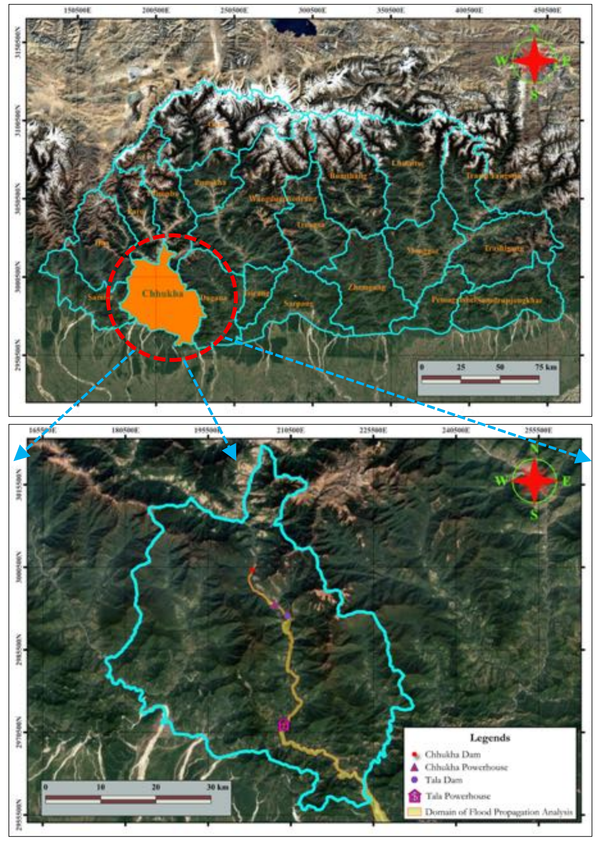

Fig. 1: *Study area and location of dams*

Table 1: *Salient features of dam*

SN	Parameters	Tala Dam	Chhukha Dam
1	Live Storage of dam	3.20 Mm^3	1 Mm^3
2	Freeboard	3m	3m
3	Height of dam	92m	43m
4	Length of dam top	130m	105m
5	Width of dam top	9m	8m
6	Length of Spillway portion	117m	72m
8	Non-overflow portion	13m	33m
7	Average river bed level	El. 1291m	El. 1813m
8	Deepest Foundation level	El. 1280.5m	El. 1802m
9	Full Reservoir Level	El. 1363m	El. 1842m

10	Minimum Draw Down Level	El. 1352m	El. 1830m
11	Top of the dam	El. 1366m	El. 1845m

4 DAM BREACH ANALYSIS

Dam failures are relatively rare but can cause significant damage to society when they do occur. The majority of historical dam failures have involved embankment dams, while failures in concrete gravity dams are minimal in comparison to other types (Leoul & Kassahun, 2019).

Dam failures can result from a range of complex factors, both structural and non-structural. Structural failures are typically classified into three main categories: overtopping by flood, foundation failure, and piping failure. Concrete dams are generally more vulnerable to foundation failure than overtopping, while earth fill dams are more prone to seepage or piping failures (The Colorado Division of Disaster Emergency Services, 1987).

Dam breach analysis involves the study and simulation of a breach hydrograph, which represents the flow through the dam breach over time, as well as the assessment of potential impacts of dam failure on downstream areas.

4.1 Estimation of breach parameters

To accurately determine the outflow hydrograph, peak discharge, and downstream inundation, the estimation of the breach location, failure type, dimensions, and development time are crucial (Beza et al., 2023; Saberi & Zenz, 2015). As concrete gravity dams are typically constructed from monoliths, USACE (USACE, 2016) recommends using an average breach width of multiple monoliths, while FERC (Federal Energy Regulatory Commission, 1988) and NWS (Fread, 1991) suggest a breach width of less than or equal to half the dam's length.

All three agencies recommend a vertical breach side slope due to the typically rectangular shape of monoliths. For modeling purposes, the range of potential failure times is between 0.1 and 0.5 hours (FEMA, 2013). According to (Tony L. Wahl, 2010), a key advantage of using empirical parametric regression equations is that they allow the user to have some control over the breach parameters in the model, enabling consideration of site-specific factors (FEMA, 2013).

4.2 Mannings Roughness coefficient

According to Brunner (Brunner, 2014), underestimating roughness coefficients can lead to lower water surface elevations, increased velocities, and potentially even supercritical flow. The Mannings roughness coefficient (*n)* is determined using VEN TE CHOW (Chow, 1959) method as quoted in Open Channel Hydraulics, guidelines by Arcement (George J. Arcement, JR, 1989) and as similar method done for the dam break analysis of Nikachhu Hydropower Project (Studio Pietrangeli Consulting Engineers, 2023).

4.3 Cascade Dam Breach Analysis

Cascade dam-break analysis involves three main components: a successive failure of individual dams from upstream to downstream, the routing of floodwaters through the riverways, and the regulation of the flood in the downstream reservoir. Consequently, accurately simulating the time-dependent hydraulic characteristics of a single dam break such as the outflow hydrograph, water level, and breach geometry etc., is essential for constructing a reliable numerical model for cascade reservoir dam breaks (Hu et al., 2020), (Zhu et al., 2021).

Generally, in a cascade dam breach analysis, the effect of an upstream dam failure on downstream hydraulic structures is evaluated by simulating a breach scenario, generating a flood hydrograph to represent the outflow, and routing it to the downstream dam to estimate the received flood volume.

5 RESEARCH METHODOLOGY

In order to simulate dam break scenarios, state-of-the-art hydraulic modeling tools was utilized, and two-dimensional flow models was implemented to analyze the extent of inundation in downstream areas. Fig. 2 illustrates the summary of the methodology adopted for this research.

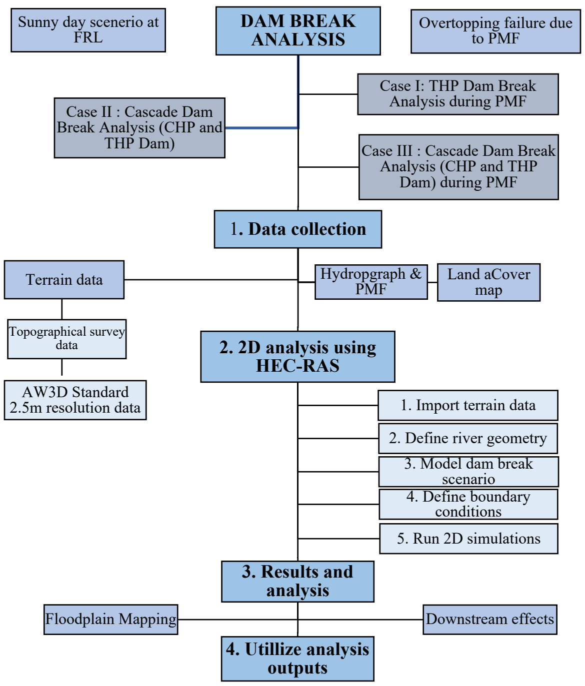

Fig. 2: Research Methodology Flow chart

5.1 Data Collection and Preparation

The data used for this study are AW3D (ALOS World 3D) DTM with resolution of 2.5m, Land Used Land Cover data (LULC), 2020 from (DoSAM, 2023) for Mannings roughness, Surveyed bridge data, social and settlement data. Different classes of land use land cover are considered. Fig. 3 shows the location and details of the surveyed bridges.

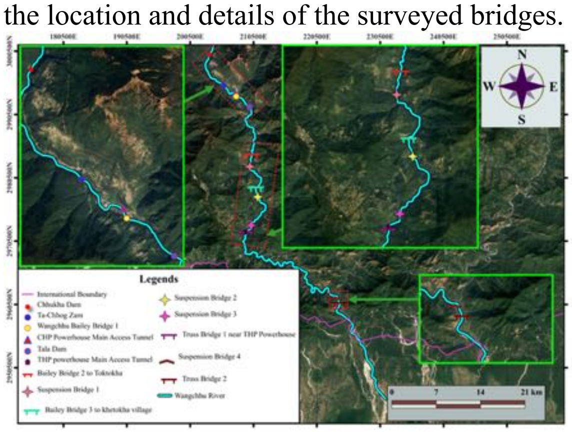

Fig. 3: Location of the bridges and infrastructures located in the study area.

The downstream settlements potentially affected by the dam breach are primarily located in two areas Tala Powerhouse area (B) and Jigmechhu area (C), whereas most of the other settlements lie at safer, higher elevations above the anticipated flood level. The settlement area (A) lies just above the Tala dam and its effect from Chhukha dam breach is already carried out in the previous study. Fig. 4 shows the areas delineated with potential impacts of flood along with the individuated cross sections.

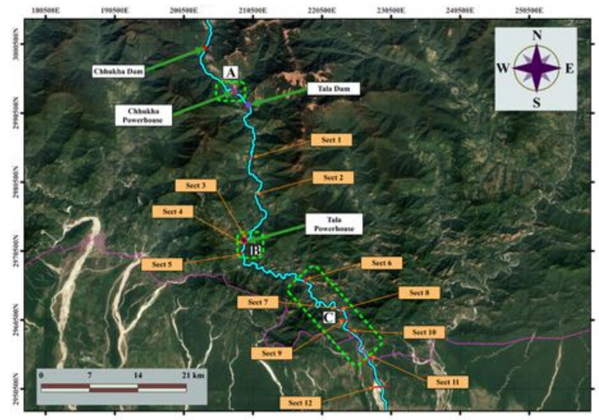

Fig. 4: Settlement area and the cross sections in the downstream area of dams

6 NUMERICAL HYDRAULIC MODELLING

For this dam breach analysis, the numerical simulation domain extends from the Tala dam toe to the Indo-Bhutan border, covering a length of approximately 66.18km with a total area of about 62.70 km². The unsteady-flow analysis was performed by applying the PMF/breach-outflow hydrograph as the upstream boundary condition and assigning normal depth as the downstream boundary condition. According to Hydraulic Engineering Centre (USACE, 2016) the slope of the water surface is frequently a reliable approximation of the friction slope.

For this study, 12 sections along the river stretch downstream from the dam are individuated along the Wangchhu river as shown in Fig. 4. The sections are individuated only at important areas such as bridges and settlement area. The flood inundation extent and associated risks are evaluated using the following parameters for the identified sections:

- Distance from the dam axis in km
- Peak Flood in m^3/s
- Maximum water velocity in m/s
- Mean water velocity in m/s

- Maximum Water Surface Elevation (WSE) in m asl
- Mean Water Surface Elevation (WSE) in m asl
- Arrival time of peak flood in hr:min

For the cascade scenarios, inundation maps and hydraulic parameters are provided only for areas located downstream of the Tala Dam.

7 SCENARIOS FOR DAM BREAK ANALYSIS

7.1 Case I – Dam Break analysis of THP dam during Probable Maximum Flood (PMF)

The dam break analysis for the Tala Hydropower Plant dam was conducted considering failure induced by overtopping during the PMF event. The PMF for Tala dam is computed as 10,600 m^3/s (Tala Hydropower Plant, 2021). The failure of the dam is due to overtopping. In this scenario, the presence of the upstream Chhukha Dam is not considered. This scenario considers the incoming inflow of the river besides the maximum discharge of PMF. Thus, the following conditions were defined for the model:

❖ Upstream boundary condition
  - PMF hydrograph with peak discharge (Q_{peak}) of 10,600m^3/s

❖ Downstream boundary condition
  - Average friction slope of 0.06m/m

Fig. 5 shows the inundation map in the downstream area of the Tala dam due to Probable Maximum Flood scenario.

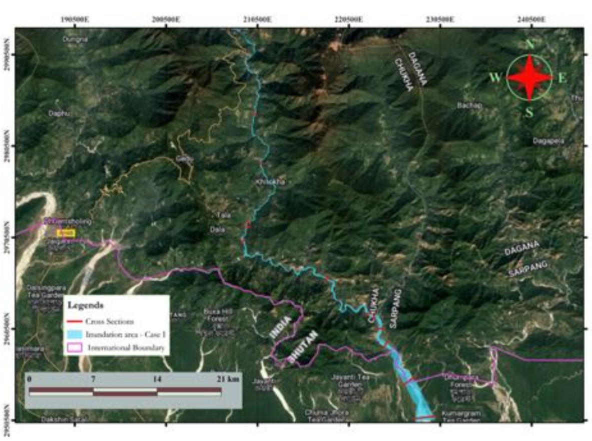

Fig. 5: *Flood Inundation map due to PMF failure scenario for Case I*

Fig. 6 illustrates the propagation of flow along the identified sections, showing the variation of discharge over time in the downstream reaches while Fig. 7 illustrates the propagation of peak flow, depicting the relationship between peak discharge and arrival time at each identified section.

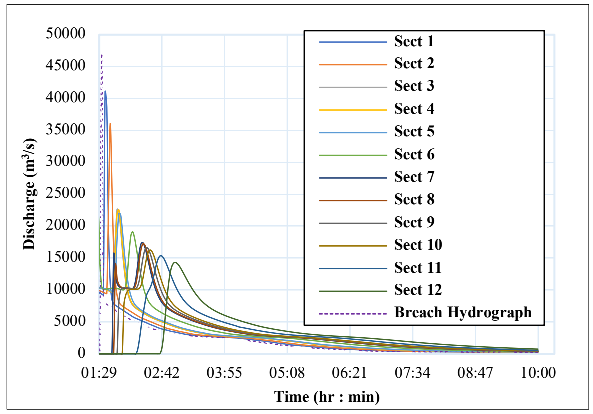

Fig. 6: *Propagation of the flow during PMF failure scenario - Case I*

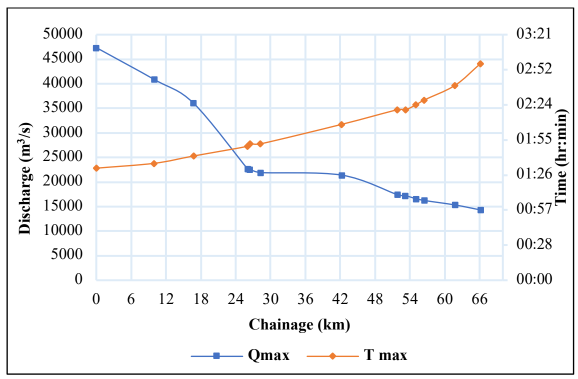

Fig. 7: *Propagation of the peak flow - Case I*

The peak flow of the breach flow varies from 47,364.95m^3/s at the dam toe to 14,310.07m^3/s at the last section approximately about 66.18km from the dam. The net change in the peak discharge is computed as 33,054.88m^3/s. The peak arrival time, which represents the difference in time between the peak at the dam toe and the peak of the flow hydrograph simulated in the last downstream section, is approximately about 1 hour 26 minutes.

7.2 Case II - Cascade Dam Breach analysis during Sunny Day Failure at Full Reservoir Level

The Case II Cascade dam break analysis of Chhukha and Tala Hydropower Plant dam is modelled as a sunny day failure at Full Reservoir Level (FRL). In the cascade dam break scenario, the outflow breach hydrograph generated from the Chhukha dam breach was applied as the input hydrograph for the downstream Tala dam. The breach of Chhukha dam is considered first, and the adequacy of Tala dam to route the resulting inflow from Chhukha dam is evaluated. In the cascade sunny-day failure scenario, the Chhukha dam is assumed to fail due to internal erosion through piping, whereas the downstream Tala dam is considered to fail as a result of overtopping. For breaching the Chhukha dam, a hydrograph corresponding to a total reservoir volume of 812,100 m³ was used as the input for flood propagation, based on the bathymetric data.

The following boundary conditions were defined for the cascade dam breach model of Tala dam.

- Upstream boundary condition
  - Breach outflow hydrograph from Chhukha dam breach with peak discharge (Q_{peak}) of 3963.57m^3/s
- Downstream boundary condition
  - Average friction slope of 0.015m/m

The inundation area due to sunny day dam break scenario for Case II in the downstream area of dam is mapped in Fig. 8.

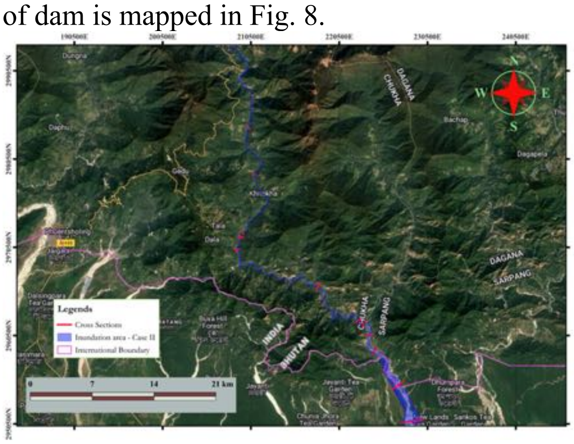

***Fig. 8:** Flood Inundation map due to Sunny day failure scenario for Case II*

The peak flow of the breach flow varies from 37,469.66m^3/s at the dam toe to 2983.82m^3/s at the last section approximately about 66.18km from the dam. The net change in the peak discharge is computed as 34,85.84.84m^3/s. The peak arrival time, which represents the time difference between the peak at the dam toe and the peak of the flow hydrograph at the final downstream cross-section, is approximately about 2 hour 40 minutes. Fig. 9 illustrates the propagation of flow along the identified sections, showing the variation of discharge over time in the downstream reaches while Fig. 10 illustrates the propagation of peak flow, depicting the relationship between peak discharge and arrival time at each identified section.

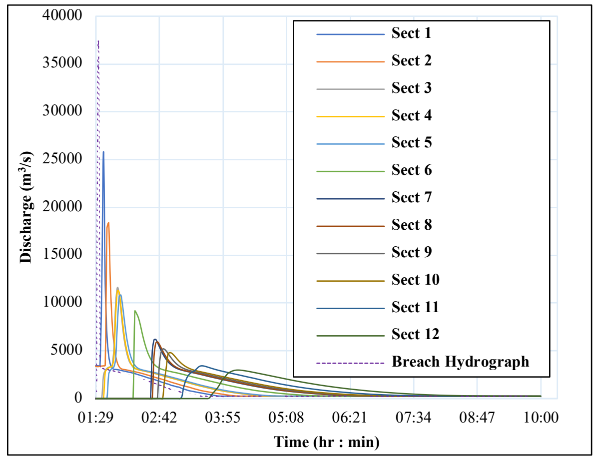

***Fig. 9:** Propagation of the flow during Sunny day failure scenario - Case II*

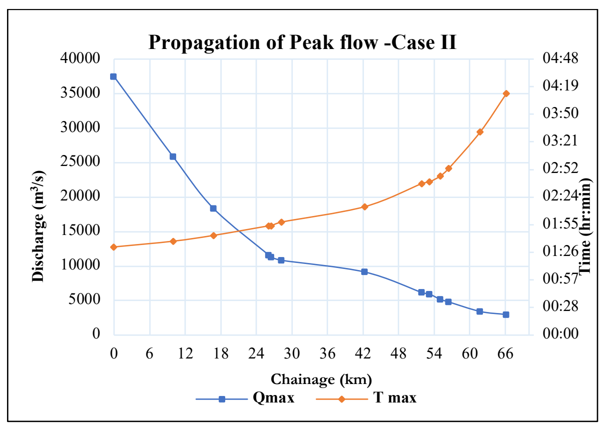

***Fig. 10:** Propagation of the peak flow for Sunny day failure scenario - Case II*

7.3 Case III-Cascade Dam Breach Analysis due to Overtopping during Probable Maximum Flood

The Case III Cascade dam break analysis of Chhukha and Tala Hydropower Plant dam is modelled as a failure caused by overtopping during the Probable Maximum Flood (PMF). In the cascade dam break scenario, the outflow breach hydrograph generated from the Chhukha dam breach was applied as the input hydrograph for the downstream Tala dam. The maximum flow rate during Probable Maximum Flood for Chhukha dam is computed as 7,690m^3/s. The dam failure is attributed to overtopping. In this scenario, the PMF of the Chhukha Dam is applied to simulate its breach, and the resulting outflow hydrograph from the Chhukha PMF breach is used as the input for the cascade dam breach analysis of the Tala Dam.

This scenario considers the incoming inflow and storage area of Tala dam besides the breach outflow hydrograph from Chhukha dam breach. The boundary conditions used for this scenario are:

- Upstream boundary condition.
  - Breach Outflow hydrograph of Chhukha dam with peak discharge of 17,222 m^3/s.
- Downstream boundary condition.
  - Normal depth with an average friction slope of 0.02 m/m.

The inundation area due to PMF dam break scenario for Case III in the downstream area of dam is mapped in Fig. 11.

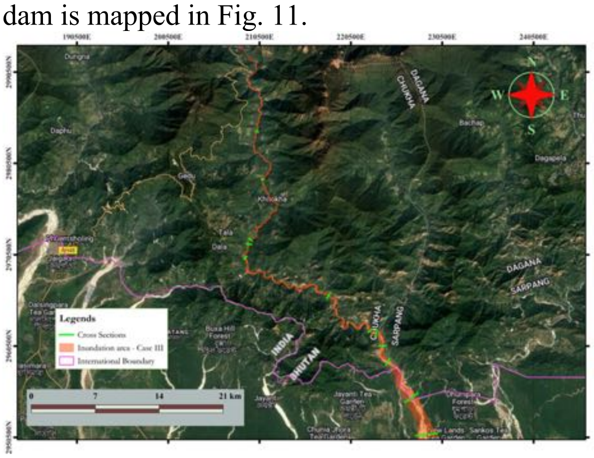

Fig. 11: Flood Inundation map due to PMF failure scenario for Case III

Fig. 12 illustrates the propagation of flow along the identified sections, showing the variation of discharge over time in the downstream reaches while Fig. 13 illustrates the propagation of peak flow, depicting the relationship between peak discharge and arrival time at each identified section.

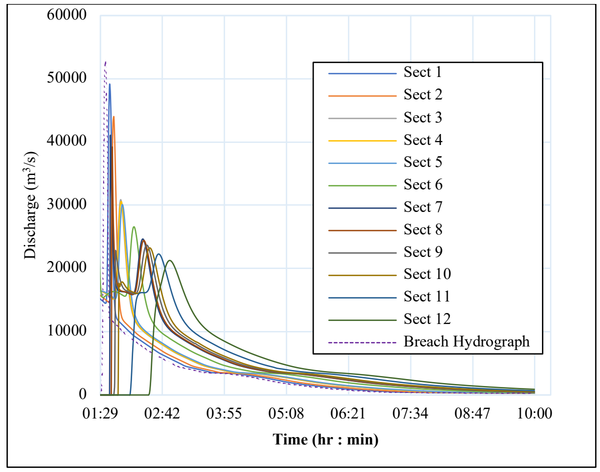

***Fig. 12:** Propagation of the flow during PMF failure scenario-Case III*

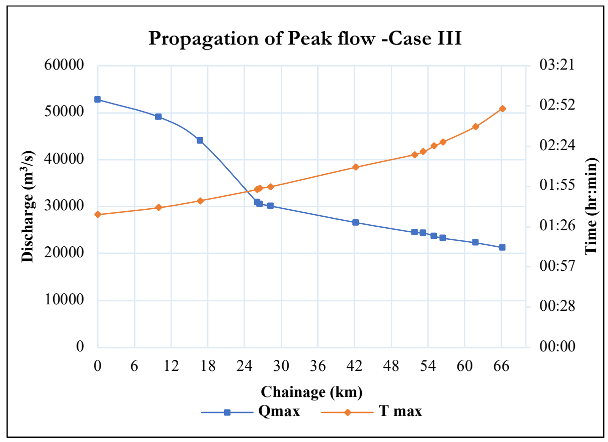

***Fig. 13:** Propagation of the peak flow during PMF failure scenario-Case III*

The peak flow of the breach flow varies from 52,771.27m^3/s at the dam toe to 21,269,29m^3/s at the last section approximately about 66.18km from the dam. The net change in the peak discharge is computed as 31,501.98m^3/s. The peak arrival time, which represents the time difference between the peak at the dam toe and the peak of the flow hydrograph at the final downstream cross-section, is approximately 1 hour 16 minutes.

8 RESULTS AND DAMAGE ASSESSMENT

Table **2** shows the comparison of discharge and Volume between the three cases.

Table 2: *Comparison of the propagation of the flood for the simulated scenarios*

Descriptions		Case I	Case II	Case III
Q_{peak} (Breach flow)	m^3/s	47,364.95	37,469.66	52,771.27
Breach Volume (V_{in})	M m^3	1,544.61	572.90	2,509.19
$Q_{sect\ 12}$	m^3/s	14,310.07	2,983.82	21,269,29
ΔQ	m^3/s	33,054.88	34,486.66	31,501.98

Based on the hydraulic parameters obtained for the delineated sections, the analysis indicates that all the major bridges lose their freeboard under the simulated flood scenarios, with the exception of the Truss Bridge 1 near Tala powerhouse, which remains above the flood level under Case II conditions. The results further show that the THP Main Access Tunnel (MAT) experiences peak flood arrival between 18–22 minutes for all three scenarios, corresponding to peak discharges of 22,622.48 m^3/s, 11,615.87 m^3/s, and 30,879.18 m^3/s for Case I, Case II, and Case III respectively. The maximum water surface elevations at the MAT are 549.84 m.a.s.l., 532.70 m.a.s.l., and 559.68 m.a.s.l. for Case I, Case II, and Case III respectively. Similarly, the Tala Main Store registers peak discharges of 21,952.21 m^3/s, 10,834.02 m^3/s, and 30,113.53 m^3/s, with peak arrival times ranging from 20 to 26 minutes, and corresponding maximum water surface elevations of 504.33 m.a.s.l., 499.05 m.a.s.l., and 513.30 m.a.s.l. for the three cases. At Settlement Area (B), peak discharge values are 22,553.00 m^3/s, 11,288.57 m^3/s, and 30,562.08 m^3/s, arriving at 20, 22, and 19 minutes for Case I, Case II, and Case III respectively. Meanwhile, Settlement Area (C), located at the Jigmechhu camping site, experiences peak discharges of 17,406.80 m^3/s, 6,187.94 m^3/s, and 24,488.58 m^3/s, with corresponding arrival times of 48 minutes, 1 hour 6 minutes, and 43 minutes. The observed maximum water surface elevation at settlement area (B) are 531.54m.a.s.l, 521.83m.a.s.l, 543.81m.a.s.l while at camping site has 189.55m.a.s.l, 184.93m.a.s.l and 198.10m.a.s.l for Case I, Case II and Case II respectively. Overall, the velocity profile indicates that maximum water velocities are highest in the upstream sections close to the dam, with progressively lower peak velocities observed further downstream. Fig. 14 to Fig. 23 shows a detailed of the inundation area in correspondence to above affected areas. Fig. 24 to Fig. 29 shows a maximum inundation depth and velocity in correspondence to the three simulated cases.

Fig. 14: *Detailed view of Inundation area for bailey bridge 2 to Toktokha village*

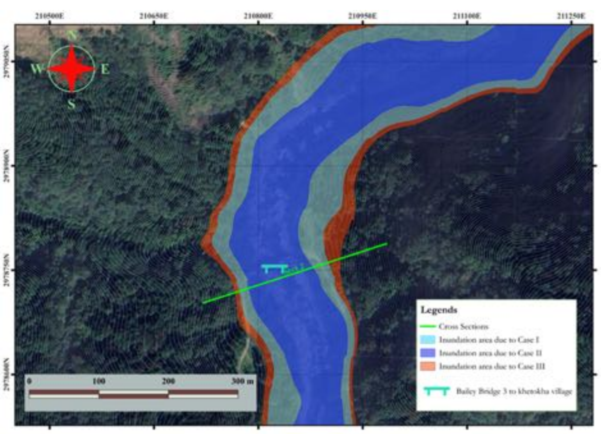

Fig. 15: *Detailed view of Inundation area for bailey bridge 3 to Khetokha village*

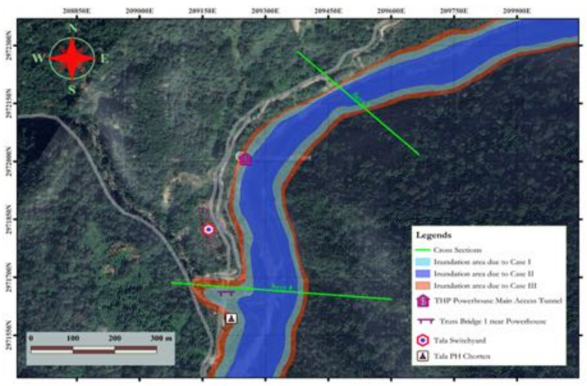

Fig. 16: *Detailed view of Inundation area for Tala Powerhouse Main Access Tunnel area and Truss bridge 1*

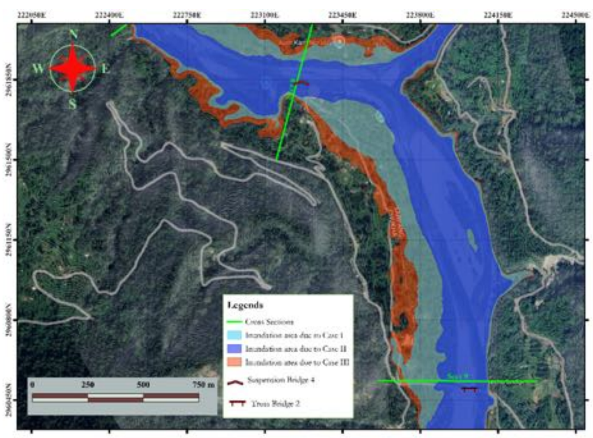

Fig. 17: *Detailed view of Inundation area for Suspension bridge 4 and Truss bridge 2*

Fig. 18: *Detailed view of Inundation area for THP main store and its vicinity*

Fig. 19: *Detailed view of Inundation area for settlement area B*

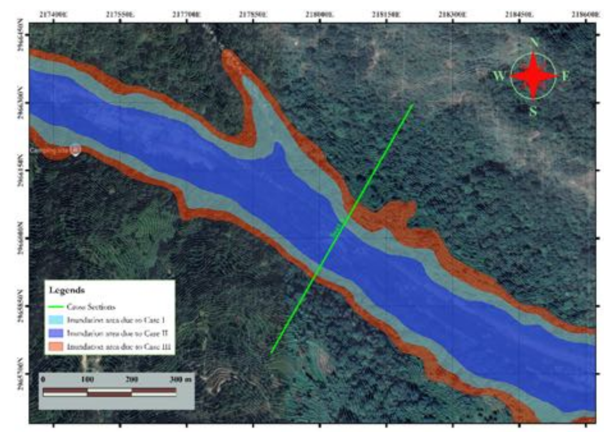

Fig. 20: *Detailed view of Inundation area for settlement area C (Vicinity of section 6)*

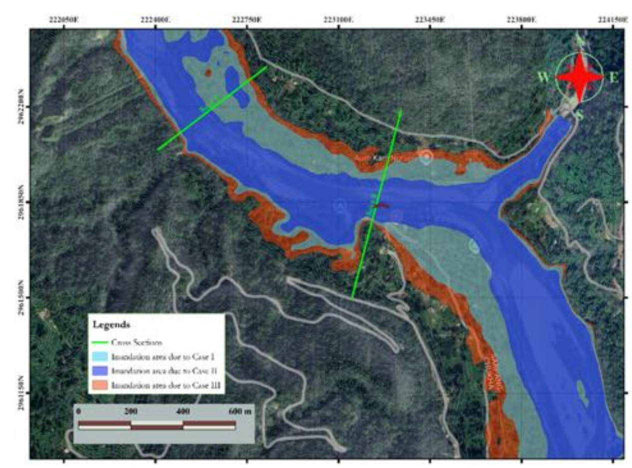

Fig. 21: *Detailed view of Inundation area for settlement area C (Between sections 7 and 8)*

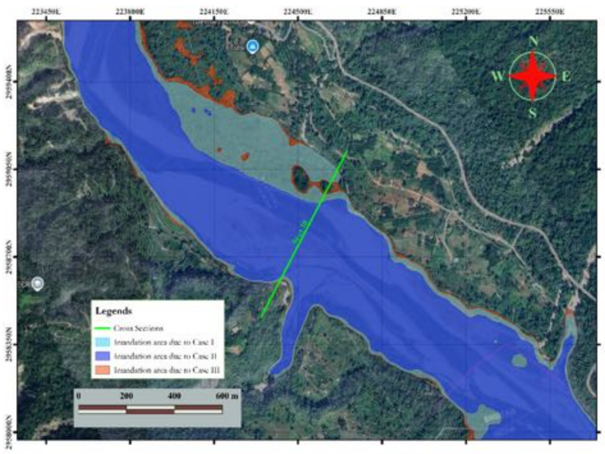

Fig. 22: *Detailed view of Inundation area for settlement area C (Vicinity of section 10)*

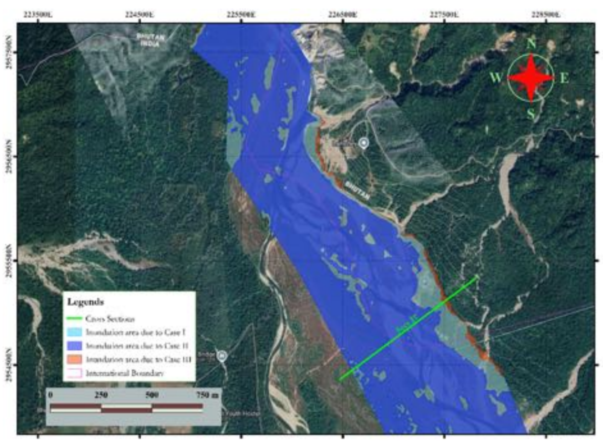

Fig. 23: *Detailed view of Inundation area for settlement area C (Vicinity of section 11)*

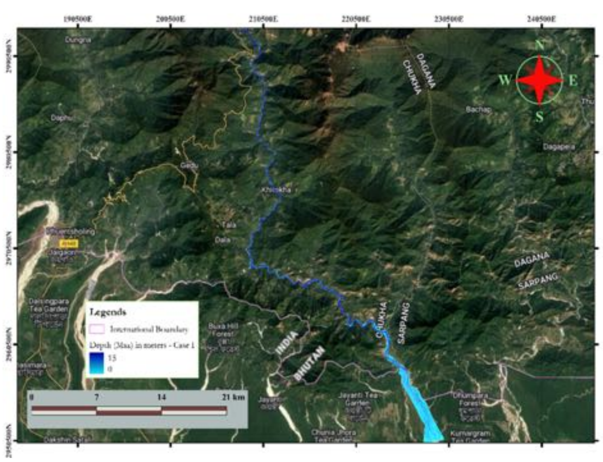

Fig. 24: *Maximum depth due to dam breach from Case I*

Fig. 25: *Maximum velocity due to dam breach from Case I*

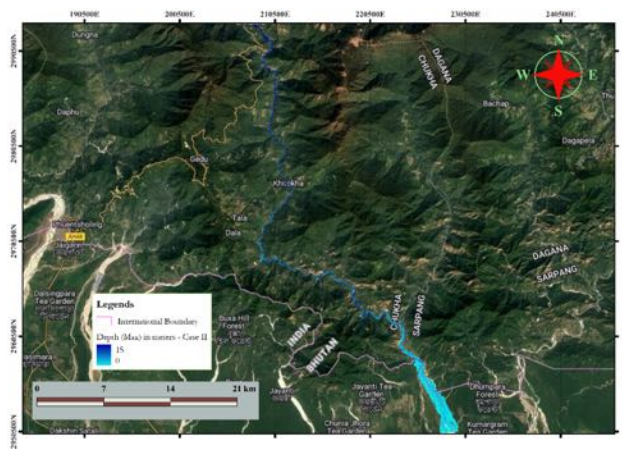

Fig. 26: *Maximum depth due to dam breach from Case II*

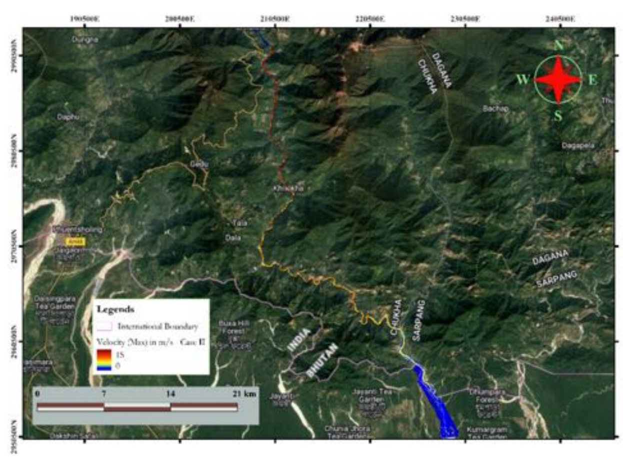

Fig. 27: *Maximum velocity due to dam breach from Case II*

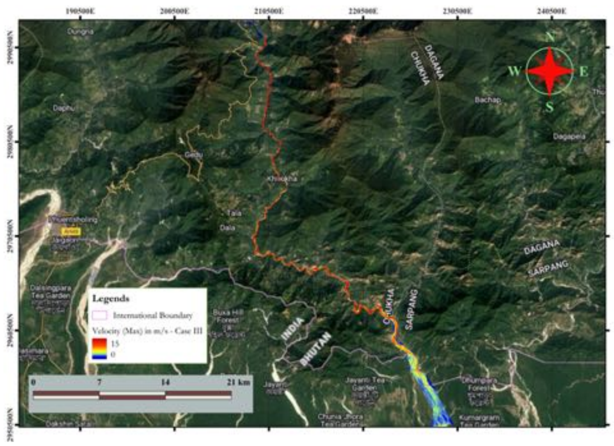

Fig. 28: *Maximum velocity due to dam breach from Case III*

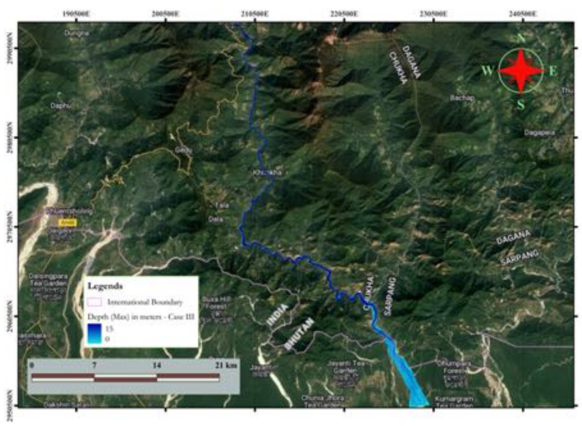

Fig. 29: *Maximum depth due to dam breach from Case III*

9 THRESHOLD LEVELS

The threshold levels, as per (Gautam & Dulal, 2013) has defined the warning level as the flood flow that just passes over the riverbank but does not affect the nearby settlement. The danger level corresponds to the discharge at which floodwaters overtop the main channel and begin to enter nearby settlements, posing risks to people and property, although the inundation depth does not exceed one meter.

Based on the above, the warning level and danger levels have been identified for THP by analyzing the flood inundation scenario so that warning could be given to the specific areas for the emergency response. The threshold inflow for the warning and danger levels for THP is shown in Table 3.

Table 3: *Threshold inflow for warning and danger level for THP Powerhouse area and settlement area B*

SN	Threshold level	Inflow (m^3/s)	Elevation (m)	Area
1	Warning Level	3,260.39	527.10	Settlement area B and Powerhouse area
2	Danger Level	3,760.63	528.00	
3	Warning Level	7,134.541	307.91	Settlement area C at Jigmechhu area
4	Danger Level	7,887.782	308.06	

10 SENSITIVITY ANALYSIS

A sensitivity assessment was carried out to evaluate how changes in the dam-breach parameters influence the overall results. The parameters include the breach elevation, breach width and breach formation time. This analysis follows a sensitivity framework presented by Khanal et al, (2025), which evaluates how changes in each parameter influence the peak discharge, the time of flood arrival, and the resulting water surface elevations. The evaluation focused on downstream impacts on the selected cross sections, specifically analyzing flow elevation, flood arrival time, and peak discharge to assess the effects of these parameters.

The analysis indicates that lowering the breach elevation results in increased water surface elevations and peak discharges, accompanied by a slight decrease in the time of arrival of the peak discharge at the evaluated sections. For instance, at section 9, the peak discharge increases from 31,259.70m^3/s to 40,877.34m^3/s, when the breach elevation reduces from 1,315 to1,291m. Similarly, at section 4, this reduction in the breach elevation leads to a substantial rise in peak discharge from 20,814.83 to 22,553.00 m^3/s. This indicates a direct correlation between breach elevation and increased flow rates. Lowering the breach elevation reduces the flood arrival time at downstream locations, indicating a more rapid flood propagation. For instance, at section 1, the peak arrival time reduces from 6 minutes to 4 minutes when breach elevation drops from 1315m to 1291m.

This illustrates that breach elevation is a critical factor influencing the magnitude and timing of flood impacts, with lower elevations leading to more severe and rapid flooding, particularly in regions closer to the dam. Breach width also significantly affects downstream flood dynamics, with wider breaches causing higher peak discharges and increased flood propagation. For instance, increasing the breach width from 45 to 65m increases the peak discharge 14, 310.07 m^3/s to 15,248.43m^3/s. Increasing the breach formation time from 0 hour to 0.5 hour reduces the peak discharge from 18,665.11m^3/s to 23,553.00m^3/s.

Thus, the breach formation time has also a considerable impact on the parameters such that with quicker breach formation time resulting in greater peak discharges. These findings highlight the significant influence of breach parameters on the magnitude and timing of downstream flooding. Among these, breach elevation is the most sensitive parameter, followed by breach width and breach formation time compared to other factors.

11 CONCLUSIONS AND RECOMMENDATIONS

The dam break analysis of the Tala Hydropower Plant has revealed critical insights into the potential risks and impacts associated with a dam failure. The analysis indicates that a dam break could lead to significant inundation in downstream areas, posing threats to both human life and infrastructure. The study carried out provides crucial insights into downstream flood risks which could aid in planning safety measures and disaster risk reduction. The total inundated areas for Case I-THP dam breach during PMF condition, Case II-Cascade dam breach during Sunny Day at Full Reservoir Level, and Case III-Cascade dam breach due to Overtopping during PMF condition are 19.50 km², 15.67 km², and 21.12 km², respectively, with flood propagation extending up to the Indian plains (Indo-Bhutan border).

From the results, it shows that no freeboards are left for key downstream bridges during all the three cases. The maximum water surface elevations exceed the critical thresholds, indicating significant inundation risks and potential structural failure in all the cases. In the sunny day cascade scenario, the inundation extent and flow propagation does not affect the Tala Main store area. However, PMF scenarios demonstrates a significant escalation in flood risks, with higher peak discharges and water surface elevations extending inundation all the downstream structures such bridges and Tala powerhouse MAT including the THP main store area. This highlights the heightened vulnerability of these areas under extreme flood conditions. The dam-break analysis of the Tala Hydropower Plant underscores critical implications for downstream areas, emphasizing the need for this study due to the presence of vulnerable settlements and infrastructure.

Notably, the Jigmechhu camping site, Tala Main store and Tala powerhouse MAT located downstream of the dam, could be at risk of rapid flooding in the event of a dam failure, posing potential hazards to occupants and associated facilities. Additionally, the analysis is crucial for planning and safeguarding future hydropower projects in the region, ensuring that flood risks are adequately assessed and mitigated. A sensitivity analysis performed for the study indicates the breach elevation is a critical factor influencing the magnitude and timing of flood impacts, with lower elevations leading to more severe and rapid flooding, particularly in regions closer to the dam.

Thus, it can be concluded that peak flood discharges and flood stage are more sensitive to breach elevation (breach height) than other dam breach parameters. A potential dam-break event would pose substantial hazards to downstream areas, as the resulting high discharge could trigger rapid erosion and landslides. Critical infrastructure, including bridges, offices, and nearby settlements, would be highly vulnerable to flooding impacts. To reduce these risks and enhance the safety of downstream communities, the implementation of an early warning system supported by real-time monitoring of water levels and flow rates is essential. Furthermore, the flood inundation maps generated in this study can assist in identifying high-risk zones, thereby enabling timely evacuation and effective emergency response planning.

This dam break analysis was conducted utilizing a 2.5m Digital Terrain Model (DTM) as the primary source of topographic data. Although this analysis offers valuable insights, it is evident that the accuracy and level of detail of the results could be substantially enhanced through the use of advanced modeling techniques and increased computational resources. Since the analysis utilizes 2.5 m satellite-derived DTM data, which exhibits minor deviations from ground-survey benchmarks, a degree of uncertainty is expected in the output values, particularly in elevation-dependent flood estimations. In addition, the reliability of the results is subject to the limitations of model assumptions and the inherent uncertainties associated with hydraulic modelling processes.

Thus, to ensure the accuracy and reliability of numerical dam break models, it is crucial to validate and calibrate them against experimental data obtained from physical modeling. It can help in improving model accuracy, reducing uncertainty and helps in overall decision-making. Therefore, it is strongly recommended to integrate both numerical and physical modeling approaches.

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