

# Flood Arrival Time Reporting in Dam-Breach Emergency Action Planning: Why the Reference Point Matters

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## Short Report

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# Abstract

Emergency Action Plans (EAPs) for dam-breach hazards rely on flood arrival time as the primary basis for warning protocols, yet arrival time is frequently reported from simulation start rather than from the moment of breach initiation. This short communication demonstrates the practical consequences of that distinction using a two-dimensional HEC-RAS breach analysis of the proposed (not yet constructed) Naumure Dam, a 169 m concrete-face rockfill dam on the West Rapti River, Nepal. Under the worst-case breach scenario (S3: sudden overtopping, 0.5-hour breach formation time), simulated flood arrival times at 148 downstream villages ranged from 14.33 to over 20 hours measured from simulation start. Because breach initiation itself occurred 14.33 hours into the simulation, the actual warning time available to the three nearest communities was only 10–40 minutes, not 14 + hours as a simulation-referenced reading would suggest. We term this discrepancy the "warning time paradox" to emphasize its operational implications for emergency planning and argue that it reflects a systematic ambiguity in how arrival time is conventionally reported, rather than a limitation specific to this case. The remaining villages retained 40 minutes to 5 hours 40 minutes (90 villages, 61.1%) or more than 5 hours 40 minutes (55 villages, 36.9%) of actual, breach-referenced warning. We recommend that arrival-time reporting in dam-breach studies be explicitly referenced to breach initiation rather than simulation start, to avoid overestimating the time available for emergency response, and we propose a tiered, warning-time-based evacuation zoning scheme for the Naumure Dam with wider applicability to EAP design.

## 1. Introduction

Dam failure can produce uncontrolled downstream inundation and mass displacement within hours (USACE 2014; Xu and Zhang 2009). In Nepal, steep terrain, active Himalayan geology, and a rapidly expanding hydropower portfolio combine to elevate both the likelihood and consequence of dam-breach events, and embankment and rockfill dams are frequently sited in narrow gorges immediately upstream of populated valleys, leaving downstream communities very little time to react (Schwanghart et al., 2018).

For any dam-breach Emergency Action Plan, one of the most operationally important outputs of a hydraulic model is flood arrival time: the interval available to warn, mobilize, and evacuate downstream communities before floodwaters arrive. Warning protocols, siren placement, evacuation route capacity, and drill frequency are, in practice, designed around this number. It is therefore essential that arrival time be reported in a way that corresponds to the actual decision window available to emergency managers, rather than to an arbitrary modelling clock.

A persistent but under-discussed issue in the dam-breach modelling literature is that arrival time is conventionally reported from the start of the simulated hydrological event; typically the onset of the inflow hydrograph rather than from the moment the dam actually breaches. In slow-forming floods this distinction is immaterial, but in breach-driven floods, where the reservoir may take many hours to reach a triggering water level before failure initiates rapidly, the gap between simulation-referenced and breach-

referenced arrival time can be substantial. This is consistent with broader observations that translating hydraulic model output into decision-relevant guidance for emergency planning remains inconsistently addressed in the dam-breach consequence literature (Ge et al. 2019).

This paper uses the worst-case breach scenario from a HEC-RAS 2D analysis of the proposed Naumure Dam, building on an earlier numerical dam-break study of the same project (Nepal et al. 2023), to quantify and illustrate this gap, which we term the “warning time paradox”: simulation-referenced arrival times that appear to offer 14 or more hours of warning in fact correspond to as little as 10 minutes of actual warning once breach initiation is accounted for. The contribution of this paper is not the recalculation itself, which is arithmetically straightforward, but the demonstration of its operational consequences. EAP elements such as siren activation, staffing, and drill frequency may be calibrated to arrival-time figures reported by supporting hydraulic studies; therefore, an arrival time that is not explicitly referenced to breach initiation can lead to misinterpretation of the time actually available for emergency response. Our objective is threefold: (i) to present this discrepancy using village-level arrival-time data; (ii) to translate it into a warning-time-based zoning framework with direct EAP application; and (iii) to argue for breach-referenced arrival-time reporting as standard practice in dam-breach studies intended to inform emergency planning.

## 2. Methods

The study area, hydraulic model, and breach-scenario design summarized below were developed as part of a broader dam-break hazard assessment of the Naumure Dam; a companion manuscript (submitted separately) provides the full model description, sensitivity analysis, and hazard/vulnerability mapping, and is referenced here only to the extent necessary to interpret the arrival-time results that are the focus of this communication.

### 2.1 Study area

The proposed Naumure Multipurpose Project is a 169 m concrete-face rockfill dam (CFRD) on the West Rapti River in western Nepal (27.92°N, 83.17°E), approximately 2 km downstream of the confluence of the Jhimruk and Mari Khola tributaries, with a catchment area of 3,414 km<sup>2</sup> and a crest length of 690 m. The downstream corridor passes through a steep, narrow Himalayan valley before opening into more densely settled terrain across the Pyuthan, Arghakhanchi, and Dang districts, where 149 villages were identified within the maximum simulated inundation extent.

### 2.2 HEC-RAS 2D model and breach scenarios

A two-dimensional hydraulic model was developed in HEC-RAS using a 30 m Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM) (USGS 2015), with a 200 m × 200 m base computational mesh refined to 30–50 m near the dam toe, breach zone, and narrow valley sections. Five breach scenarios were simulated by systematically varying breach width, formation time, failure mechanism, and location, following Froehlich (2008) breach parameter relationships, which are widely applied to

CFRD and embankment dams of comparable scale (Awal et al. 2024; Regmi et al. 2025). Scenario S3 (sudden overtopping, 199 m breach width, 0.5-hour formation time) produced the highest peak discharge and shortest time to peak (40 minutes) of the five scenarios and was identified as the worst-case condition for downstream hazard assessment; it is the scenario used throughout this communication. Rapid, overtopping-induced breaching of concrete-face rockfill dams of comparable design has been documented elsewhere (e.g., the Upper Taum Sauk Dam failure; Mei et al. 2023; Zuo et al. 2024), indicating that the short formation time assumed in S3 is a physically plausible upper-bound scenario rather than a purely theoretical construct.

## 2.3 Arrival time calculation

Arrival time rasters for Scenario S3 were imported into QGIS and sampled at all 149 village locations. Arrival time was defined as the time at which simulated flow depth first exceeded 0.1 m at each location, measured from the start of the hydrological simulation (00:00 on the model start date). One village with incomplete data was excluded from the arrival-time and risk analyses, leaving 148 villages in Table 1. Breach initiation in S3 occurs 14.33 hours (14 h 20 min) into the simulation, after the reservoir inflow hydrograph reaches the triggering water level. The actual, breach-referenced warning time at each village was recalculated as the simulation-referenced arrival time minus 14.33 hours. This breach-referenced value, not the simulation-referenced value, represents the warning interval genuinely available to downstream communities and emergency responders. The breach initiation time of 14.33 hours is itself a model output, subject to the same hydrological and breach-triggering assumptions as the rest of the simulation; its uncertainty, and the implications for interpreting breach-referenced warning time, are discussed in Section 4.4.

## 3. Results

### 3.1 Arrival time distribution

Under Scenario S3, all 148 affected villages recorded simulation-referenced arrival times exceeding 14 hours (Table 1). At first glance, this would suggest that every community has at minimum a 14-hour warning window which is an interpretation that would substantially overstate the time actually available for EAP design. The spatial pattern of simulation-referenced arrival times is illustrated in Fig. 1.

### 3.2 The warning time paradox

Breach initiation in S3 occurs at 14.33 hours into the simulation. Recalculating each village's arrival time relative to this breach onset, rather than to simulation start, produces a starkly different picture (Table 1). The three nearest villages, whose simulation-referenced arrival times fall in the 14.33–15-hour class, in fact receive only 10 to 40 minutes of actual warning between breach initiation and flood arrival. This is the core of the warning time paradox: a simulation-referenced arrival time of '14 + hours' and a breach-referenced warning time of '10–40 minutes' describe the same physical event, but only the latter is operationally meaningful for emergency response.

Table 1  
Village arrival-time and warning-time classes for Scenario S3 (n = 148)

| Arrival class               | Simulation-referenced arrival time (h) | Breach-referenced (actual) warning time | Villages   | %            |
|-----------------------------|----------------------------------------|-----------------------------------------|------------|--------------|
| Moderate (shortest warning) | 14.33–15                               | 10–40 min                               | 3          | 2.0          |
| Slow                        | 15–20                                  | 40 min – 5 h 40 min                     | 90         | 61.1         |
| Very slow (longest warning) | > 20                                   | > 5 h 40 min                            | 55         | 36.9         |
| <b>Total</b>                | <b>14.33–&gt;20</b>                    | <b>10 min–&gt;5 h 40 min</b>            | <b>148</b> | <b>100.0</b> |

For the remaining villages, the practical warning window remains substantial once correctly referenced to breach onset: 90 villages (61.1%) retain between 40 minutes and 5 hours 40 minutes of actual warning, and 55 villages (36.9%) retain more than 5 hours 40 minutes. This confirms that the paradox is concentrated in a small but critical subset of near-dam communities, while the majority of the downstream population retains a genuinely workable evacuation window, provided that a warning system is triggered immediately at breach onset rather than at some later observation of downstream flooding.

### 3.3 Integrated hazard and risk context

A combined flood hazard index (depth × velocity) classified 28 villages (18.9%) as Extreme hazard and 89 (60.2%) as High hazard under S3, together exposing an estimated 242,891 people across six local government units, of whom 196,993 (81.1%) fall within Extreme-hazard local levels. Combining hazard level with warning-time-based vulnerability in an integrated risk matrix (Hazard × Vulnerability); consistent with internationally recognized disaster risk reduction frameworks that combine hazard and vulnerability to prioritize response measures (UNDRR 2015) identifies 3 villages (2.0%) as Extreme Risk, those facing Extreme or High hazard with less than 15 hours of simulation-referenced arrival time, corresponding to the 10–40-minute breach-referenced warning band, alongside 67 villages (45.3%) at High Risk and 71 villages (48.0%) at Moderate Risk. The spatial distribution of integrated risk, with Extreme Risk villages concentrated near the dam, is shown in Fig. 2.

Together, these results show that the villages facing the shortest actual warning time are also, in most cases, those facing the most severe flood hazard, compounding the urgency of correctly referencing arrival time for this subgroup in particular.

## 4. Discussion

### 4.1 Why the reference point matters for EAP design

The warning time paradox is not a modelling artefact; it is a reporting convention with direct safety consequences. An EAP author who reads Table 1 using simulation-referenced values alone might conclude that no village in the study area requires a warning response faster than 14 hours, and design siren activation, staffing rosters, and drill frequency accordingly. In reality, the three nearest villages require an automated response capable of alerting residents within minutes of breach detection, since 10–40 minutes leaves little margin for manual decision-making, verification, or phone-tree cascades.

## **4.2 Relation to prior work on breach consequence reporting**

This finding is consistent with broader concerns raised in the dam-breach consequence assessment literature regarding the difficulty of translating hydraulic model output into decision-relevant guidance (Ge et al. 2019). Similar HEC-RAS-based breach analyses have been developed for other dams in Nepal (e.g., Khanal et al. 2025, for the Nagmati and Dhap dams; Shrestha et al. 2025, for the Dudhkoshi Storage Hydroelectric Project) and internationally (e.g., Aldrees et al. 2025, for the Tiga Earth Dam, Nigeria), indicating that the modelling approach used here reflects a broader, internationally applied practice rather than a method specific to Nepal or to this dam. This suggests that the reference-point ambiguity identified here is unlikely to be unique to the Naumure case, although a systematic review of arrival-time reporting conventions across this wider literature is beyond the scope of the present communication. Where prior studies have focused on rapid estimation of breach consequences at a regional scale, our results point to a complementary and more basic issue: even when a detailed 2D hydraulic model is available, the arrival-time metric it produces can be reported in a form that obscures rather than clarifies the true warning window, unless the reference point is made explicit and tied to breach initiation. We suggest that dam-breach studies intended to inform EAPs should, as standard practice, report both the simulation-referenced arrival time (for hydraulic transparency) and the breach-referenced warning time (for operational use), together with the breach initiation time that connects them.

## **4.3 Recommendations for dam safety practice**

Based on these results, we recommend that: (i) dam-breach studies explicitly state the breach initiation time relative to simulation start, and report arrival time in both simulation-referenced and breach-referenced forms; (ii) EAPs for dams with near-field communities design automated, breach-triggered warning systems (e.g., reservoir-level and rate-of-rise triggers linked directly to SMS, sirens, and direct calls) rather than relying on manual detection of downstream flooding, given warning windows as short as 10 minutes; (iii) evacuation drills for the shortest-warning communities be conducted at least twice annually, reflecting the near-total absence of decision time; and (iv) risk communication materials for downstream communities present warning time in breach-referenced terms only, since simulation-referenced figures could otherwise overstate the time available for response. The tiered warning framework in Table 2, derived directly from the breach-referenced classes in Table 1, offers a template for such implementation at Naumure Dam. Implementation of the Zone A protocol, in particular, presumes reliable cellular or radio communication infrastructure near the dam; where such infrastructure

is not yet in place, its establishment should be treated as a prerequisite for automated warning capability rather than assumed.

Table 2

Proposed tiered warning-zone framework for the Naumure Dam, derived from breach-referenced warning time

| Warning zone       | Actual warning time (from breach) | Villages | Recommended warning method                                                                                                    |
|--------------------|-----------------------------------|----------|-------------------------------------------------------------------------------------------------------------------------------|
| Zone A – Immediate | 10–40 min                         | 3        | Automated SMS, sirens, direct phone calls to village leaders; twice-yearly evacuation drills; pre-positioned rescue resources |
| Zone B – Rapid     | 40 min – 5 h 40 min               | 90       | Mobile alerts, radio broadcasts, door-to-door warnings; annual drills; community warning teams                                |
| Zone C – Phased    | > 5 h 40 min                      | 55       | Public announcements, community mobilization, phased and livestock evacuation                                                 |

## 4.4 Limitations

This analysis carries several limitations common to pre-construction dam-breach hazard studies. Breach parameters follow the Froehlich (2008) empirical relationships, which carry reported prediction intervals of approximately  $\pm 30\%$  for breach width and  $\pm 50\%$  for formation time; alternative empirical approaches (e.g., Von Thun and Gillette 1990; MacDonald and Langridge-Monopolis 1984) would yield different absolute breach-parameter estimates and, consequently, different absolute arrival and warning times, although the direction of the effect described here, a compressed warning window for near-dam communities relative to a simulation-referenced reading would be expected regardless of the specific empirical method used. The 30 m SRTM DEM introduces topographic generalization in narrow valley sections, and no observed breach or flood event exists for model calibration, as the Naumure Dam is not yet constructed. The 0.5-hour formation time in Scenario S3 is an intentionally conservative, upper-bound assumption for EAP purposes and should not be read as a predicted failure mode.

A further source of uncertainty specific to the warning time paradox itself is the breach initiation time (14.33 hours), which is a model output rather than an observed quantity: it depends on the inflow hydrograph used to drive the simulation and on the reservoir water level assumed to trigger failure. Under a different inflow scenario, or a different triggering-level assumption, breach initiation could occur earlier or later in the simulation, which would shift the absolute breach-referenced warning times reported in Table 1 without changing the underlying relationship between simulation-referenced and breach-referenced reporting. The magnitude of the warning-time compression reported here (10–40 minutes for the nearest villages) should therefore be treated as illustrative of the scale of the effect rather than as a precise operational figure, and EAP developers should treat the shortest-warning class in Table 1 as an upper-bound estimate of available response time rather than a guaranteed minimum. These uncertainties affect the precise magnitude of arrival and warning times but do not affect the qualitative conclusion: any breach-driven flood with a rapid formation time will produce a warning

window at near-dam locations that is materially shorter, and potentially an order of magnitude shorter, than simulation-referenced arrival time alone would suggest.

## 5. Conclusions

Flood arrival time is the operational backbone of dam-breach Emergency Action Plans, but its value depends entirely on the reference point from which it is measured. In the worst-case breach scenario for the proposed Naumure Dam, simulation-referenced arrival times of 14 hours or more translate, once correctly referenced to breach initiation, into actual warning times of only 10 to 40 minutes for the three nearest downstream villages. The remaining 145 villages retain substantial, genuinely usable warning windows once similarly re-referenced. We recommend that dam-breach studies intended to support emergency planning report arrival time in explicit breach-referenced terms alongside any simulation-referenced value, and that EAPs for near-field communities be built around automated, breach-triggered warning systems rather than manual response protocols, subject to confirmation of local communication infrastructure. Applied to Naumure Dam, this reframing identifies a small, high-priority group of communities for which automated warning capability should be treated as a leading priority in EAP development.

## Declarations

## Competing Interests

The author has no relevant financial or non-financial interests to disclose.

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## Author Contributions

Prashant Chaudhary: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review and editing.

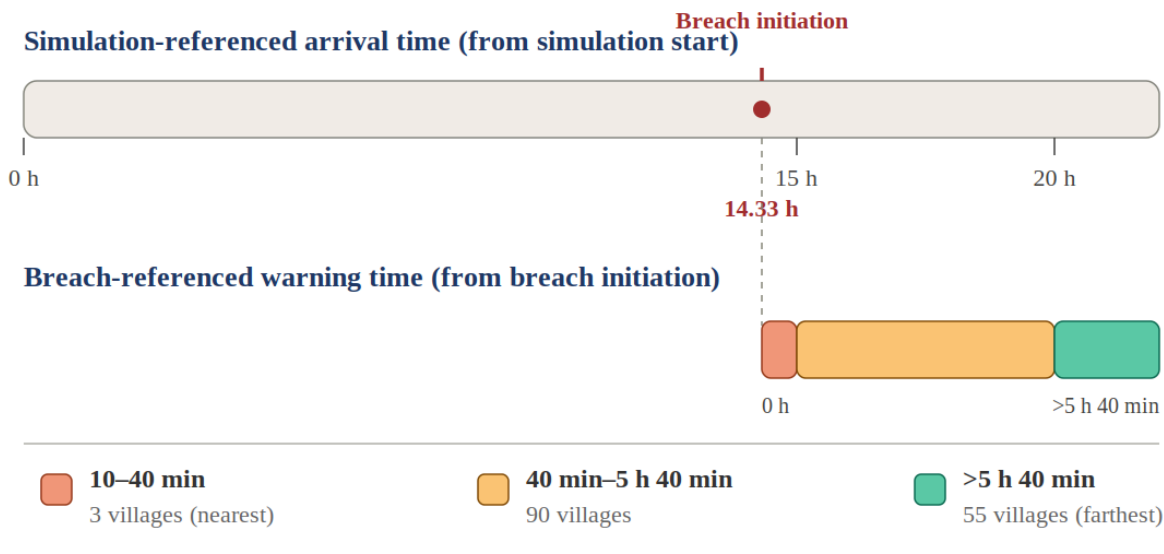
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Figures



Same physical event, two reference frames: reading the top axis alone overstates warning time for the nearest villages by more than an order of magnitude.

Data: Table 1 (Scenario S3, 148 villages). Diagram concept is original to this manuscript.

Figure 1

Comparison of simulation-referenced arrival time and breach-referenced warning time for Scenario S3. The dashed line indicates the breach initiation time (14.33 h)

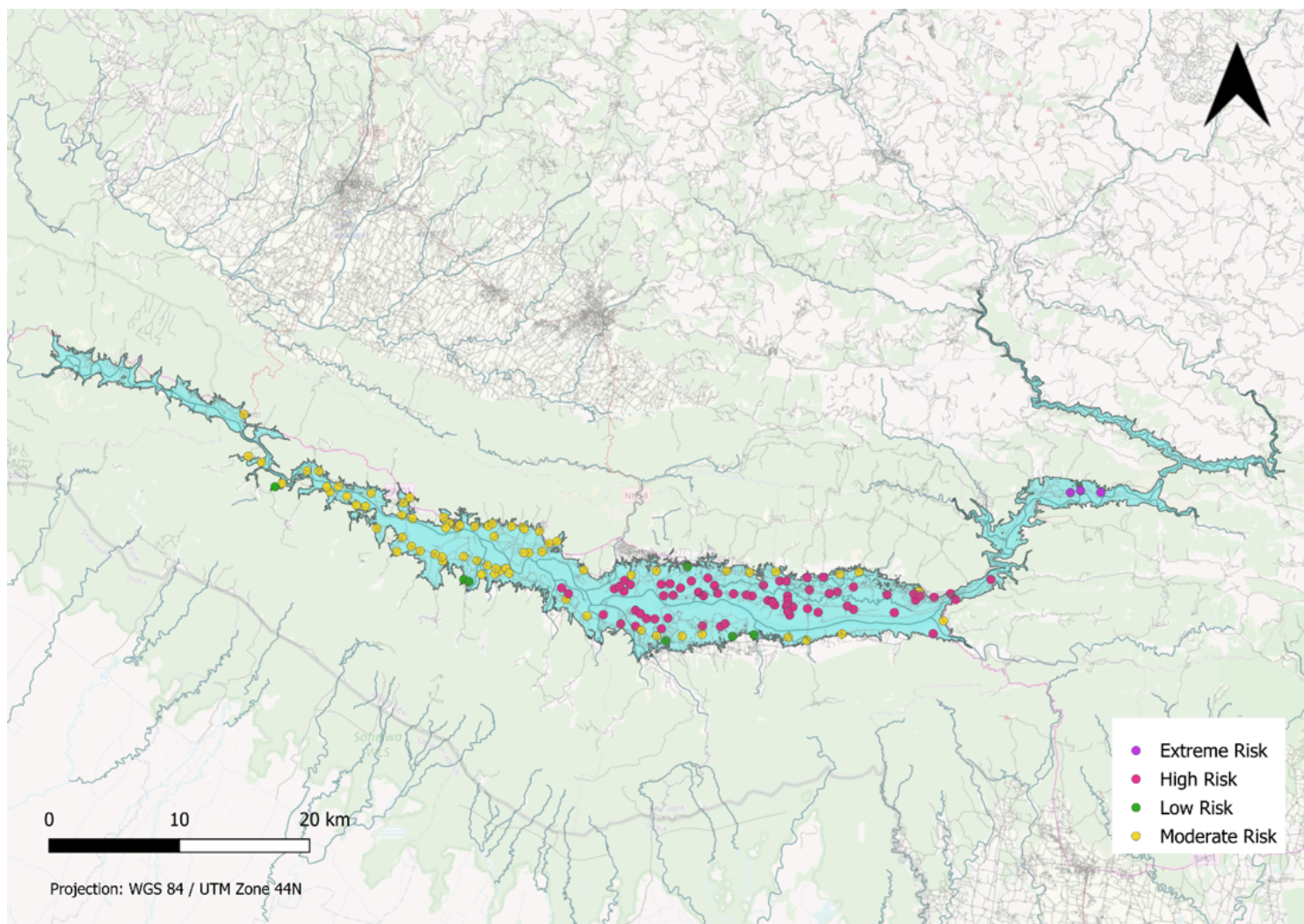


**Figure 2**

**Integrated risk map for the worst-case scenario (S3). Village points are coloured by risk category (Hazard × Vulnerability)**