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Peer-review status

This manuscript is a non-peer-reviewed preprint submitted to EarthArXiv. It has not been peer reviewed.

The manuscript has also been submitted to *Landslides*. It has not been accepted for publication.

This file includes the manuscript and Supplementary Information.

Preprint DOI: [10.31223/X5250R](https://doi.org/10.31223/X5250R)

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Updated: 7 September 2026

A rock–ice avalanche and the 2026 Bhote Koshi–Trishuli flood, Nepal

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Abstract

On 26 August 2026 a rock–ice avalanche in the Langtang Himal produced a debris flow and flood that destroyed the Rasuwagadhi–Gyirong border crossing within minutes and reached Devghat about six hours later. We reconstruct the cascade with a depth-averaged mixture-flow model constrained by the seismic origin time, a CCTV frame, gauge outages in the gorge and downstream stage records. The model distinguishes rock, ice and water densities and conserves mass during melting. For a release of 35.4 million cubic metres with 20% ice, added at rest, the front reaches Gyirong Port at 390 s and Syabrubesi at 1050 s, within the working observation windows. Parameter comparisons favour low effective resistance within the tested source and terrain scenarios. Downstream routing selected using waveform errors gives stage rises of 8.94 m at Galchhi and 4.98 m at Kali Khola, compared with observed rises of about 8.8 and 5.6 m. Their model rise times of 1.85 and 4.77 h also fall within the observation windows. Without prescribing an additional outburst from a temporary landslide dam, the reconstruction reproduces the upper timing windows and broadly follows these two downstream hydrographs. The results support an avalanche-derived surge followed by valley-controlled redistribution and identify low effective resistance and lateral storage as controls within the adopted model.

Keywords: rock–ice avalanche, cascading hazards, debris flow, flood routing, Himalaya, mass conservation

Introduction

Rock–ice avalanches that turn into long-runout floods are among the most destructive process chains of the high mountains (Shugar et al. 2021, Kääb et al. 2021, 2018, Hungr et al. 2014). In the Himalaya they share their corridors with glacial-lake outburst floods, whose hazard and geomorphic work are far better documented (Westoby et al. 2014, Cook et al. 2018, Veh et al. 2020), and the 2016 Bhote Koshi outburst flood ran down the same gorge as the 2026 event (Cook et al. 2018). The 2021 Chamoli disaster showed how a seismically dated release, satellite mapping, eyewitness video and flow modelling together constrain the sequence of such a cascade (Shugar et al. 2021, Mergili et al. 2020). Two questions remained open there. How does a granular mass of rock and ice acquire the mobility of a flood within minutes of the release, and what controls the flood wave once it leaves the mountains?

The 26 August 2026 Langtang event has a hydrometric record along the cascade in addition to the Chamoli-type constraints. A seismically dated release (02:52:10 UTC), a CCTV frame near the border and stations of the Department of Hydrology and Meteorology bracket the front through the gorge and along the Trishuli. Rasuwagadhi and Syabrubesi lost telemetry in the gorge, Betrawati stopped reporting, Malekhu crossed its warning level, and Galchhi, Kali Khola and Devghat recorded the wave. Satellite mapping identifies the affected surface and channel elevation change, extending the products that the 2015 Gorkha earthquake response established for this region (Kargel et al. 2016). Instrument failure, trimlines and gauge stage each constrain a different part of the process and are not interchangeable measurements of the front.

We use these records to answer the two questions with a forward model scored against working criteria defined from the records (Methods). The reconstruction follows one process chain: the release descends into the gorge, moves as a solids-rich mixture, melts and entrains water and sediment, and enters the Trishuli as a surge whose downstream evolution depends on the storage and conveyance of the valley floor. We test whether this chain reproduces the observations without adding a separate reservoir release. Agreement would not by itself exclude a short-lived blockage or establish how the material acquired its mobility.

Figure 1 provides an overview of the reconstructed passage through the upper corridor.

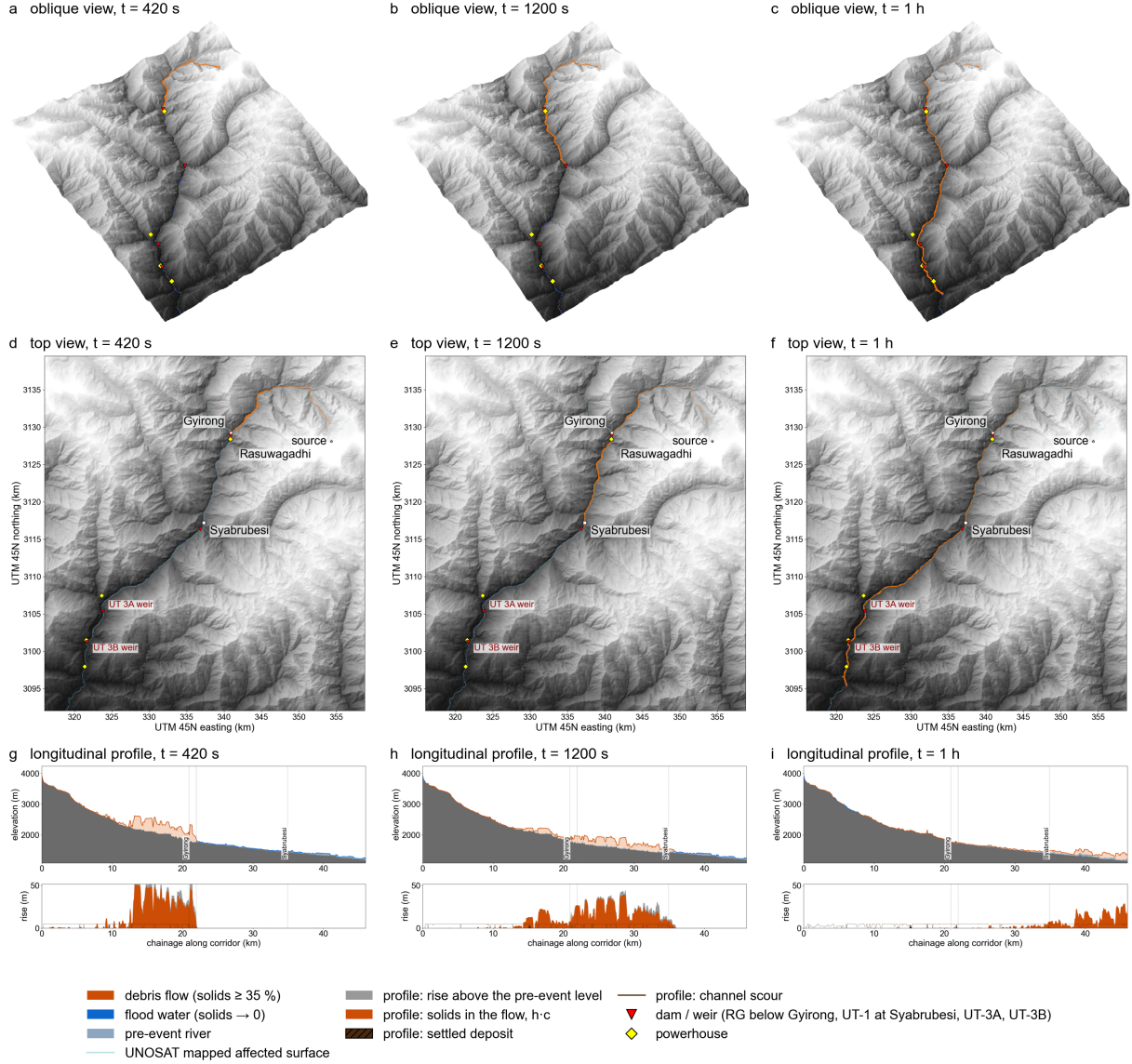


Figure 1: The release crossing the gorge. Oblique (a–c) and plan (d–f) views and the longitudinal profile (g–i) of the corrected reconstruction on the 60 m corridor grid at 420, 1200 and 3600 s. Orange denotes solids-rich mixture and blue denotes diluted flood water. Muted cyan outlines the archived UNOSAT affected surface. Flow depth in the oblique views is exaggerated fourfold. Profiles show the model bed and flow, with depth exaggerated eight times in the upper profile and stage change at true scale below. Dam and powerhouse symbols retain the archived infrastructure mapping. The spatial reconstruction is a model prediction, not an observed inundation map. The 30 m calculations provide the upper timing comparison. Flow cells are drawn in the foreground with minimum-width coloured edges for visibility. Terrain decimation is not applied to the flow overlay. The numerical cell footprint and depth are unchanged.

Methods

Observations and their interpretation

Time is measured from the archived USGS origin of 02:52:10 UTC on 26 August 2026 (U.S. Geological Survey 2026). Nepal time is UTC plus 5 h 45 min. The Gyirong video frame reads 10:59:53 China Standard Time, or 463 s after the catalogue origin. We retain the working window of 373–553 s to allow for clock and front-picking uncertainty. The camera clock was not independently synchronised. The local seismic onset reported by Qinghai Normal University is 32 s later than the USGS origin and is derived from a different instrument (Qinghai Normal University 2026). Neither offset is tuned to the simulations.

The last and first missing ten-minute transmissions define windows of 170–770 s at Rasuwagadhi and 770–1370 s at Syabrubesi. They are compared with simulated arrivals under the explicit assumption that the approaching surge disabled the stations. We do not assign independent probabilities to these failures, because shared telemetry infrastructure and unrelated outages can couple them. The video and the two telemetry records consequently provide three comparisons, not three independent measurements of front position.

DHM stage series are taken from the archived agency-derived records distributed with the warning-chain analysis (Acharya 2026). Galchhi rose from about 360.63 to 369.45 m on its station datum. Kali Khola rose from 6.77 to 12.35 m. Devghat reached a sampled maximum of 6.573 m, about 1.9 m above the pre-event level. Stage change is compared with stage change, without identifying gauge datum with flow depth. The lower-gauge timing windows and the model comparisons are given in Table 1. The Malekhu report refers to a warning-level crossing, and is not used as an exact leading-edge arrival. No contemporary rating curves at Galchhi or Kali Khola were available to convert their records into discharge.

Rapid satellite products provide context for the affected corridor (UNOSAT 2026, Geo-PERA 2026, Weedman 2026). We use the corrected stereo interpretation where discussing sediment redistribution. The earlier parallax-based sediment wedge was retracted by its producer and is excluded. The corrected measurements cover only cloud-free parts of the valley and therefore do not measure the total deposit. Their flow heights are not imposed as exact depths in a source-volume inversion. Observation identifiers, archived file paths and the differing meanings of the timing records are listed in the Supplementary Information.

Terrain and release scenario

The upper domain uses a 30 m terrain grid over approximately 26×28 km from the source to below Syabrubesi. A 60 m corridor grid extends through the Trishuli to Devghat. Both were prepared from the archived Copernicus-derived terrain in UTM zone 45N and EGM2008 heights (European Space Agency 2021). The upper grid has 130,591 active cells and the corridor grid has 311,936. Priority-flood drainage conditioning (Barnes et al. 2014) identifies flow paths. Channel depressions are breached to preserve downstream connectivity, with a minimum imposed slope of 5×10^{-4} . Channel modification is a modelling assumption, not a surveyed bathymetry. Below Syabrubesi, a monotone channel profile and widths related to contributing area represent the unresolved river. The width rule reaches 115 m at 2900 km² contributing area and 400 m at 9000 km². The actual extracted routing section is about 115 m at Galchhi and 307 m at the Devghat comparison point.

The reference release is 35.42×10^6 m³, the approximate volume of the Qinghai Normal University rapid estimate (Qinghai Normal University 2026). That estimate combines a 0.6552 km² source area with an estimated mean thickness of 54.06 m. Our release instead distributes the same volume across the larger archived UNOSAT detachment mask, approximately 1.96 km², giving a mean thickness near 18 m. These are different source geometries. The imposed volume and thickness are therefore a scenario, not an independent measurement of the mapped mask. Ice initially occupies 20% of the release volume, with rock occupying the remainder and no initial free water.

The mass is added over 30 s at rest. A separate sensitivity run assigns an initial downslope

speed of 150 m s^{-1} . This speed is comparable to the free-fall speed through 1.1 km, but adding it at the elevated source also adds energy to the subsequent resolved descent. The high-speed diagnostic also has a numerical mass residual of about 2.18%, so it is excluded from physical interpretation. It is not an energy-neutral representation of unresolved impact.

Mixture flow and phase change

The model advances depth h , unit discharge (hu, hv) , total solid depth hc , ice depth hi and heat per unit bed area H . The solids include rock and ice. Face fluxes use an HLL finite-volume scheme, with hydrostatic reconstruction and a depth-limited representation of bed slope (Audusse et al. 2004). Resistance follows

$$\frac{\tau}{\rho_m h} = g\mu_s c + gn(c)^2 |\mathbf{u}|^2 h^{-4/3}, \quad n(c) = n_w + (n_d - n_w)c. \quad (1)$$

The Coulomb term is an effective bulk resistance, combined with a velocity-dependent term. The model has one velocity and does not resolve granular stress, excess pore pressure, air entrainment or phase separation. Such processes require additional constitutive assumptions (Iverson 1997, Iverson and George 2014, Pudasaini 2012).

Rock, ice and water densities are 2650 , 900 and 1000 kg m^{-3} . The mixture density and mass per unit bed area are

$$\rho_m = 1000 + 1650c - 1750i, \quad m_A = 1000h + 1650hc - 1750hi. \quad (2)$$

Thus the dry reference mixture has density 2300 kg m^{-3} . When an ice depth δ melts, the updates are

$$hi' = hi - \delta, \quad hc' = hc - \delta, \quad h' = h - 0.1\delta. \quad (3)$$

They convert one unit of ice volume to 0.9 units of water volume, preserving mass. Unit discharges are scaled by h'/h to retain local velocity during the phase change. This corrects the constant-depth melting approximation used in the earlier preprint. It does not convert the single-velocity shallow-water equations into a complete variable-density momentum model. Source and boundary momentum, impact and mixing remain depth-averaged approximations.

Entrainment removes available channel material at $K(|\mathbf{u}| - u_c)_+$ where $c > 0.05$, with $K = 0.0074$, $u_c = 6 \text{ m s}^{-1}$ and at most 5 m of erodible bed. Entrained material contains 70% rock by volume. Rock settles where velocity falls below 1.833 m s^{-1} , with a timescale of 337 s. The reference roughness values are $n_w = 0.0208$ and $n_d = 0.0145 \text{ s m}^{-1/3}$. These parameters were obtained in the earlier exploratory calibration and are held fixed for the revised comparisons. They have not been independently measured. We vary μ_s over 0, 0.005, 0.01 and 0.02 at the reference roughness. The original joint grid is repeated with μ_s of 0, 0.002, 0.005, 0.01 and 0.02 and equal water and debris roughness of 0.02, 0.025, 0.03 and 0.035. Six release-volume scales (0.5, 0.75, 1, 1.5, 2 and 3) and three ice fractions (0.1, 0.2 and 0.3) are compared separately at the reference roughness over 1440 s. Heat-transfer, release-speed and time-step sensitivities are also retained.

The river starts from the archived pre-event spin-up states. Uniform runoff and boundary discharges provide a conditional monsoon baseflow, including $150 \text{ m}^3 \text{ s}^{-1}$ on the Bhote Koshi and the larger downstream tributary inflows. These are prescribed background conditions. The two-dimensional Devghat transect has a baseline discharge near $2753 \text{ m}^3 \text{ s}^{-1}$, whereas the one-dimensional routing gives about $1985 \text{ m}^3 \text{ s}^{-1}$ because its reduced drainage and inflow representation differs. We therefore do not transfer the former value to the routed discharge or infer a unique storage volume from a discharge budget. This baseline discrepancy limits the interpretation of downstream stage and attenuation. Inflow, entrainment, deposition, boundary loss and remaining mixture mass are recorded separately. An isolated melting test and closed-domain wet dam-break tests check phase-change accounting and transport. Their results and the residual mass ledger of each terrain run are supplied with the code.

Thermal diagnostics

The thermal calculation credits a fraction η of the positive decrease of domain mechanical energy to the heat store, after subtracting the energy carried by material removed at the boundary. Heat is distributed among wet cells in proportion to depth times speed. The energy diagnostic includes shock-capturing and numerical dissipation, and does not resolve the location or rate of grain-scale heat exchange. Consequently $\eta = 1$ is a maximum-transfer scenario within this implementation, not a verified thermodynamic upper bound on the real event. The comparison with $\eta = 0.5$ measures sensitivity to that assumption.

Additional assumed heat comes from river water at 12 °C, rock cooling from 3 °C and a surface flux of 300 W m⁻². Melting consumes $\rho_i L = 3.006 \times 10^8$ J per cubic metre of ice, with $L = 334$ kJ kg⁻¹. These temperatures and fluxes were not measured during the event. The phase-change update is energy-limited but instantaneous within a cell, and cannot demonstrate that large ice blocks melt in transit.

We therefore calculate a separate finite-rate requirement. For spherical ice initially at the melting point, with constant net heat flux q into its shrinking surface, melting a volume fraction f in time t requires

$$q = \frac{\rho_i L d}{2t} \left[1 - (1 - f)^{1/3} \right], \quad (4)$$

where d is initial diameter. This idealisation neglects warming of cold ice, changing flow conditions and finite heat supply. It provides a required flux rather than a prediction of the flux available. Ice diameter has not been measured for this event. No melting fraction is treated as an observational constraint on the initial ice content.

Arrival extraction and downstream routing

Upper-corridor discharge and stage are extracted on the archived cross-channel transects. Arrival is the first sampled stage rise above 0.5 m or discharge exceeding twice its pre-event magnitude plus 50 m³ s⁻¹. The offset prevents a very small background discharge from triggering an arrival. At Gyirong the transect includes a side channel, so discharge determines the crossing. Upper outputs are 30 s apart, giving a sampling uncertainty of approximately 15 s. A halved Courant number tests time-step sensitivity.

The revised 60 m simulation supplies discharge and solid flux at Syabrubesi to a one-dimensional Saint-Venant routing model. The main channel conveys the wave. An additional width W_s stores mixture above a bank level h_b , so cross-sectional area is $A = Wh + W_s(h - h_b)_+$. Stored material is assumed to mix with the channel, while longitudinal momentum is assigned to the conveying section. The solid tracer is conserved in the total cross-sectional area. No settling or further melting is applied during routing, so this stage tests hydraulic delay and attenuation rather than downstream sediment composition.

We compare a channel-only case with compound sections whose bank thresholds are 2, 3 or 4 m above the initial normal depth and storage widths are one, two or three channel widths. The routing uses $n_w = 0.03$ and $n_d = 0.02$ s m^{-1/3} and an eight-hour spin-up. The nine compound sections form a limited sensitivity set, not an exhaustive parameter inversion. We select the member with the lowest weighted mean of station-wise squared waveform errors over the first eight hours. Each station error is divided by the square of its observed stage rise, and station weights are 0.6 at Galchhi, 0.3 at Kali Khola and 0.1 at Devghat. The larger upstream weights prioritise the nearer records because uncertain channel geometry, tributary input and storage can accumulate along the downstream reach. They are analysis priorities, not measured inverse variances or evidence that the Devghat gauge is less accurate. Available stage samples are compared at their recorded times without fitted time shifts. The station-specific baselines, weight sensitivity and earlier timing-feature criterion are reported in Supplementary Note 6. All three gauges enter the revised selection, so none is treated as independent validation. Betrawati and Malekhu retain separate timing comparisons. We report stage discrepancies even where arrival times agree. Differences in time-

integrated excess discharge between stations over a finite window cannot by themselves be identified with a unique floodplain storage volume.

Computational assistance

OpenAI Codex was used to assist code inspection, implementation of the revised mass accounting, execution of numerical checks, preparation of figures and revision of the manuscript. The numerical results reported here are generated by the supplied scripts. The author is responsible for the interpretation and final submitted text.

Results

The mass crossed the gorge with low effective resistance

The apparent friction of an event, the drop divided by the distance travelled, includes the effects of impact, channel geometry and velocity-dependent resistance. It differs from the Coulomb part of the resistance, which governs whether a mass at rest on a low-gradient slope moves. Rock–ice avalanches such as Kolka–Karmadon attain low apparent friction (Huggel et al. 2005, Sosio et al. 2008), but that observation alone does not determine a grain-scale coefficient.

Figure 1 shows the reconstructed flow from the release through the gorge. The three upper-corridor timing comparisons are the CCTV frame at Gyirong Port (463(90) s after onset), the loss of telemetry at Rasuwagadhi (170–770 s) and at Syabrubesi (770–1370 s). With the roughness inherited from the exploratory calibration ($n_w = 0.0208$, $n_d = 0.0145$), the front reaches Gyirong Port and Rasuwagadhi at 390 s and Syabrubesi at 1050 s on the 30 m grid. At $\mu_s = 0.005$ the corresponding arrivals are 390, 420 and 1200 s. At $\mu_s = 0.01$ Syabrubesi is reached at 1410 s, outside its working window. With $\mu_s = 0.02$ it is not reached during the 1440 s calculation.

The constraint becomes clearer through the lower-gradient reach to Syabrubesi. The border timing alone separates the tested friction values poorly. Supplementary Fig. S7 retains the joint comparison over basal friction and roughness, recomputed with the corrected phase-change accounting and release at rest. It measures the tradeoff within this geometry and source scenario. A low fitted resistance is consistent with high mobility, but does not establish zero friction or identify ice at the grain contacts as its cause. The telemetry windows remain conditional proxies for front passage, because an instrument outage need not mark direct inundation.

All three timing windows are met at $n = 0.02$ with $\mu_s \leq 0.005$, $n = 0.025$ with $\mu_s \leq 0.002$, $n = 0.03$ with $\mu_s = 0$. These bounds apply to the sampled grid with equal water and debris roughness. They are not confidence limits on a material coefficient.

The timing constrains the tested flow response, and it does not uniquely fix the volume. Source thickness, channel roughness and entrainment can compensate for resistance. We therefore retain the source-volume and ice-fraction comparison as a separate part of the reconstruction, without treating the thermal calculation or an incomplete momentum derivative as independent observations of the source.

The gorge and the gauges test the moving mass

We compare the same six release-volume scales and three ice fractions as in the preprint (Supplementary Fig. S8). The volumes range from 0.5 to 3 times $35.42 \times 10^6 \text{ m}^3$, and the initial ice fractions are 0.1, 0.2 and 0.3. Each cell is recomputed on the 30 m grid with the mass-conserving phase change. The figure retains the volume–composition grid, but shows the upper timing, stage and melting responses separately. Stage and melt output are model predictions, not additional measured constraints. No confidence region is assigned by adding them to the timing score.

Of the 18 source scenarios, 6 meet all three upper timing windows. Among the scenarios arriving by 1440 s, the Syabrubesi rise ranges from 750 to 1200 s. The maximum modelled Rasuwagadhi stage rise ranges from 22.8 to 65.9 m, and the fraction of initial ice melted by 24 min ranges

from 68 to 100%. The distinct timing, stage and melting responses should be tested against their corresponding observations rather than combined into a single source estimate without independent constraints.

The reference volume comes from the Qinghai Normal University rapid estimate, which combines a 0.6552 km^2 source area and an estimated mean thickness of 54.06 m (Qinghai Normal University 2026). The reconstruction distributes that volume over the larger archived UNOSAT detachment mask, approximately 1.96 km^2 , yielding a mean thickness near 18 m. These are different spatial supports. The imposed thickness is therefore a release scenario and must not be described as the measured thickness of the UNOSAT scar. A source-area elevation difference is needed to constrain the released volume independently.

The gorge and gauges offer additional tests, but their meanings differ. A satellite trimline includes runup and splash as well as flow depth, and a superelevation estimate depends on the bend geometry. The corrected stereo interpretation covers cloud-free parts of the channel and provides partial erosion and deposition measurements (Weedman 2026). The earlier parallax-based sediment wedge was retracted by its producer and is excluded (Geo-PERA 2026). We consequently do not retain the preprint’s joint estimate of 27 (18–35) million cubic metres or its inferred ice-fraction range. The new grid shows which model responses could help distinguish release scenarios once independently measured heights and source changes are available.

The original two-phase and seismic calculations require separate interpretation. In the two-phase model, prescribing an initial pore-pressure ratio of one imposes a weakened state. Similar arrivals with locked and more weakly coupled phases test the response given that assumption, and do not prove that phase separation was absent or identify how the material weakened (Supplementary Note 1).

For the seismic comparison, differentiating the momentum of an open, entraining domain omits momentum carried through its boundary and supplied by material sources. That derivative cannot alone be identified with the force on the Earth. The force methods of Ekström and Stark (2013) and Allstadt (2013) require a consistent source description. We do not use the incomplete calculation to infer a larger seismic source or a mass stranded above the river. The source process remains relevant, but the discrepancy claimed in the preprint needs a complete momentum budget before it can be interpreted.

Ice melting and river dilution changed the mixture

The release is rock and ice with no initial free water. The river adds water, the channel supplies sediment and melting changes the proportions of the moving mixture (Fig. 2). Rock, ice and water now have their separate densities. A release of $35.42 \times 10^6 \text{ m}^3$ with 20% ice therefore has mass $8.15 \times 10^{10} \text{ kg}$, rather than assigning the density of rock to the ice. Melting conserves that mass and contracts one cubic metre of ice to 0.9 cubic metres of water.

The mechanical energy that the flow loses is credited to the mixture as heat in the maximum-transfer scenario. This includes the numerical dissipation of the depth-averaged scheme, so it is a thermal diagnostic rather than a verified heat budget of the event. With a fifth of the release as ice, the corrected reference run melts 69% in three minutes and 91% in seven minutes. Giving only half the diagnosed mechanical loss to the heat store reduces these fractions to 39% and 54%. The melt histories and a finite-rate calculation are retained in the Supplementary Information. The sensitivity is substantial even before considering ice below its melting point or heat lost to the surroundings.

The energy available for melting is not its kinetics. For spherical ice at the melting point, melting 65% in 180 s requires a constant net surface flux of about 2.5 kW m^{-2} for a 1 cm particle, 25 kW m^{-2} for a 10 cm particle and 247 kW m^{-2} for a 1 m block. Fragmentation increases the surface area, but rock-boulder sizes in a deposit do not measure the evolving ice-particle size. Thermomechanical models identify the uncertainty in heat exchange and path conditions (Pudasaini and Krautblatter 2014, Munch et al. 2024). No ice-particle distribution was measured for this event.

The meltwater may affect mobility, but the present calculation does not resolve grain contacts or basal pore pressure. Experiments show that ice content changes the bulk friction of gravel–ice mixtures (Schneider et al. 2011). They also show that small amounts of meltwater can inhibit motion through liquid bridges, while larger amounts may enhance it through pore pressure (Chang and Xing 2025). The net effect depends on material state. The preprint’s water-dependent friction tests are conditional tests of their prescribed constitutive law (Supplementary Note 2), and cannot select a contact-melting mechanism uniquely. Likewise, the absence of published reports of ice downstream is not a measurement of complete melting. We retain the composition history as a model prediction, without using 95% melting to infer the initial ice fraction.

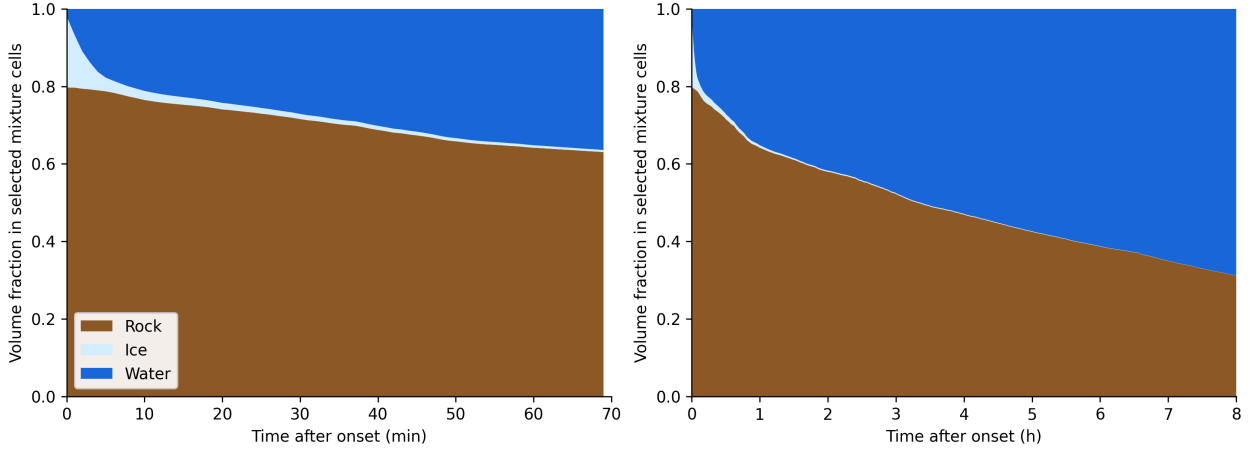


Figure 2: Composition of the moving mixture. Volume fractions of rock, ice and water in saved wet cells with more than 5% solids, over the first 70 min and over eight hours of the corrected 60 m corridor run. Cells enter and leave this diagnostic subset, so its changing proportions are not a closed material budget. Output is saved every 60 s. Melting uses the maximum-transfer thermal scenario. The independent downstream routing has no additional melting or settling.

Valley-floor storage delayed the flood wave below Syabrubesi

The gauges below the gorge record the rise at Galchhi at 1.6–2.2 h after onset with a stage increase of 8.8 m, at Kali Khola at 4.5–5.2 h with 5.6 m, and at Devghat at 5.88–6.05 h with about 1.9 m. The Devghat peak occurs near 7.4 h. The Malekhu warning-level report and Betrawati telemetry failure provide separate, less direct timing comparisons. These records are plotted on each station’s own datum as stage changes, rather than treating gauge elevation as water depth.

The surge delivered at Syabrubesi by the corrected 60 m model is routed through a compound section. The channel conveys the flow and the valley floor above the bank stores mixture. The solid tracer is conserved in the total cross-sectional area, including the storage section. The comparison retains the original question of how lateral storage changes the incoming wave, with all cases driven by the same upstream calculation.

The channel-only control produces a Devghat rise at 4.32 h. Adding lateral storage shifts that rise across 5.50–7.77 h among cases arriving during the eight-hour calculation. One of the nine storage scenarios does not reach the rise threshold by the end. The upstream-weighted waveform criterion selects a bank threshold of 2 m and one additional channel width. The same case is selected with equal station weights and throughout the tested upstream-weighted combinations (Supplementary Note 6). It gives stage rises of 8.94 m at Galchhi and 4.98 m at Kali Khola, against observed changes of approximately 8.8 and 5.6 m. Their model rise times are 1.85 and 4.77 h. Devghat rises at 6.42 h, approximately 22–32 min after its observed 5.88–6.05 h window, and peaks at 7.88 h. Its stage rise is 3.75 m, against about 1.9 m. Selection by waveform error improves the representation of the nearer hydrographs relative to the earlier timing-feature selection but does not resolve the downstream residual. Equal waveform weights select the same case.

The revised comparison uses the complete available stage samples from Galchhi, Kali Khola and Devghat. The earlier six-feature score selected a 3 m bank threshold and one additional channel width, with a Devghat rise at 5.90 h but larger waveform errors at all three gauges. Its narrow 300 s Devghat arrival scale favoured timing agreement over the hydrograph shape. The 2 m-bank selection is also obtained with equal waveform weights, so the change cannot be attributed to upstream weighting alone. It reflects the revised waveform objective as well as the weighting choice. Figure 4 shows the wave over the full corridor at 1, 3 and 6 h. Figure 3 and Table 1 retain the observation-by-observation comparison, including residuals. A warning-level crossing is not equated with a model’s first detectable rise.

The difference between the excess volumes passing two stations during an eight-hour window is not by itself the volume of valley-floor storage. Water can remain in transit and in the main channel at the end of that window. The routing also excludes settling, while the two-dimensional mixture model includes it. Those are separate budgets. The preprint’s estimate of 23–28 million cubic metres of uniquely identified storage is therefore not retained. The comparison supports an effective delay and attenuation associated with storage under the adopted channel representation.

The water of the modelled flood comes from the release, its meltwater and the river. Under the adopted source and channel assumptions, the avalanche-derived surge reproduces the upper timing windows and broadly follows the Galchhi and Kali Khola hydrographs without an additional outburst from a temporary landslide dam. The Devghat residual prevents this from being interpreted as a complete reconstruction of the downstream flood. The calculation does not exclude a short-lived blockage. Pre-event recession at stations on the main river cannot rule out impoundment in an unmonitored tributary. The rapid assessments describe a possible temporary blockage and residual ponds, which remain compatible with the available timing precision (Liu et al. 2026, Geo-PERA 2026).

Table 1: Timing and stage comparisons for the upper-corridor model and the downstream routing selected with upstream-weighted waveform errors. The weights are 0.6, 0.3 and 0.1 at Galchhi, Kali Khola and Devghat. All timing and amplitude discrepancies remain separate reported outcomes. At Malekhu the observed warning-level crossing is compared with the model rise and is not an equivalent arrival measure.

Site	Feature	Observed comparison	Selected routing
Gyirong Port	arrival	373–553 s	390 s
Rasuwadadhi	arrival	170–770 s	390 s
Syabrubesi	arrival	770–1370 s	1050 s
Betrawati	arrival	2570–3170 s	3360 s
Galchhi	arrival	1.6–2.2 h	1.85 h
Galchhi	peak	1.9–2.6 h	2.18 h
Galchhi	stage rise	8.8 m	8.94 m
Malekhu	warning / model rise	9540–10140 s	10080 s
Kali Khola	arrival	4.5–5.2 h	4.77 h
Kali Khola	stage rise	5.6 m	4.98 m
Devghat	arrival	5.88–6.05 h	6.42 h
Devghat	peak	7.38 ± 0.25 h	7.88 h
Devghat	stage rise	1.9 m	3.75 m

Discussion

The 2026 flood can be reconstructed as an avalanche-derived surge followed by a flood along the Trishuli. A release of 35.4 million cubic metres of rock and ice, with no initial free water, reproduces the principal upper timing windows under low effective resistance. The mass accounting correction preserves this timing result. It does not establish the source volume independently, prove that ice contacts removed the resistance or exclude additional water from a brief blockage.

Below the mountains the control changes from the material to the valley. The surge leaving the

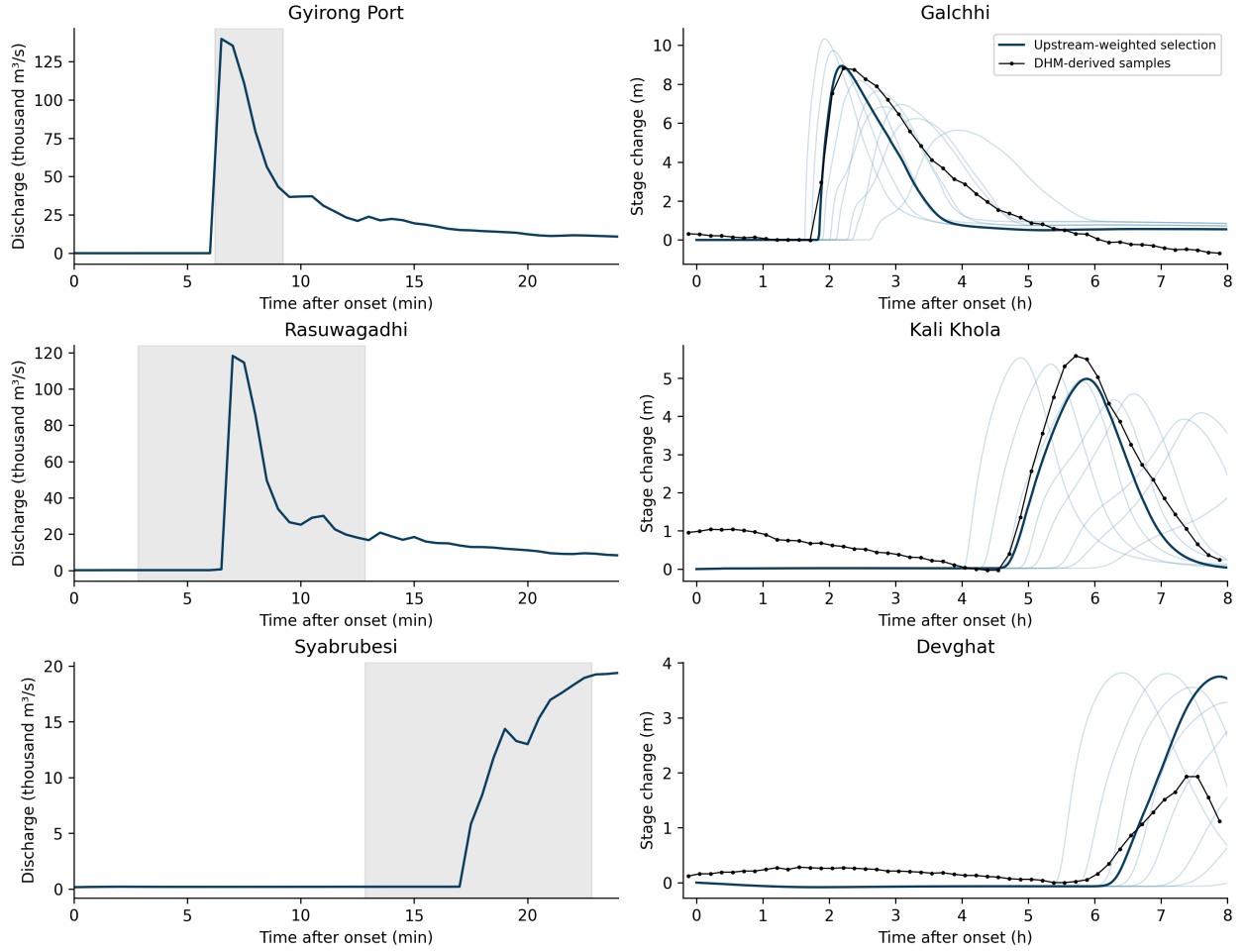


Figure 3: Reconstruction against the record. Upper-corridor discharge from the corrected 30 m reference run with the video and telemetry windows, and downstream stage changes from the corrected routing with the DHM-derived samples. All three gauges enter the revised storage-section comparison. The dark blue line is selected by the normalised waveform-error criterion with weights of 0.6, 0.3 and 0.1 from Galchhi to Devghat. Pale blue lines show the storage sensitivity set. Gauge datum is removed using a local pre-rise baseline.

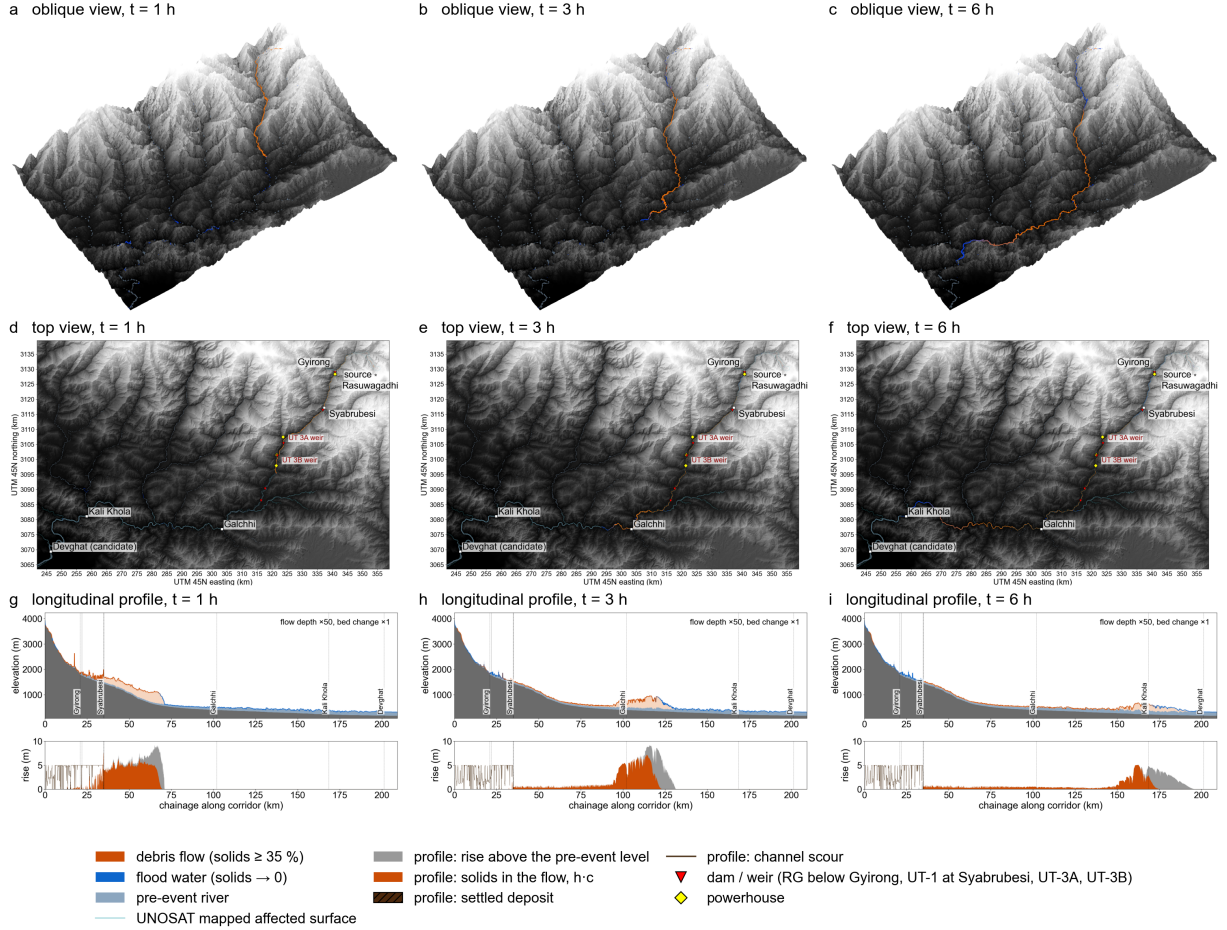


Figure 4: The flood wave over the full corridor. Oblique (a–c) and plan (d–f) views and the longitudinal profile (g–i) at 1, 3 and 6 h, retaining the original arrangement. Map panels show the corrected 60 m mixture model. The oblique views use fourfold flow-depth exaggeration and a threefold terrain vertical scale. Below Syabrubesi the profiles show the selected one-dimensional compound-section routing. These are distinct model representations and should not be interpreted as a single validated inundation map. The colours are as in Fig. 1. Dam and powerhouse symbols appear only in the plan views. In the upper part of each longitudinal profile, flow depth is exaggerated 50 times, while bed elevation, scour and deposit thickness retain their actual scale. The lower rise panels retain true metres and use a 0–10 m range. Flow cells are drawn in the foreground with minimum-width coloured edges for visibility. Terrain decimation is not applied to the flow overlay. The numerical cell footprint and depth are unchanged.

gorge reaches Devghat too early in the channel-only calculation. The upstream-weighted selection better follows the Galchhi and Kali Khola hydrographs, but its Devghat arrival is late and the stage rise remains too large. The more distant gauge tests unresolved cumulative routing effects, rather than becoming an observation that can be discarded. Additional tests around the earlier 3 m-bank reference help separate some of the sensitivities (Supplementary Fig. S5). Increasing the Devghat section width from about 307 to 400 m reduces the rise from 3.81 to 3.24 m. Increasing the background inflow alone gives 3.73 m. Halving the incoming excess discharge and solid flux brings the rise to 2.11 m, but lowers Galchhi and Kali Khola to 6.71 and 3.12 m and delays the Devghat arrival to 6.48 h. These tests do not identify a unique correction to the source or channel. They show why fitting one gauge cannot validate the whole cascade.

The original reconstruction also missed some stage amplitudes. Its Galchhi and Kali Khola rises were too small, whereas the corrected selected section is closer to those two records and farther from the Devghat amplitude. The solver, release prescription and routing selection changed together, so this difference cannot be attributed to a single parameter. A consistent comparison must retain the observations and report both the improvements and the remaining residuals.

Three groups of measurements would sharpen the reconstruction. Source-area elevation change would constrain the release volume and its distribution over the scar. Contemporary cross-sections, rating curves and floodplain connectivity would help distinguish excessive incoming volume from inadequate conveyance or attenuation. Field observations of ice, sediment and deposition would test the composition history. The maximum-transfer thermal calculation and the fitted effective resistance are useful conditional diagnostics while those data remain unavailable. They are not substitutes for measured melt kinetics or a constitutive law for ice-rich debris.

Conclusions

The rock-ice release crosses the gorge rapidly in the corrected reconstruction, and the upper timing comparison favours low effective resistance within the tested source and terrain. The source volume and ice content remain scenario parameters. Mass-conserving melting changes the predicted composition without demonstrating a unique weakening mechanism.

An additional outburst from a temporary landslide dam is not required to reproduce the upper timing windows and broadly follow the nearer downstream hydrographs within this reconstruction. This does not establish that temporary impoundment was absent. The downstream record constrains the delay and attenuation of the avalanche-derived surge. The upstream-weighted compound section improves the nearer hydrographs but reaches Devghat late and overestimates its stage rise. The remaining discrepancy requires joint evaluation of the incoming wave and channel geometry. The reconstruction explains parts of the cascade and defines specific tests of its unresolved source, thermal and hydraulic assumptions.

Statements and Declarations

Funding. No external funding was received for this study.

Competing interests. The author declares no competing interests.

Author contributions. Hyoseok Park is the sole author and is responsible for the study and manuscript. Computational assistance is described in Methods.

Data and code availability. The original reconstruction repository is <https://github.com/hyoseokp/langtang-2026-cascade>. The prior code and dataset archives are identified there. The revised solver, routing code, run parameters, verification records, numerical tables and figure scripts accompany this submission as supplementary files. The input manifest records the original archived terrain and spin-up files needed to reproduce the runs. DHM-derived records are attributed to their agency and the archived compilation (Acharya 2026). Third-party satellite data retain their original licences. No third-party satellite photograph is reproduced in the manuscript.

Preprint. An earlier version is available on EarthArXiv at <https://doi.org/10.31223/X5250R>. This manuscript revises its mass accounting, simulations and interpretation.

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Supplementary Information for: A rock–ice avalanche and the 2026 Bhote Koshi–Trishuli flood, Nepal

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Supplementary Notes

Supplementary Note 1: two-phase test

The preprint’s two-phase test used the equations of Pitman and Le (2005) in the form of Pudasaini (2012), with solid and fluid phases coupled by drag. The prescribed pore-pressure ratio controls the effective Coulomb resistance (Iverson and George 2014). With $p_0 = 1$, the solid is weakened by assumption. The test therefore asks how phase coupling affects a flow already assigned that state. It does not independently establish the cause of weakening.

The archived two-phase runs use a different phase representation from the corrected single-velocity model. Their old arrival values are not presented as new verification results. The corrected reconstruction retains one velocity, so phase separation remains an unresolved limitation. A coupled two-phase and thermal reanalysis would require its own mass and momentum validation.

The momentum diagnostic is retained as Supplementary Fig. S2, with separate rock, ice and water densities. It shows the horizontal components of the negative derivative of stored domain momentum and the kinetic energy in the first 600 s. The output interval is 30 s and cells shallower than 0.05 m are omitted from the saved frames. Boundary fluxes and material-source momentum are not restored by taking this derivative. Its units are force, but it is not the total force on the Earth and is not used in a seismic source-volume inversion.

Supplementary Note 2: friction coupled to the water content

The preprint explored a basal friction that falls with local water fraction $w = 1 - c$, following $\mu = \mu_{\text{dry}}(1 - w/w_{\text{sat}})_+$. That comparison is a conditional test of the prescribed relation between water content and resistance. Its failure to reproduce an arrival does not uniquely establish an alternative grain-contact mechanism. The old melting bookkeeping and impact-speed prescription also prevent direct transfer of its numerical arrival values to the corrected reference run.

The corrected comparisons retain an effective Coulomb term, a joint friction–roughness grid and thermal sensitivity tests. Supplementary Figs. S1 and S3 keep the source-composition and melting comparisons separate from observed constraints. The model has no grain-contact law. No field measurement fixes the ice-particle diameter or the rate of heat transfer into ice.

Supplementary Note 3: flow height and speed in the gorge

Supplementary Fig. S4 repeats the spatial speed comparison with the corrected 30 m run. Maximum depth-averaged speed is extracted from saved states at 30 s intervals over the first 1440 s. The plotted observational values and ranges are the unflagged entries in the archived superelevation-velocity table. They remain conditional on the producer’s bend radius, cross-channel height difference and chainage correspondence. The source origins differ by approximately 0.3 km, so matching by distance alone has additional uncertainty.

The model velocity and the superelevation estimate are not identical quantities. Superelevation is related to the balance of centrifugal acceleration and lateral pressure gradient under assumptions

about the bend (Prochaska et al. 2008). Departures cannot simply be assigned to a surface-to-depth-average velocity factor. Similarly, a mapped disturbance boundary includes splash, erosion and runup, and its elevation above the channel is not necessarily a flow depth. The old numerical trimline and velocity ratios are not retained as results of the corrected solver.

The corrected stereo product covers cloud-free channel windows, with partial erosion and deposition measurements (Weedman 2026). It does not measure all sediment transported through the valley. The earlier retracted parallax-based wedge is excluded. New flow-height and deposition comparisons require matched spatial footprints and uncertainty in the terrain as well as the satellite product.

Supplementary Note 4: volume ledger

The isolated melting test places 10 m of mixture in a closed cell, comprising 8 m of rock and 2 m of ice. Its mass is 23,000 kg per square metre. Sufficient stored heat melts all ice without generating mechanical heat. The final depth is 9.8 m and mass is 23,000.00019 kg per square metre. The difference is single-precision roundoff. A calculation with fixed depth would not conserve mass when rock, ice and water are assigned their physical densities.

The wet dam-break tests use a flat closed domain with 441 active cells. A deeper central cell drives motion. After 500 steps, relative total mass errors are 5.69×10^{-8} without thermal conversion and 8.96×10^{-8} with it. The tests check a specific accounting and transport property. They do not validate the rheology or impact representation for the real avalanche.

For the terrain runs the ledger sums mixture mass before and after each step, adds material removed at the open edge, subtracts entrainment, and adds deposition. River inflow and the prescribed release are applied before each step and therefore cancel in this per-step residual. Residuals are normalised by the initial release mass, which is $35.42 \times 10^6 \times 2300$ kg for the reference volume and composition. For each volume-ice scenario, the normalising mass is its own release volume multiplied by $2650(1 - i_0) + 900i_0$, where i_0 is the initial ice volume fraction. The residuals are reported as numerical errors rather than statistical uncertainties. The release-at-rest reference and corridor cases have residual magnitudes below 0.02% of the initial release mass.

Table S1: Net mixture-mass residual normalised by initial release mass. Positive values denote net numerical gain after the ledger terms. The release-at-rest cases are used in the physical comparison.

Run	Relative residual	Interpretation
upper_ref	-4.481e-05	Retained
upper_mu005	-4.108e-05	Retained
upper_mu01	-3.857e-05	Retained
upper_mu02	-3.444e-05	Retained
upper_eta05	-4.768e-05	Retained
upper_cfl	-4.168e-05	Retained
upper_fast	2.182e-02	Excluded
corridor_ref	-1.177e-04	Retained

The diagnostic run with an initial speed of 150 m s^{-1} at the default Courant number accumulates a positive mass residual of about 2.18% of the initial release mass and reports slightly more melting than the initial ice volume. It is excluded from the physical results and figures. The residual exposes limitations of positivity clipping under this energetic release prescription. The full-corridor residual is approximately 0.012% of the initial release mass. The difference from exact conservation reflects transport and clipping in addition to floating-point roundoff. Retaining the failed run in the archive makes the exclusion reproducible. No result from this diagnostic is used to claim that an impact-speed prescription leaves the solution unchanged.

Melting preserves mass but reduces volume. Initially, the release contains $28.34 \times 10^6 \text{ m}^3$ of rock and $7.08 \times 10^6 \text{ m}^3$ of ice. During the eight-hour corridor run, about $7.06 \times 10^6 \text{ m}^3$ of ice

melts. This reduces the mixture volume by about $0.706 \times 10^6 \text{ m}^3$. Approximately $29.95 \times 10^6 \text{ m}^3$ of channel material is entrained and $20.33 \times 10^6 \text{ m}^3$ is deposited. These are domain-wide model quantities, not measurements over the stereo footprint. The downstream routing is a separate calculation without settling or further melting.

Supplementary Note 5: observation provenance

The supplied manifest identifies local archived sources and their checksums. The original input files are those referenced by the public reconstruction repository, <https://github.com/hyoseokp/langtang-2026-cascade>. This revision uses the observational records and terrain inputs, not the results of a different reconstruction as observations. No raw seismic waveform has been analysed for the present revision.

Table S2: Timing comparisons and their interpretation. All times are seconds after 02:52:10 UTC unless stated otherwise.

Record	Working value	Interpretation and limitation
Gyirong video	373–553 s	Frame reads 10:59:53 China Standard Time. The clock offset and exact camera position are not independently surveyed.
Rasuwagadhi	170–770 s	Last transmission at 08:40 Nepal time and first missing ten-minute sample. A front passage is inferred from failure.
Syabrubesi	770–1370 s	Last transmission at 08:50 Nepal time. Failure may share a cause with upstream telemetry loss.
Betrawati	2570–3170 s	Last transmission at 09:20 Nepal time. Used as a conditional comparison, not a calibrated arrival.
Malekhu	9540–10140 s	Reported 11:26 Nepal time crossing of a 7 m warning level. Comparison with a model front is only indicative.
Galchhi	Rise 1.6–2.2 h	Stage change and peak timing are assessed separately. No event rating curve is used.
Kali Khola	Rise 4.5–5.2 h	Stage change of about 5.6 m on the native gauge datum.
Devghat	Rise 21170–21770 s	Rapid-rise bracket from the stage series. The later reported 15:20 Nepal time is a confirmation during the rise.

The observation registry retains source identifiers and dependency groups. The original CCTV screenshot is a timestamped repost, while the accompanying official report identifies the border disaster at 10:59 China Standard Time. The Qinghai Normal University account reports the local seismic onset at 10:52:42 and an approximately 430 s transit to the port. These descriptions partly share the same video and should not be counted as independent timing constraints.

DHM series are read from the archived compilation’s `gauge_timeseries.json`. Its metadata state that the agency service used twelve-hour labels without meridiem. The compilation reconstructs clock time from fixed ten-minute sampling and checks it against the labels and reports. We retain that reconstruction and disclose it as a source of uncertainty. Missing samples are not filled across station destruction. Background stage for the plotted waveforms is the median of three pre-rise samples. The Nepal-time windows are 10:00 to 10:20 at Galchhi, 12:40 to 13:00 at Kali Khola and 14:00 to 14:20 at Devghat. These station-specific windows remove the slow background recession immediately before the local wave.

The UNOSAT detachment geometry and the smaller Qinghai Normal University source estimate are not interchangeable measurements. The archived UNOSAT metadata also contain a sensor-date inconsistency, with a September date in a field associated with an August event layer. The geometry is used as a scenario mask, without using that field to infer the event chronology. The revised analysis does not score the absence of reported ice as complete melting, or the stereo change in cloud-free windows as a complete sediment budget.

Supplementary Note 6: thermal and routing details

The model uses a single heat store and an instantaneous local phase-change update. In the mechanical heat diagnostic, energy removed by a numerical shock or mixing process is not distinguished from heat delivered to ice. The diagnostic can also be sensitive to the treatment of variable density and open boundaries. Even with improved mass accounting it is not a complete entropy-conserving or thermomechanical formulation. The heat-transfer fraction is varied to expose this limitation.

For the independent shrinking-sphere calculation, mass is $4\pi\rho_i r^3/3$ and power entering the surface is $4\pi r^2 q$. With ice initially at 0 °C, balancing latent heat gives $-dr/dt = q/(\rho_i L)$. Integrating and writing the melted fraction as $f = 1 - (r/r_0)^3$ yields Eq. 4 of the main text. No heat-transfer coefficient is prescribed. A smaller initial radius lowers the required flux linearly. The result assumes the available heat maintains a constant net flux over the full shrinking surface. Fragmentation, shielding and a distribution of particle sizes would require a different model.

The routing code advances total cross-sectional area, main-channel momentum and a solid-volume tracer. The tracer concentration uses the total area, including storage, and is carried through interfaces at the channel discharge. This corrects the earlier approximation in which tracer concentration was capped using channel depth alone. The routing keeps no separate ice phase and has no settling in these experiments. Its concentration only adjusts roughness. Downstream rock or ice fractions should not be inferred from this stage of the calculation.

The compound-section sweep uses bank thresholds of 2, 3 and 4 m and additional widths of one, two and three channel widths. The control uses zero additional width. The revised selection compares the complete available stage records over the first eight hours. Model stage changes are linearly interpolated to the recorded sample times, missing samples are omitted and no time shift is fitted. For station k with N_k available samples, the selection score is

$$J = \sum_k w_k \frac{1}{N_k A_k^2} \sum_{j=1}^{N_k} [\Delta h_{k,\text{model}}(t_j) - \Delta h_{k,\text{obs}}(t_j)]^2. \quad (1)$$

The observed stage rises A_k are 8.82, 5.58 and 1.933 m at Galchhi, Kali Khola and Devghat. Normalisation prevents the largest-amplitude station from dominating solely through its units and scale. We use station weights $w_k = 0.6, 0.3$ and 0.1 in the same upstream-to-downstream order. These are explicit analysis priorities rather than measured error variances. Downstream model discrepancies can reflect accumulated errors in channel geometry, tributary inflow and storage. Distance alone does not quantify their covariance or establish that the observations are less accurate.

The score selects the 2 m-bank, one-width case from the nine storage cases. Its root mean squared stage errors are 1.15, 0.66 and 0.64 m at the three gauges. All 44 non-increasing upstream-to-downstream weight combinations on a 0.05 grid, with weights summing to one, select this same case. The grid includes boundary cases with zero downstream weight. Equal station weights also select it. These tests concern the fixed nine-case ensemble and eight-hour window, not an exhaustive inversion or a statistical confidence region. A finite-window waveform score can be calculated even if a model peak falls beyond the end of the window. Such peaks remain censored in the reported timing comparisons and are not assigned artificial times.

The earlier screening criterion averaged squared residuals for six timing and amplitude features. At Galchhi, rise time, peak time and stage amplitude had centres of 1.9 h, 2.25 h and 8.8 m and scales of 0.3 h, 0.35 h and 1 m. At Devghat, the corresponding centres were 21470 s, 26570 s and 1.9 m, with scales of 300 s, 900 s and 0.4 m. Those scales were working tolerances, not observation-error standard deviations. Missing arrivals and censored peaks prevented a finite feature score. This criterion selected the 3 m-bank, one-width case. Its stage RMSE values are 1.71, 1.41 and 0.94 m, but its Devghat rise at 5.90 h is closer to the observed window than the revised selection at 6.42 h. The original feature score was 4.35 for that case and 9.18 for the revised selection. We retain the earlier selection as a comparison and report the change of criterion explicitly. Because the revised ranking also occurs with equal waveform weights, it must not be described as a consequence of upstream weighting alone. No gauge used in either selection is an untouched validation record.

Rise at Galchhi, Kali Khola and Devghat is the first sampled model stage change above 0.3 m. Model peak time uses the maximum stage within the eight-hour calculation. The main comparison table reports the selected routing. The complete sensitivity set is provided as a numerical table and in the hydrograph figure. Betrawati uses the upper-model discharge or stage threshold. Malekhu is shown with that same model threshold only as a timing comparison, because there is no calibrated translation between the model datum and the reported warning level. Output spacing is approximately 60 s. The volume ledger checks the conservative area update, including imposed tributary flows and boundary discharge.

Supplementary Tables

The numerical tables accompany this supplement as CSV and JSON files. They include all corrected friction–roughness and volume–ice cells, station-by-station routing comparisons, phase-change tests and downstream diagnostic runs. Censored arrivals are retained as missing values rather than assigned a synthetic arrival time. The scripts and exact parameter files define every case.

Supplementary Figures

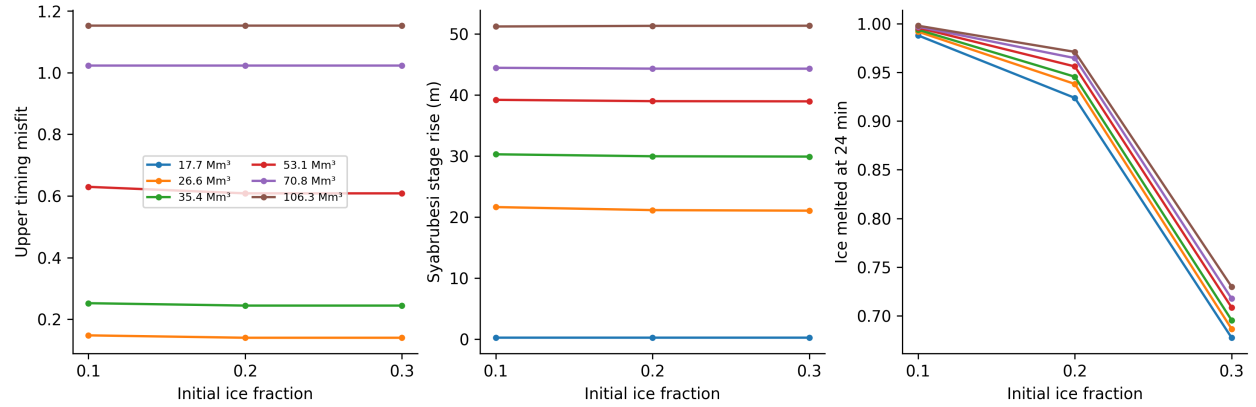


Figure S1: What the model says about the ice fraction. Upper timing misfit, Syabrubesi stage rise and melted fraction after 24 min for the corrected six-volume, three-ice-fraction grid. Different colours denote release volumes. Stage and melting are model outputs rather than measured constraints. No complete-melting threshold is used to infer the source composition.

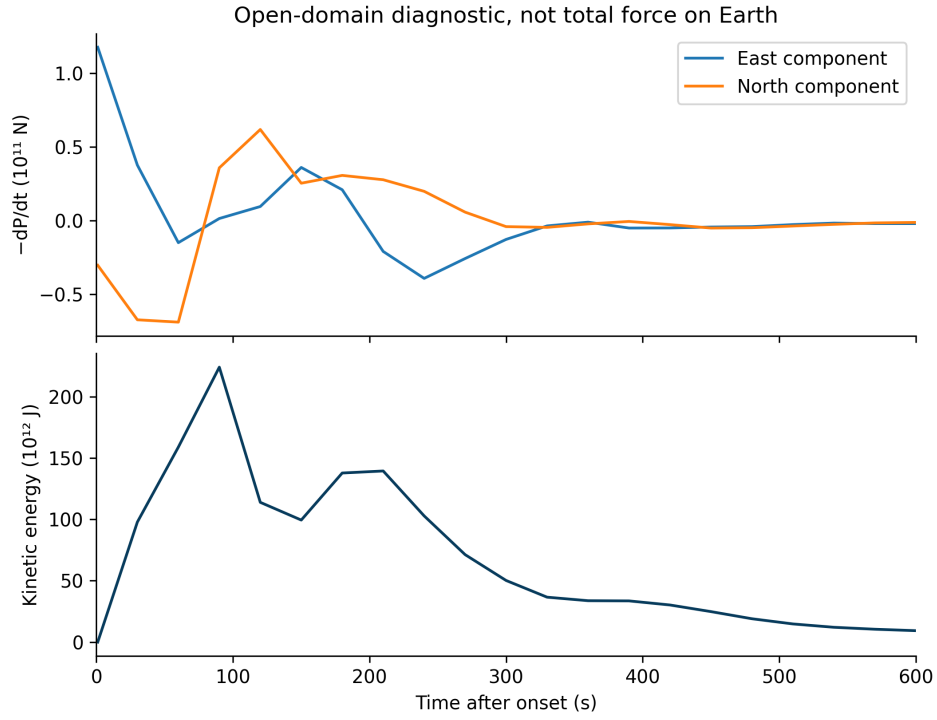


Figure S2: Domain momentum change and kinetic energy. Horizontal components of the negative derivative of domain momentum and kinetic energy from the corrected 30 m run released at rest. States are saved every 30 s. The first 30 s contain the prescribed release. The derivative omits boundary and source momentum terms and is not the total force on the Earth. It is retained as a diagnostic and is not compared with a seismic force inversion.

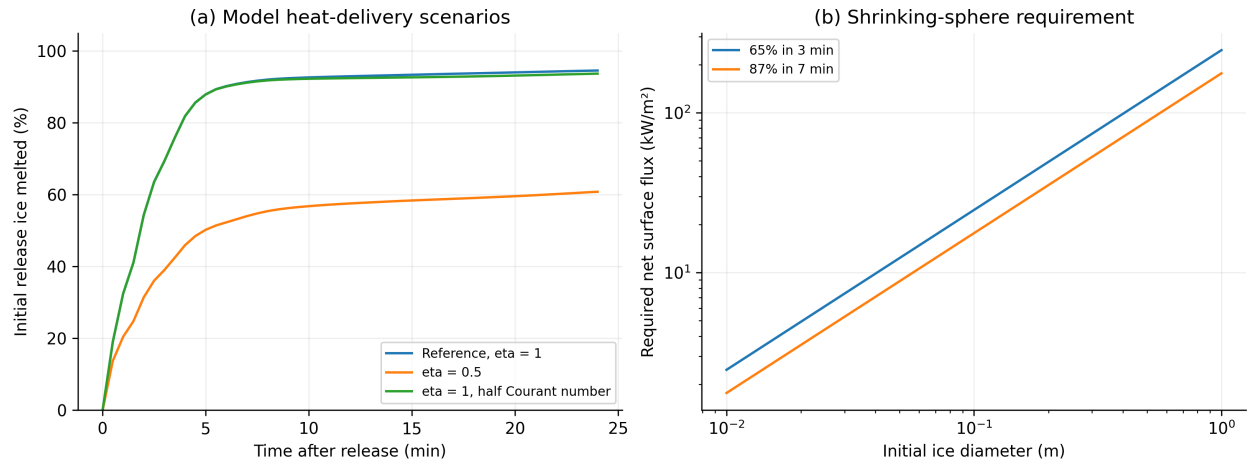


Figure S3: Melting of the release ice. Left, corrected model melt histories for different mechanical heat-transfer fractions and Courant numbers. Right, the constant net surface heat flux required to melt the indicated fractions of spherical ice within the indicated times. Initial ice is assumed to be at its melting point. Neither panel measures actual heat-transfer kinetics. The right panel distinguishes the energy requirement from the rate of heat delivery.

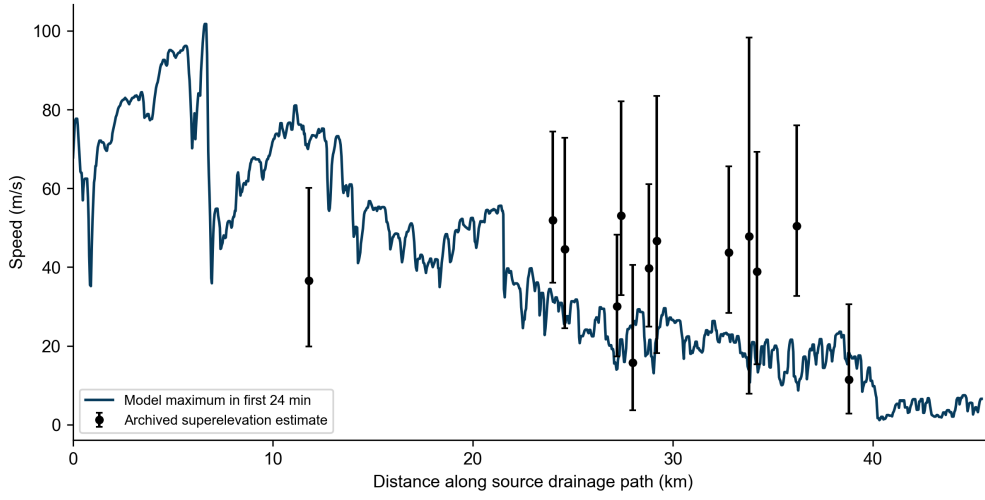


Figure S4: Speed along the gorge. Maximum modelled depth-averaged speed in the corrected 30 m run over the first 24 min, sampled every 30 s, against the archived unflagged superelevation estimates and their producer-reported ranges. Distance correspondence is approximate. The estimates depend on bend geometry and are not direct velocity measurements. Values beyond the model path are shown without a model counterpart.

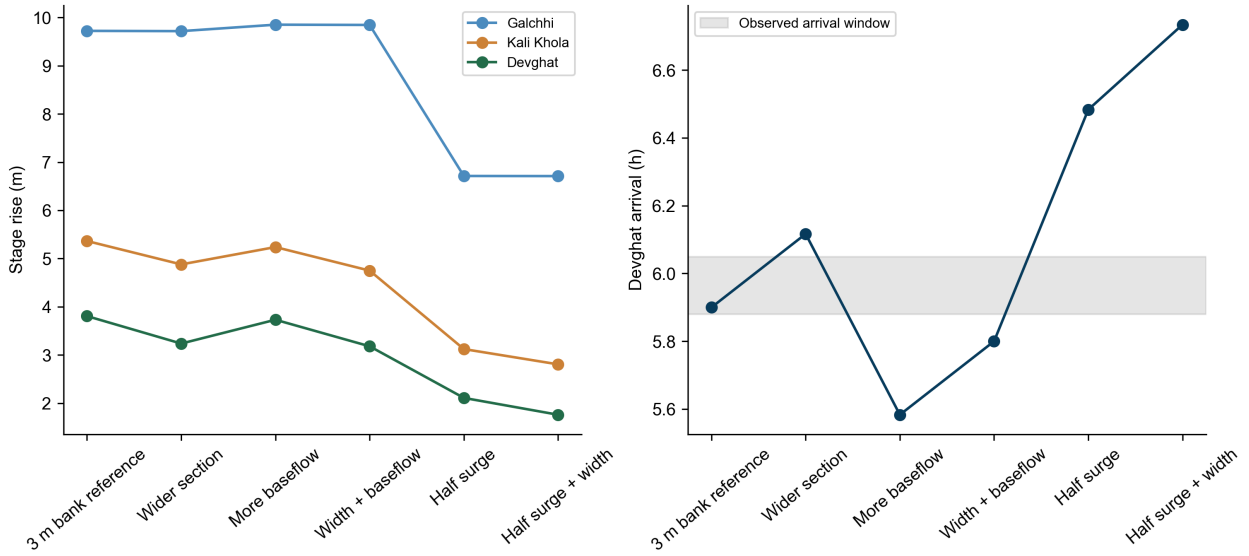


Figure S5: Downstream parameter sensitivities. Stage rises at three stations and Devghat arrival in the earlier 3 m-bank, one-width routing reference, a wider downstream channel, increased background inflows, their combination, half the incoming excess discharge and solid flux, and the half-surge case with the wider channel. Shading shows the Devghat arrival window. The width tapers from unchanged at Galchhi to 400 m at Devghat. The background multiplier is 2600/1985.32. These diagnostics retain that fixed reference to isolate hydraulic sensitivities. They are not reruns around the revised 2 m-bank selection and do not constitute a source-volume inversion.

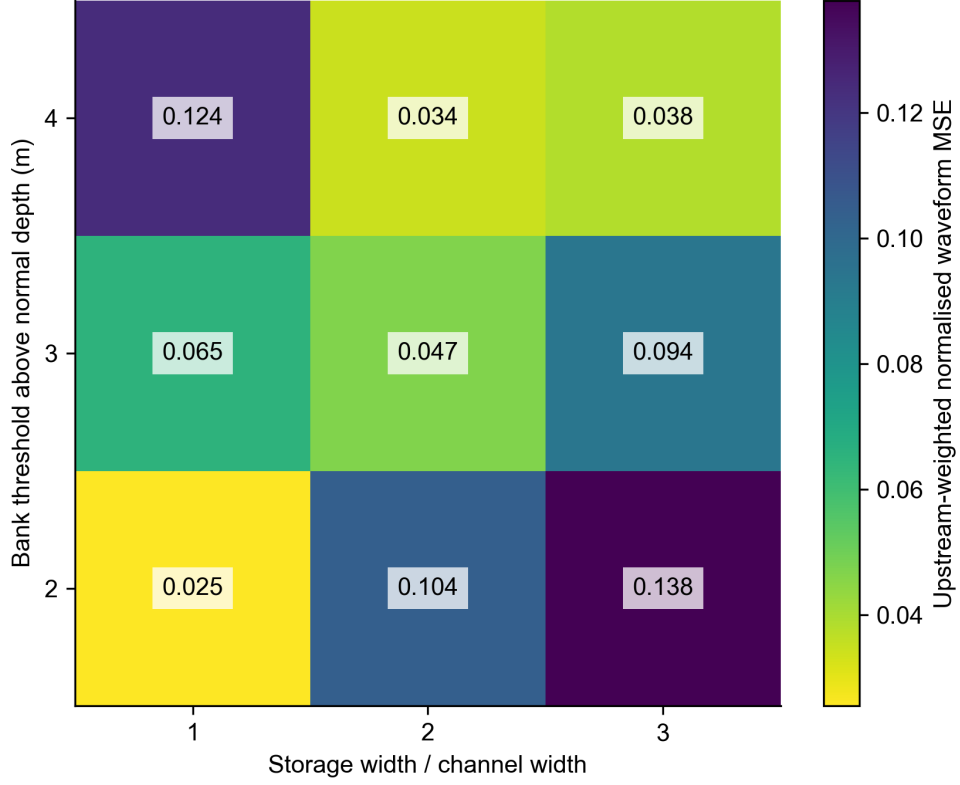


Figure S6: Storage parameters compared with upstream-weighted waveform errors. The corrected three-by-three grid of bank threshold and storage width is scored using normalised station-wise waveform errors, with weights of 0.6, 0.3 and 0.1 at Galchhi, Kali Khola and Devghat. Numbers and colours show the same dimensionless score. The lowest score is at a 2 m bank threshold and one additional channel width. Finite-window waveform scores do not establish whether later peaks are reproduced. Weight-sensitivity results and the earlier feature scores are supplied as numerical tables. The comparison does not uniquely identify physical storage volume.

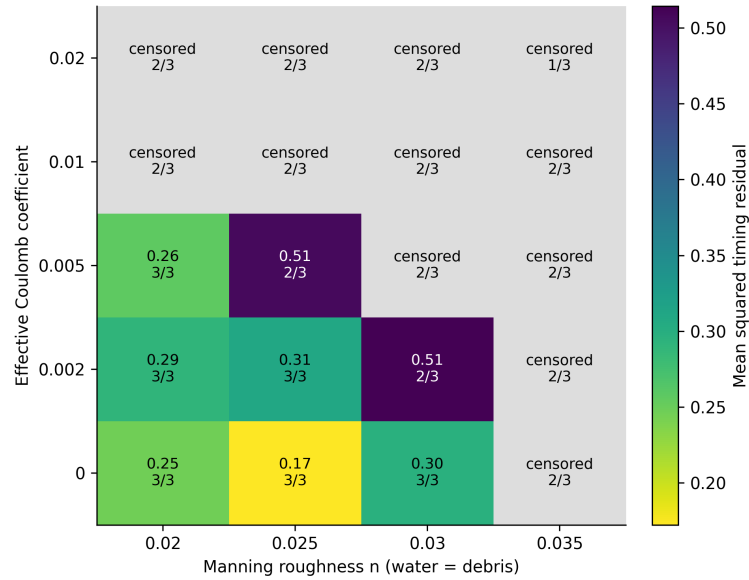


Figure S7: Timing misfit over basal friction and roughness. The original parameter-grid design, recomputed with separate phase densities, mass-conserving melting and release at rest. Each cell gives the mean squared deviation from the three timing-window centres in units of their half-widths, together with the number of windows met. Missing arrivals by 1440 s are marked separately. Equal water and debris roughness is imposed within this grid. It differs from the concentration-dependent reference roughness. The telemetry windows are conditional proxies for front passage.

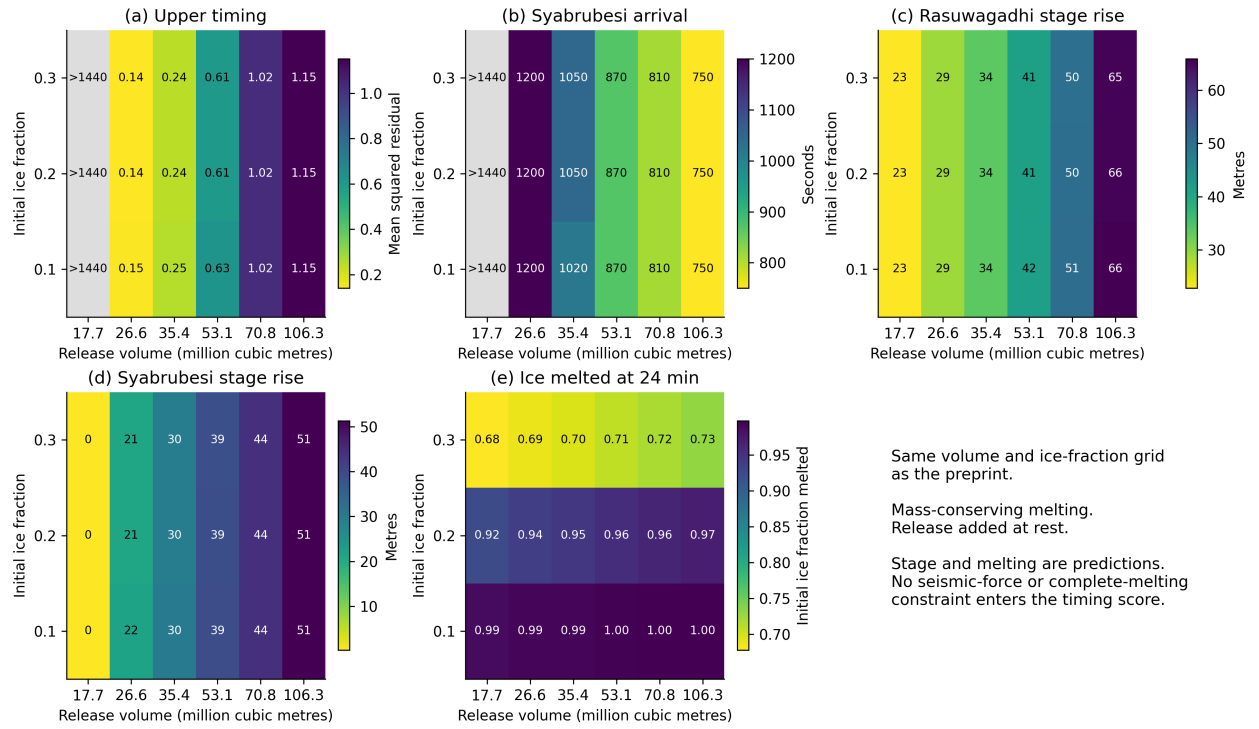


Figure S8: Release-volume and ice-fraction sensitivity. The original six-volume, three-composition grid recomputed on the 30 m domain over 1440 s. Panels show timing misfit, Syabrubesi arrival, the maximum stage rises at Rasuwagadhi and Syabrubesi, and melted fraction at the end of the calculation. Stage and melting panels are model responses, not scored observations. A missing arrival is censored at the end of the run. No seismic-force or complete-melting criterion is included, and no confidence region is inferred.

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