

Counterfactual Evaluation of a Satellite-Connected Multi-Sensor Early-Warning System During the 26 August 2026 Bhote Koshi–Trishuli Disaster

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Abstract

The 26 August 2026 Bhote Koshi–Trishuli disaster raised an important question: could a warning system continue to reach people if local infrastructure failed? This study tests a proposed system using satellite communication, a reviewed river network, 15 radar-gauge stations, 2 candidate geophone stations, a camera site and 32 mapped target references. The analysis consists of two segments. The first compares three possible routes from source references to Friendship Bridge at Gyirong port, with lengths of 21.764510–22.653727 km. The second uses a separately reviewed 80.614468 km river line from the Friendship-side reference to Galchhi bridge. Gyirong Port is a separate border-area site. The actual disaster source, upstream channel and arrival times remain unverified. The warning calculations therefore start when an operating gauge is assumed to detect the hazard, rather than when the disaster starts at origin. Of the 32 target points, 27 lie inside UNOSAT’s preliminary mapped mudflow/rockflow area. The other five points, Timure, Syabrubesi, Trishuli HPS powerhouse/tailrace (HP09), Battar Bazaar and Devighat, lie inside the area UNOSAT studied but outside its mapped affected area. Being inside or outside the mapped affected area does not confirm whether an individual site was damaged. We tested assumed propagation speeds of 2, 5 and 10 m/s, alert delays of 2, 10 and 30 min, and action times of 5, 15 and 30 min. In the downstream analysis, 696 of 864 tested combinations left enough calculated time for action, assuming working satellite communication and a channel that could reach recipients. This count shows how many tested scenarios gave enough time to act. It does not tell us the chance of success or whether warnings worked during the actual event. At Friendship Bridge and Rasuwagadhi, an earlier assumed trigger from RG-01 left enough calculated time in 14 of 27 combinations. RG-02 alone left no positive action margin in any of the 27 combinations. These results show how detector location, alert delay and delivery to recipients affect the model. Hydrographs, calibrated triggers, outage logs, verified recipient coverage and site-specific damage records are needed to assess whether the system could have worked during the event.

Keywords: flash flood; ice-rock avalanche; early warning; satellite communications; QGIS; Nepal; counterfactual modelling; last-mile delivery

1. Introduction

Nepal's Ministry of Foreign Affairs reported severe flash floods on the morning of 26 August 2026 and damage to homes, roads, bridges and hydropower facilities. Its 17:00 update describes the situation at that time. It does not provide a hydrograph or a record of arrival times [1]. ICIMOD subsequently discussed a high-mountain slope failure involving rock and glacier ice, but the exact source, sequence and timing remain uncertain [2]. This study is not to classify this event as a glacial-lake outburst because the available evidence does not establish a lake or a lake-outburst mechanism.

This study asks whether a proposed satellite-connected multi-sensor system could have provided warnings with enough time for action to selected places along the Bhote Koshi–Trishuli corridor if parts of the communications network had failed. It asks what might have happened under a proposed design. The instruments, satellite link, alert hub and relays are proposed for this study. We have no evidence that they were operating on 26 August 2026. The analysis links mapped sensor positions and along-river distances to failure scenarios and the time needed to reach people in that area. World Meteorological Organization (WMO) distinguishes detection from warning dissemination and preparedness, while ITU recommends multiple channels for delivery from the local warning system to people [3,4].

Rui Li's 7 September 2026 v2 preprint estimates the area of surface change near the source and traces a representative 21.8 km route from the source to Gyirong Port [14]. We cite this earlier physical reconstruction and do not claim to be the first to map the event source or route. This study asks a different question: if specified components failed, could a proposed sensor and communication system provide sufficient warning time to downstream sites so that they have enough time to act? Li's mapped route does not provide an observed flood travel time for our model.

Several recent preprints address the same event. Acharya reports reconstructed gauge arrivals, an alert chronology and comparisons among warning architectures [15]. Park presents a mixture-flow reconstruction constrained by reported CCTV and stage information [16], while Xu discusses alternative origins of an early flood wave using open data [17]. Their observations, time references and assumptions must be checked against original records before they can be used to calibrate this model. This study here does not claim to be the first to analyse warning delays for this event. This study is to propose a mapped sensor network and satellite communication and tests how the equipment and communication failures affect the warning time. Warning mechanism here also requires a working local communication channel to convey the warning message.

2. Event evidence and observation limits

USGS ComCat records accessed on 29 September 2026 list two reviewed seismic events classified as landslides. The first, us7000tbwb, **had a magnitude of 5.2** and occurred at 02:52:10 UTC (08:37:10 Nepal time), at 28.271°N, 85.515°E [5]. The second, us7000tc90, **had a magnitude of 4.2** and occurred at 06:00:35 UTC (11:45:35 Nepal time), at 28.3281°N, 85.4798°E [6]. Both records list a depth of 0 km and magnitude type ms_vx. These are catalogued seismic-event times, not measured flood-arrival times. They do not directly record flood release or water arrival at Friendship, and do not prove a second flood pulse. Neither event time is used as the starting time for calculating flood travel.

The Department of Hydrology and Meteorology (DHM) lists a hydrological station at Bhotekoshi, Rasuwagadi, index 446.22, with a registry coordinate of 28.271297°N, 85.377649°E [7]. The quality-controlled 26 August time series, station datum and warning log could not be obtained. The registry identifies a potential primary measurement source but provides no flood arrival time for this analysis.

The National Disaster Risk Reduction and Management Authority (NDRRMA), in Situation Report #19 issued during the later response period, reports an arrival and warning timeline [8, PDF p. 1]. These reported times were not used to calibrate the model because the underlying time-stamped observations and operator logs were not obtained. The same report lists communications interruptions at Nepal Telecom BTS sites in Timure, Chilime Khola and Trishuli 3B, and Ncell mobile signal interruptions in Timure, Tiru, Gatlang and Goljung. It also states that 12 of 29 arranged satellite internet terminals were operating [8, PDF p.10]. The report does not give the start time, duration or coverage of these outages. It also does not show who could receive warnings as the flood first rushed downstream. These records show why communication failures need to be

tested. They do not show whether the proposed satellite warning system could have delivered a warning to a particular household. The same report summarises infrastructure damage, but its bridge totals cannot be directly matched to the individual bridges mapped in this study [8, PDF p. 4]. The report's 'Rasuwagadhi 120 MW' entry is unclear, so this study does not use it to confirm damage to a specific hydropower project [8–10].

Table 1. Evidence used in this study and its limitations.

Evidence class	Used in this study	Cannot establish
Primary event and response records	Flood date and broad impacts [1]; recorded seismic events [5,6]; communication conditions during the later response period [8]	When the flood reached each site, who could receive warnings during the first hour, or whether the proposed system was operating
Published remote-sensing studies	Preliminary mapped affected area [11]; source and route interpretation from a preprint [14]	Damage to individual assets, flood-arrival times, or the exact path taken by the flood
GIS calculations in this study	Distances along reviewed routes, site positions along those routes, and comparison of 32 target points with the mapped affected area (27 inside and five outside).	Flood speed, a confirmed source-to-Friendship route, or the performance of installed sensors
Hypothetical warning calculations	Tests using assumed flood speeds, warning delays, action times and equipment failures	The probability of successful warning, lives saved, or whether warnings reached people during the actual event

3. Data and methods

3.1. Reviewed river geometry and the target references

The analysis follows two segments in the order of downstream. Segment A compares three possible routes from the source references to Friendship Bridge. These routes are not confirmed. Segment B measures the river route from Friendship-to-Galchhi Bridge and evaluates whether gauge triggered warning could be given to people downstream with enough time to act. Segment A describes possible routes. It cannot show how long it would take for a gauge to detect the flood after the source collapses. Segment B provides the separately reviewed river line used in the warning scenarios. Gyirong Port is beside Friendship Bridge. It is not a separate target among the 32 modelled sites, and no separate port distance or warning margin was calculated. All working spatial calculations use WGS 84 / UTM zone 45N (EPSG:32645). The saved imagery traced Friendship Bridge to Galchhi route is a single 80.614468 km line. Distance starts at the saved northern line tip. A separately recorded Friendship Bridge landmark is 37.649 m from that tip. The user-designated Galchhi route tip at 27.80261472°N, 85.00277617°E projects about 0.082 m from the saved southern tip. The reported distance is therefore the length of the saved line. The distance is measured following the river on the map and has not been physically surveyed between the two bridges.

The terrain analysis used four SRTM Global 1 arc-second (SRTMGL1) tiles: N27E084, N27E085, N28E084 and N28E085. The official documentation describes version V003 [20], but the version and download date of the local files were not recorded. The QGIS processing log records merging the four HGT tiles and clipping the

mosaic with Study_Area_Final.gpkg on 11 September 2026, followed by reprojection from EPSG:4326 to EPSG:32645 on 18 September using bilinear resampling, 30 m cells, Float32 output and NoData -9999. The DEM used in the study DEM_Study_Area_UTM45N.tif represents terrain of earlier days and does not show the changed terrain after the 2026 event. The saved UP analysis line is 20.108937 km and meets the downstream route through a 4.017 m connecting line. A least-cost search using the 30 m DEM identified three possible routes from the recorded source reference points to the start of the saved upstream line. Their approximate lengths were 2.541 km for ORIGIN_CSV, 1.790 km for ORIGIN_IMAGERY and 1.652 km for PAPER_SOURCE_SECTOR_APPROX. The calculations use the full lengths of the saved candidate lines rather than the rounded lengths reported above. We checked that the endpoints met before adding each candidate to the UP line and connector. These are geometric scenarios, not confirmed channels or 2026 hazard trajectories. The approximate references have different locations and sources. No single origin coordinate is selected as the observed initiation point. The 117-feature review network is connected in the geometric endpoint-to-line check, but this does not establish flow direction or the debris contribution from each branch. The study uses 32 main-river receptor references: 14 bridges, 10 hydropower sites/components and eight settlement references. Their locations were compiled from the cited records and reviewed using Google Maps, Google Earth and Esri World Imagery in QGIS. Mailung Bridge (TB-M) and Langtang HP04 are tributary sites and are excluded from main-channel timing

The sharing package also retains 16 bridge records and 170 riverside settlement records. These different inventories are separate from the 32 target points in the model: 14 bridge, 10 hydropower sites and eight working affected-settlement references. The 170 settlement points do not list confirmed damage at all the settlements. The release documentation identifies excluded tributary sites and older records that have been replaced. The CS18 Galchhi point marks the route last point and is not included among the warning targets.

Figure 1 shows the reviewed downstream river route and the UP line used as a possible upstream flood route. It also shows proposed radar posts, target locations and UNOSAT's preliminary mapped areas. The figure reports the calculated distances from three source reference points to Friendship Bridge but does not draw the DEM-derived candidate paths.

3.2. Candidate sensing layout

The proposed layout has 15 radar-gauge bases and 15 separate radar posts (RG-01–RG-15), two geophone sites (GEO-01/02), and CAM-01 at 28.310275°N, 85.493889°E. The 33 saved points matched the selected coordinates within 0.05 m. None represents an installed instrument. RG-01 and RG-02 are projected onto the UP stream line for distance calculations. RG-03–RG-15 are projected onto the downstream line. These projections do not move the saved posts. Distances between sensor posts and the mapped river centreline, and between base stations and sensor posts, are used for an initial GIS check of the proposed locations. They do not confirm a clear view of water, safe mounting, cable access or survival during a disaster. The geophone detection range, trigger thresholds and ability to distinguish hazard signals from earthquakes and other noise have not been tested. Assuming the camera and targets were 2 m above the ground, the 30 m DEM indicated that terrain blocked the view from CAM-01 to one approximate source-sector point by 13.16 DEM elevation units. The same check found no terrain obstruction toward the other two source reference points. The camera site remains fixed. No measured camera detection time is used in the simulation.

RG-01 and RG-02 are 8.168396 km apart, measured by following the UP analysis line. On the downstream route, the largest gap between neighbouring gauges is 11.341152 km, between RG-07 and RG-08. These distances provide the spacing between the proposed gauges but do not confirm detection coverage or sufficient warning time.

Across the 15 stations, straight-line distances between base stations and sensor posts range from about 11.32 to 111.72 m. Actual cable routes, cable specifications and mounting sites have not been checked.

The sensor inventory uses the updated GEO-02 location from geophone review v4 and the verified radar-post locations from review v2. The separate GeoPackage containing 15 base stations was created from inventory records labelled 'radar_base'.

3.3. Satellite-detected impact screening

UNOSAT's 26–27 August mudflow/rockflow product, distributed by UNESCO IHP-WINS with DOI 10.63253/1y26ihdq, includes an EPSG:32645 extent and a separate analysis-area polygon [11]. The 32 saved target points were overlaid without changing their locations. On 29 September 2026, the two downloaded source ZIP files were checked against the saved version 1 overlay tables. No differences were found, and no files were changed. Twenty-seven points intersect the preliminary mapped polygon. Five Timure, Syabrubes, the HP09 powerhouse tailrace reference, Battar Bazaar and Devighat fall outside the mapped polygon but inside the area analysed by UNOSAT; all 32 fall inside the analysis area. The dataset is preliminary and has not been checked in the field. It does not confirm damage to individual assets or when the flood reached them. Its dataset summary and resource description give different approximate area totals. The reported totals are not used in this study, and the report's GLOF label is not taken as proof that a glacial-lake outburst caused the disaster in that area. To confirm damage at a site, clearly mapped asset boundary and an independent damage record is required.

3.4. Counterfactual warning model

For an operating gauge upstream of a target on the assumed flood flow route, travel time is calculated from the river distance D (km) and an assumed constant flood speed (v) (m/s): $T_{\text{travel}} = 1000D/(60v)$ minutes. T_{delivery} is the total time for hazard detection, processing and approval of the warning, transmission to the alert hub, and delivery to recipients.

$T_{\text{lead}} = T_{\text{travel}} - T_{\text{delivery}}$, and $T_{\text{actionable}} = T_{\text{lead}} - T_{\text{local action}}$.

A positive action margin means that some calculated time remains after alert delivery and the assumed action time. This requires successful detection and delivery to recipients. We tested $v = 2, 5, 10$ m/s, total delay bundles 2, 10, 30 min, and local action times 5, 15, 30 min. The 2–10 m/s range is a limited set of test values. It does not describe all the speeds that may have existed during the event. Recent preprints on this event report much higher speeds in parts of the upstream area [16,17]. Estimated debris-flow speeds cannot be treated as flood-wave speeds and conversely flood wave speed cannot be treated as debris flow speed. This study has not independently checked these estimates. The 696/864 count applies only to the sampled values of speed, warning delay and action time. The tested values were not derived from measurements of this event. The terrain profile from the 30 m DEM was used to examine terrain and possible routes and was not used to estimate or calibrate flood speed. Water-level and rate-of-rise triggers remain unspecified for each site because gauge datum, baseline variability and event hydrograph are missing. A USGS study of travel times of dissolved substances in rivers states that its estimates need calibration and verification for the river section being studied [12]. It does not provide calibrated debris-flow or flood-wave speeds for this study.

The DEM was checked at 82 points on the UP line and 324 points on the Friendship Bridge to Galchhi Bridge line. Points were about 250 m apart, with both the route endpoints included. Every point returned an elevation value.

Moving downstream, the UP profile showed 10 apparent increases in elevation. Eight exceeded five DEM units, and the largest was 216.69 units. The Friendship to Galchhi line showed 105 apparent increases. Of these, 45 exceeded five DEM units, and the largest among them was 64.36 units.

Each DEM cell covered about 30 × 30 m. Official SRTM documentation gives elevations in metres relative to EGM96 [20]. However, the processed file does not record its vertical reference, and the processing logs do not record any change to the elevation units or vertical reference. The results are therefore reported in the file's original units.

The DEM shows terrain before the event, so it does not show changes caused by the 2026 disaster. The apparent rises may come from the mapped river line or the DEM's limited detail. They do not mean water flowed uphill and cannot tell us the water surface slope or flood speed.

Segment A joins each of the three DEM derived paths to the saved UP line and its connection to Friendship. These are three possible mapped routes, not a calculated range showing the uncertainty of the actual route. They do not show how long the flood took to reach a gauge from the source or how fast it travelled over the full route.

Segment B starts at the saved river-line endpoint near Friendship. Warning times are calculated from assumed gauge detections and river distances between gauges and targets. They do not start from a selected disaster-origin point. Adding the three source-route distances does not change the warning calculations already checked.

The RG-01 and RG-02 tests assume that the flood follows the UP route to Friendship. For downstream targets, the model uses the first working gauge along the river before each target, considering RG-03 onward. One test uses only RG-02 for sites near Friendship. A separate backup test considers RG-01 and RG-02, plus RG-03 for HP02. Results from each test are reported separately.

The proposed system sends a signal from the sensor/controller through a satellite link to an authorized alert hub. The hub then uses a local channel to warn people, who must have time to act to save their life. A working satellite link alone cannot send a warning to an ordinary mobile phone if the local mobile network and other delivery channels are unavailable.

The script field **warning_delivered_MODEL** means that the model has selected a communication path and assumes that the local warning channel is in function. It is called "model path/channel available" in the narrative and tables, and does not mean that a person was verified to have received an alert.

For all 32 targets, mobile service, sirens or radio, direct satellite receiving equipment, power and confirmation of receipt during the event remain unverified. Common Alerting Protocol (CAP) is proposed as a standard message format that different warning systems can share; its use during the 2026 event has not been documented [13]

4. Illustrative results

4.1. Segment A: conditional source references to Friendship

The three possible routes from the source reference points to Friendship Bridge are 21.764510 km, 21.902925 km and 22.653727 km long. These correspond to the approximate source-sector point reported in the paper, the imagery reference and the catalog coordinate. The longest route is 0.889217 km longer than the shortest.

The mapped river route from Friendship Bridge to Galchhi Bridge is 80.614468 km. Adding this gives total possible route lengths of 102.378978 km, 102.517393 km and 103.268195 km, respectively.

These are calculated map distances. They do not confirm the actual disaster origin or the route taken by the flood. The Friendship-to-Galchhi distance remains unchanged. Each source point, DEM path, UP line and connection is saved separately so the distances can be checked without choosing one point as the true origin. The 0.889217 km difference compares the three mapped routes; it does not show how uncertain the actual flood route is. These routes do not tell us when the flood reached Friendship, when a warning was issued or when the first gauge detected it. Arrival-time estimates from other studies [15–17] are reported separately because the original dated and timed records have not yet been checked.

4.2. Segment B: Friendship to Galchhi and downstream warning

The downstream v3 file contains 4,320 test results: 32 targets × five scenarios × 27 combinations of speed, warning delay and action time. The baseline uses the first eligible downstream gauge. For four sites near Friendship, it uses RG-02 and assumes that the flood follows the UP route. All 864 combinations assume a working communication path to people. Of these, 696 leave enough calculated time for the assumed action. The mobile-network outage test gives the same results because it assumes that satellite communication and a separate local warning channel still work. That local channel was not verified during the event. Satellite communication alone would not reach people who depended only on a failed mobile base station. If the satellite link fails and no backup is available, the model cannot send warnings. Adding 10 minutes to confirm the warning reduces the combinations with enough action time to 662 out of 864. If the first selected upstream gauge fails, the model finds another gauge in 729 combinations. It gives a positive action margin in 661 combinations. The remaining 135 combinations have no selected gauge and concern five sites near Friendship. This happens because the script checks only limited backup options; another gauge in the wider network might still be available.

These counts describe the tested combinations. They are not measured warning outcomes or probabilities of success

Table 2. Results of the five hypothetical warning scenarios

Hypothetical scenario	Model rows	Path and recipient channel assumed available	Positive computed action margin	Conditional UP-route rows
Baseline satellite link functioning	864	864	696	108
Terrestrial outage; independent recipient channel assumed	864	864	696	108
Satellite backhaul fails; no fallback	864	0	0	108
First selected upstream gauge fails; restricted selection	864	729	661	0
Confirmation adds 10 min	864	864	662	108

On 29 September, every saved v3 model row and all five summary records were checked without changing the files. No calculation or ID differences were found. ‘Path and recipient channel assumed available’ means the model assumes that a warning can reach people. It does not confirm that anyone received one. The UP route counts show which cases use that route, even when the satellite link is assumed to fail. Figure 2 compares the scenario results and the separate backup tests for sites near Friendship. The bars count tested combinations; they do not show probabilities or warnings received during the event.

4.3. Conditional UP-gauge comparison for early downstream targets

On 29 September, all 594 rows in the UP-route backup analysis were checked without changing the files. No differences were found in site IDs, routes, distances, time calculations, result flags or tested values. At Friendship Bridge and the Rasuwagadhi settlement reference, RG-01 leaves enough calculated time to act in 14 of 27 combinations. If RG-01 fails and only RG-02 operates, none of the 27 combinations leaves enough time.

The results for other sites are:

Table 3. Combinations with enough calculated action time at three early targets.

Site	RG-01 operating	RG-01 fails; RG-02 operates
HP01	15 of 27	1 of 27
Timure	18 of 27	5 of 27
HP02	20 of 27	12 of 27

A separate HP02 test gives enough action time in 4 of 27 combinations with RG-03 operating, and 12 of 27 with RG-02 as backup after RG-03 fails. RG-01 gives more calculated warning time because it is farther upstream. These results assume that the flood follows the modelled route, the gauge detects it and the warning reaches people. They do not confirm that these things happened during the event.

RG-02 is 0.435952 km from the Friendship route start, measured by following the saved line. At the slowest tested speed of 2 m/s, the flood would cover this distance in 3.633 minutes. The shortest assumed warning-delivery and action time is 7 minutes (2 + 5). Therefore, none of the 27 combinations leaves enough time to act at Friendship. RG-01 is 8.604348 km from the same point. The calculated travel times are 71.703, 28.681 and 14.341 minutes at assumed speeds of 2, 5 and 10 m/s, respectively. This shows how gauge location affects warning time if the flood follows the connected UP route. These are calculated times, not warning times measured during the 2026 event.

For enough time to act, the flood's travel time from the gauge to the target must be longer than the time needed to send the warning and take action. The required river distance is:

$$D > 0.06v(T_{\text{delivery}} + T_{\text{local action}}) \text{ km},$$

Even with the shortest assumed total of 7 minutes (2 minutes for delivery and 5 minutes for action), the distance must exceed 0.84 km at 2 m/s or 4.20 km at 10 m/s. These distances assume a constant flood speed. They are not a sensor-placement rule or a prediction of the 2026 event.

4.4. Reproducibility and assumption ledger

Table 4. Model inputs and assumptions.

Model quantity	Values in saved v3 script	Evidence status
Flood-wave propagation speed	2, 5, 10 m/s, constant over the selected path	Hypothetical sensitivity grid; no 2026 hydrograph calibration
Detection, processing, backhaul, dissemination delays	0.5 + 0.5 + 0.5 + 0.5; 2 + 2 + 2 + 4; or 5 + 5 + 10 + 10 min	Three hypothetical bundles totalling 2, 10, 30 min
Local action interval	5, 15, 30 min	Hypothetical common grid; no target evacuation survey
Corroboration case	Additional 10 min processing	Hypothetical; no false-alarm or verification performance measured
Satellite outage case	No fallback path; model delivery fails	Defined failure scenario, not an observed outage
Terrestrial outage case	Independent recipient dissemination assumed available	Conditional assumption; no target channel verification
First upstream gauge failure	Remove the first selected upstream gauge, then select another gauge allowed by the restricted model rule.	Limited backup selection; additional RG-01/RG-02 backup cases tested separately

The downstream v3 script uses the saved CSV files containing positions along the river for 15 gauges and 32 targets. These distances are reported to six decimal places. Each combination of speed, warning delay and action time is counted equally, without assigning a probability. The five scenarios test the proposed system; they do not represent five conditions observed during the event. On 29 September, all 4,320 results and five summaries were checked against the saved inputs without changing the files. Routes, distances, times, margins and result flags were recalculated. No differences were found. This confirms that the calculations and site IDs agree with the saved inputs. It does not confirm that the assumed flood behaviour or communication system would work in practice

5. Discussion

An upstream sensor can give people time to act only if the hazard reaches its sensing location and triggers a warning quickly. The satellite link and warning approval process must work. A local warning channel must also have power and reach people who can respond. The geophones and camera may help monitor the area, but how quickly they could detect the hazard is unknown. The UNOSAT map shows whether target points are inside or outside the mapped affected area. It does not show flood travel times or communication coverage. The three possible DEM routes show how choosing a different source reference changes the calculated distance. They do not tell us the flood speed or when RG-01 or RG-02 would detect it.

Acharya's study [15] examines delays in actual warnings, although its findings still need to be checked against the original records. It therefore asks a different question from this study of a proposed system.

Park and Xu [16,17] show why one assumed speed may not represent the whole event. Avalanche movement near the source, material collected along the route, blocked channels and downstream flooding can behave differently. Studies looking for signs before the event in satellite images also draw different conclusions from limited observations [18,19]. In this study, satellite images help monitor the area, while the satellite

communication link carries sensor data and warnings. The cited preprints do not confirm the proposed sensors' trigger settings or whether warnings would reach people.

Results for sites near Friendship depend strongly on whether RG-01 or RG-02 triggers the warning. This shows why backup sensors and every step of the warning system need testing. It does not prove that deaths could have been prevented or show the actual warning time on 26 August. A greater distance downstream may give more time to act, but flood speed can change, sensors can be destroyed, and power failures can stop local warnings.

The proposed system has several steps: detecting the hazard, sending data to the alert hub, issuing a warning, sending it to a local gateway and reaching people. The v3 script does not test each step separately. Its 'warning_delivered_MODEL' field assumes that the selected communication path works. To confirm effectiveness, evidence would be needed that people received warnings with enough time to act.

6. Limitations and next verification

The DEM-derived routes have not been confirmed. The actual source route, the time the flood began, when it first reached Friendship and how much debris came from each branch remain unknown. The 30 m DEM cannot give the water-surface slope or flood speed. The preliminary affected-area map was made from satellite images taken on two dates. A point inside this area does not confirm damage at that site. Dated and timed records of local communication failures and warning receipt are also missing. The proposed sensors, camera, satellite link, relays, sirens or radio, backup power and action times have not been tested. Radar trigger settings have not been established. These gaps mean the study cannot confirm that the system would have worked during the event. They also mean the assumed speeds remain unverified, and the counts of tested combinations cannot be treated as probabilities of success.

The most useful additional data would be records from DHM station 446.22, including its reference water level, time zone and data-quality notes; dated and timed records of communication failures and warnings; damage reports and mapped boundaries for individual assets; and technical details of the sensors and communication equipment. Any new evidence should be saved with its source and version, then used to improve the model. It should not be treated as proof that the current assumptions were correct.

7. Conclusion

This study examines the possible source-to-Friendship routes separately from the mapped Friendship-to-Galchhi river route. It also uses proposed sensor locations and UNOSAT's preliminary affected-area map. The calculations show how gauge location, warning delay and delivery to people change the time left to act. They do not demonstrate actual warning success or avoided damage. The results can help plan further tests. River-level records, event timing records and proof that people received warnings are still needed to check the model.

Bhote Koshi-Trishuli: reviewed geometry and candidate warning sites

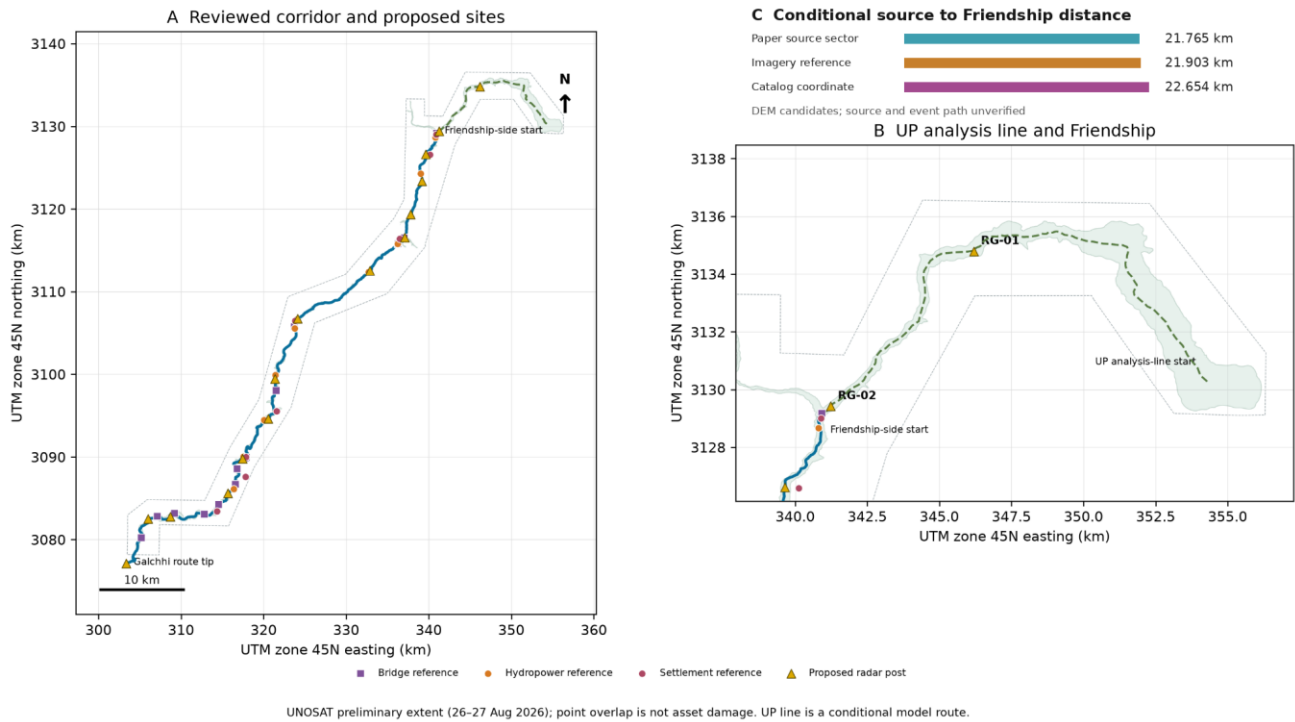


Figure 1. Mapped river routes, proposed sensor sites and possible source to Friendship distances.

Panel A shows the mapped route from near Friendship Bridge to Galchhi, proposed radar posts and 32 bridge, hydropower and settlement points in WGS 84 / UTM zone 45N. Panel B shows the UP analysis line and gauges RG-01 and RG-02. Panel C gives distances from three source reference points to Friendship, calculated using the saved DEM paths. These paths are not drawn in the figure and have not been confirmed as routes taken by the 2026 flood. Gyirong Port is discussed separately. It has no separately measured point in the figure and is not among the 32 model targets. The pale area shows UNOSAT's preliminary mapped mudflow/rockflow extent, and the dashed boundary shows the area analysed using satellite images from 26–27 August 2026 (DOI: 10.63253/1y26ihdq). The UP line starts at a selected analysis point, not a confirmed disaster origin. Sensor locations are proposed. A target point inside the mapped affected area does not confirm damage.

Sources: reviewed river-route, radar-post and target layers; source-route distance-check CSV; and two UNOSAT source ZIP files

Illustrative warning-margin sensitivity, not historical warning success

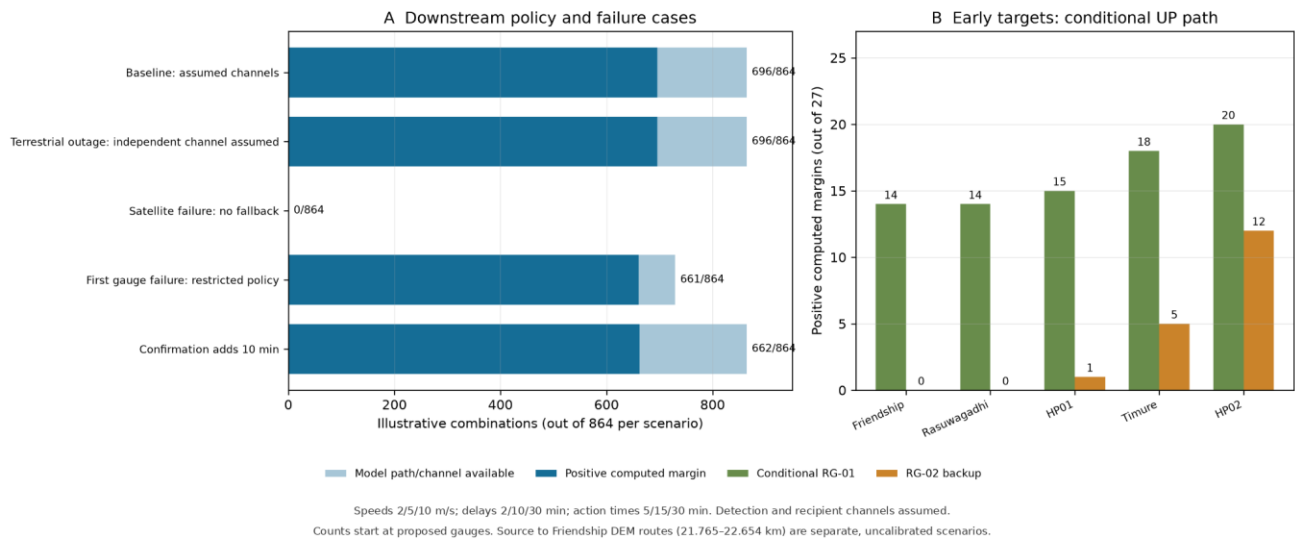


Figure 2. Illustrative warning-margin sensitivity under stated design assumptions.

Panel A compares how many tested combinations leave enough time to act and how many have an assumed working warning channel across five scenarios. Each scenario has 864 combinations. Panel B shows separate RG-01 and RG-02 tests for five sites near Friendship, with 27 combinations per case. The tests use assumed speeds of 2, 5 and 10 m/s, warning delays of 2, 10 and 30 minutes, and action times of 5, 15 and 30 minutes. They assume that a working communication channel reaches people; they do not confirm that anyone received a warning. The calculations start when a gauge is assumed to detect the hazard. They do not use the possible source-to-Friendship route lengths of 21.765–22.654 km. The actual flood route, sensor detection performance and arrival times during the 2026 event remain unconfirmed.

Sources: checked v3 scenario summary and the 594-row backup-analysis CSV.

Data availability

A sharing package was prepared on 3 October 2026. It contains a QGIS project, 13 GeoPackage layers, 11 CSV tables and supporting documentation. The files include reviewed river routes, possible source routes, bridge and hydropower locations, settlement references, proposed sensor locations, river-distance tables, model results and UNOSAT overlap tables. The reference inventories are separate from the 32 model targets.

The QGIS project was previously tested in another folder. All 13 layers opened correctly, their data sources were inside the copied folder, and the base-station coordinates matched the selected inventory. These checks confirm file access and coordinate agreement; they do not validate the scientific results.

The documentation explains the included layers, saved fields, assumptions and limitations. A file list includes checksums so users can check file integrity. GIS data and calculation results are provided; analysis code is not included. The package does not automatically reproduce the calculations or manuscript figures.

Third-party data that are not included must be obtained from their original providers and used under their respective terms. The data package is publicly available on Zenodo, version 1.0.0, published on 3 October 2026: <https://doi.org/10.5281/zenodo.23117695> [21].

Author declarations

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Reuse: The original manuscript, GIS layers, calculation tables and documentation created for this study are licensed under the Creative Commons Attribution 4.0 International License (CC BY 4.0). Third-party materials remain subject to their respective licenses and attribution requirements.

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