Overview

A concrete design for a "Borromean Risk" assessment tool for mass movements (landslides, rockfalls, debris/mudflows, lava flows) is described below.

The central idea is that three factors—(1) Event Drivers (hazard likelihood), (2) Local Lore & History (place-based evidence), and (3) Site Vulnerability—form a Borromean triad: high actionable risk emerges only when all three "rings" are engaged. If any one ring is weak or missing, the linkage "falls apart", and overall risk should drop sharply.

1) What the software does

- **Scope:** Map and score risk for user-selected mass-movement types at a location (parcels, road segments, or raster cells).
- **Inputs:**
  - **Event Drivers (H):** slope/relief from DEMs; lithology & structure; soil depth; root cohesion/proximity to burn scars; rainfall intensity-duration/flood data; seismic shaking; distance to scarps/faults; historical runout paths; for lava, vent proximity & flow-path models.
  - **Local Lore & History (L):** crowd-sourced narratives, indigenous knowledge, field notes, newspapers, prior event inventories (with uncertain georeferencing allowed), expert annotations. Text is encoded to quantitative evidence via fuzzy rules or NLP with human review.
  - **Vulnerability (V):** exposure (people, roads, utilities, buildings), criticality (hospitals, schools), and fragility (construction type, lifeline redundancy), producing expected-consequence scores.
- **Outputs:**
  - Interactive **risk map** with Borromean overlay (a tri-color ring widget showing each factor's strength).
  - **Explanations**: factor contributions, threshold hits/misses, "what would lower risk here?" levers.
  - **Scenario mode**: e.g., +50 mm/3h rain; or "new retaining wall" to see risk response.
  - **Audit trail**: data provenance and uncertainty bands.

2) The Borromean mathematics (core scoring)

Let each factor be normalized to [0,1][0,1][0,1]:

- H∈[0,1]H \in [0,1]H∈[0,1] = Event Driver strength (hazard likelihood proxy)
- L∈[0,1]L \in [0,1]L∈[0,1] = Local Lore & Historical evidence strength
- V∈[0,1]V \in [0,1]V∈[0,1] = Vulnerability/Consequence strength

2.1 Base “all-three-needed” aggregator

Use a strict t-norm or product as the base, so all three must be present:

Product t-norm

Rprod=Hα·Lβ·VγR_{\text{prod}} = H^\alpha \cdot L^\beta \cdot V^\gammaRprod=Hα·Lβ·Vγ

with α,β,γ\alpha,\beta,\gammaα,β,γ weights (default 1). This already encodes “AND”: if any ring ≈ 0, the product collapses.

Łukasiewicz t-norm (strict AND)

Rluk=max(0, H+L+V−2)R_{\text{luk}} = \max\big(0,\; H + L + V - 2 \big)Rluk =max(0,H+L+V−2)

This returns >0 only when all three are high (sum > 2), producing a crisp Borromean-like gate.

You can combine both (smooth product inside a strict gate):

R0=Rprod·1{H>τH, L>τL, V>τV}R_0 = R_{\text{prod}} \cdot \mathbf{1}\{H>\tau_H,\; L>\tau_L,\; V>\tau_V\}R0=Rprod·1{H>τH,L>τL,V>τV}

2.2 Explicit “Borromean synergy” term

To emphasize that **triple co-occurrence** (not pairwise) drives escalations, add a 3-way interaction that is **zero** if any factor is zero but does not double-count pairwise overlaps.

A practical option:

Smin=κ·min(H,L,V)S_{\text{min}} = \kappa \cdot \min(H,L,V)Smin=κ·min(H,L,V)

This is simple, monotonic, and preserves the Borromean feel (the weakest ring limits the chain). Or use a centered cubic term:

Scube=κ·(H−H¯)(L−L¯)(V−V¯)S_{\text{cube}} = \kappa \cdot \big(H-\bar{H}\big)\big(L-\bar{L}\big)\big(V-\bar{V}\big)Scube=κ·(H−H¯)(L−L¯)(V−V¯)

where H¯,L¯,V¯\bar{H},\bar{L},\bar{V}H¯,L¯,V¯ are regional means. This behaves like **three-way interaction information**: it’s positive only when the joint high/low pattern departs from average **in all three** simultaneously.

Final risk (0–1), with uncertainty σR\sigma_RσR:

R=clip(λ R0 + (1−λ) S, 0,1),S∈{Smin,Scube}R = \text{clip}\Big(\lambda \, R_0 \;+\; (1-\lambda) \, S,\; 0, 1\Big), \quad S \in \{S_{\text{min}}, S_{\text{cube}}\}R=clip(λR0 +(1−λ)S,0,1),S∈{Smin,Scube} σR from ΔH,ΔL,ΔV via Monte Carlo or delta method\sigma_R \;\text{from}\; \Delta H,\Delta L,\Delta V\; \text{via Monte Carlo or delta method}σR fromΔH,ΔL,ΔVvia Monte Carlo or delta method

- τ∗\tau_*τ∗: factor thresholds (e.g., rainfall I–D exceedance, validated lore confidence, fragility tier).
- κ\kappaκ: synergy strength; λ\lambdaλ: mixing weight between pure AND and synergy.
- Calibrate τ∗\tau_*τ∗, α,β,γ,λ,κ\alpha,\beta,\gamma,\lambda,\kappaα,β,γ,λ,κ on known events (hindcasting).

2.3 Probability framing (noisy-AND)

If each ring is a **probability** that a required precondition is "on", the Borromean mechanism is a **noisy-AND**:

P(event)≈p0·H·L·VP(\text{event}) \approx p_0 \cdot H \cdot L \cdot VP(event)≈p0·H·L·V

with p0p_0p0 a base rate modulated by event class and time window. Add a triple-only excess term to capture synergy:

P(event)=p0·HLV + η·(HLV−HL¯ V¯)P(\text{event}) = p_0 \cdot H L V \;+\; \eta \cdot \big(HL V - \overline{HL} \,\overline{V}\big)P(event)=p0·HLV+η·(HLV−HLV)

This ensures pairwise effects alone don't inflate risk; the **three-body** component η\etaη only activates when all three are aligned.

2.4 Fuzzy rules for lore/history

Lore and partial records are naturally fuzzy. Define membership functions:

- μrecent(t)\mu_{\text{recent}}(t)μrecent(t) increases as historical event recency improves.
- μcredible(s)\mu_{\text{credible}}(s)μcredible(s) for source credibility (eyewitness, instrumented, oral tradition).
- μspatial(d)\mu_{\text{spatial}}(d)μspatial(d) decreases with distance between reported event and site.

Combine to a single LLL with weights wiw_iwi:

L=w1μrecent+w2μcredible+w3μspatialL = w_1 \mu_{\text{recent}} + w_2 \mu_{\text{credible}} + w_3 \mu_{\text{spatial}}L=w1μrecent+w2μcredible+w3μspatial

(then clamp to [0,1]). Human-in-the-loop curation can override outliers.

3) How each ring is computed

H: Event Driver score (hazard likelihood)

- **Static susceptibility:** slope angle (from DEM), curvature, lithology erodibility, soil thickness, landcover/root cohesion, proximity to faults/scarps, known source areas.
- **Dynamic triggers:** rainfall I–D exceedance, snowmelt rate, reservoir drawdown, ground shaking, wildfire burn severity, for lava: vent activity index, effusion rate proxies, channelization likelihood.
- Normalize via logistic transforms, then blend with learned weights from past events of the same movement type.

L: Local Lore & History

- **Sources:** historical inventories, local reports, indigenous knowledge, newspaper archives, field notebooks, geotagged photos.
- **Processing:** NLP extracts place/time; geocoding supplies spatial buffers; a credibility score is assigned; fuzzy memberships produce LLL. Provide a **confidence band** (wider where sources are sparse).

V: Vulnerability/Consequence

- **Exposure:** population at time-of-day, roads, pipelines, power lines, structures.
- **Fragility:** building typology vs. movement type (e.g., rockfall fragility curves), redundancy of lifelines.
- **Criticality:** hospitals, evacuation routes, water intakes.
- Combine to expected-impact proxy and normalize to [0,1][0,1][0,1].

4) Calibration & validation

- **Hindcasting:** run the model on historical intervals with known events; optimize α,β,γ,τ∗,λ,κ\alpha,\beta,\gamma,\tau_*,\lambda,\kappaα,β,γ,τ∗,λ,κ to maximize spatial AUC / Brier skill while penalizing false alarms.
- **Triple-only test:** verify that removing any ring (e.g., masking L to zero) collapses high-risk hotspots—mirroring Borromean unlinking.
- **Uncertainty:** propagate input uncertainties; publish R±σRR \pm \sigma_RR±σR per cell.

5) Software architecture (practical)

- **Pipelines:**
  - ETL for DEMs, geology, landcover, rainfall, seismic catalogs, inventories, text archives.
  - NLP + geocoder for lore extraction (with human validation UI).
- **Engine:** factor calculators for H,L,VH,L,VH,L,V; fuzzy membership library; probabilistic **noisy-AND** + synergy; Monte Carlo uncertainty.
- **UI:** map layers, per-site Borromean ring glyph (ring thickness = factor magnitude), sliders for thresholds, scenario toggles, and an explanation panel.
- **APIs:** raster in/out (Cloud-Optimized GeoTIFF), vector features (GeoJSON), batch scoring for corridors (roads, pipelines).
- **Governance:** provenance logs; editable lore evidence with versioning; embedded bias/ethics notes for community-sourced data.

6) Example (toy numbers)

Suppose a road cut cell has:

- H=0.8H=0.8H=0.8 (steep slope + forecast rain exceeds I–D curve),
- L=0.6L=0.6L=0.6 (two credible reports of past debris flow nearby, 40–60 yrs ago),
- V=0.9V=0.9V=0.9 (arterial road + buried fiber).

Choose α=β=γ=1\alpha=\beta=\gamma=1α=β=γ=1, τH=τL=τV=0.4\tau_H=\tau_L=\tau_V=0.4τH=τL=τV=0.4, λ=0.7\lambda=0.7λ=0.7, κ=0.3\kappa=0.3κ=0.3.

R0=(0.8)(0.6)(0.9)=0.432(passes thresholds)R_0 = (0.8)(0.6)(0.9) = 0.432 \quad (\text{passes thresholds})R0=(0.8)(0.6)(0.9)=0.432(passes thresholds) Smin=0.3·min(0.8,0.6,0.9)=0.18S_{\text{min}} = 0.3 \cdot \min(0.8,0.6,0.9) = 0.18Smin =0.3·min(0.8,0.6,0.9)=0.18 R=clip(0.7·0.432+0.3·0.18, 0,1)=0.352R = \text{clip}\big(0.7\cdot 0.432 + 0.3 \cdot 0.18,\; 0,1\big) = 0.352R=clip(0.7·0.432+0.3·0.18,0,1)=0.352

If lore were absent (L=0.0L=0.0L=0.0), R0=0R_0=0R0=0 and S=0S=0S=0: the Borromean linkage breaks, and the score collapses—exactly the intended behavior.

7) Why this “Borromean” framing helps

- It guards against false alarms when only hazard is high but **consequences or credible evidence** are weak.
- It elevates sites where local knowledge and past experience indicate latent pathways, **but only** when the physics (H) and consequences (V) also align.
- It is transparent: each ring is visible, editable, and auditable.