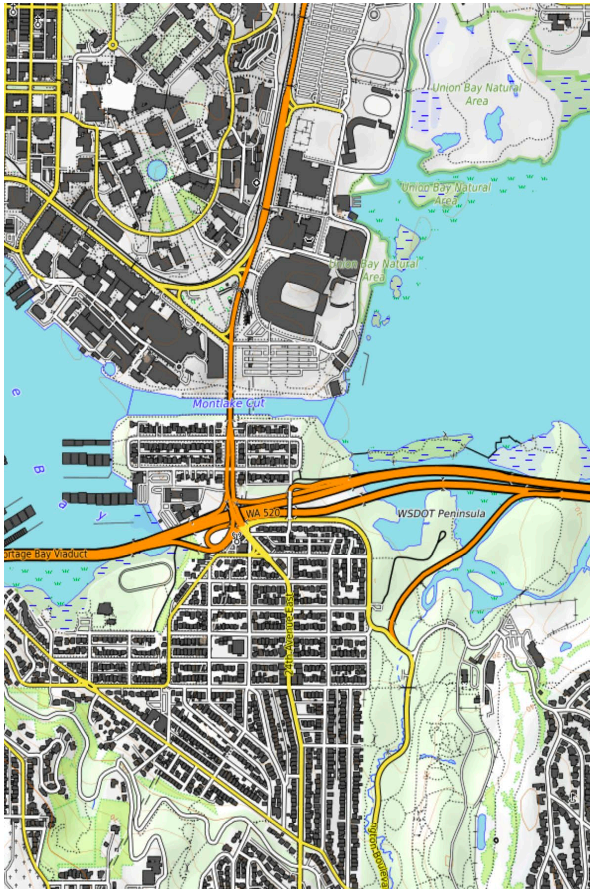
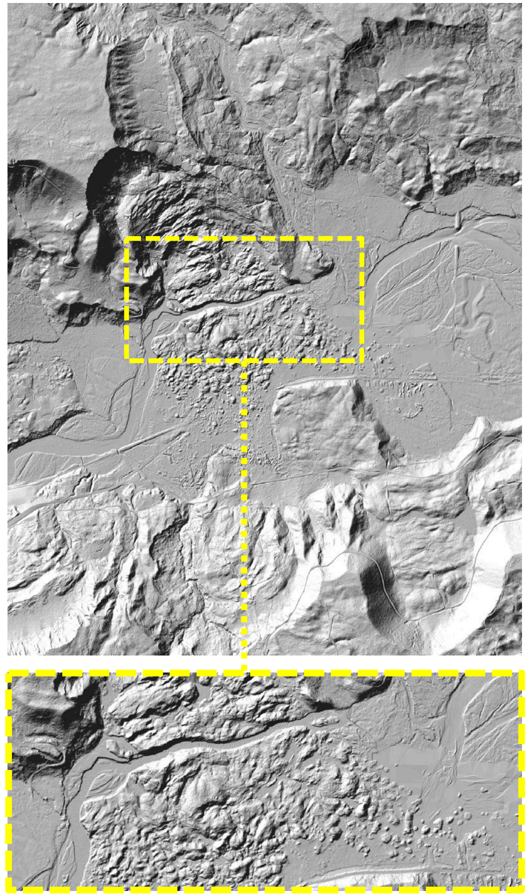
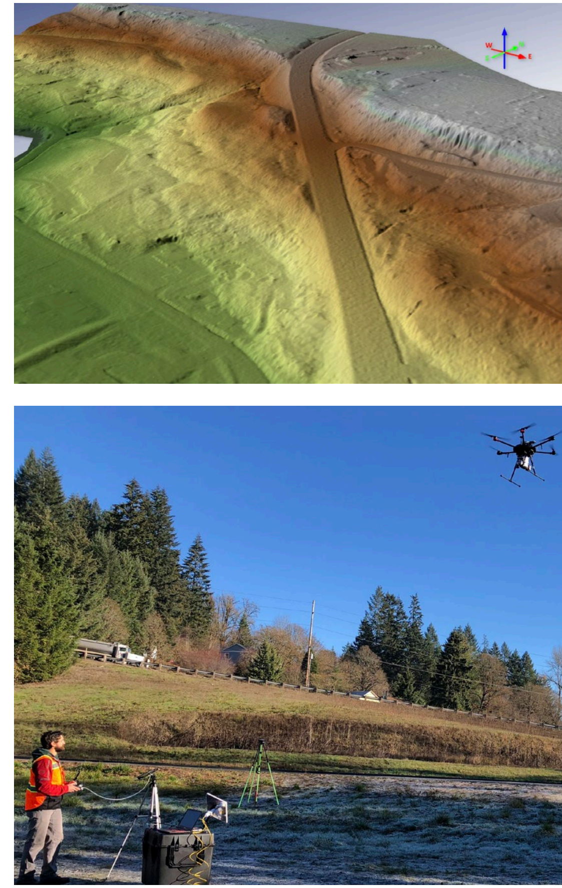
Regional-Scale Landslide Risk Assessment: Methodology and Application



Opentopomap.org



Lidar at different scales



Drone-derived bare-earth lidar DEM

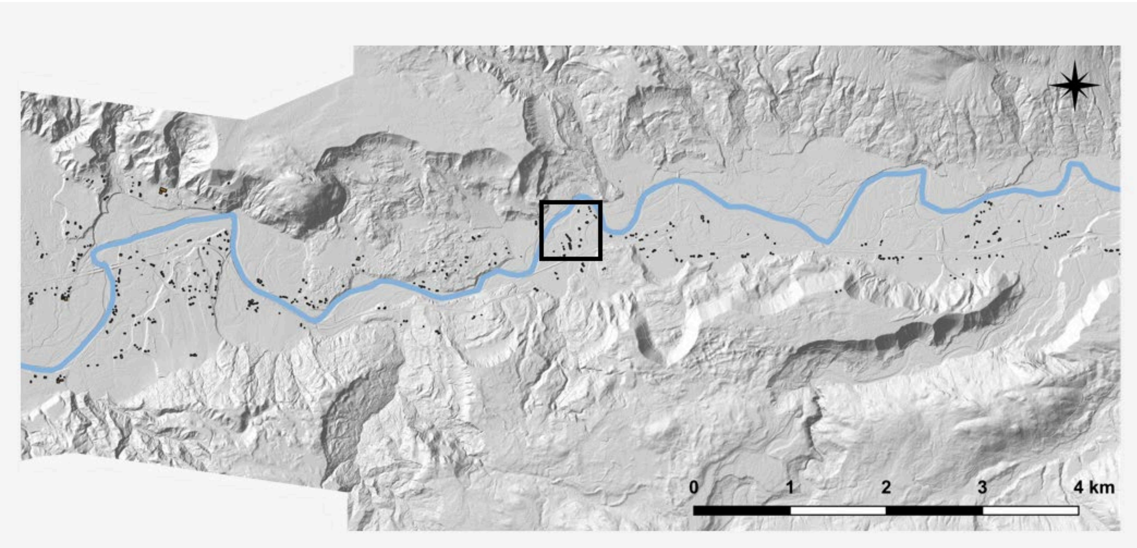
Joseph Wartman

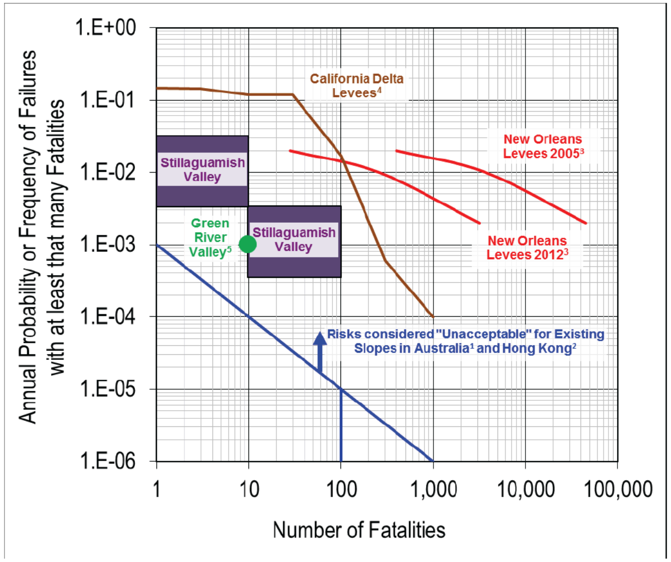
H. R. Berg Professor; and Director, RAPID Facility

UNIVERSITY OF WASHINGTON

RAPID NHERI
Natural Hazards Reconnaissance Facility

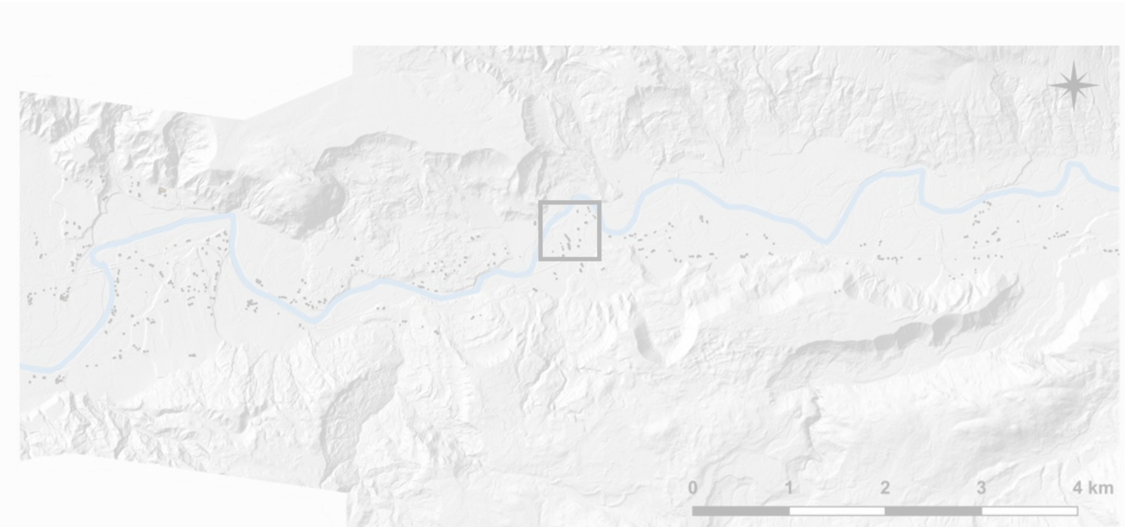
Mapping and Risk in Oso, Washington at the Time of the 2014 Landslide

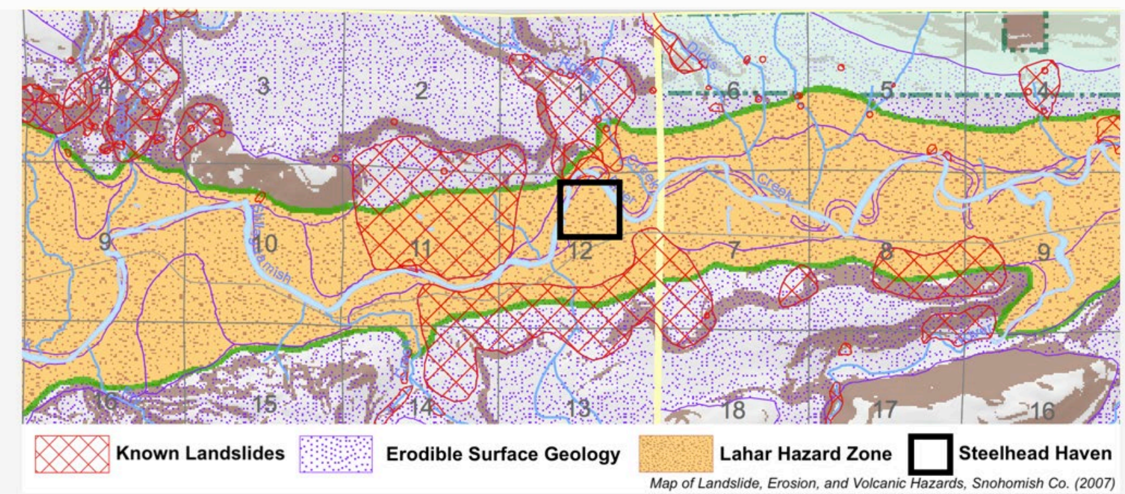




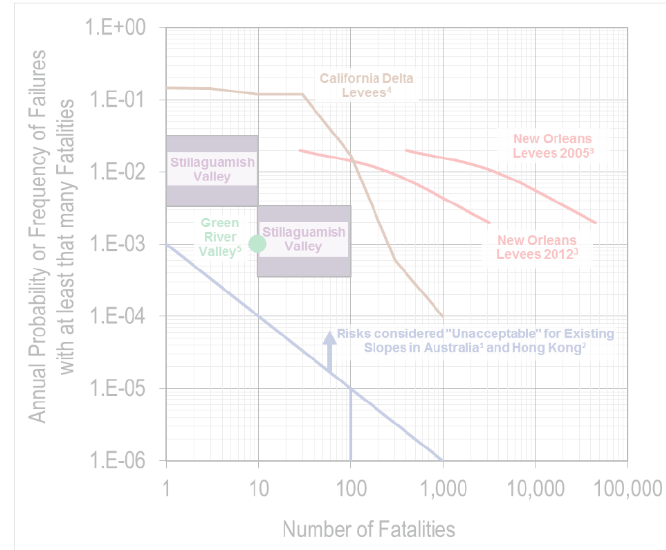
Estimated risk from landslides in 5-km stretch of North Fork Stillaguamish River Valley in vicinity of Oso compared with related benchmarks for human safety risk (GEER, 2014, doi:10.18118/G6V884)

Mapping and Risk in Oso, Washington at the Time of the 2014 Landslide



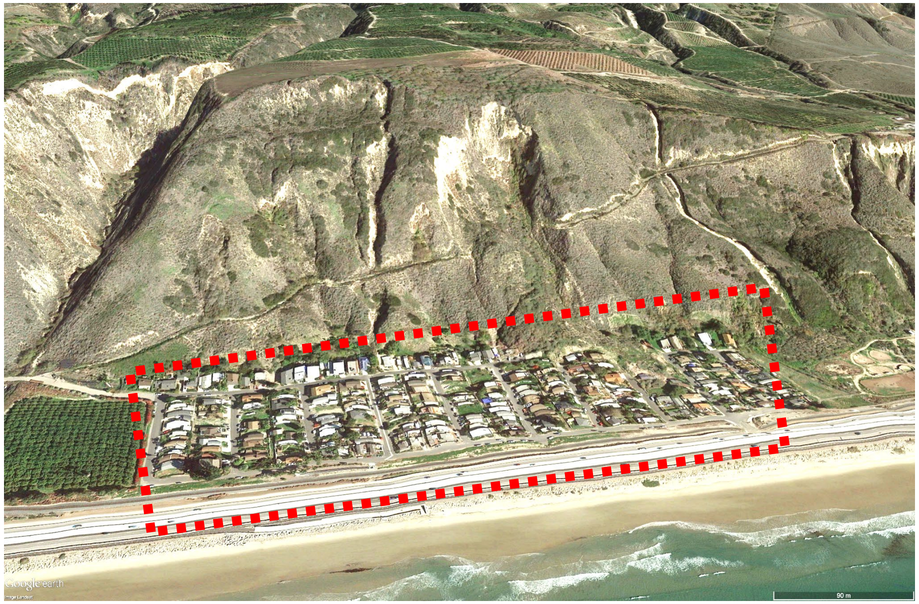


Lower: Landslide hazard map in vicinity of Oso (Snohomish Co., 2007)



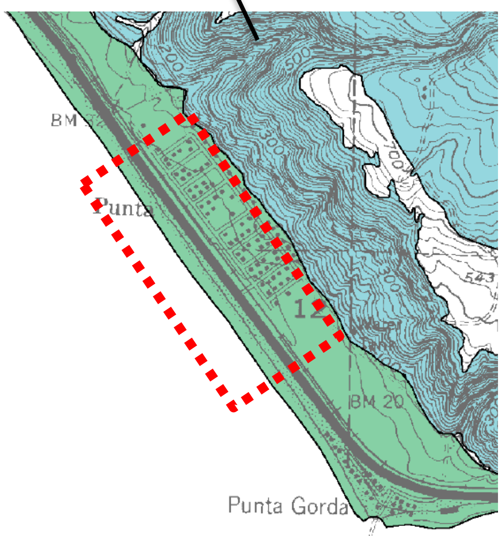
Estimated risk from landslides in 5-km stretch of North Fork Stillaguamish River Valley in vicinity of Oso compared with related benchmarks for human safety risk (GEER, 2014, doi:10.18118/G6V884)

La Conchita, California

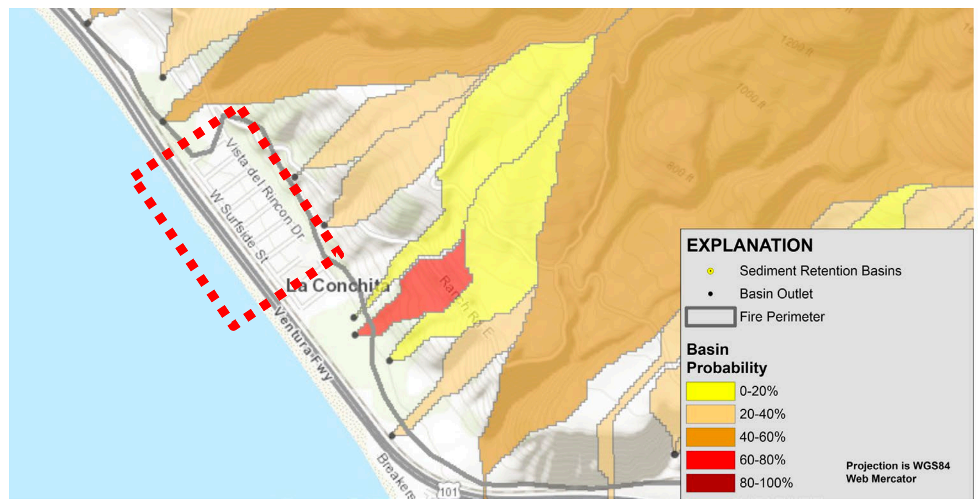


La Conchita, California

blue denotes landslide hazard zone

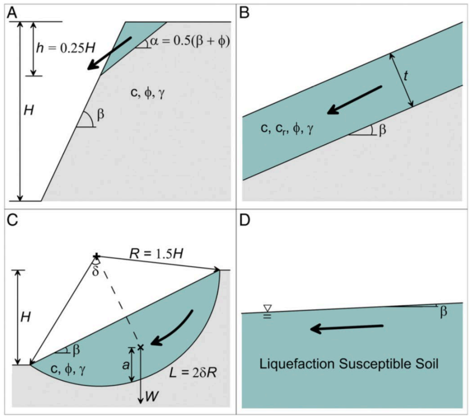


California Dept. of Geol. Coseismic Landslide Hazard Zones



USGS, 2017, Thomas Fire Debris Flow Hazard Map ("*does not predict downstream impacts, potential debris-flow runout paths, and the areal extent of debris-flow*")

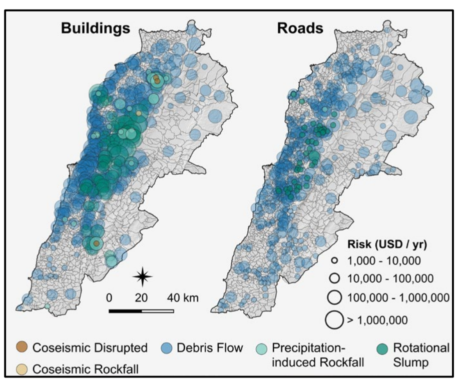
Landslide Hazard and Risk Mapping Research



Multimodal Method
(Grant et al. 2016, Saade et al. 2016)

- Regional-scale model
- Coseismic landslides, including
  - rock-slope failures
  - shallow, disrupted slides
  - deeper rotational failures
  - lateral spreading
- Compute displacements to estimate relative hazard

Alex Grant, Grace Abou-Jaoude, William Pollock, Miriam Tawk; and Angela Saade and Chris Massey



Risk Assessment Platform, Version 1
(*Pollock et al. 2019a,b*)

- Modifications to geotechnical models
- Precipitation-induced slides
- Runout modeling
- Risk assessment

Central theme: low cost, high resolution mapping

National Landslide Preparedness Act

- Sponsored by Rep. Susan DelBene (D-WA 1st District, *includes Oso, WA*)

- Includes provisions to

  (1) "develop and maintain a publicly accessible national landslide hazard and ***risk inventory***"

  (2) "establish a national 3D Elevation Program"

- Status: out of committee

- Prognosis: 50% chance of being enacted according to Skopos Labs

116th CONGRESS
1st Session

H. R. 1261

To establish a national program to identify and reduce losses from landslide hazards, to establish a national 3D Elevation Program, and for other purposes.

IN THE HOUSE OF REPRESENTATIVES

February 14, 2019

Ms. DelBene (for herself, Mr. Kilmer, Mr. Cartwright, Ms. Bonamici, Mr. Heck, and Mr. Smith of Washington) introduced the following bill; which was referred to the Committee on Natural Resources, and in addition to the Committee on Science, Space, and Technology, for a period to be subsequently determined by the Speaker, in each case for consideration of such provisions as fall within the jurisdiction of the committee concerned

---

A BILL

To establish a national program to identify and reduce losses from landslide hazards, to establish a national 3D Elevation Program, and for other purposes.

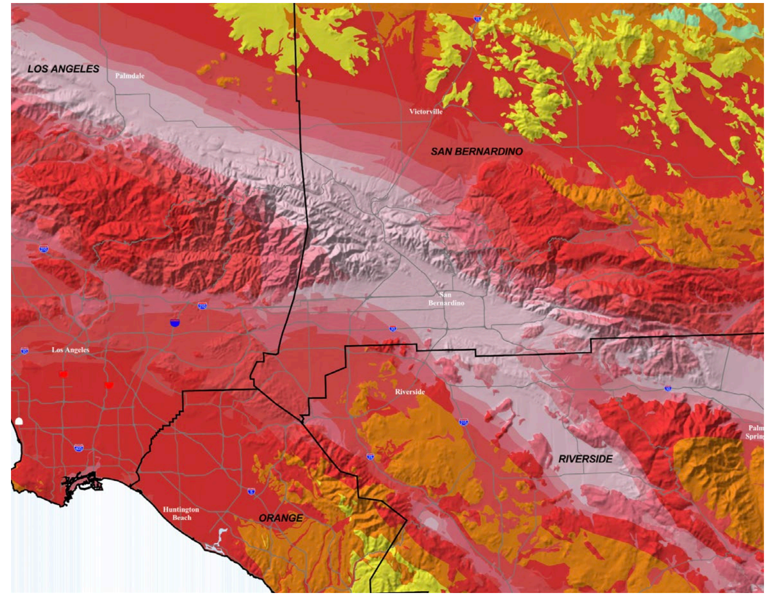
Be it enacted by the Senate and House of Representatives of the United States of America in Congress assembled,

SECTION 1. SHORT TITLE.

This Act may be cited as the ''National Landslide Preparedness Act''.

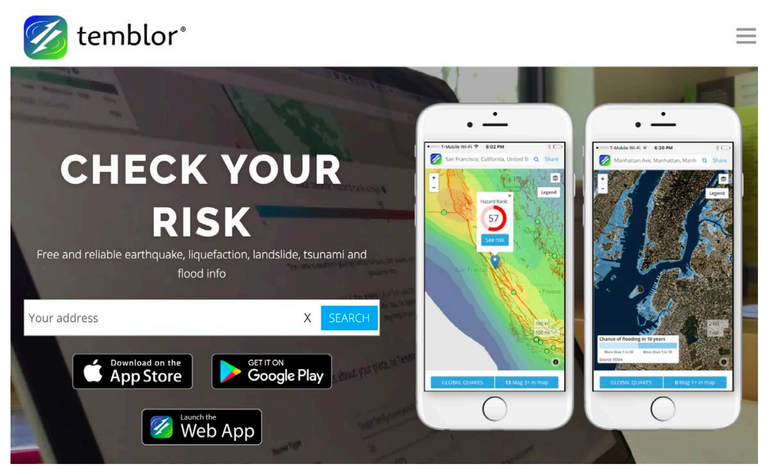
Benefits of Regional-Scale Hazard Mapping and Risk Assessment

- Cost-effective investment
- Supports land use planning
- Serves as a transparent basis for decision making
- Allows mitigation to be prioritized



Earthquake ground shaking hazard map

- Allows people to make informed decisions
- Enables land and housing markets to operate efficiently
- Unless people understand the risks we face, it is difficult to inspire action for risk mitigation

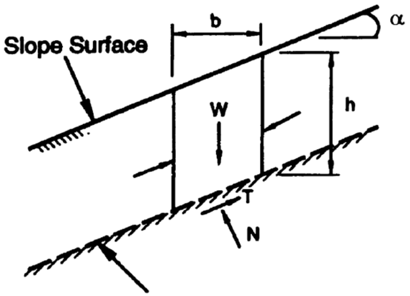


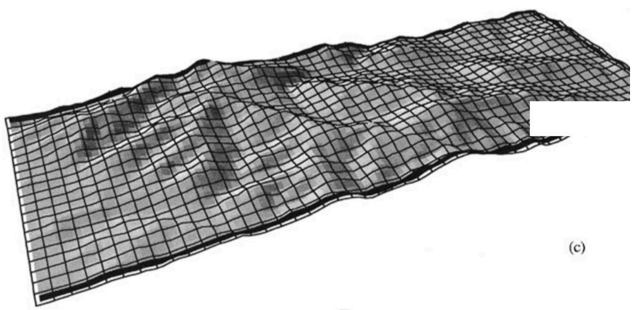
Risk estimate application

World Bank (2010) "Naural Hazards…"; conservation.ca.gov/cgs/Pages/PSHA/OFR96-08/psha-ofr.aspx; temblor.com

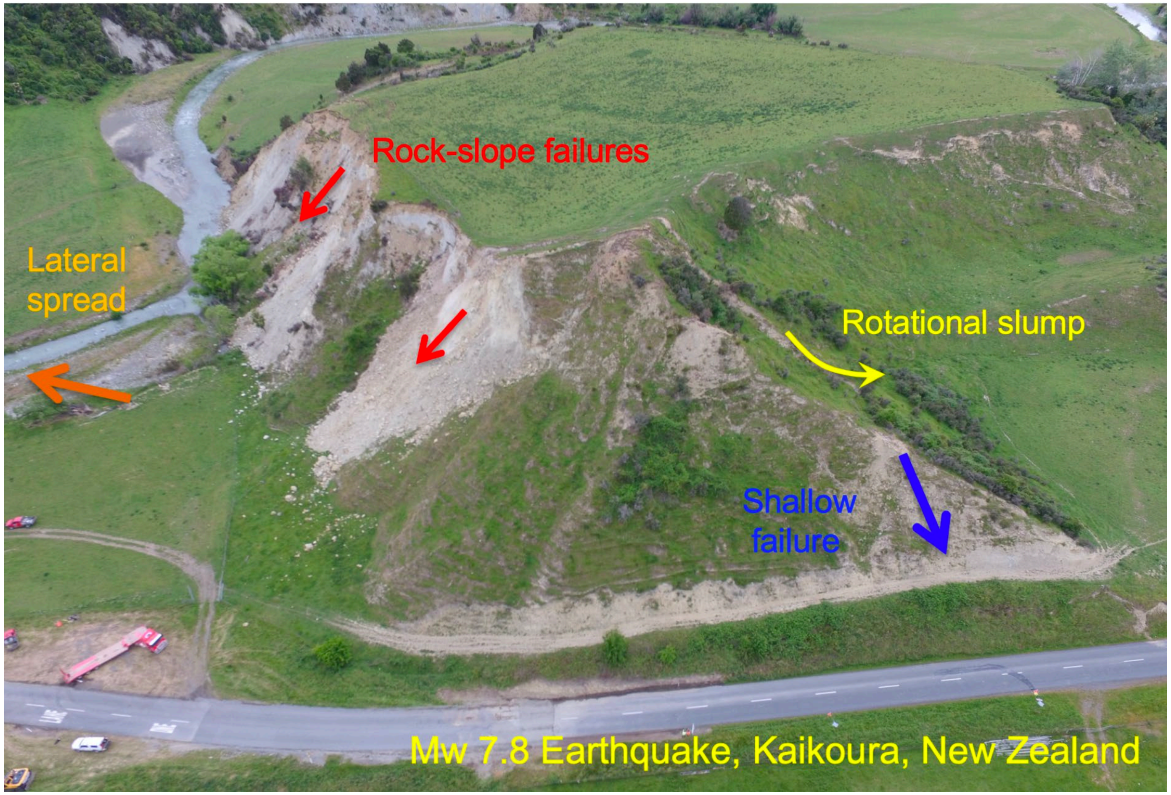
Landslide Modes of Failure

Traditional Infinite Slope Model
Used for Regional-Scale Studies

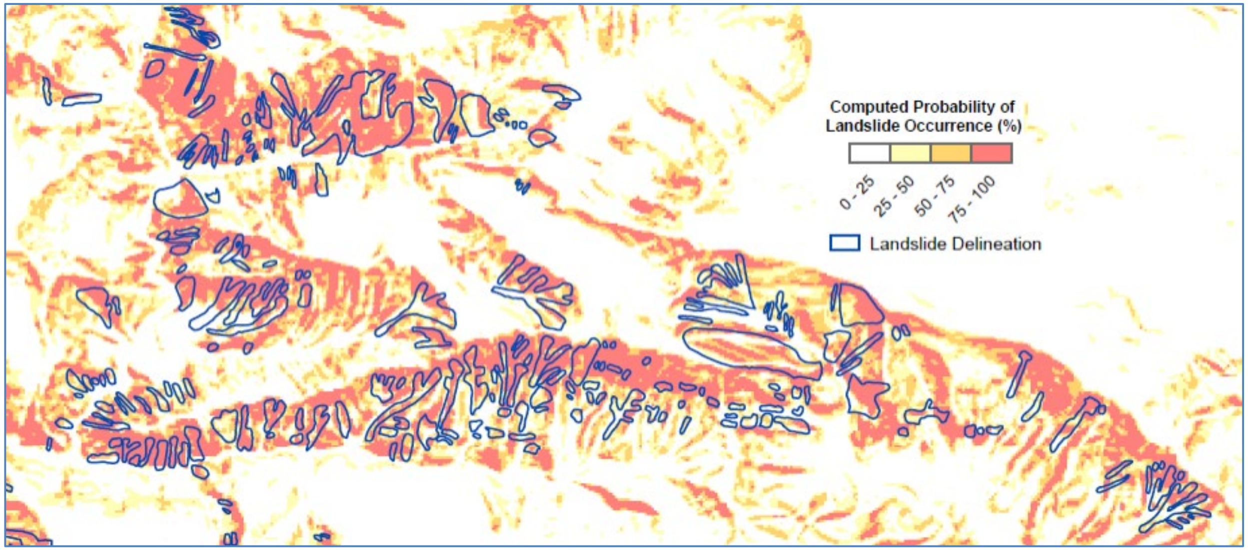




Miles and Ho (1999), *Soil Dyn. Eq. Eng.*



Statistically-Based Landslide Hazard Models



Northridge Landslides, Wartman and Gillespie, 2011

Based on observations, what combination of geology, morphology, and forcing (e.g., ground motion) resulted in the initiation of landslides?

- Formulates and "trains" statistical models using landslide inventories

- Key advantage

  - No need to quantify geotechnical properties over large regions

- Some Issues

  - Model is as strong as the landslide inventory "training set"
  - Does not tell us, "why"
  - Transferability to other regions, terrains, and geologic settings
  - Training inventory represents "predictor" conditions at the time of the forcing event
  - Can not (*yet*) effectively capture complex, cascading-type impacts

Landslide Risk Assessment at the Site-Specific Scale

$$R_{(Loss\ of\ Life)} = \sum_{1}^{n} (P_{l(S:T)}\ x\ P_{r(S)}\ x\ P_{e(S:T)}\ x\ V_p\ x\ N_P)$$

$$R_{(Infrastructure)} = \sum_{1}^{n} (P_{l(S:T)}\ x\ P_{r(S)}\ x\ (1)\ x\ V_i\ x\ E)$$

$P_{l(S:T)}$: spatio-temporal probability of occurrence

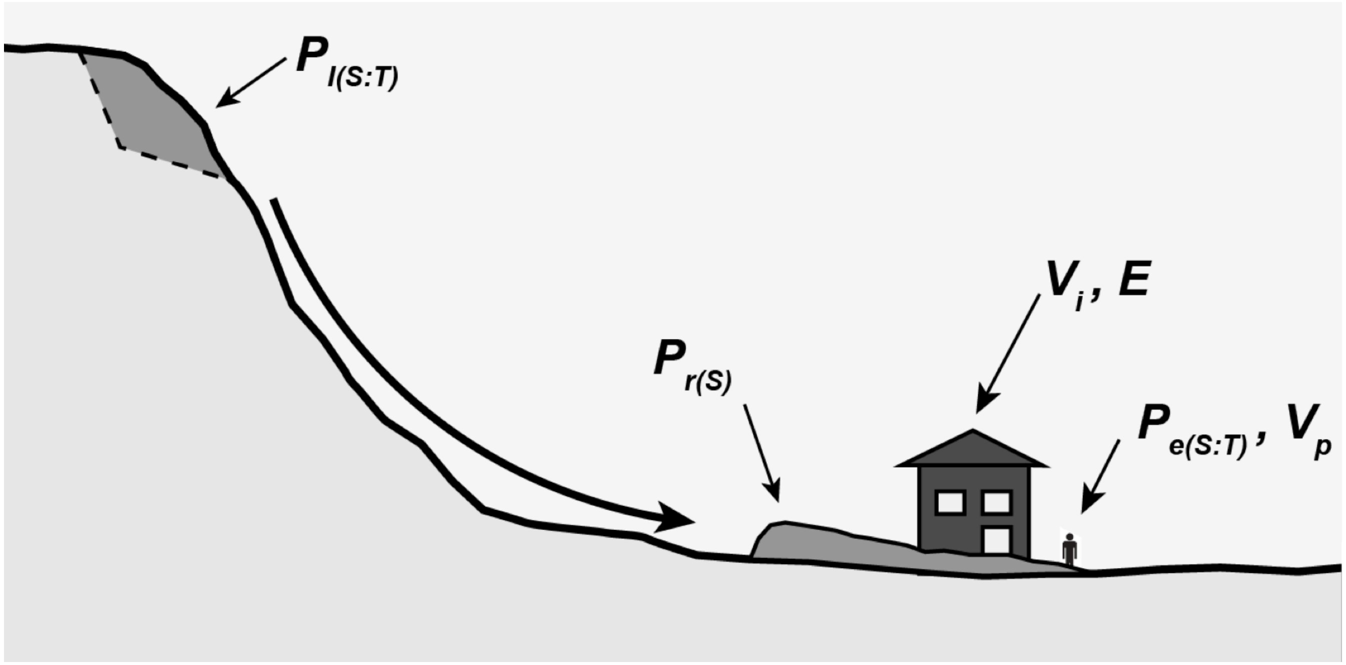
$P_{r(S)}$: spatial probability of impact

$P_{e(S:T)}$: spatio-temporal probability of occupancy

V: physical vulnerability

N_p: number of people

E: value



after Fell et al. 2005

Landslide Risk Assessment Methodology

I. Regional-scale hazard assessment using the "*Multimodal Method*"

• Explicitly accounts for different modes of failure

• Two-step application procedure:

1. Susceptibility to each landslide mode is evaluated based on topography

2. Hazards are assessed using mode-specific geotechnical models

Grant et al. 2016, *Eng. Geology*

II. Runout estimation, when applicable

• Empirically-based

III. Risk Assessment

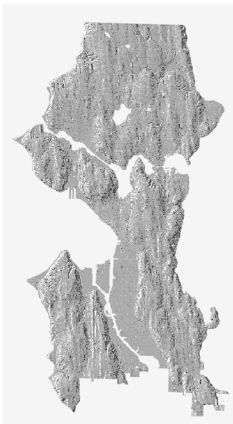
• Human and/or capital losses

Repeated for other return period events

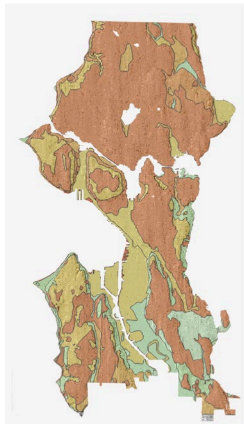
Pollock et al. 2019a,b, *IJDRR*

Data and Parameters

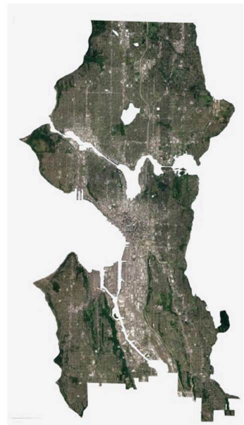
I. Regional-scale hazard assessment using the "*Multimodal Method*"



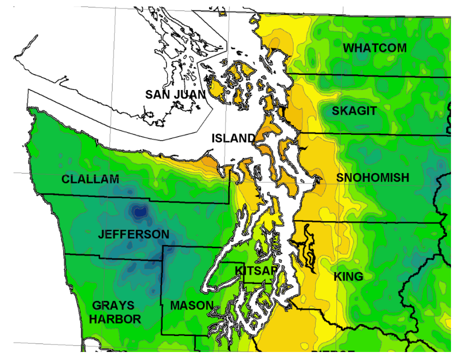
Terrain



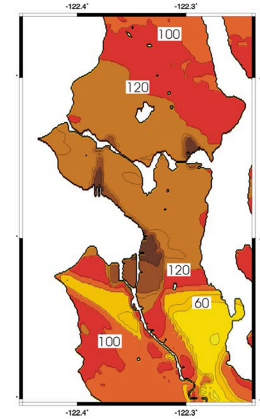
Geology



Satellite



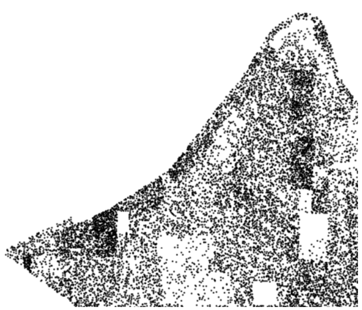
Precipitation



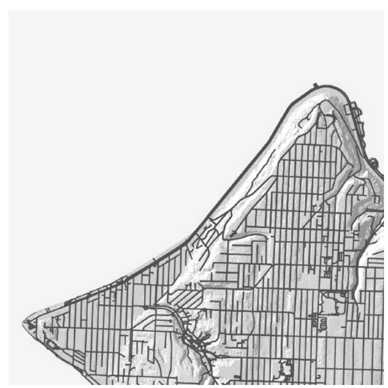
Ground motion intensity

II. Runout estimation: Terrain data (above)

III. Risk Assessment



Census



Open mapping data

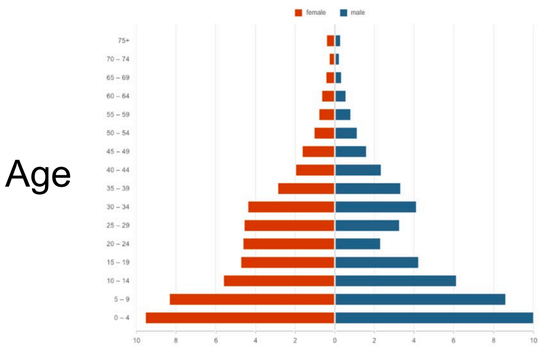
Government databases

Example Datasets for Seattle

Application for Lebanon

Why Lebanon?

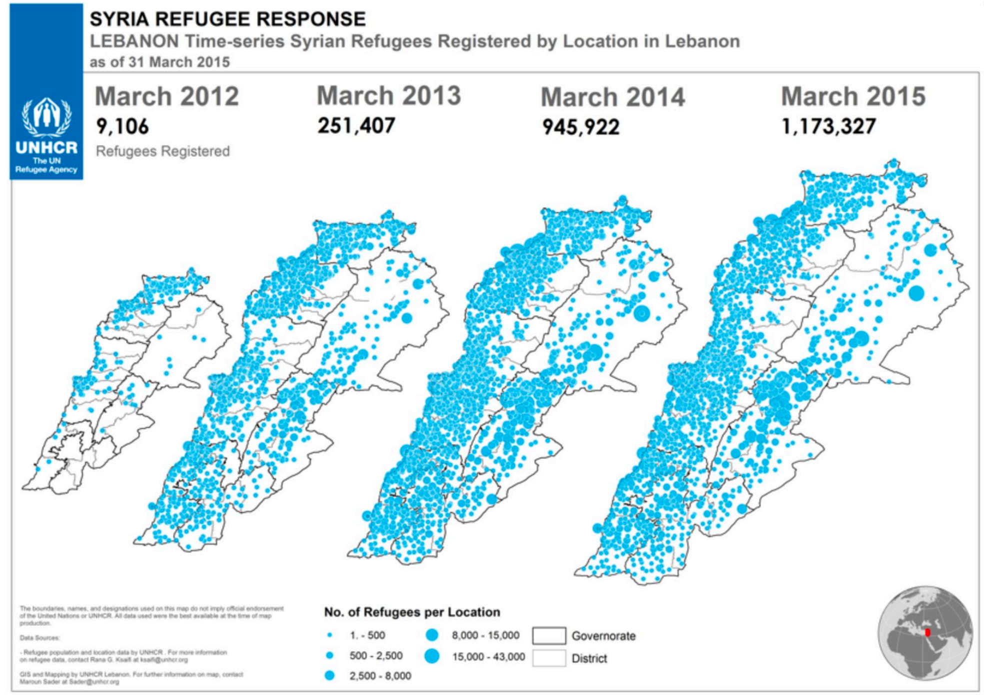
• 2011 civil crisis in Syria has led an influx of refugees in Lebanon, raising population by 40% over several years



• Population expansion has occurred without benefit of land use planning, leading to pressing questions about Lebanon's refugee placement policies

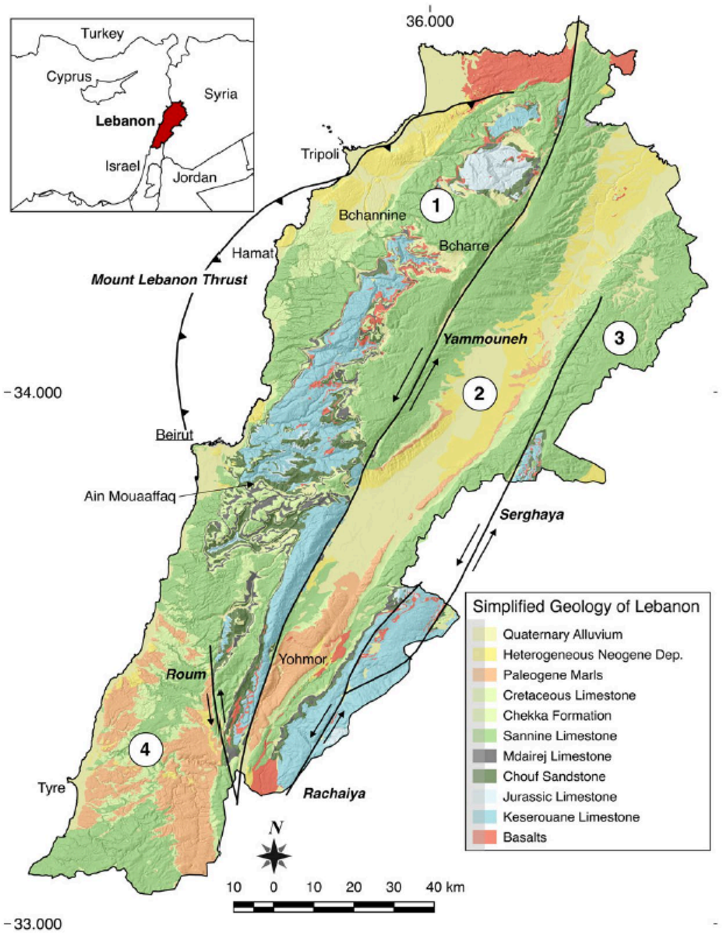
• How do regional crises, humanitarian disasters, and policy-making affect a country's geologic risk profile?

• Unique challenges: data limited setting, highly active landscape affected by both precipitation and seismicity



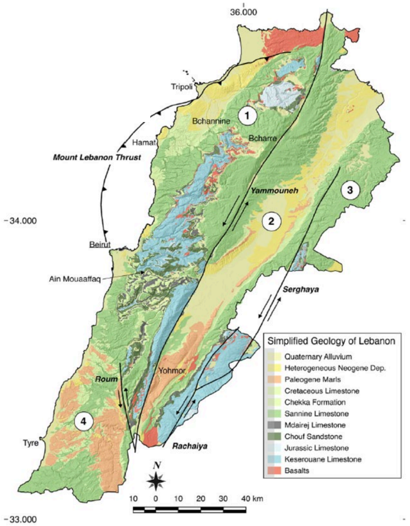
Mapping: United Nations Human Rights Council (2015); Photo: UKAID

Geology and Landslides of Lebanon

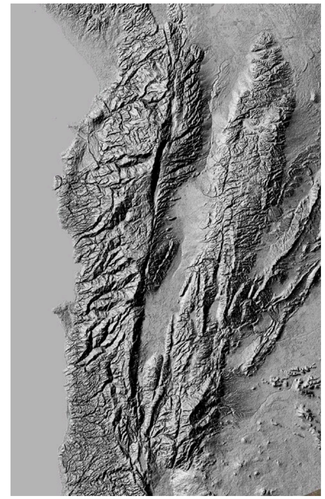


(1) Mt. Lebanon Range
(2) Bekaa Valley
(3) Anti-Lebanon Range

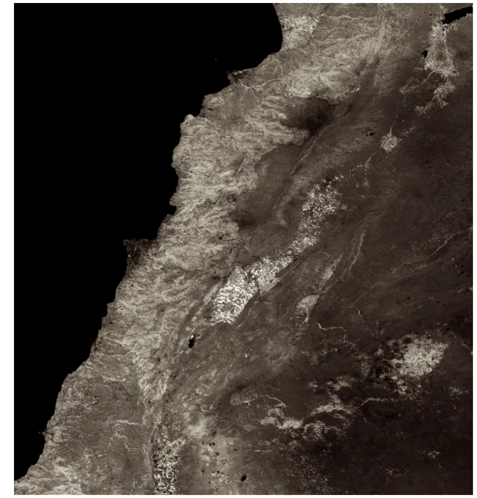
Lebanon Datasets



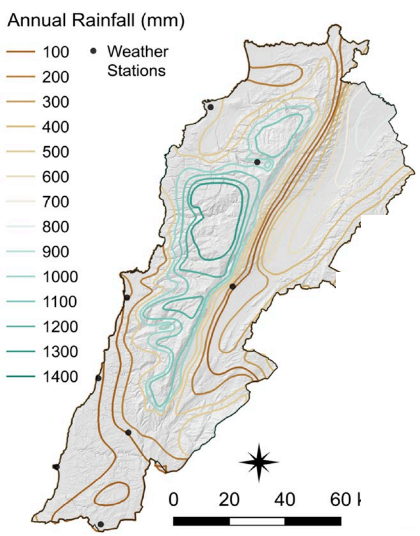
Geology (geotechnical properties)



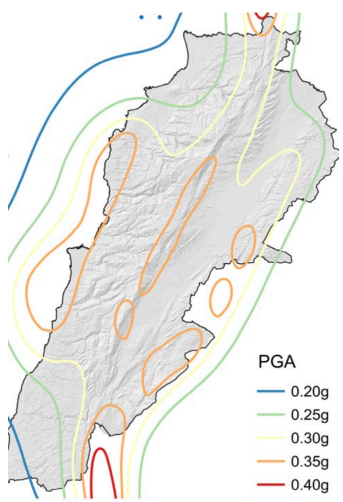
15-m DEM



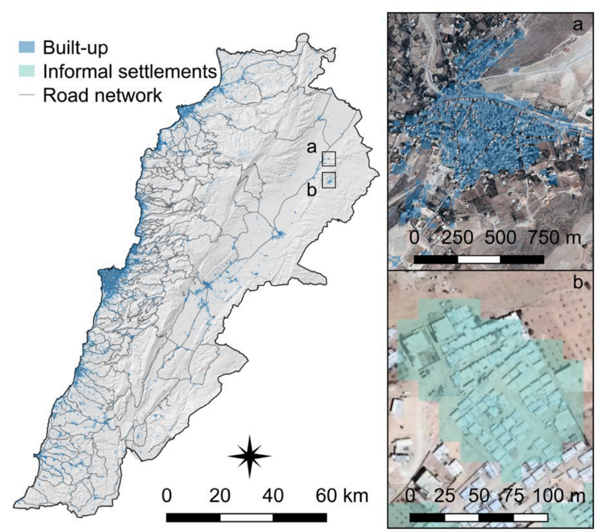
Landsat (root cohesion via NVDI)



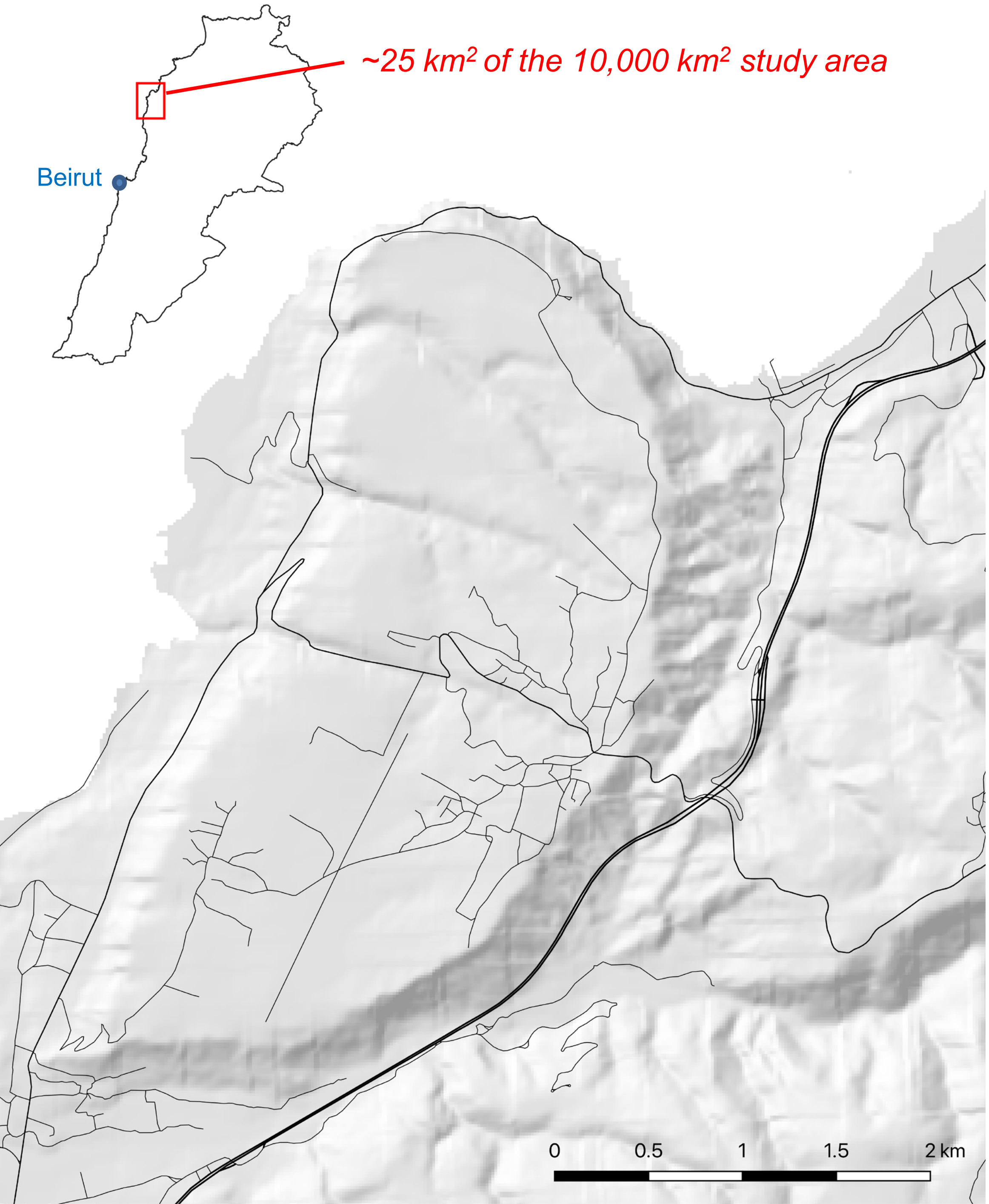
National precipitation maps



PSHA-derived ground motions



Population data from national census and NGOs



I. Hazard Assessment:

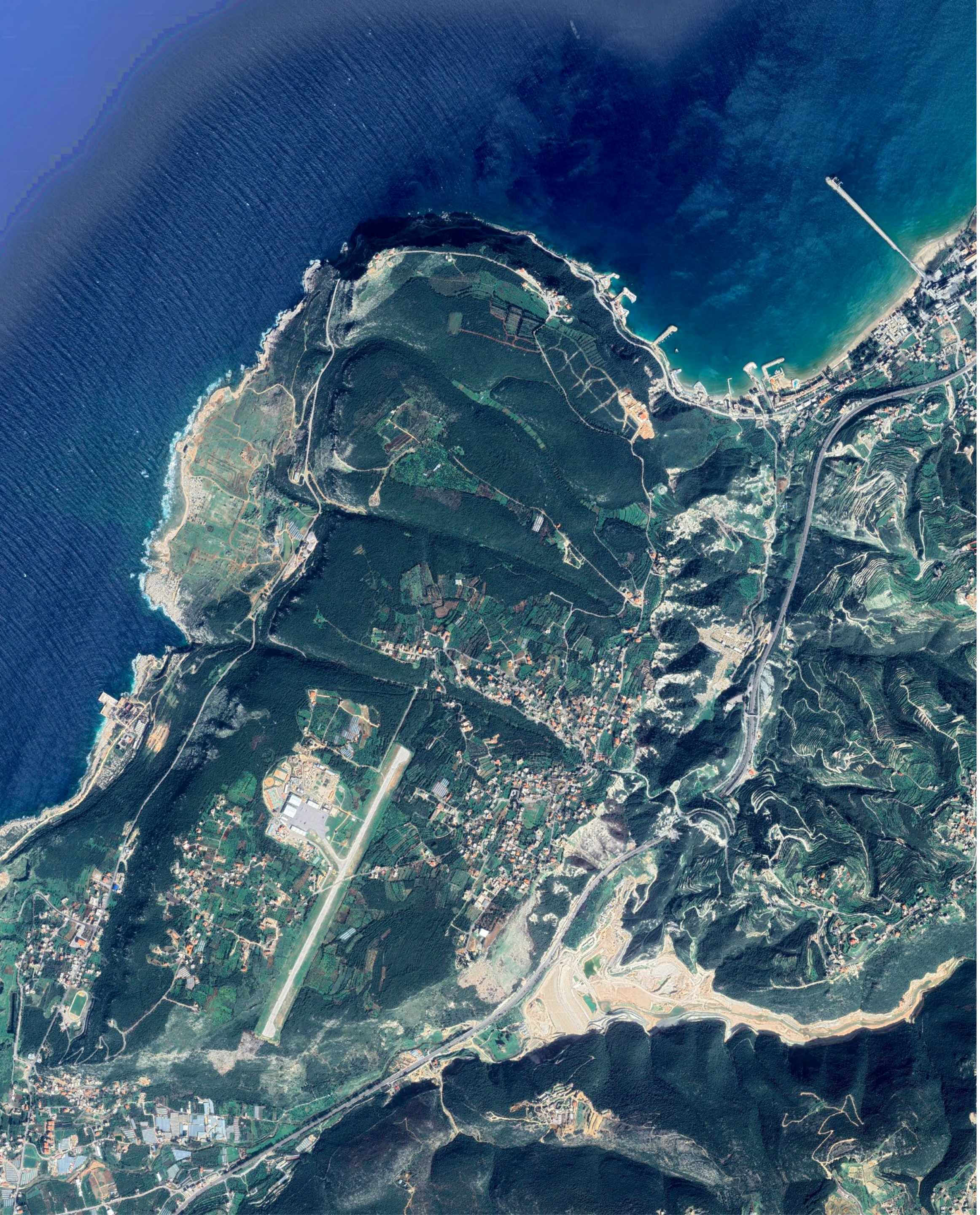
Hamat Focus Area

Step-by-step example for two forcing “scenarios”

- 50 year storm

- 949 year (10% in 100 years) seismic event

Overall risk results will be presented later for all scenarios combined

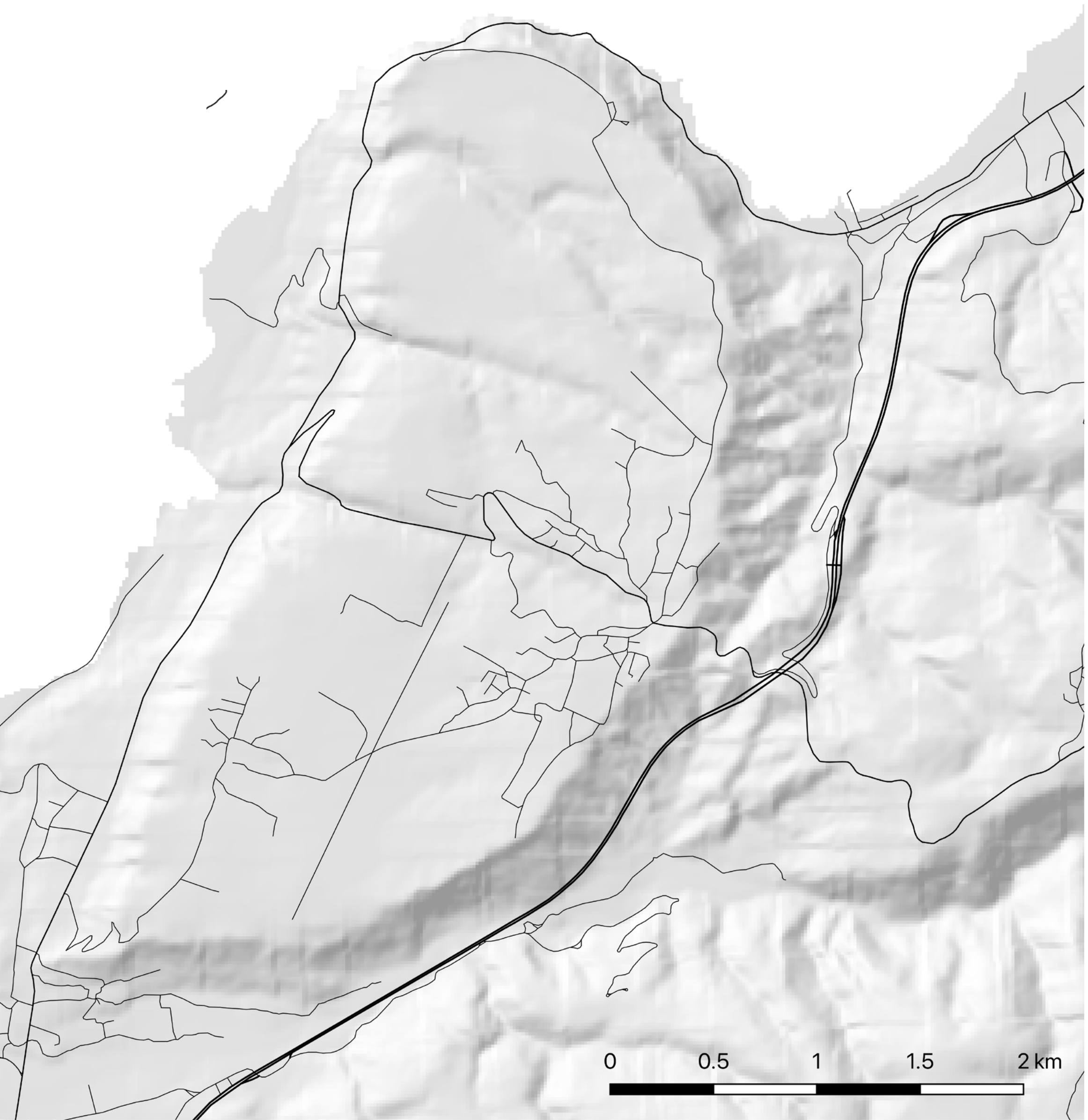


I. Hazard Assessment:

Hamat Focus Area

I. Hazard Assessment

Landslide Susceptible Terrain



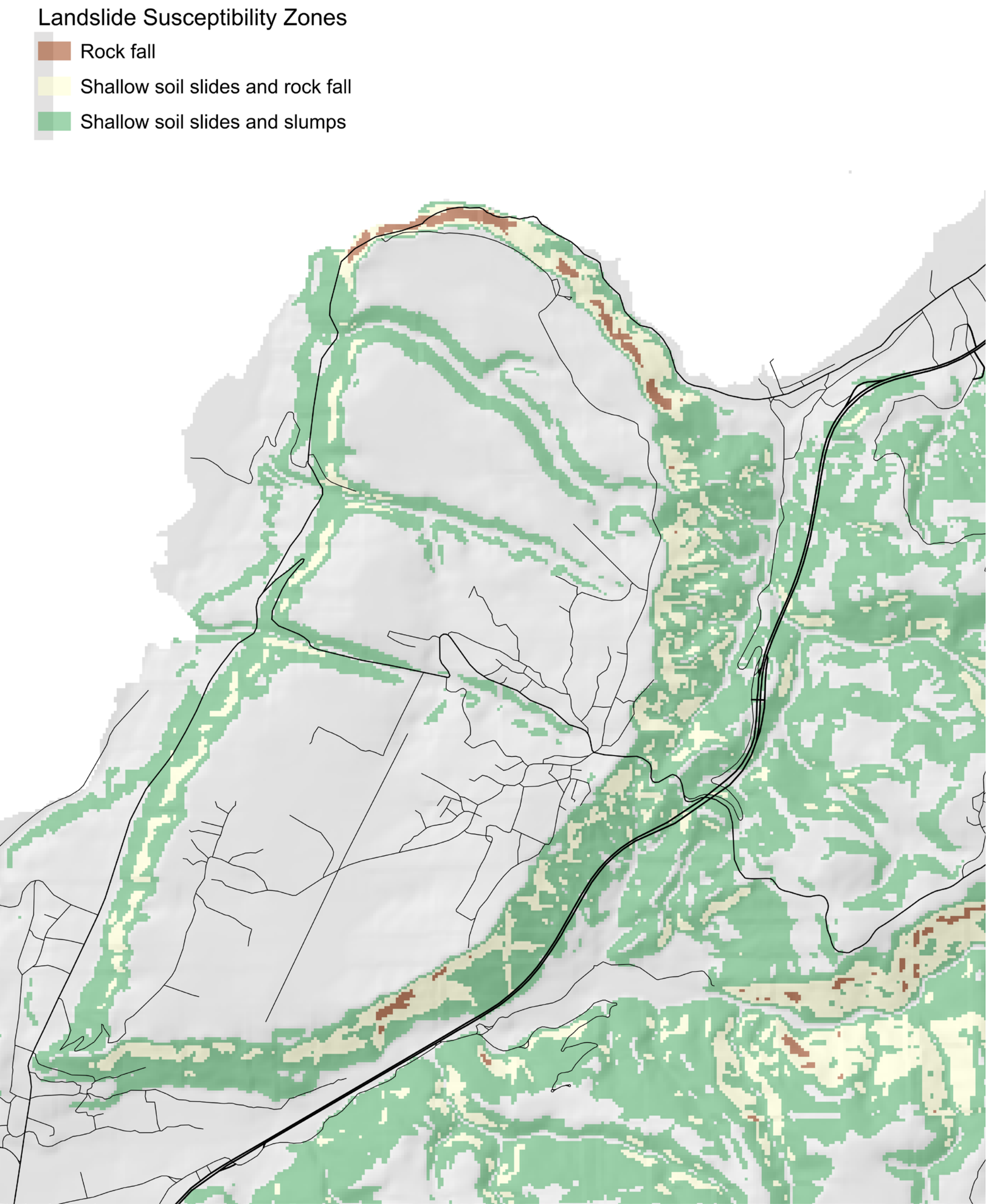
- Statistical studies show a correlation between slope and landslide mode
- Divide the terrain into slope-based zones susceptible to failure mode(s)

15-50° prone to shallow, planar slides

15-35° prone to rotational, coherent slumps in soil and rock

>35° prone to rockfall

<15° not likely to fail in any mode



I. Hazard Assessment

Landslide Susceptible Terrain

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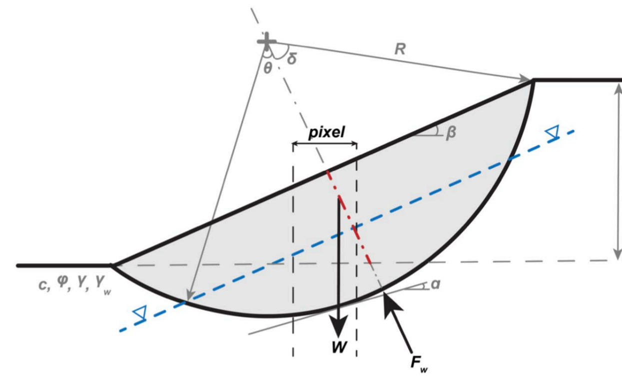
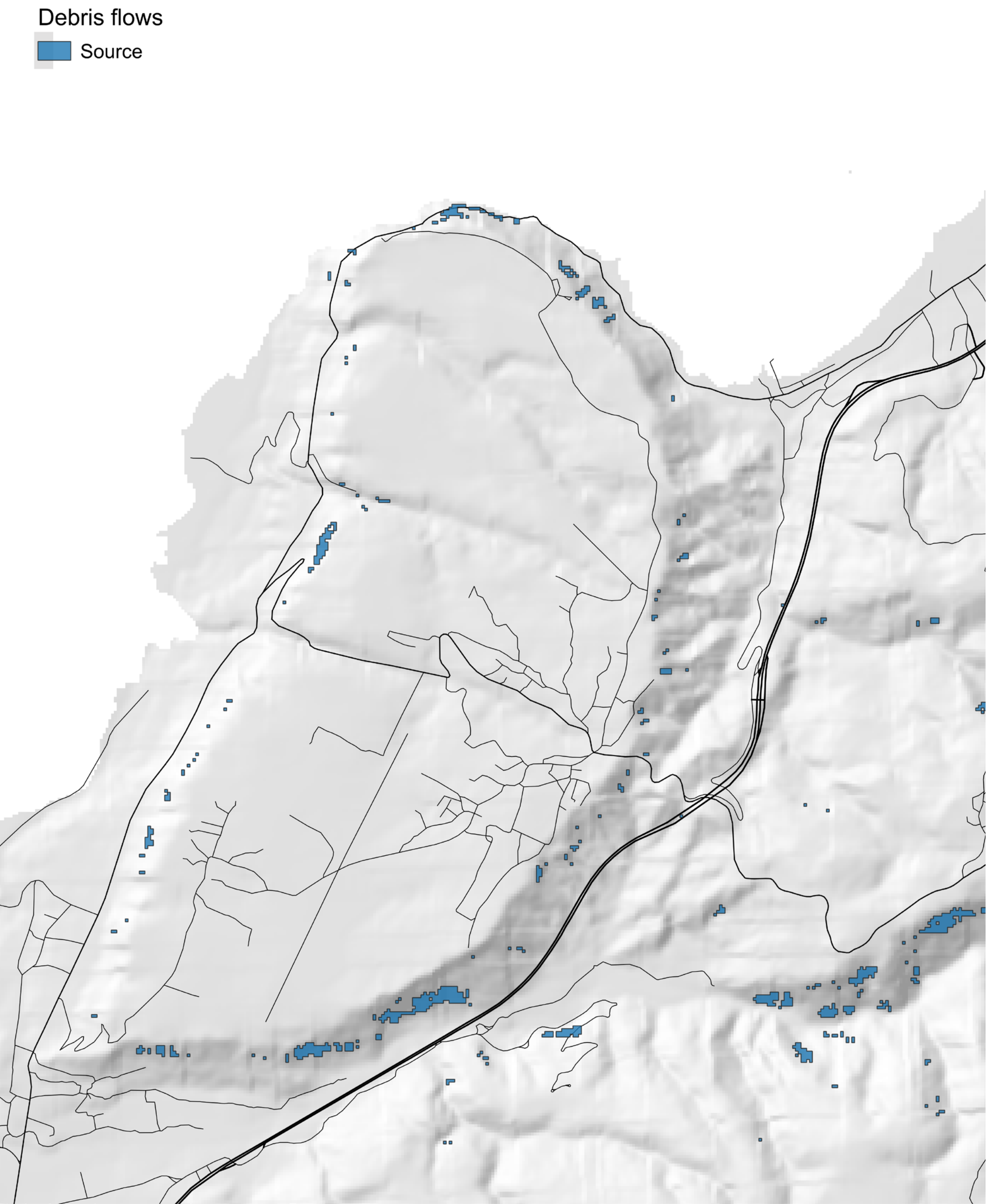
15-50°	prone to shallow, planar slides
15-35°	prone to rotational, coherent slumps in soil and rock
>35°	prone to rockfall
<15°	*not likely to fail in any mode*

I. Hazard Assessment

Precipitation-Induced Rotational Slides, or “Slumps”

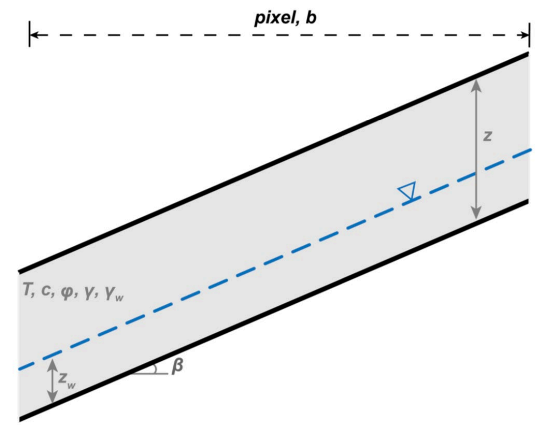


3D spherical surface, whose radius of failure is a function of local relief (measured within a moving window)



I. Hazard Assessment

Debris flow source areas

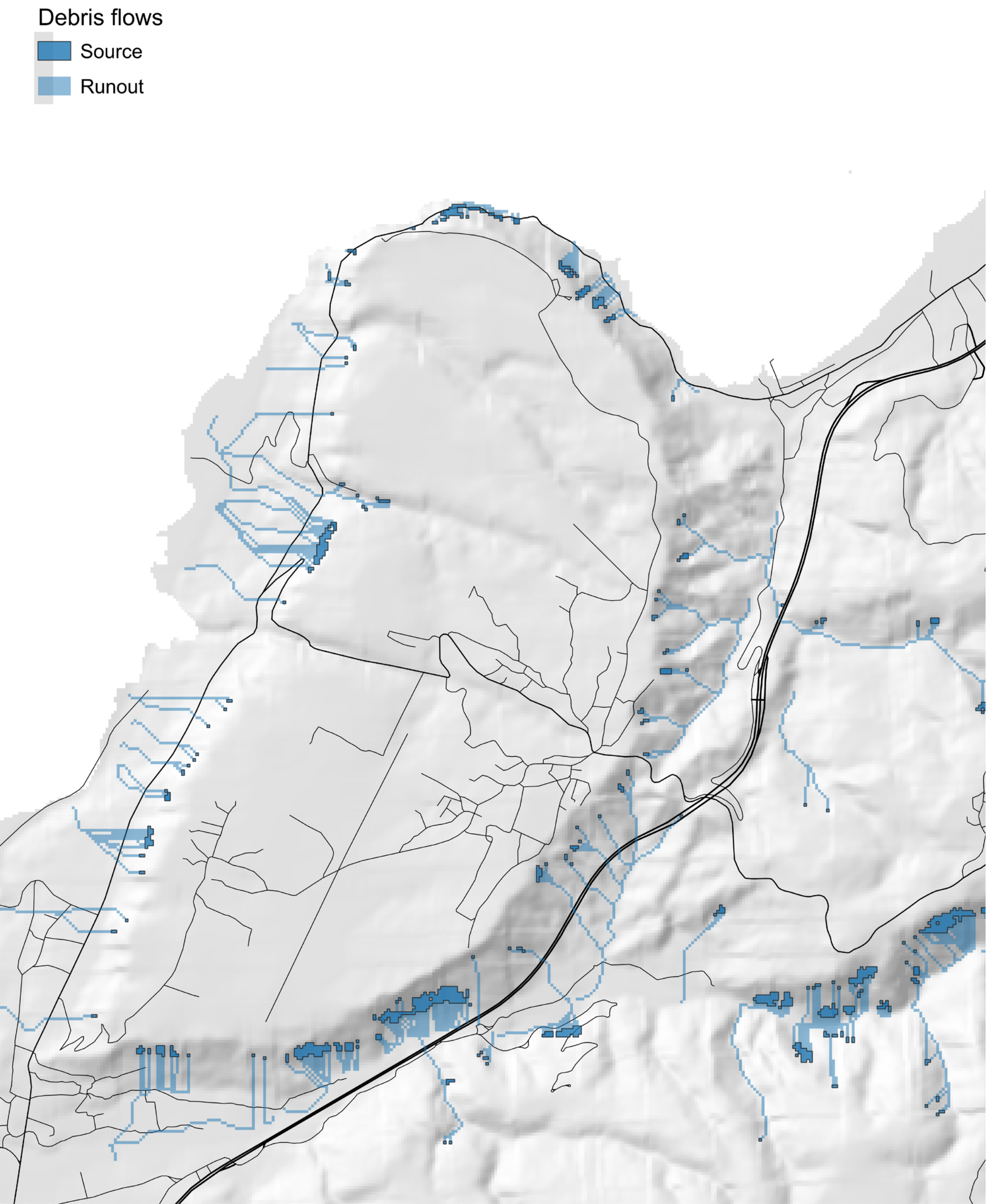


SHALSTAB model, which couples hydrologic and limit-equilibrium slope stability models to compute the critical daily rainfall to trigger a shallow soil failure.

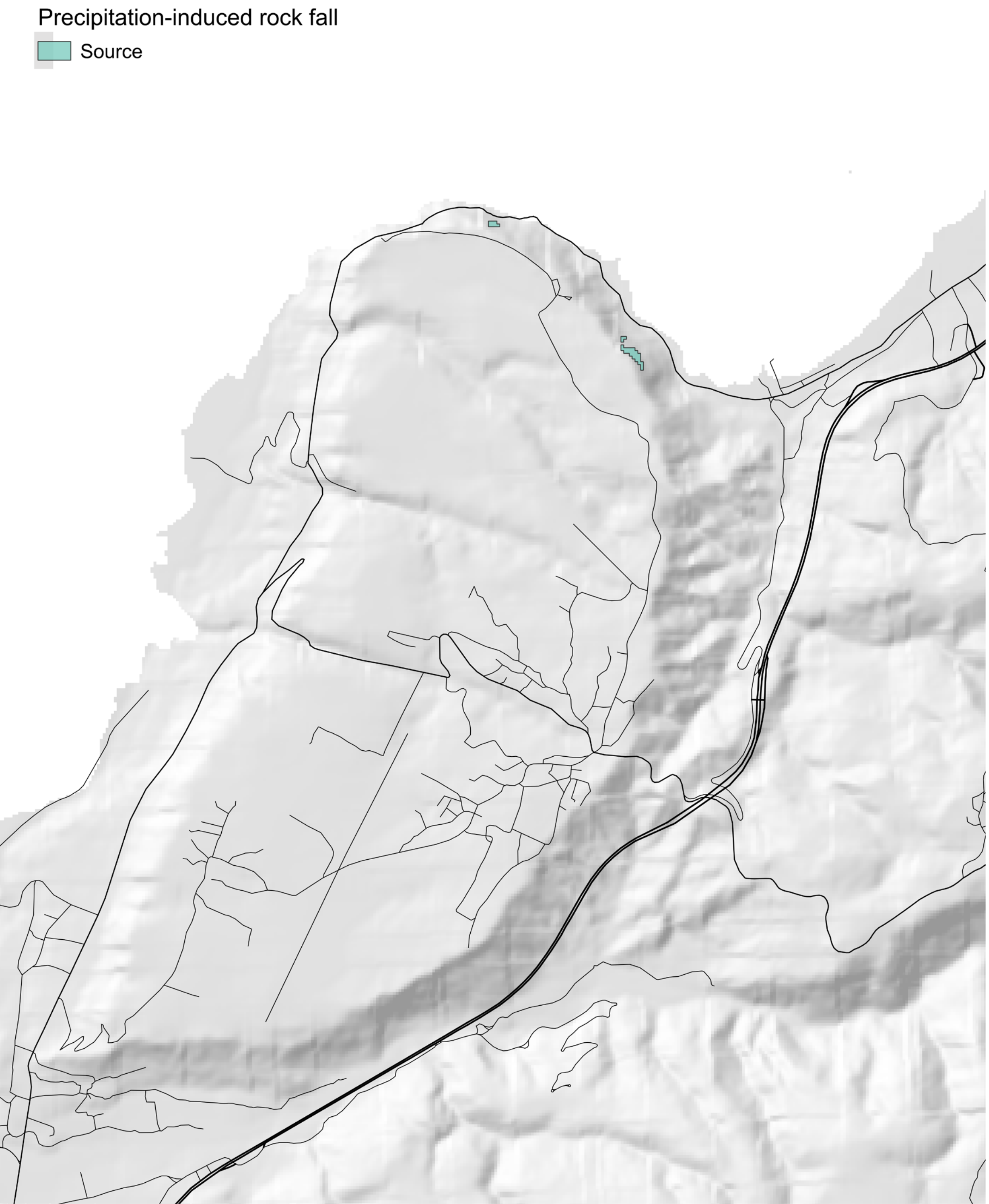
Modest root cohesion assigned based on NDVI for moderately and highly vegetated areas

II. Hazard Assessment

Debris flow source + runout areas

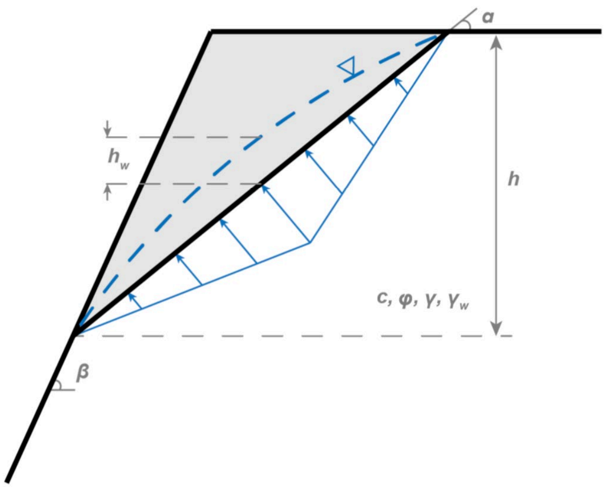


Based on flowlines from the DEM, with path limited to 750 m based on region-specific statistical analysis.

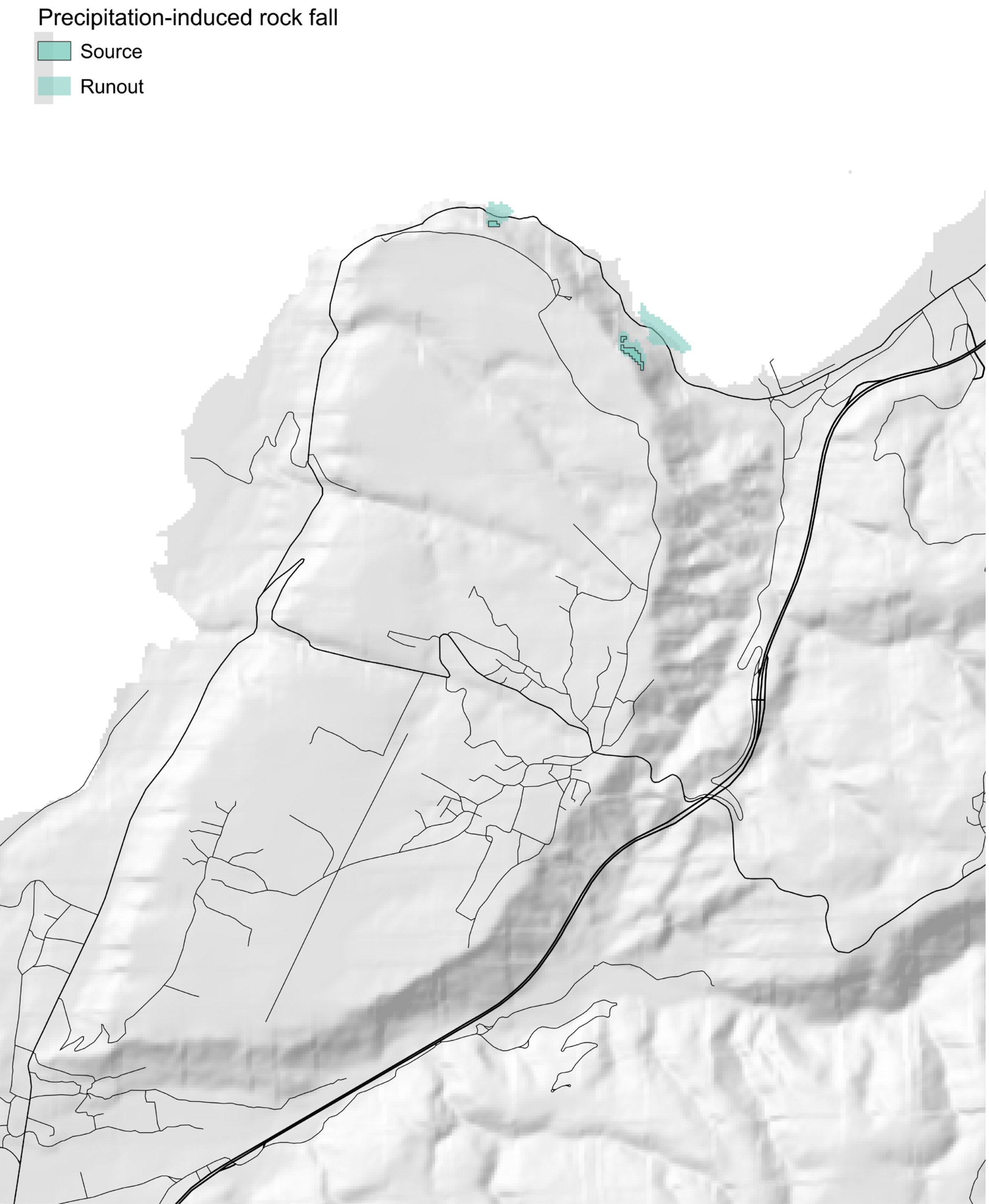


I. Hazard Assessment

Precipitation-induced rock-slope failure (rockfall)

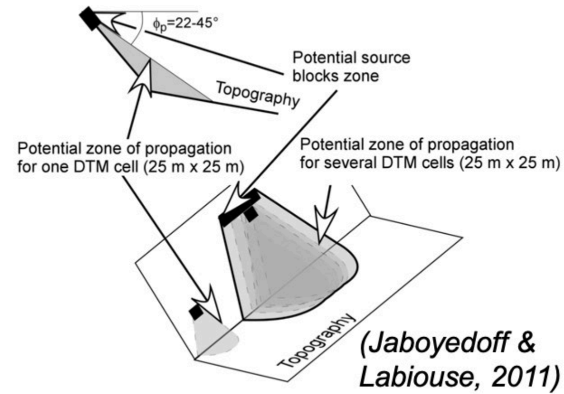


Rainfall-induced rock slope failures are modeled as Culman wedge-like masses, including the effects of pore-pressure acting on the failure plane



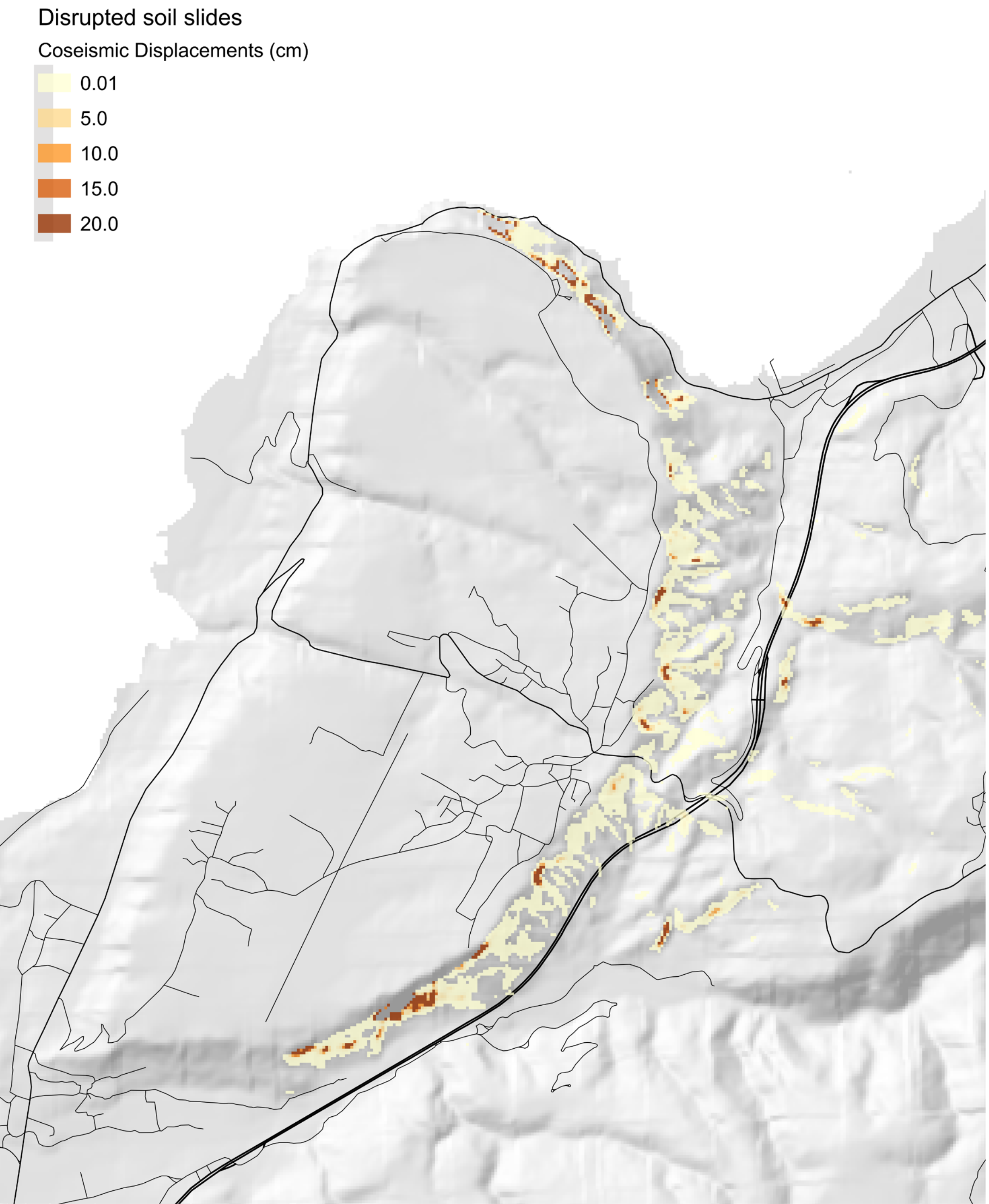
II. Hazard Assessment

Precipitation-induced rockfall + runout areas



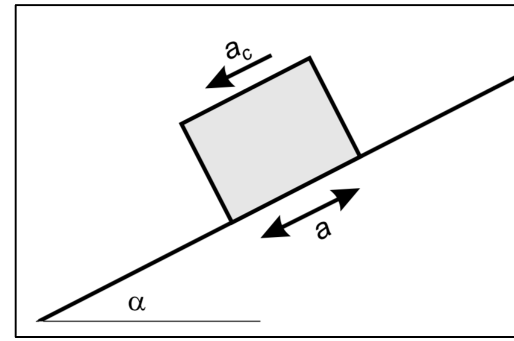
Runout zones were calculated using a viewshed analysis from each initiation point.

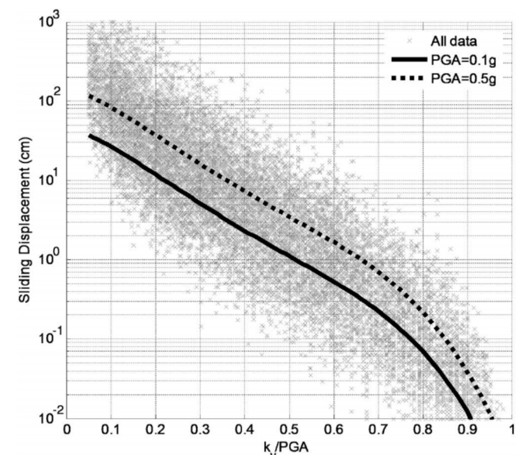
The horizontal extent of the rockfall zone was limited by the maximum and minimum aspect of the source cliff face plus 17 deg. based on observed lateral dispersion angles. The “angle of reach” from 34 to 42 deg. depending on rockfall size.



I. Hazard Assessment

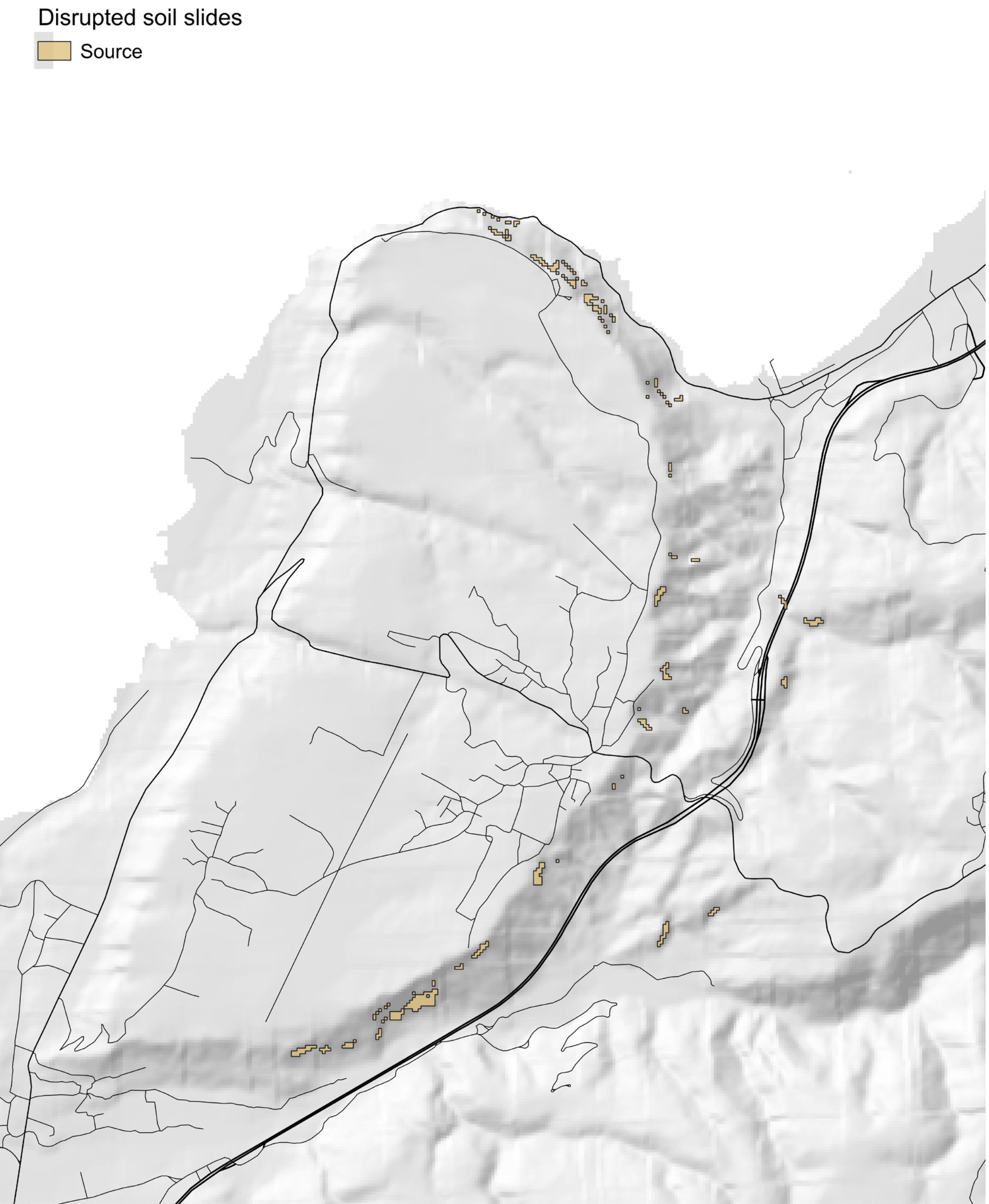
Coseismic disrupted (shallow) slide displacements





Compute critical acceleration (Ky), and combine with local PGA to estimate co-seismic displacement using regression.

(Saygili & Rathje, 2008 Jibson et al., 2000)

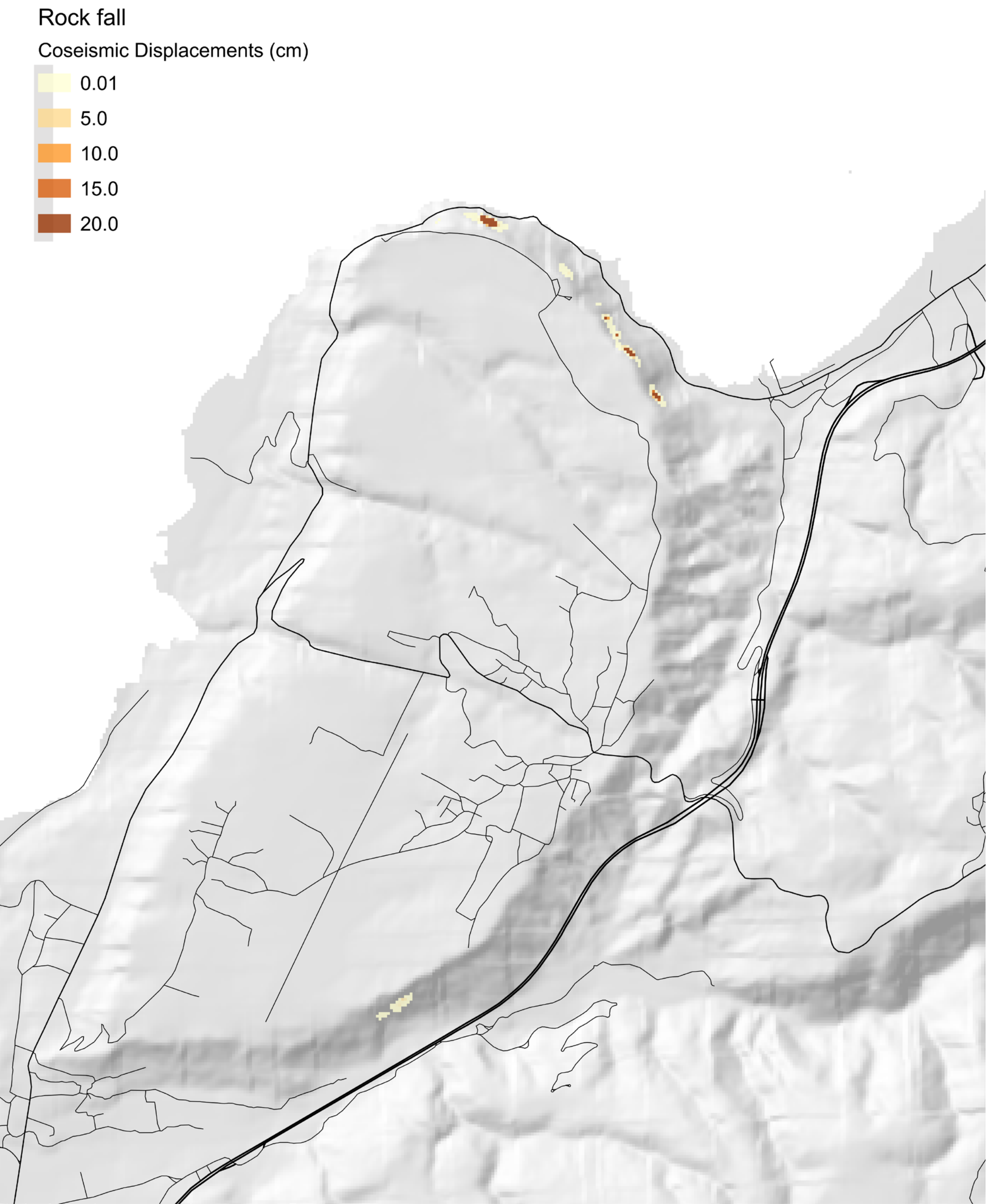


I. Hazard Assessment

Coseismic disrupted slides

"Failure" defined as coseismic displacement of 5 cm or more based on the observed performance of slopes in past earthquakes.

(For coseismic slumps, threshold is 15 cm)

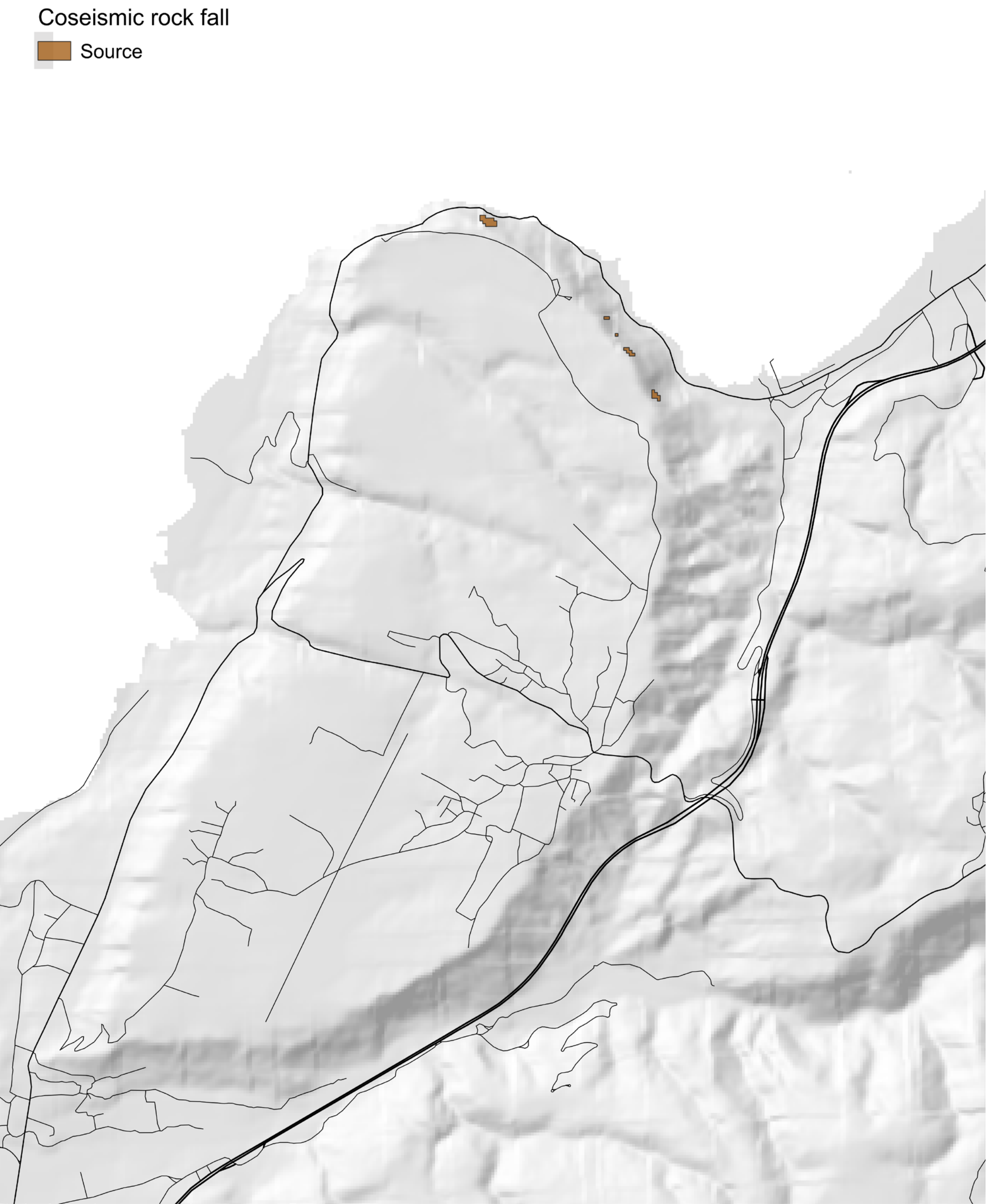


I. Hazard Assessment

Coseismic rock slope displacement

I. Hazard Assessment

Coseismic rockfall



“Failure” defined as coseismic displacement of 5 cm or more.

II. Hazard Assessment

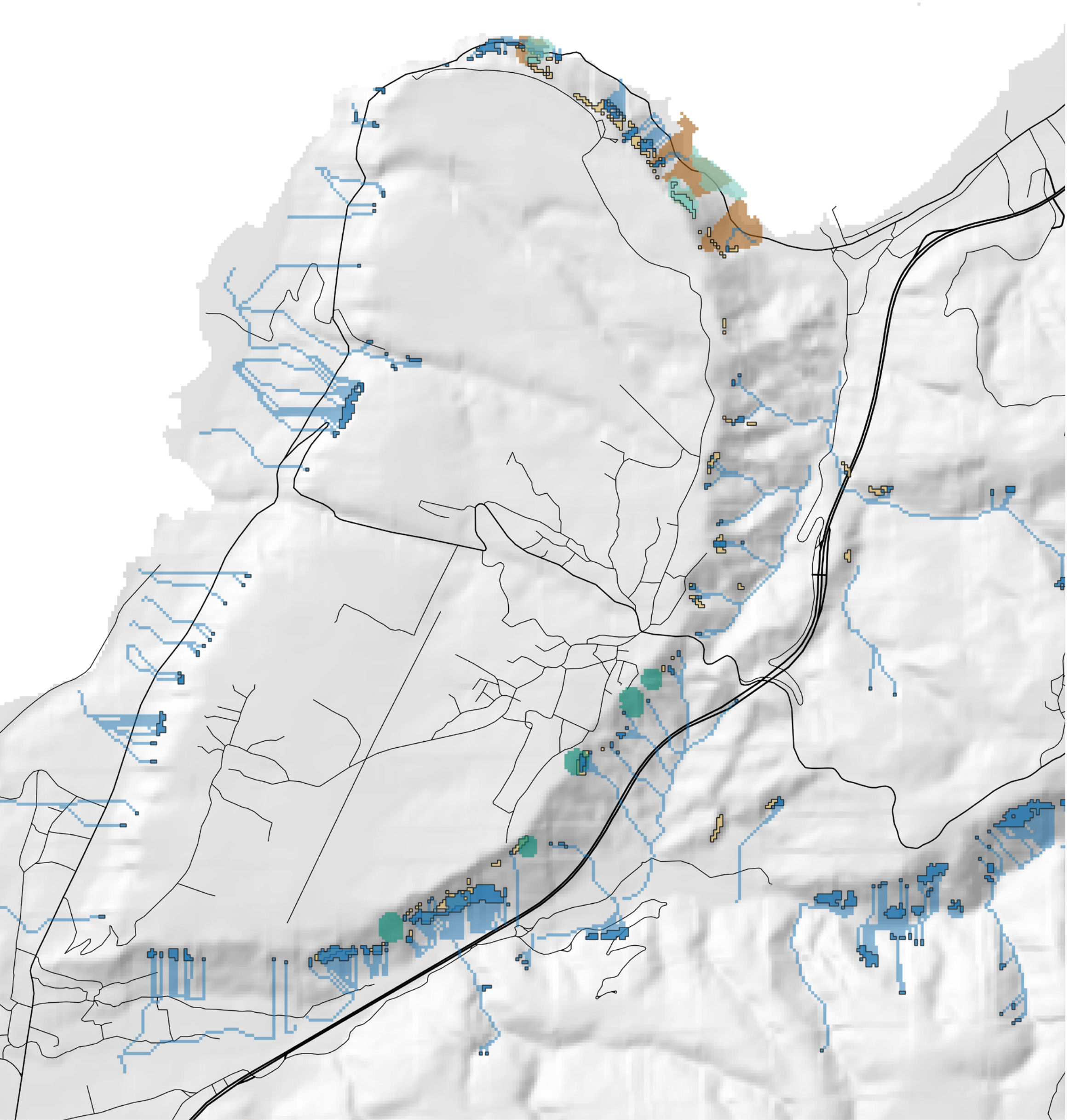
Coseismic rockfall + runout areas

I./II. Hazard + Runout Assessment For All Modes of Failure

Precipitation-induced
- Debris flows
- Rock fall
- Slumps

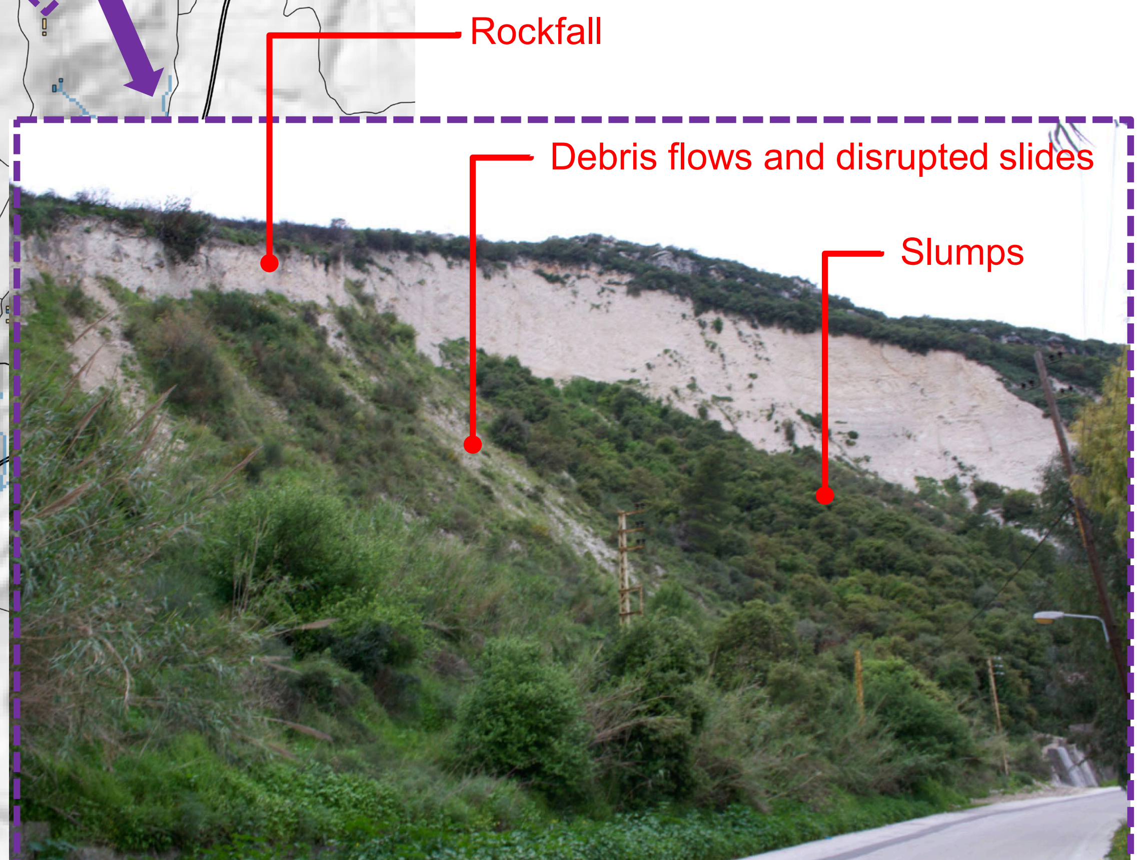
Coseismic
- Disrupted soil slides
- Rock fall

(No coseismic slumps found for this area)



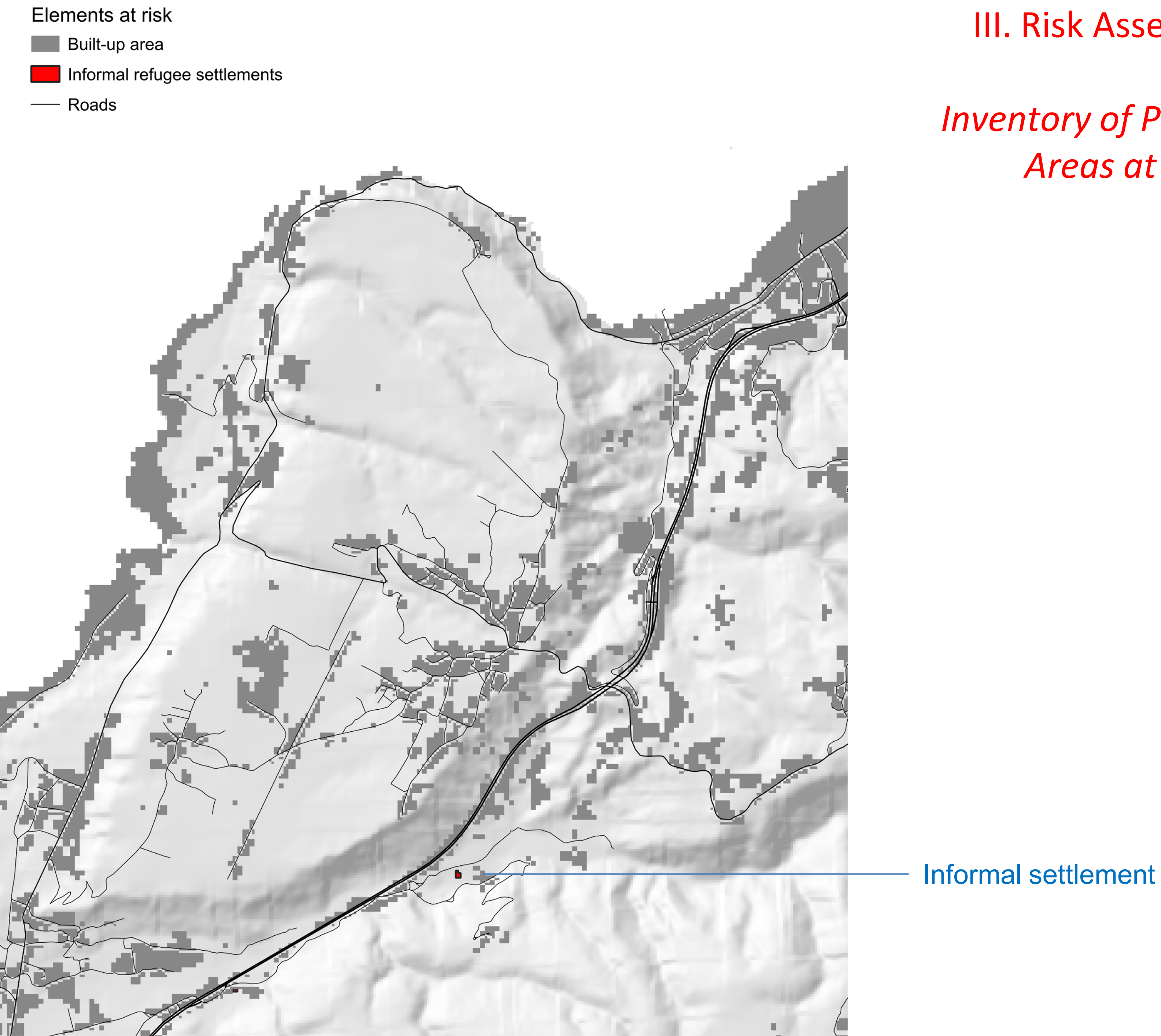
I./II. Hazard + Runout Assessment For All Modes of Failure

Comparison with field observations



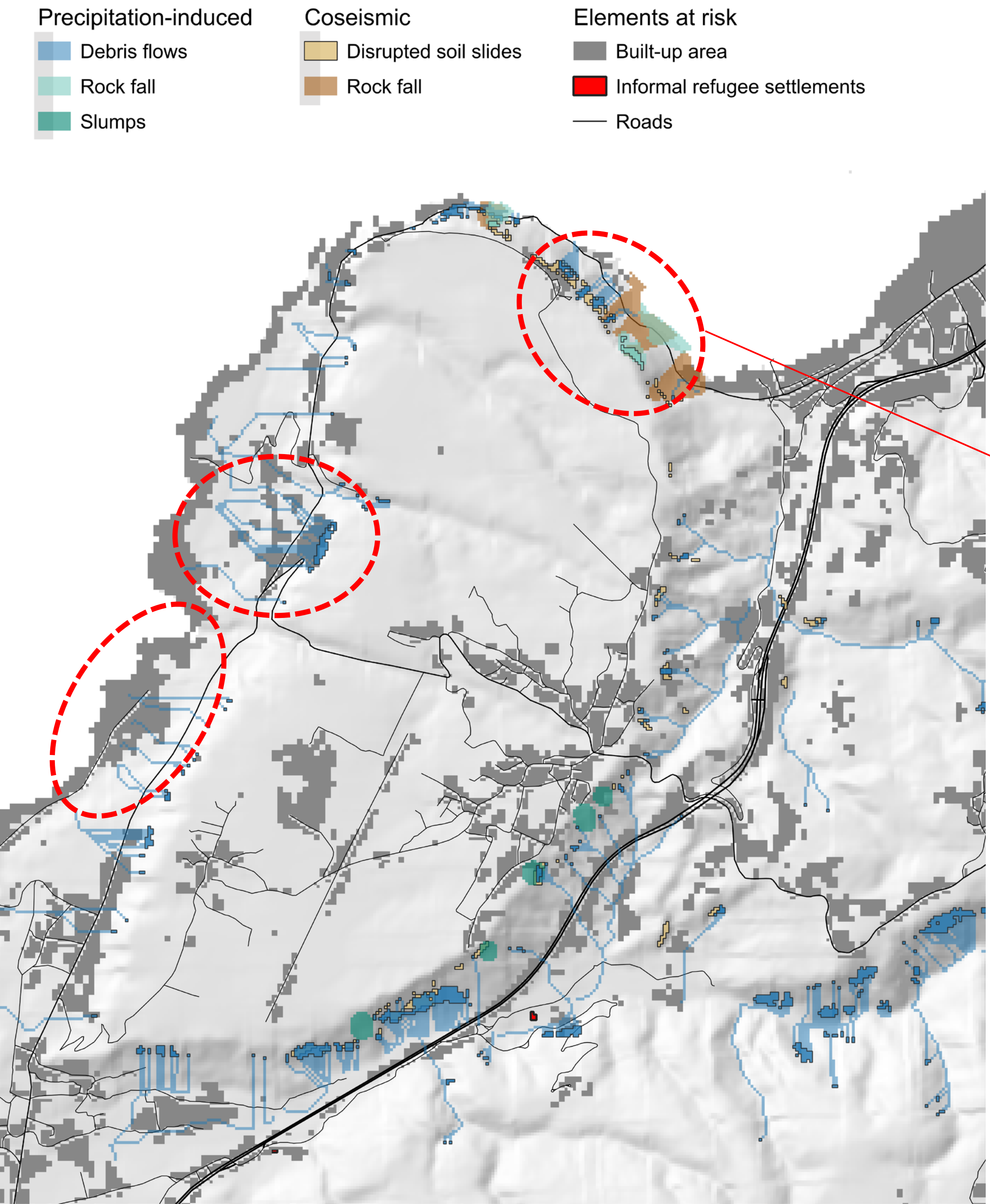
III. Risk Assessment

Inventory of Population Areas at Risk

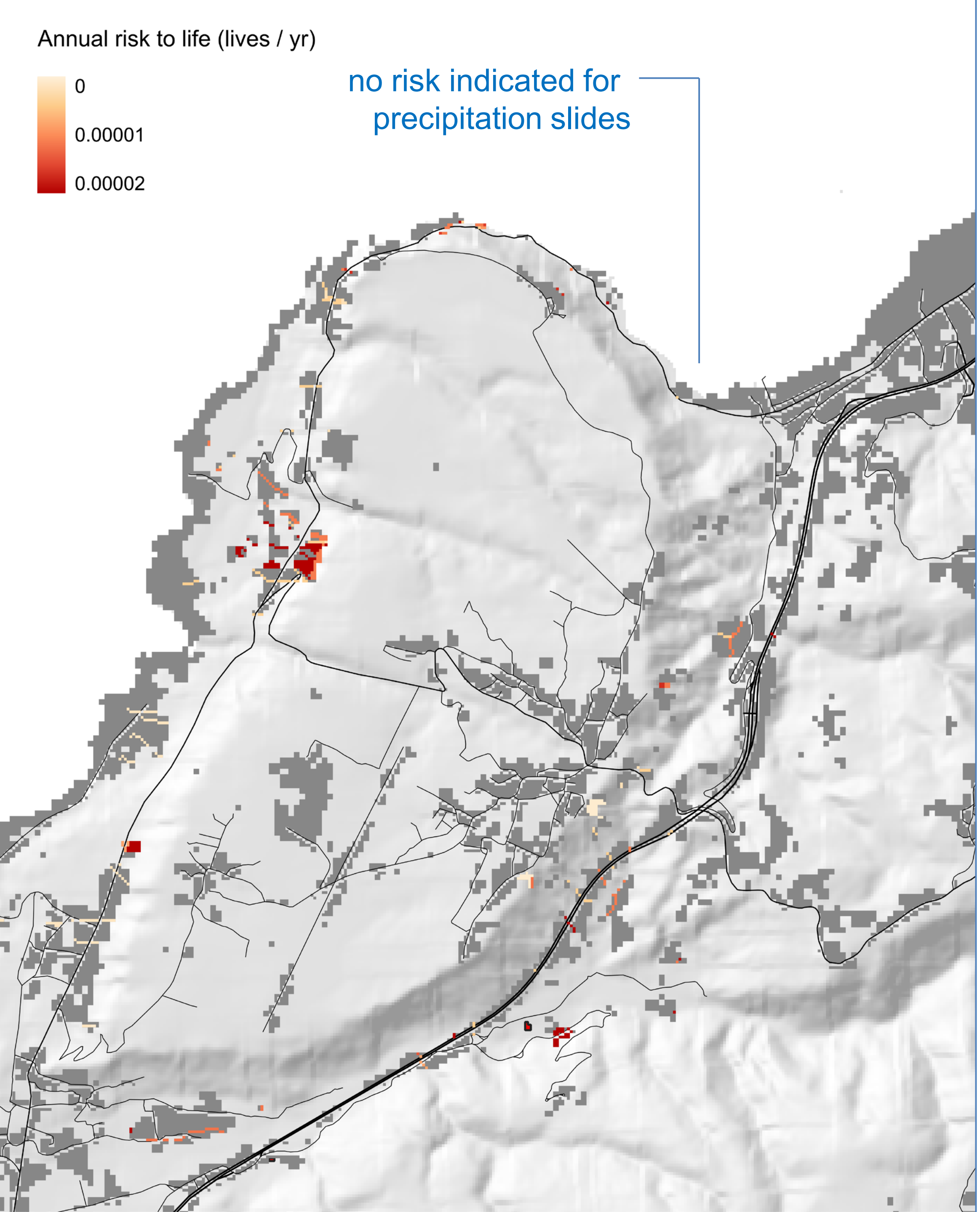


III. Risk Assessment

Elements Impacted by All Modes of Sliding



Hazards intersect populated areas



III. Risk Assessment

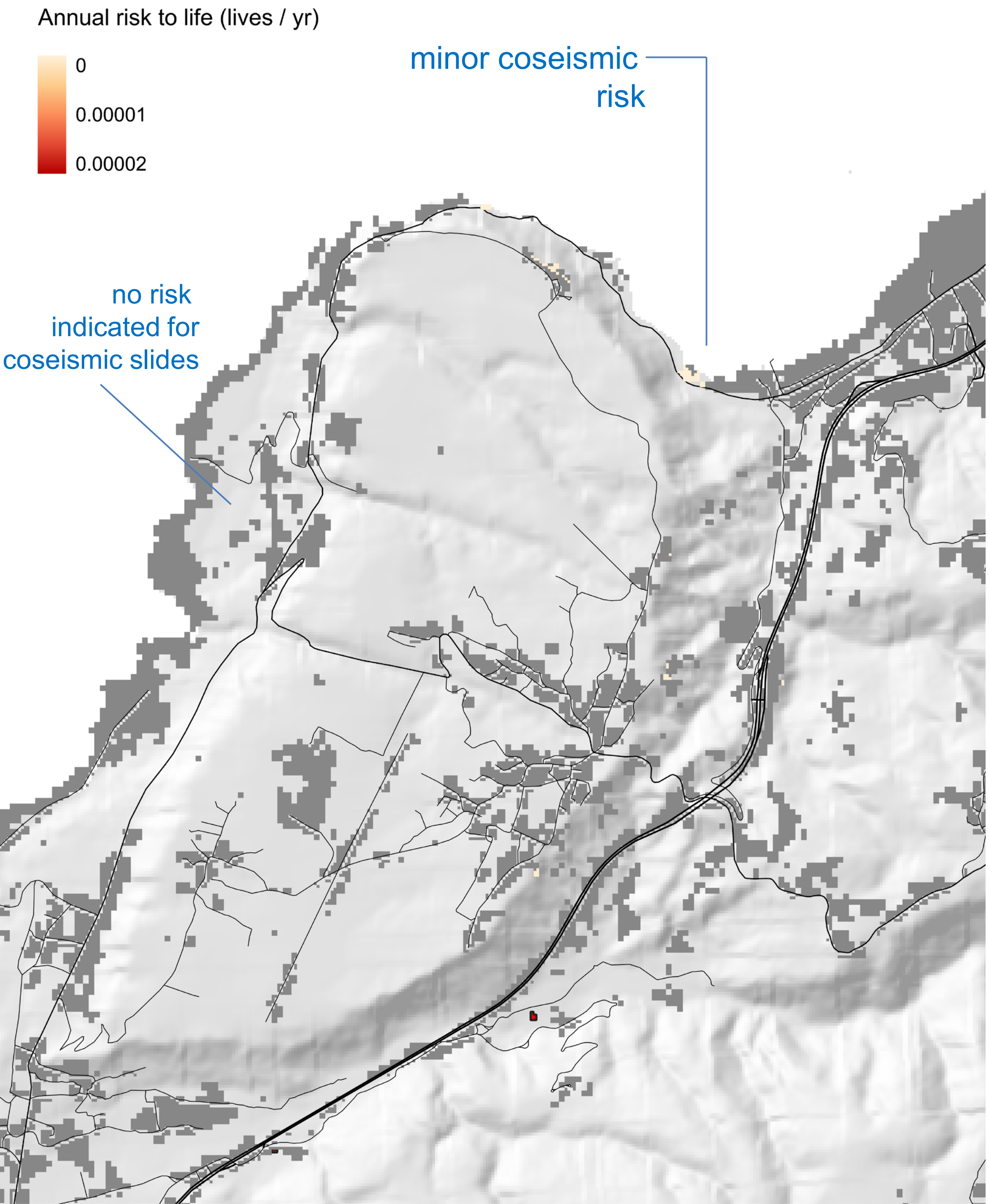
Results: *Mapping Risk from Precipitation-Induced Landslides*

Estimate physical vulnerability of the urban population based on data from from nations having similar building styles to Lebanon.

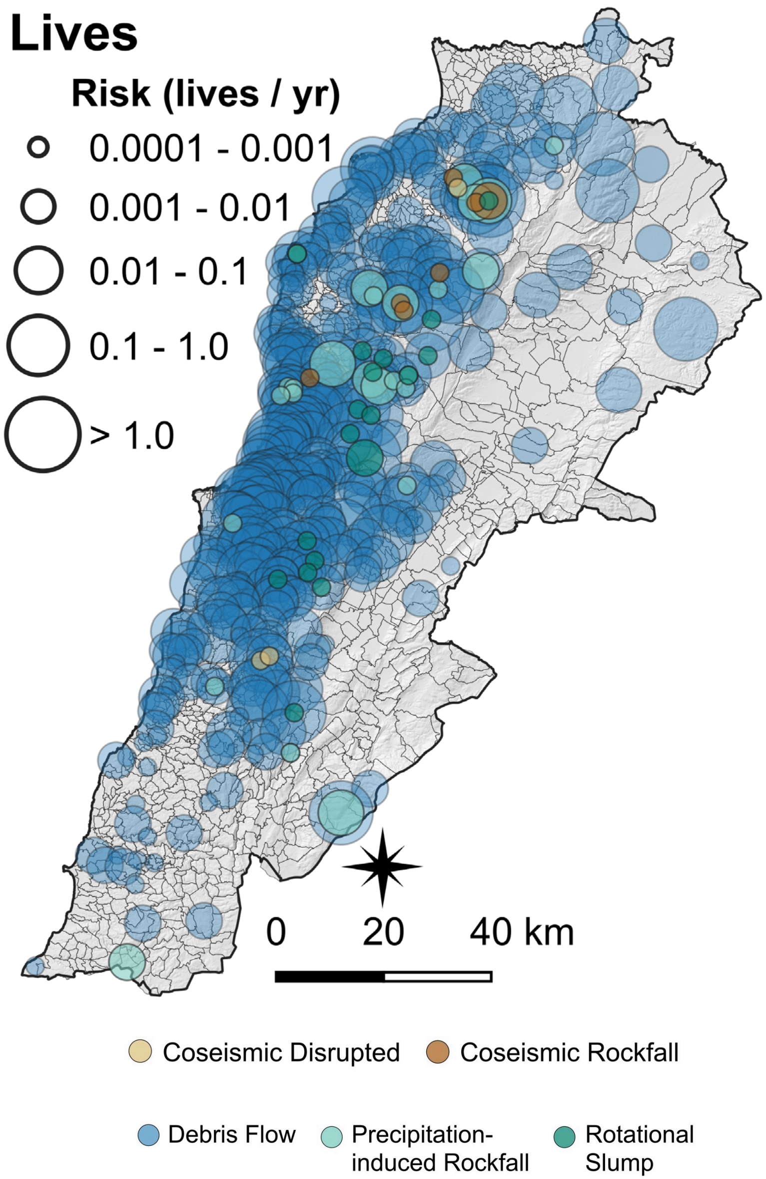
Encamped residents are assessed vulnerability values consistent with an outdoor population.

III. Risk Assessment

Results: *Mapping Risk from Coseismic Landslides*



Landslide Risk Across Lebanon: Lives



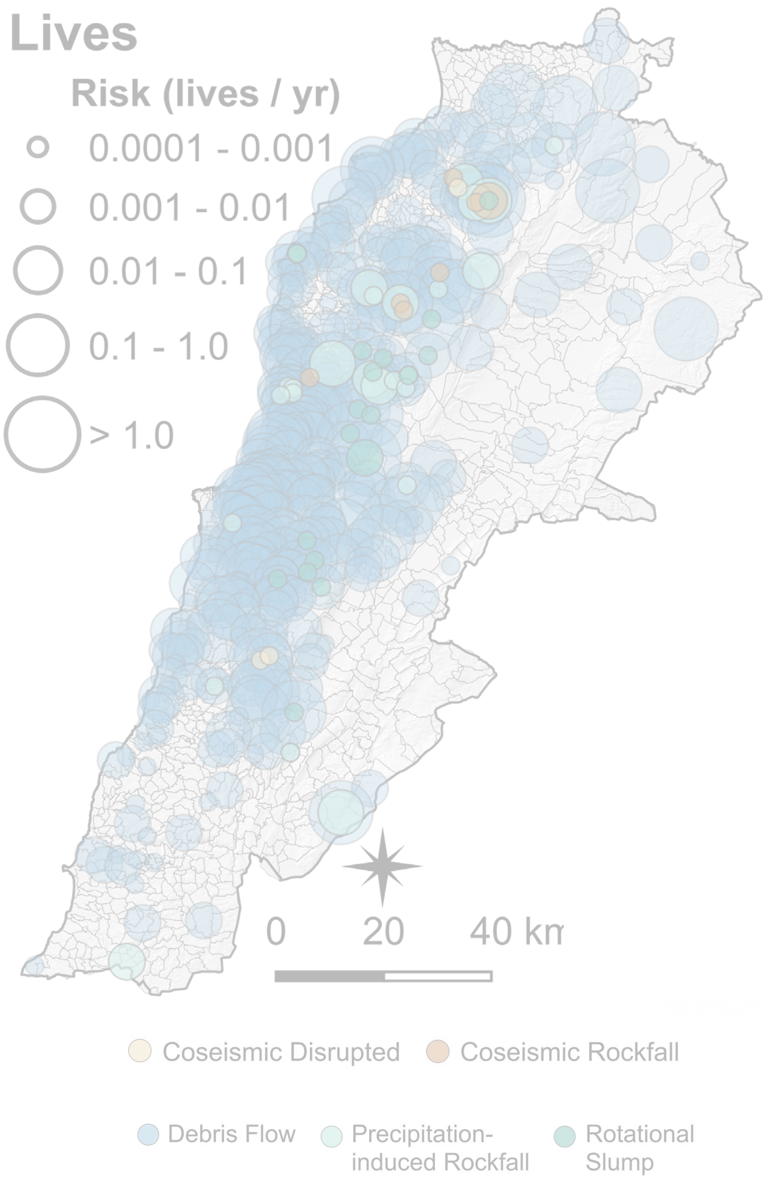
Disaggregating Risk

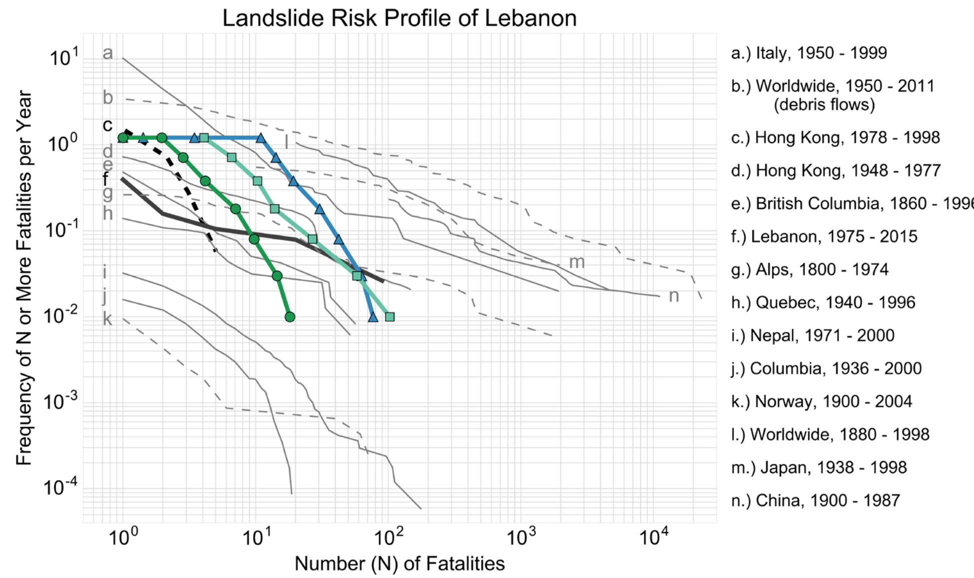
Debris flows and associated runout are responsible for 93% of the landslide risk in Lebanon

A majority of losses are from frequent and widespread low-intensity events

Other types of landslides have a less significant impact because of their limited "footprint"

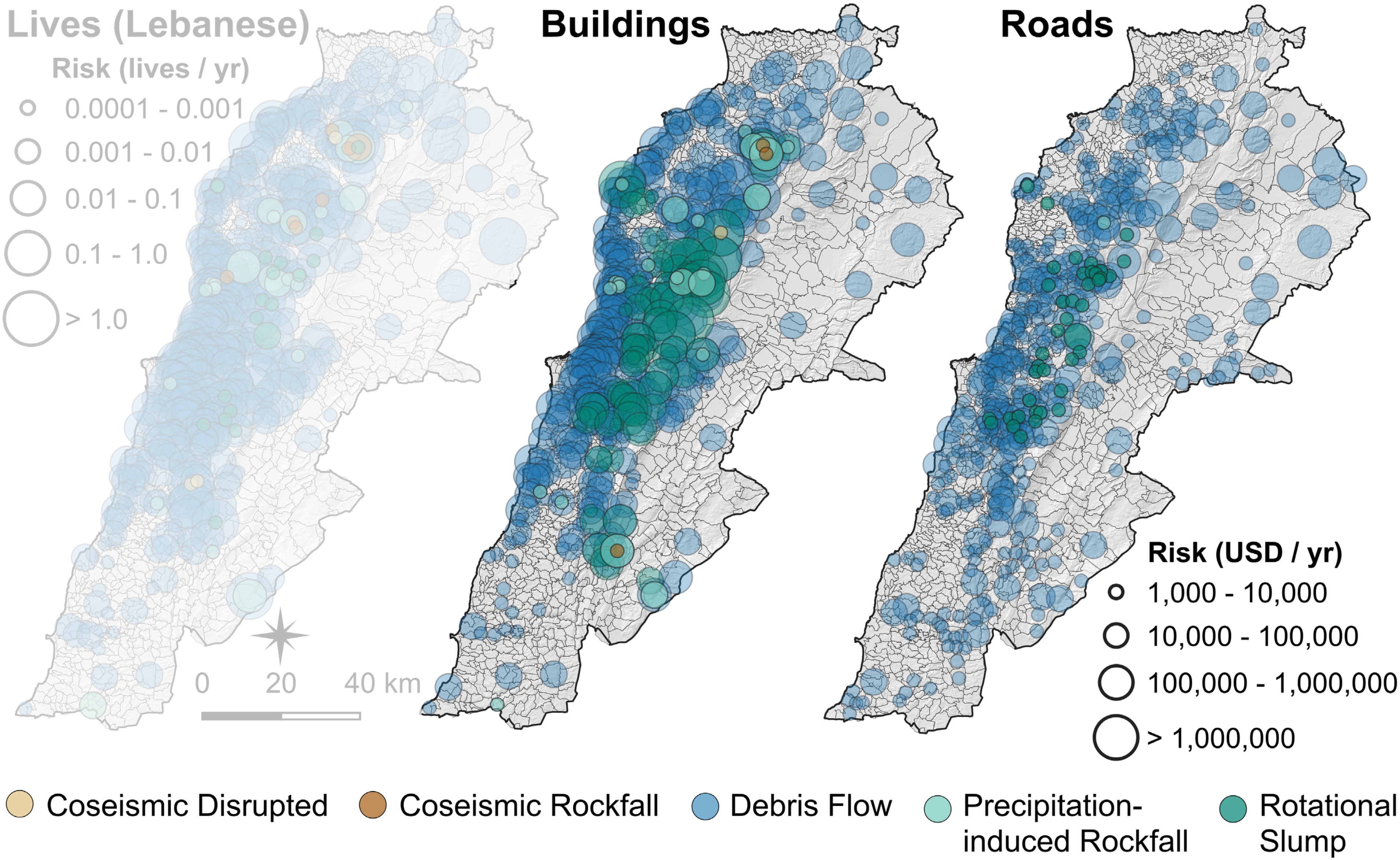
Landslide Risk Across Lebanon: Lives





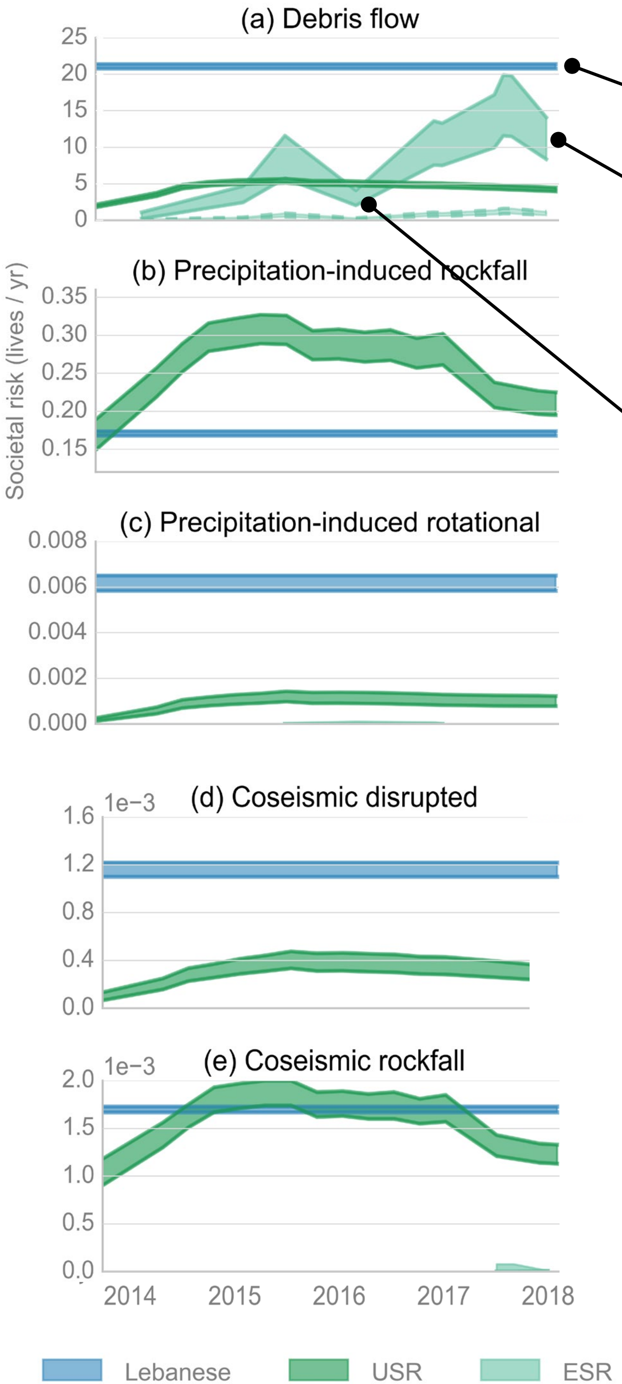
Overall, risk in Lebanon is on par with other landslide-prone nations

Landslide Risk Across Lebanon: Lives and Capital Losses to Buildings and Infrastructure



Pollock et al. (2019c)

Landslide Risk in Lebanon by Modes *and Time*



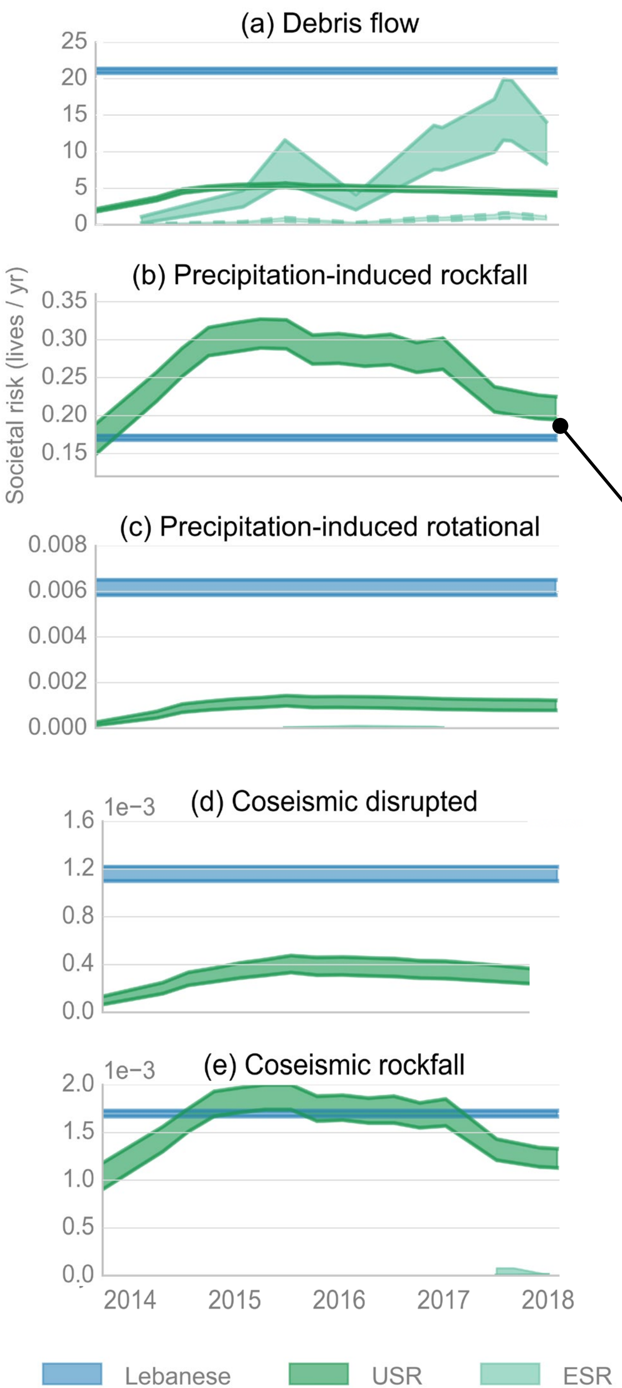
1. Lebanese hold a majority of the societal risk for all nearly modes due to their population

2. Risk to encamped Syrian refugees is highly variable throughout time, reflecting transient nature of the encamped population.

3. Encamped refugees are at a significantly greater risk than urbanized refugees due in part to highly vulnerability

4. Drop in 2016 reflects movement from debris flow-prone Arsal of rebel-allied Syrians during period of conflict

Landslide Risk in Lebanon by Modes and Time



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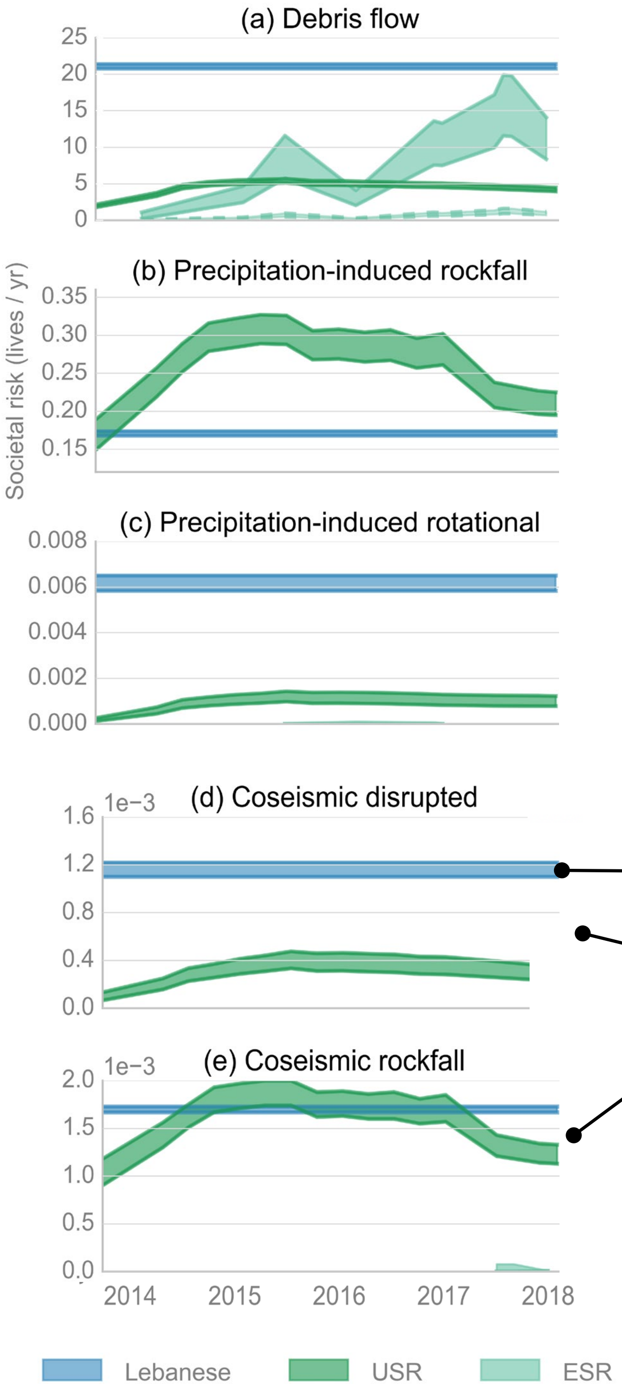
Landslide Risk in Lebanon by Modes and Time



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7. Coseismic landslides a low probability events that pose little treat to populations.

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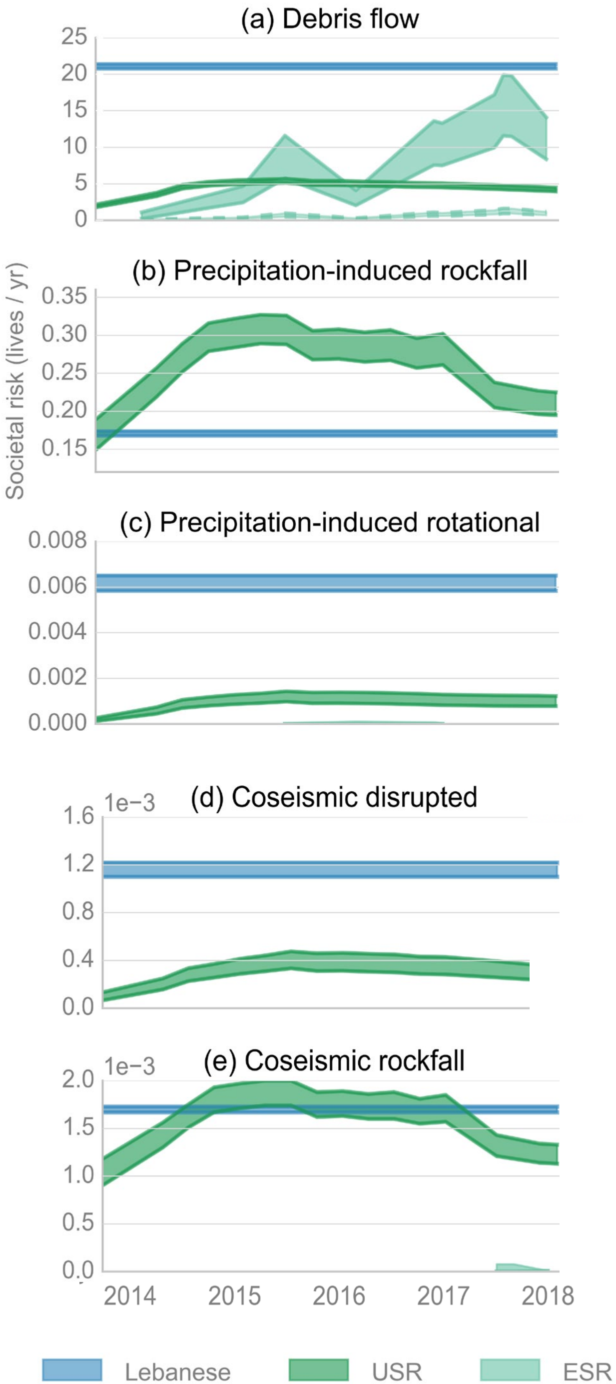

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7. Coseismic landslides a low probability events that pose little treat to populations.

8. Overall, there is a disproportionate 75% increase in landslide risk in Lebanon since the start of the Syrian crisis due to:

- Population increase in susceptible villages and urban areas
- Higher exposure and vulnerability of encamped refugees

"Verification" of Results, Part I: January 2019 Local Storm Event

- Unknown return period
- 10 Landslides near Chekka
- 3 people injured by slides
- Closed Highway

Warnings of more landslides after one injured in Chekka

The Daily Star (Lebanon) 15 Jan 2019 By Sahar Houri and Emily Lewis

BEIRUT: At least one person was injured Monday morning in a landslide on the Chekka-Batroun highway caused by heavy rains overnight, with more landslides expected to follow with heavy rainfall in the coming days.

Pictures and videos shared by the Traffic Management Center's Twitter account showed a cascade of dirt covering the entire southbound side of the highway and part of the northbound half. The southbound side had previously been closed as a precaution, according to North Lebanon Governor Ramzi Nohra, but cars heading north were hit with a wave of soil as erosion burst through the retaining wall that had been supporting the hillside.

Nohra said in televised remarks that he checked the retaining walls last week and had warned that "they were old and may fall ... and there is still a risk of more landslides as the storm intensifies." The NNA reported he contacted the Public Works Ministry requesting the ministry to bring down all the crippled retaining walls to avoid catastrophe.

As a team from the Public Works and Transport Ministry worked to clear the road, one of the engineers also warned that further landslides are likely to occur, as soil and stones were still falling from the hillside.

"We're waiting for the storm to end to decide more clearly what can be done," the engineer told reporters.

He corroborated earlier reports that three people had suffered minor injuries, however, the Director General of Roads and Buildings at the Public Works Ministry Tanios Boulos told The Daily Star that only one person had suffered a minor injury as a result of the landslide.

After the reported landslides, Public Works and Transport Minister Youssef Fenianos held an emergency meeting at his office with Boulos and the ministry's relevant teams for a briefing on the landslide reports.

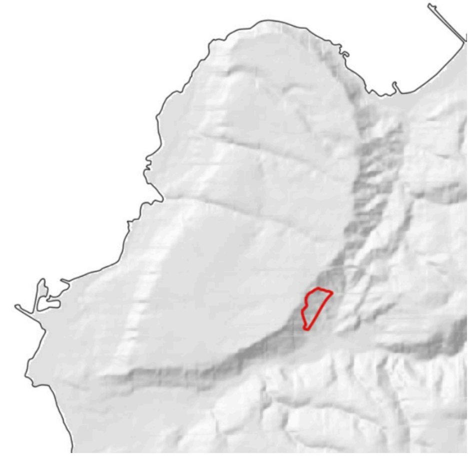
The landslide on the Chekka-Batroun highway.

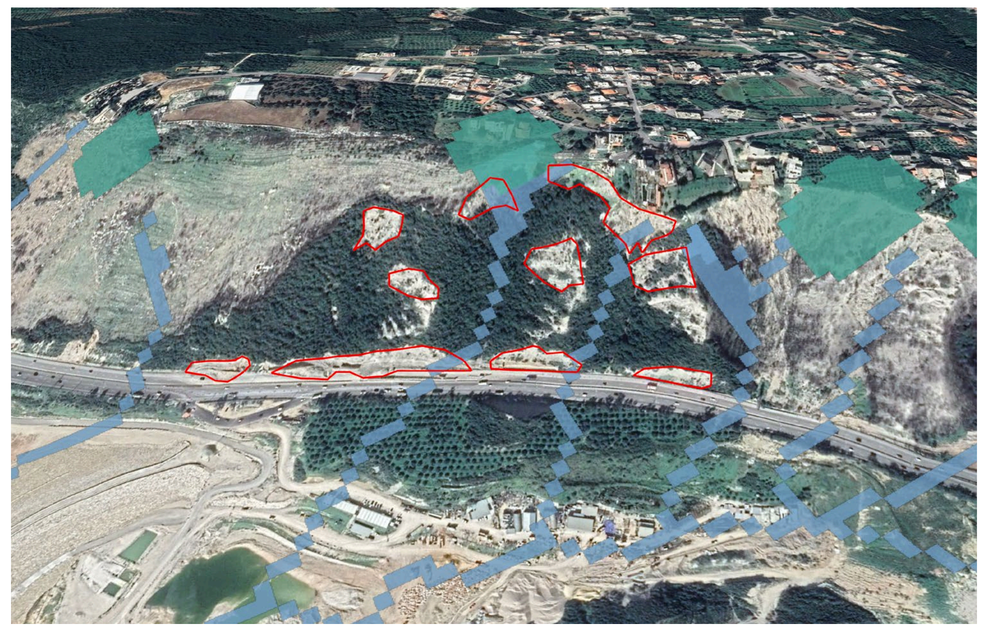
Boulos told The Daily Star that multiple small landslides were reported across the country, particularly in mountainous areas, and that teams from the ministry were working to clear the roads.

As a precaution, the ministry is proposing alternative routes that bypass roads potentially at risk of landslides and rockfall, Boulos said.

"What's happened is normal, it happens across the world in winter conditions," he explained, adding that the teams from the ministry and the local municipalities check the status of the roads on a daily basis.

It remained unclear how many cars were affected, though a number of cars were seen scratched, dented and covered in dirt in the footage





Pre-Event Forecast Map (50-Year Storm)
And Landslides from 2019 Storm Event (red)

"Verification" of Results, Part II: Comparison with Known Loss-of-Life

• Database search of recorded landslide fatalities in Lebanon from 1975 – 2015 (Arabic and English-language search news) reveals 146 fatalities conclusively caused by landslides (averages ~4 deaths/yr.)

- Incomplete inventory; many deaths are simply attributed to storms and flooding and thus omitted from our database

- Strong recording bias in time, with more recent events better documented (80% of the low consequence events are from the last 20 years).

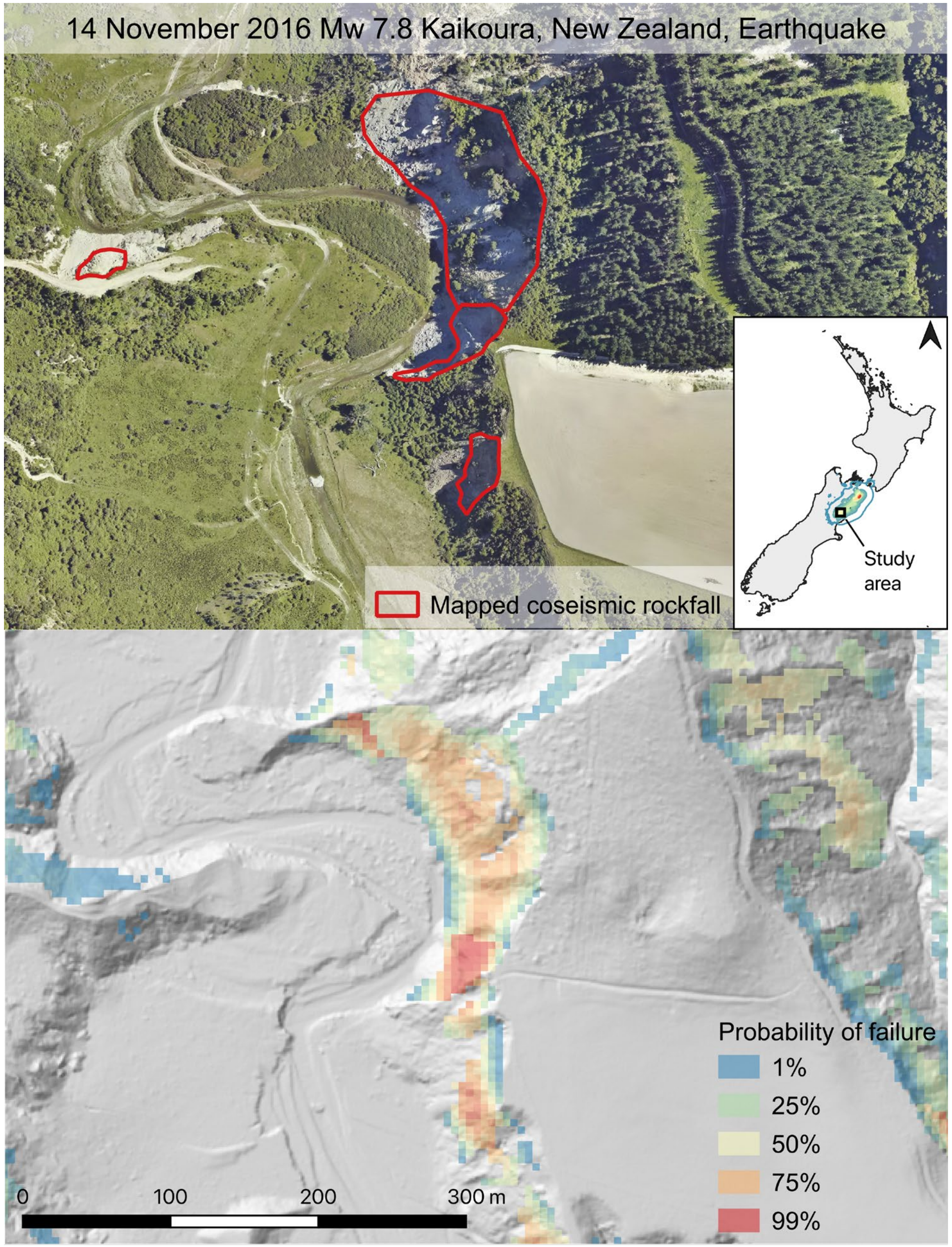
- No records of fatalities for refugees

• Our projections of ~39 death/yr. significantly exceeds the recorded data (4/yr).

Why?

- Underreporting of landslide fatalities
- Our physically-based models lean toward conservativism
- 15-m resolution obscures small-scale debris flow mitigation action
- We do not account for short-term variations in exposure
- We do not accounts for the ability to respond to impending or ongoing hazards.

What's Next? Risk Assessment Platform, Version 2 (W. Pollock)



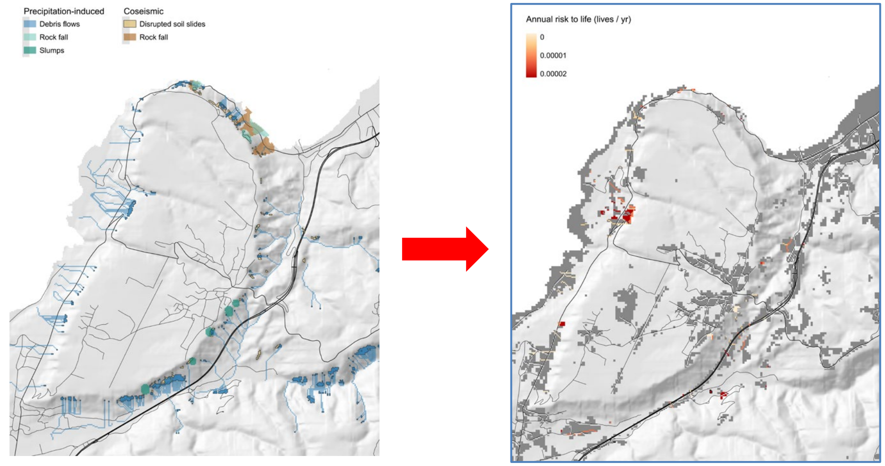
- Optimized 3D failure surface
- Enhanced rock-slope failure model
- Transient rainfall infiltration model (TRIGRS[1])
- "Random-walk," 3D runout trajectory[2]
- Vulnerability fragility functions
- Fully probabilistic (Monti-Carlo) simulations
- Comprehensive testing against well-documented landslide event (GNS Kaikoura, New Zealand Ver. 2 landslide database, left)
- Testbed regions: Seattle, Portland, and New Zealand; each with high-resolution lidar mapping and population and event data

Robust python-based, modular-type code

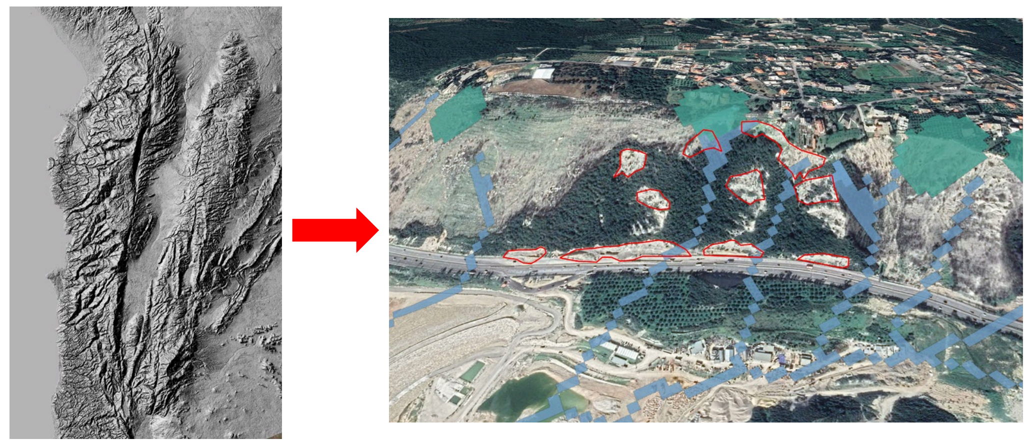
(1) Baum, R.. (2008) USGS; (2) Mergili et al. (2015) Geo. Mod. Dev.

Closing Thoughts

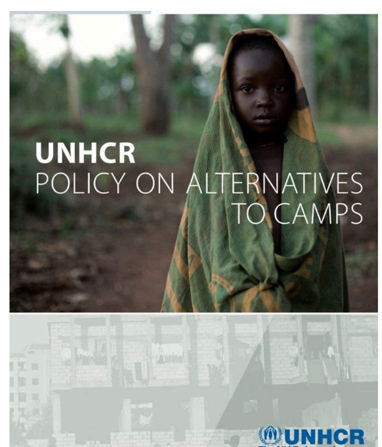
Landslide risk maps provide significant "value" over traditional hazard maps

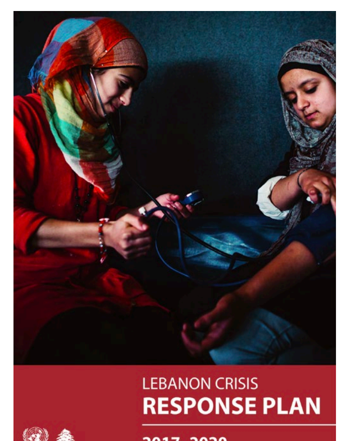


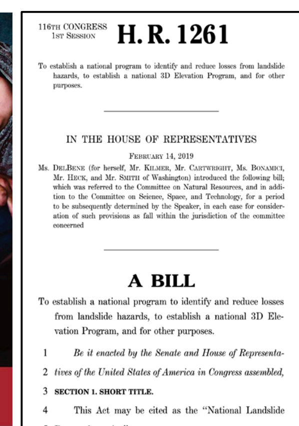
Landslide risk mapping is realistic and achievable



Landslide risk mapping provides fundamental understanding; and serves as a scientific reference for policy






116TH CONGRESS
1ST SESSION

H. R. 1261

To establish a national program to identify and reduce losses from landslide hazards, to establish a national 3D Elevation Program, and for other purposes.

IN THE HOUSE OF REPRESENTATIVES

FEBRUARY 14, 2019

Ms. DELBENE (for herself, Mr. KILMER, Mr. CARTWRIGHT, Ms. BONAMICI, Mr. HECK, and Mr. SMITH of Washington) introduced the following bill; which was referred to the Committee on Natural Resources, and in addition to the Committee on Science, Space, and Technology, for a period to be subsequently determined by the Speaker, in each case for consideration of such provisions as fall within the jurisdiction of the committee concerned

A BILL

To establish a national program to identify and reduce losses from landslide hazards, to establish a national 3D Elevation Program, and for other purposes.

Be it enacted by the Senate and House of Representatives of the United States of America in Congress assembled,

SECTION 1. SHORT TITLE.

This Act may be cited as the "National Landslide Preparedness Act".

Key References

Grant., A. et al. (2016) Multimodal method for coseismic landslide hazard assessment," *Engineering Geology*, doi 10.1016/j.enggeo.2016.08.005

Montgomery, D. and Wartman, J. (2015) "How to Make Landslides Less Deadly," Op-Ed, *New York Times*

Pollock et al. (2019a) "Risk at the Margins: A Natural Hazards Perspective on the Syrian Refugee Crisis in Lebanon," *International Journal of Disaster Risk Reduction*, doi 10.1016/j.ijdrr.2018.11.026

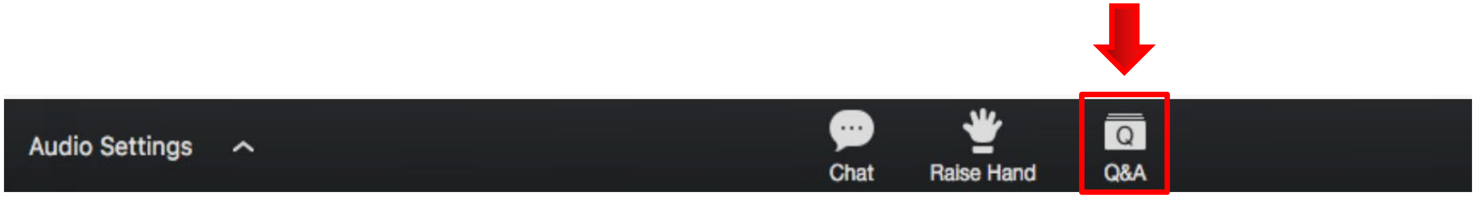
Pollock, W. et al. (2019b) "Multimodal Method for Landslide Risk Analysis," *MethodsX*, doi 10.1016/j.mex.2019.04.012

Pollock, W., et al. (2019c). Quantitative coseismic and precipitation-induced landslide risk mapping for the country of Lebanon. ASCE Geo-Congress.

Saade, A., et al. (2016) “Regional-scale co-seismic landslide assessment using limit equilibrium analysis,” *Engineering Geology*, doi: 10.1016/j.enggeo.2016.02.004

Wartman, J. (2014) "How to avert the next Oso landslide disaster," Op-ed, *Seattle Times*

Ask questions by clicking Q&A Box
on the tool bar at the bottom of the Zoom screen.
Hit “send.” We will read your questions as time permits



For more information about the Committee on Geological and Geotechnical Engineering (COGGE), contact:

Sammantha Magsino
Director, COGGE
National Academies of Sciences, Engineering, and Medicine
202.334.3091 smagsino@nas.edu

COGGE