Using high-resolution DEMs for debris-flow detection based on topographic signatures:

A case study in the Quebrada del Toro, NW Argentina

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Welcome to this PICO presentation on DEMs, debris flows and topographic signatures!

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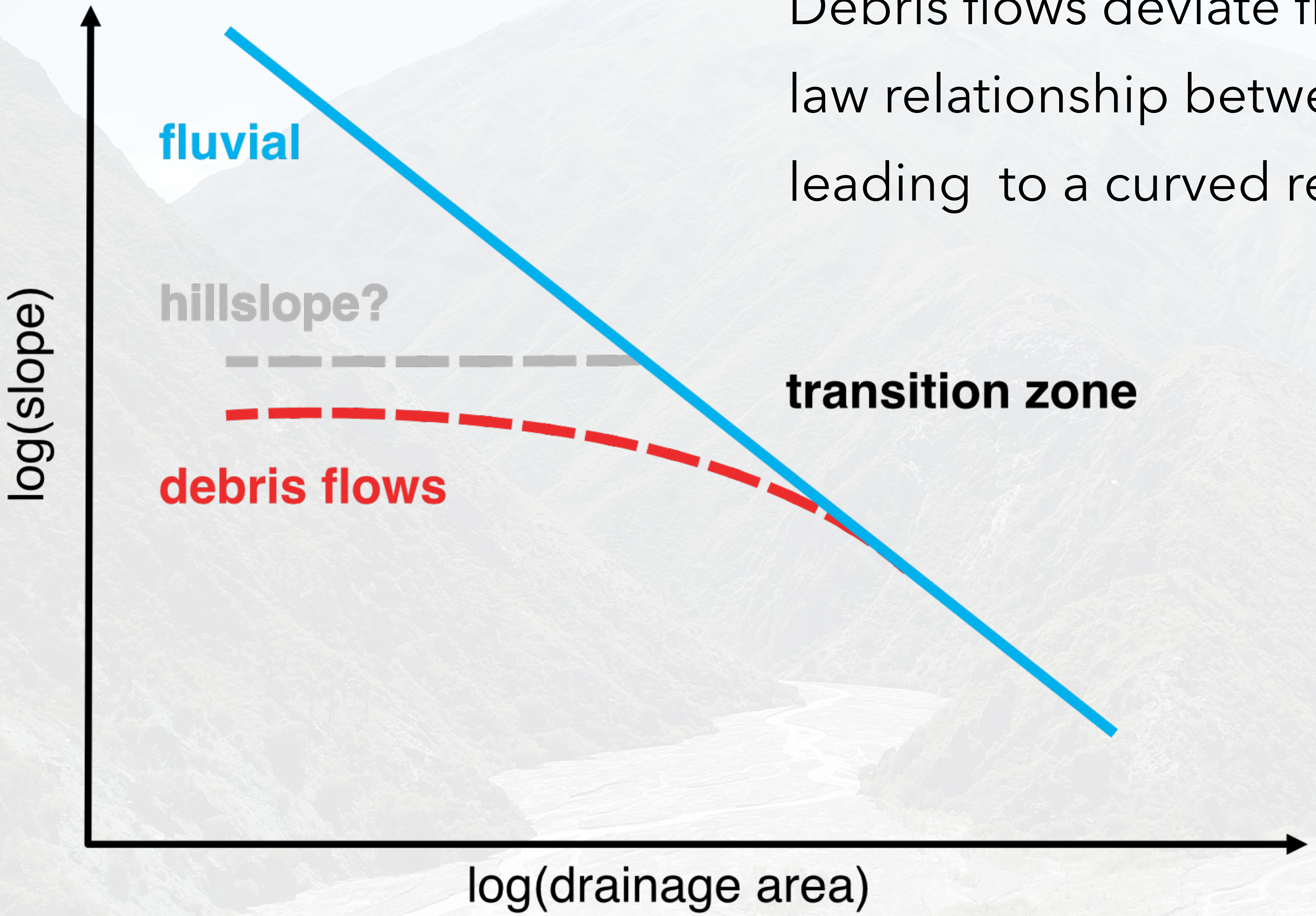
Introduction

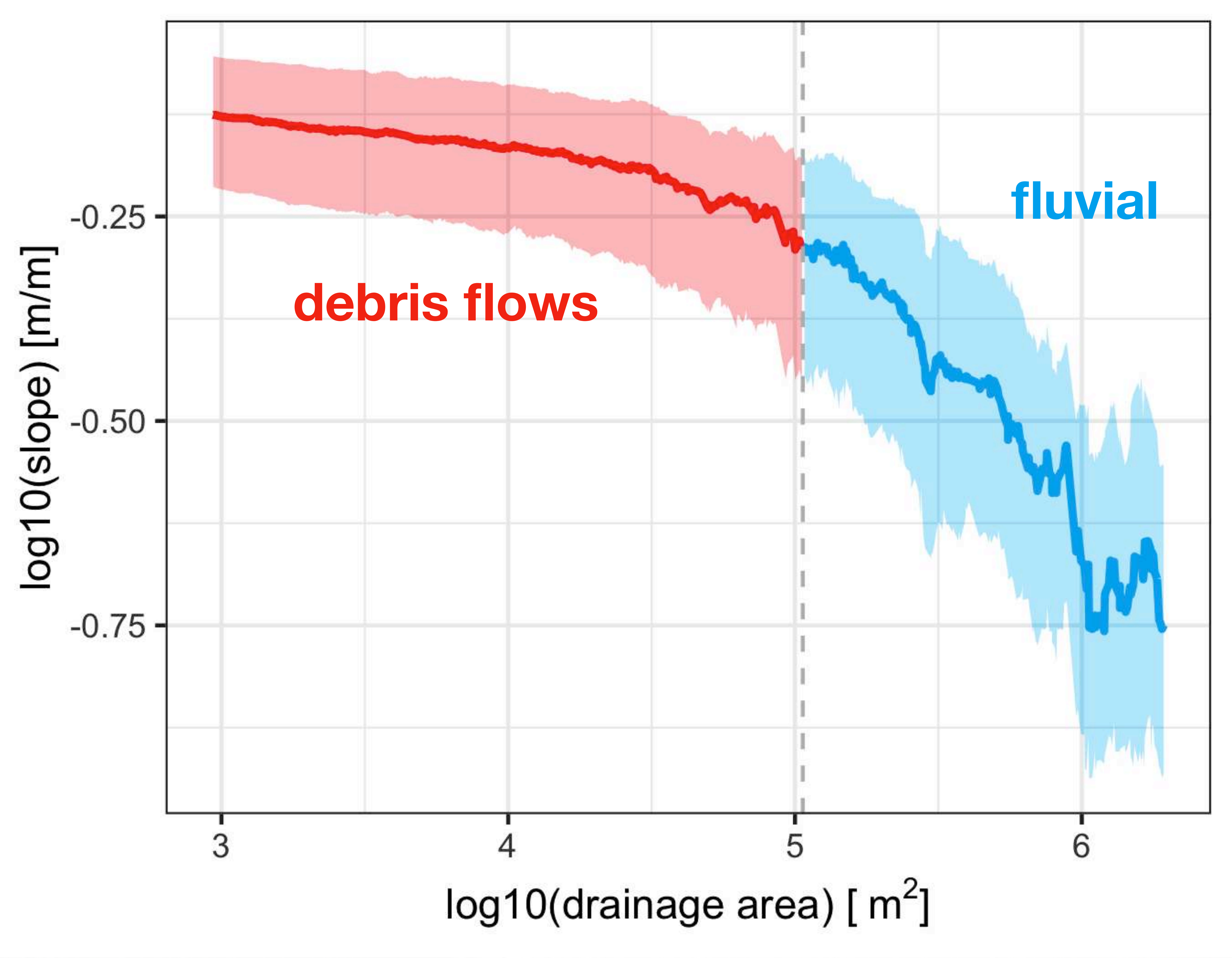
This study aims to identify debris flows based on their characteristic topographic signature, a phenomenon first described by Stock and Dietrich (2003).

We use DEMs derived from SPOT-7 tri-stereo data with a resolution of 3 m and also explore the potential of lower-resolution products, such as SRTM and TanDEM-X.



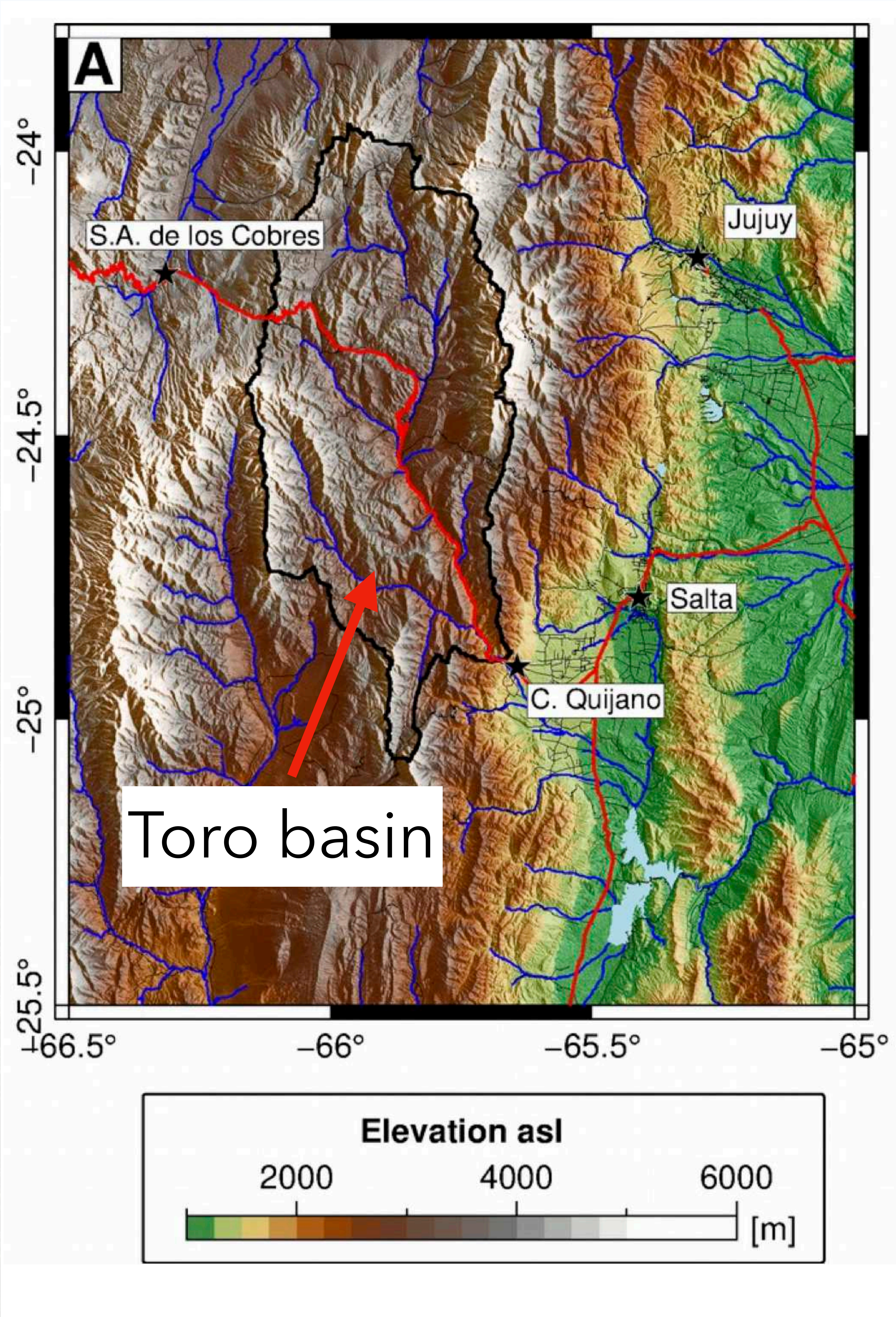
Debris flows deviate from the conventional power-law relationship between slope and drainage area leading to a curved relationship in log-log space.

Conceptual slope-drainage area plot adapted from Stock and Dietrich (2003).



This phenomenon is also evident in our study area, a high-relief mountainous environment that is frequently impacted by debris flow scour.

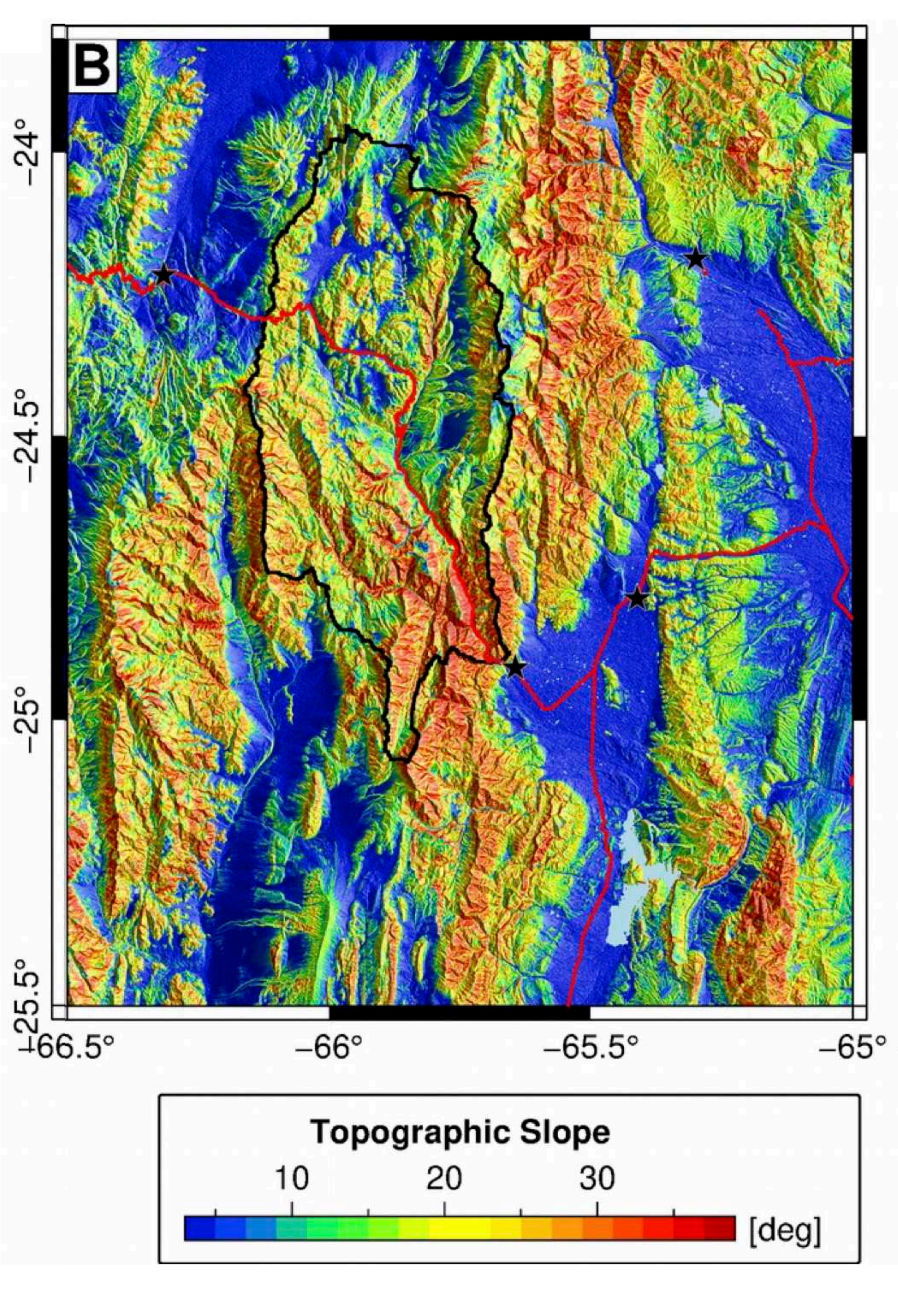
The curvature is clearly visible in this exemplary slope-drainage area plot from a basin to the south of our study area.



Study area

Our study area, the Quebrada del Toro (QdT), is situated in the Eastern Cordillera of NW Argentina.

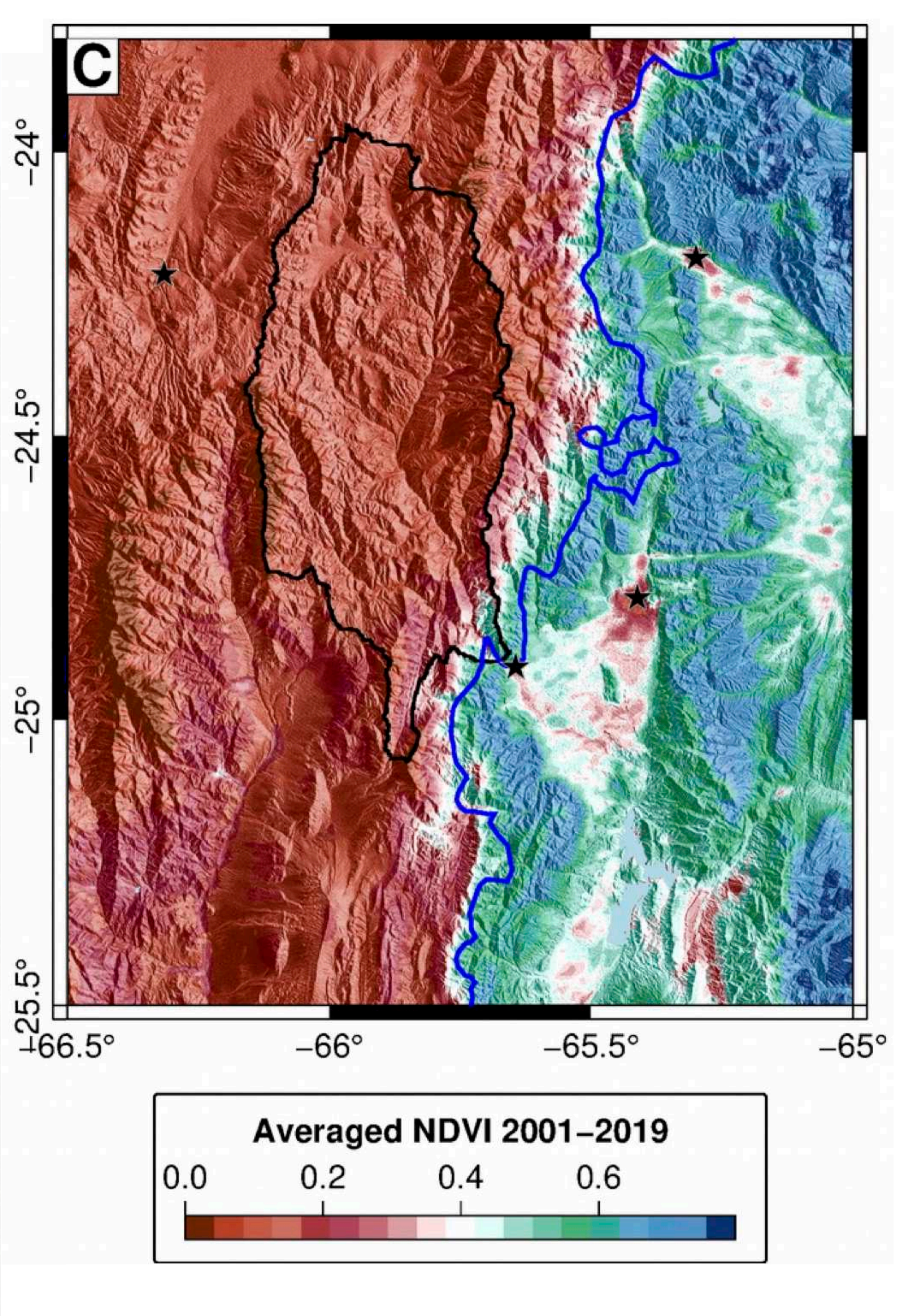
The QdT connects the arid Altiplano-Puna plateau at an average elevation of 3700 m with the more humid foreland at about 1100 m.



Study area

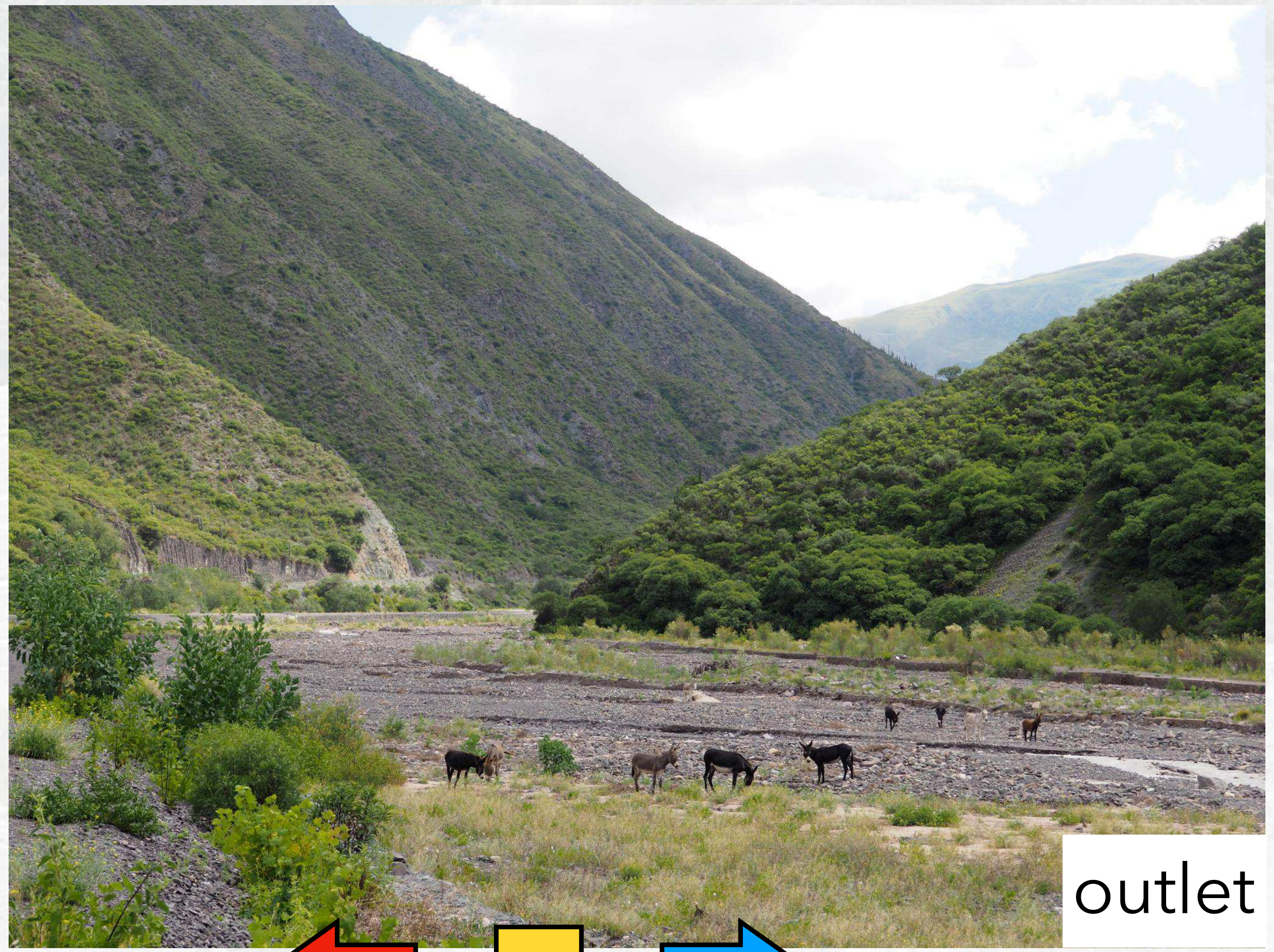
The area is characterized by steep gradients in topography, rainfall and erosion.

Incision of the Río Toro has created a deep narrow bedrock gorge in the southern part of the Toro basin, while the north exhibits a more gentle terrain.



Study area

The basin shows a pronounced orographic rainfall gradient. Rainfall measurements range from ~ 900 mm/yr at the outlet of the basin to < 200 mm/yr in the interior of the catchment.



blocked railroad bridge

debris-flow deposits

Study area

Debris flows are a common phenomenon in the QdT, as these photos from our field campaign in March 2019 show.

Due to sustained sediment input, the main route leading through the QdT requires permanent, costly maintenance in the form of longitudinal defense work or excavation of the river bed.

DEM generation through stereogrammetry

Our study requires good-quality elevation models.

We use satellite stereogrammetry to generate DEMs from tri-stereo SPOT-7 data.

Stereo correlation is carried out using **Ames Stereo Pipeline**.

A set of ground control points collected at easily identifiable locations, such as bridges and road intersections, is used to ensure spatial coherence.

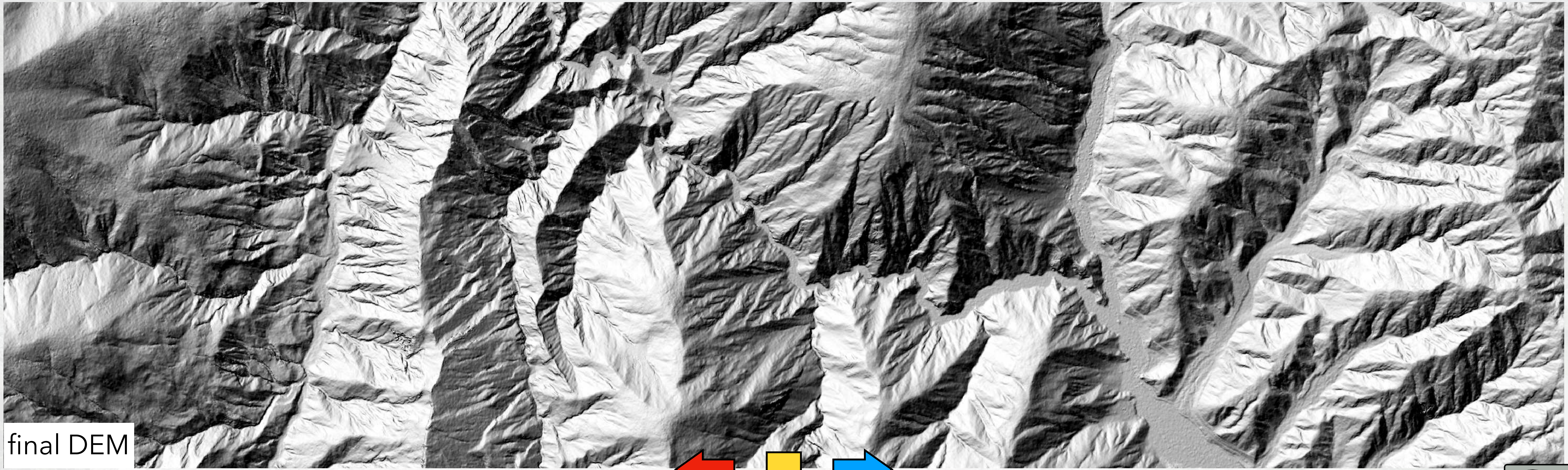
DEM generation through stereogrammetry

Through computing dozens of DEMs, optimal parameters employed in the stereo-correlation process are identified.

Processing step	Purpose	Optimal parameters/input
Bundle adjustment	Minimize satellite position and orientation errors	Use ground control points
Map-projection	Make images “more similar“ which aids stereo correlation	Smooth, void-filled 90 m SRTM as reference surface
Stereo correlation	Match pixels and create 3D point cloud	Kernel size: 15 x15 pixel Bayes EM weighting

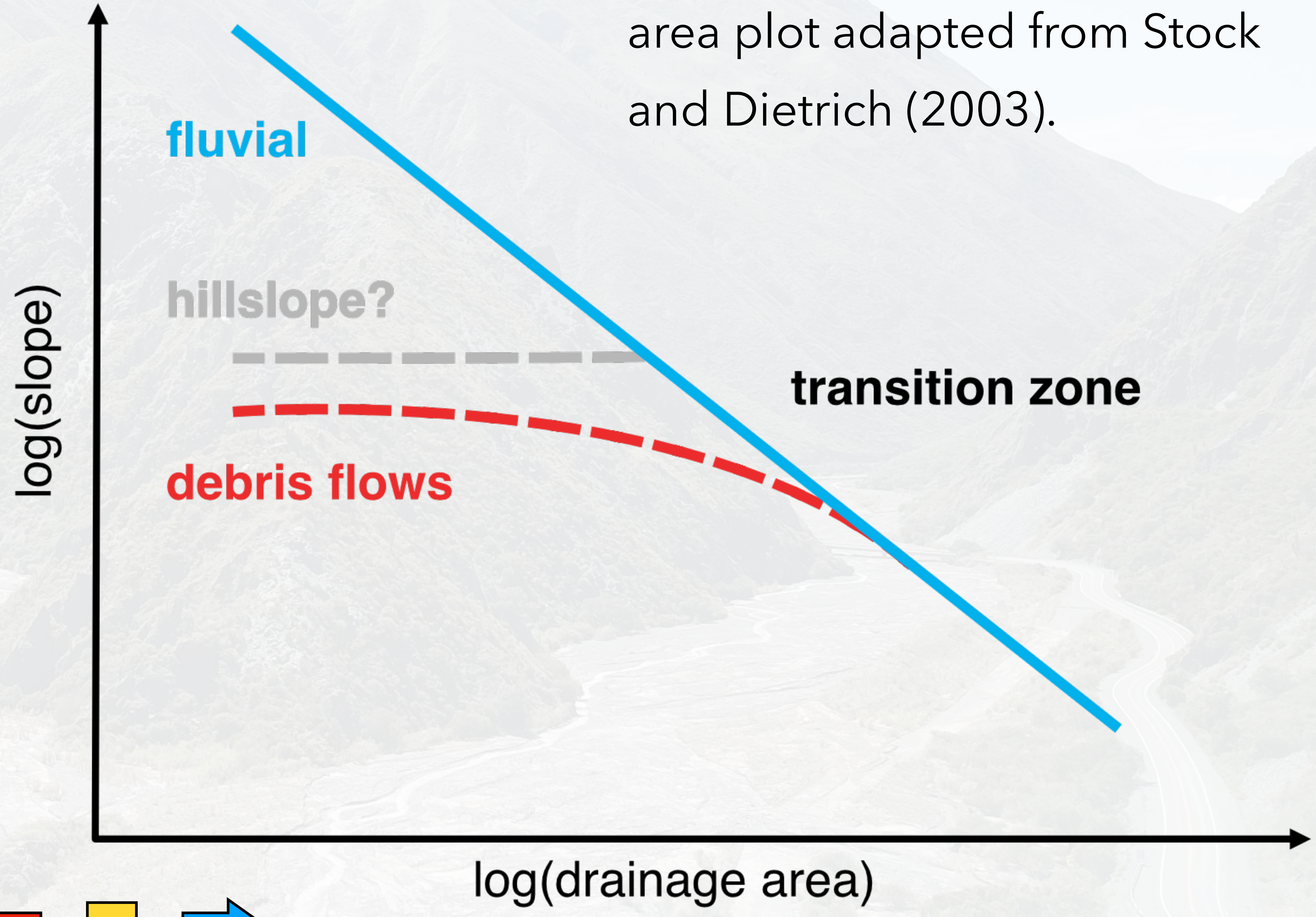
DEM generation through stereogrammetry

Finally, a smoothing filter is applied in areas where triangulation errors are high. This practice removes small artifacts, without altering those regions where stereo correlation was successful. The result is a smooth, 3 m DEM.



Debris-flow detection

Following the assumption that debris flows show a different relationship of slope against drainage area, we aim to identify this characteristic signature in different catchments, if present.

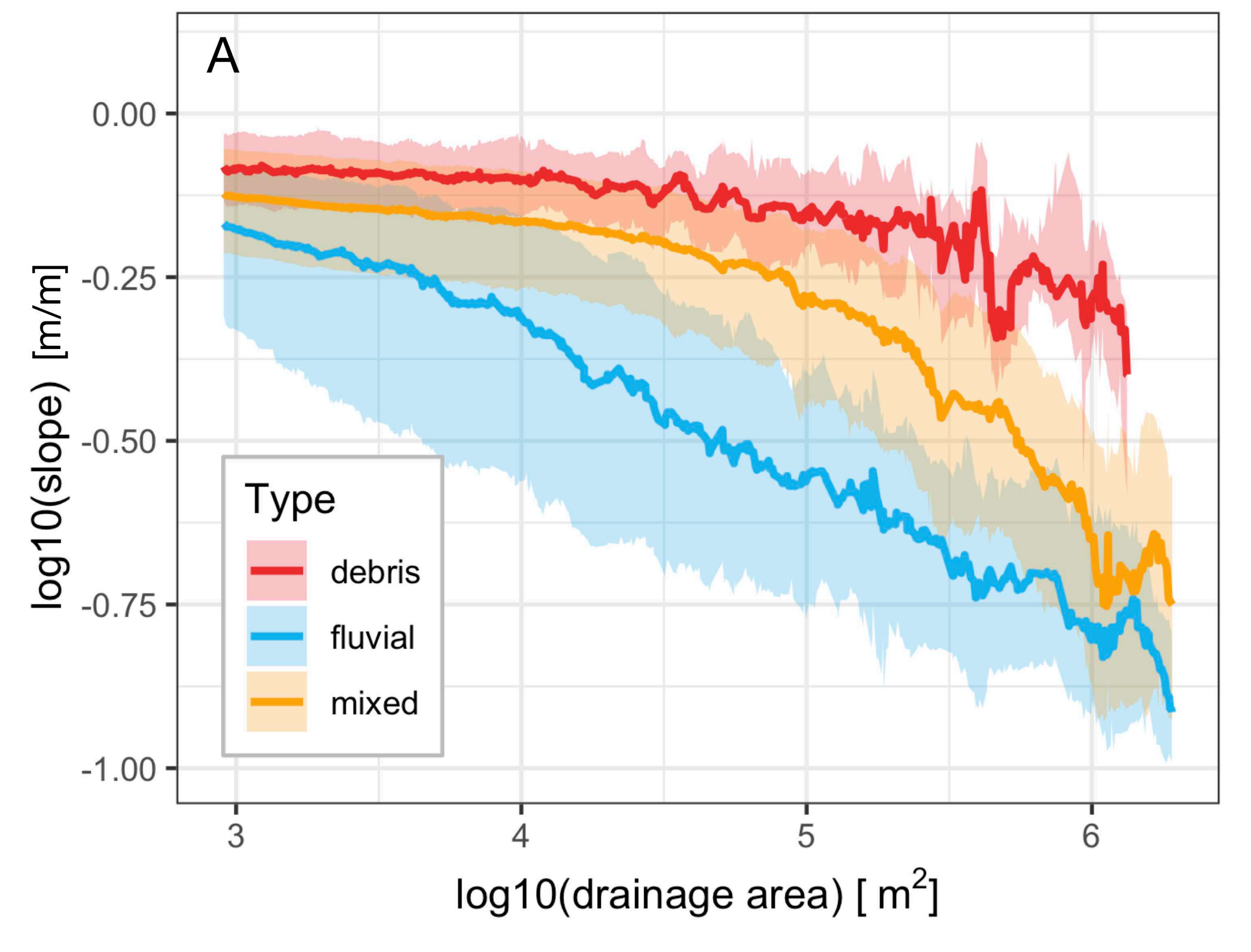


Conceptual slope-drainage area plot adapted from Stock and Dietrich (2003).

Debris-flow detection

Within the QdT, we identify three different basin types based on their topographic signature:

- basins dominated by fluvial transport processes
- basins with a signature of debris flows
- basins that show a curved relationship, indicating different transport regimes

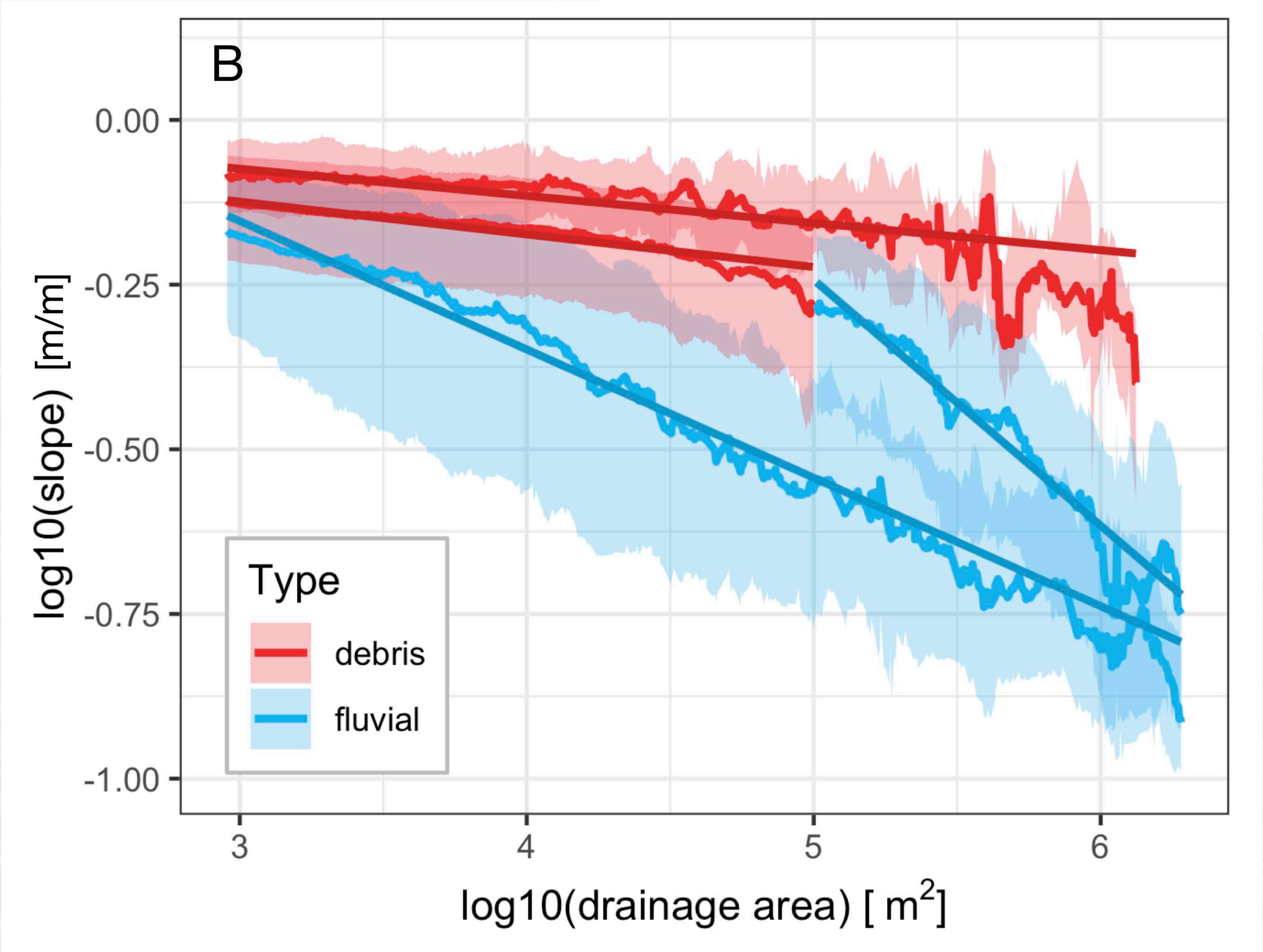


Slope drainage area relationship of three exemplary watershed basins in the QdT

Debris-flow detection

The slope-area relationship of basins dominated by a single transport process can be approximated through linear regression.

A broken-line relationship is the better fit for basins with indications of different transport regimens.



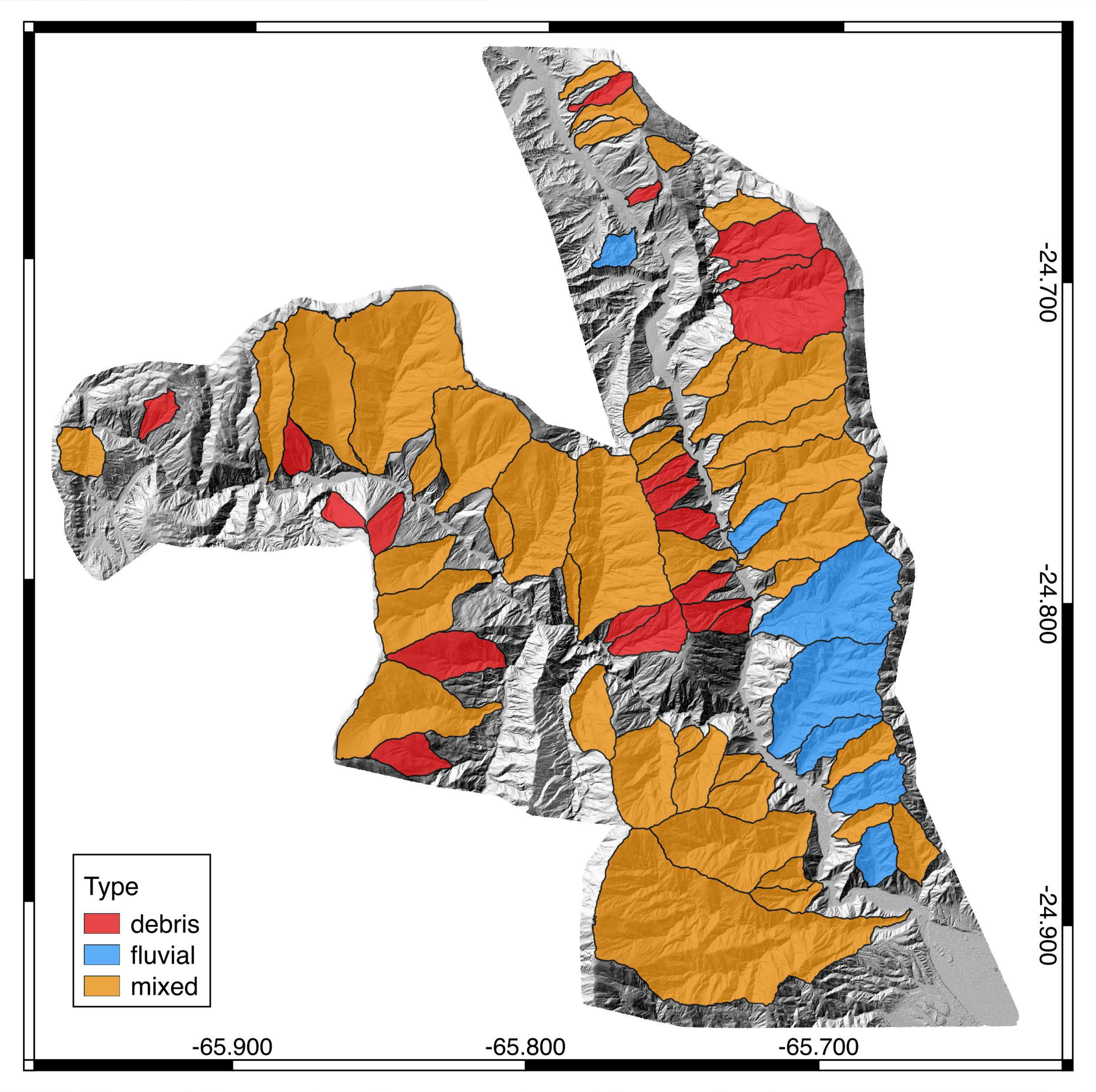
Interpreted slope drainage area plot of three exemplary watershed basins in the QdT

Debris-flow detection

Fluvial and debris-flow signatures differ most prominently regarding the slope of the fitted line segments (θ).

A θ-threshold of -0.089 is established for the QdT using 68 manually classified drainage basins.

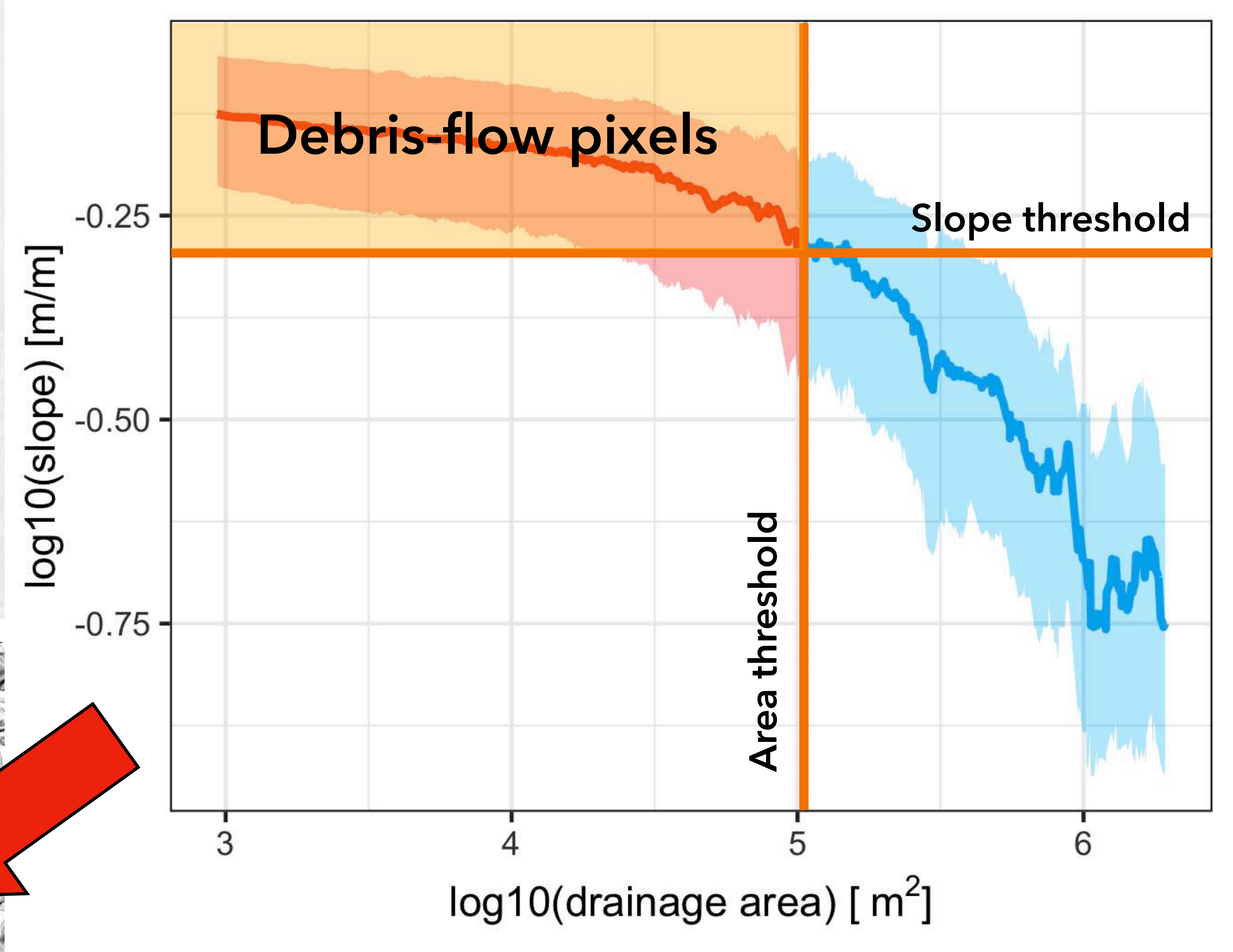
The transition between debris-flow and fluvial transport regimes is identified through **breakpoint analysis**.

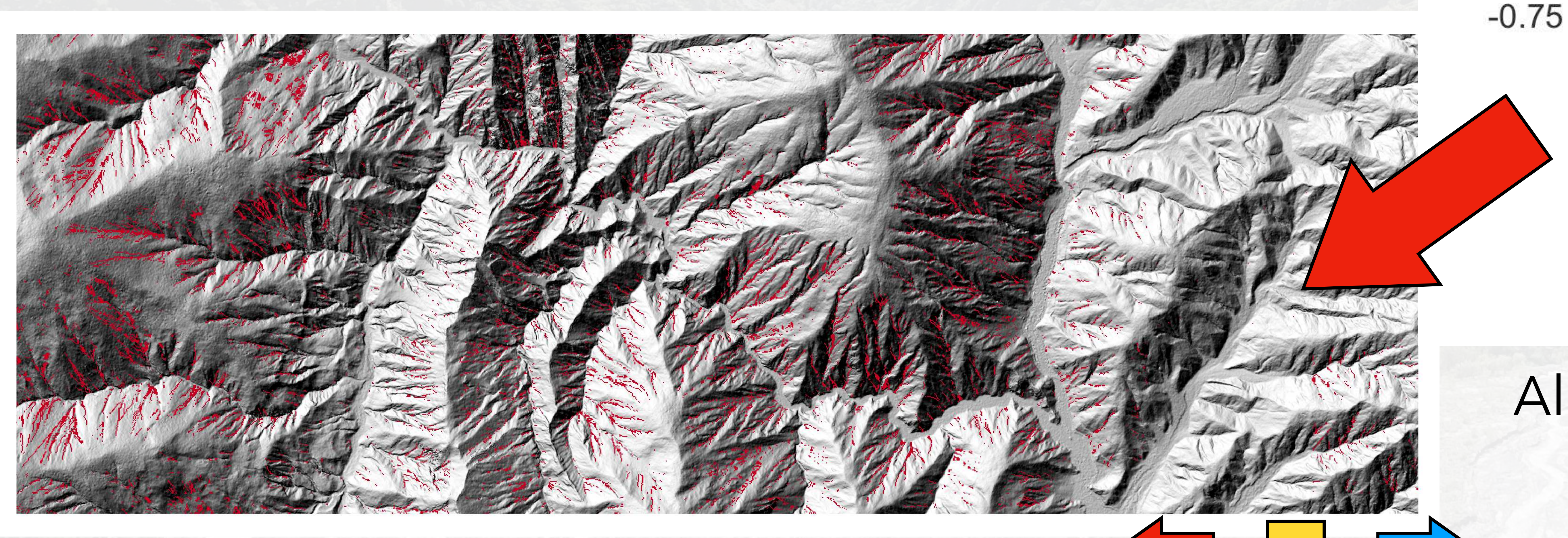


Manually classified control basins in the QdT.

Debris-flow detection

Information on the location of the transition zone (breakpoint) can be back-translated into 2D space to identify pixels that show the topographic signature of debris flow.





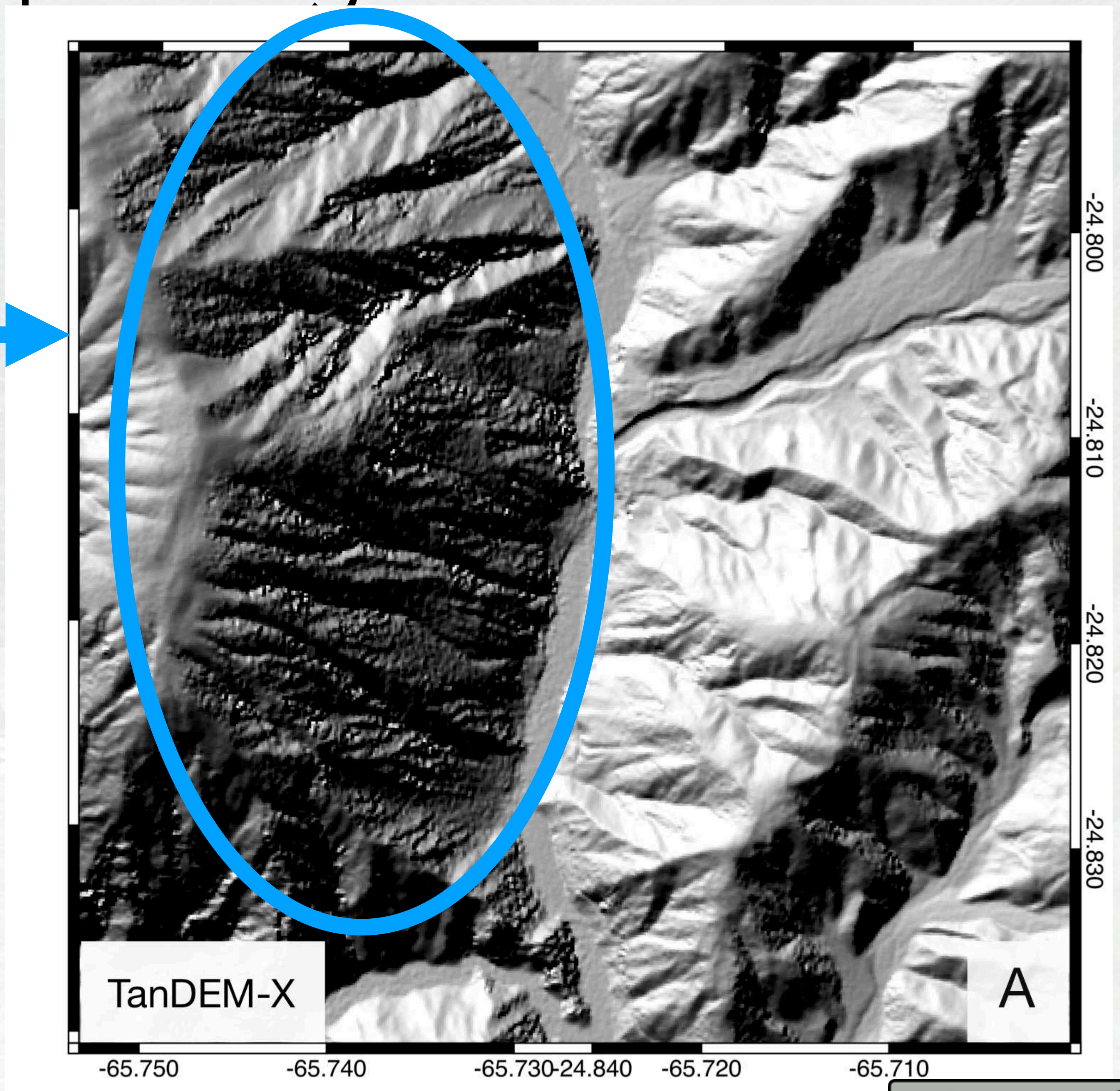
All pixels that fall into a certain slope and drainage-area domain are extracted.

Debris-flow detection on TanDEM-X

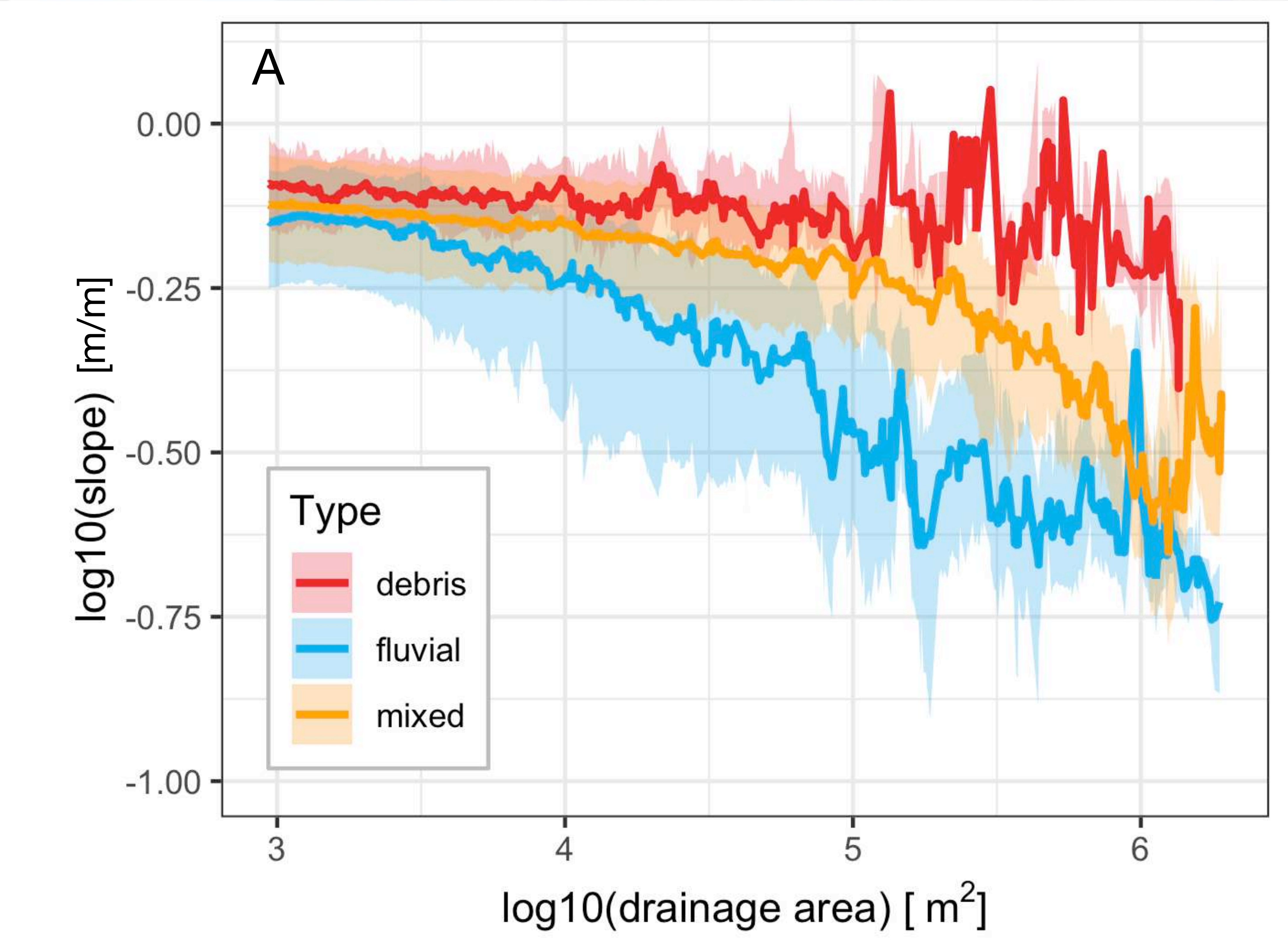
Stereo data is ideal but not necessarily available/affordable for very large areas. Thus, we explore the applicability of TanDEM-X (12 m) and the SRTM DEM (30 m) for debris-flow detection based on topographic signature.

Both SRTM and TanDEM-X, however, often have problems in high-relief areas that result in artifacts and data gaps.

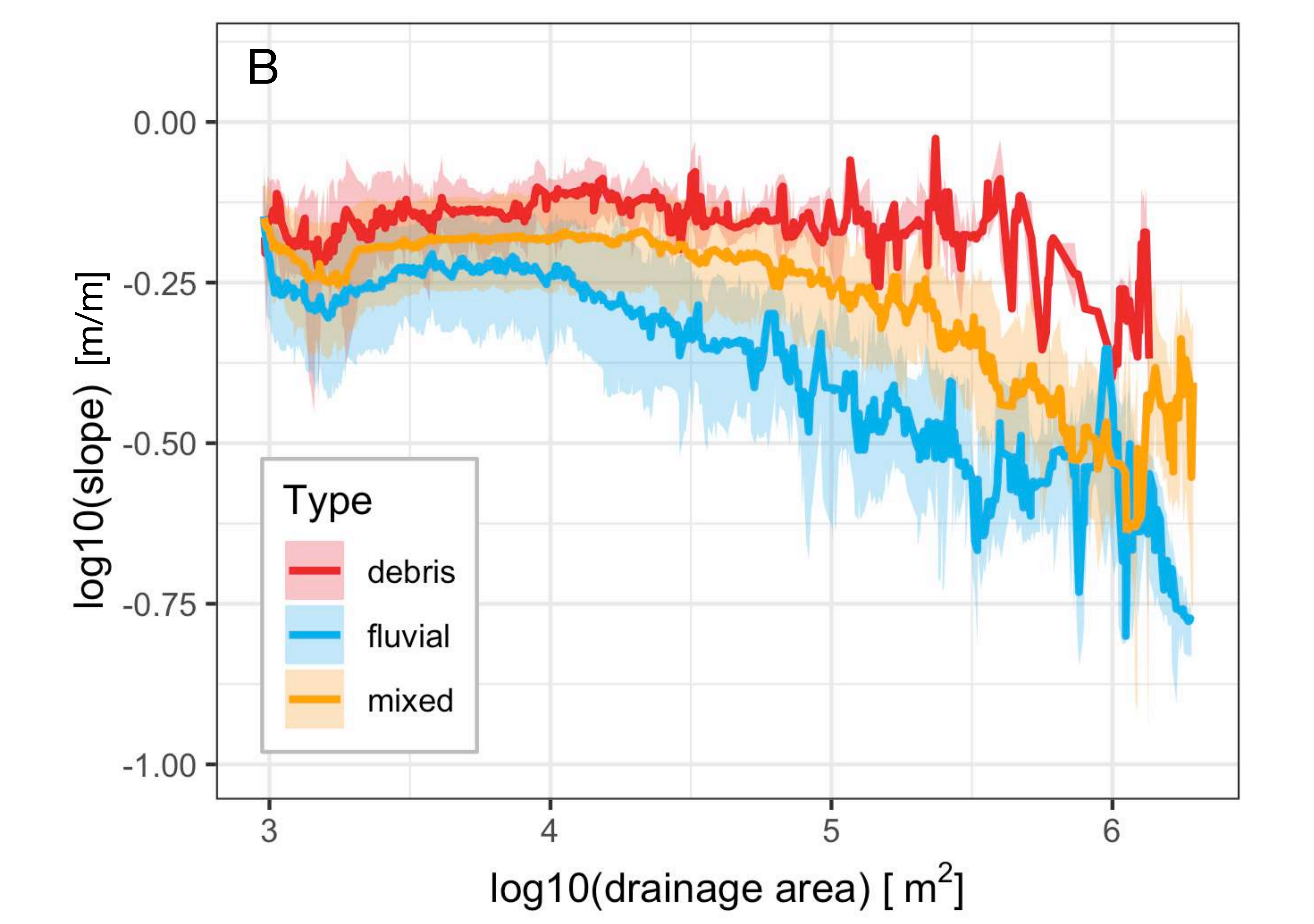
Also, a lower resolution increases scatter in the slope-area plot, which makes accurate classification difficult.



Debris-flow detection on TanDEM-X

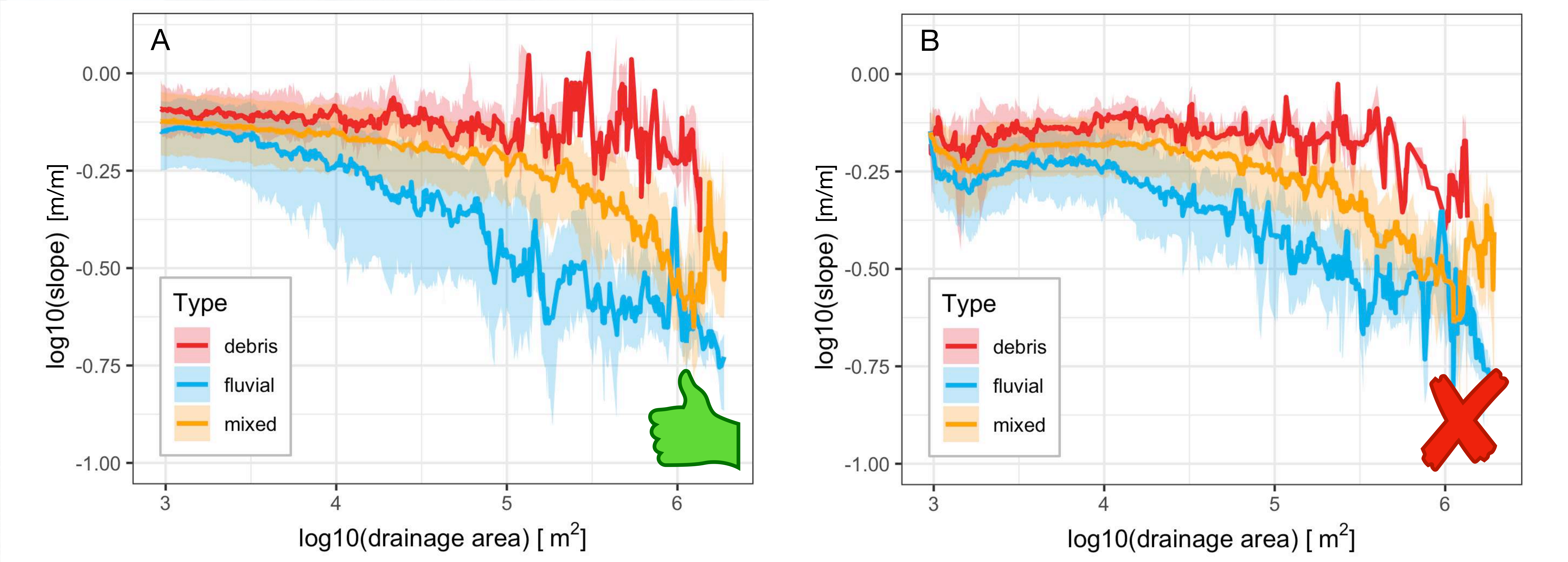


Slope-drainage area relationship using TanDEM-X data



Slope-drainage area relationship using the SRTM DEM

Debris-flow detection on TanDEM-X



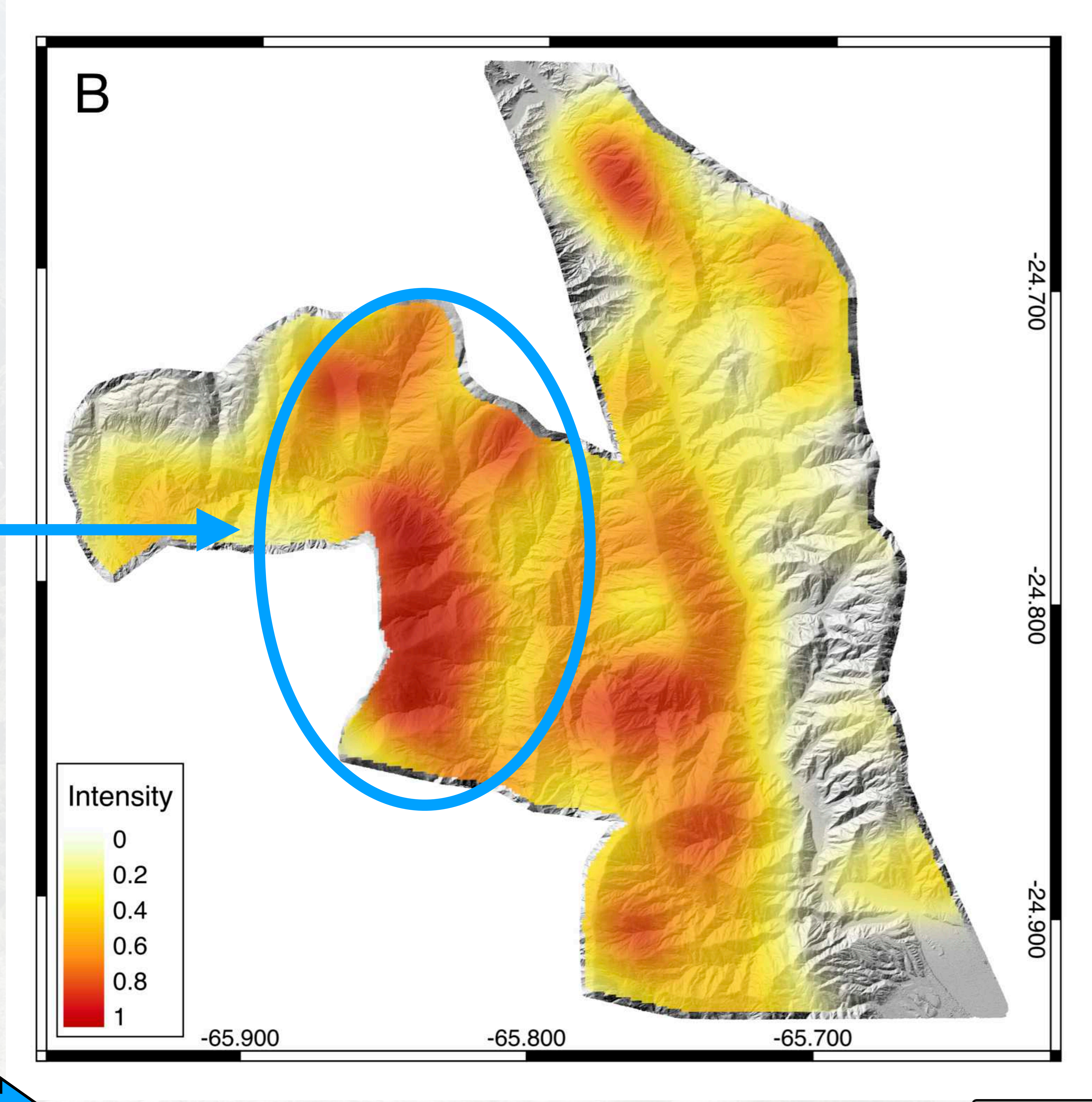
TanDEM-X is not ideal, however, it is possible to reasonably differentiate between topographic signatures.

SRTM is not suitable, as there is no clear distinction between individual basin types and too few data points at low drainage areas.

Debris flows in the Quebrada del Toro

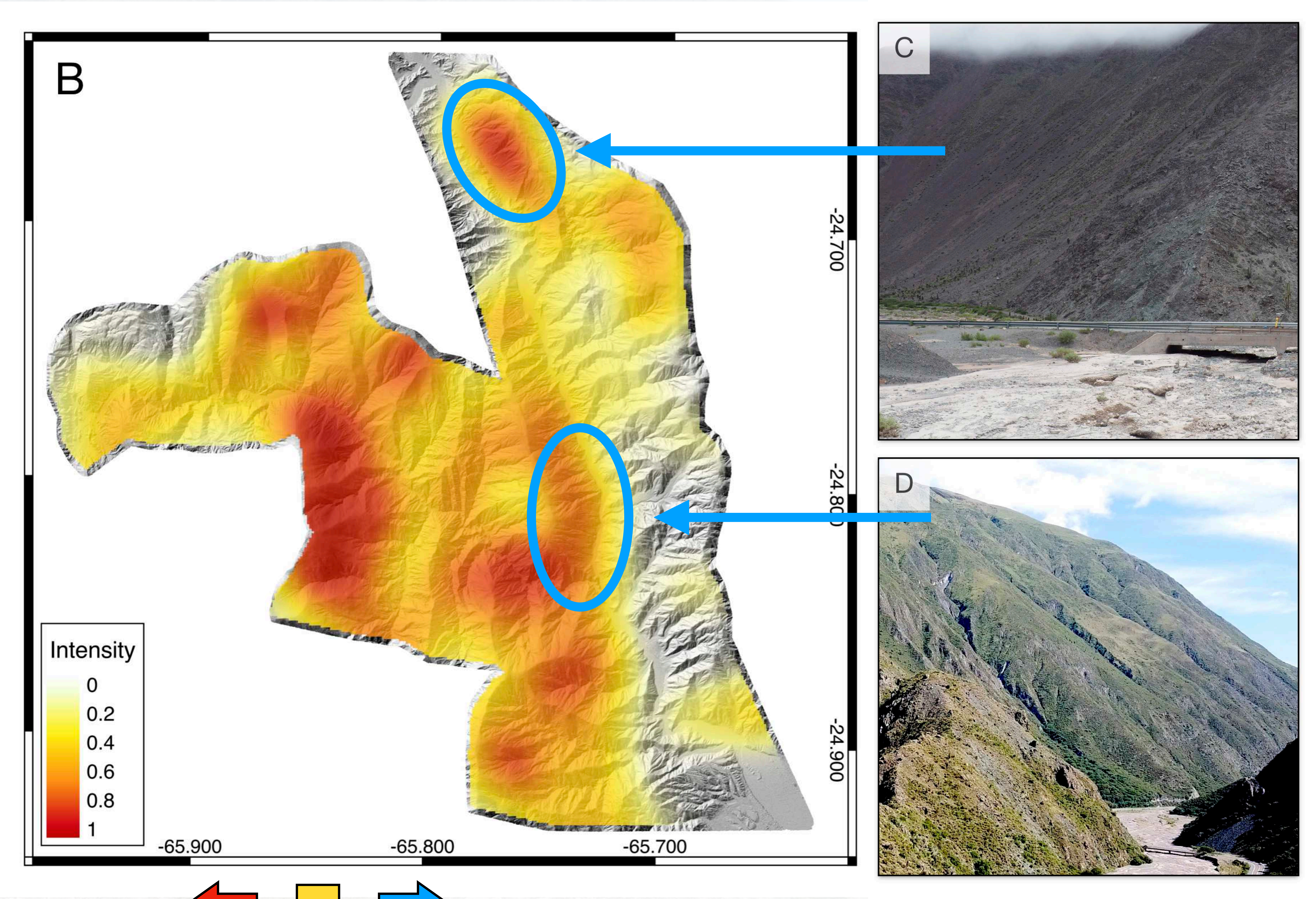
We refer to the number of debris-flow pixels per square kilometer as debris-flow intensity.

Highest intensities exist within the Río Capilla catchment to the west, which we did not visit during our field campaign as it is difficult to access.



Debris flows in the Quebrada del Toro

Nevertheless, we find that other debris-flow hotspots correspond to regions where we did witness debris-flow deposits in the field.

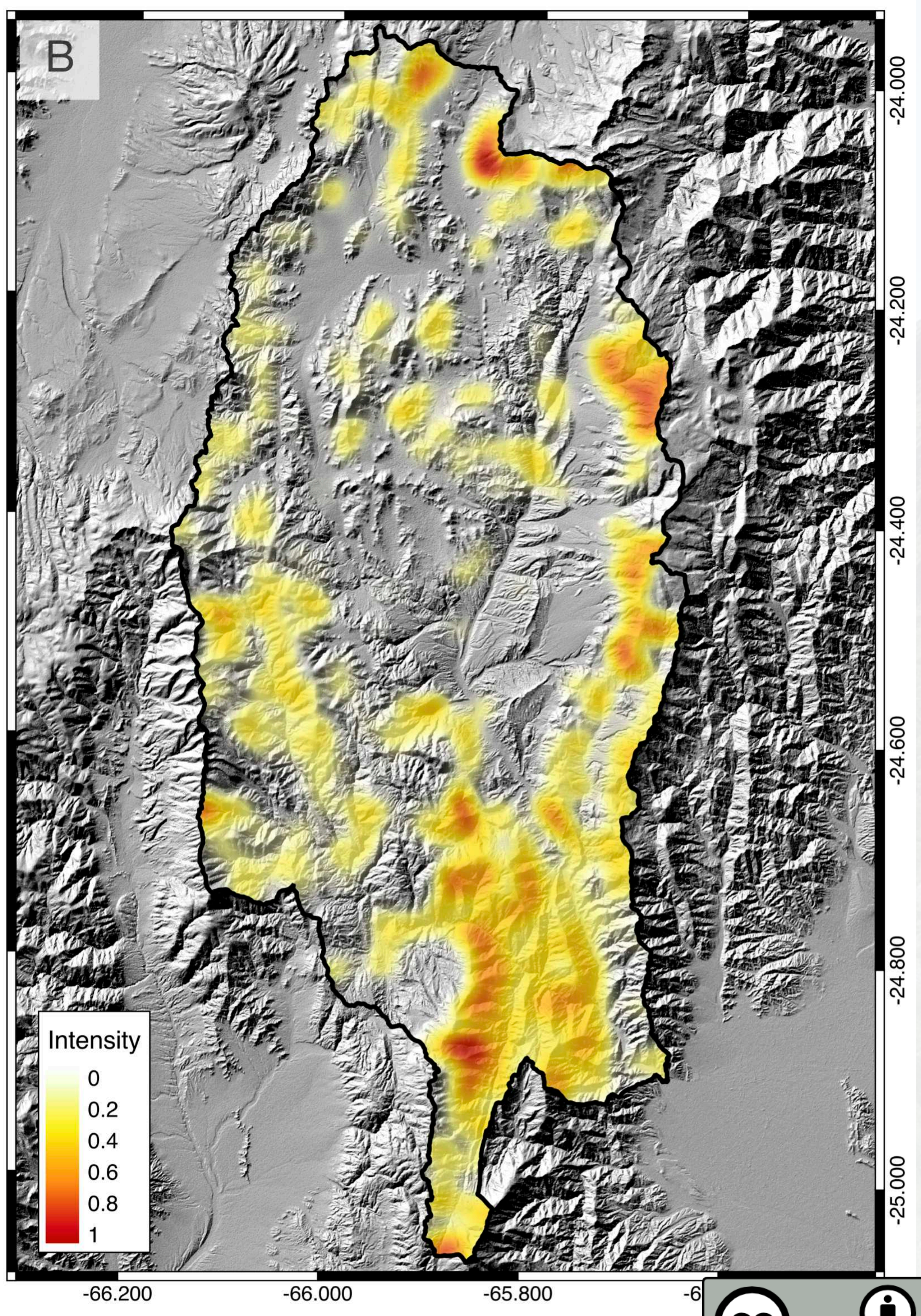


Debris flows in the Quebrada del Toro

Using TanDEM-X, we analyze debris-flow intensity within the entire Río Toro watershed.

Highest intensities are located within the deeply entrenched gorge to the south and along the western flank of the basin.

The latter sector is characterized by pervasively sheared fault-zone rocks bounding the basin.



Normalized debris-flow intensity throughout the Toro basin.

Triggering factors of debris flows

Debris flows result from the interplay of several factors, including local relief, availability of unconsolidated sediment, climate, vegetation cover, and tectonic setting.

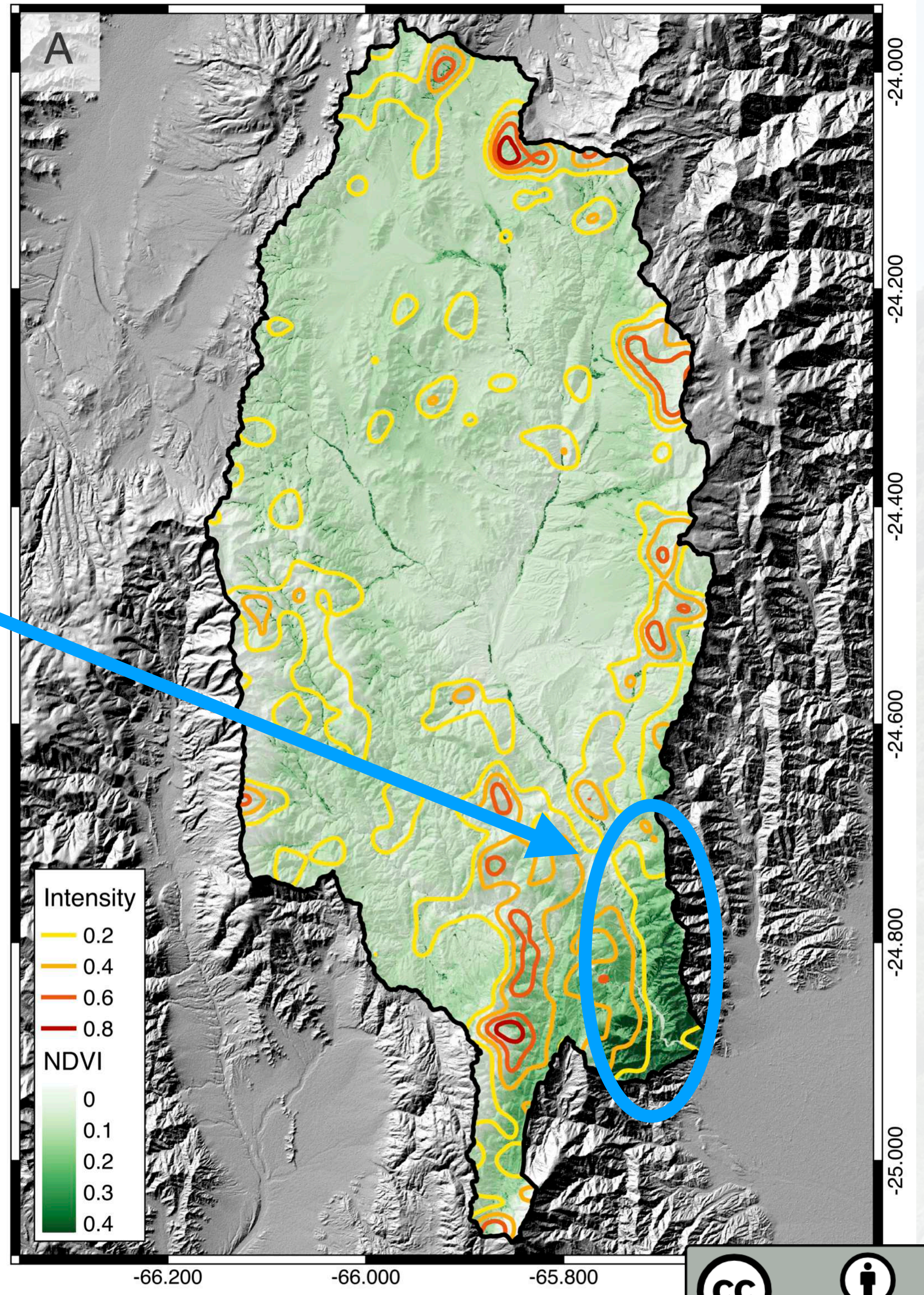
Within the Toro basin, topographic slope undoubtedly exerts an important impact on generating debris-flows, as the highest debris-flow intensities occur in areas with high relief.

There are, however, other variables that make the QdT an ideal environment for debris flows.

Triggering factors of debris flows

I. Vegetation Cover

Most of the Toro basin is relatively dry, so there is no or little vegetation cover to enhance soil cohesion. We find indications for the stabilizing character of vegetation in the south of the basin, which receives significantly more rainfall Here, relatively low debris-flow intensities are associated with high relief. Most likely, the dense vegetation cover prevents the efficient removal and transport of large amounts of talus downhill.

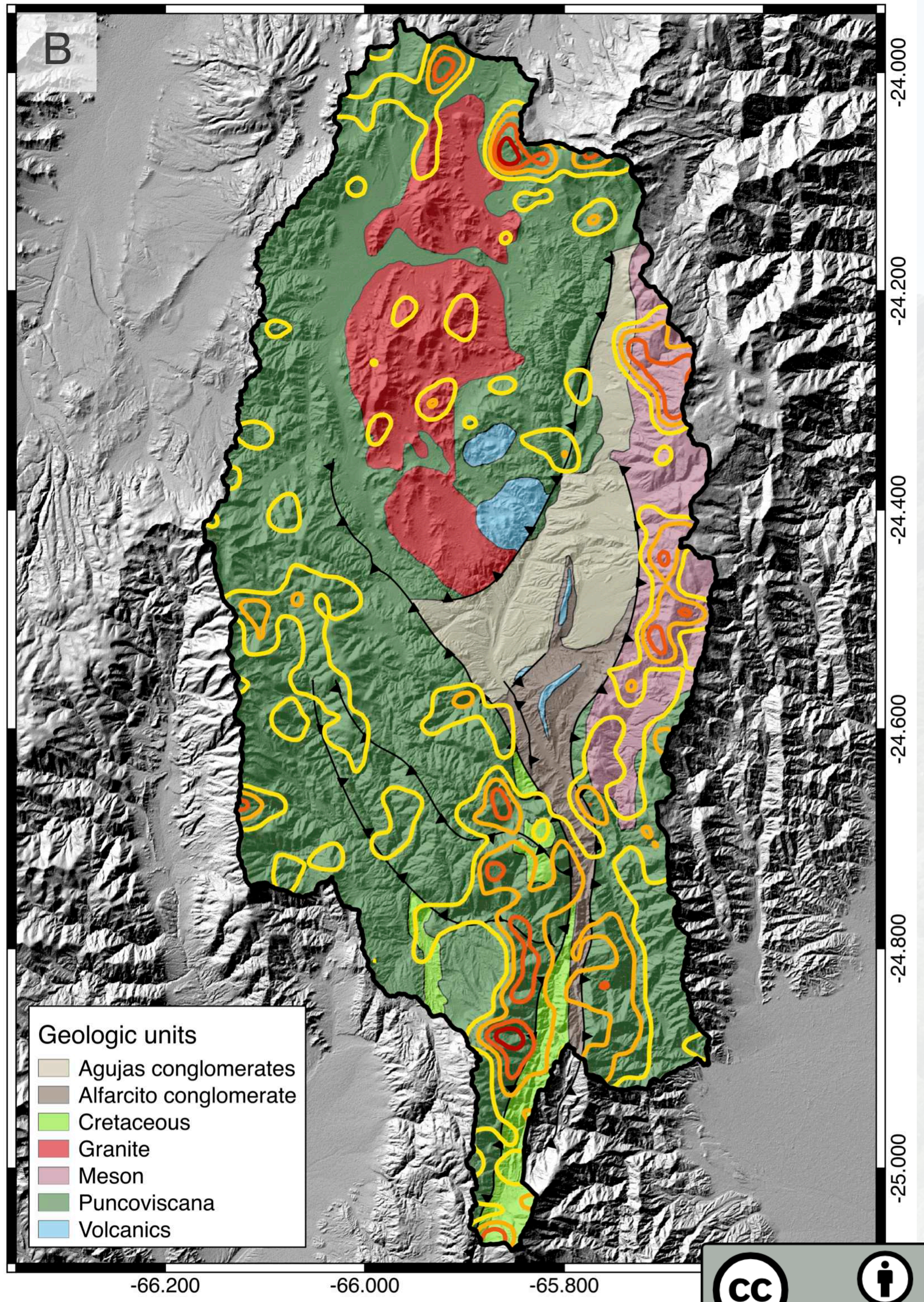


Triggering factors of debris flows

II. Lithology

Within the Toro basin, the areally extensive exposure of pervasively sheared meta-sediments of the Puncoviscana formation constitutes ideal lithologic conditions for the removal of material.

The cataclacized rocks provide ample surface area and incohesive material for weathering and erosion.



Triggering factors of debris flows

III. Seismicity

The region surrounding Salta has been repeatedly affected by seismic activity ($M_w < 6.3$) in the past. Sudden rupture events can trigger rock falls, and landslides that supply large volumes of unconsolidated, broken material that can be entrained in subsequent debris flows.

IV. Extreme rainfall events

During the summer monsoon, the QdT is frequently affected by rainstorm events that can effectively destabilize slopes and mobilize debris flows.

Conclusions - Stereogrammetry

- In high-relief areas, stereogrammetry is a viable tool for obtaining high-resolution surface models that contain significantly fewer errors than publicly available elevation data
- Stereo DEMs hold great potential for geomorphologic analyses at the meter scale and help to assess potential debris-flow activity
- Optimal results require careful data pre- and post-processing. Ground-control points can be helpful, but are not required

Conclusions - Debris-flow detection

- Debris-flow incision leaves a characteristic topographic signature on the landscape, marked by channel gradients close to zero
- This unique feature can be employed to distinguish between different hillslope processes
- Higher-resolution DEMs (≤12 m) are necessary for more accurate debris-flow detection

Conclusions – Debris flows in the QdT

- The deeply entrenched river gorge and the steep-sloping eastern flank of the Toro catchment are prime areas for the initiation of debris flows → these areas constitute the greatest hazard for humans and infrastructure

- The main driver of debris-flow generation in the QdT is slope steepness, but the availability of pervasively sheared meta-sediments, the existence of sparse vegetation cover and recurring heavy rainfall events are equally important to the removal of large amounts of sediment downhill

Thank you for your interest!

If you have any questions, don't hesitate to **contact** me.

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