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Graph theory-based sediment connectivity analysis of a glacierised Alpine basin for different event scenarios

Anuschka Buter (anuschka.buter@natec.unibz.it), Tobias Heckmann, Lorenzo Filisetti, Antonia Spitzer, Luca Mao, Bernhard Gems, Francesco Comiti

unibz
Freie Universität Bozen
Libera Università di Bolzano
Università Liedia de Bulsan

Katholische Universität Eichstätt-Ingolstadt

universität innsbruck

University of Lincoln

BOKU

unibz

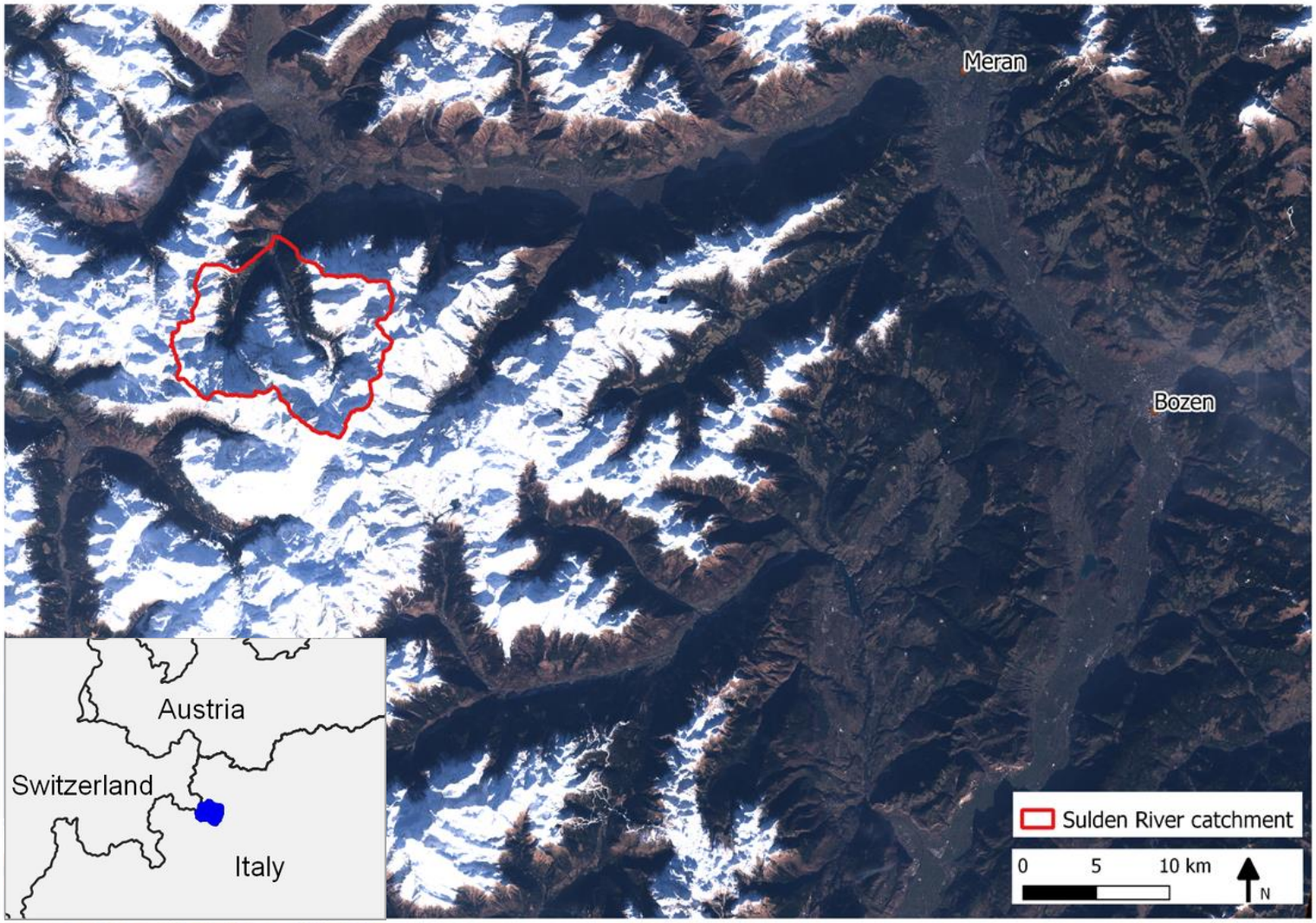
Introduction

Motivation

Why studying sediment connectivity / sediment transport processes in high mountain areas?

- Complex system of different interacting sediment transport processes
- Partly hazardous sediment transport processes like rockfall, debris flows, landslides, etc.
- Hazardous sediment transport might increase due to expected more frequent storm events and intensive heat periods in summer in the next decades (Pfleiderer et al. 2019)
- More sediment will be available because of melting glaciers and retreating permafrost

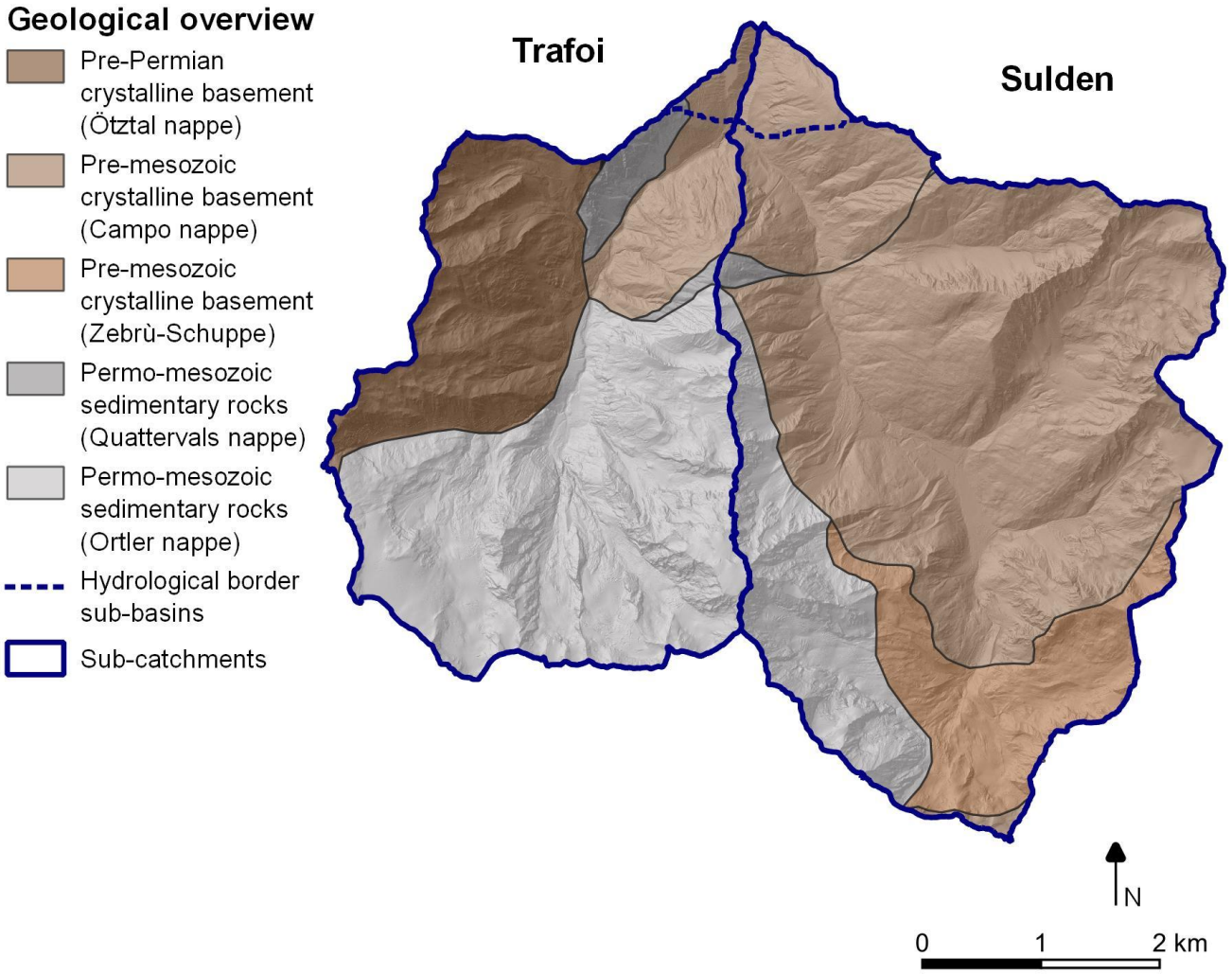
Study area


Meran
Bozen
Austria
Switzerland
Italy
Sulden River catchment
0
5
10 km
N

Study area

- Sulden River catchment
- ~130 km²
- ~18 km² glaciated
- 1100 – 3905 m.a.s.l. elevation range
- Metamorphic and sedimentary lithological units

Study area


Geological overview
Pre-Permian crystalline basement (Ötztal nappe)
Pre-mesozoic crystalline basement (Campo nappe)
Pre-mesozoic crystalline basement (Zebrù-Schuppe)
Permo-mesozoic sedimentary rocks (Quattervals nappe)
Permo-mesozoic sedimentary rocks (Ortler nappe)
Hydrological border sub-basins
Sub-catchments
Trafoi
Sulden
N
0
1
2 km

Aims

- Identification of sediment transport processes occuring in the catchment forming sediment cascades

- Characterization of the sediment cascades / the resulting graph for scenarios of heat waves and rain storm in both snow and glacier melting periods and for the two sub-catchments considering:

  - Hotspots of sediment transport
  - Cascades / sub-graphs connected the outlet
  - Important sediment transport processes
  - Properties of source and link landforms

- Calculation of a relative connectivity degree for each scenario and each sub-catchment based on the area of connected landforms to have a measure of functional connectivity

Geomorphological mapping

Digitization of landforms and processes

- Creation of a geomorphological map based on remote sensing data and field observations
  - non-overlapping, gapless polygons
  - 31 categories
- Digitization of potential occurrence of sediment transport processes based on visual evidences and topographic / geomorphological characteristics
  - Rock fall
  - Dry ravel
  - Sub-/Supraglacial transport
  - Surface erosion
  - Debris flow
  - Landslide
  - Fluvial transport
  - Stream entrainment / Fluvial erosion
  - In-channel deposition/ Fluvial deposition

Geomorphological landforms

Rock fall related landforms
- Bedrock
- Couloir
- Talus slope
- Talus fan
- Colluvial fan

Debris flow related landforms
- Debris flow channel
- Vegetated channel
- Debris fan
- Vegetated debris fan
- Forest-covered debris fan
- Debris flow run-out area

Landforms related to hillslope processes
- Debris-covered hillslope
- Vegetated hillslope
- Forest-covered hillslope
- Landslide
- Landslide deposition

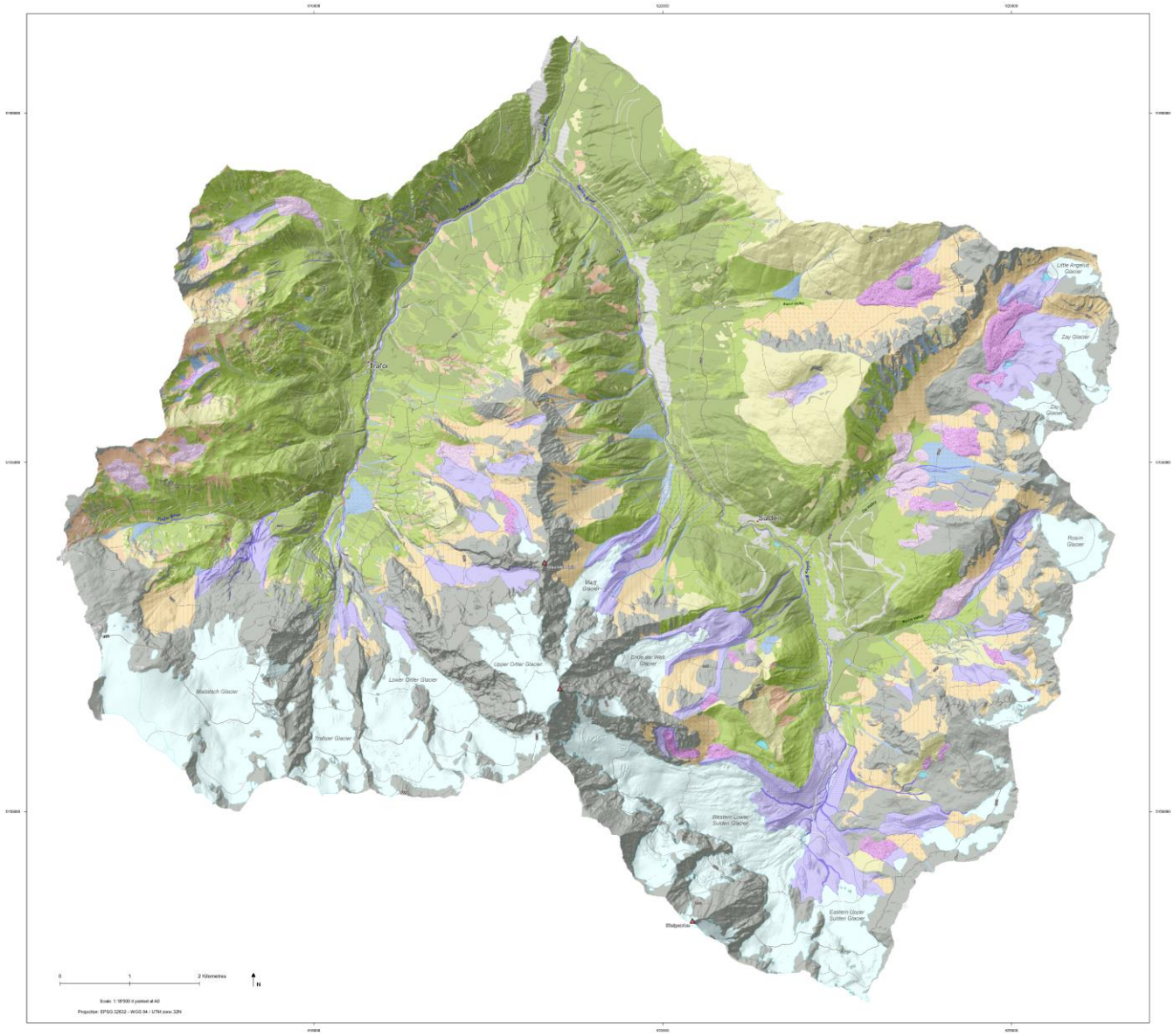
Landforms related to glacial and periglacial processes
- Glacier
- Active rock glacier
- Inactive rock glacier
- Fossil rock glacier
- Glazio-fluvial deposits
- Moraine
- Vegetated moraine
- Forest-covered moraine

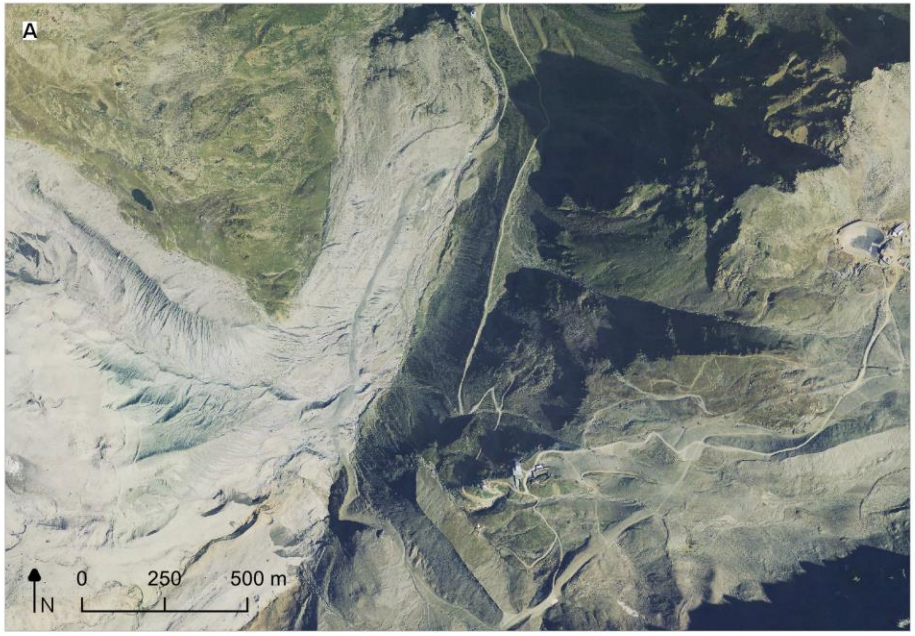
Landforms related to fluvial processes
- Fluvial channel
- In-channel deposits
- Bank erosion
- Vegetated flood plain
- Lake

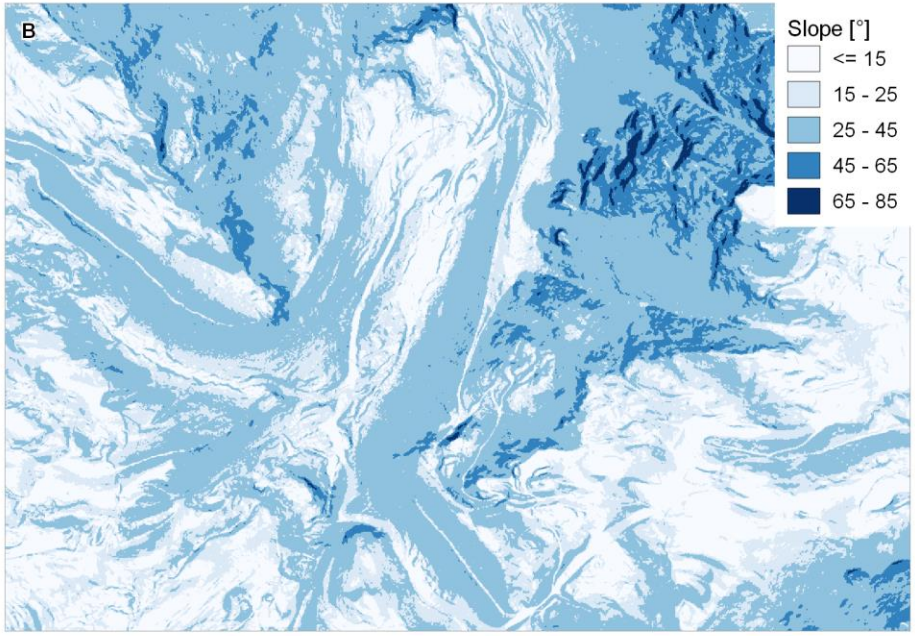
Anthropogenic areas
- Anthropogenic structures
- Agricultural fields

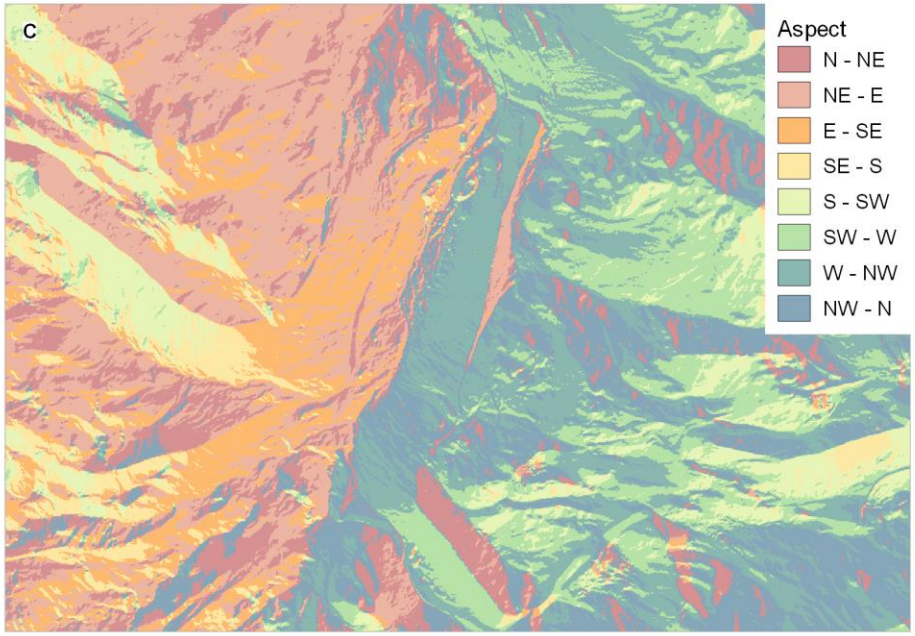
Point and line signatures
- Mountain peak
- Town

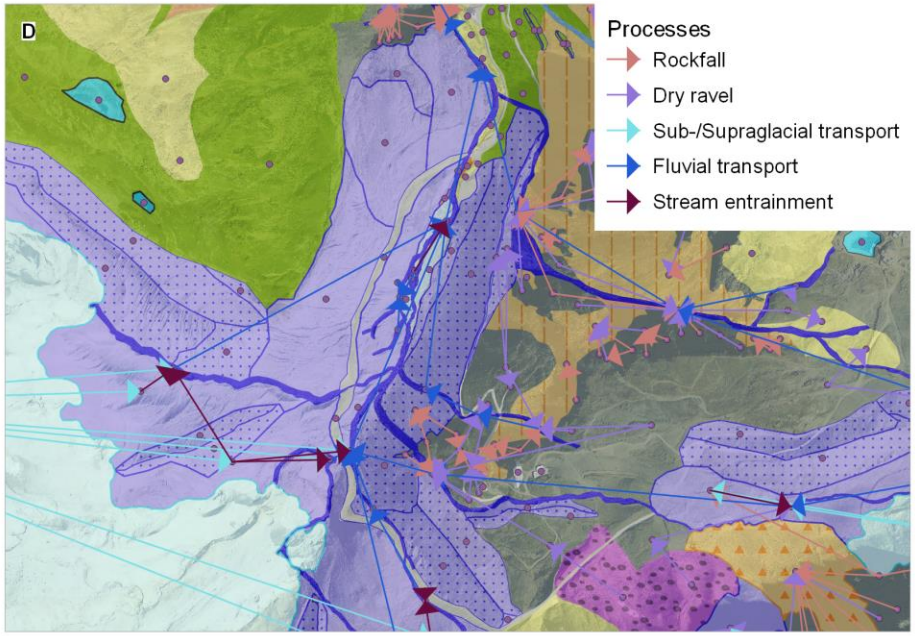
Contour lines
- 1000 m interval
- 250 m interval




A
N
0
250
500 m


B
Slope [°]
<= 15
15 - 25
25 - 45
45 - 65
65 - 85


C
Aspect
N - NE
NE - E
E - SE
SE - S
S - SW
SW - W
W - NW
NW - N


D
Processes
Rockfall
Dry ravel
Sub-/Supraglacial transport
Fluvial transport
Stream entrainment

Network analysis of sediment transport processes

Method

Creation of a graph object

Resulting graph is built up by “nodes” and corresponding “edges”

- Tool: R “igraph” package (Csardi and Nepusz 2006)

- Nodes = Central nodes of geomorphological units
- Edges = Sediment transport pathways

- Attributes of nodes and edges are kept
  - Geomorphological / lithological unit (nodes)
  - Area (nodes)
  - …
  - Sediment transport process (edges)

Design of 6 scenarios

Snow melt phase

Base

- Rockfall
- Dry ravel
- Fluvial transport
- Fluvial deposition

Heat wave

+ Fluvial erosion
+ Surface erosion
- Fluvial deposition

Rain storm

+ Surface erosion
+ Debris flow
+ Landslide
+ Fluvial erosion
- Fluvial deposition

Glacier melt phase

Base

- Rockfall
- Dry ravel
- Fluvial transport
- Sub-/Supraglacial transport
- Fluvial deposition

Heat wave

+ Fluvial erosion
- Fluvial deposition

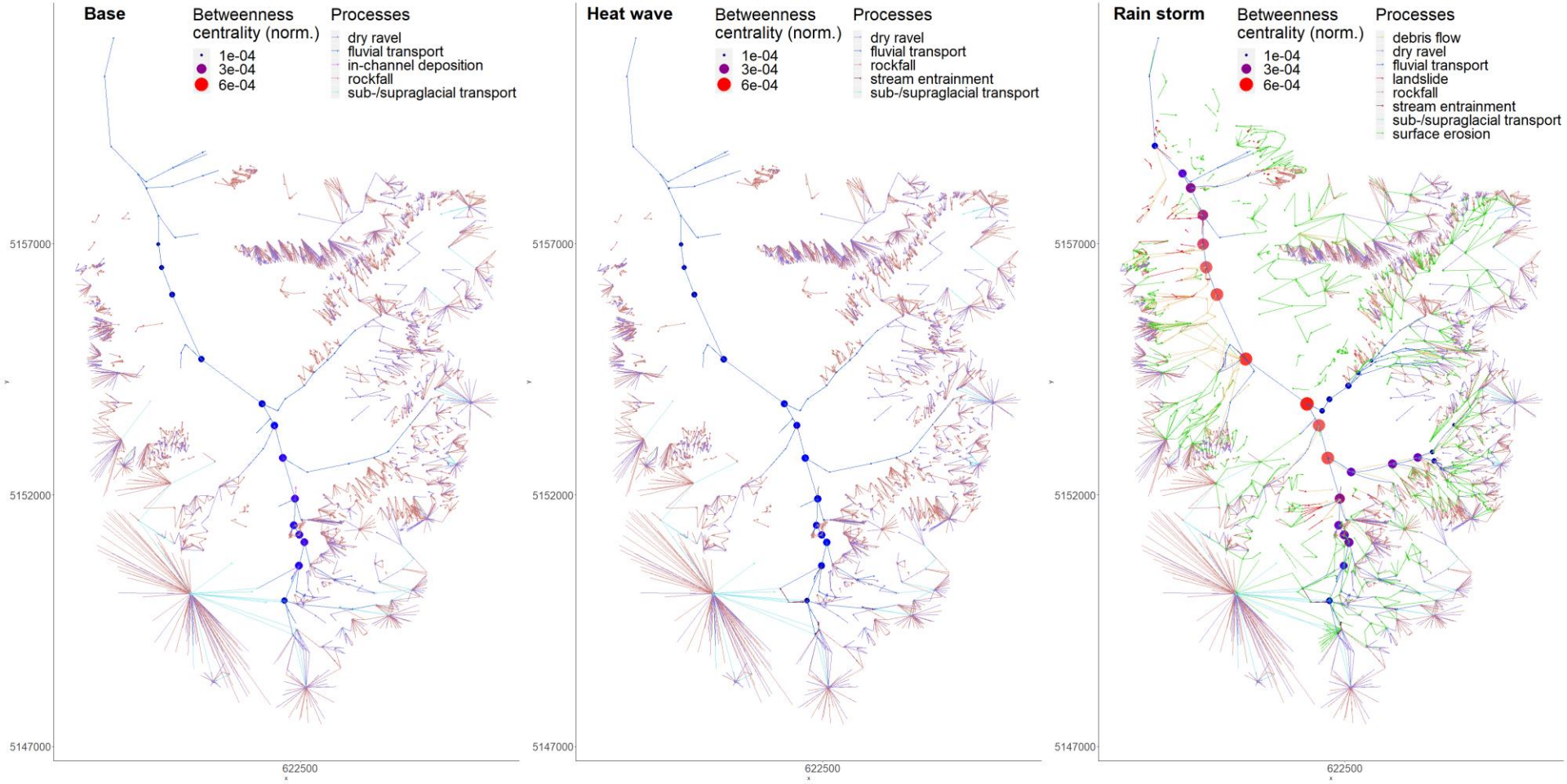
Rain storm

+ Surface erosion
+ Debris flow
+ Landslide
+ Fluvial erosion
- Fluvial deposition

Network analysis of sediment transport processes

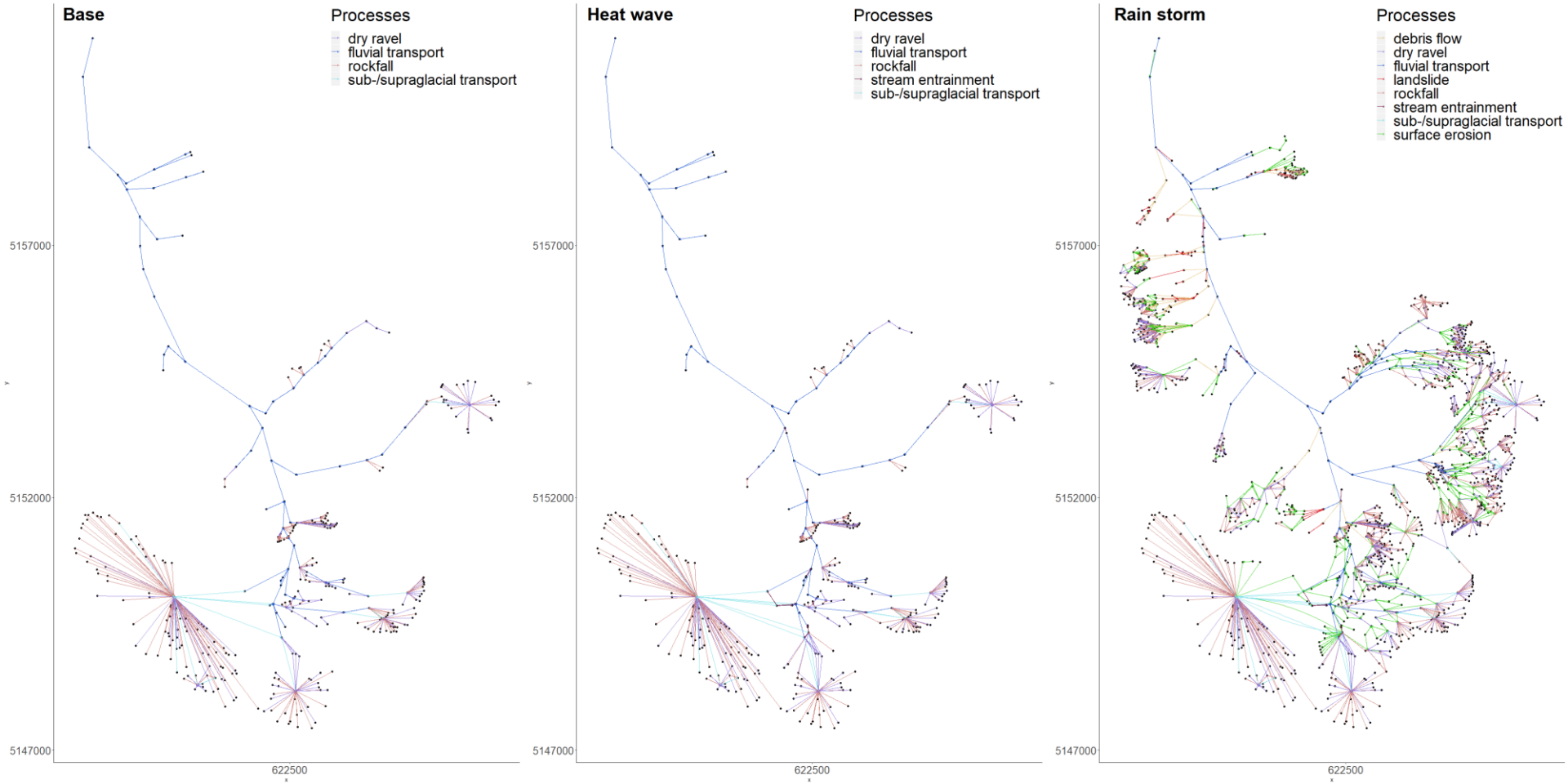
Exemplary preliminary results
for glacier melt scenarios
of the Sulden sub-catchment

Where are the hotspots ?



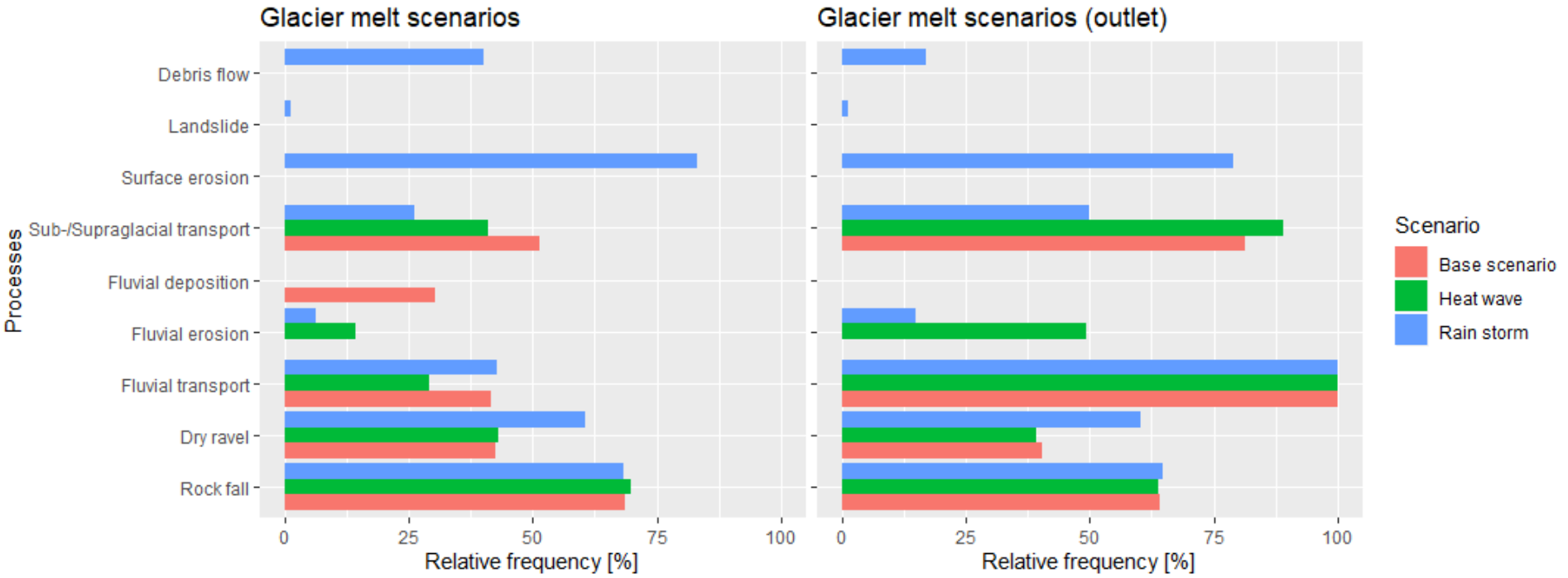
Glacier melt phase: Significant increase in connectivity in the rain storm scenario due to activation of debris flow, landslide and surface erosion edges; hotspots then especially at conjunctions with trib. valleys

Which area is connected to the outlet under which conditions?



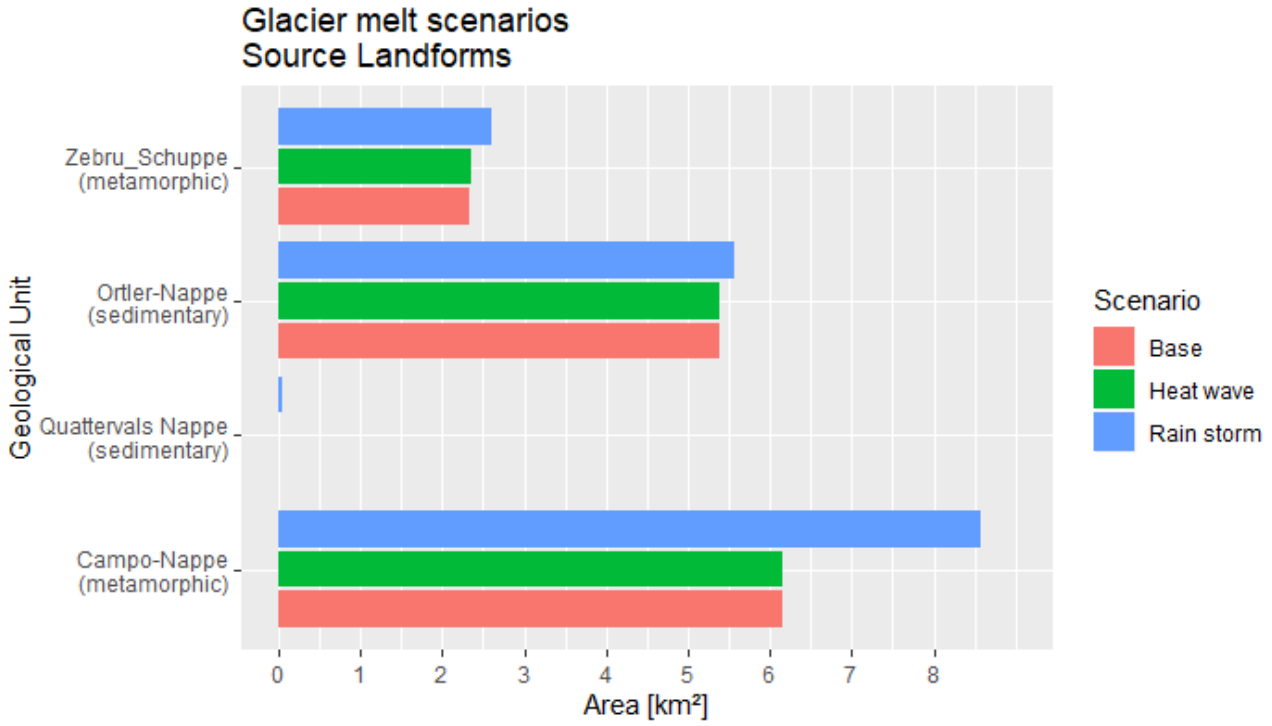
Glacier melt phase: North-western area and large parts of the two main tributary valleys in the eastern part of the sub-catchment only connected to outlet during rain storm scenario

How frequently appears which process type in the cascades?



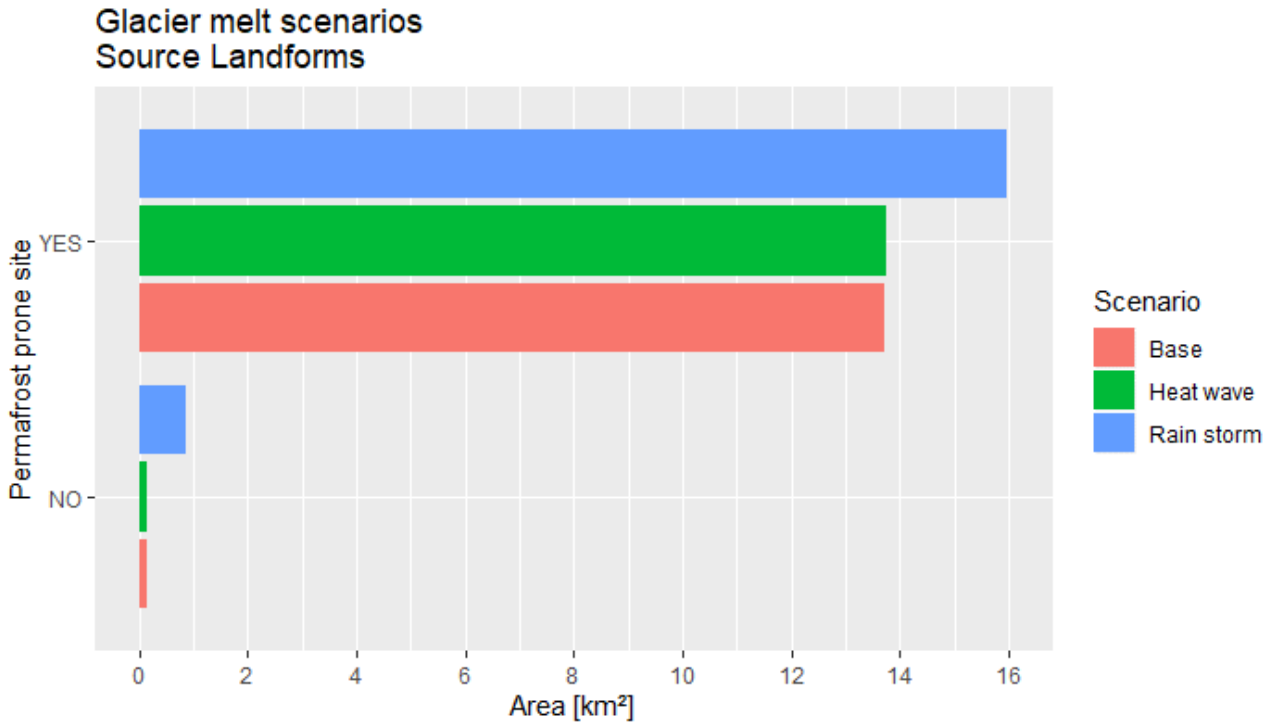
- Around 40% of all cascades in the rain storm scenario include the process debris flow, but especially in the tributary valleys they often terminate at debris fans on the wide valley bottom (not connected to the outlet)
- Surface erosion is an important process to interconnect landforms, however one has to keep in mind the magnitude of transport capacity of this process type
- Due to a high amount of steep and bare rock faces, rock fall and dry ravel are the most important initiation processes

What are the characteristics of the source landforms?



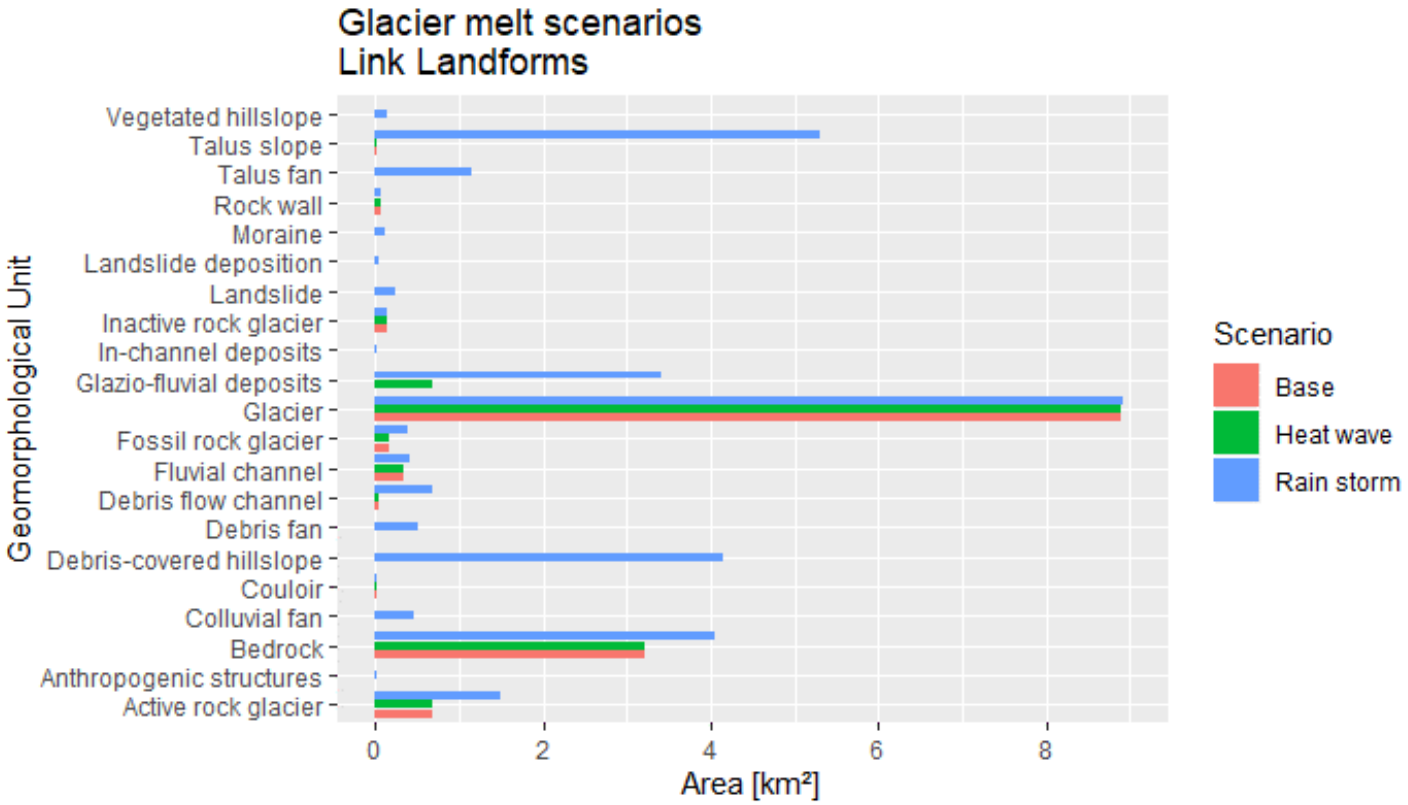
- Even if only 14.5 % of the Sulden sub-catchment area is characterized by sedimentary rocks, mostly build up by dolomite and limestone, they are highly represented as lithological unit of the source landforms
- Large and steep sedimentary rock walls situated in the south-west of the sub-catchment are feeding the debris-covered “Western Lower Sulden Glacier”, the “Ende der Welt Glacier” and the “Marlt Glacier”

What are the characteristics of the source landforms?



- Based on the results of the statistical permafrost distribution model developed in the "PermaNET" project (Boeckli et al., 2011), a high amount of the source landforms are potentially subject to permafrost
- However, the summed up values given here are most probably overestimating the actual spatial distribution of permafrost , as all meteorological conditions for permafrost given by Boeckli et al. (2011) were included.

What are the characteristics of the link landforms?



- In graph theory terms, a link is a node with in-coming and out-going edges. Geomorphologically speaking these link landforms might also be sources or temporary storages
- In the Sulden sub-catchment the large debris-covered glaciers represent important “link landforms” in all scenarios
- Other link landforms (e.g. talus slopes or glazio-fluvial deposits) are especially relevant during rain storm conditions

To which areal percentage is the catchment "connected" for the different scenarios?

Scenario	Connected Landforms [km²]	Landforms connected to outlet [km²]	Connected area [%]	Connected area to the outlet [%]
Base	44,30	12,23	57,14	15,77
Heat wave	44,33	13,07	57,17	16,86
Rain storm	61,95	27,12	79,91	34,97

- Based on the results on the graph analysis, in 57 % of the sub-catchment area geomorphological landforms may be part of sediment cascades during "base" and "heatwave" conditions
- This value increases to about 80 % in the rain storm scenario due to the potential occurrence of surface erosion, debris flows and landslides
- Landforms being part of sediment cascades that are reaching the outlet sum up to around 16-17 % of the sub-catchment during "base" and "heat wave" conditions, whereas during "rain storm" conditions this value doubles to around 35 %

Network analysis of sediment transport processes

Conclusion

Summary of the presented results

- Abundant steep rock cliffs are source areas for rock fall → important initiation process
- Due to a generally high sediment availability on the slopes, surface erosion leads to enhanced lateral connectivity in the rain storm scenario during glacier melt
- Lithological units of sedimentary origin show a high density of source landforms
- A high proportion of the source landforms might be subject to permafrost
- The glaciers of the sub-catchment are important “link” landforms
- Rain storms during glacier melt phase might double the area connected to the outlet

Conclusion of the presented results

- Due to an expected higher frequency of rain storm events in the next decades, more sediment might be transported within the catchment and exported out of the catchment
- Permafrost degradation within the source landforms might induce slope instabilities and thus increase sediment availability
- Glaciers of the Sulden sub-catchment are temporarily storing high amounts of sediment, which gradually will be transported downslope in case of glacier retreat

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R Core Team (2018): *R: A language and environment for statistical computing*, R Foundation for Statistical Computing, Vienna