# Automatic optimization and multi-scale delineation of nested slope units with r.slopeunits v2.0

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# A story about complaining

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# DIFFERENT MAPPING UNITS

Possible choices for mapping units in landslide studies:

- Grid Cells: typically aligned with a digital elevation model (DEM) grid. Have little relation with the underlying topographic properties but are by far the standard choice.

- Terrain units (TU): subdivisions of the terrain that maximize the within-unit (internal) homogeneity and the between-unit (external) inhomogeneity across distinct physical or geographical boundaries.

- Slope unit (SU): morphological TU bounded by drainage and divide lines. Slope Units are a wiser mapping unit choice for a variety of applications, for they bear a strong relationship with topography.

**Carrara et al. (1991); Guzzetti et al. (1999)**

## Slope Units: Motivation

- SU are real-world features, easily recognizable in the field
- Related to hydrological and geo-morphological processes that shape natural landscapes
- Minimize mapping errors: use data sources of different type and resolution

- Well suited for hydro- and geo-morphological studies
- Typical example: landslide susceptibility zonation
- Also useful to reconcile models with different models and zonation

# SLOPE UNITS: MOTIVATION

**First round of complaining!**

"...I do not know how to draw slope units!"

"...it is too tedious to do it manually..."

"...my slope units are different from those delineated by my colleague!"

## THE `r.slopeunits` GRASS GIS MODULE

**(Main) Inputs:**

- **DEM**
- Initial flow accumulation **THRESHOLD**
- Aspect homogeneity (circular variance, ***C***)
- Tentative SU minimum area (***A***)

**Output:**

**SLOPE UNITS POLYGONAL MAP**

**Alvioli et al., GMD (2016)**

# ADAPTIVE SLOPE UNITS DELINEATION

The software **`r.slopeunits`** implements an **iterative** algorithm:

- An **initial subdivision** is calculated by `r.watershed` with a trial (large) flow accumulation threshold
- At **each iteration**, half-basins are checked against input parameters constraints (*c*, homogeneity; *a*, size)
- Only those *half-basins **not meeting** the requirements*, are **split further** at next iteration by `r.watershed` with a smaller accumulation threshold

→ ***ADAPTIVE SU DELINEATION***

Alvioli et al., GMD (2016)

# PARAMETRIC SLOPE UNITS DELINEATION

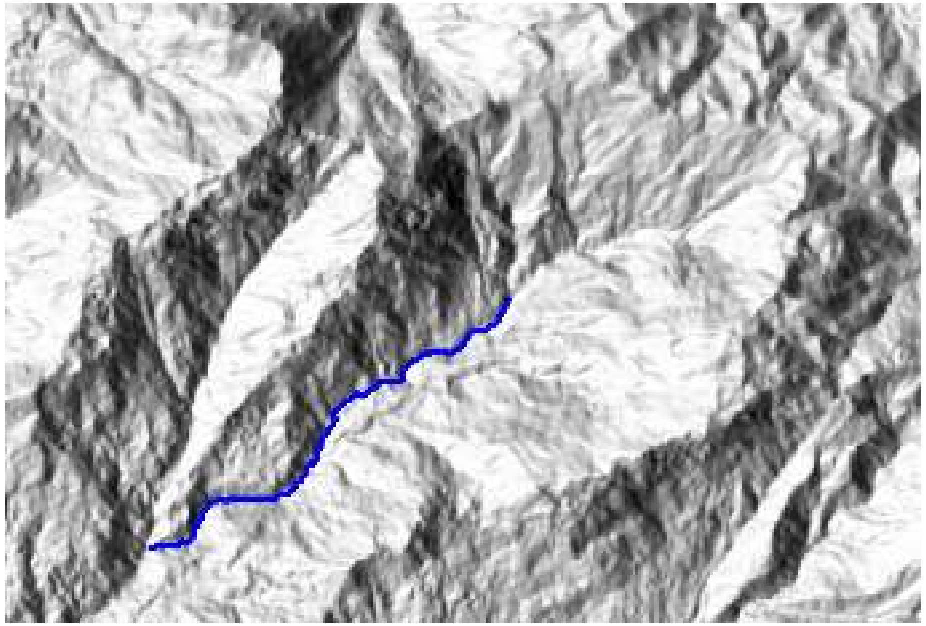
- The **r.watershed** model defines half-basins of decreasing size at each iteration

For a given value of

***flow accumulation***

***threshold t*** :

STREAM



# PARAMETRIC SLOPE UNITS DELINEATION

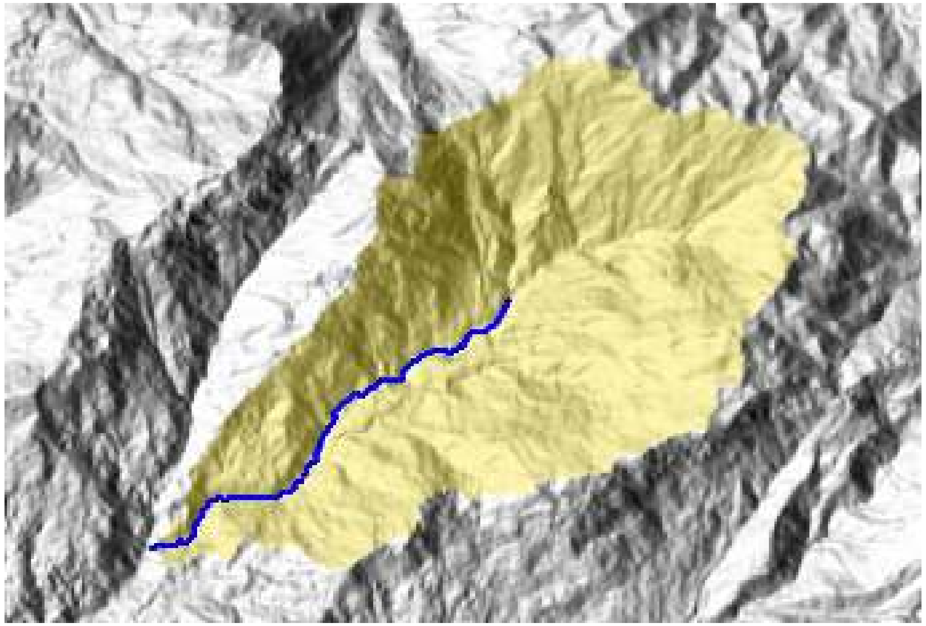
- The **r.watershed** model defines half-basins of decreasing size at each iteration

For a given value of

***flow accumulation***

***threshold t*** :

Drainage BASIN



# PARAMETRIC SLOPE UNITS DELINEATION

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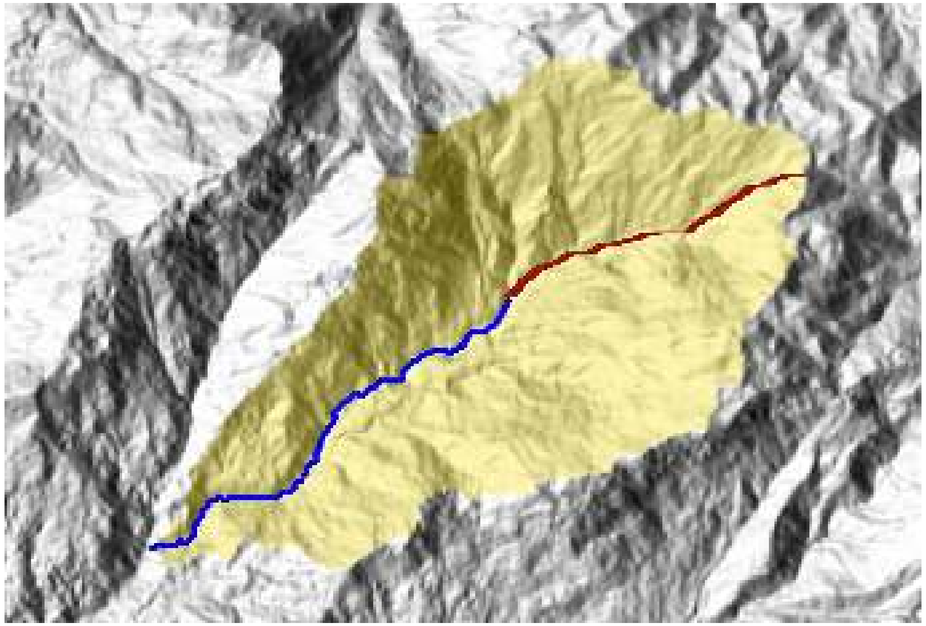
For a given value of

***flow accumulation***

***threshold t*** :

EXTENDED STREAM



# PARAMETRIC SLOPE UNITS DELINEATION

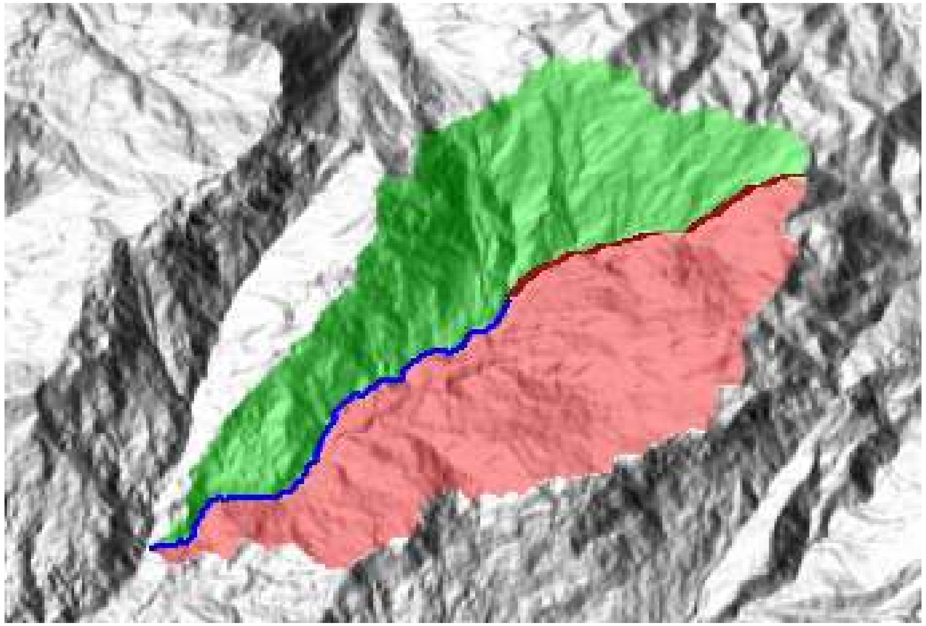
- The **r.watershed** model defines half-basins of decreasing size at each iteration

For a given value of

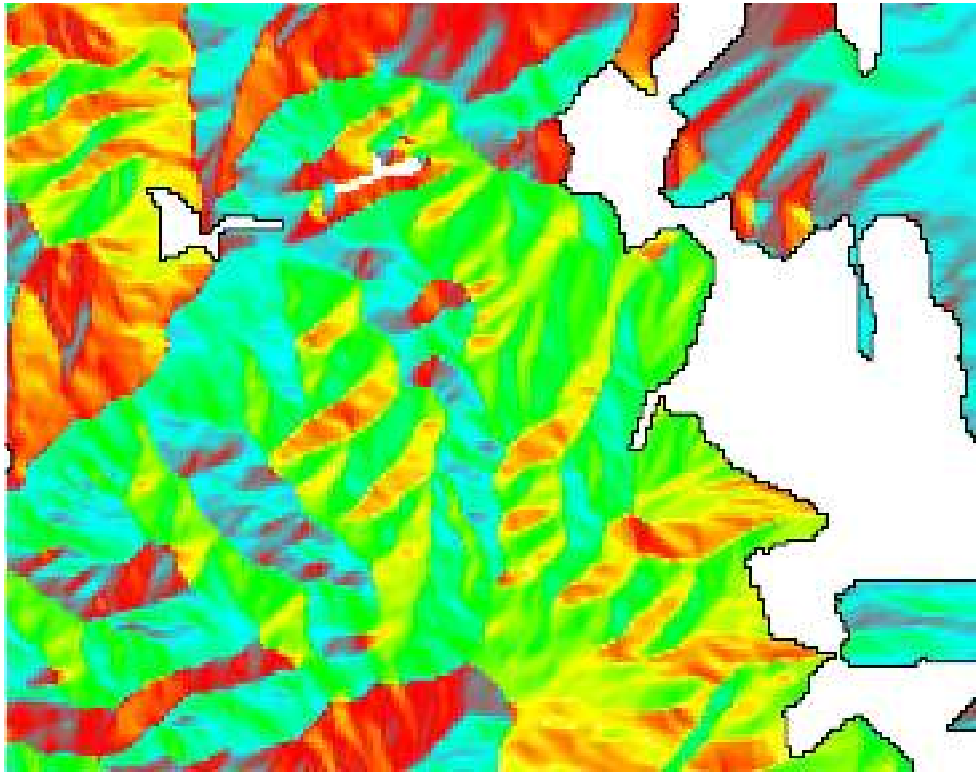
***flow accumulation***

***threshold t*** :

LEFT - RIGHT
HALF BASINS



# Parametric Slope Units Delineation

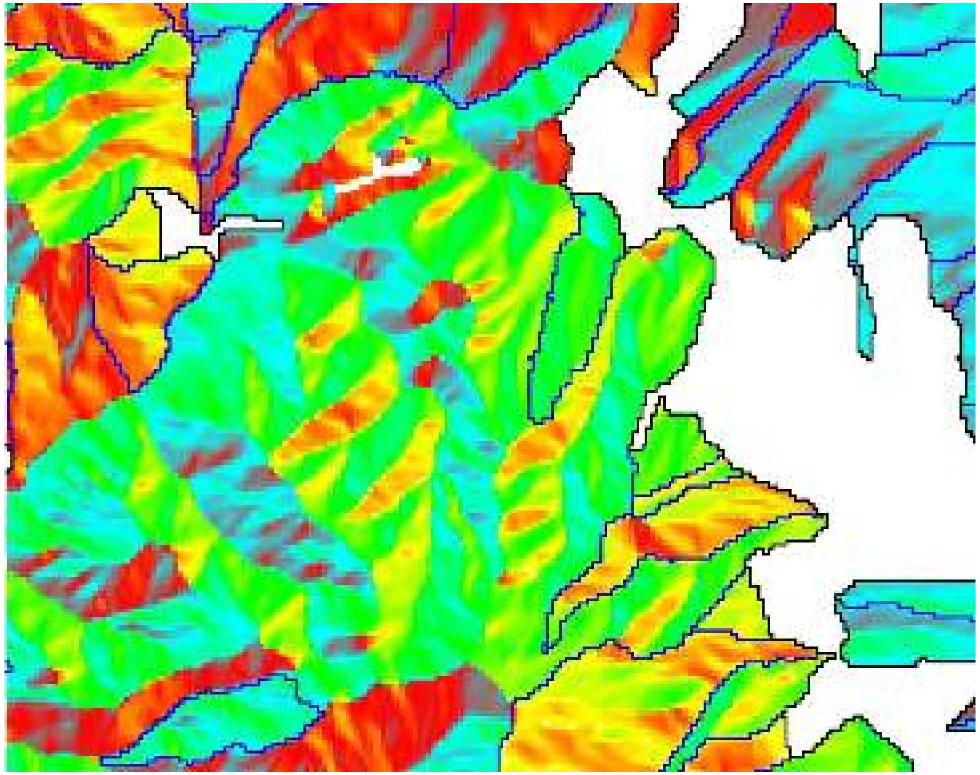


## Example of r.slopeunits run

- Plains are in white
- Different aspect directions are in red, green, yellow, cyan

**Alvioli et al., GMD (2016)**

# Parametric Slope Units Delineation



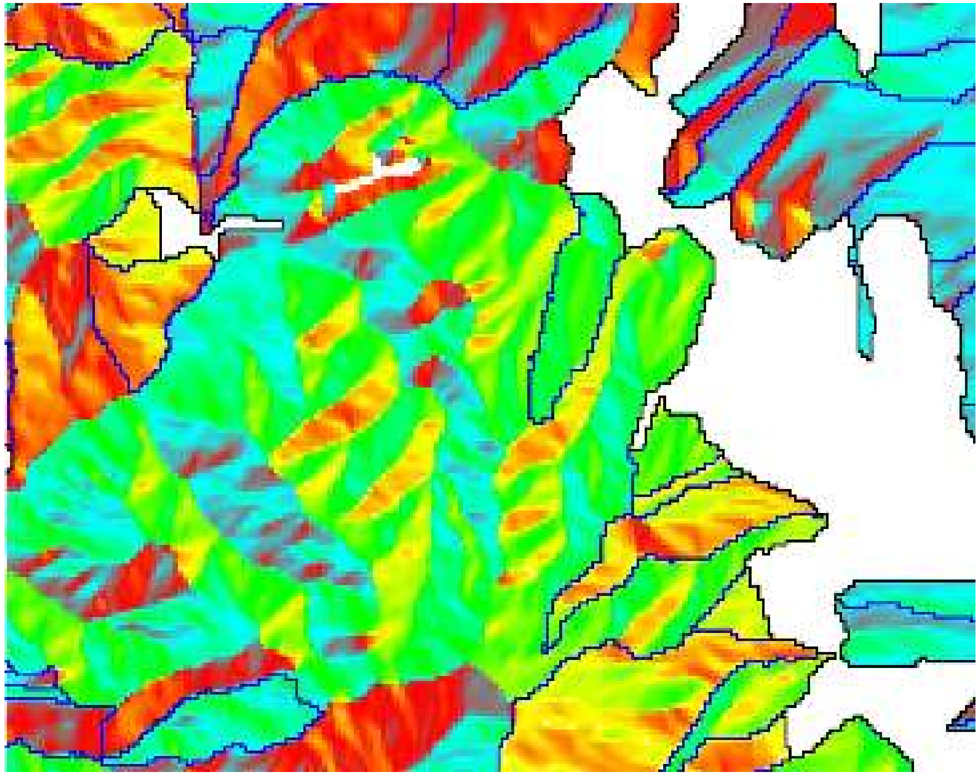
Example of r.slopeunits run

Iteration #1:

$HB_{child}$ flagged as slope units are in blue

**Alvioli et al., GMD (2016)**

# Parametric Slope Units Delineation



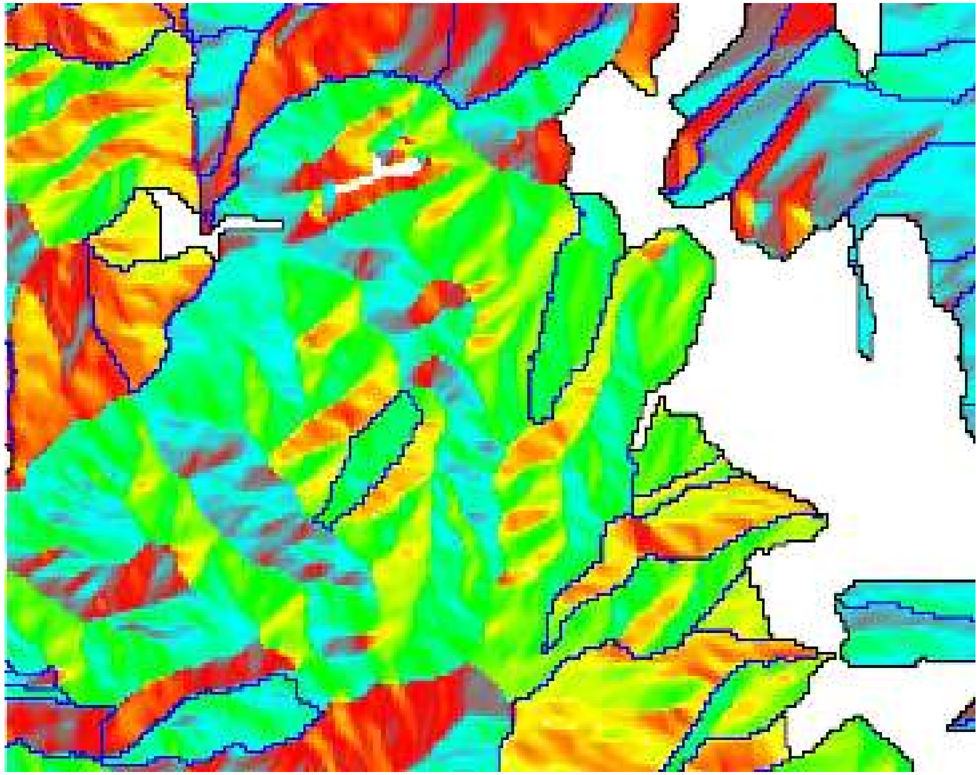
Example of r.slopeunits run

Iteration #5:

A few polygons (in blue) were added to the candidate slope unit set – not all of the values of *t* produces new candidates

**Alvioli et al., GMD (2016)**

# PARAMETRIC SLOPE UNITS DELINEATION



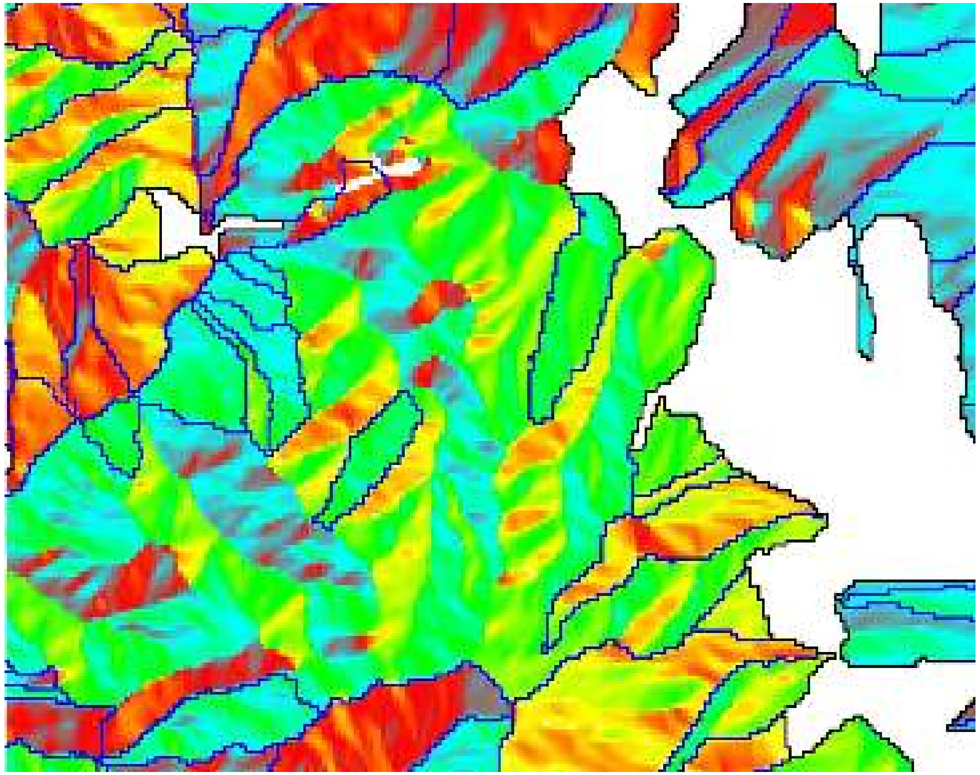
Example of r.slopeunits run

Iteration #10:

A few polygons (in blue) were added to the candidate slope unit set – not all of the values of *t* produces new candidates

**Alvioli et al., GMD (2016)**

# PARAMETRIC SLOPE UNITS DELINEATION



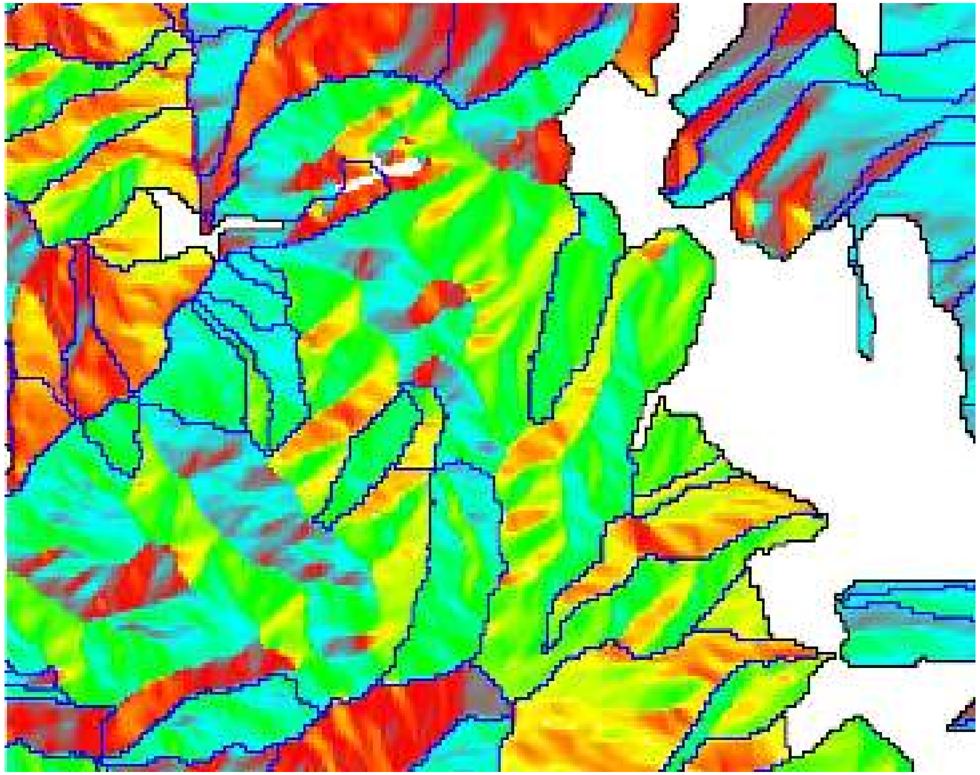
Example of r.slopeunits run

Iteration #15:

A few polygons (in blue) were added to the candidate slope unit set – not all of the values of *t* produces new candidates

**Alvioli et al., GMD (2016)**

# PARAMETRIC SLOPE UNITS DELINEATION



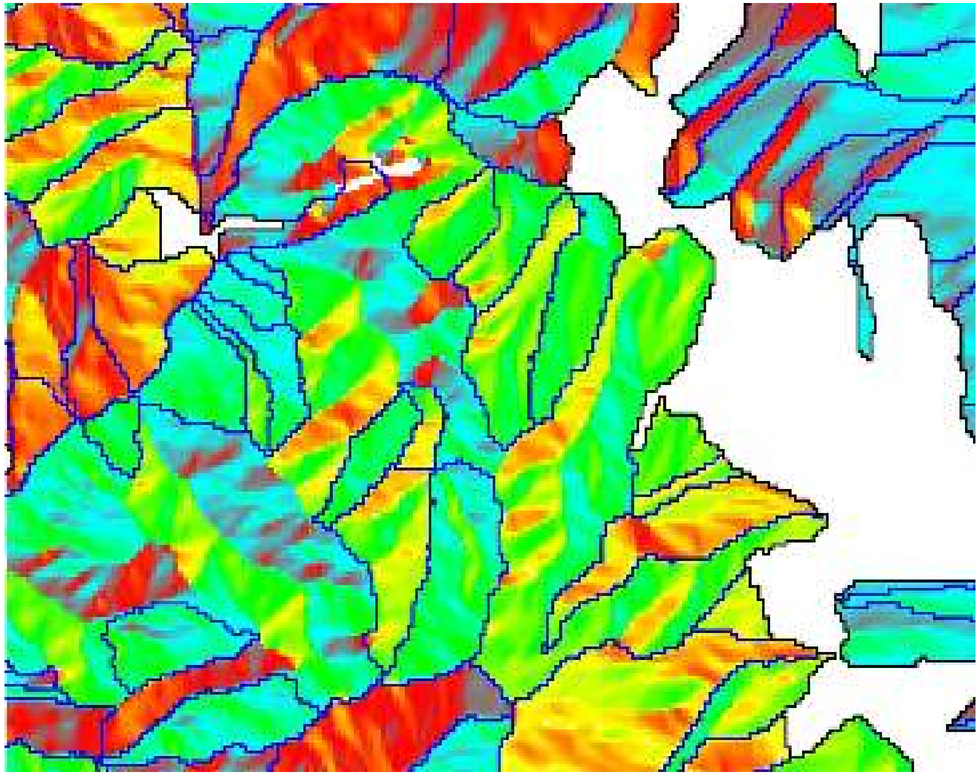
Example of r.slopeunits run

Iteration #20:

A few polygons (in blue) were added to the candidate slope unit set – not all of the values of *t* produces new candidates

**Alvioli et al., GMD (2016)**

# Parametric Slope Units Delineation



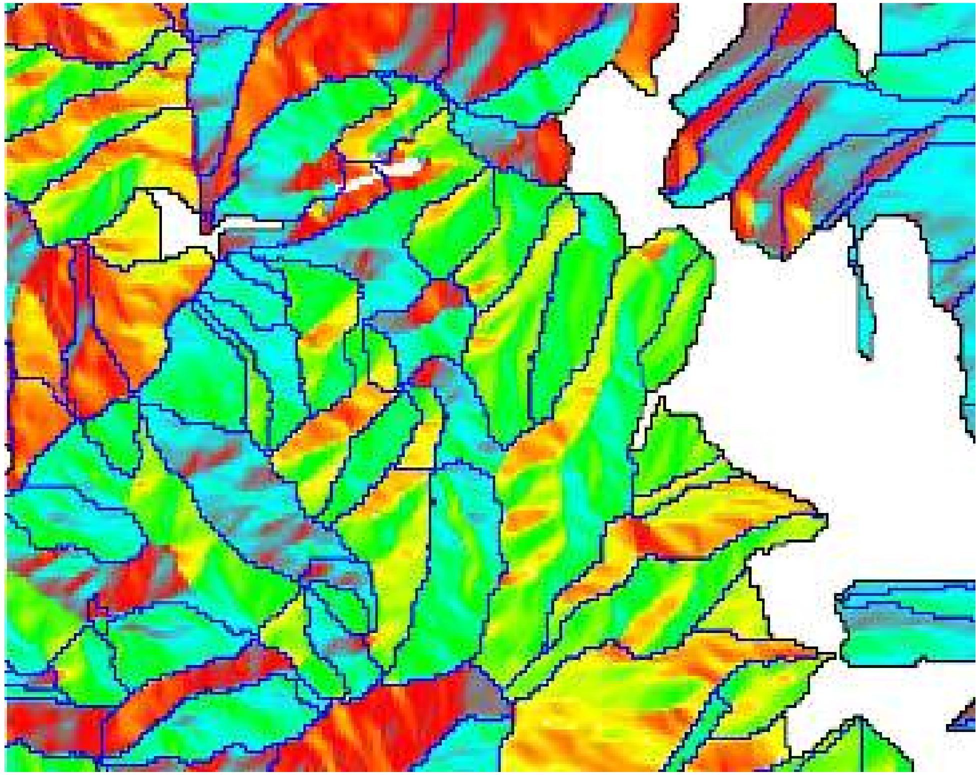
Example of r.slopeunits run

Iteration #25:

A few polygons (in blue) were added to the candidate slope unit set – not all of the values of *t* produces new candidates

**Alvioli et al., GMD (2016)**

# PARAMETRIC SLOPE UNITS DELINEATION



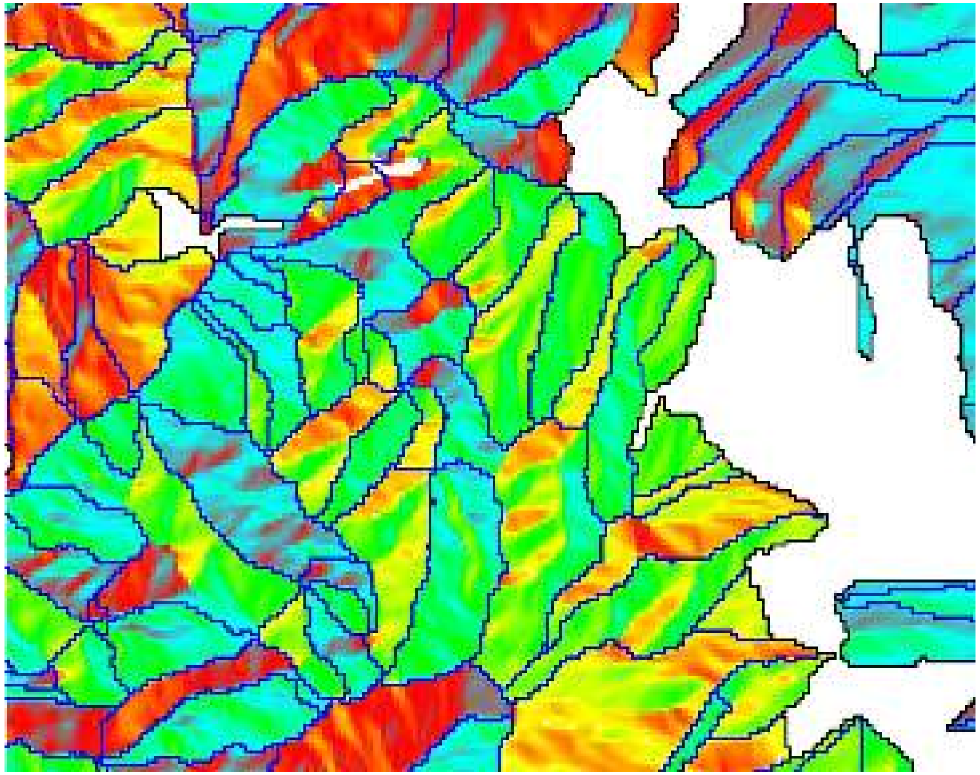
Example of r.slopeunits run

Iteration #30:

A few polygons (in blue) were added to the candidate slope unit set – not all of the values of *t* produces new candidates

**Alvioli et al., GMD (2016)**

# <u>Parametric Slope Units Delineation</u>



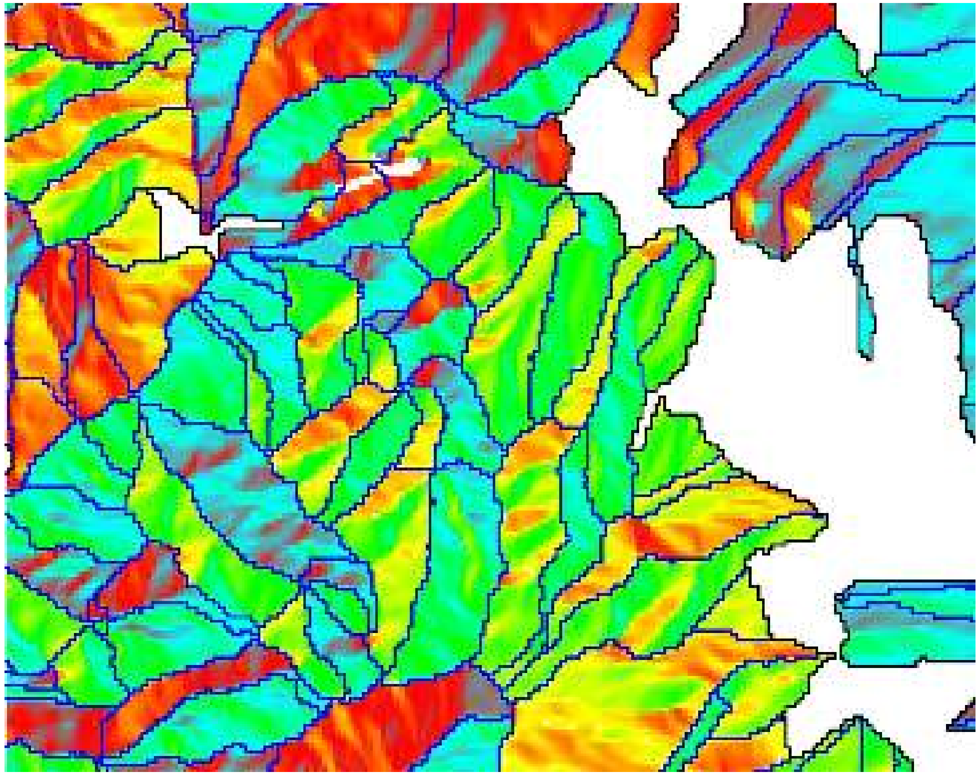
<u>Example of r.slopeunits run</u>

Iteration #35:

A few polygons (in blue) were added to the candidate slope unit set – not all of the values of *t* produces new candidates

**Alvioli et al., GMD (2016)**

# Parametric Slope Units Delineation



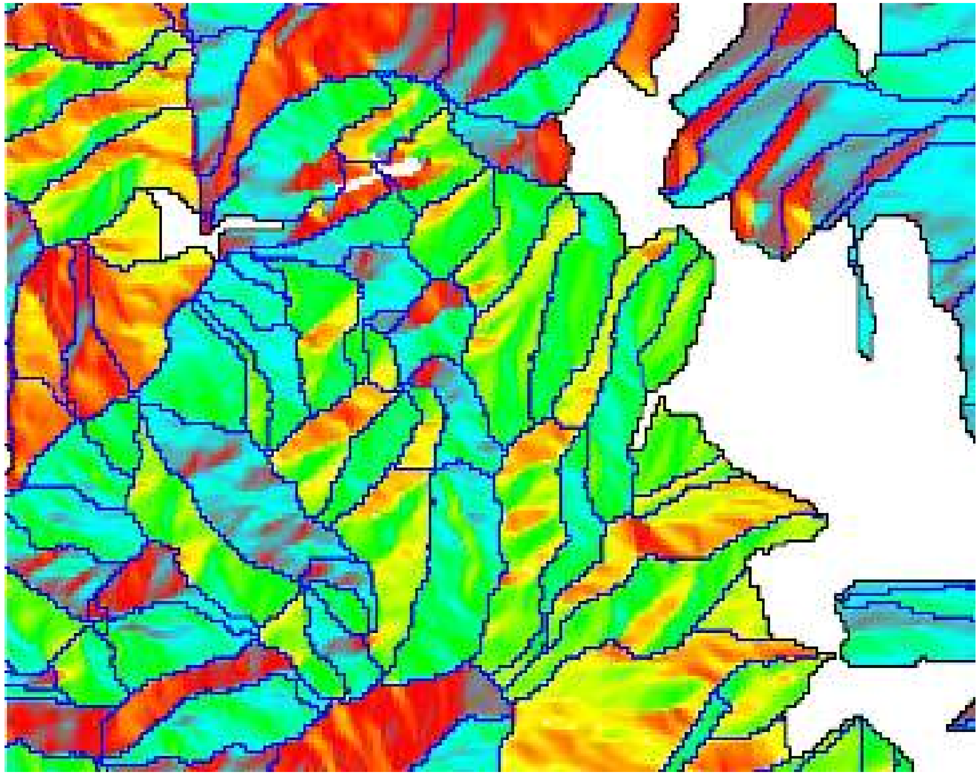
Example of r.slopeunits run

Iteration #40:

A few polygons (in blue) were added to the candidate slope unit set – not all of the values of *t* produces new candidates

**Alvioli et al., GMD (2016)**

# PARAMETRIC SLOPE UNITS DELINEATION



Example of r.slopeunits run

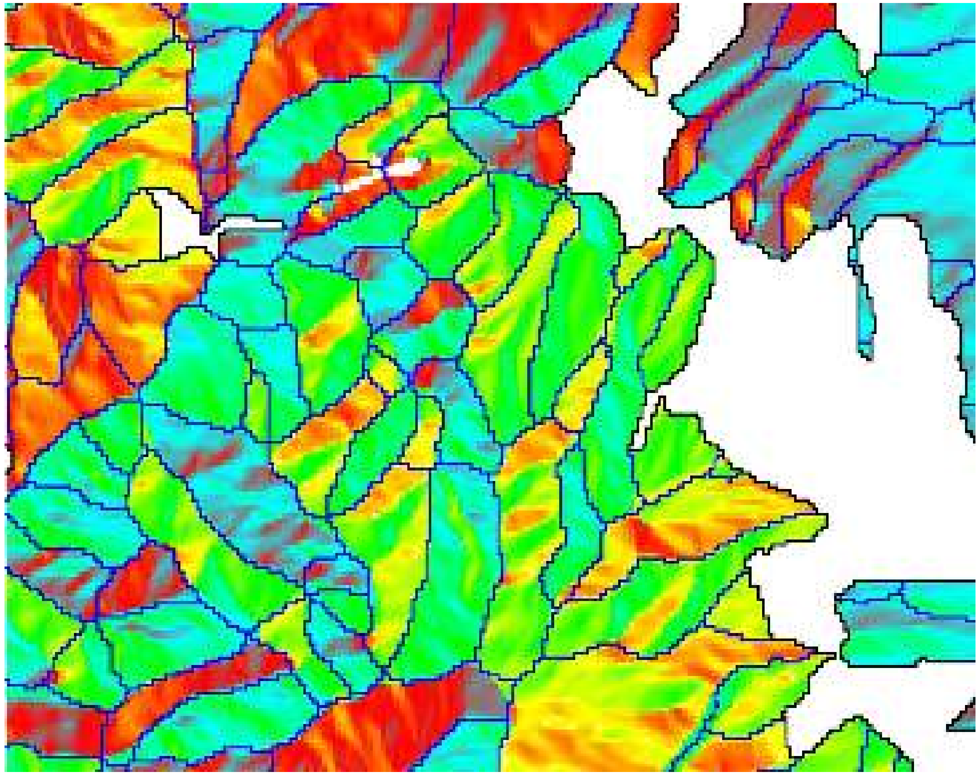
Iteration #45:

A few polygons (in blue) were added to the candidate slope unit set – not all of the values of *t* produces new candidates

No new half-basins could be added after this step

**Alvioli et al., GMD (2016)**

# Parametric Slope Units Delineation

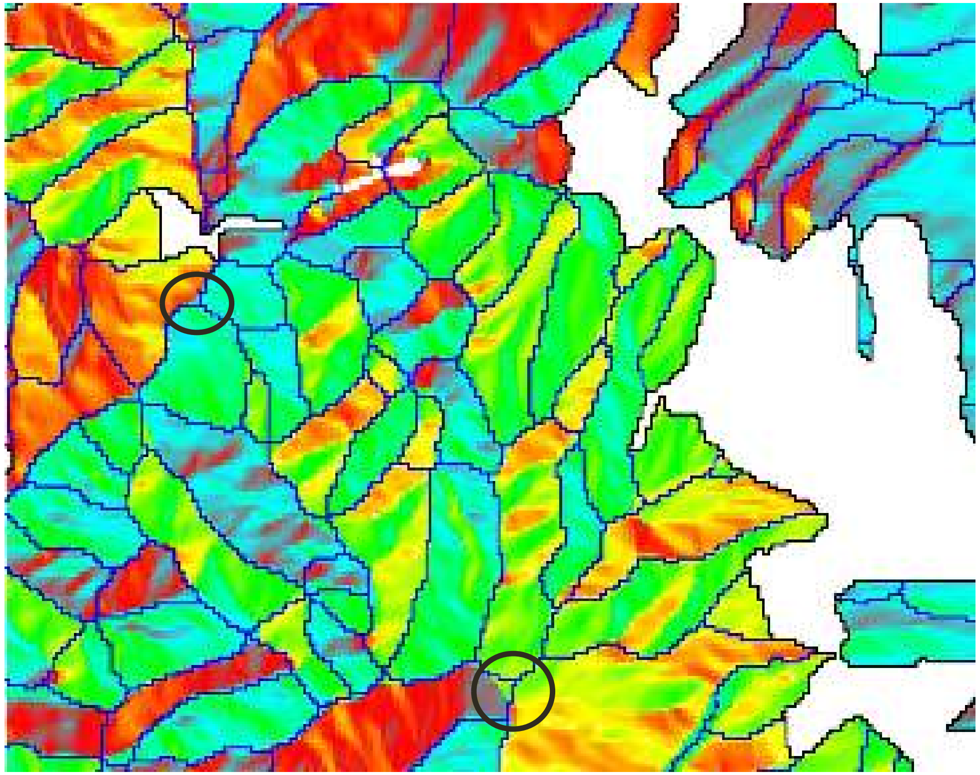


Example of r.slopeunits run

**Cleaning** of the final SU map using the procedure n. 2: removal of small (smaller than *cleansize*), elongated and narrow polygons

**Alvioli et al., GMD (2016)**

# Parametric Slope Units Delineation



Example of r.slopeunits run

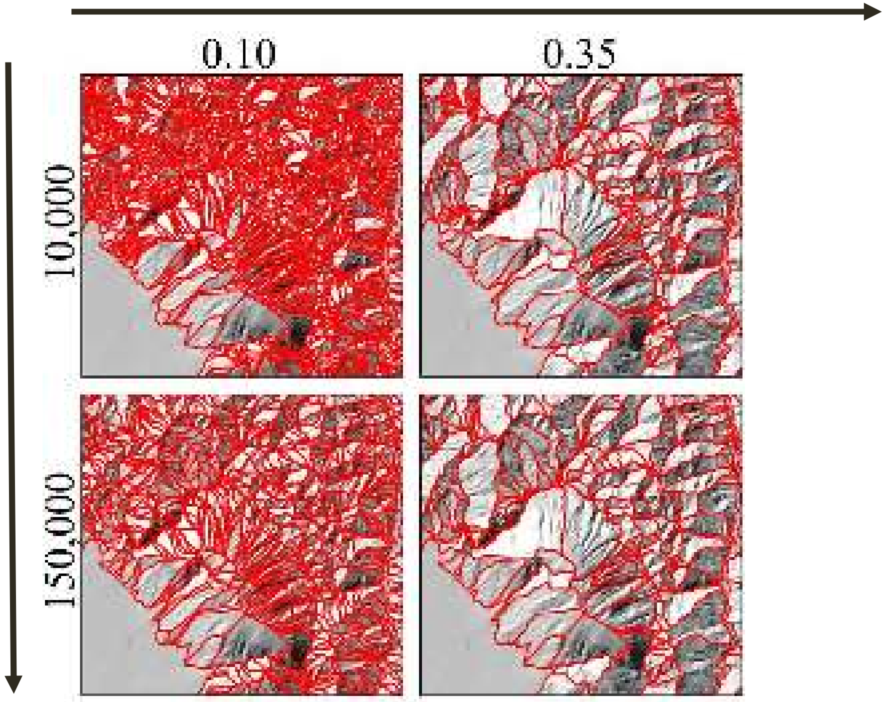
**Cleaning** of the final SU map using the procedure n. 2: removal of small (smaller than *cleansize*), elongated and narrow polygons

Note that small errors may be introduced by this procedure as well – this may be viewed as a trial-and-error step

# Parametric Slope Units Delineation

Each combination of the *a*, *c* parameters determines a well-defined SU subdivision

minimum aspect circular variance
**c**
(cvmin in the code)



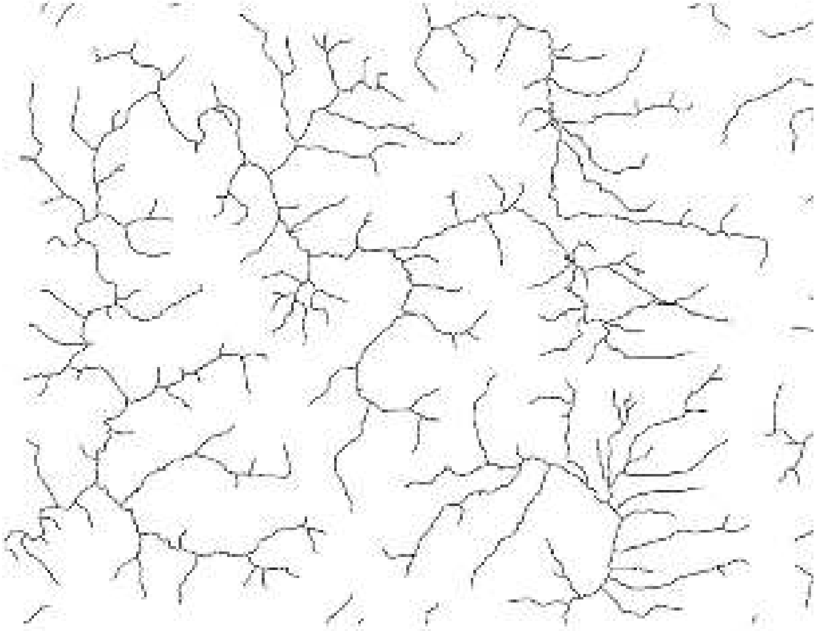

minimum area [m²]
**a**
(areamin in the code)

**Alvioli et al., GMD (2016)**

# <u>Challenges in Slope Units Delineation</u>

Need to stop the process at the *right scale*

Drainage Network ⟷ Half-Basins



**WATERSHED THRESHOLD: 5000 CELLS**

WATERSHED THRESHOLD: 5000 CELLS

# Second round of complaining!

"...I don't know how to select input parameters!"

"...I do not want to run the code several times with different parameters!"

WATERSHED THRESHOLD: 5000 CELLS

WATERSHED THRESHOLD: 5000 CELLS

# Slope Units Optimization: Aspect Segmentation Metric

Aspect segmentation metric *F*(*a*, *c*): measures internal homogeneity/external inhomogeneity

$$V = \boldsymbol{V}(\boldsymbol{a},\boldsymbol{c}) = \frac{\sum_n^N c_n s_n}{\sum_n^N c_n}$$

$$I = \boldsymbol{I}(\boldsymbol{a},\boldsymbol{c}) = \frac{N \sum_{n,l}^N \omega_{n,l}(\alpha_n - \bar{\alpha})(\alpha_l - \bar{\alpha})}{\sum_n^N (\alpha_n - \bar{\alpha})^2 \; \sum_{n,l}^N \omega_{n,l}}$$

$$F = \boldsymbol{F}(\boldsymbol{a},\boldsymbol{c}) = \frac{V_{max} - V(a,c)}{V_{max} - V_{min}} + \frac{I_{max} - I(a,c)}{I_{max} - I_{min}}$$

- ***V*(*a*, *c*)** represents internal aspect variance and assigns more importance to large SUs to avoid numerical instabilities
- ***I*(*a*, *c*)** is an autocorrelation index, measures external aspect variance and has minima for SU sets exhibiting well-defined boundaries between adjacent SUs

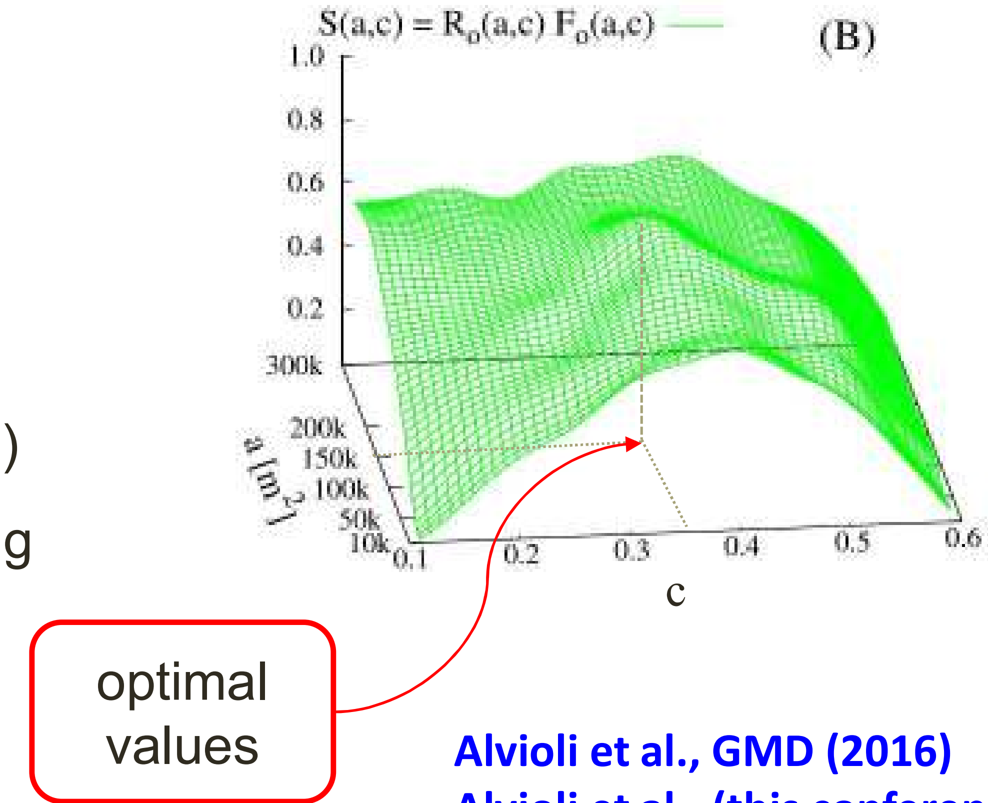
**Espindola et al., Int. J. Rem. Sens. (2016)**

# Slope Units Delineation & Optimization

No unique SU subdivision exists!

We follow a workflow:

- Parametric delineation
- Calculation of the metric(s)
- Optimization (**r.slopeunits v2.0**)
- Landslide susceptibility modeling with statistical and/or machine learning model




**Alvioli et al., GMD (2016)**
**Alvioli et al., (this conference)**

# EXAMPLE: SLOPE UNITS OF ITALY

- Number of polygons: 331,926
- Average area: 0.45 km$^2$
- Total coverage: 224,000 km$^2$

  (excludes near-flat areas)

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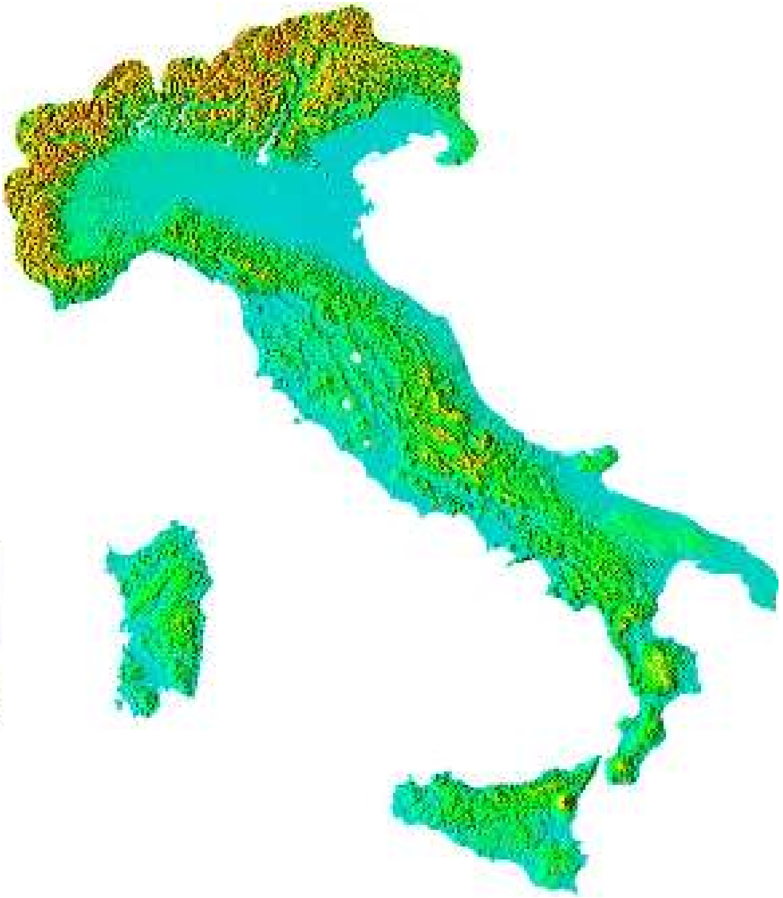
journal homepage: www.elsevier.com/locate/geomorph

Parameter-free delineation of slope units and terrain subdivision of Italy

Massimiliano Alvioli ("Massi") *, Fausto Guzzetti, Ivan Marchesini



Alvioli et al., Geomorphology (2020)

# GRASS GIS R.SLOPEUNITS TOOLSET

***r.slopeunits*** - Toolset for calculating metrics for slope units

## DESCRIPTION

• *r.slopeunits* is a GRASS GIS addon toolset that creates, cleans and calculate metrics for slope units. Additionally, optimal input values can be determined. The *r.slopeunits* toolset consists of currently four modules:

• r.slopeunits.create: Creates a raster layer of slope units. Optionally, a vector map.

• r.slopeunits.clean: Cleans slope units layer, e.g. results of r.slopeunits.create.

• r.slopeunits.metrics: Creates metrics for slope units.

• r.slopeunits.optimize: Determines optimal input values for slope units.

Main authors: Ivan Marchesini, Massimiliano Alvioli, CNR-IRPI

M. Metz, C. Tawalika (translation to Python, refactoring), mundialis GmbH

# Third round of complaining!

"…Your optimized slope units are too SMALL!"

"…Your optimized slope units are too LARGE!"

"…I want several layers of slope units with different size!!"

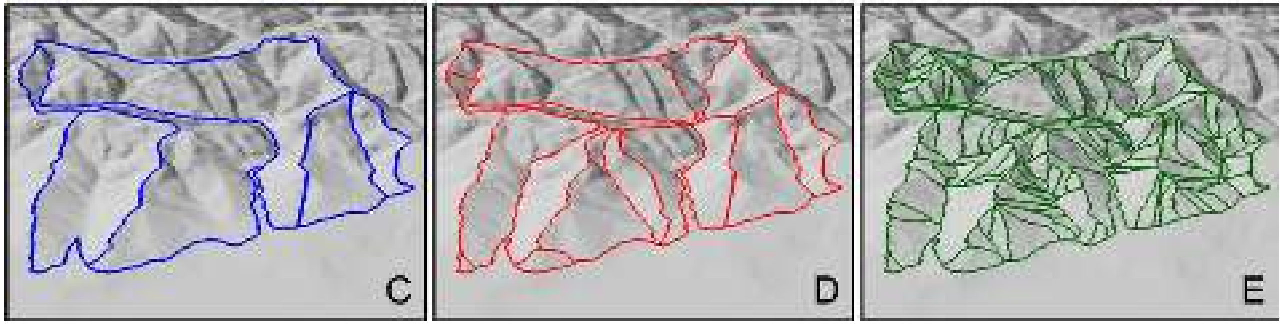
M. Metz, C. Tawalika (translation to Python, refactoring), mundialis GmbH

# PARAMETRIC DELINEATION -> NESTED SLOPE UNITS

- Each combination of the parameters determines a well-defined SU subdivision

Alvioli et al., GMD (2016)

- The larger ***a*** input parameter, the bigger the slope units
- The larger ***c*** input parameter, the bigger the slope units
- Increasing only one of the two parameters, we get (almost) **nested slope units**



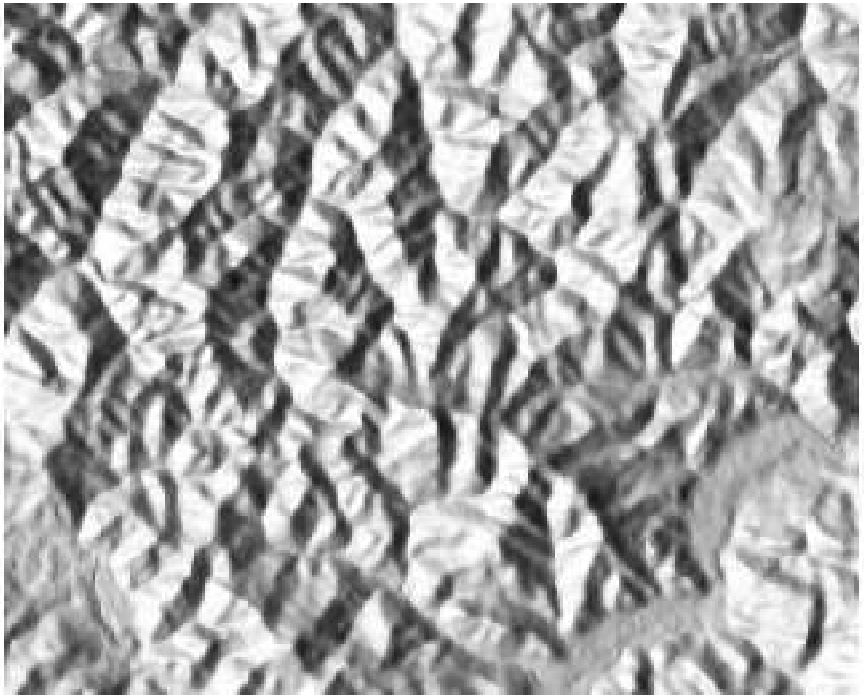

- Adjustment of the edges is necessary → **r.slopeunits v2.0**

Alvioli et al., (this conference)

# NESTED SLOPE UNITS OF ITALY

- We delineated a set of five multi-layer slope unit maps
- Layer 0 is the *existing optimized* SU map
- Layer 0 nested into layer 1
- Layer 1 nested into layer 2
- Layer 2 nested into layer 3
- Layer 3 nested into layer 4
- Layer 4 nested into layer 5
- Nested delineation feature to be published in r.slopeunits v2.1

**r.slopeunits v2.0**



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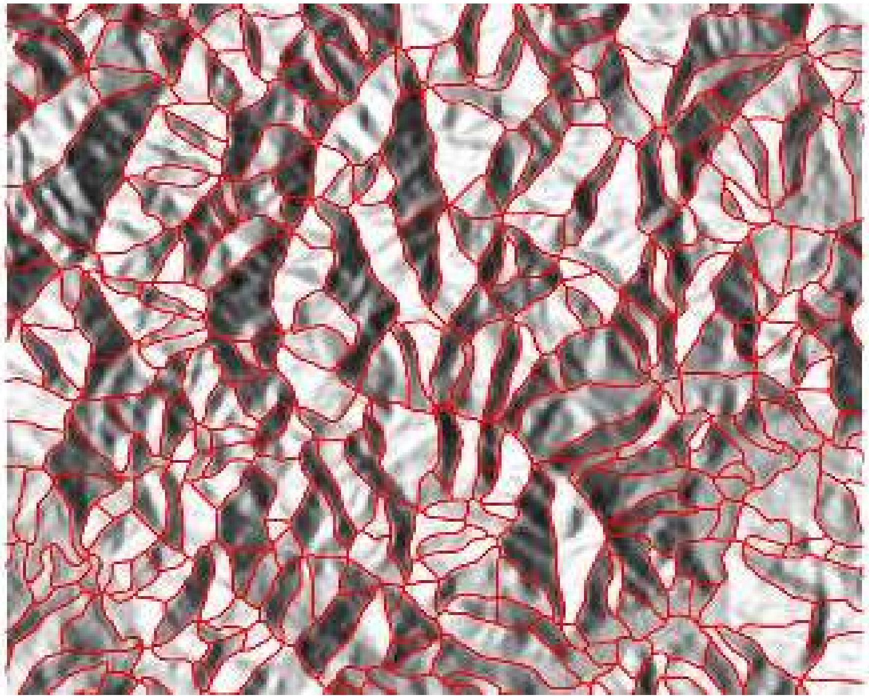
**r.slopeunits v2.0**



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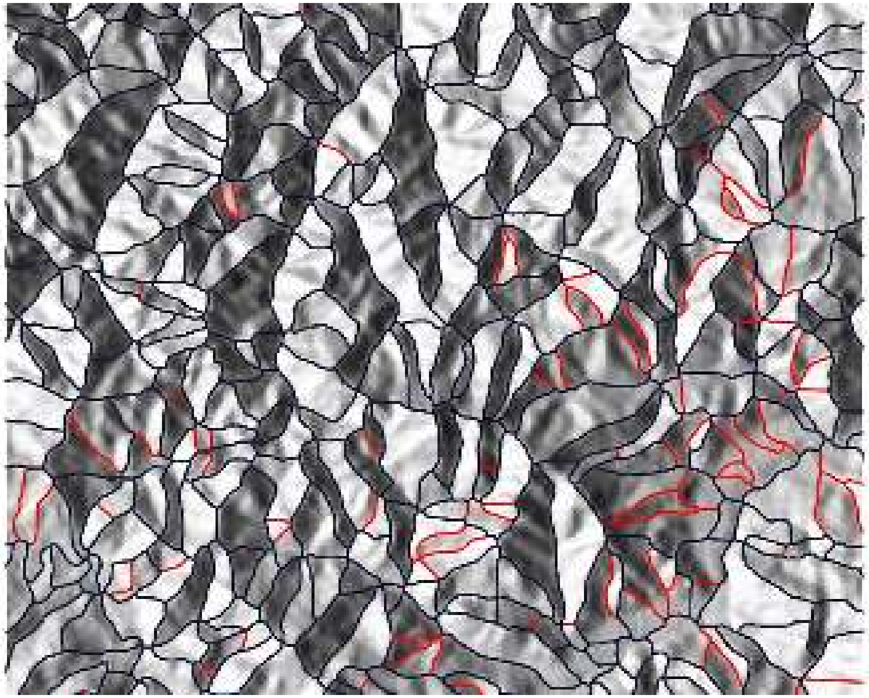
**r.slopeunits v2.0**



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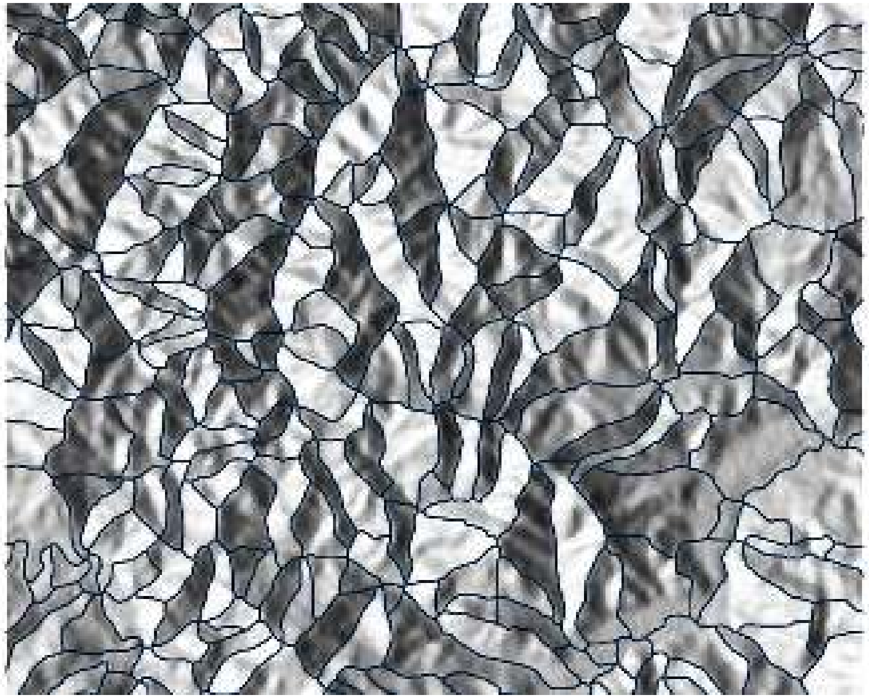

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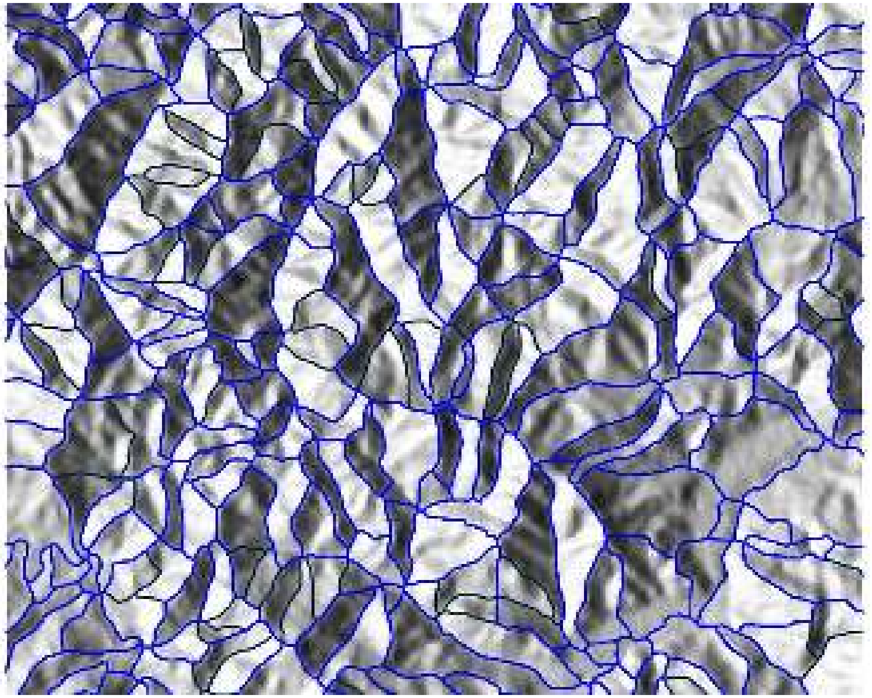

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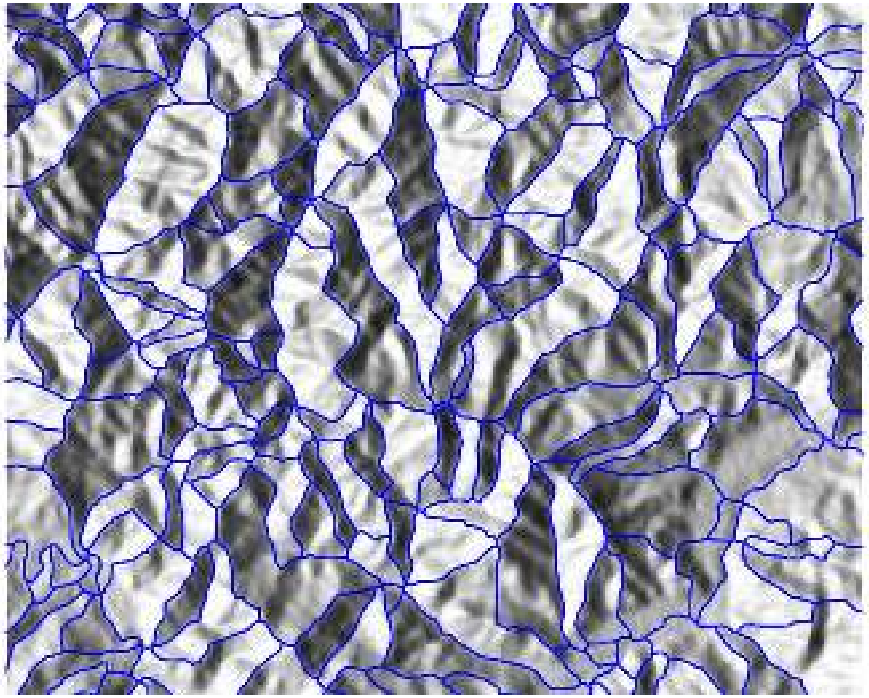

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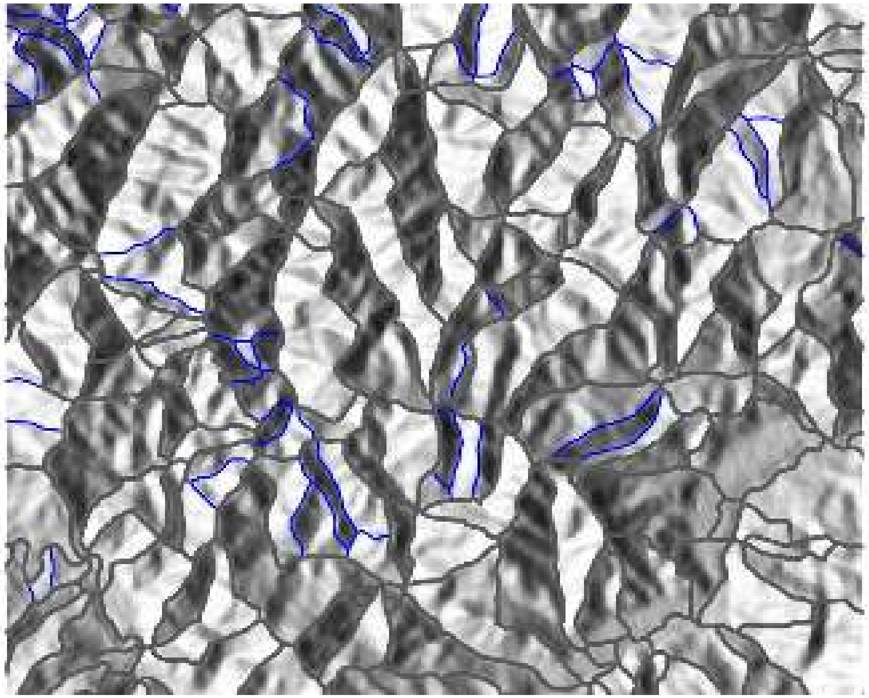

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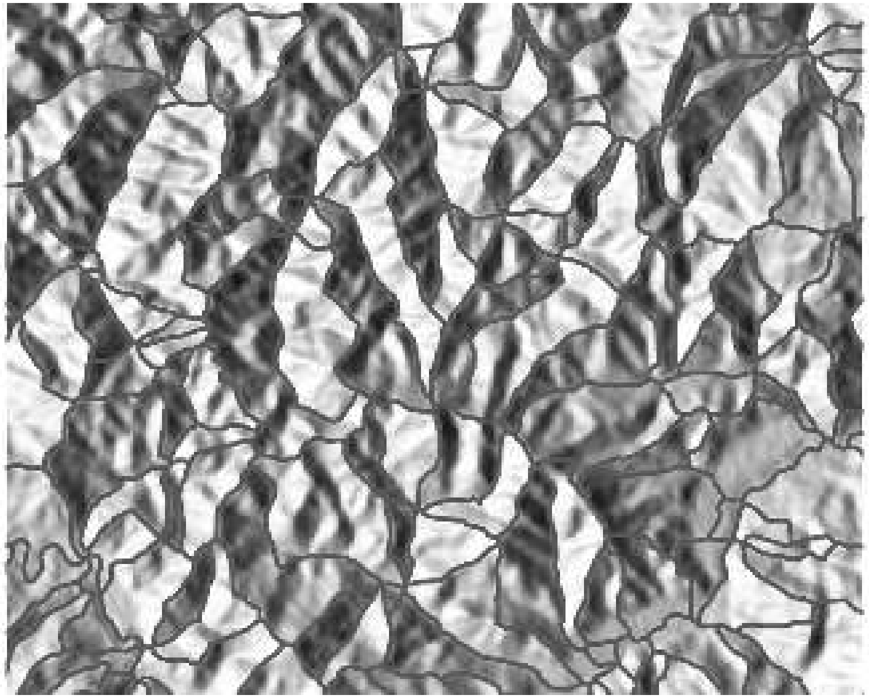

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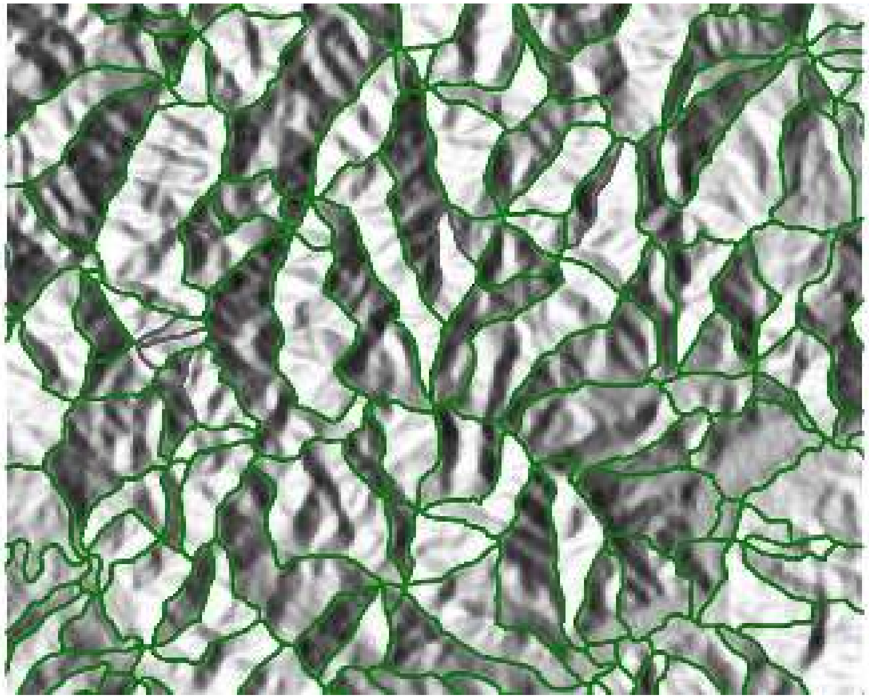

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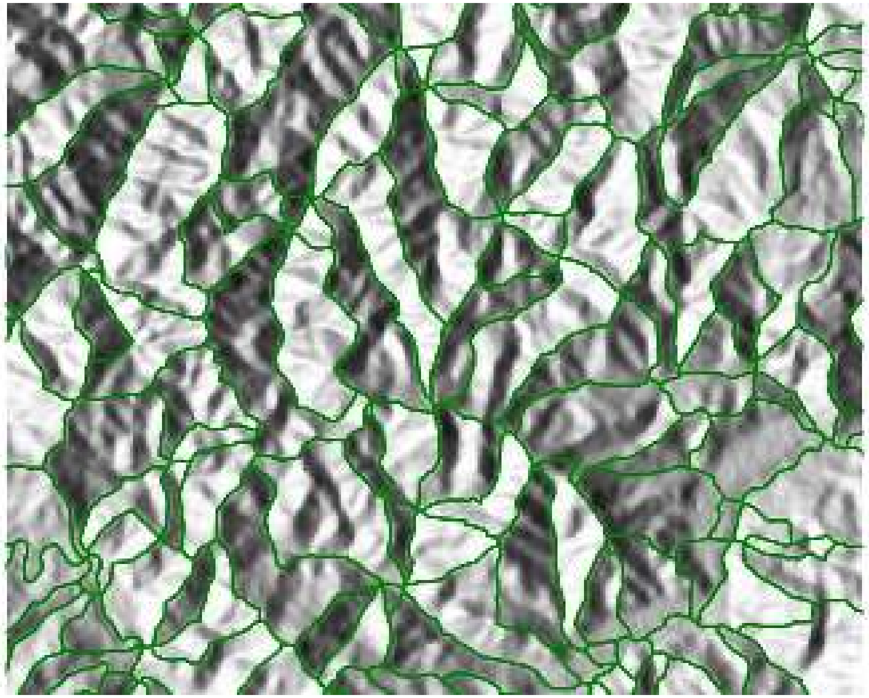

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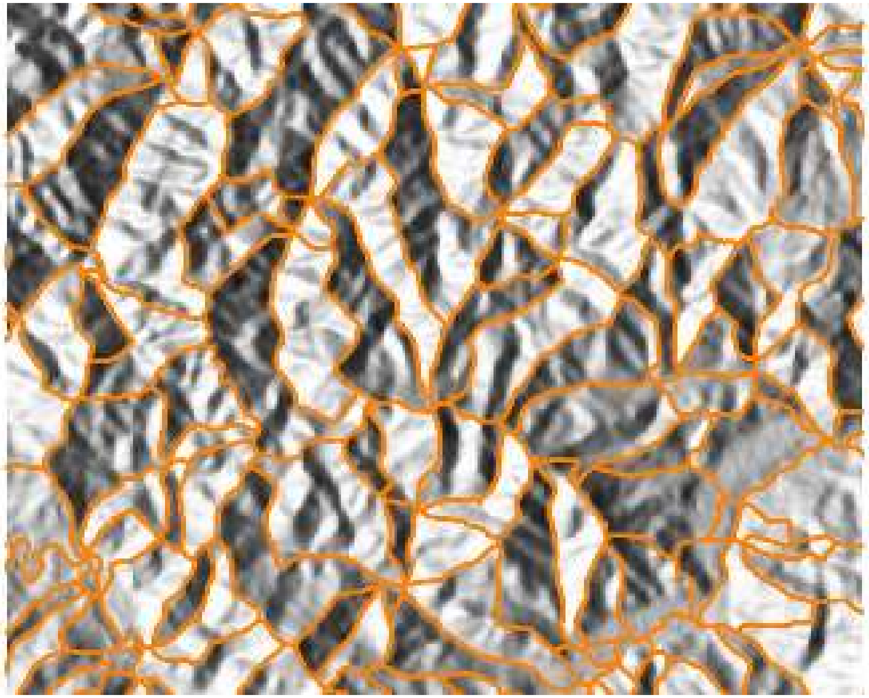

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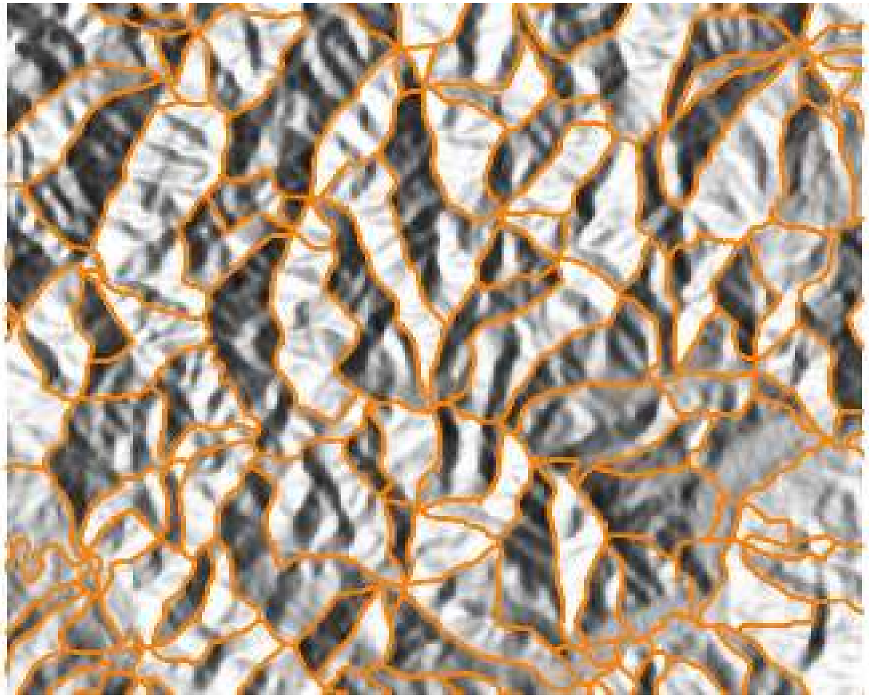
- Layer 0 nested into Layer 1
- Layer 1 nested into Layer 2
- Layer 2 nested into Layer 3
- Layer 3 nested into Layer 4
- Layer 4 nested into Layer 5
- Nested delineation feature to be implemented into r.slopeunits v2.1, funded by RETURN/HySTC project

**r.slopeunits v2.0**



# NESTED SLOPE UNITS OF ITALY

- We prepared a set of five+1 multi-layer slope unit maps

| Layer no. | Minimum area [km²] | Average area [km²] | Maximum area [km²] | Number of polygons | % units with area > average |
|---|---|---|---|---|---|
| 0 | 0.092 | 0.69 | 15.51 | 325,578 | 29.9 |
| 1 | 0.096 | 1.02 | 147.73 | 220,308 | 31.2 |
| 2 | 0.096 | 1.32 | 267.46 | 170,240 | 34.3 |
| 3 | 0.096 | 1.55 | 277.20 | 144,430 | 36.5 |
| 4 | 0.096 | 1.67 | 277.20 | 133,928 | 37.1 |
| 5 | 0.096 | 1.72 | 287.81 | 129,961 | 37.3 |

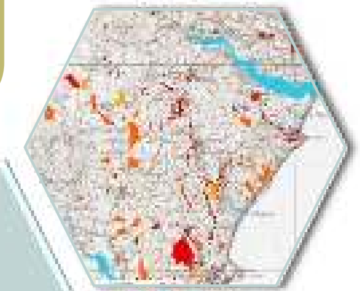
Maps and software available at: https://geomorphology.irpi.cnr.it/tools/slope-units

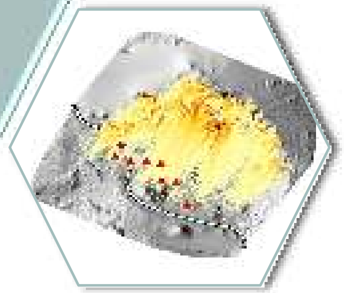
GRASS GIS addon: https://grass.osgeo.org/grass-stable/manuals/addons/r.slopeunits.html

# CONCLUSIONS: R.SLOPEUNITS IN GRASS GIS

| Feature | v1.0 | v2.0 | v2.1 |
|---|---|---|---|
| Parametric delineation | ✓ | ✓ | ✓ |
| Adaptive iterative method | ✓ | ✓ | ✓ |
| Parameter optimization | ✗ | ✓ | ✓ |
| Automated installation | ✗ | ✓ | ✓ |
| Nested layers | ✗ | ✗ | ✓ |
| Exclusion of plains | ✗ | ✗ | ✓ |
| Built-in parallelization | ✗ | ✗ | ✓ |

Please keep complaining 😇 and help us improve our software!





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**Essential BIBLIOGRAPHY**


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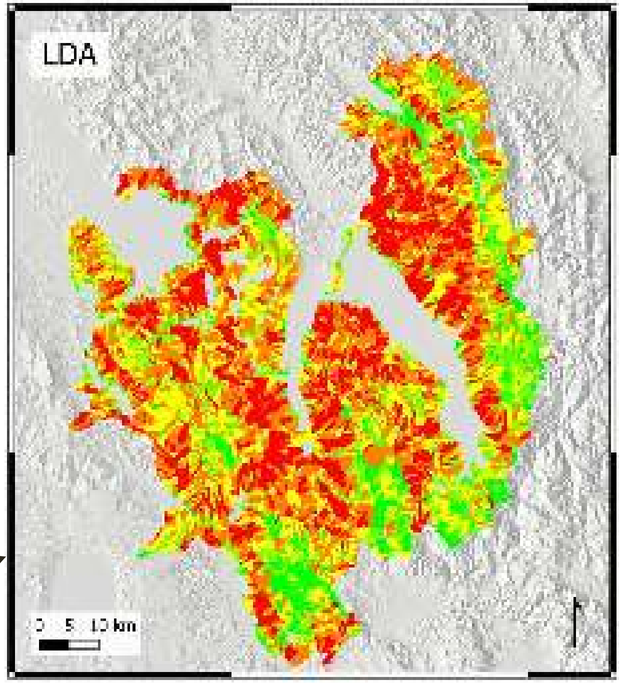
## ADDITIONAL SLIDES

# P2. LANDSLIDE SUSCEPTIBILITY: WHICH METHOD?

Several different methods exist. Results also depend on application strategy:

- Mapping units
- Variable selection
- Data preprocessing, correlations removal
- Training-test strategy, cross validation
- Choice of performance metrics

Same data, same strategy,
different method,
different research group:




**Alvioli et al., Earth-Sci. Rev. (2024)**

# P2. LANDSLIDE SUSCEPTIBILITY: WHICH METHOD?

- We recently compiled a comparative review of landslide susceptibility methods

- 11 independent research groups
- A common dataset
- A common strategy
- All methods explored in detail
- **Benchmark dataset/results**:

Earth-Science Reviews 258 (2024) 104927

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A benchmark dataset and workflow for landslide susceptibility zonation

Massimiliano Alvioli, Marco Loche, Liesbet Jacobs, Carlos H. Grohmann, Minu Treesa Abraham, Kunal Gupta, Neelima Satyam, Gianvito Scaringi, Txomin Bornaetxea, Mauro Rossi, Ivan Marchesini, Luigi Lombardo, Mateo Moreno, Stefan Steger, Corrado A.S. Camera, Greta Bajni, Guruh Samodra, Erwin Eko Wahyudi, Nanang Susyanto, Marko Sinčić, Sanja Bernat Gazibara, Flavius Sirbu, Jewgenij Torizin, Nick Schüßler, Benjamin B. Mirus, Jacob B. Woodard, Héctor Aguilera, Jhonatan Rivera-Rivera

https://geomorphology.irpi.cnr.it/tools/slope-units

**Alvioli et al., Earth-Sci. Rev. (2024)**

## P2. Landslide susceptibility: The case of Italy

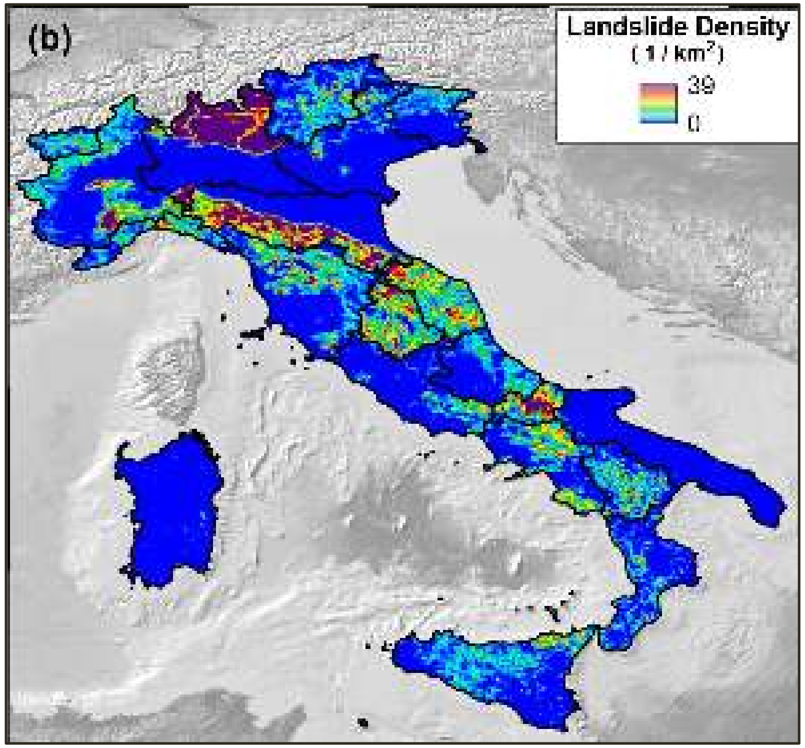
A national landslide inventory exists for Italy:

Inventory compiled independently

- by different people,
- in different regions,
- at different times:

result is very inhomogeneous!

**Is it suitable** to train a national **susceptibility map**?




Loche et al., Earth-Sci. Rev. (2022)

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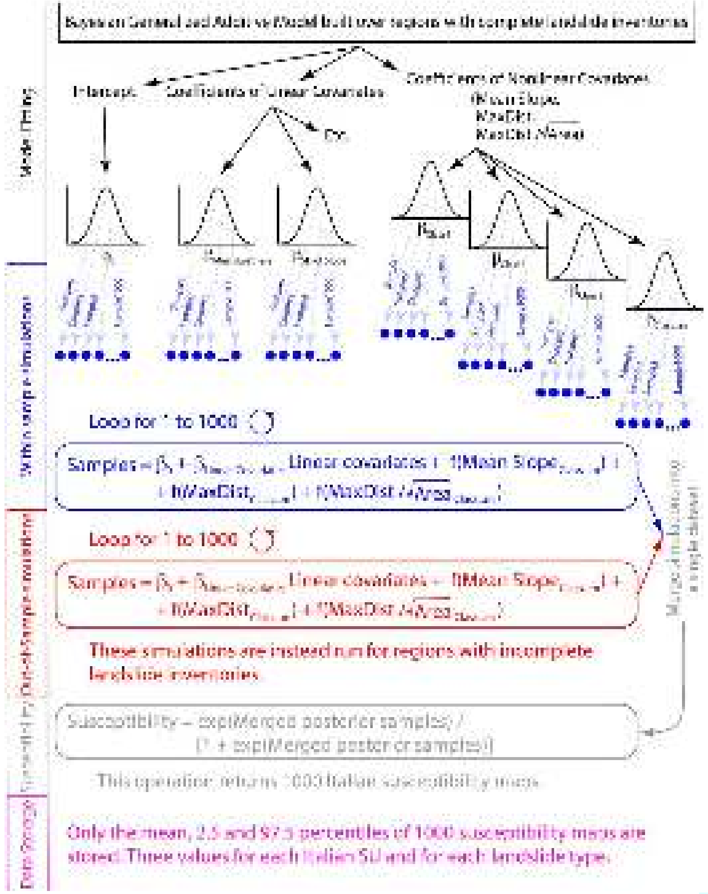
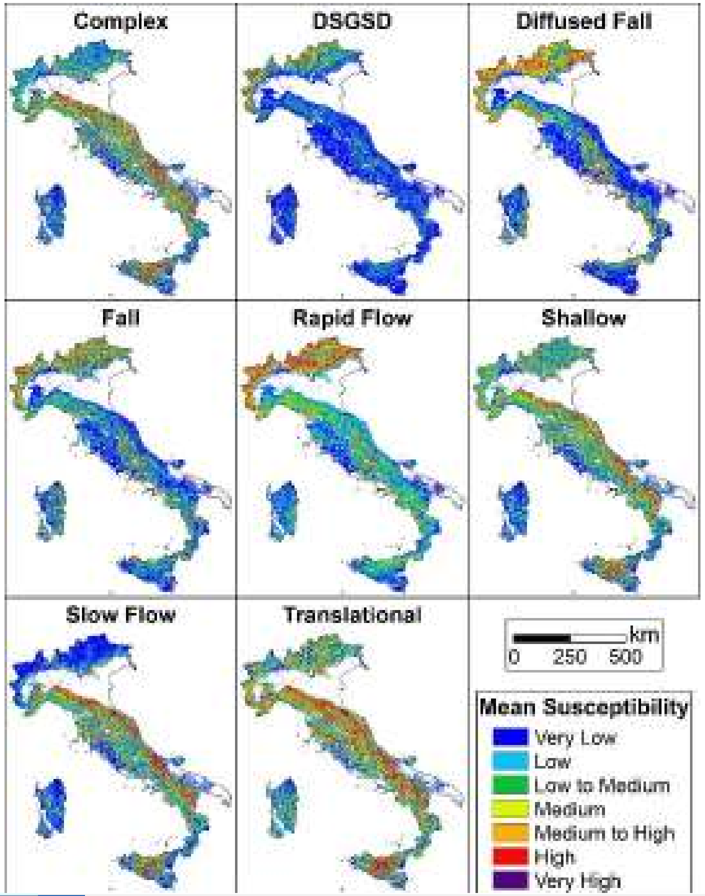


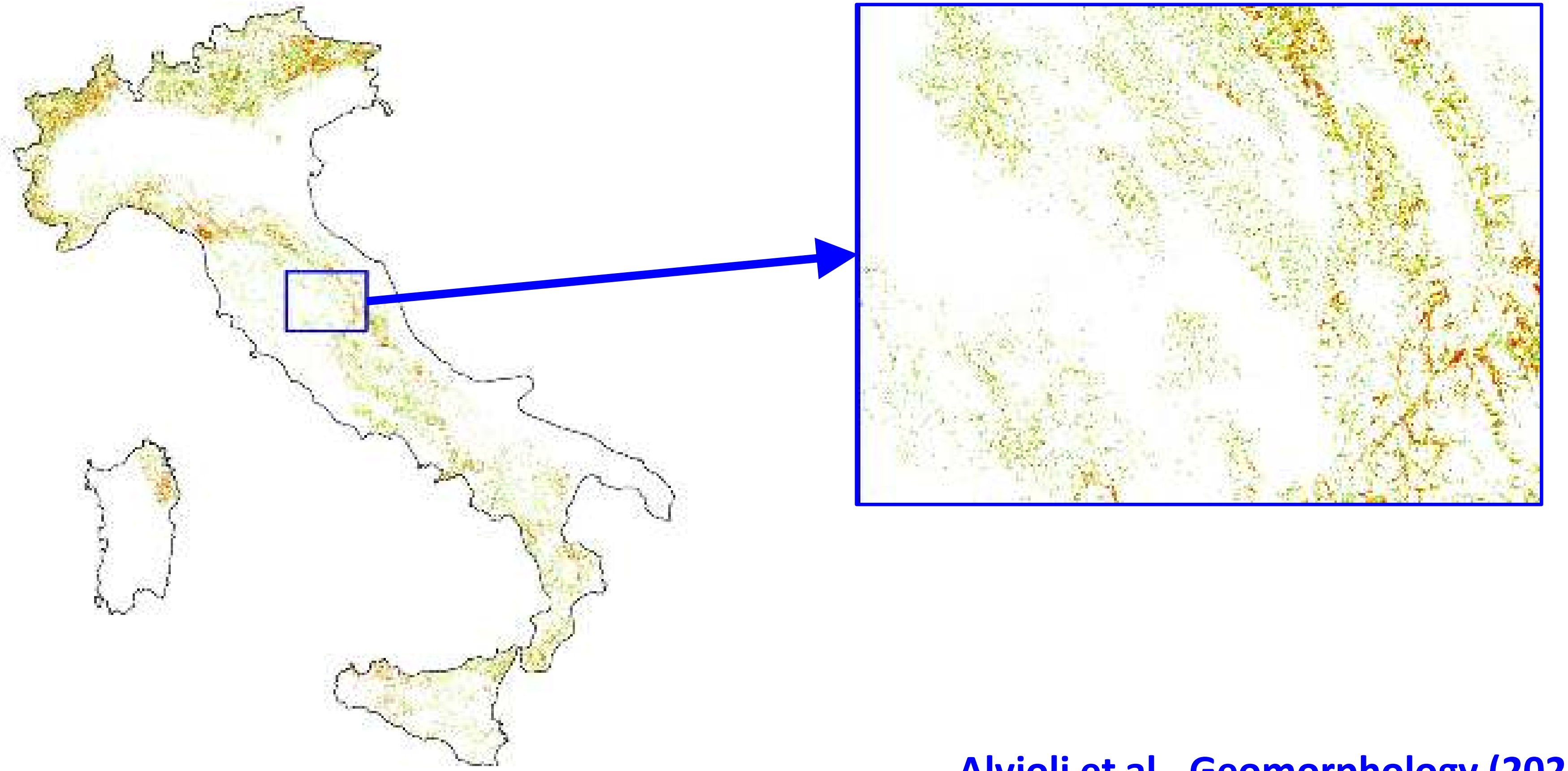

Loche et al., Earth-Sci. Rev. (2022)

# P3. NATIONAL ROCKFALL SIMULATION: SPATIAL AGGREGATION

- Spatial aggregation is crucial for presentation of the results

**Alvioli et al., Geomorphology (2023)**

# P3. National rockfall simulation: spatial aggregation



Alvioli et al., Geomorphology (2023)

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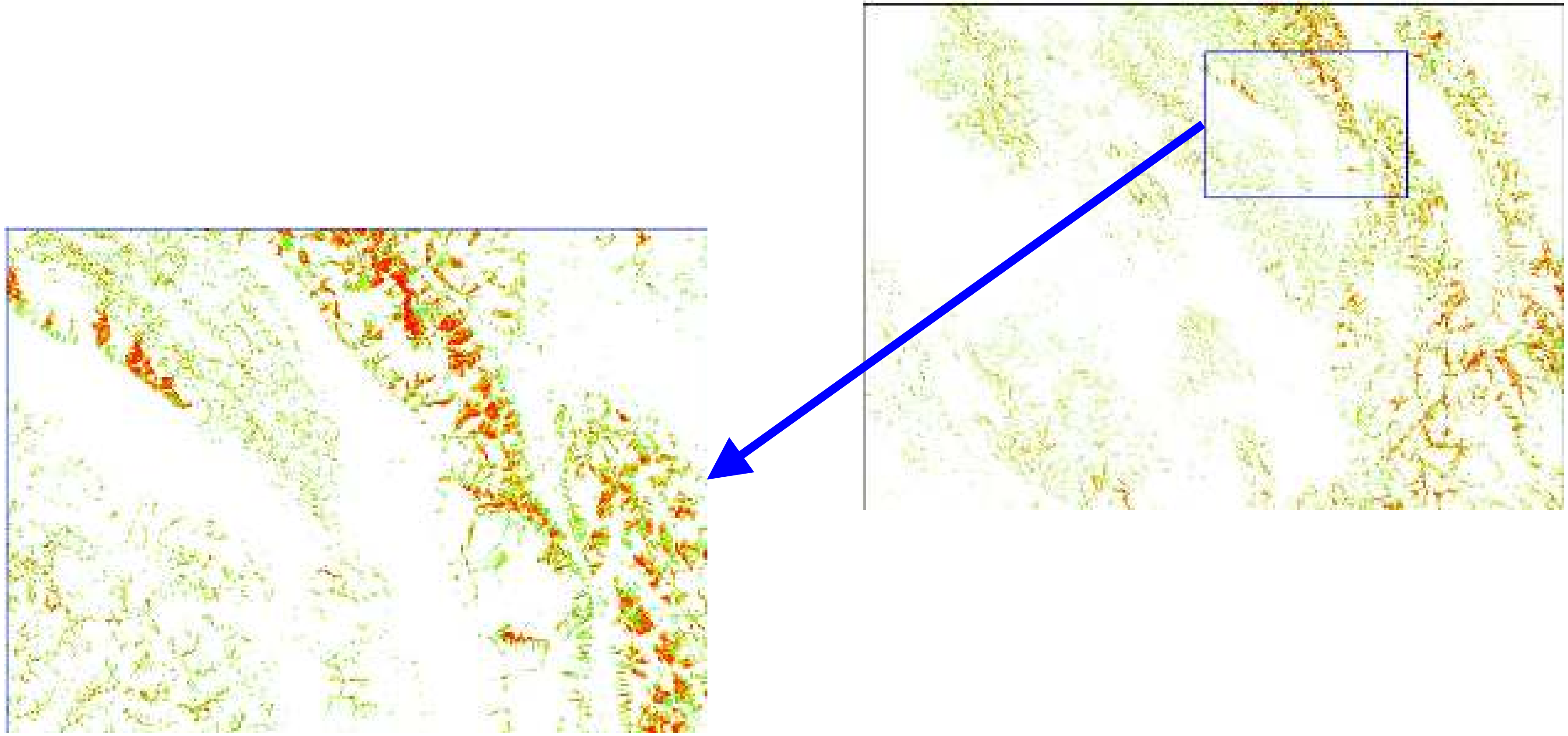

Alvioli et al., Geomorphology (2023)

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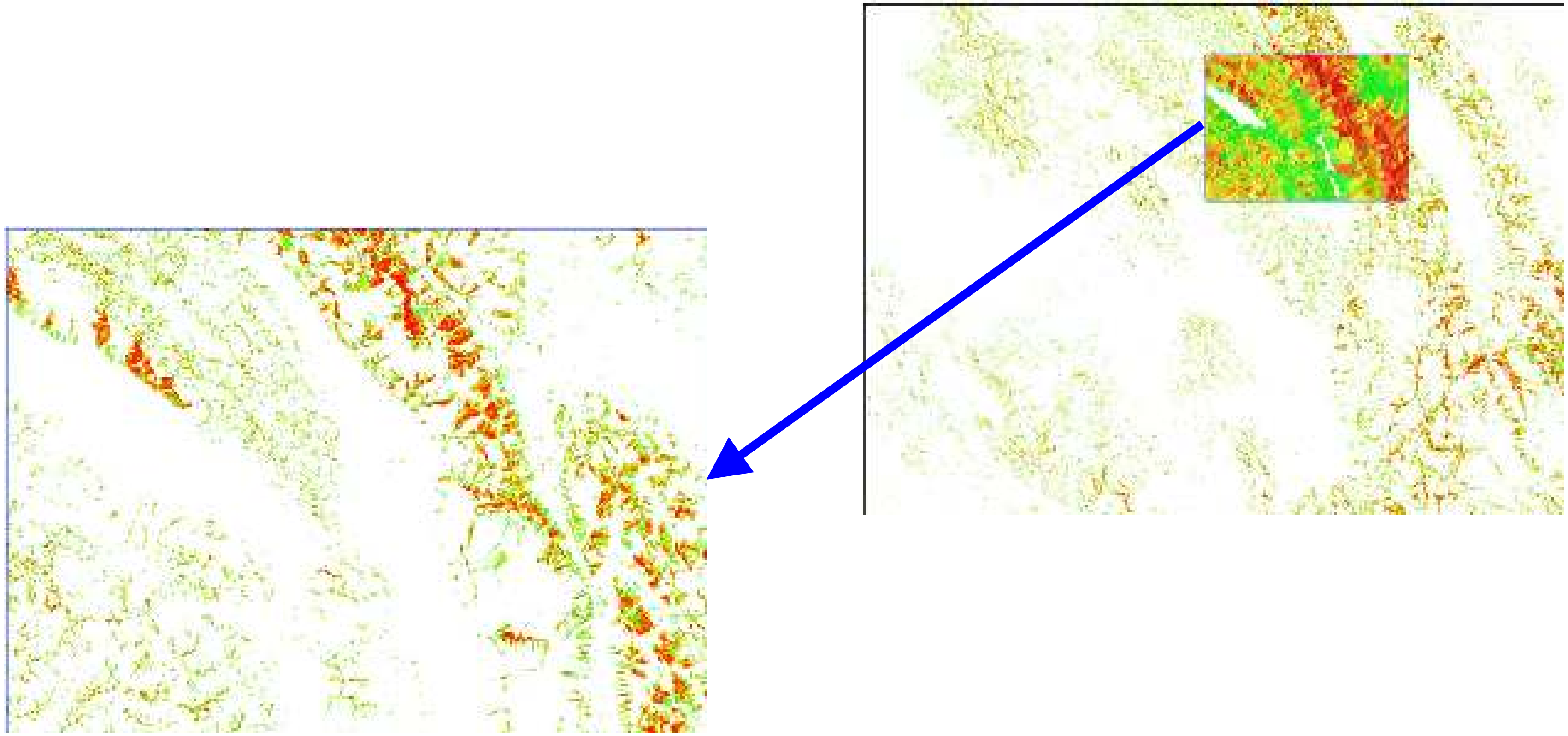

Alvioli et al., Geomorphology (2023)

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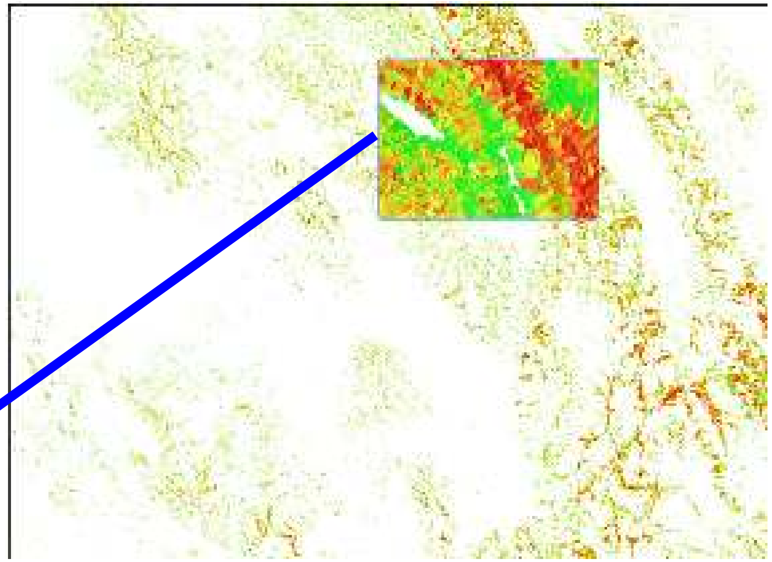
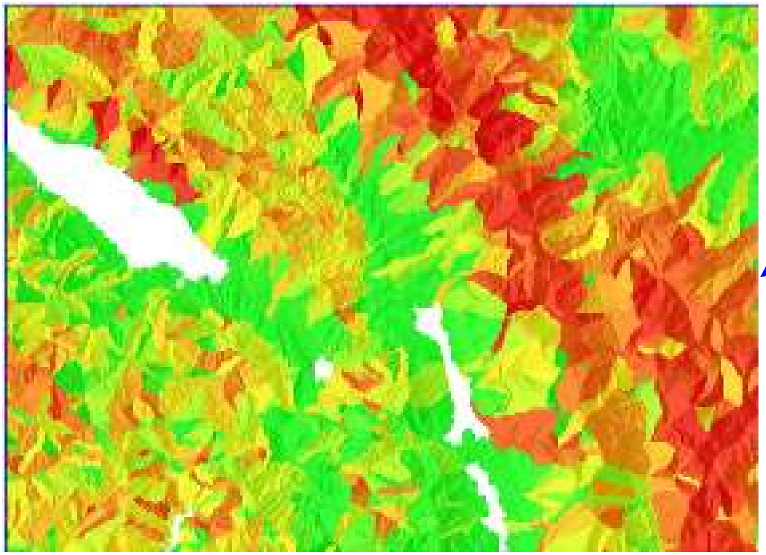
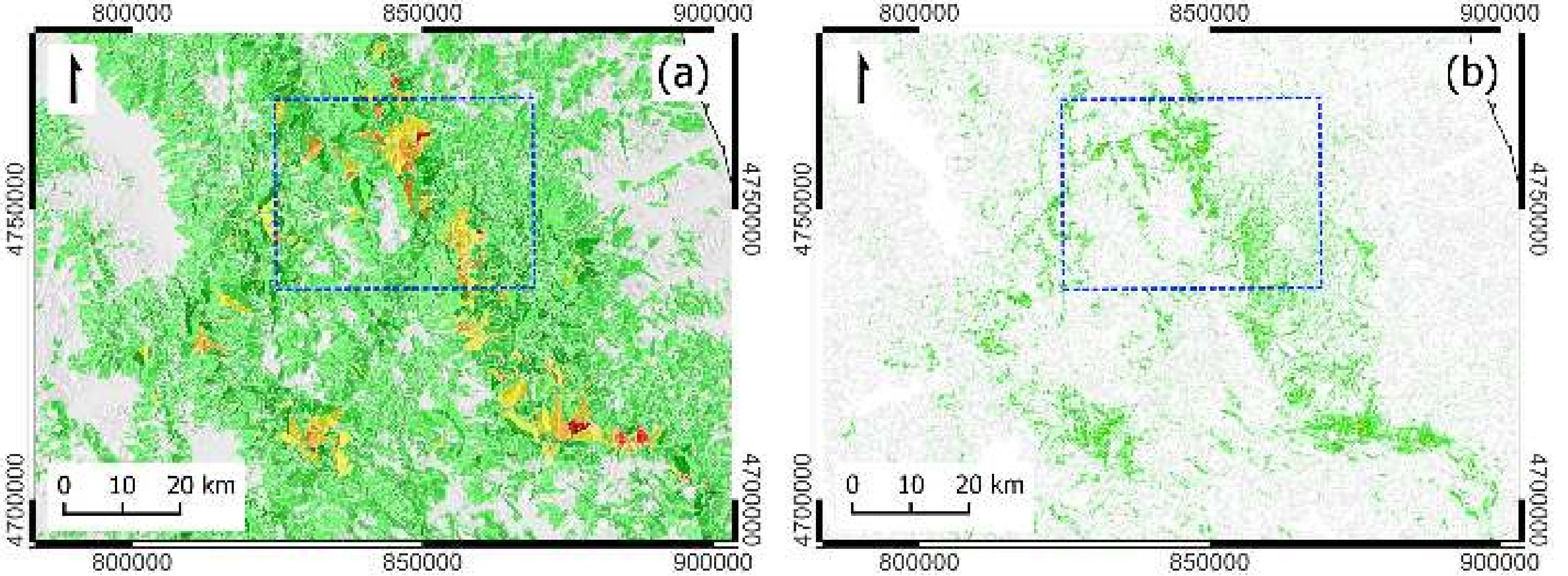




**Alvioli et al., Geomorphology (2023)**

# P3. National rockfall simulation: spatial aggregation




**Alvioli et al., Landslides (2023)**

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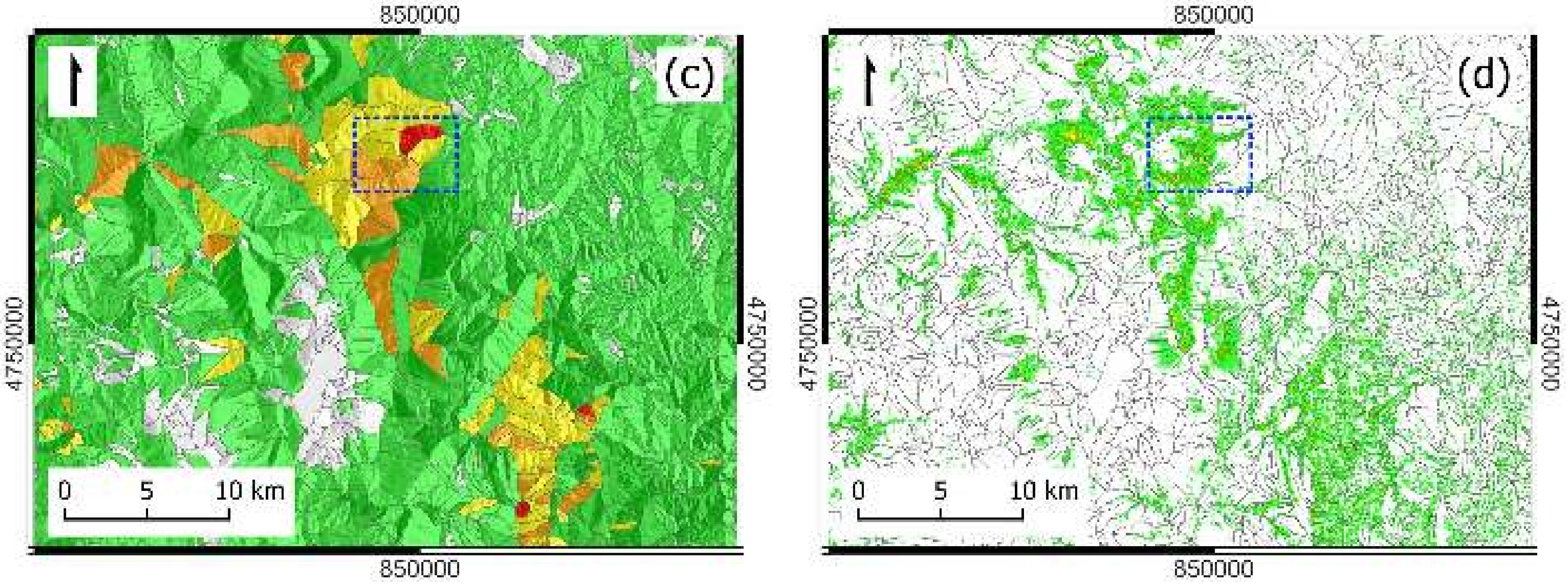


**Alvioli et al., Landslides (2023)**

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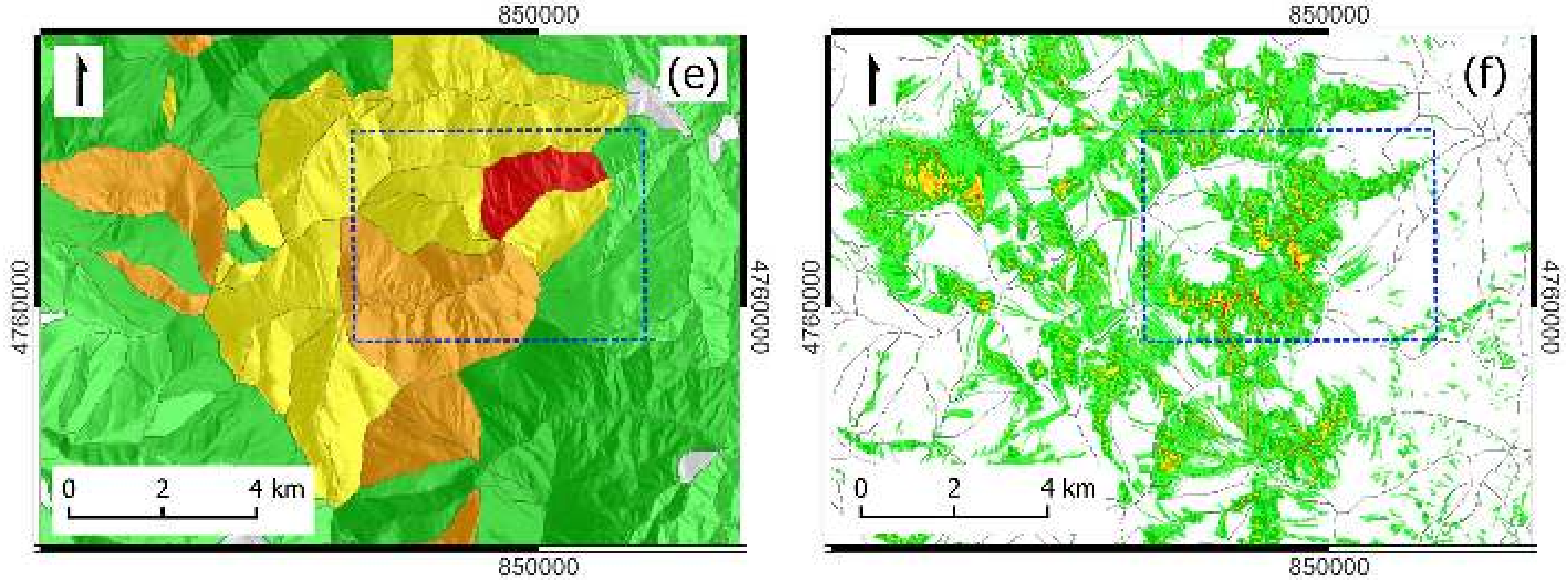


**Alvioli et al., Landslides (2023)**

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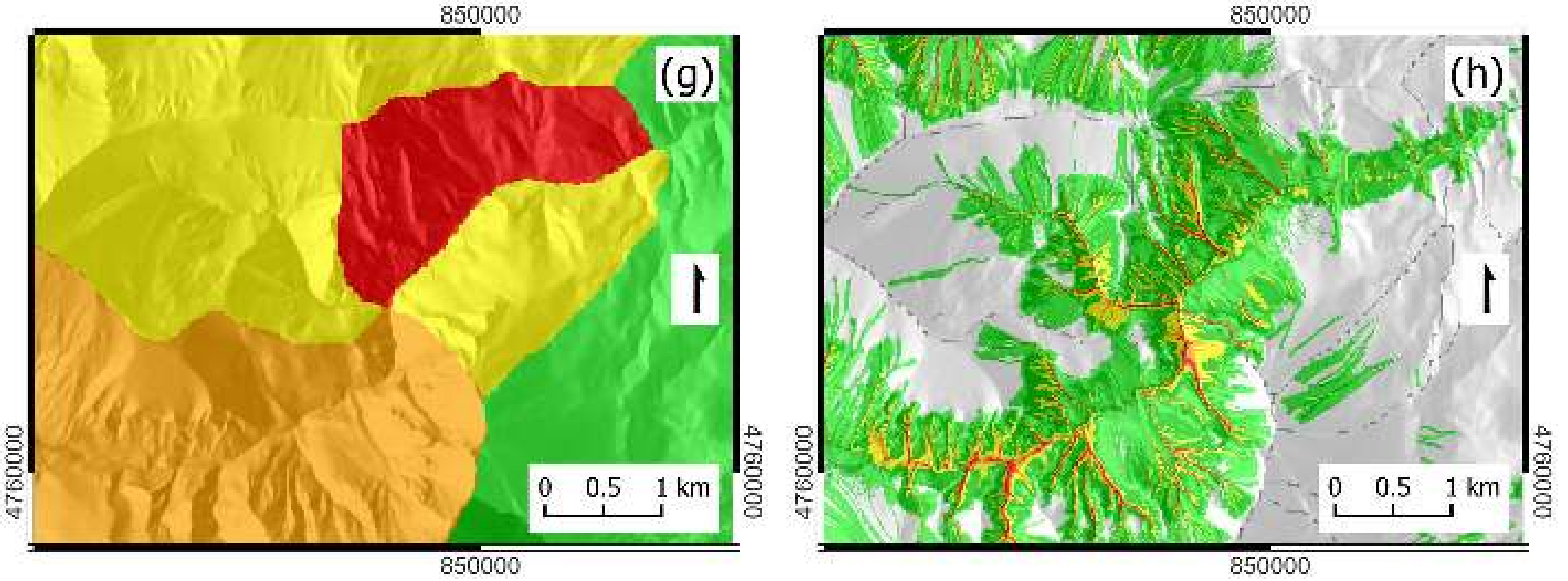


**Alvioli et al., Landslides (2023)**

# P3. Application to Earthquake-Induced Rockfalls

National scale

A truly multiscale approach!

Geomorphology

Seismically induced rockfall hazard from a physically based model and ground motion scenarios in Italy

Massimiliano Alvioli, Giacomo Falcone, Antonio Mendicelli, Federico Mori, Federica Fiorucci, Francesco Ardizzone, Massimiliano Moscatelli

Regional scale

Original Paper

Massimiliano Alvioli · Valerio Poggi · Antonella Peresan · Chiara Scaini · Alberto Tamaro · Fausto Guzzetti

A scenario-based approach for immediate post-earthquake rockfall impact assessment

Landslides (2023)
DOI 10.1007/s10346-023-02127-2
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Published online: 11 September 2023

Local scale

GEOMATICS, NATURAL HAZARDS AND RISK
Taylor & Francis
OPEN ACCESS

Three-dimensional simulations of rockfalls in Ischia, Southern Italy, and preliminary susceptibility zonation

Massimiliano Alvioli[a], Ada De Matteo[b], Raffaele Castaldo[b], Pietro Tizzani[b] and Paola Reichenbach[a]

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