Sediment connectivity assessment through a geomorphometric approach: review of recent applications

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GEOMORPHOMETRY 2021
PERUGIA, ITALY

SEPT
13 - 17
2021

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Outline of the presentation

- Introduction
- Index of sediment connectivity and tools
- Overview on recent applications
- Considerations and perspectives


Strimm Creek

Coupling

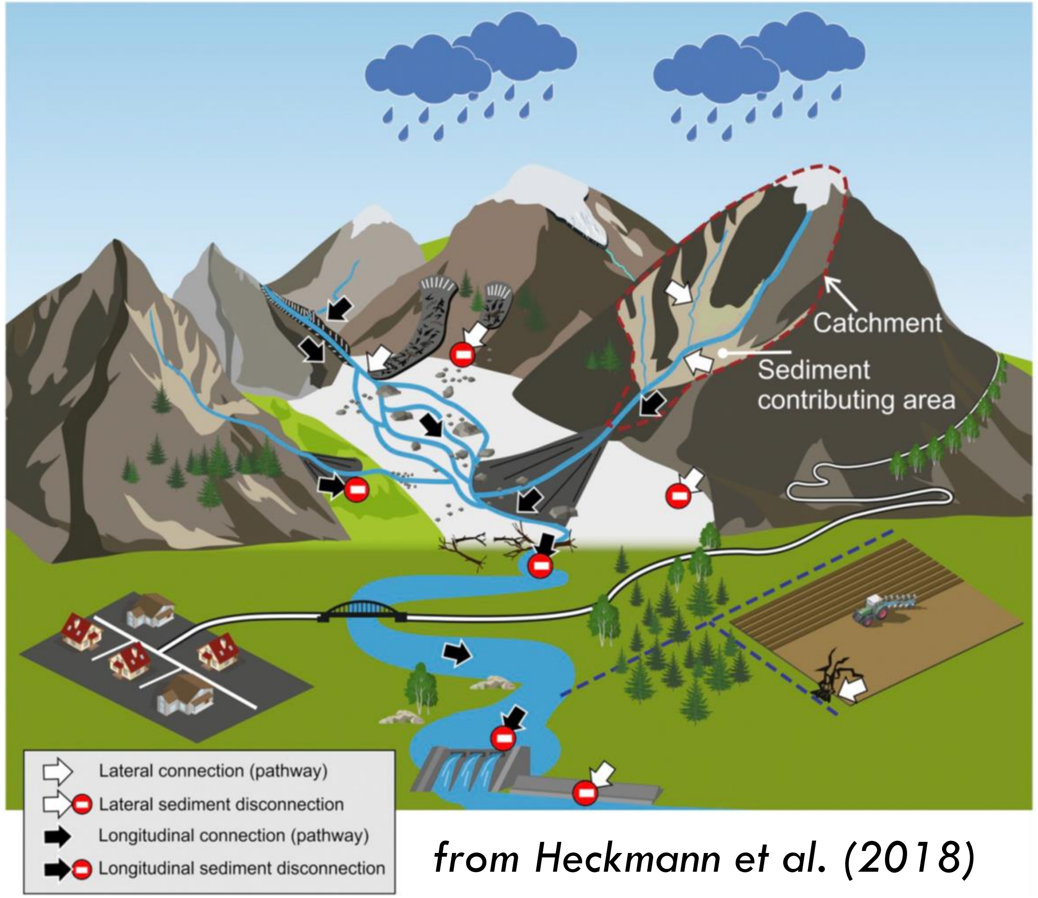
Decoupling

Sediment connectivity

Hydrological and sediment connectivity: the degree to which a system facilitates the transfer of water and sediment through itself, through coupling relationships between its components. In this view, connectivity becomes an emergent property of the system state, reflecting the continuity and strength of runoff and sediment pathways at a given point in time. (Heckmann et al., 2018)

Structural connectivity represents the spatial configuration of system components

Functional connectivity is inferred from the actual transfer of water and sediment, i.e. the system's process dynamics



from Heckmann et al. (2018)

Heckmann T., Cavalli M., Cerdan O., Foerster S., Javaux M., Lode E., Smetanova A., Vericat D., Brardinoni B., 2018. Indices of sediment connectivity: opportunities, challenges and limitations. Earth-Science Reviews, 187, 77-108. DOI: 10.1016/j.earscirev.2018.08.004.

- Three different types of linkages in catchments (Fryirs, 2013):

✓ Lateral: hillslope-channel;

✓ Longitudinal: channel and interaction tributary-main stream;

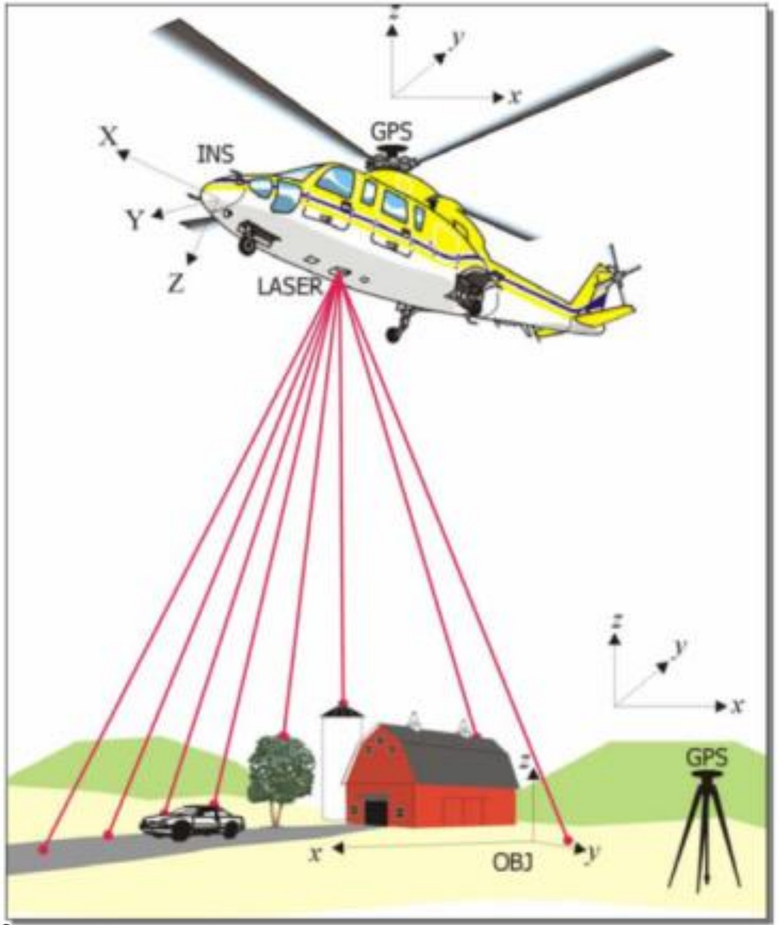
✓ Vertical: interactions between surface-subsurface.

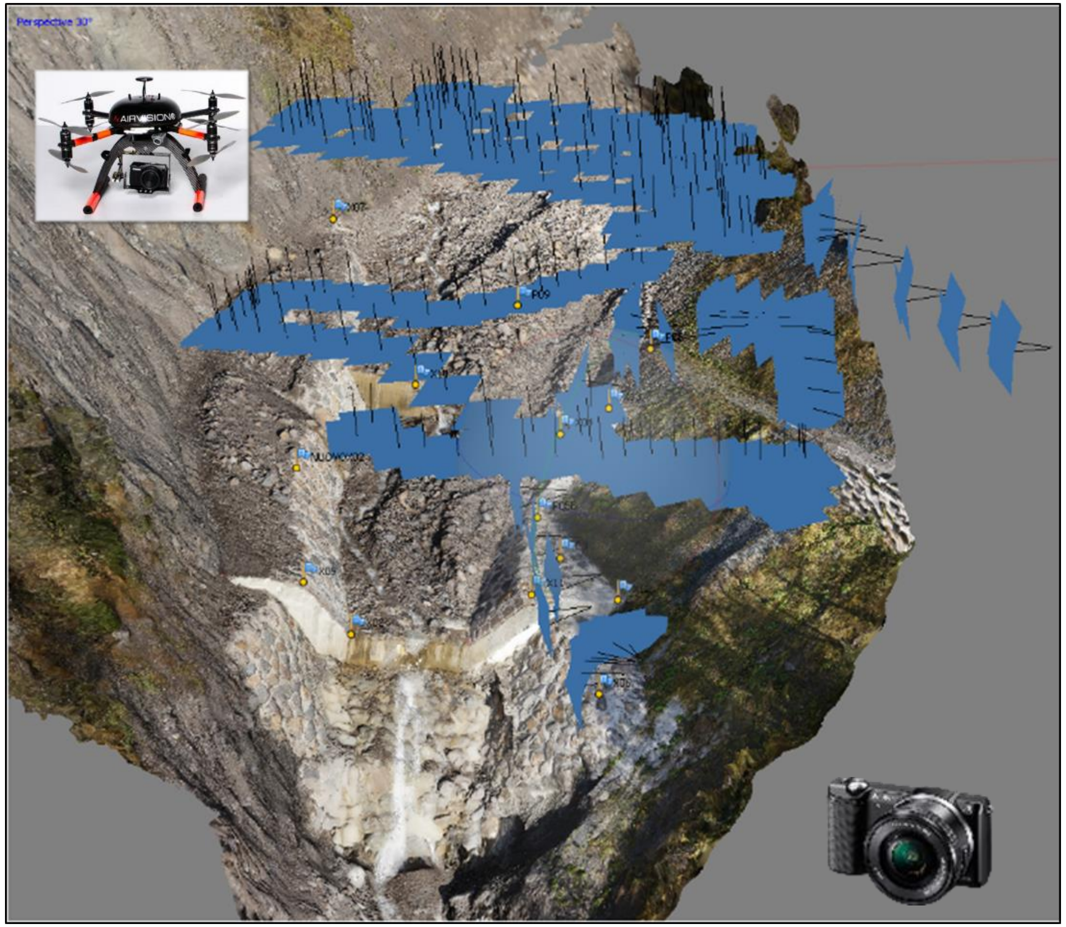
- They can be disrupted by different types of blockages: *buffers, barriers e blankets*

Fryirs K. 2013. (Dis)Connectivity in catchment sediment cascades: a fresh look at the sediment delivery problem. Earth Surf. Process. Landforms 38: 30–46

High-resolution Digital Elevation Models enable the quantitative modeling of sediment fluxes and connectivity via geomorphometric analysis.

LiDAR: Light Detection And Ranging Structure from Motion





Index of sediment connectivity

The connectivity index (IC) is computed using two components:

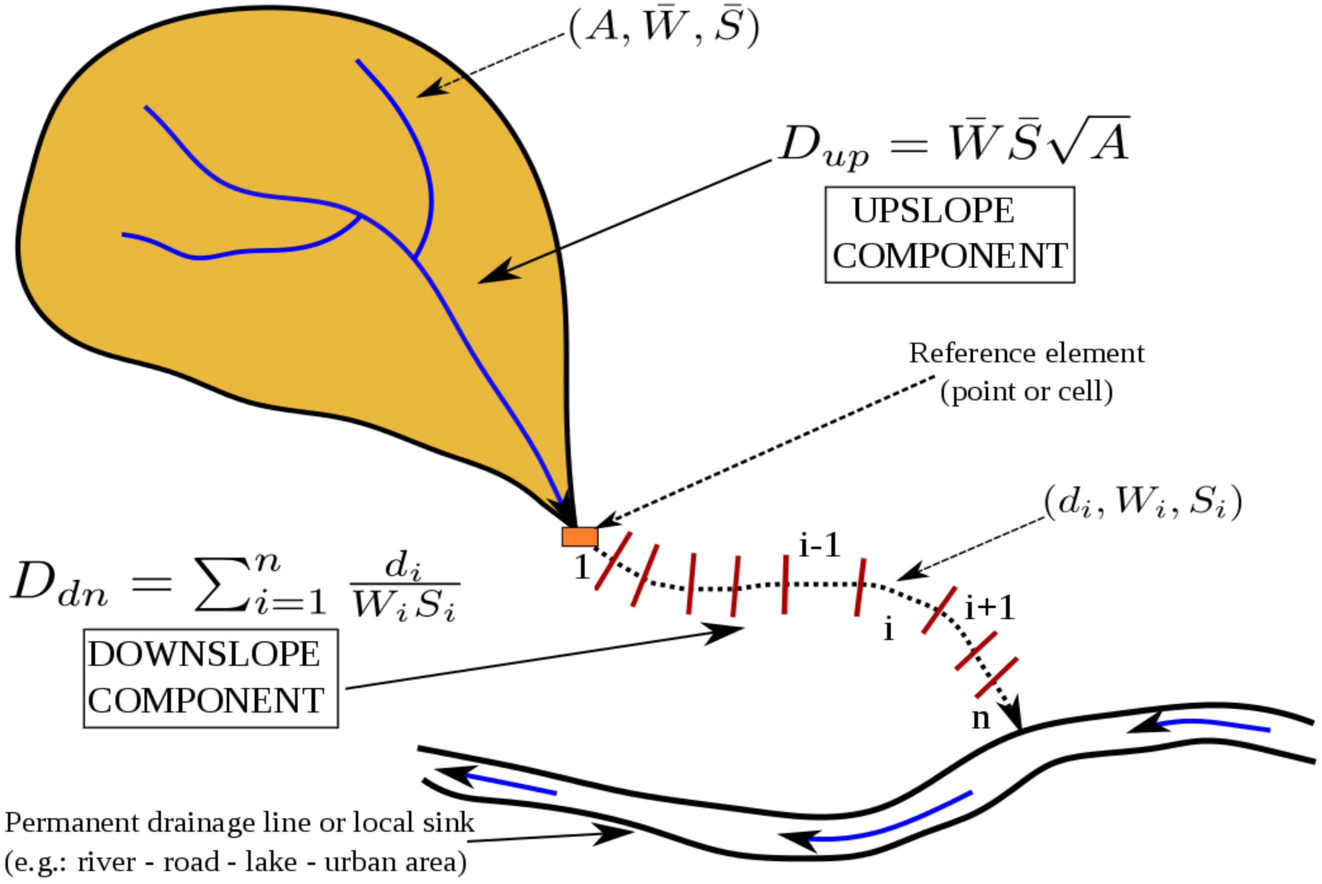
Upslope component D_{up}

potential for downward routing due to upslope area, mean slope and impedance factor.

Downslope component D_{dn}

flow path length that a particle has to travel to arrive to the nearest target or sink.

$$IC = \log_{10}\left(\frac{D_{up}}{D_{dn}}\right)$$



Borselli L., Cassi P., Torri D., 2008. Prolegomena to sediment and flow connectivity in the landscape: a GIS and field numerical assessment. Catena, 75(3), 268-277.

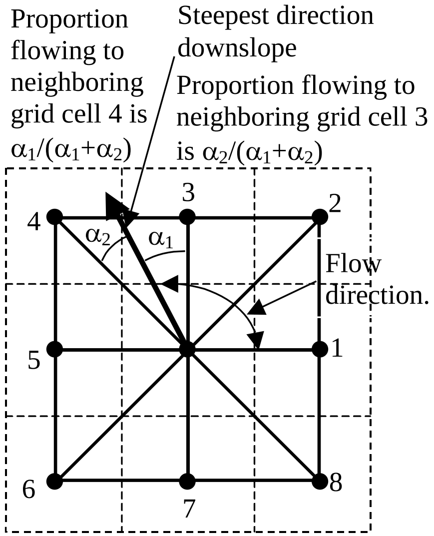
Cavalli M., Trevisani S., Comiti F., Marchi L., 2013. Geomorphometric assessment of spatial sediment connectivity in small alpine catchments. Geomorphology, 188, 31-41.

Slope S (m/m) (steepest descent direction)

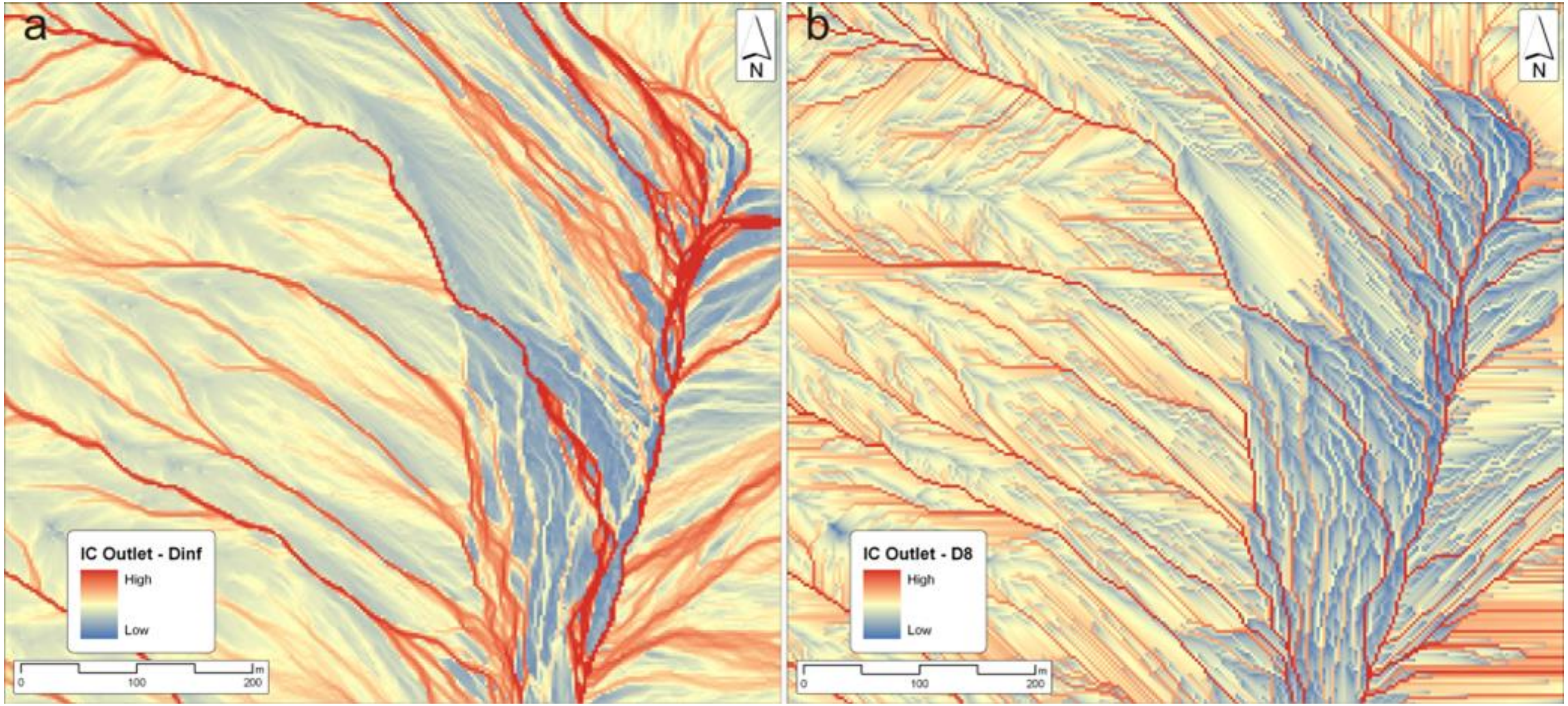
S < 0.005 ➡ S = 0.005 to avoid ∞ in the downslope component equation

S > 1 ➡ S = 1 to limit the bias due to very high values of IC on steep slopes (e.g. rocky outcrop)

Flow Direction (D∞ algorithm)



Tarboton, 1997. Water Res. Research, 33(2): 309-319.



Weighting factor (W)

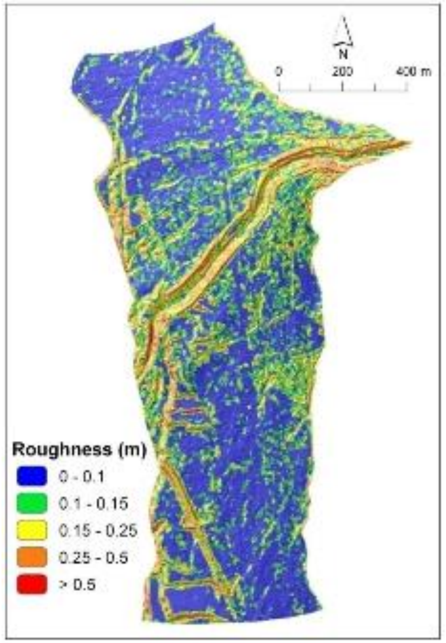
- The weighting factor W is intended to model the impedance to runoff and sediment fluxes;
- W ranges from 0 to 1. Based on the C-factor of USLE-RUSLE models in Borselli et al. (2008).

C-factor for the Bilancino watershed, Florence, Italy

Level 1	Level 2	Level 3	C-factor
1. Artificial surfaces	1.1 Urban fabric		n.c.
	1.2 Industrial fabric		n.c.
	1.3 Mines, dumps and construction sites	1.3.1 Mineral extraction sites	1
		1.3.3 Construction sites	1
	1.4 Artificial non agricultural vegetated areas	1.4.1 Green urban areas	0.05
		1.4.2 Sport and leisure facilities	0.05
2. Agricultural areas	2.1 Arable land	2.1.1 Non irrigated arable land	0.1
		2.1.4.1 Vegetables cultivation[a]	0.1
		2.1.4.2 Nursery cultivation and cultivation under plastic[a]	0.001
	2.2 Permanent crops	2.2.1 Vineyards	0.451
		2.2.2 Fruit trees and berries plantations	0.296
		2.2.3 Olive groves	0.296
	2.3 Pastures	2.3.1 Pastures	0.15
		2.3.2 Pastures with shrubs[a]	0.13
	2.4 Heterogeneous agricultural areas	2.4.4 Agro-forestries	0.05
3. Forest and seminatural areas	3.1 Forest	3.1.3.1 Mixed forests[a]	0.001
		3.1.3.2 Discontinuous forests[a]	0.006
		3.1.4 Riparian vegetation[a]	0.006
	3.2 Shrub and/or herbaceous vegetation associations		0.04
	3.3 Open spaces with little or no vegetation	3.3.2 Bare rocks	0.9
4. Wetlands	4.2 Coastal wetlands	4.2.3 Intertidal flats	1
5. Water bodies	5.1 Continental waters	5.1.1 Stream courses	n.c.
		5.1.2 Water bodies	n.c.

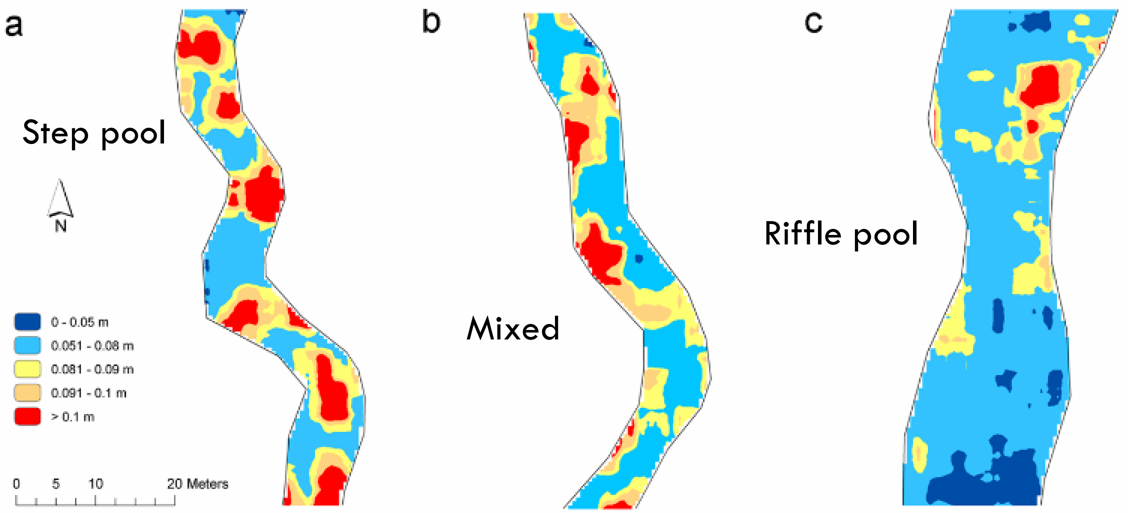
[a] Based on CORINE Land Cover (modified) assigned from literature data ERSO (1990).

Borselli et al. (2008)



Moscardo Creek alluvial fan

Cavalli and Marchi, 2008



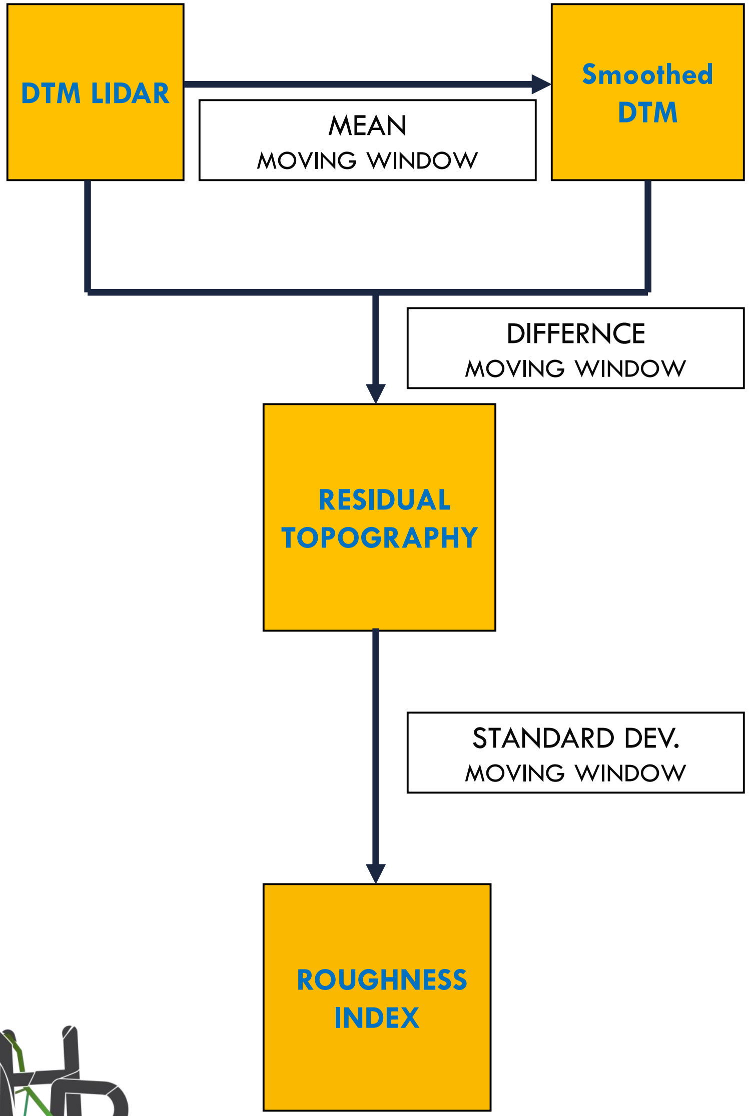
Rio Cordon main channel

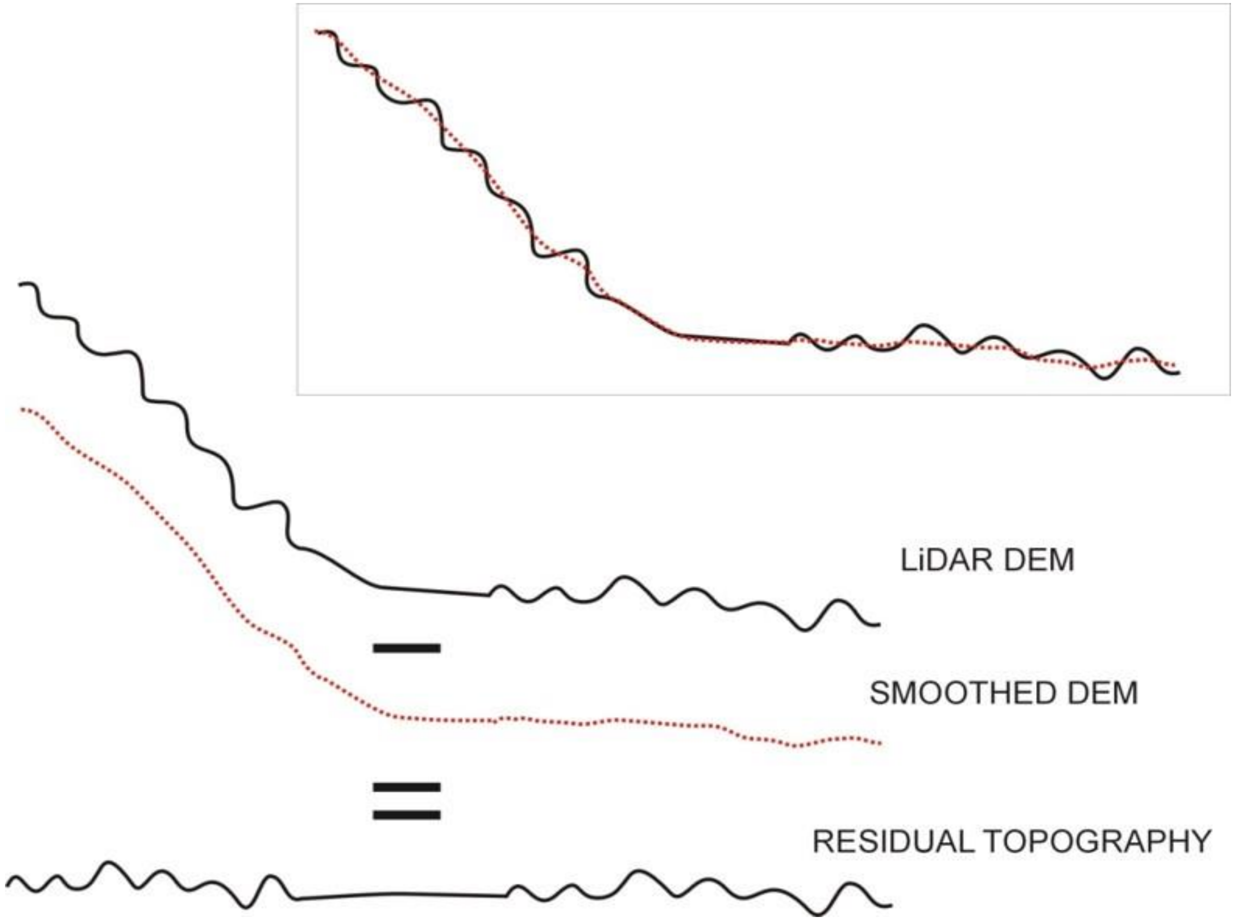
Cavalli et al., 2008

Cavalli M., Tarolli P., Marchi L., Dalla Fontana G., 2008. The effectiveness of airborne LiDAR data in the recognition of channel-bed morphology. Catena, 73(3), 249-260. doi: 10.1016/j.catena.2007.11.001.

Cavalli M., Marchi L., 2008. Characterisation of the surface morphology of an alpine alluvial fan using airborne LiDAR. Natural Hazards and Earth System Science, 8, 323-333. doi:10.5194/nhess-8-323-2008.

Roughness Index





The roughness value on each cell corresponds to the topographic variability over the investigated area (DTM resolution – moving window size)

$$W = 1 - \left(\frac{RI}{MAX(RI)} \right)$$

Lower limit = 0.001

The standardization of roughness value was introduced for three reasons:

(i) to have the same range of variation as for S factor in order to weight them equally in the model (0 – 1);

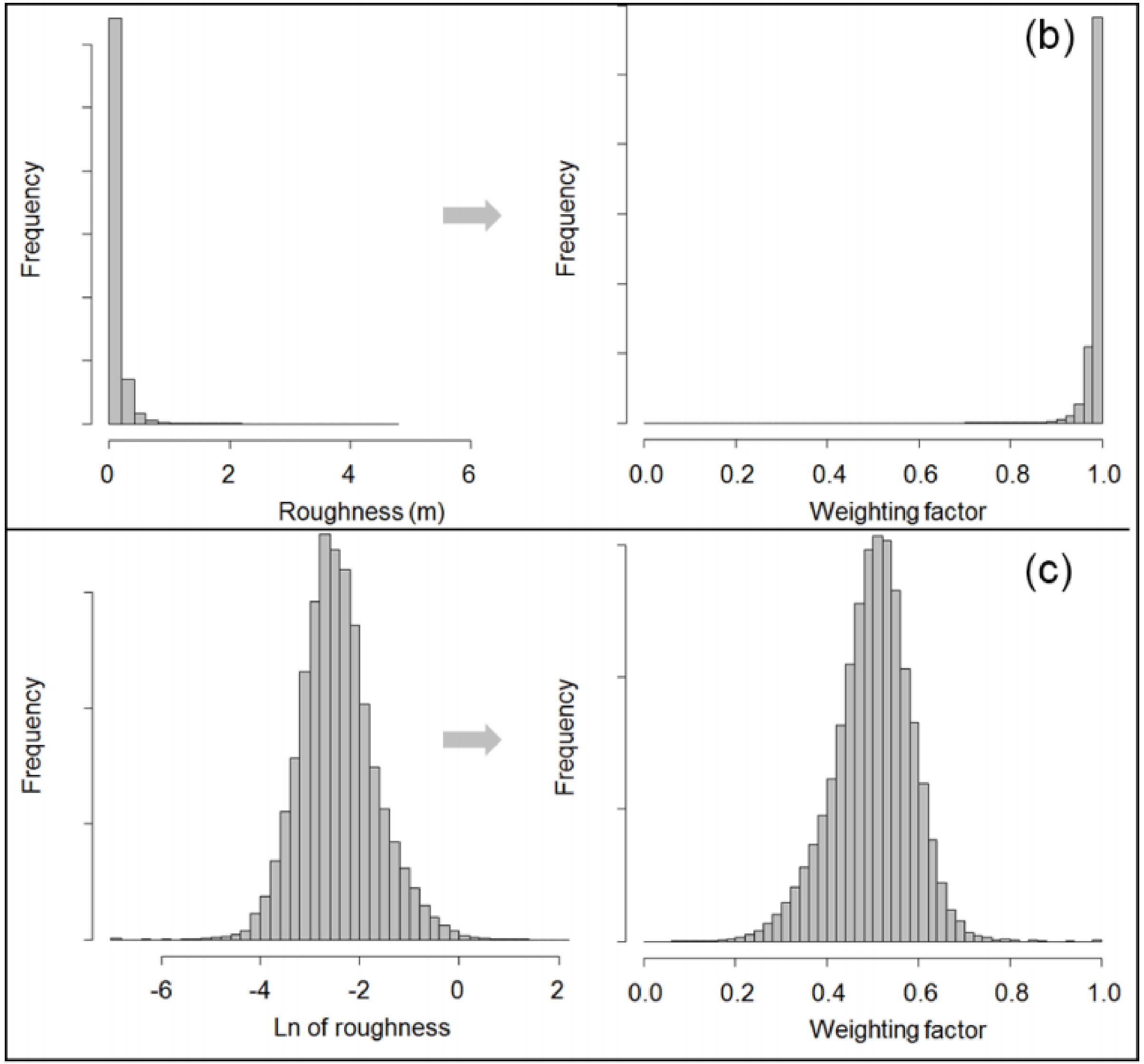
(ii) to remove the bias due to high RI values in steep areas;

(iii) to provide comparable values with USLE C-factor and therefore with the original model.

The use of a roughness index as weighting factor has several advantages:

- the weight is estimated objectively;
- it avoids the use of tabled data;
- it allows the model to be applied straightforwardly (only DTM as an input).

$$W = 1 - \frac{\mathrm{Ln}(R) - \mathrm{Ln}(R_{\min})}{\mathrm{Ln}(R_{\max}) - \mathrm{Ln}(R_{\min})}$$

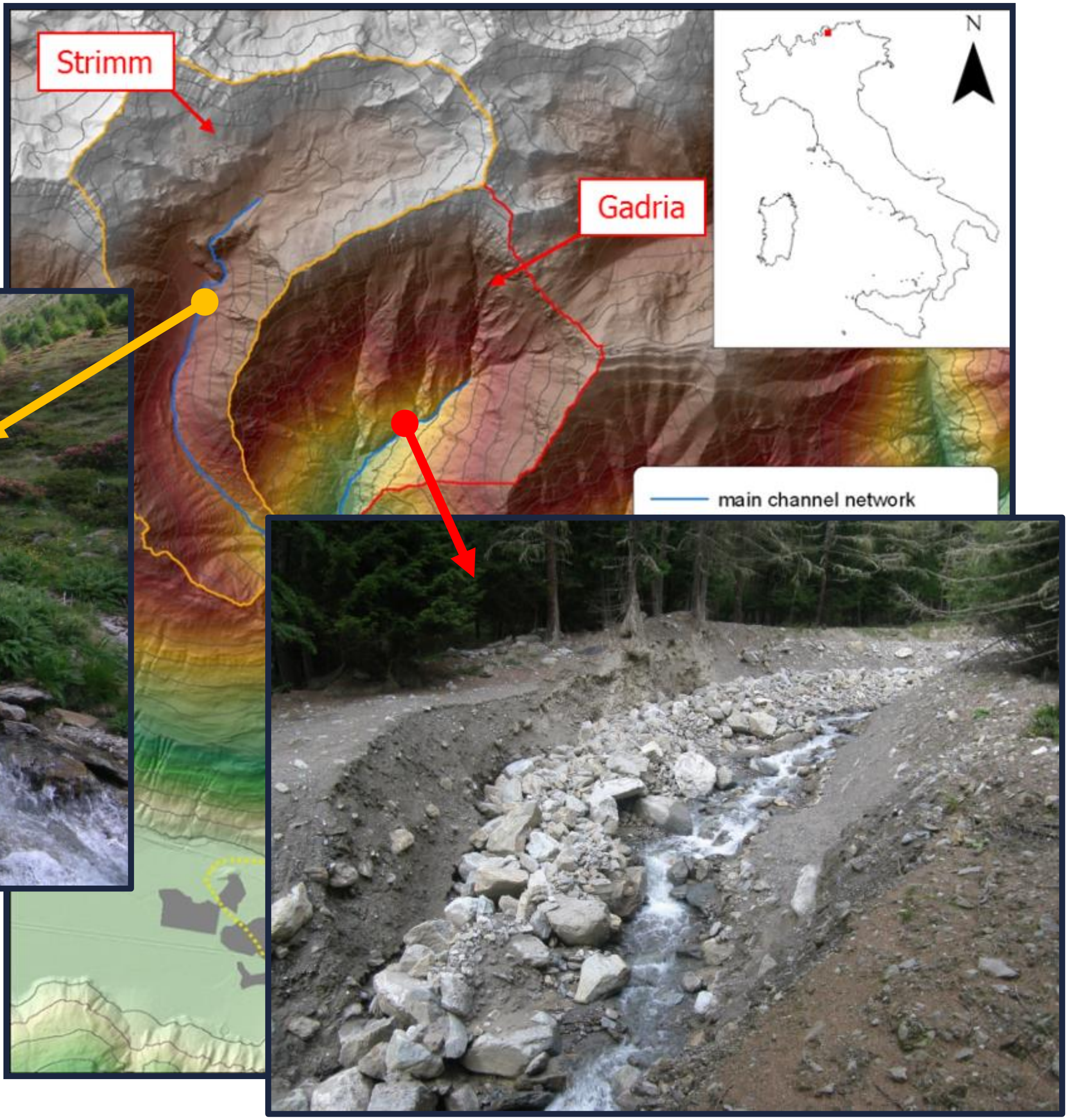


Trevisani, S., Cavalli, M., 2016. Topography-based flow-directional roughness: potential and challenges. Earth Surf. Dyn. 4, 343–358. doi:10.5194/esurf-4-343-2016

Gadria and Strimm study case

Gadria and Strimm catchments

(Eastern Italian Alps)



Lithology: mica-schist, gneiss, an

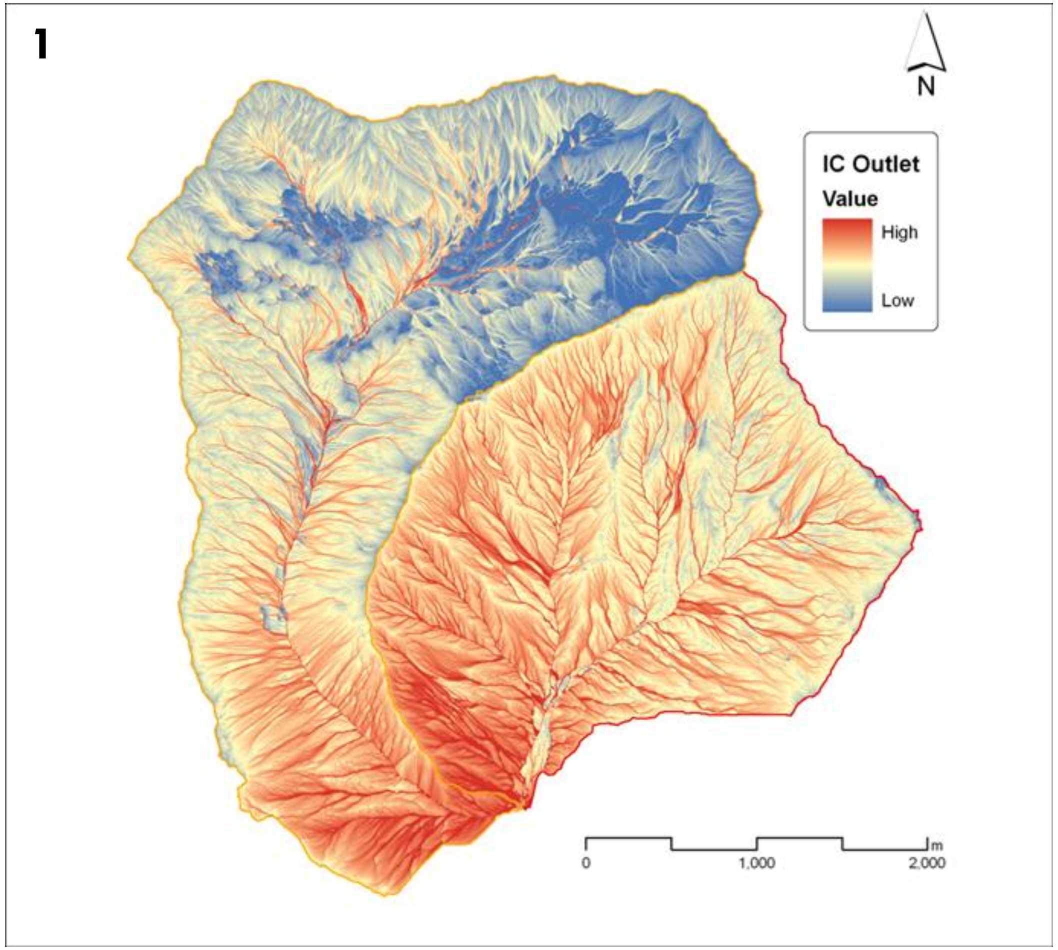
Land use: coniferous forest, mou debris.

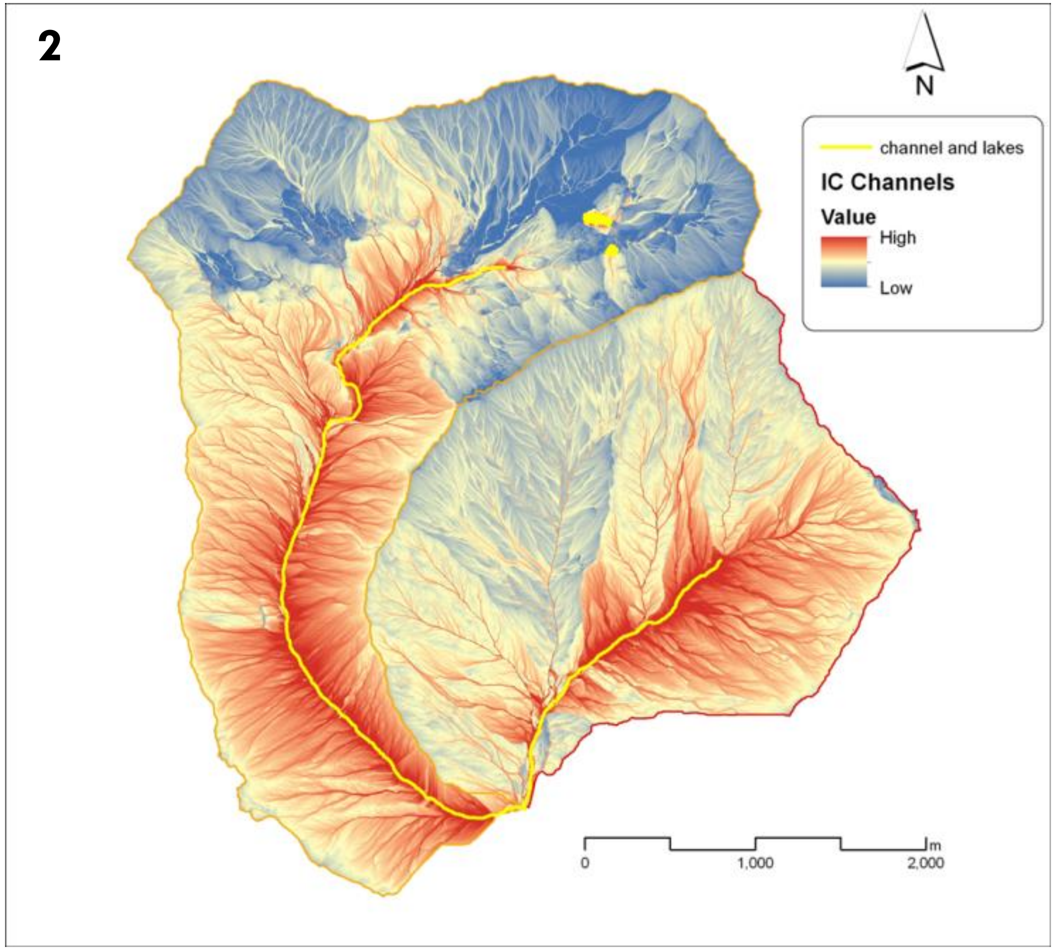
Annual rainfall: around 500 mm increase with elevation.

Gadria: drainage area 6.36 km 2945 m.

Strimm: drainage area 8.5 km^2, m.

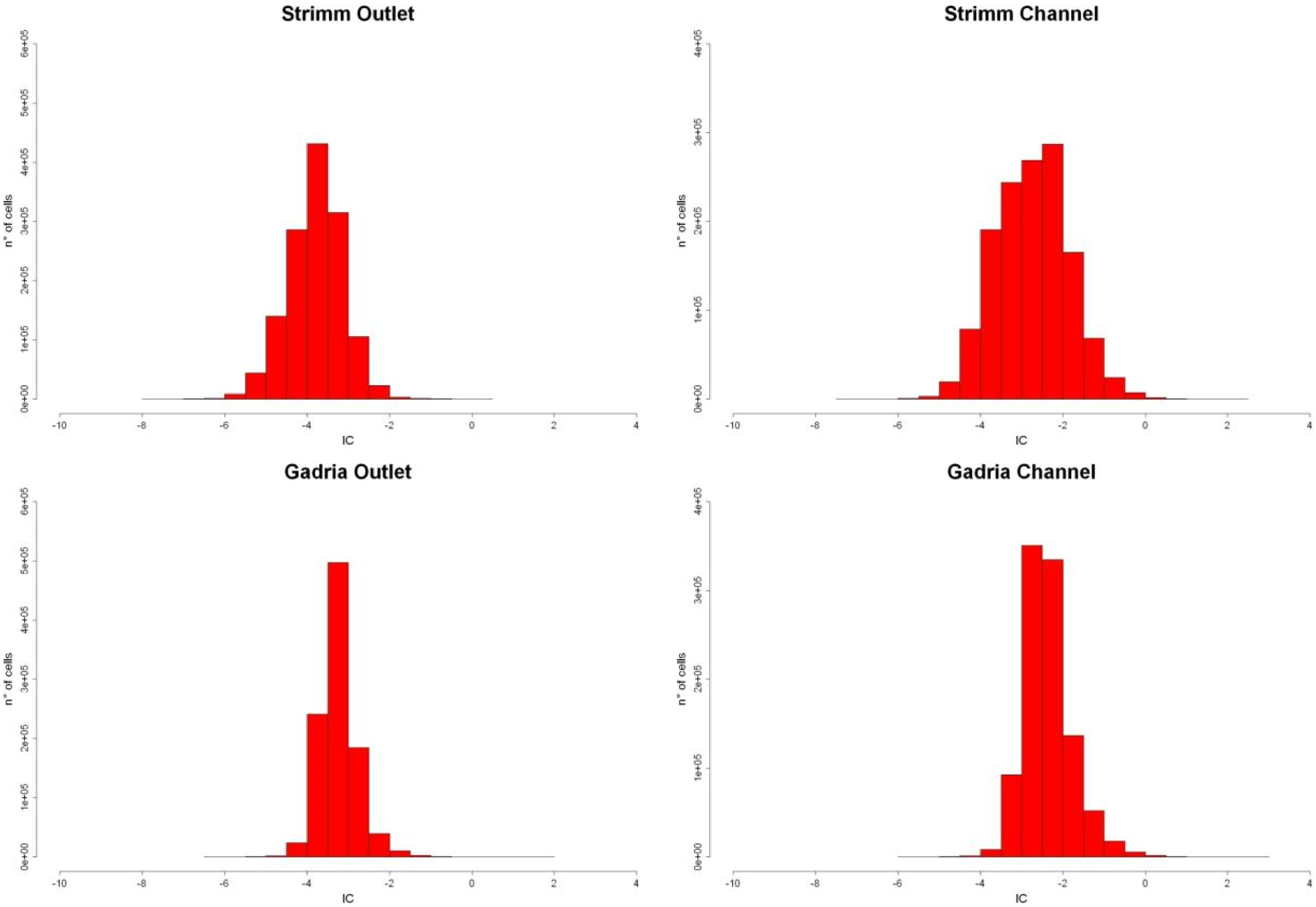
Two scenarios





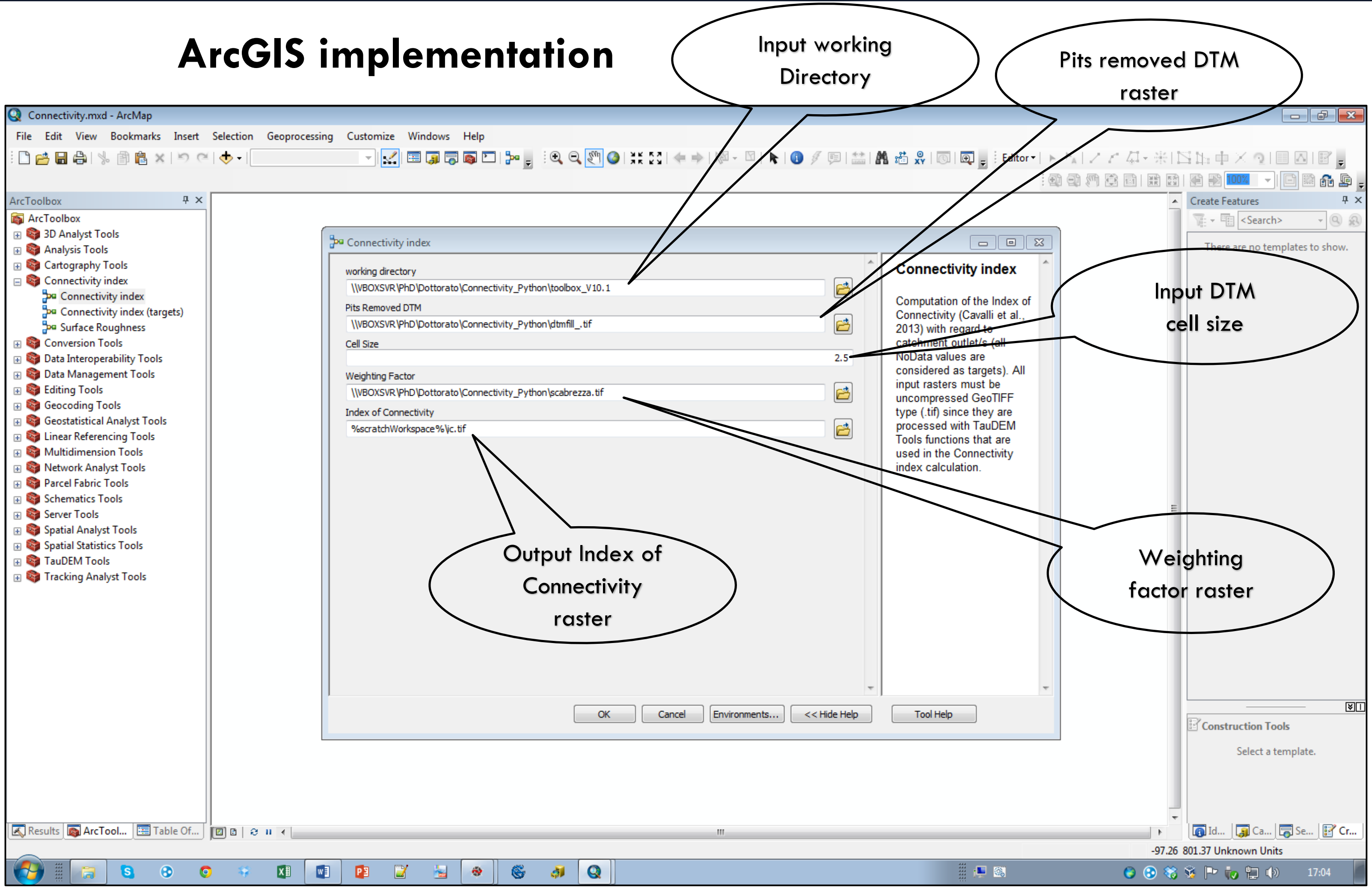
Calculation of IC in order to evaluate the connectivity between:

1. Hillslopes and catchment outlet (IC outlet);
2. Hillslopes and main streams (IC channels).


Strimm Outlet
Strimm Channel
Gadria Outlet
Gadria Channel
n° of cells
IC
0e+00
1e+05
2e+05
3e+05
4e+05
5e+05
6e+05
-10
-8
-6
-4
-2
0
2
4

Tools for IC computation

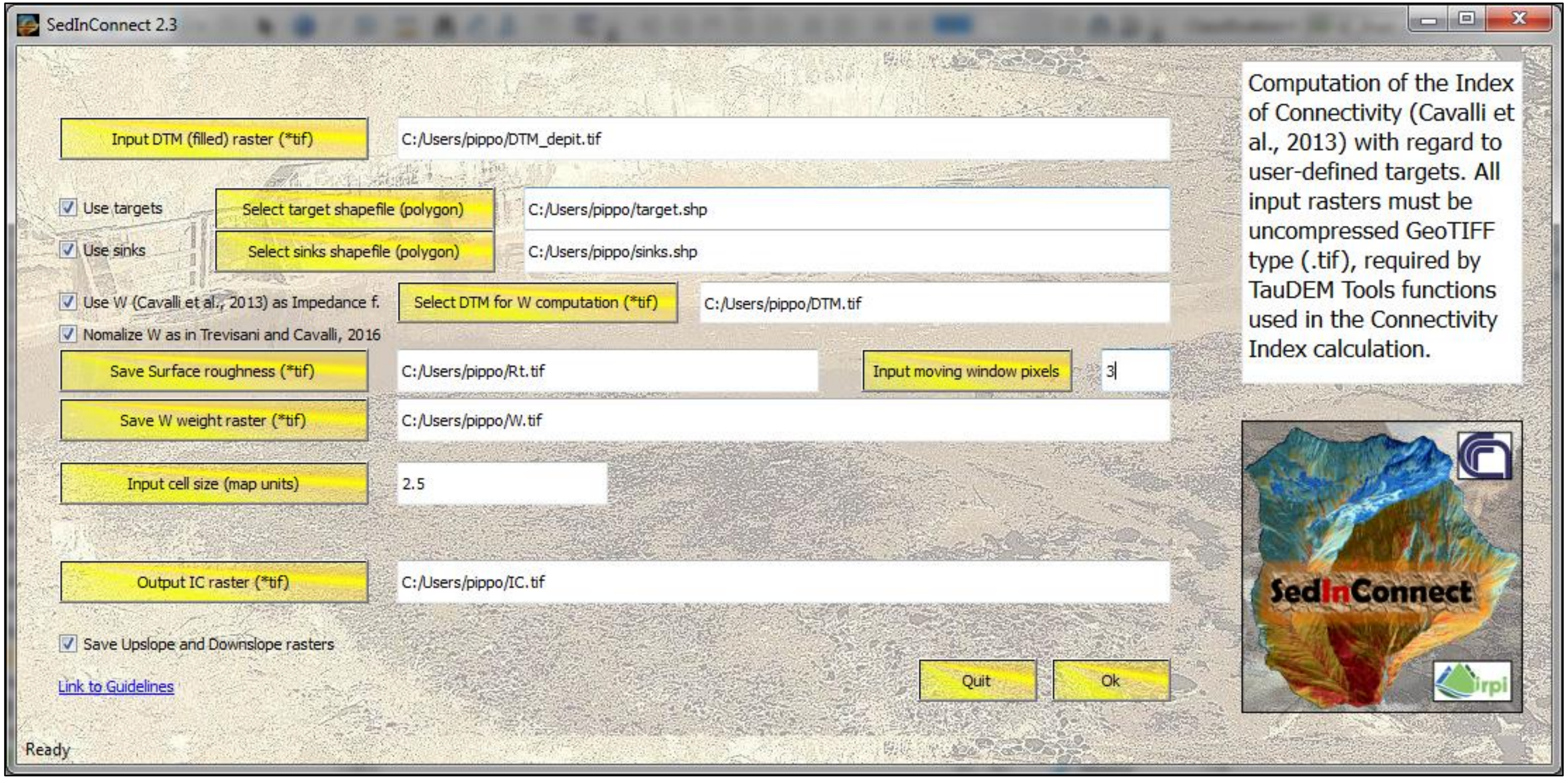
ArcGIS implementation



- Running under ArcGIS version 10.1 (with SP1!) or higher.
- It requires the installation of TauDEM 5.x

https://github.com/HydrogeomorphologyTools/Connectivity-Index-ArcGIS-toolbox

Open-source implementation (**SedInConnect 2.3**) (Crema & Cavalli, 2018)



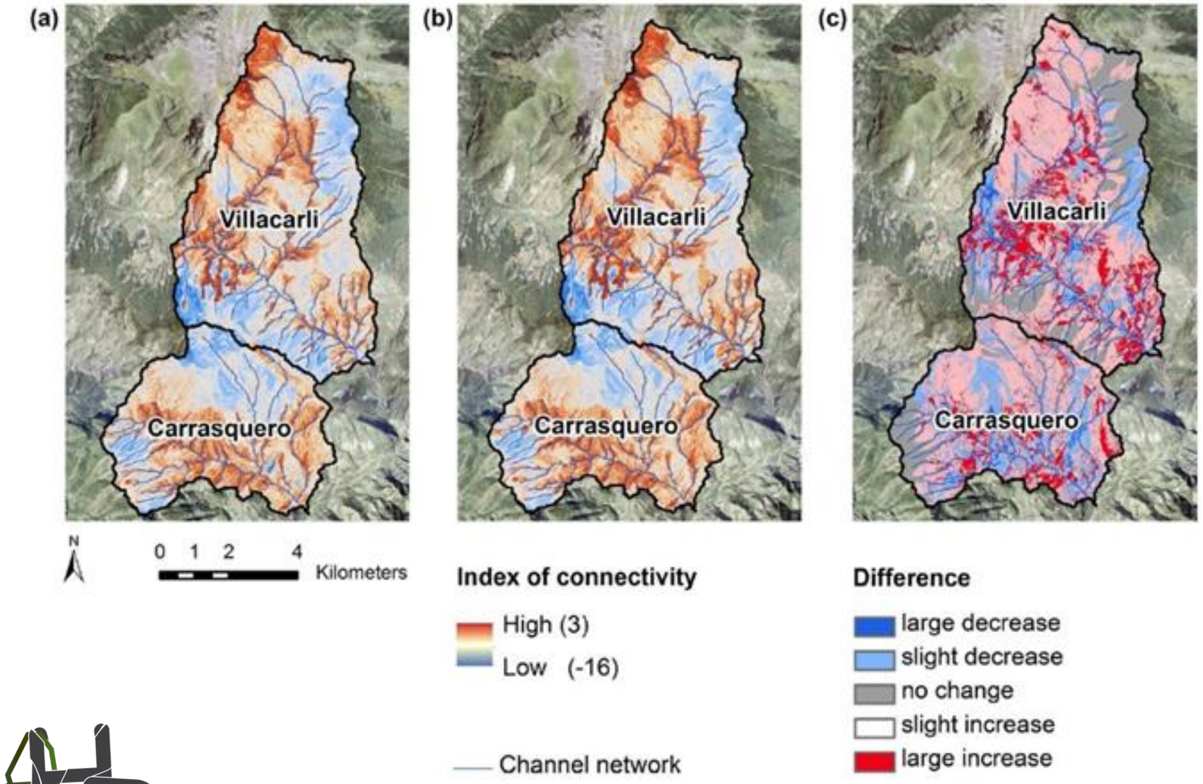
- It avoids the use of commercial GIS;
- It implements the “Sink” function.

https://github.com/HydrogeomorphologyTools/SedInConnect_2.3

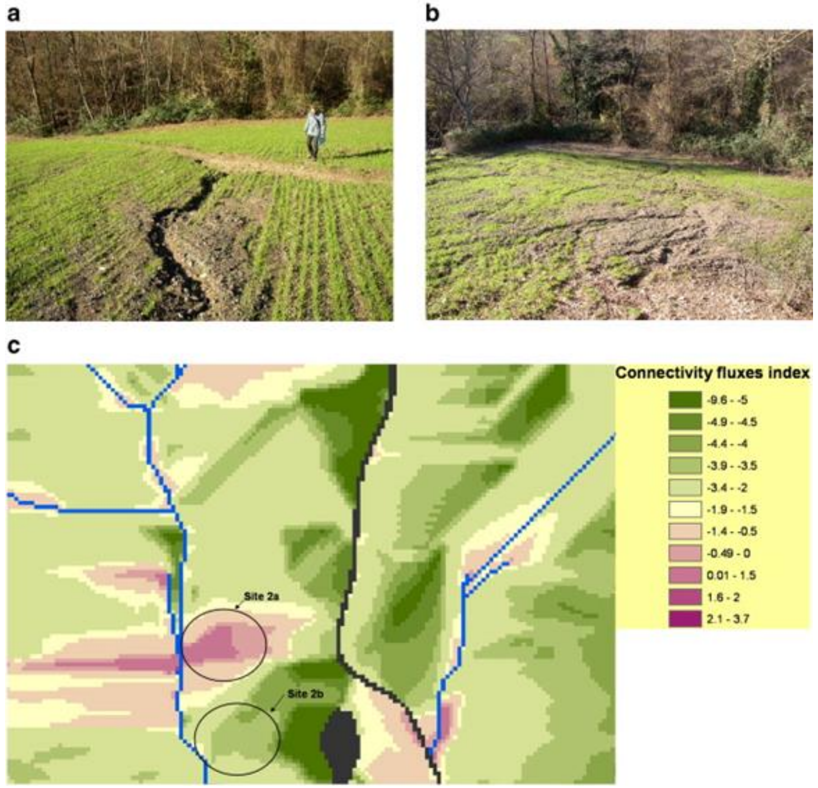
http://www.sedalp.eu/download/tools.shtml

Applications of IC using the C-factor

- The IC by Borselli (2008) was successfully applied in other catchments in the Mediterranean region (López-Vicente et al., 2013, 2014, 2015; Sougnez et al., 2011) to estimate erosion rates and different scenarios of land use and land abandonment;
- It has proven useful also for estimating hillslope sediment delivery ratio (SDR) (Vigiak et al., 2012; Jamshidi et al., 2014).

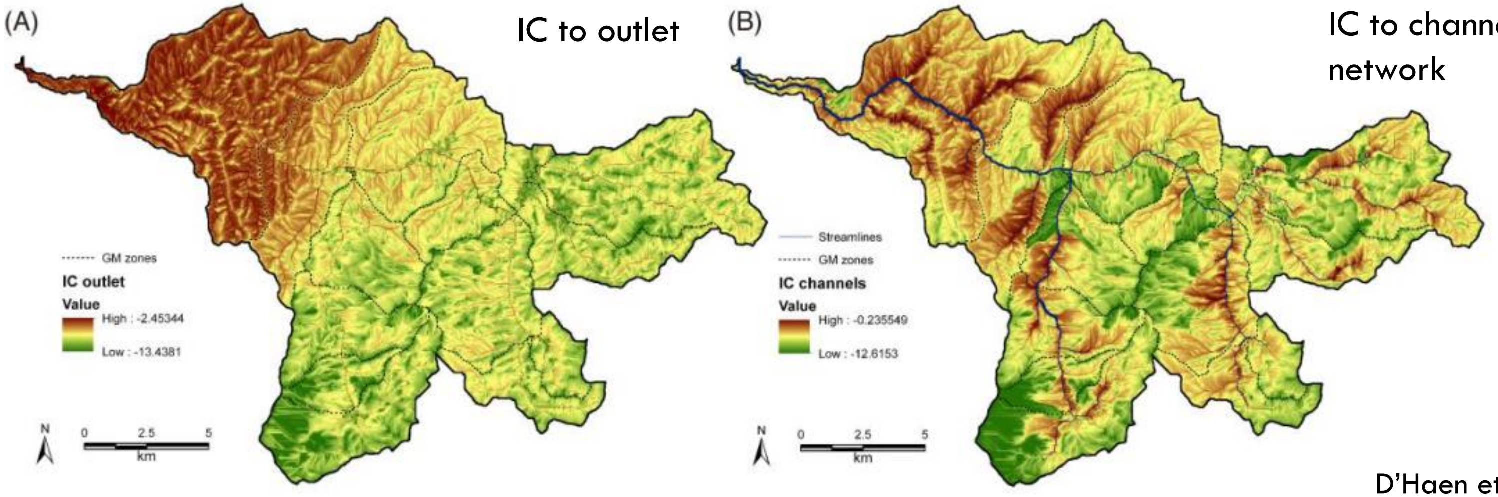


Foerster et al., 2014

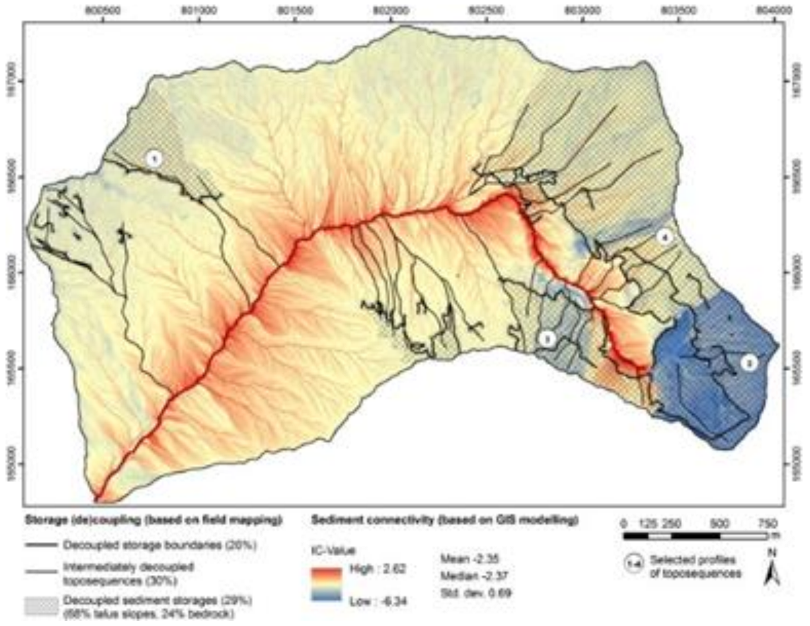


Borselli et al., 2008

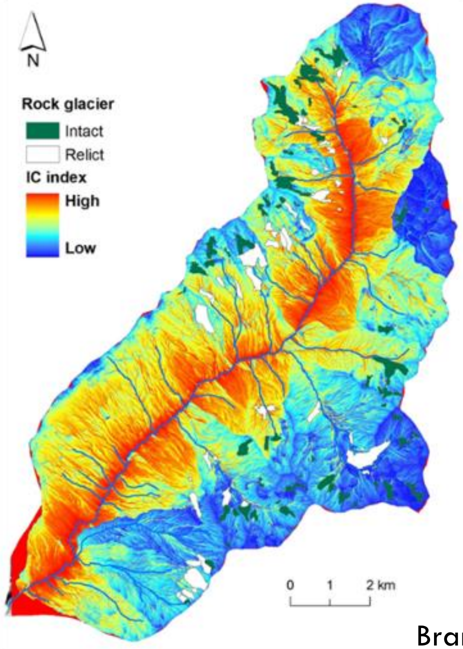
Applications of IC using the Roughness



D'Haen et al. (2013)



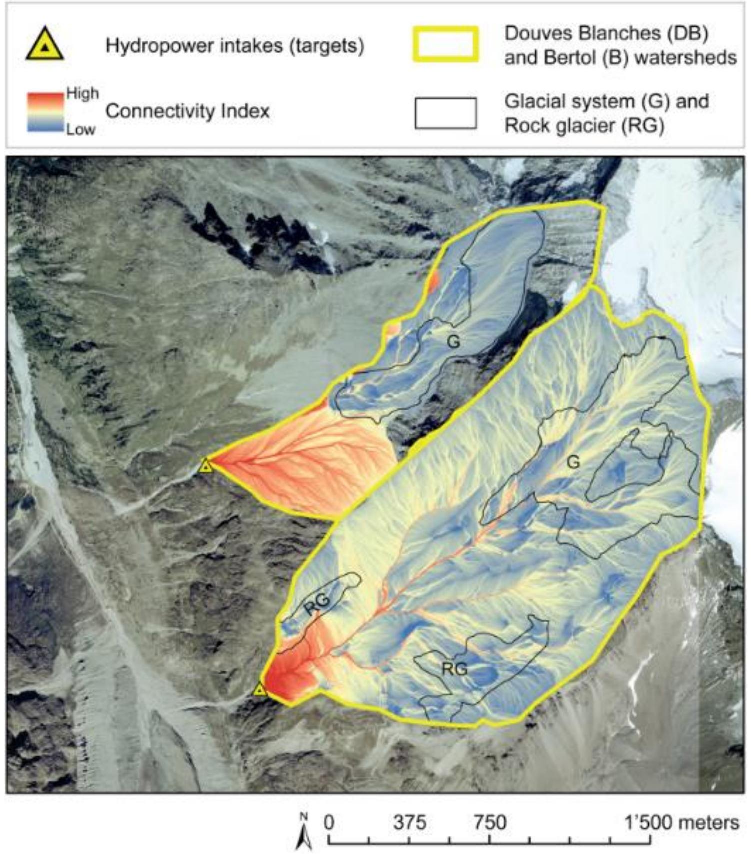
Messenzehl et al. (2014)



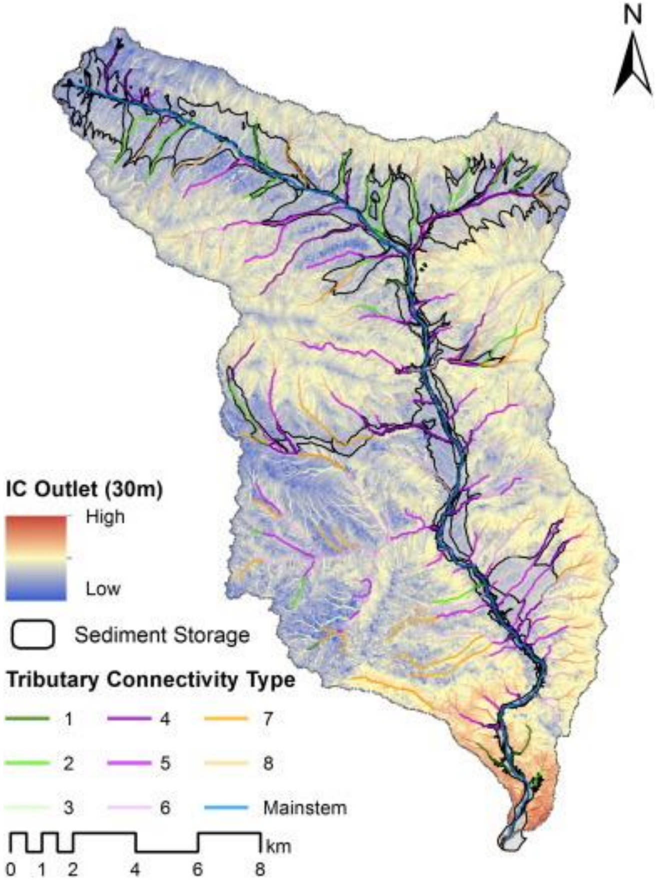
Brardinoni et al. (2015)

Applications of IC using the Roughness

- IC to evaluate the connection of sediment source inventories to the channel network in order to prioritize sediment sources or to assess sediment supply (Cavalli et al., 2016; Surian et al., 2016; Tiranti et al., 2016);
- IC supported the interpretation of radioactive dose rate measurements after the Fukushima nuclear accident in nearby catchments (Evrard et al., 2013)

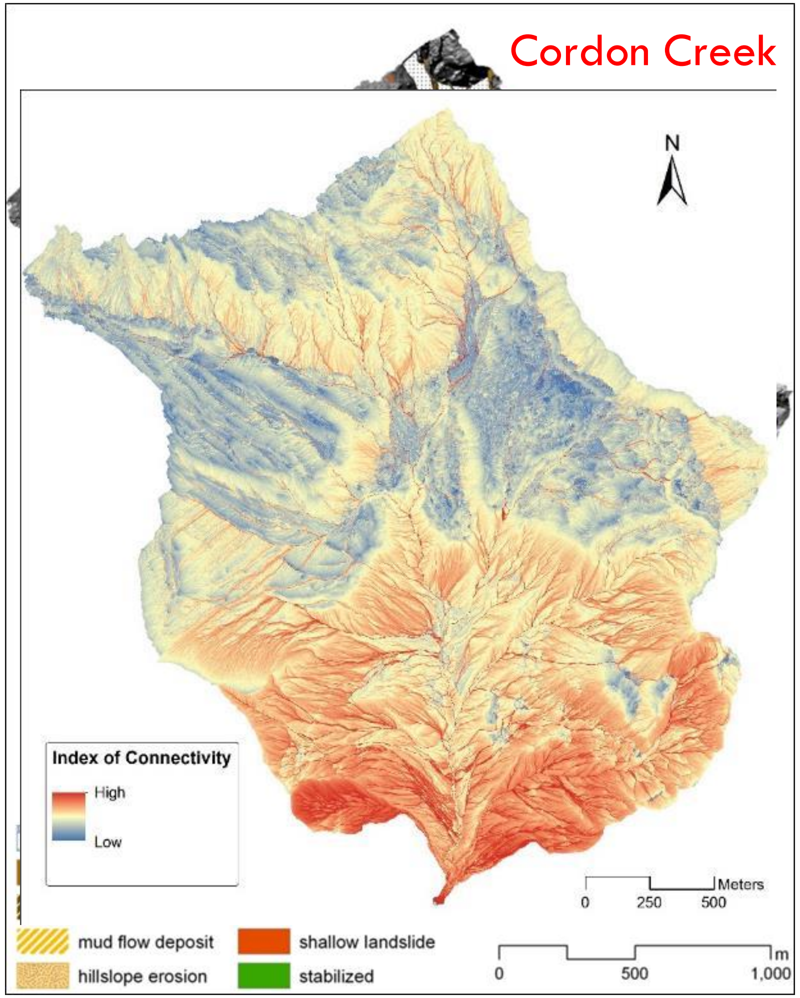


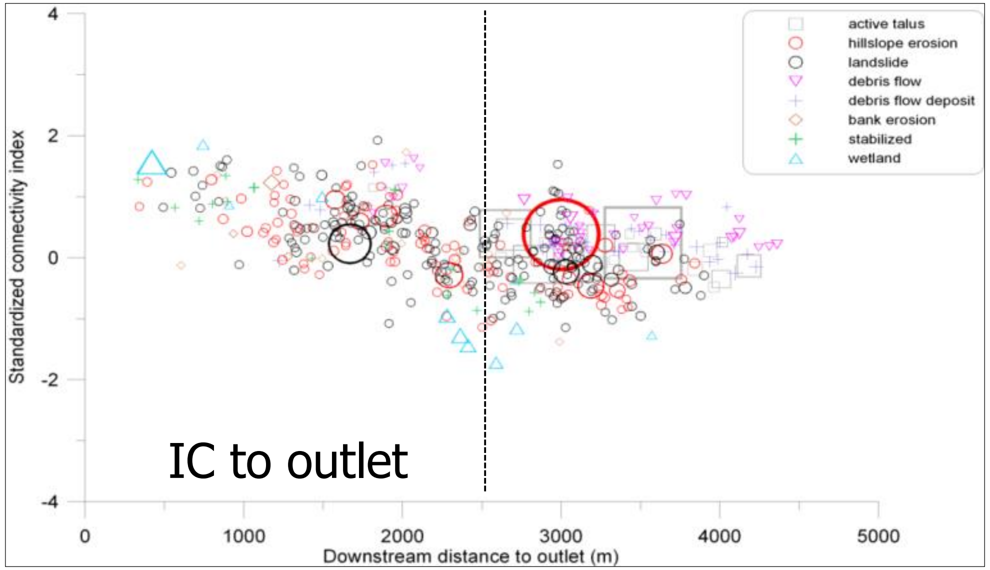
Micheletti and Lane, 2016

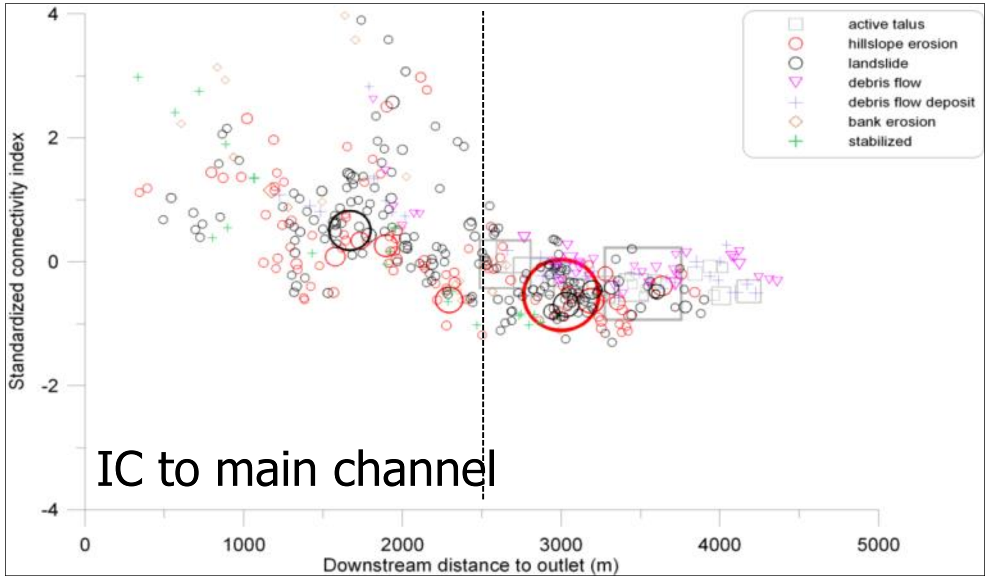


Nicoll and Brierley, 2016

IC and sediment source areas



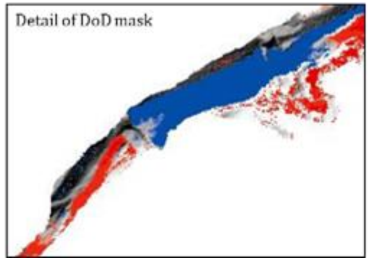


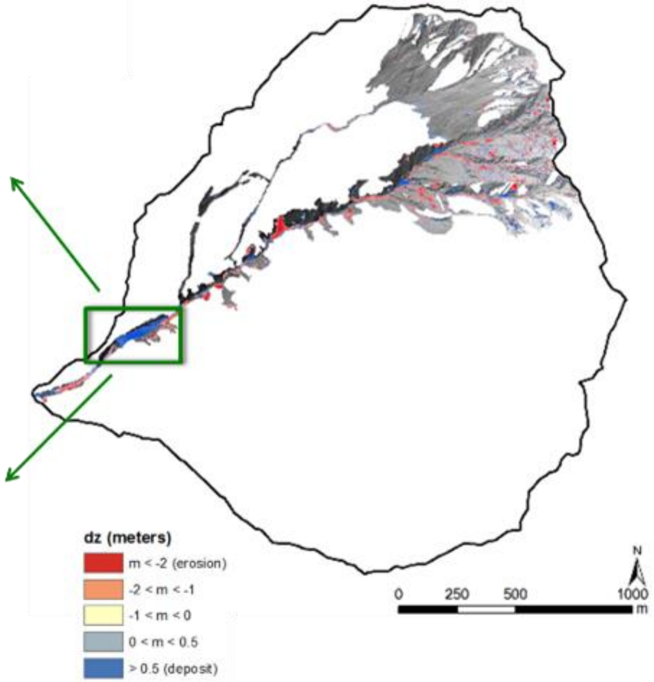


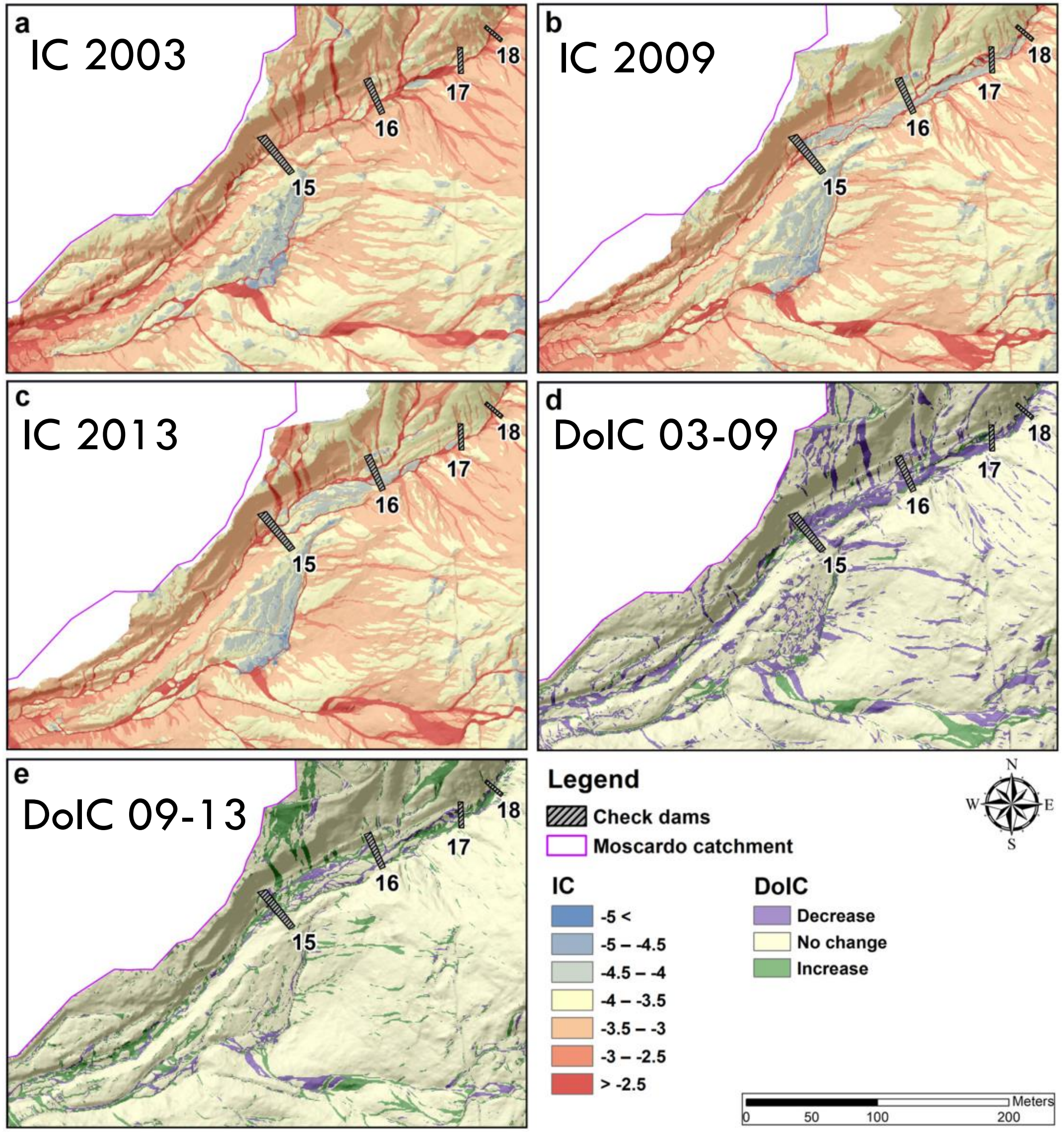
Cavalli, M., Tarolli, P., Dalla Fontana, G., Marchi, L., 2016. Multi-temporal analysis of sediment source areas and sediment connectivity in the Rio Cordon catchment (Dolomites). Rendiconti Online Della Soc. Geol. Ital. 39, 27–30.

Multitemporal analysis of IC

- Understand the check dams' effects on sediment dynamics in a debris flow catchment at different spatial scales;
- Integration of DoD and IC analyses over time.



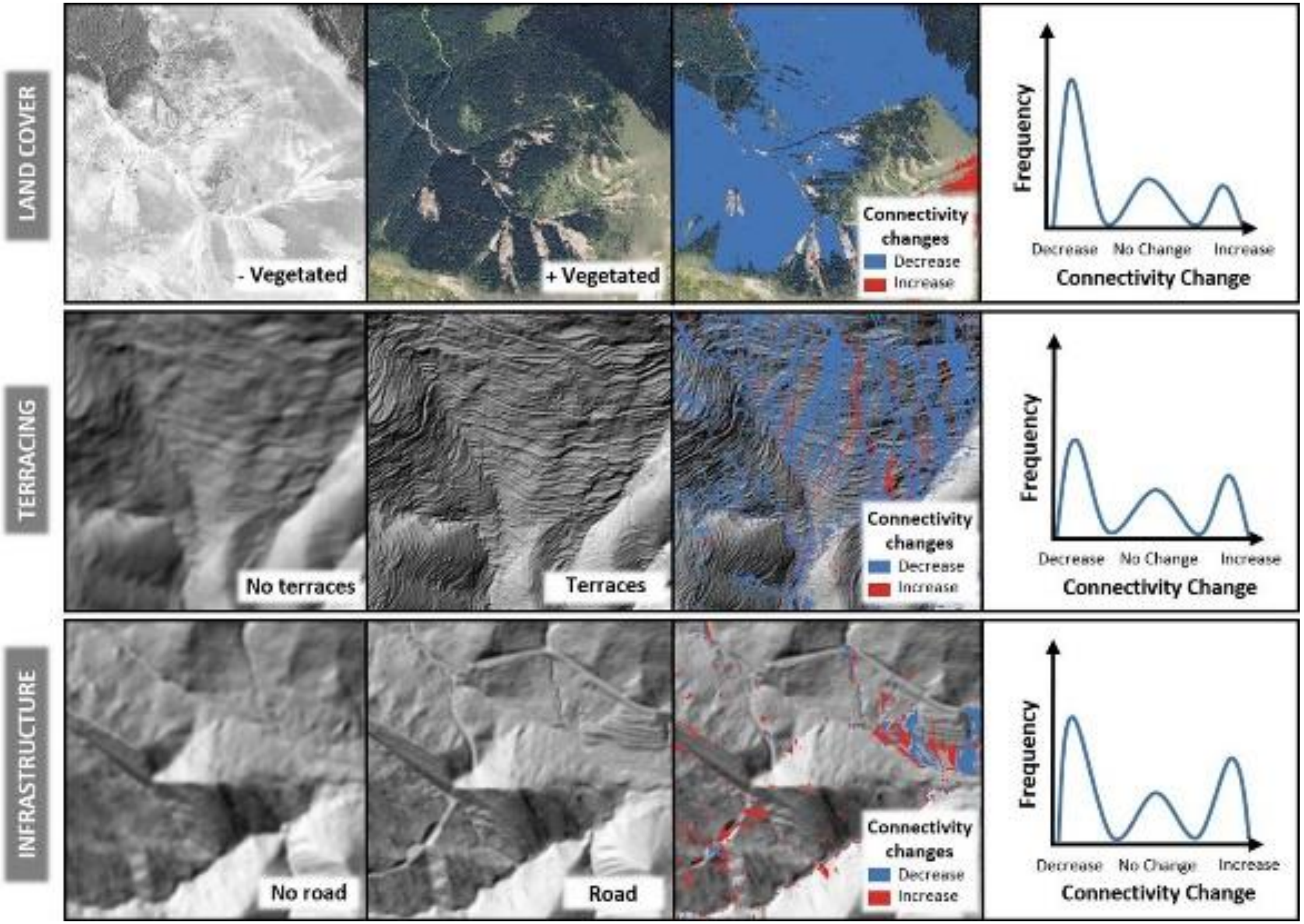




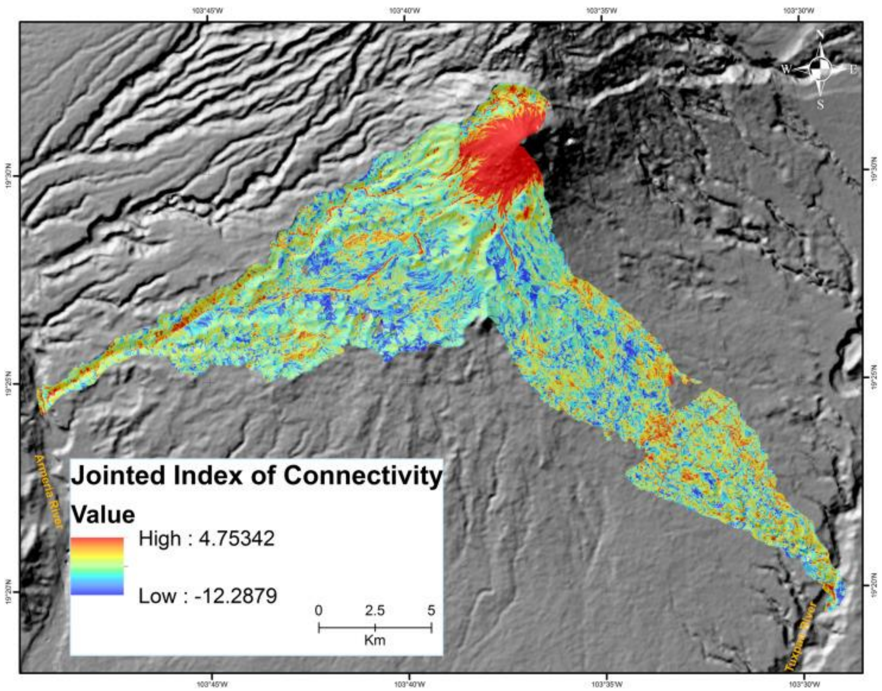
Cucchiaro S., Cazorzi F., Marchi L., Crema S., Beinat A., Cavalli M., 2019. Multi-temporal analysis of the role of check dams in a debris-flow channel: Linking structural and functional connectivity. Geomorphology, 345, 106844.

Assessment of historical IC

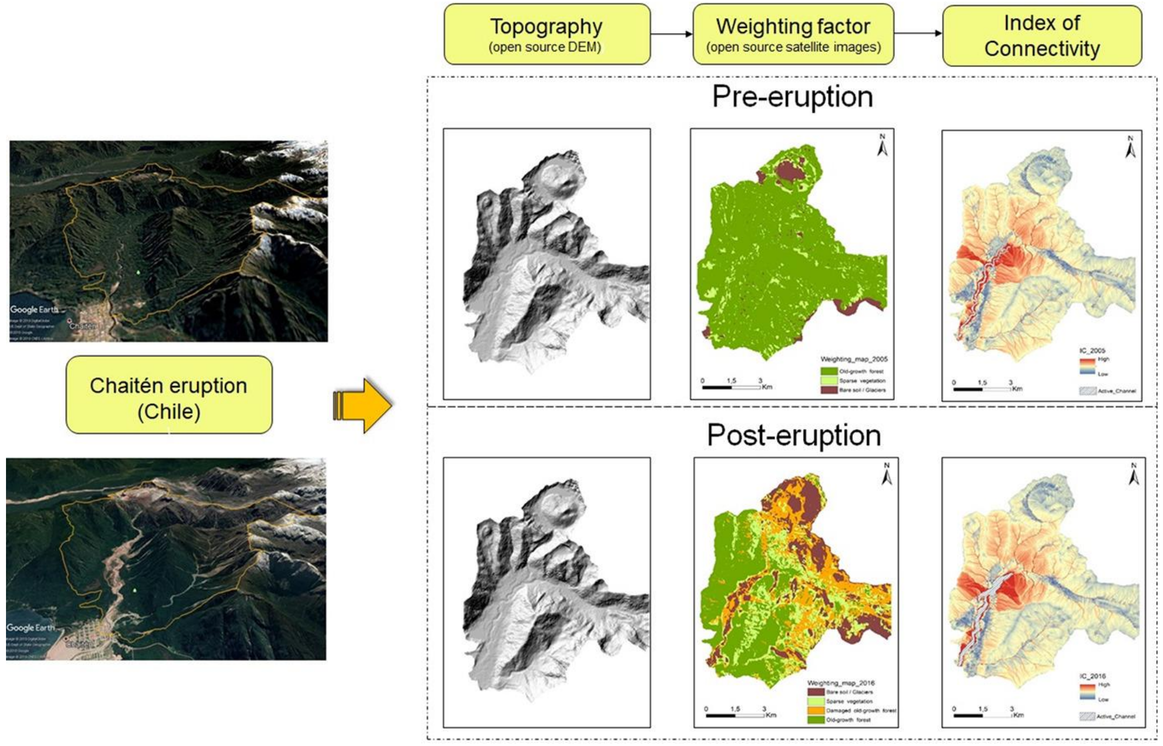
- The Pyrenees suffered significant land use changes due to agricultural abandonment inducing an increase in the vegetation cover but also a series of associated morphological changes (e.g. terraces);
- The effects of these changes on connectivity were investigated in the Upper River Cinca Catchment (Spain)



Llena M., Vericat D., Cavalli M., Crema S., Smith M.W., 2019. The effects of land use and topographic changes on sediment connectivity in mountain catchments. Science of The Total Environment, 660, 899-912.



Ortíz-Rodríguez et al., 2017



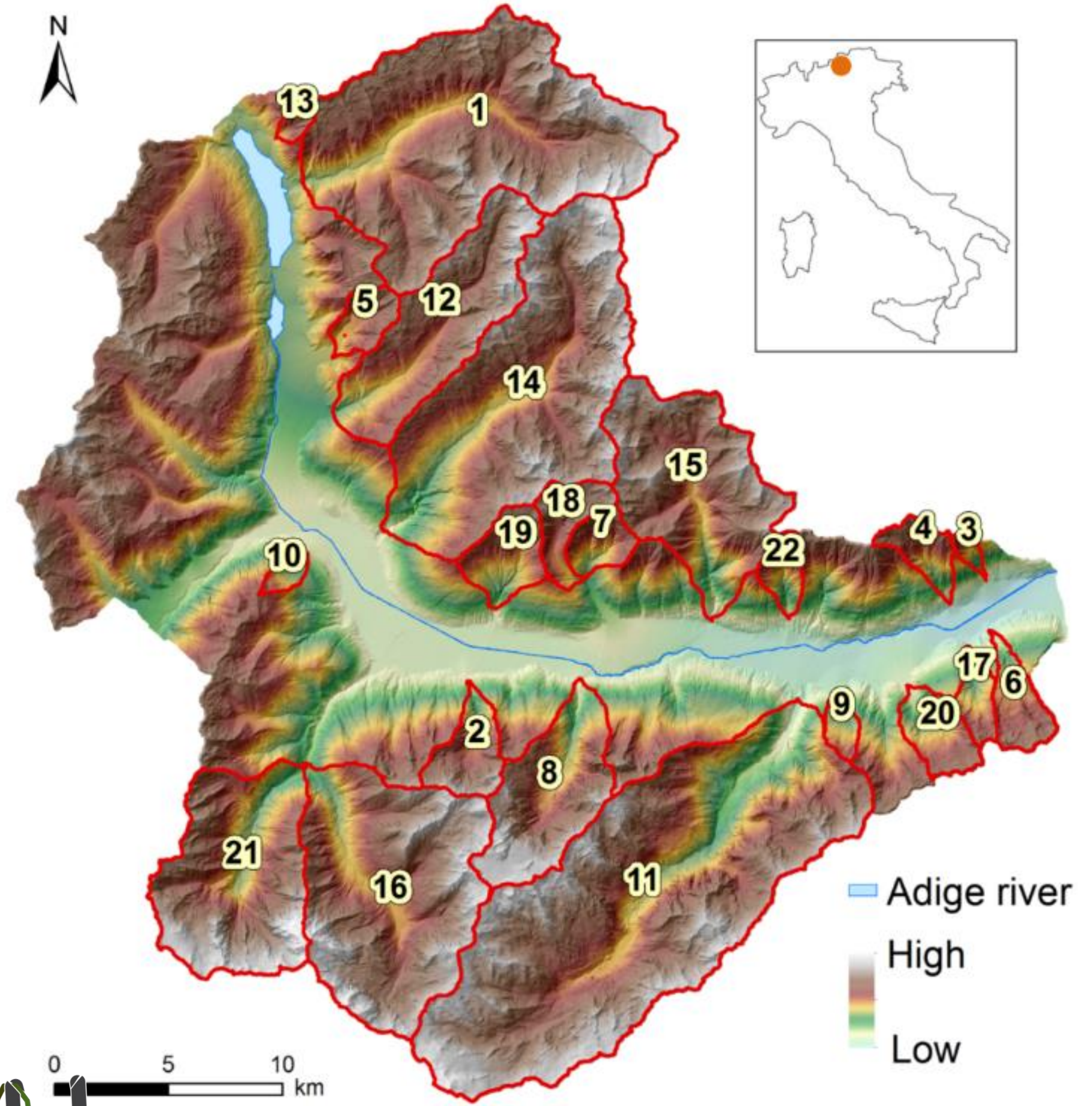
Martini et al., 2019

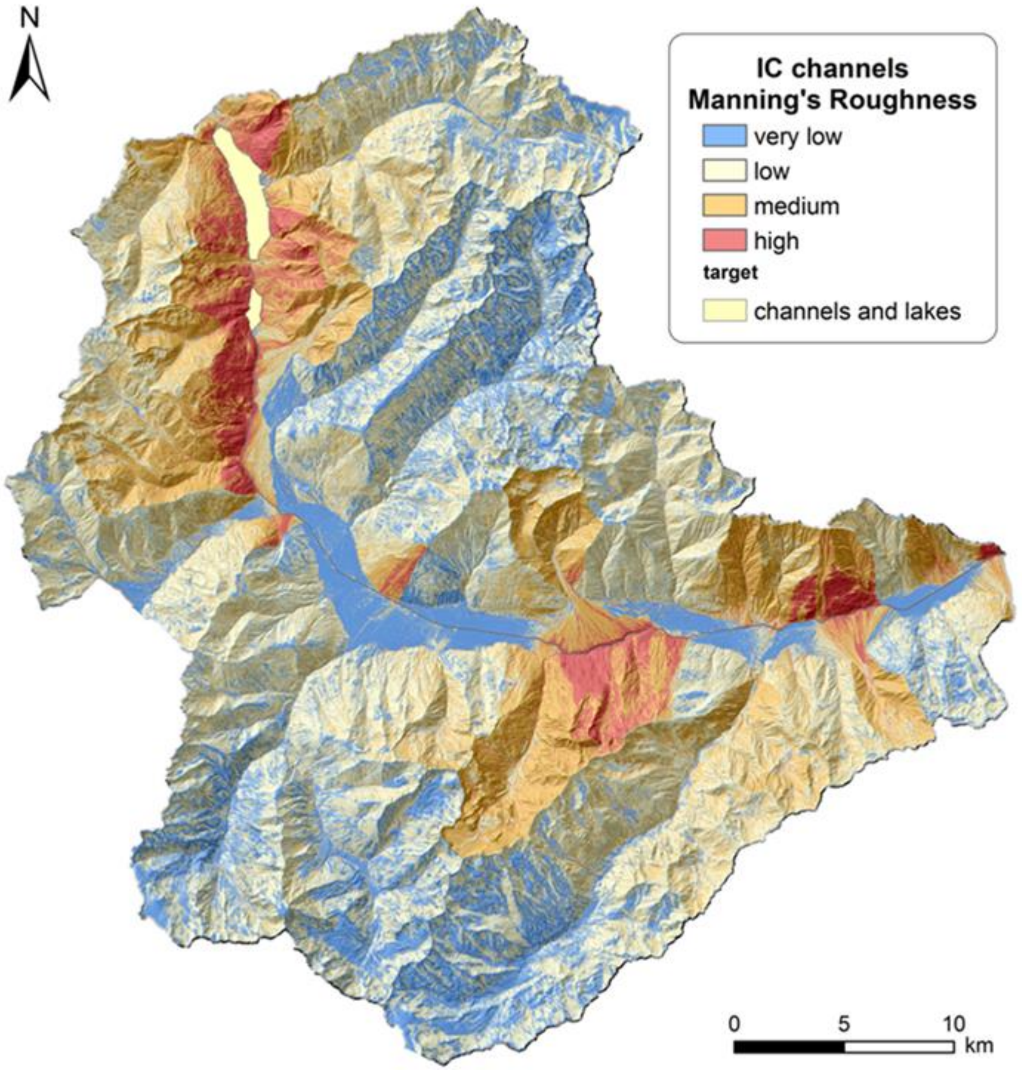
- A new joint index of connectivity (IC_J) was proposed combining two methods in the Colima Volcano (Mexico).
- A lateral hydrological efficiency index (LHEI) by using IC_J and area was developed.

Ortíz-Rodríguez, A.J., Borselli, L., Sarocchi, D., 2017. Flow connectivity in active volcanic areas: use of index of connectivity in the assessment of lateral flow contribution to main streams. CATENA 157, 90–111. https://doi.org/10.1016/j.catena.2017.05.009.

- Investigating the effect of a volcanic eruption on lateral sediment connectivity in a Chilean river basin (Chaiten Volcano).
- Multi-temporal analysis of IC summarize the response of the catchment to the eruption.

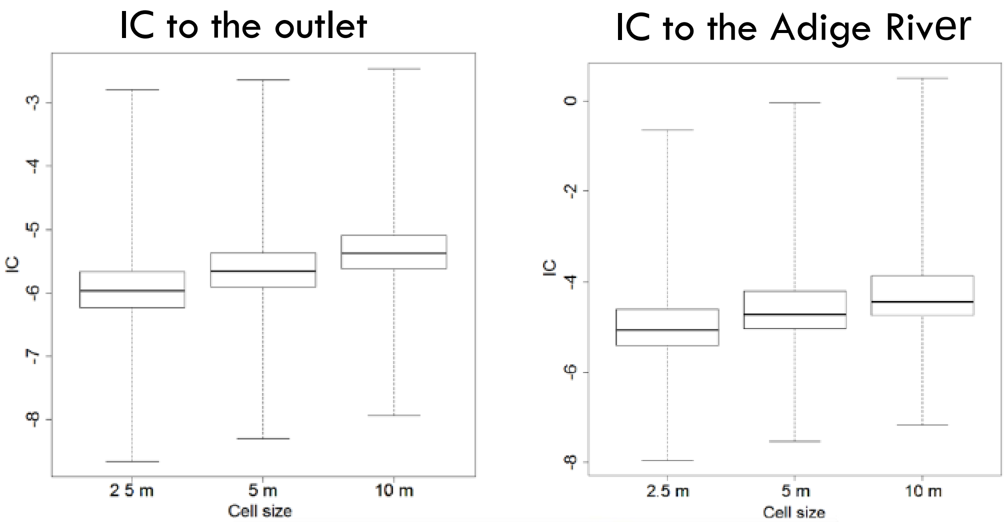
Martini L., Picco L., Iroumé A., Cavalli M., 2019. Sediment connectivity changes in an Andean catchment affected by volcanic eruption. Science of the Total Environment, 692, 1209-1222. DOI: 10.1016/j.scitotenv.2019.07.303



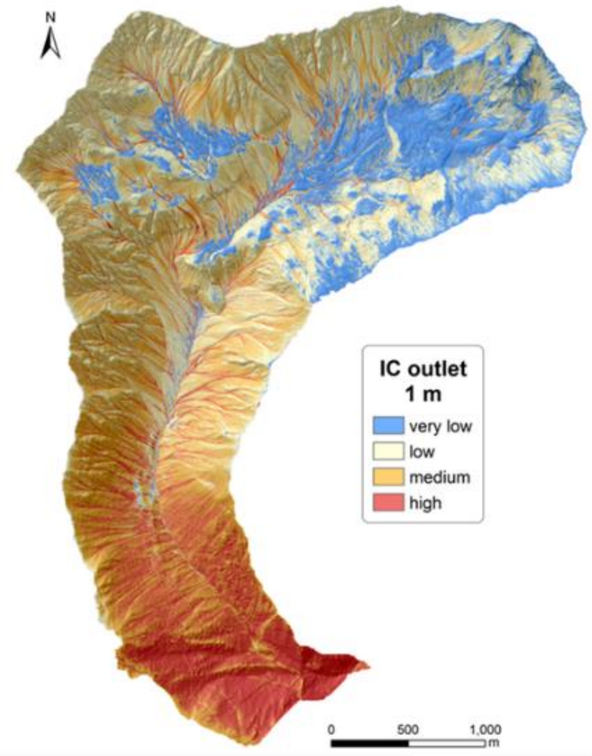


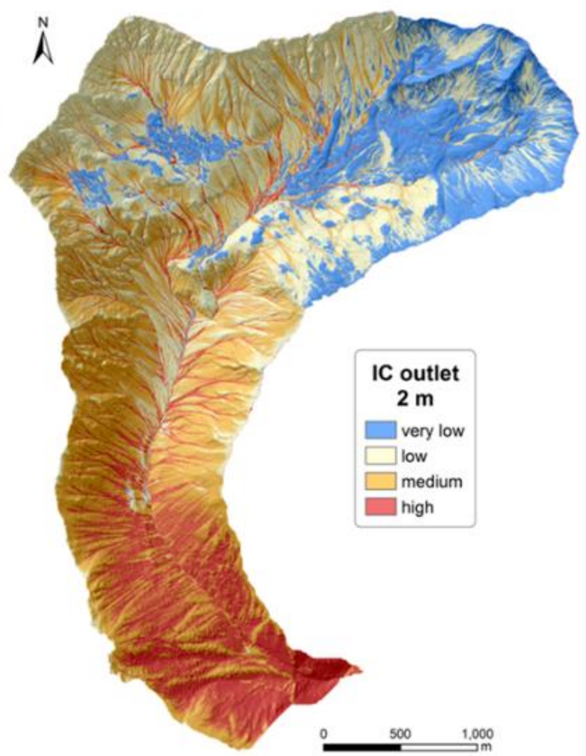
1096 km^2 area – LiDAR DTM with 2.5 m resolution

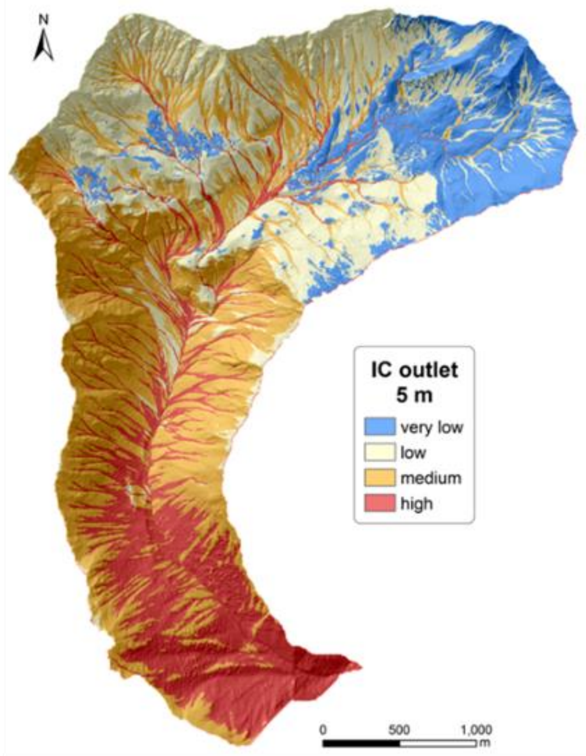
Venosta Valley (Eastern Italian Alps) is a typical inner-Alpine dry valley, dominated by metamorphic lithologies (Goldin, 2015, PhD thesis)



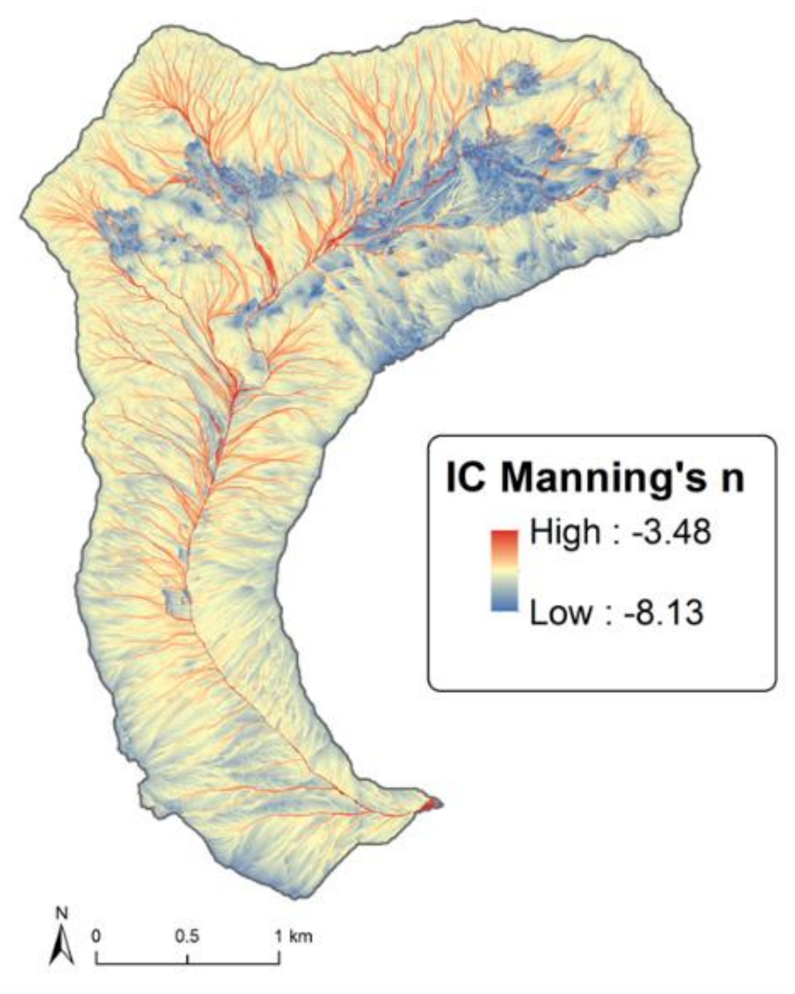
- slight increase in IC values with decreasing resolution;
- more evident for the application of IC with regard to the Adige River;
- simplification of the flow paths due to increased cell size leads to an increase of IC values.

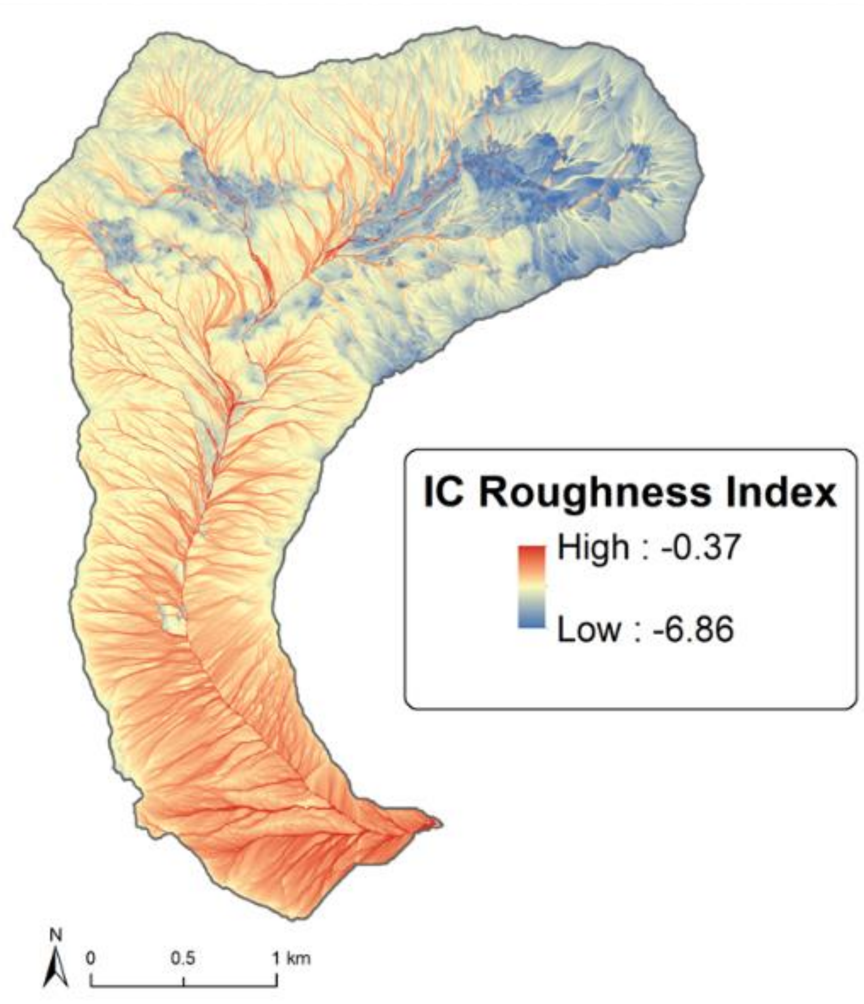


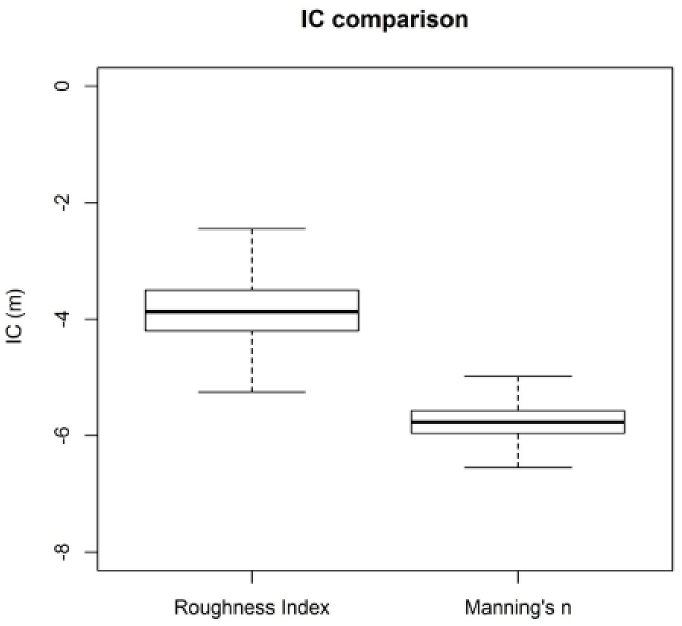




Manning’s n vs. topographic roughness

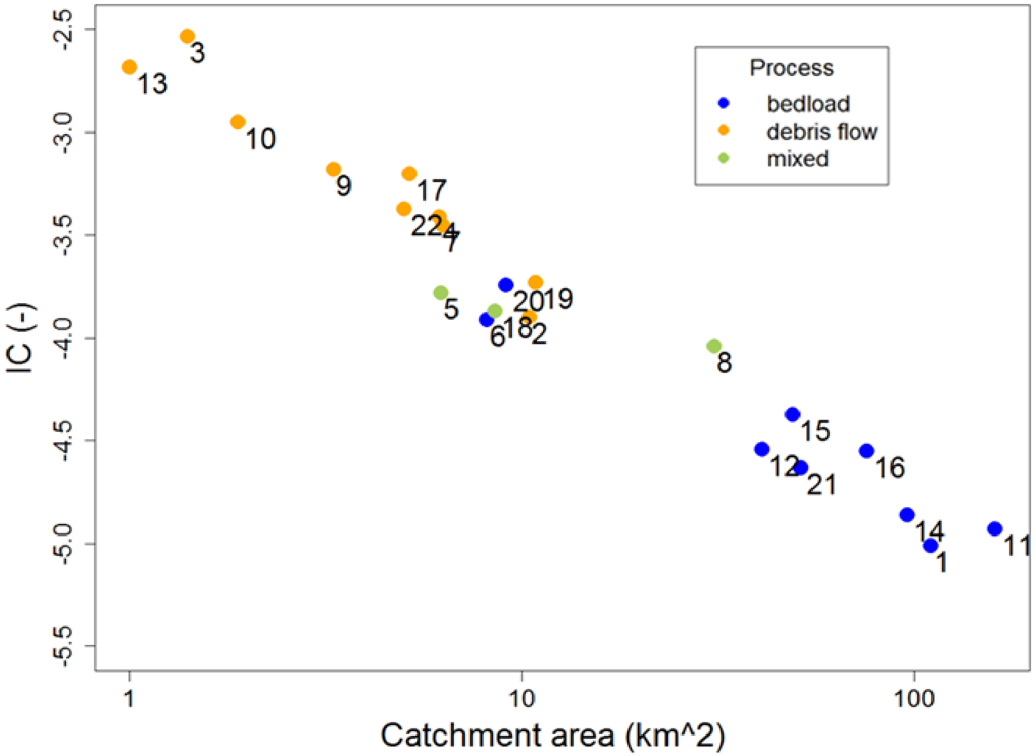




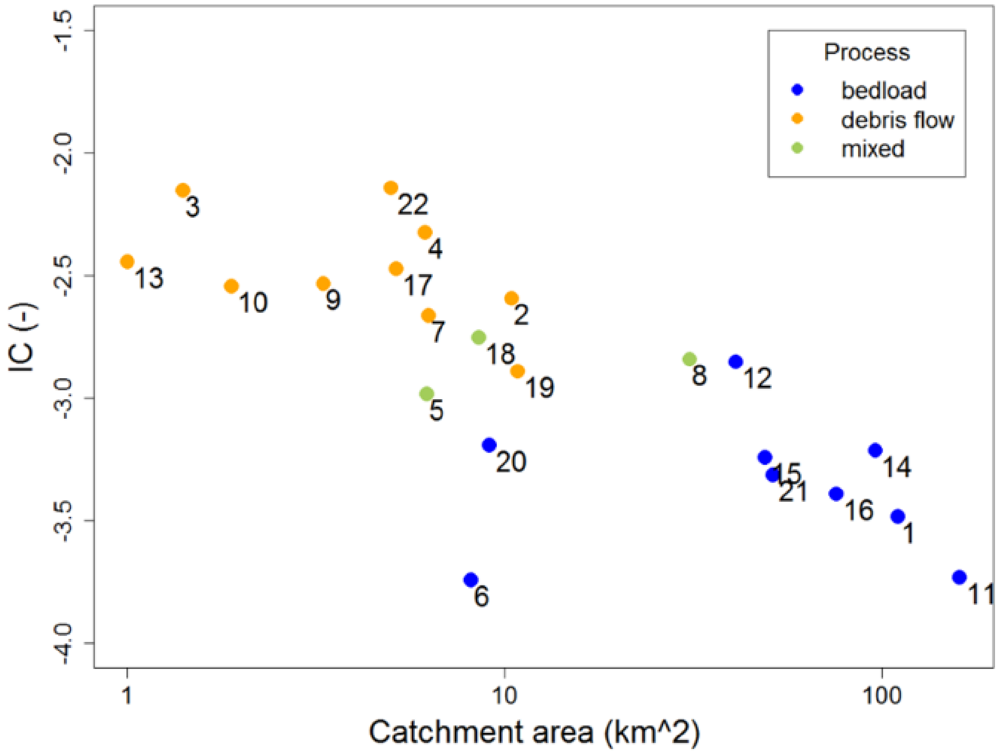


CORINE Land Cover	Manning's n
Arable land	0.2
Artificial/non-agricultural vegetated area	0.02
Bare rock	0.05
Forest	0.4
Glacier	0.01
Grassland	0.1
Heterogeneous agricultural areas	0.2
Industrial or commercial units	0.02
Mine, dump, construction sites	0.01
Open space with little or no vegetation	0.15
Pasture	0.25
Permanent crops	0.2
Road and rail networks and associated land	0.01
Shrub/herabceous vegetation association	0.3
Urban fabric	0.02
Water body	0.001
Water courses	0.001
Wetlands	0.001

- different pattern when different impedance factors are used;
- overall lower IC values with Manning’s n.



Target: catchment outlet (fan apex)



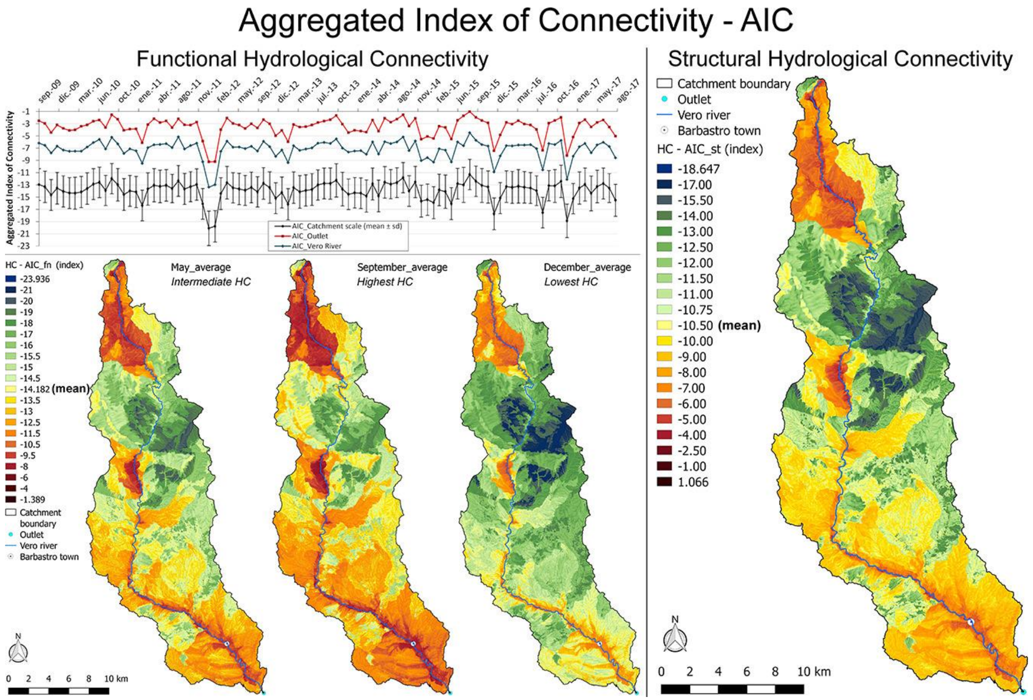
Target: main channel

When analyzing separately *Dup* and *Ddn:*

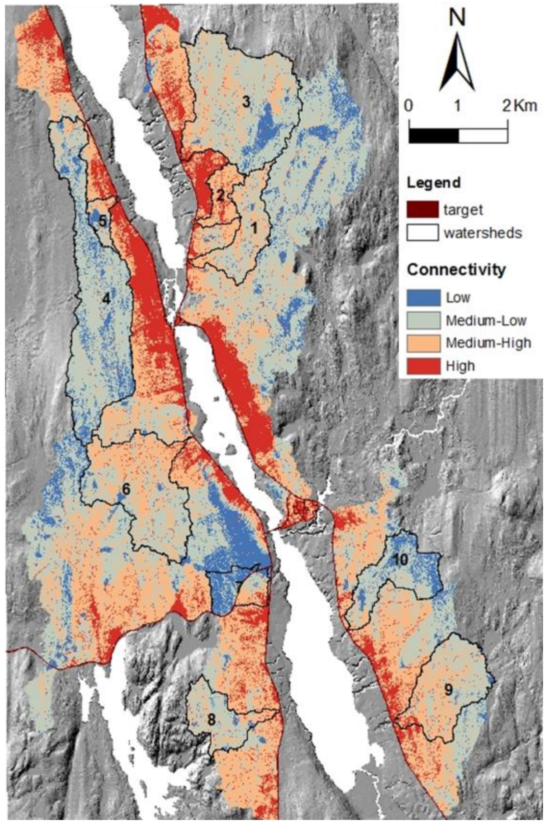
- no relationship is observed between *Dup* and catchment area;
- data show a positive correlation between *Ddn* and catchment area.

Heiser et al. (2015) used IC among other several parameters to determine the dominant flow process types for steep headwater catchments.

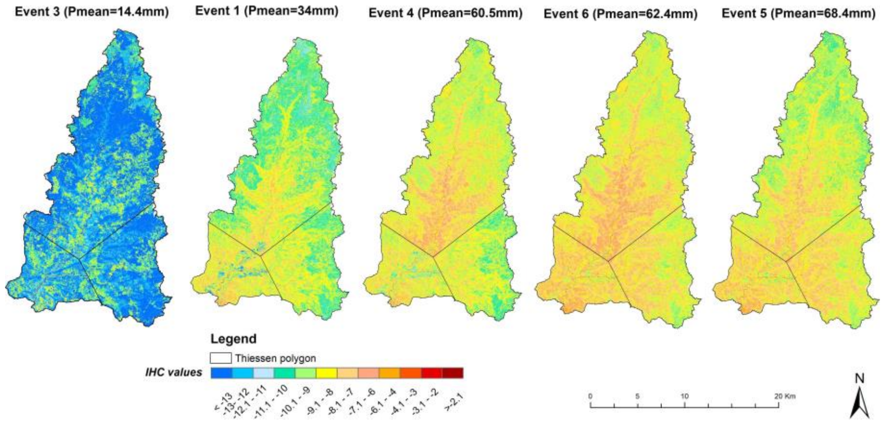
- Kalantari et al. (2017) modified IC including a functional weighting factor based on surface runoff estimate by curve numbers and considering spatially and temporally variable forcing.
- López-Vicente and Ben Salem (2019) proposed a new aggregated index (AIC) based on topography, C-RUSLE factor, RUSLE2 rainfall erosivity, residual topography and soil permeability, to model structural and functional flow and sediment connectivity.
- Zanandrea et al. (2021) integrated two parameters on the runoff generation (SCS Runoff Curve Number method) and the characteristics of the antecedent precipitation.



López-Vicente and Ben Salem (2019)

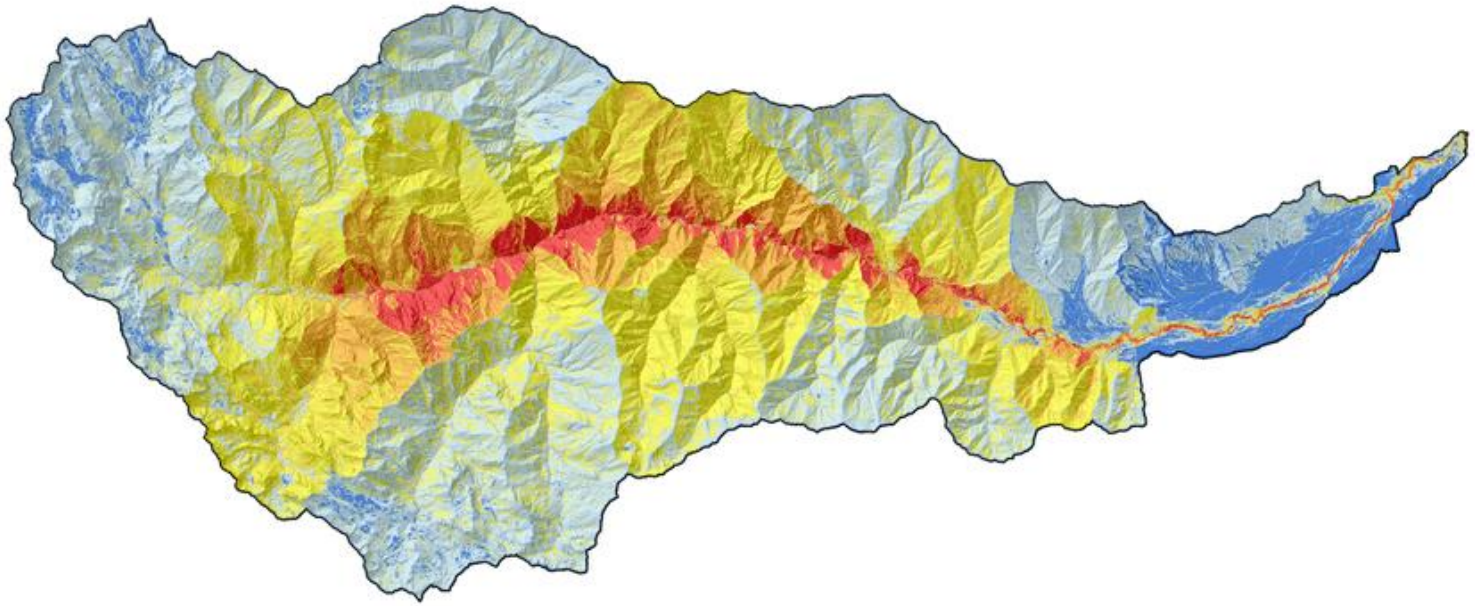


Kalantari et al. (2017)



Zanandrea et al. (2021)

1. IC has proved very promising for a rapid spatial characterization of sediment dynamics both at catchment and regional scales;
2. The reported applications demonstrate that a reliable assessment of sediment connectivity via a geomorphometric approach, especially when integrated with a sediment sources inventory, is useful for giving management priorities;
3. DEM quality and resolution and weighting factor choice have a strong effect on IC results;
4. Future development should also consider process-based connectivity and incorporate temporal variability.



Thank you for your attention!

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