Sediment connectivity and travel times: concepts and applications

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"Summer School on Geomorphology:

Sediment dynamics in high-mountain environments"

31/8-6/9 2015 , Feichten im Kaunertal, Austria

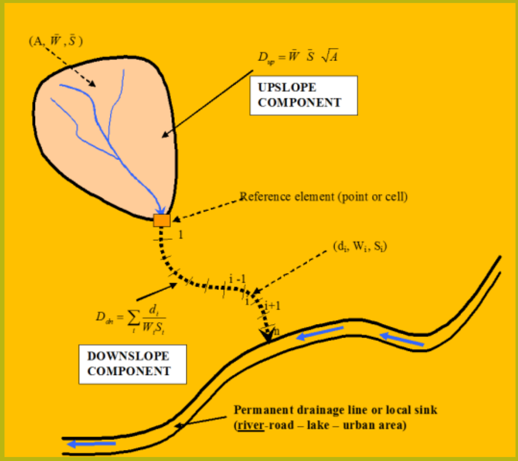
Why a need for Connectivity paradigm and modelling efforts?

MANAGING MODELLING COMPLEXITY FOR SOIL CONSERVATION HYDROGEOLOGICAL HAZARD ASSESSMENT WITH THE CONTRIBUTE OF A NEW TOOL → **Flow Connectivity Approach (FCA)**

Key points of this presentation :

PART I

- **Connectivity basic concepts, and Flow Connectivity approach (FCA) (*my personal view*)**
- **Development of index of connectivity (IC)**
- **Discussion on Theoretical basis of IC index**
- **Fields of application of FCA**
- **Calibration of IC index and IC interpretation**
- **Variants of IC index.**



PART II

- **Connecting FCA and sediment travel time.. Theory and hypotheses of work.**
- **Sediment paths,travel time and tracers a key to optimize SDR= *f*(IC) in a watershed.**
- **Highlights and speculations.**

APPENDIX 1

APPENDIX 2

PART I

Hydrological connectivity is a term often used to describe the internal linkages between runoff and sediment sources in upper parts of catchments and the corresponding sinks (Croke et al., 2005).

Connectivity paradigm has prominent importance also in geomorphology and ***landscape evolution:*** *processes and rates…*

SOURCE

WATER , SEDIMENTS,….

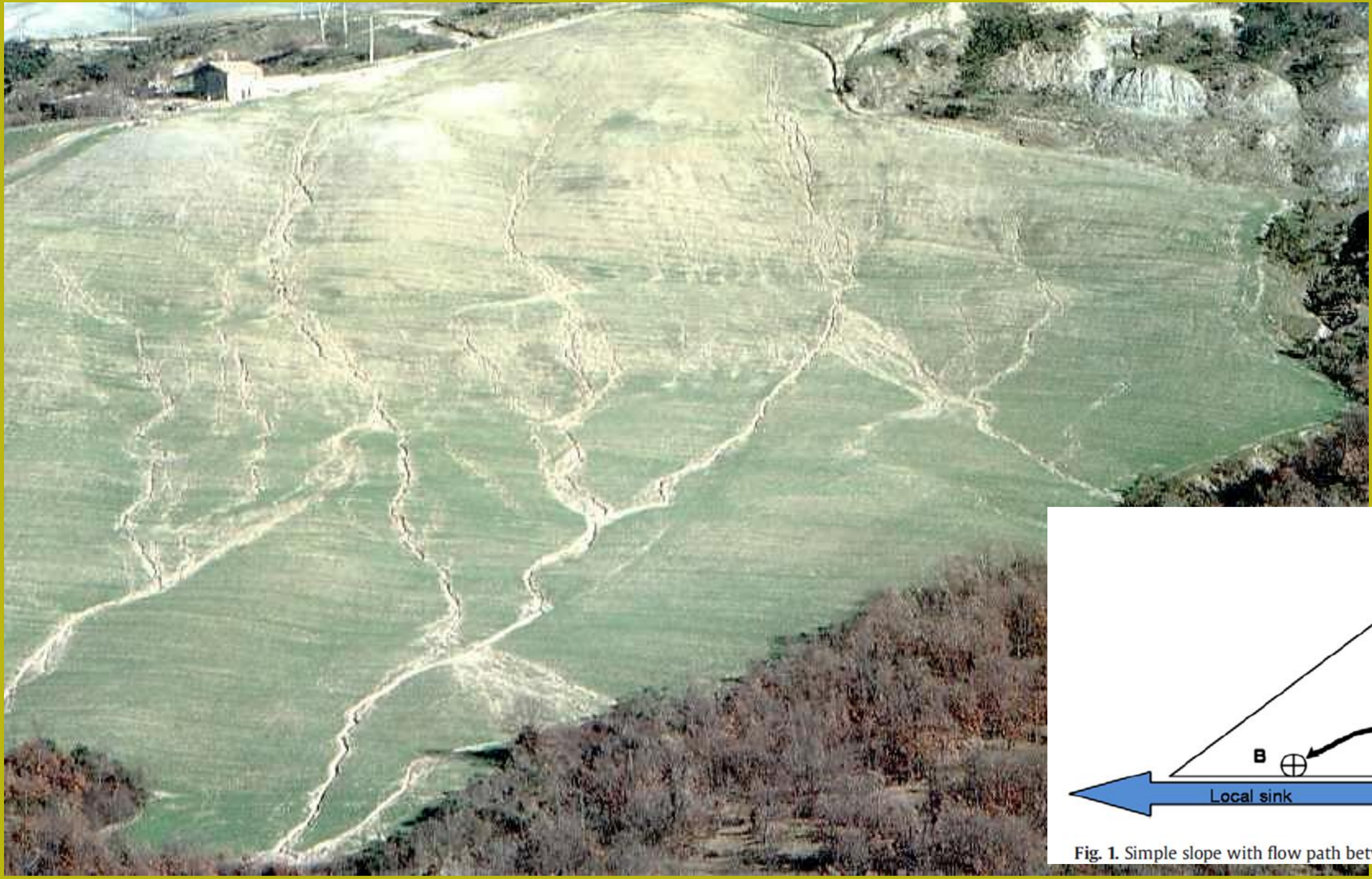
MASS and Energy TRANSFER:

SINK

(see definitions review in Bracken et al. (2013))

Definition of connectivity for sediment flow:

Connectivity may be defined as the chances that a particle has to reach the nearest sink and it depends on: **distance to the sink; characteristics of the route; water available to transport from upslope; water that is gained/lost along the downslope route**



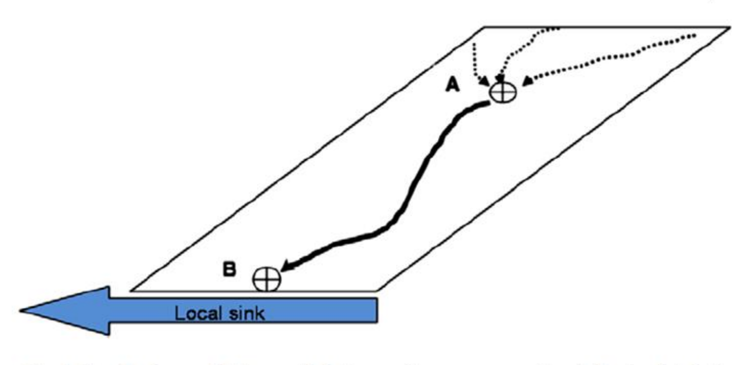


Fig. 1. Simple slope with flow path between the source area A and the local sink B.

Erosion and connectivity in an old *biancana badland* levelled field (Tuscany, Italy 2001)

Diffuse connectivity it is also influenced (Cammeraat ,2002) by :
1) soil surface irregularity (roughness), which could be very low at the patch scale, but higher at the hillslope and the catchment scales;
2) spatial organization of the vegetation at the hillslope scale and the spatial arrangement between land units at the catchment scale;
3) rainfall intensity, event duration, and thus the effective rainfall.!!!!

from Borselli et al. 2008

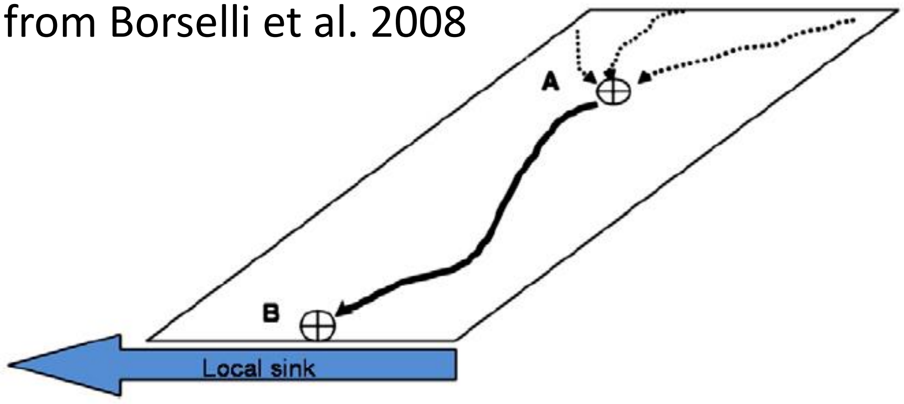
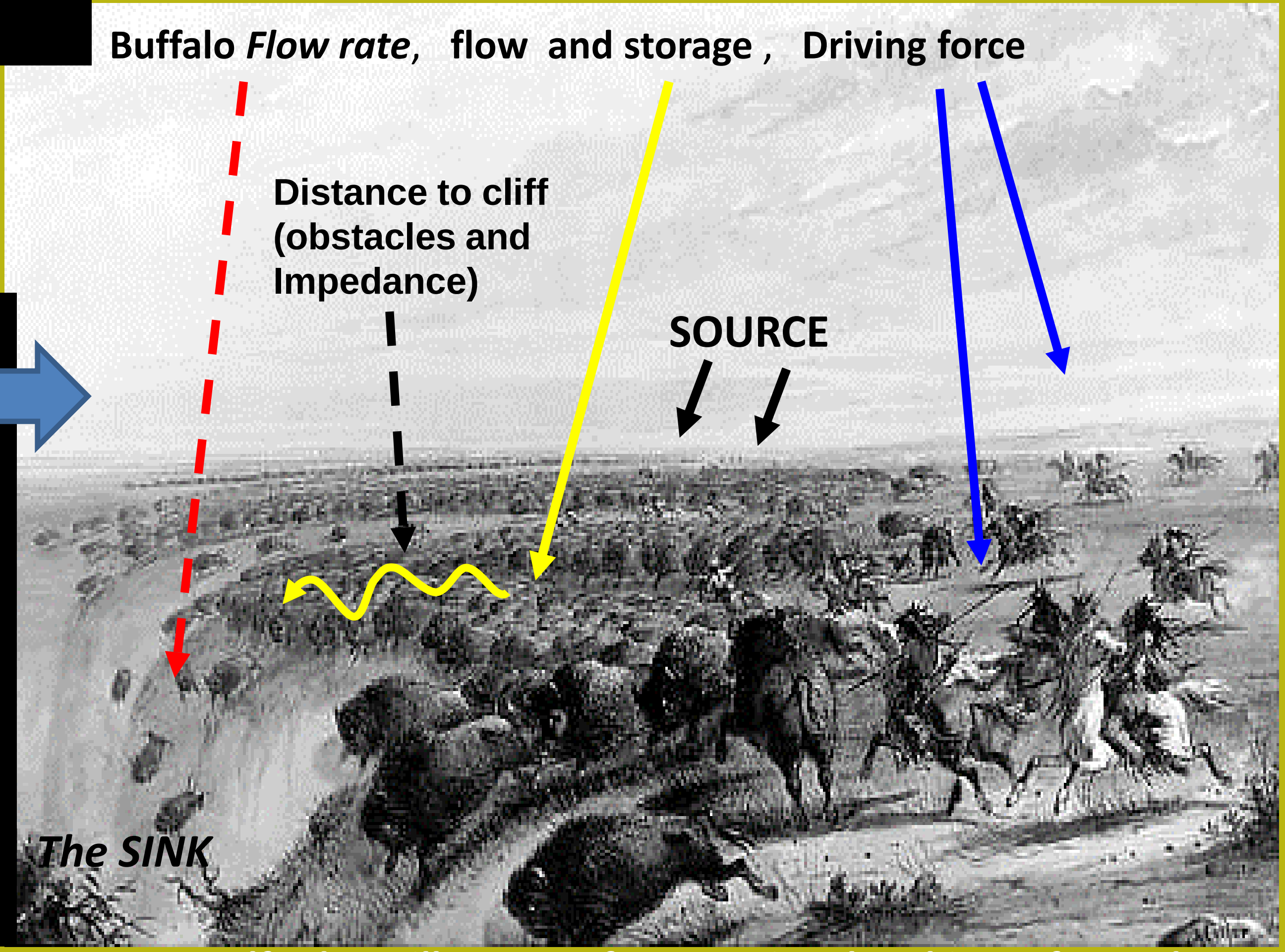


Fig. 1. Simple slope with flow path between the source area A and the local sink B.

From Cavalli 2013

The previous characteristics are defined and used, by many soil erosion distributed models in modelling and computation of erosion and deposition in whole catchments

A conceptual example…
The importance of connectivity…



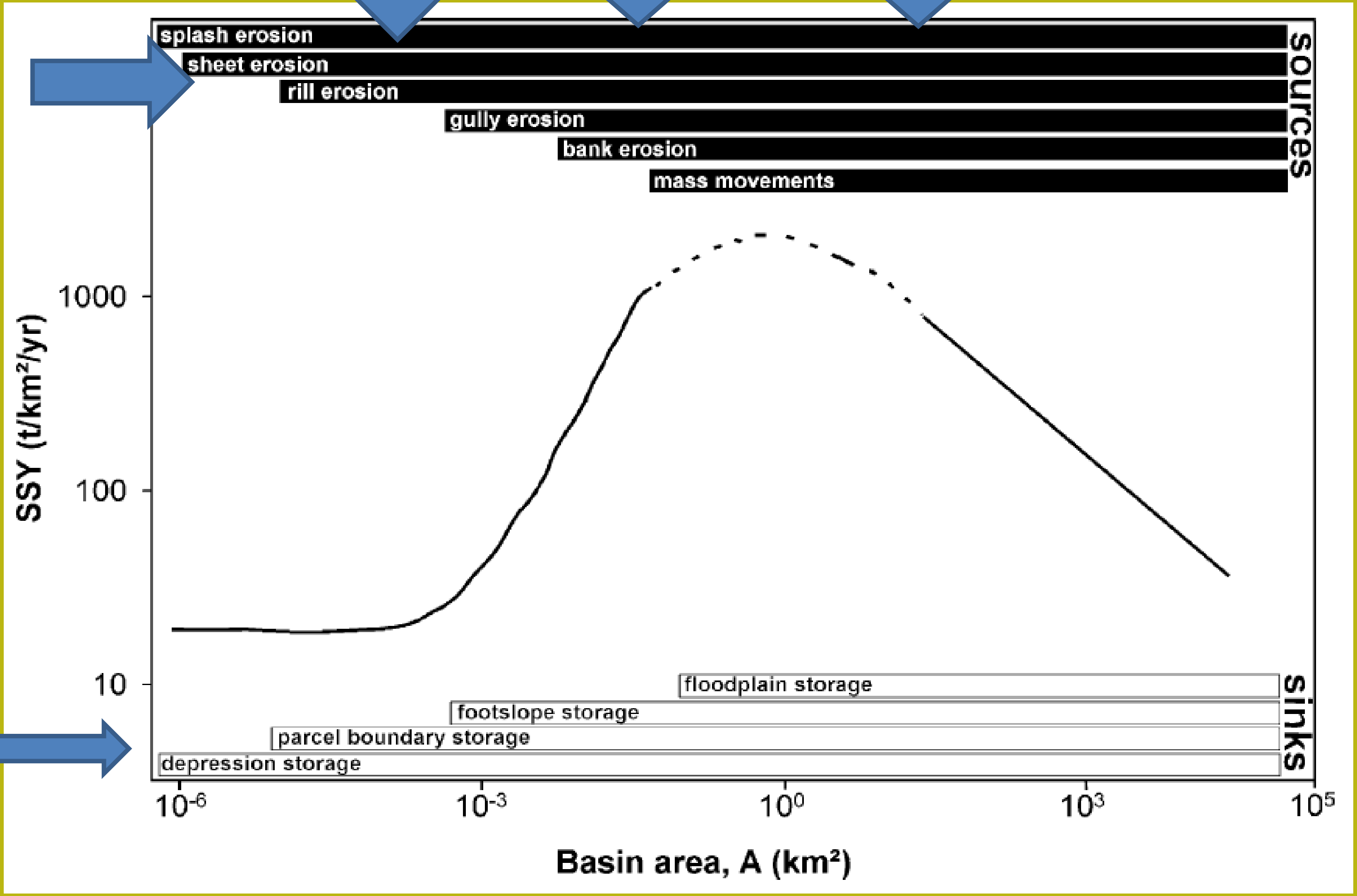
Source: Alfred J. Miller 1887 from National Archives of Canada

*The **Buffalo jump.***
A Native Americans hunting technique that has some similitude with soil erosion /runoff processes….
e.g. The chance of each buffalo to fall …. die,
.. or escape and survive….

Influence of Connectivity on sediment yield (SSY)…..from many sources…. (non only due to soil erosion….)

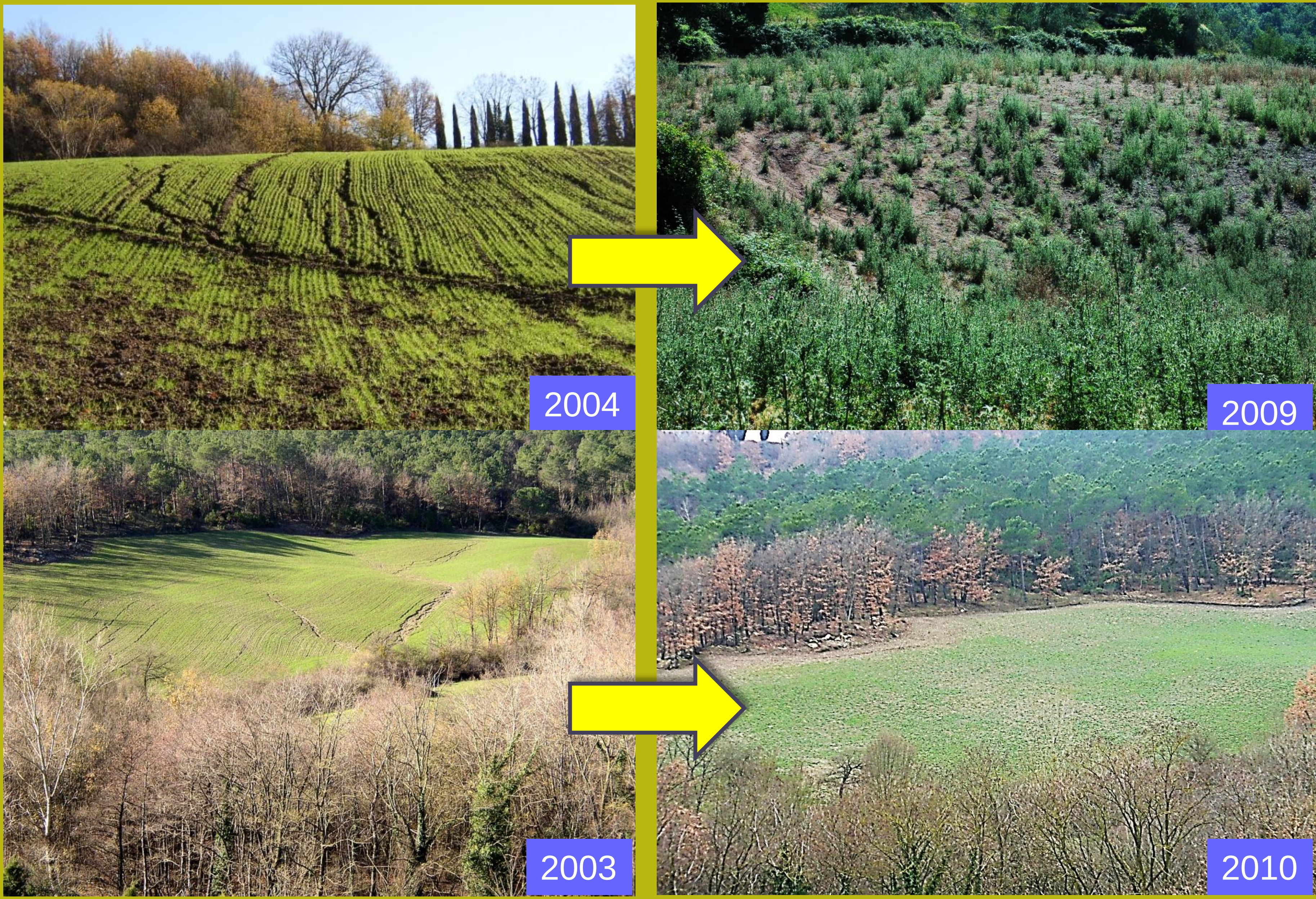
SOURCES

SINKS



Conceptual model of sediment yield at various scale and contributing sources and sinks (De Vente and Poesen, 2005)

Connectivity temporal scale efects (vegetation , land use..)



Processes, and natural hazards assessements (soil erosion, mass movements..)

Modelling (physical, distributed, empirical…models)

Scenario analyses

Decisions support tools

Policy making decisons

Connectivity approach (indexes and tools)

Were FCA may be useful….

Connectivity Indexes, a local metric for flow connectivity approach (FCA).

If an ideal model, able to simulate perfectly mass and energy transfer, redistribution and storage in the landscape, existed, probably we would not need Connectivity metrics.
(*e.g. A perfect, event based soil erosion model that could simulate erosion, transport and deposition rate on the landscape)*

But this type of models does not exist yet, and many of the existing soil erosion models are not easy to use…sometimes models are extremely complex and are affected by **parametric and modeling uncertainty, numerical problems, and occasionally by numerical instabilities** (e.g. violation of principle of mass an energy conservation).

A set of new tools are needed to consider Connectivity as stand alone metric which can be put in relation to various processes (e.g. runoff, erosion, mass movement mobility, etc...)

To do this we need to develop <u>Connectivity indexes, as local Metrics</u>, representing the local connectivity status.

But a preliminary and exhaustive *verification in field* of the evidences of the linkage between connectivity and the intensity of certain processes (e.g. soil erosion, soil deposition, landslide mobility, runoff concentration, etc.) is required….

Catena 75 (2008) 268–277

Contents lists available at ScienceDirect

Catena

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

Prolegomena to sediment and flow connectivity in the landscape: A GIS and field numerical assessment

Lorenzo Borselli *, Paola Cassi, Dino Torri

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An attempt to develop a new tool in order to represent a <u>connectivity local metric</u>

The index of connectivity IC
From Borselli et al. 2008

The study was based also on field observation in a 150km2 watershed Italy and was funded by the European Commission, Directorate- General of Research, **Global Change and Desertification Program, RECONDES project (2004–2007) "Conditions for Restoration and Mitigation of Desertified Areas using Vegetation"** and by **Autorità di Bacino del fiume Arno-Italy; BABI project** (2003–2007)

In the paper :
Two indices of connectivity were operatively defined:
1) (**IC**) that can be calculated in a GIS environment and **represents a map potential connectivity between two different parts of a catchment** (assessment based on landscape's information);
2) Another index that can be evaluated in the field (**FIC**) through **direct assessment of connected flow path after a flow or erosion event**.

IC and FIC indices were **designed to complement each other and their combined use was shown to improve accuracy.**

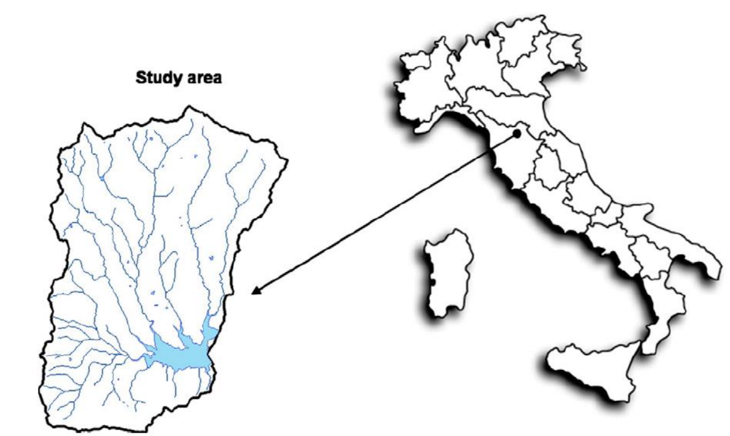
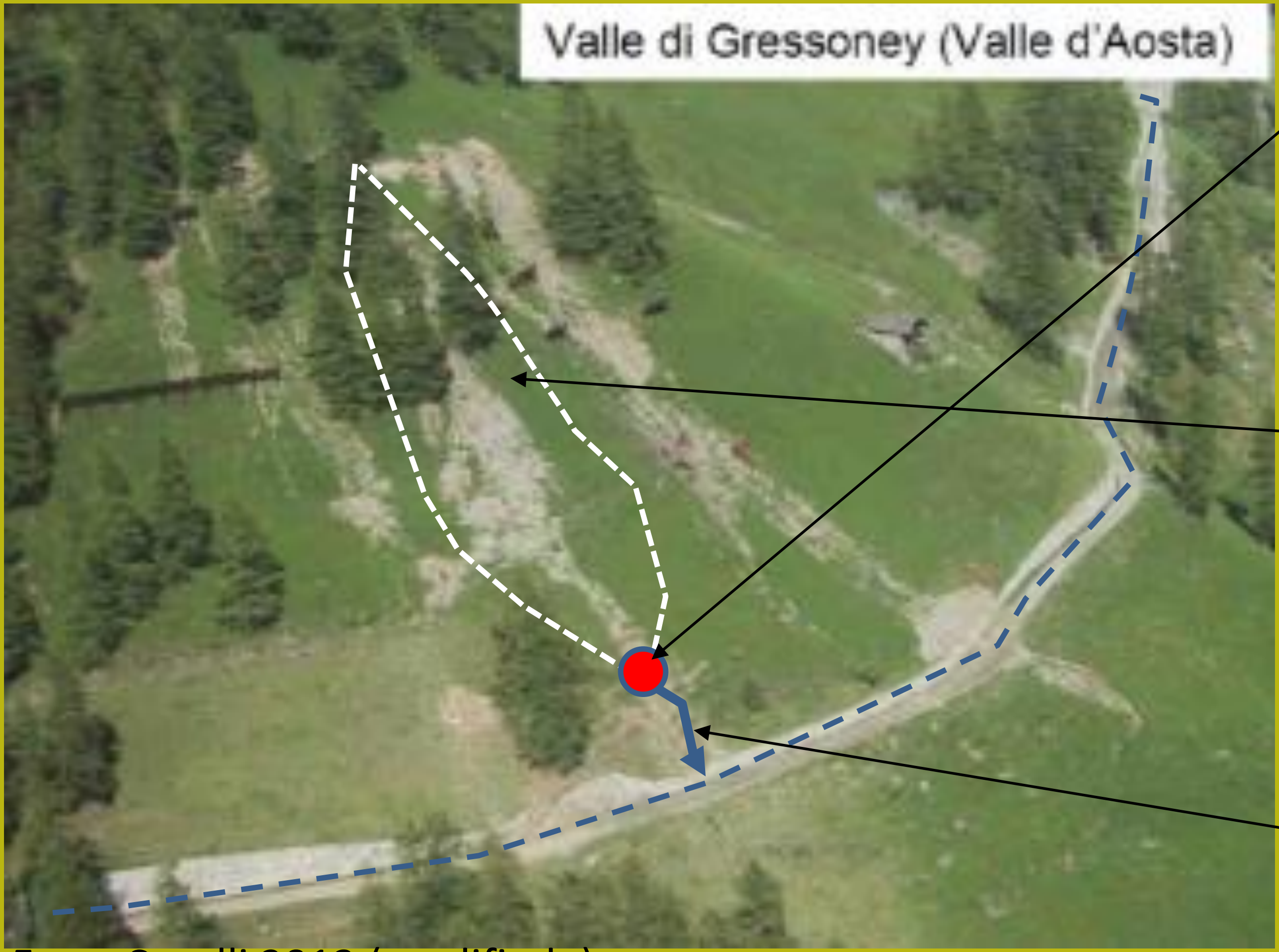


Fig. 3. Study site—Bilancino watershed (Tuscany, Italy).

IC Index



From Cavalli 2013 (modified..)

The Connectivity Index (IC) in any point of the landsacpae value is computed using two components:

Upslope component: is the potential for down routing due to upslope catchment's areas, mean upslope and land use.

Downslope component: is the sinking potential due to the path length, land use and slope along the downslope route.

Introduction to IC index and metric

from Borselli et al. 2008

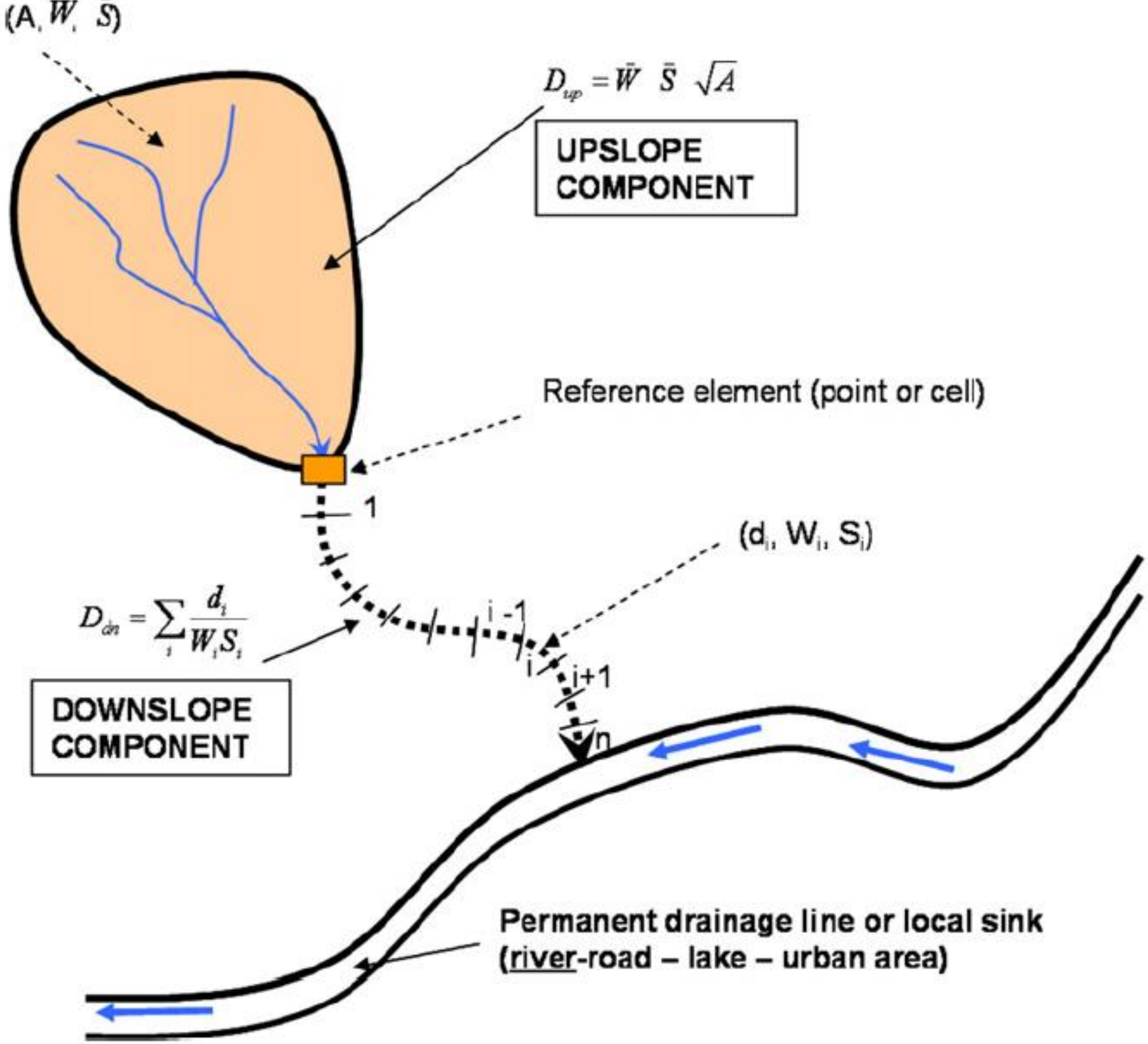


Fig. 2. Definition of IC upslope and downslope component in the landscape for index of connectivity (IC).

IC Index

The Connectivity Index (IC) value is computed using two components:

Upslope component: is the potential for down routing due to upslope catchment's areas, mean upslope and land use.

Downslope component: is the sinking potential due to the path length, land use and slope along the downslope route.

$$D_{up} = \bar{W}\,\bar{S}\,\sqrt{A}$$

UPSLOPE Component

$\bar{W}$ = **average Weigthing factor in the upslope contributing area (adimensional);**

$\bar{S}$ = **average slope gradient of the upslope contributing area (m/m)**

A = **upslope contributing area (m^2)**

$$D_{dn} = \sum_i \frac{d_i}{W_i S_i}$$

DOWNSLOPE Component

d_i = length of cell *i* along the downslope path (in m)

W_i = Weighting factor of cell *i* along the downslope path (adimensional)

S_i = slope gradient of cell *i* along the downslope path (m/m)

Final IC calculation <u>in each pixel</u>

$$IC = \log_{10}\left(\frac{D_{up}}{D_{dn}}\right) = \log_{10}\left(\frac{\bar{W}\,\bar{S}\,\sqrt{A}}{\sum_i \frac{d_i}{W_i S_i}}\right)$$

$$IC = \log_{10}\left(\frac{D_{up}}{D_{dn}}\right) = \log_{10}\left(\frac{\bar{W}\,\bar{S}\,\sqrt{A}}{\sum_i \frac{d_i}{W_i S_i}}\right)$$

Orders of magnitude of IC

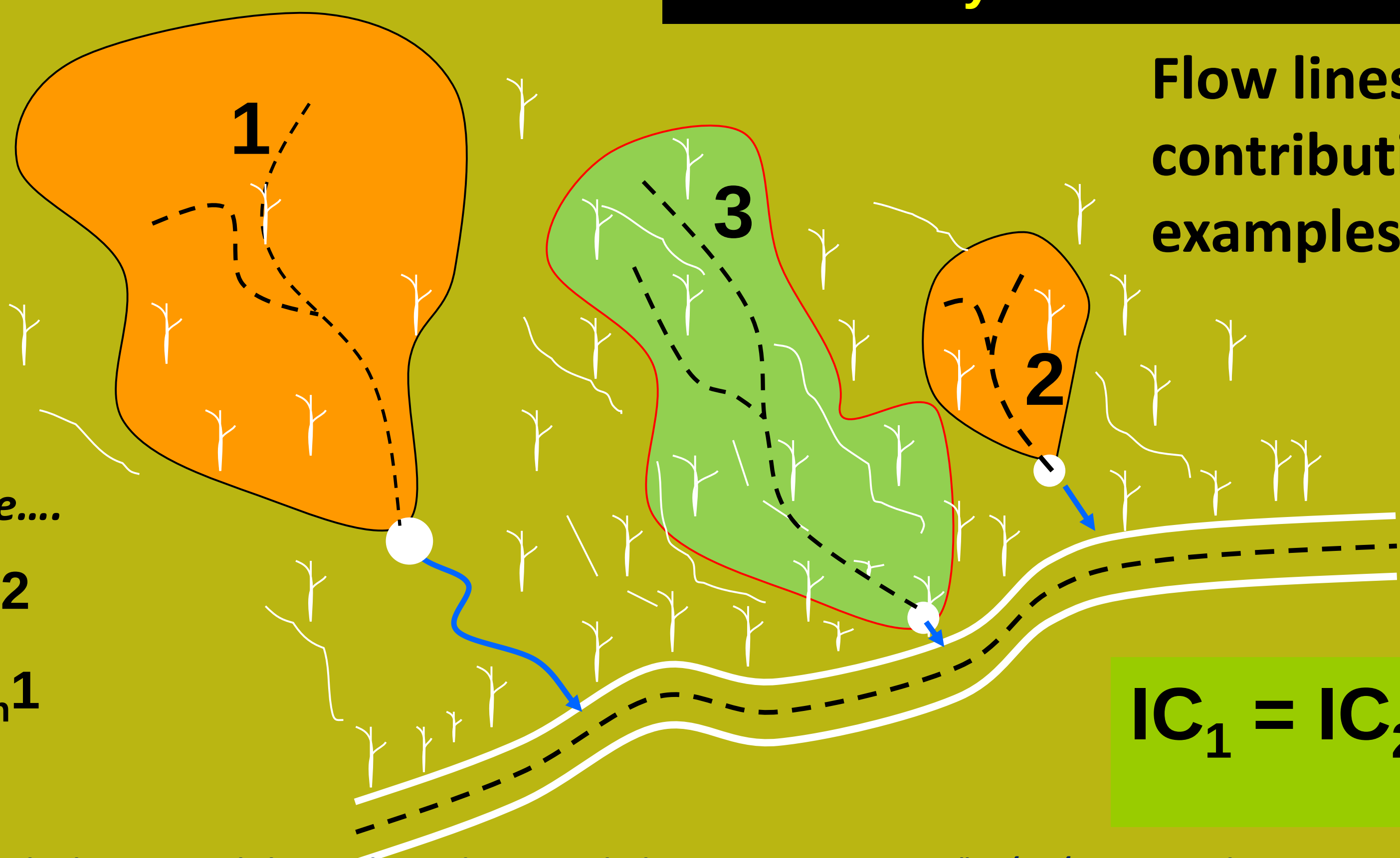
***Under this definition the local level of connectivity to permanent drainage lines/sinks is inversely proportional to IC*:**

Values *IC* > 0 high connectivity

Values *IC* < 0 medium to low connectivity

***IC* range:** $\left[-\infty, +\infty\right]$

Flow lines and contribution area examples



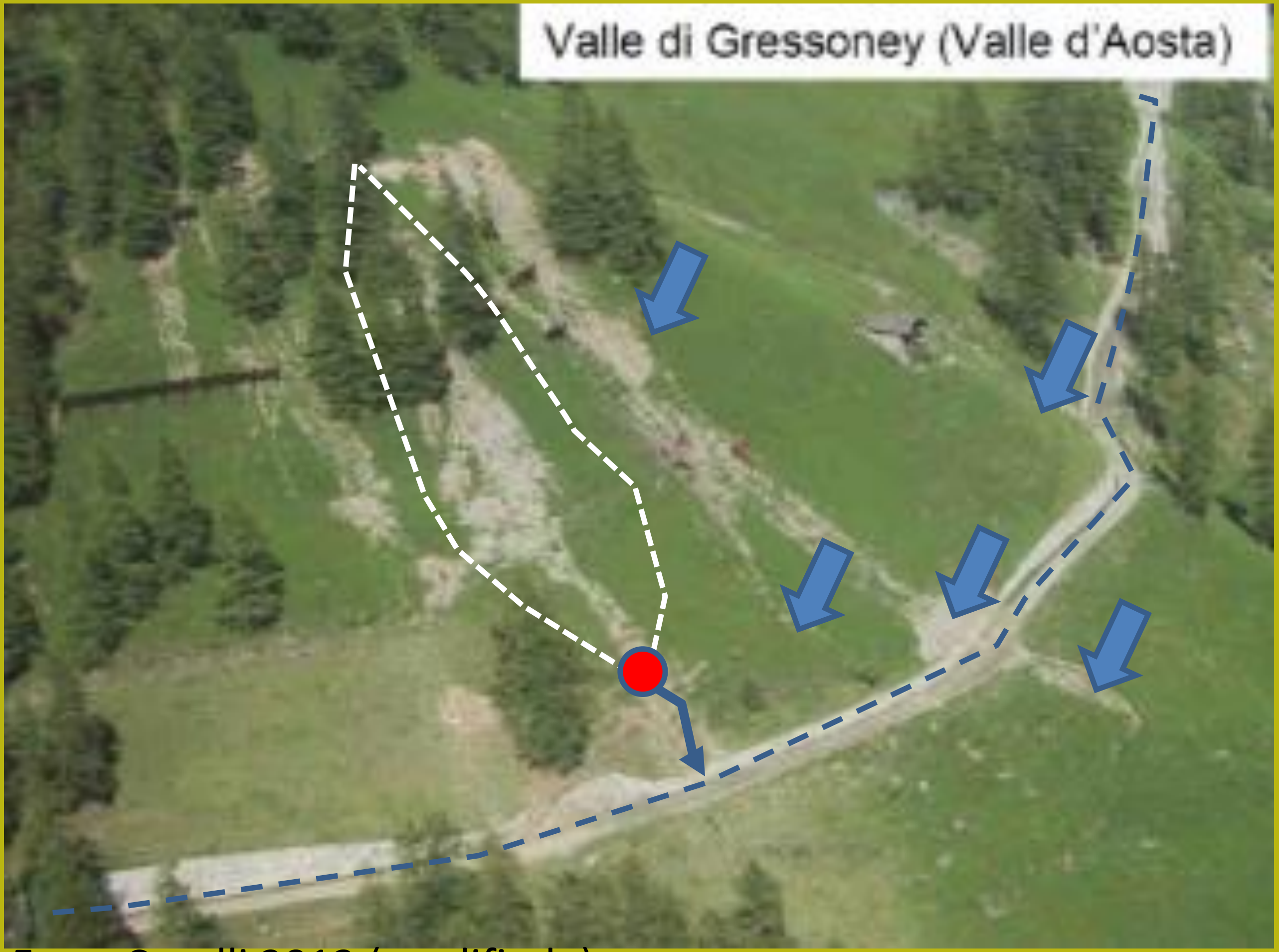
A special case….

$D_{up}1 > D_{up}2$

$D_{dn}2 < D_{dn}1$

$IC_1 = IC_2 < IC_3$

IC Index



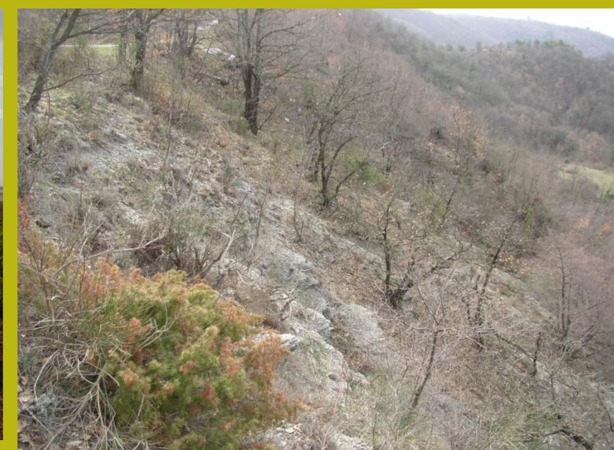
From Cavalli 2013 (modified..)

Hoh the IC metric Characterize the connectivity
in differents points and envent's scenario??

Key role of W factor in connectivity index

W factor → C factor (first approximation)

W should consider: vegetation cover
Roughness,   infiltration capacity.. And otehr factor
Related to impedance to Surface runoff flow.



IC methodology requirements (classical approach):

- **High quality and high resolution DTM are preferred**. Ideal resolution variable between 2 and 5X5 m
- Some timesResolution of DTM at least 10x10m my be sufficient
- But in some case may be acceptable until 20X20 depending from local availability and from the type of application we want to generate
- **Raster map of slope gradient**
- **Detailed Land use to obtain the local weighting (W) factor map (and associated. e.g. C values)**
- **No data value layer (internal local sink)**: river mask, roads, urban area, lakes, etc..
- **River mask must be generated starting from a maximum accumulation area** (it defines permanent drainage lines) - **usually 1-2.5 ha**.

IC Index computation notes

Permanent drainage lines, roads, urban areas, and water bodies, as well as pixels outside of the considered watershed, are usually set as no data value MASK.

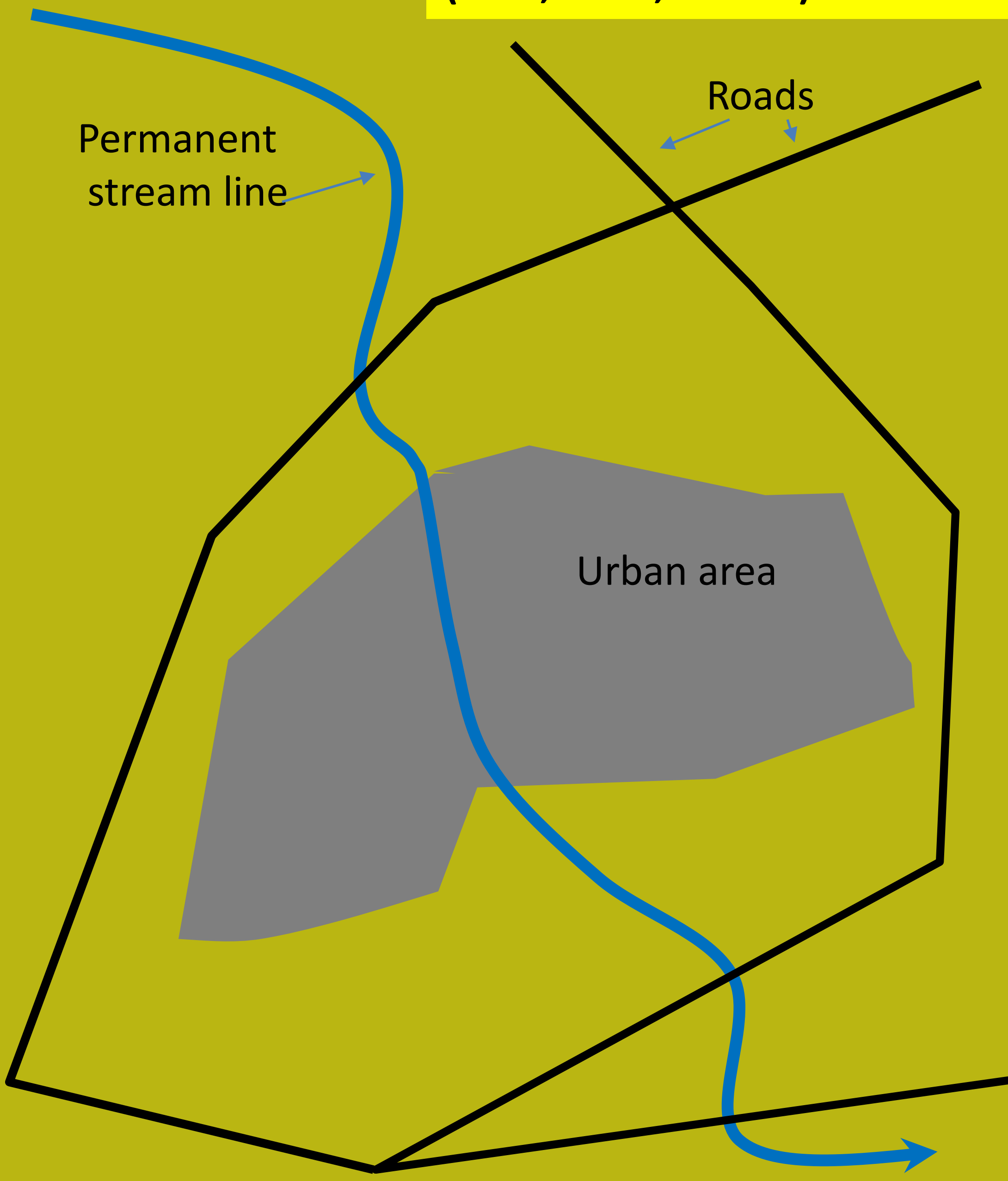
ALL internal *no data value* pixels are considered as local SINKs

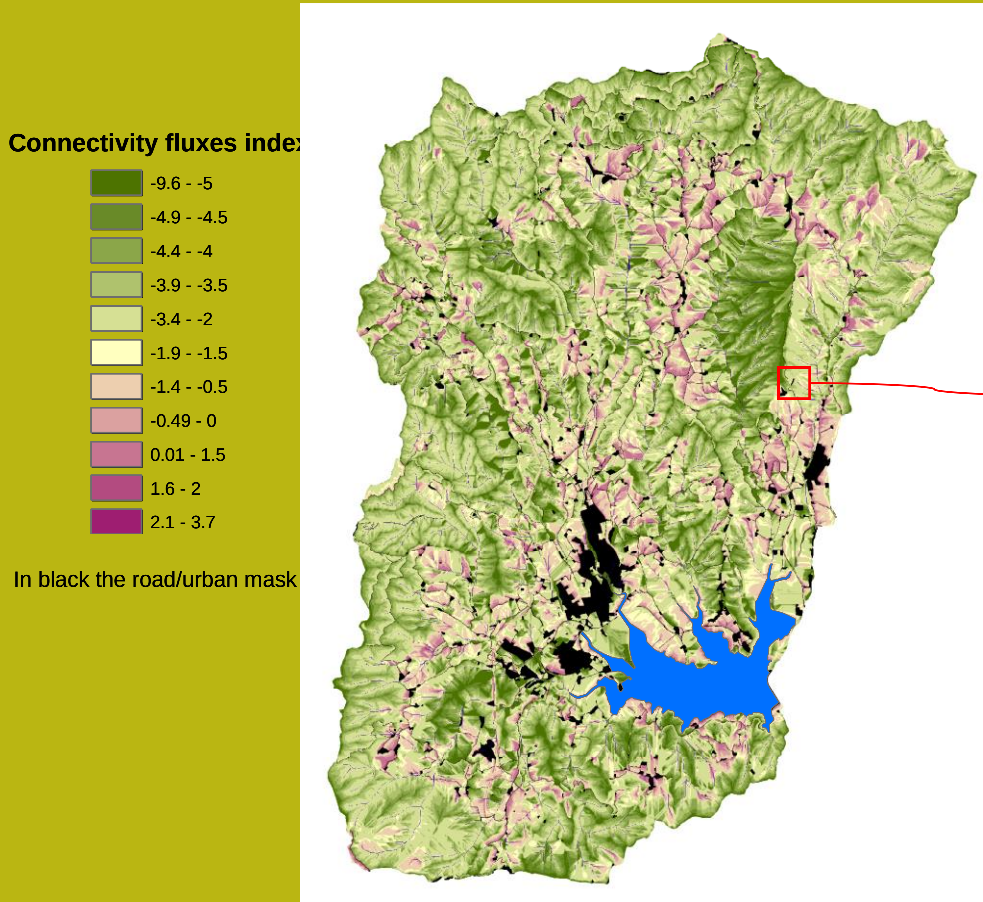
The concept of local sink is fundamental…

Of course you can choose to not consider road or urban areas as local SINK, but in this case you will generate an new type of connectivity pattern and values…

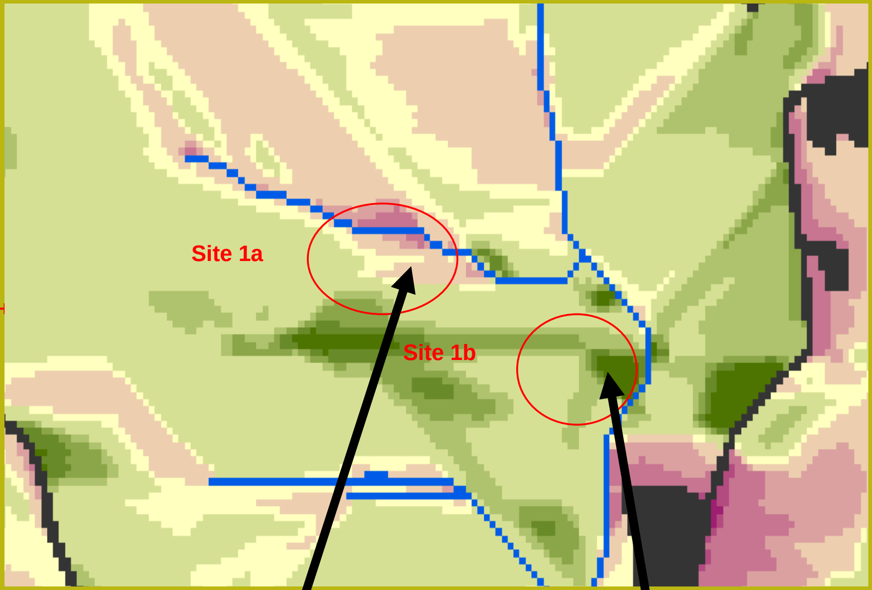
DTM quality and resolution is fundamental… !!!! In any case and at any resolution

Types of no data value masks (river,roads,urban..)





IC map of deposition and connection areas evidenced in red



Site1a -Area in proximity of local sink at field bottom: direct connection of rill system without appreciable sedimentation

Site1b-Area in proximity of local sink at field bottom: direct connection of rill system relevant sedimentation

Application at watershed scale (Bilancino – Tuscany - Italy): hot spot identification of primary sediment sources area.
From Borselli et. Al. (2007,2008)
Area: 150 km2
DTM 5x5m

Other evidences in field. Borselli et al. (2008)

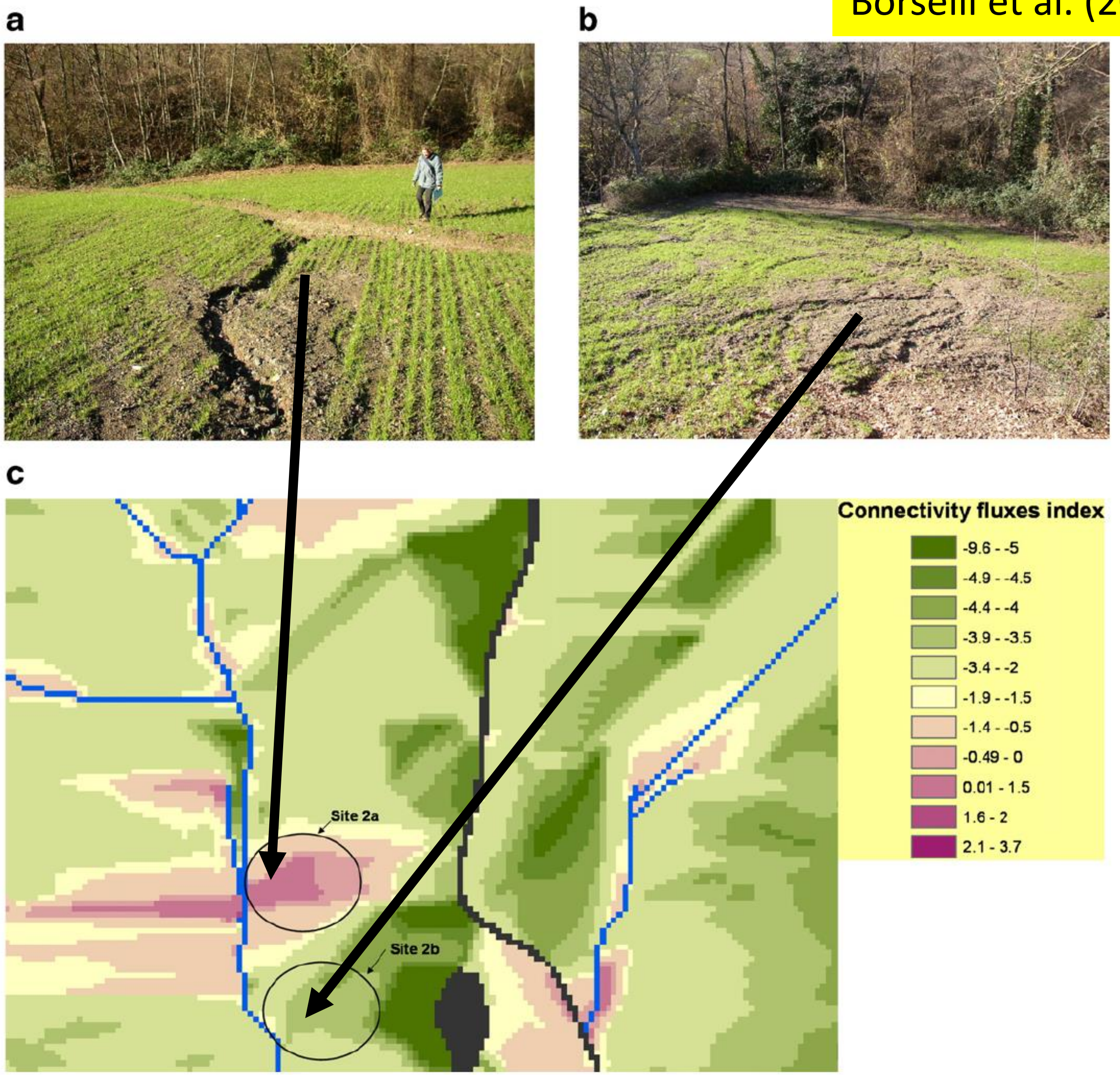
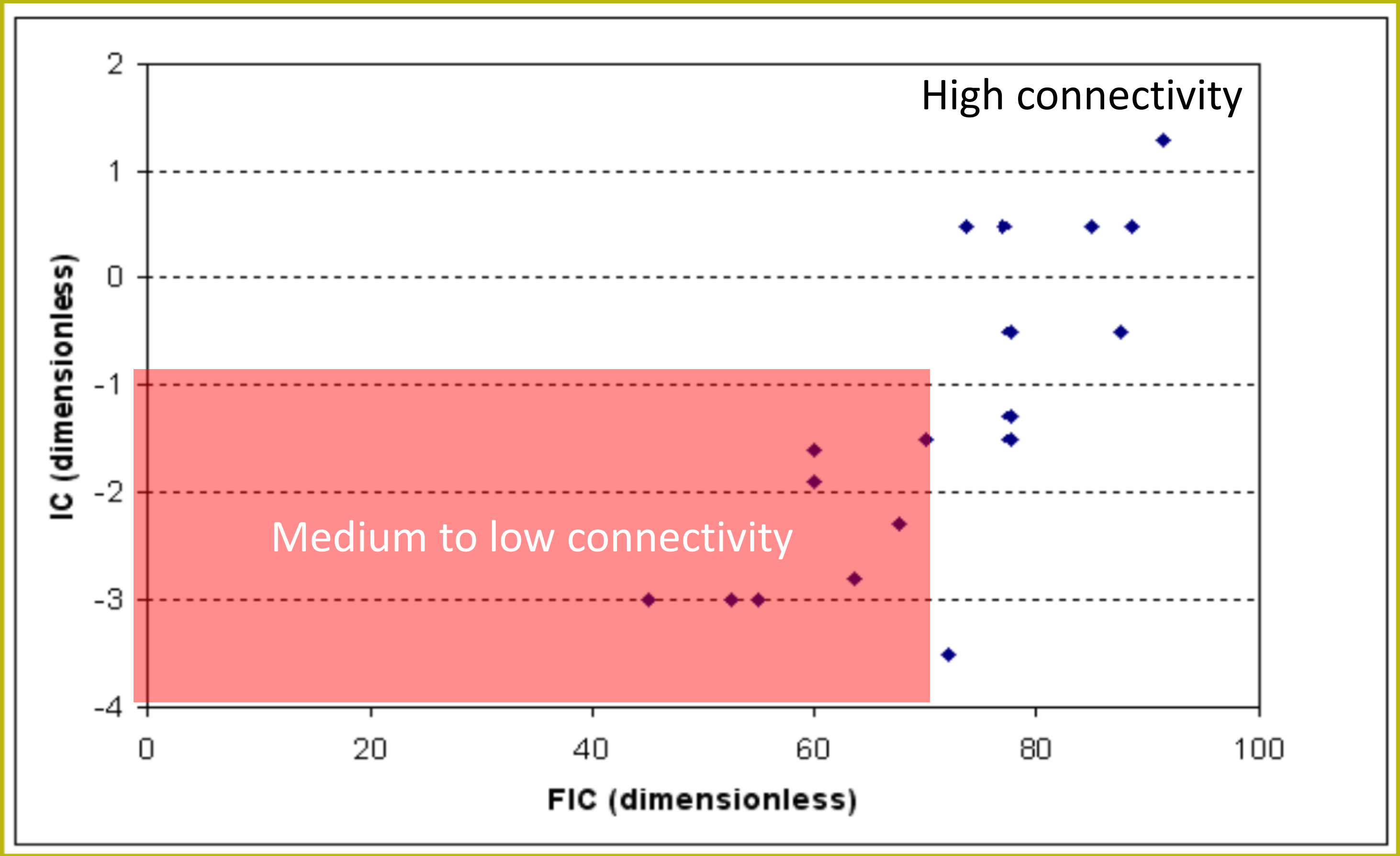


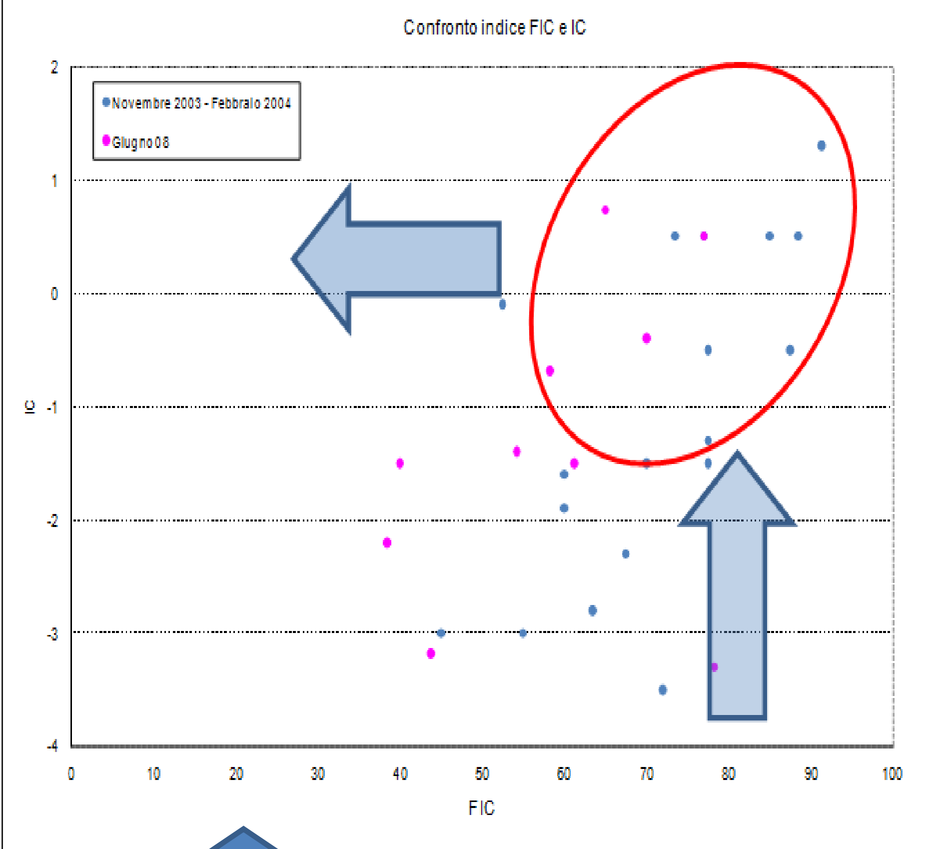
Fig. 5. a: Site 2—Area close to a local sink at the bottom of a field: direct connection of rill system without detectable sedimentation. b: Site 2—Area in proximity of local sink at the bottom of a field: direct connection of rill system with intense sedimentation. c: IC map of Site 2: deposition and connection areas are evidenced inside circular areas.

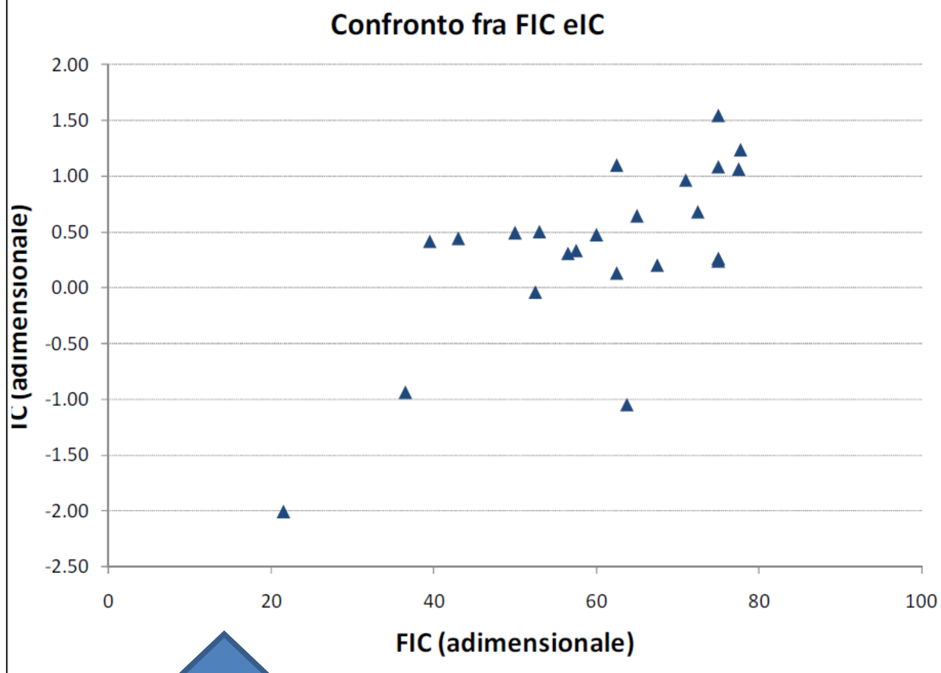
IC index versus field connectivity index (FIC) obtained by direct field survey (Borselli eta l. 2008)



The FIC values have been compared to the IC flux map obtained with the ArcGIS procedure for the entire study site

Please see the original paper for details and examples of application…

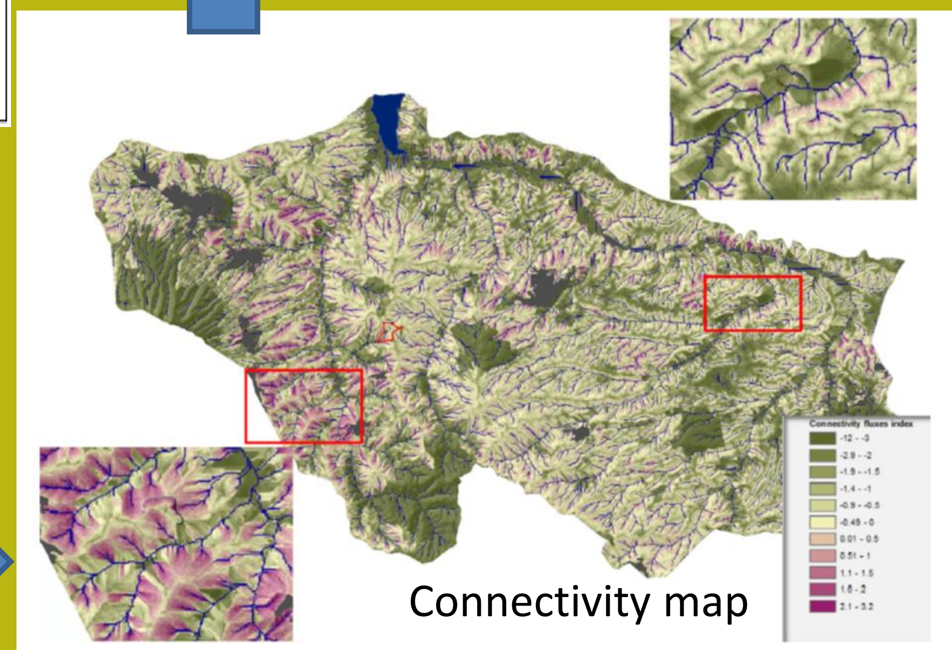




Extended dataset IC versus FIC
(Bilancino watershed; Cassi, 2010)

In both cases we observe high connectivity for IC>0.0

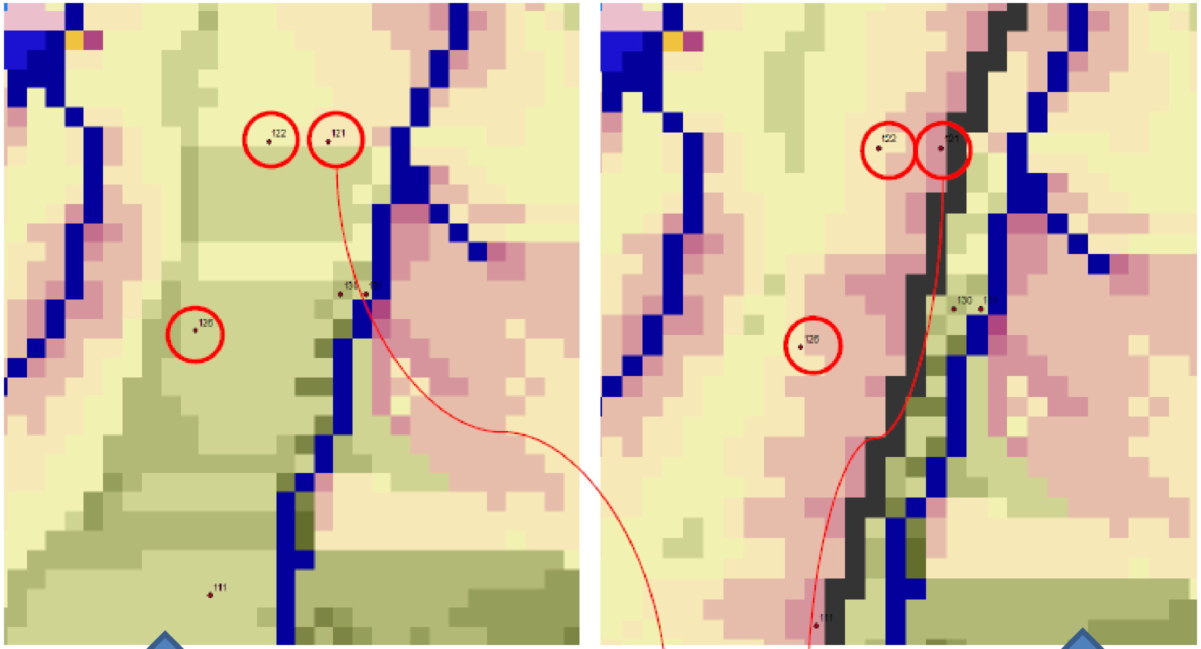
Rendina watershed,
South Italy (400 km2)
DTM 20x20
Project DESIRE
www.desire-Project.eu



RENdINA SITE
Basilicata Italy

Preject DESIRE
(2007-2011)

www.desire-project.eu



Without road mask

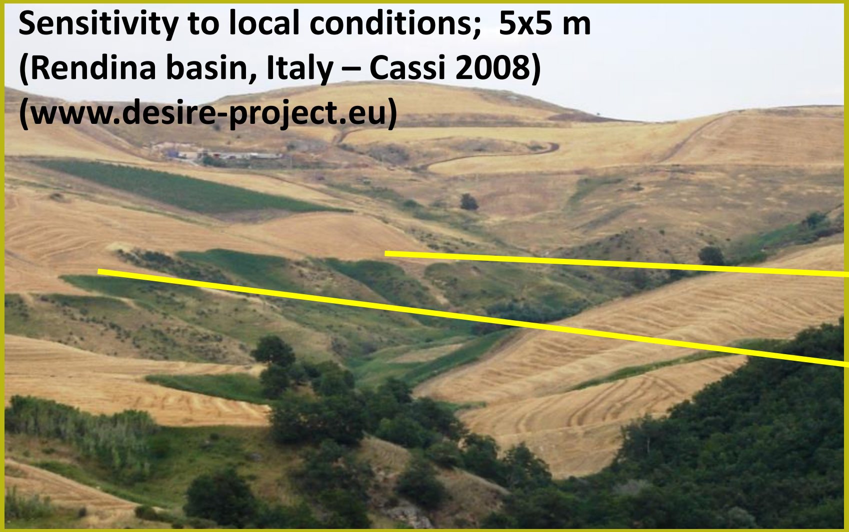
road mask considered

N punto	FIC	Ic senza strade	Ic con strade
121	78	-0.41	1.06
122	57	-0.69	0.31
126	40	-1.75	0.41

Cassi, 2010 (PhD thesis)

Scenario analysis of connenctivity evolution due to land management practice

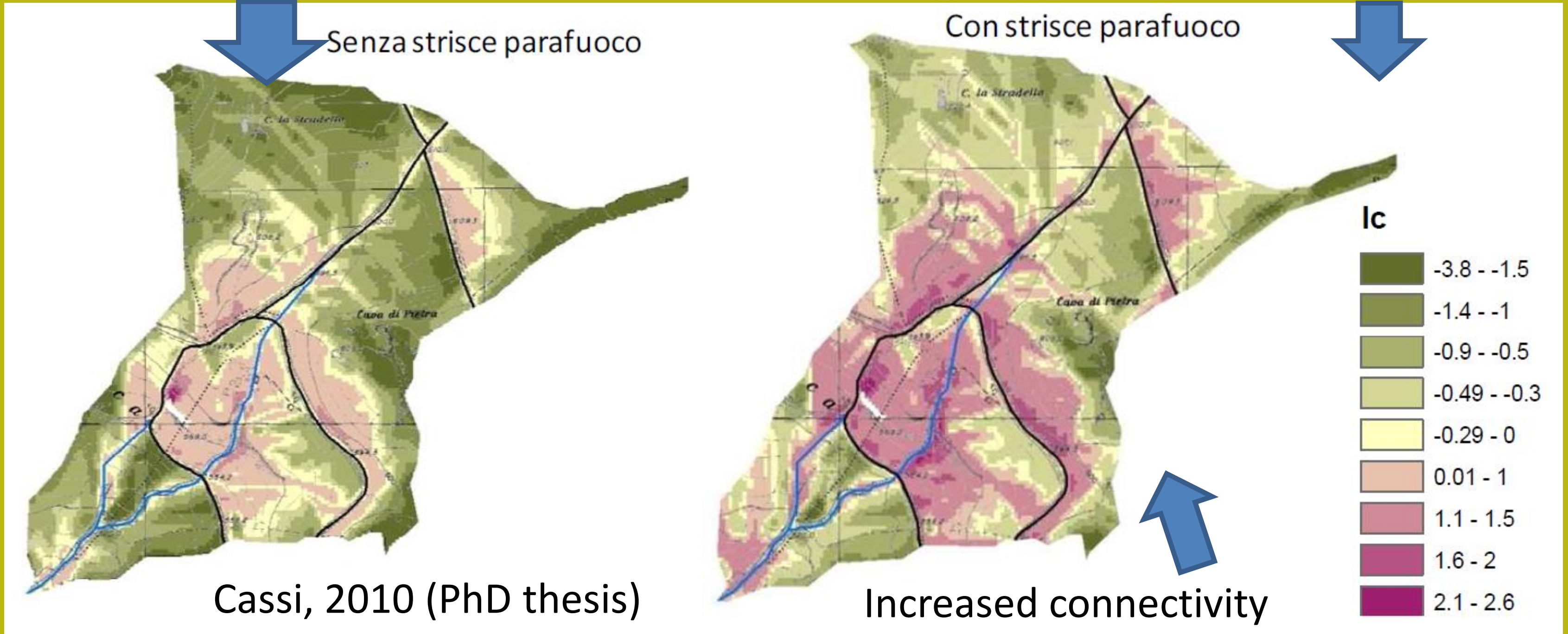
Prevailing land use of the watershed is wheat crop. The connectivity index is evaluated before and after harvesting (June) when the borders of the fields are ploughed for 5 meters wide.



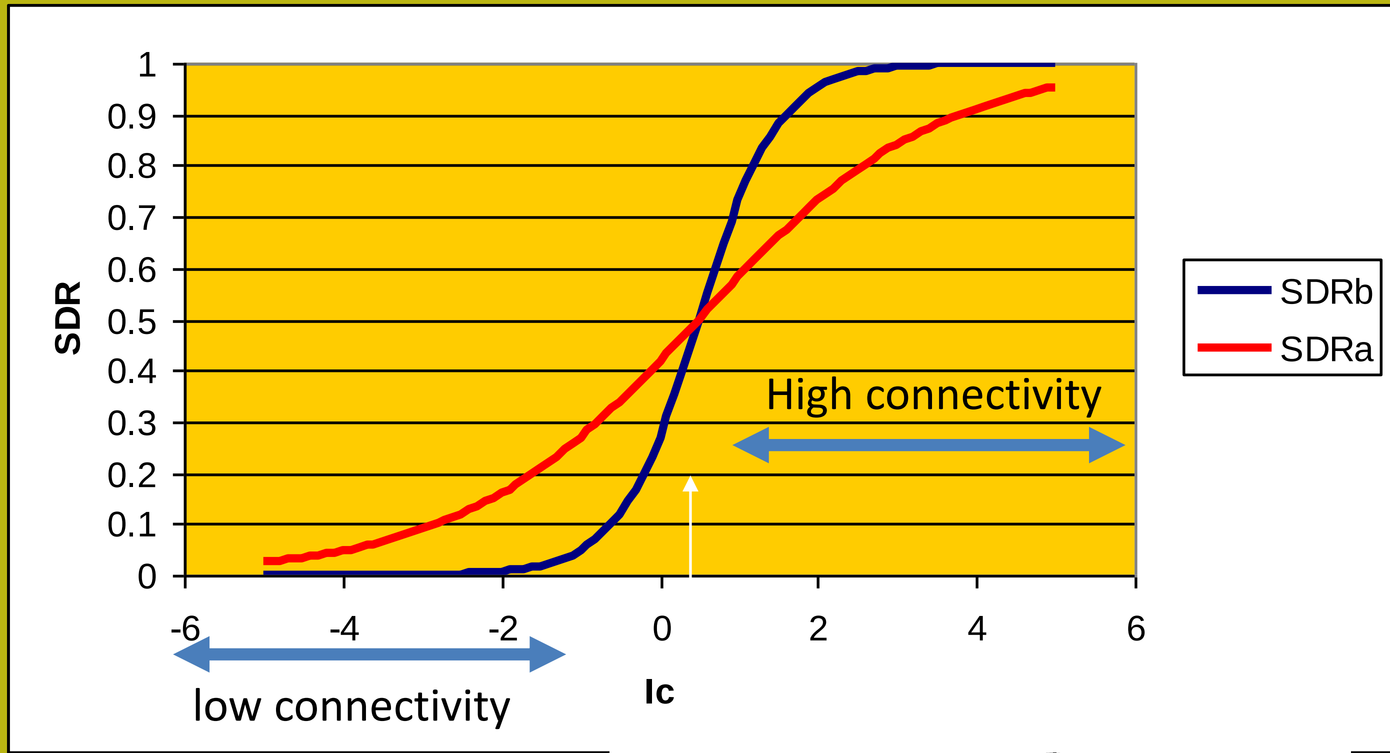
Ploughed field border with erosion evidences

Without strip of bared soil on field border

With strip of bared soil on field border



Possible functional relationships between IC and SDR…



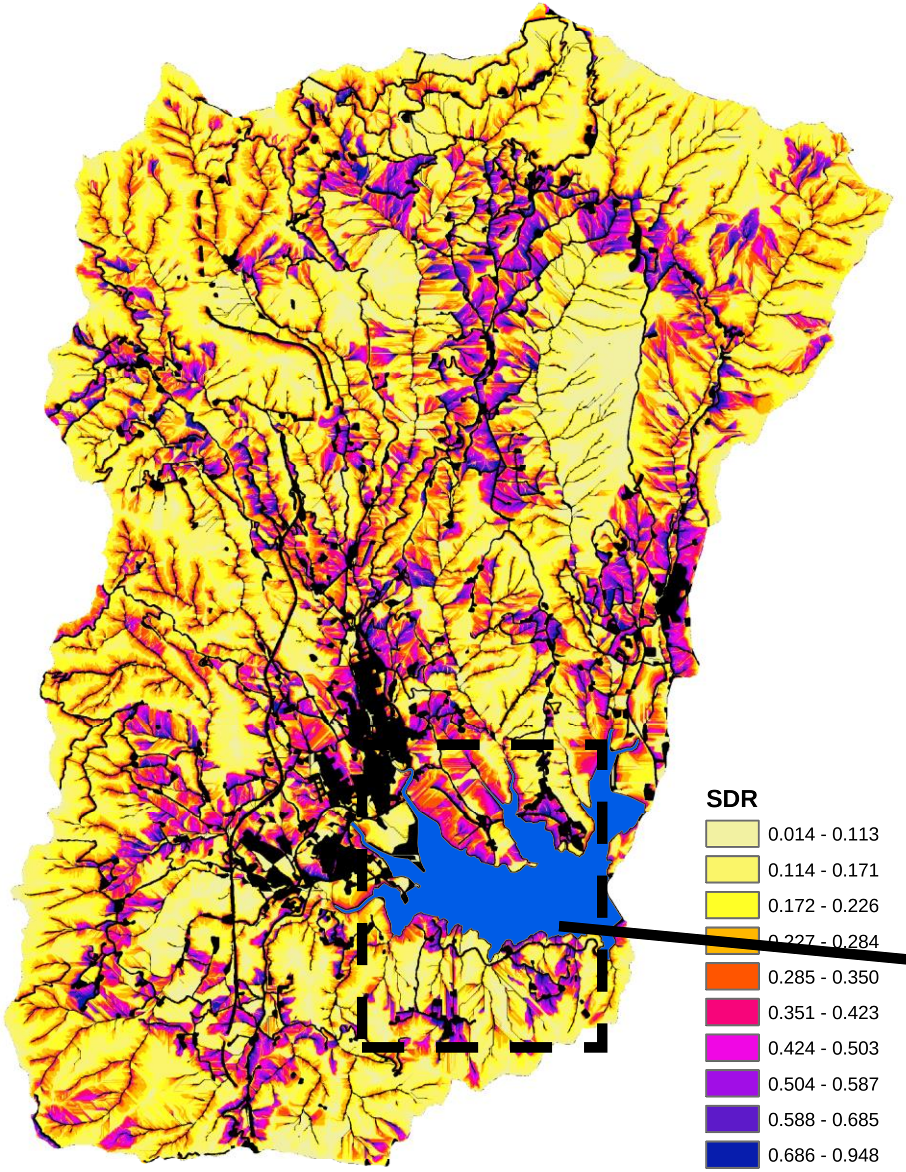
$$SDR = \frac{1}{1 + \exp\left(\frac{Ic_0 - Ic}{k}\right)}$$

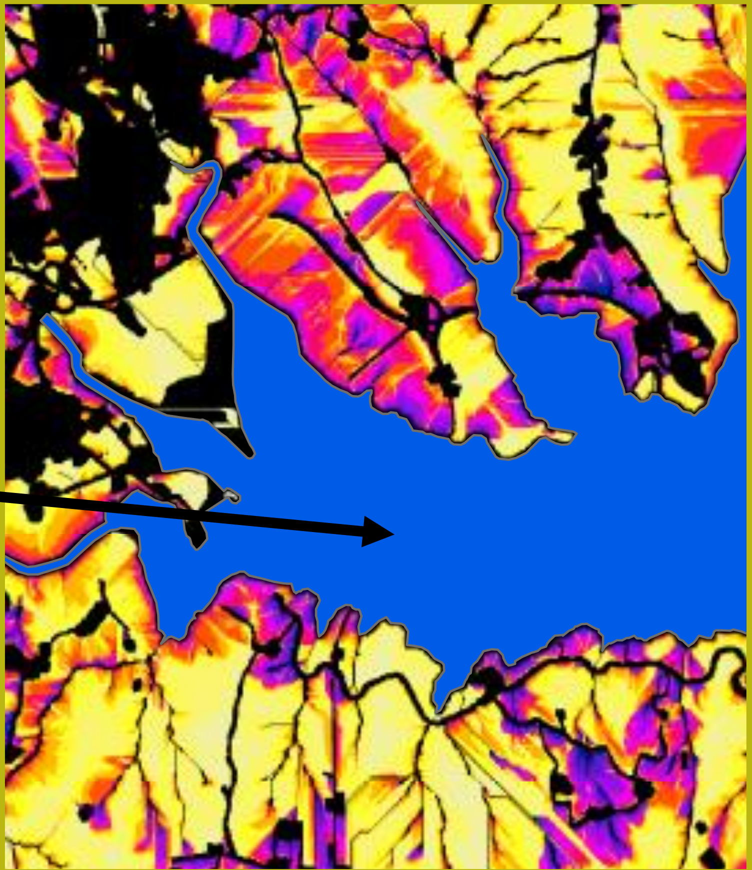
Boltzmann type function: SDR=f(IC, IC0, k)
(Borselli et al. 2007)

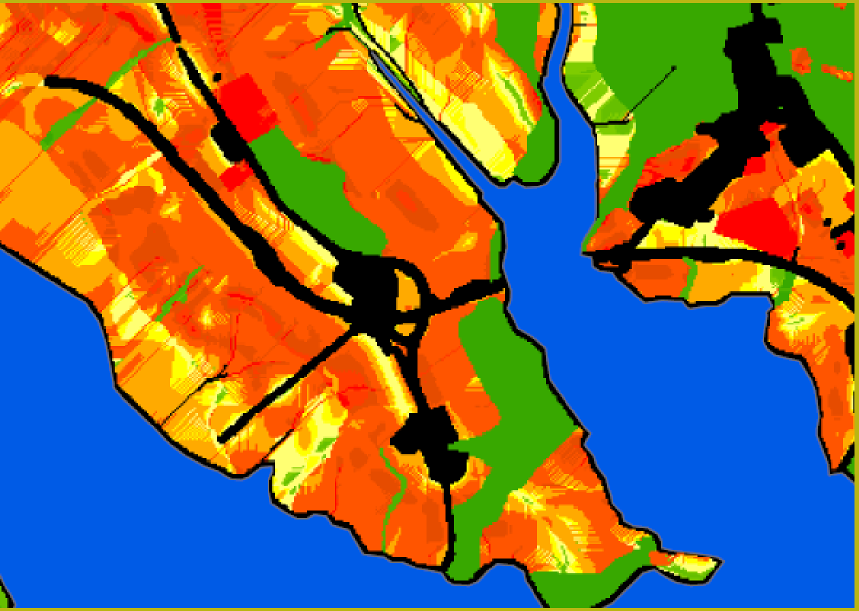
In this first application (2007) to Bilancino watershed **we speculated on a possible relationship between IC and SEDIMENT DELIVERY RATIO (SDR,** and we developed it as ***SDR=f(IC)*** at the hillsope scale.
This analysis was not officially published until 2012 after the verification made by Vigiak et al. (2012) in another catchment (in Australia).

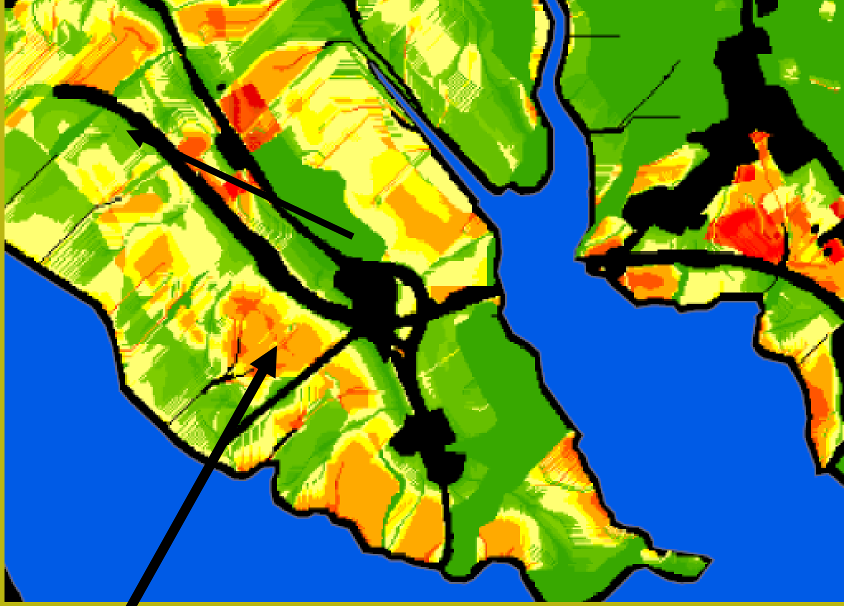
SDR map in a watershed for correction of average annual erosion rate (under USLE-type models)

Many authors have used the SDR to correct for distributed soil erosion model outputs (Ferro and Porto 2000; Lu et al., 2006)









Local average erosion rate...
Classic RUSLE 2D

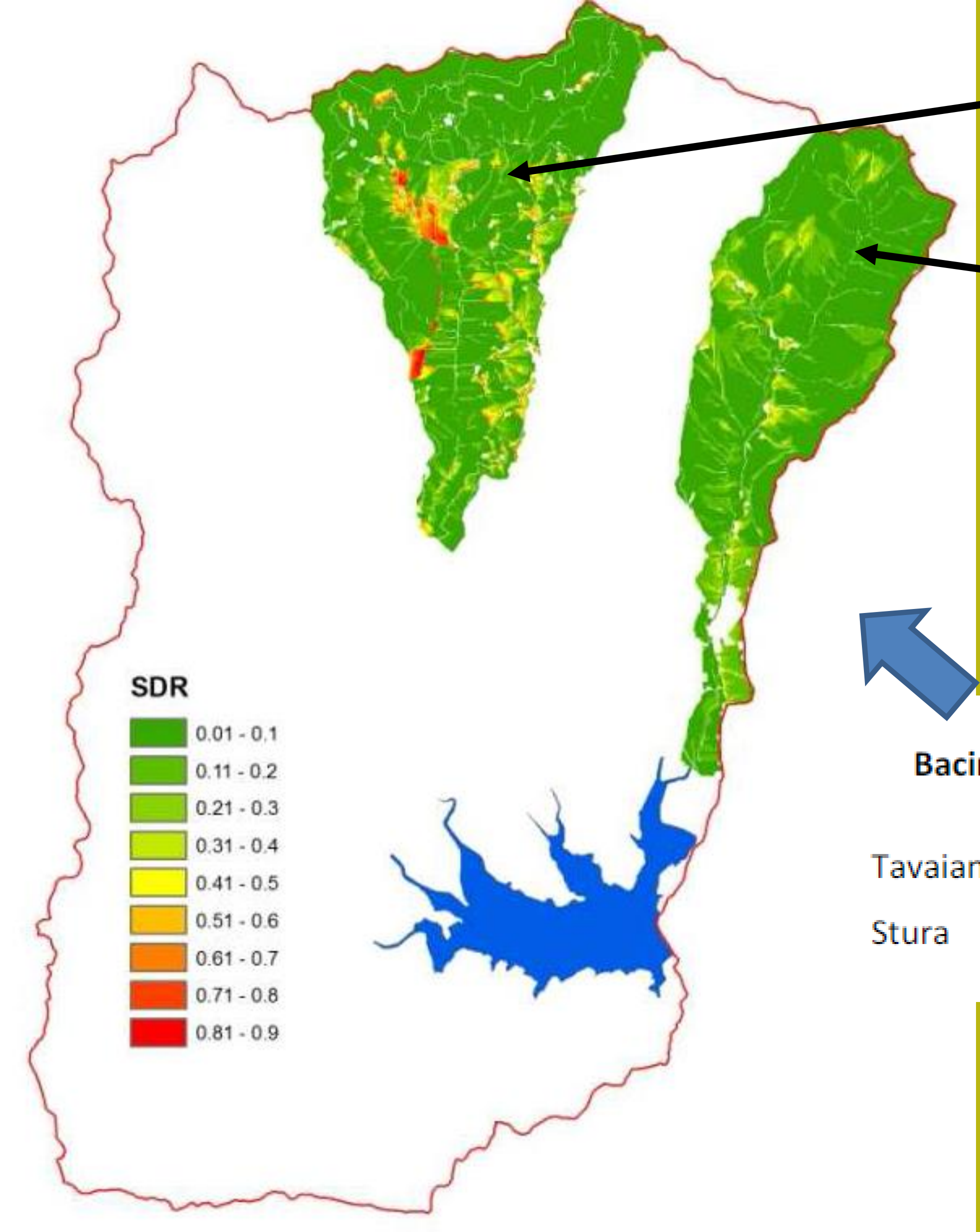
In the Bilancino application
a new algorithm for the calculation
of erodibility (k) based on global dataset and
climatic classification was also used …
KUERY software 1.4.
See Borselli al. (2009,2012) and updates..
www.Lorenzo-borselli.eu/kuery

Average sediment yield contribution:
RUSLE2D corrected according to *IC* and SDR

Primary sources of sediment are in red (higher erosion rate)

Stura watershed
Measured SSY 116 Mg/km2/y
Pelacani (2010)

Tavaiano watershed
Measured SSY 14 Mg/km2/y
Pelacani (2010)



Bacini	Erosione netta (t km-1)	Erosione totale (t km-1)	SDR
Tavaiano	47	210	0.23
Stura	105	316	0.33

application of IC
Portion of Bilancino watershed
Cassi, 2010 (PhD thesis)

Proposals for extensive applications of IC (….and FIC) *in 2008*:

The proposed procedure for the IC model contained a large set of potential applications such as:

1) **hot spot identification of primary sediment sources to permanent drainage lines;**
2) **verification of effects of eco-compatible mitigation measures to reduce or favor connectivity (Hooke and Sandercock, 2007)…. se Final report Project RECONDES**
3) **monitoring changes in the degree of connectivity in areas with high geomorphological evolution rates;**
4) **Performing scenario analysis to assess efficiency of conservation measures against soil erosion, sediment, and nutrients transport, and siltation (all strongly related to flux connectivity).**

A first Tool :
In the paper there is as sequence of commands for arcMap (ArcGIS 8.3) was provided to facilitate the calculation of IC
The procedure is not yet outdated….
even if now exists some other valid and more rapid alternatives (e.g. Connectivity Toolbox , Cavalli et al. 2014 see forward..)

Pseudocode fragment for IC calculation - Borselli et al. 2008

Appendix A. ArcGIS 8.3, ArcMap (spatial analyst extension)

Given data
grid: elevation, C
shapefile: road, urban area
Computation of input data

1. *Slope without null value*
   a. Enable Spatial Analyst
      under *View… Toolbars*, select *Spatial Analyst*
   b. Calculate Slope
      from the Spatial Analyst toolbar, select *Surface Analysis… Slope*
      name the new theme *Slope*
   c. Raster Calculator
      from the Spatial Analyst toolbar, select *Raster Calculator*
      build an expression *(([Slope]==0)*0.005)+[Slope]);*
      name the new theme *S*
2. *Road/urban mask*
   a. create a raster map of road and urban areas
      from the Spatial Analyst toolbar, select *Convert.. feature to raster*
      ….

Other applications of connectivity index IC, were found in the international scientific literature, after 2010….Only publications in ISI journals area have been considered these tables… Exist more but aren’t not considered here…

Authors	Year	site	Journal	Area of app.
Sougnezet al.	2011	Spain	Catena	**Soil erosion**
Vigiak ,Borselli et al.	**2012**	**Australia**	**Geomorphology**	**Soil erosion, SSY, SDR**
Lopez-vicente et al.	2013	Spain	Catena	**Soil erosion**
Cavalli et al.	2013	Italy	Geomorphology	**Debris flow**
D’Haen et al.	2013	Turkey	Geomorphology	**Sediment Surface redistribution and origin**
Shneider et al.	2013	Germany	Earth Surface processes and landforms	**Surface Drainage network evolution**
Chartin et al.	2013	Japan	Anthropocene	**Fukushima- radioactive pollution dispersión by rivers**

Continue…

Authors	Year	site	Journal	Area of app.
Messenzel et al.	2014	Switzerland	Geomorphology	**morphometric GIS modelling**
Jamshidi et al.	2014	Australia	Hydrological Processes	**Specific sediment yield and SDR**
Kumar et al.	2014	India	Geomorphology	**Impact of /antropic structures (road and railways) on mega alluvial fan in Himalaya**
Foerster et al.	2014	Spain	Jurnal of soil and sediments	**Connectivity change by vegetation cover (lidar+remote hyperspectral images)**
Heiser et al.	2015	Austria	Geomorphology	**Watershed classification for debris flow processes**
Gay et al.	2015	France	Jounal fo soil and Sediments	**Connectivity index applied to lowland and big watershed and low res. DTM**

Details for each papers in the APPENDIX 2 of this presentation…

IC computations and variants in published papers

Some main tested variants:

- Areas from 0.04 km2 to 155.000km2
- DEM resolution: from 1x1 m to 50X50m
- Use (or not) of river mask as local sink (cavalli et al. 2013)
- Variable Minimum contributing area to generate permanent drainage lines (river mask) from 0.5 ha to 20 ha, or more…
- Use (or not) of roads and urban areas as SINK (like river mask do)
- W factor (classical is W=C(USLE TYPE)) or W=RI(Cavalli 2013)
  IC2 by Cassi (2010) , $IC_{variant}$ (Gay et al. 2015)
- Different countries, environments, landscapes , climates and anthropogenic impacts
- At moment has been published 13 applications (the more importants or with some innovative contents has been considered only)

W factor: an evolution for IC2 model

Cassi, 2010 (PhD thesis) Universisty of Florence . Directed by L.B.

The second version of IC accounts of : *hydrologic soil properties , magnitude of rainfall event, surface roughness*

$$C_r = 1 - \frac{I_{dt} + S}{P_{dt}}$$

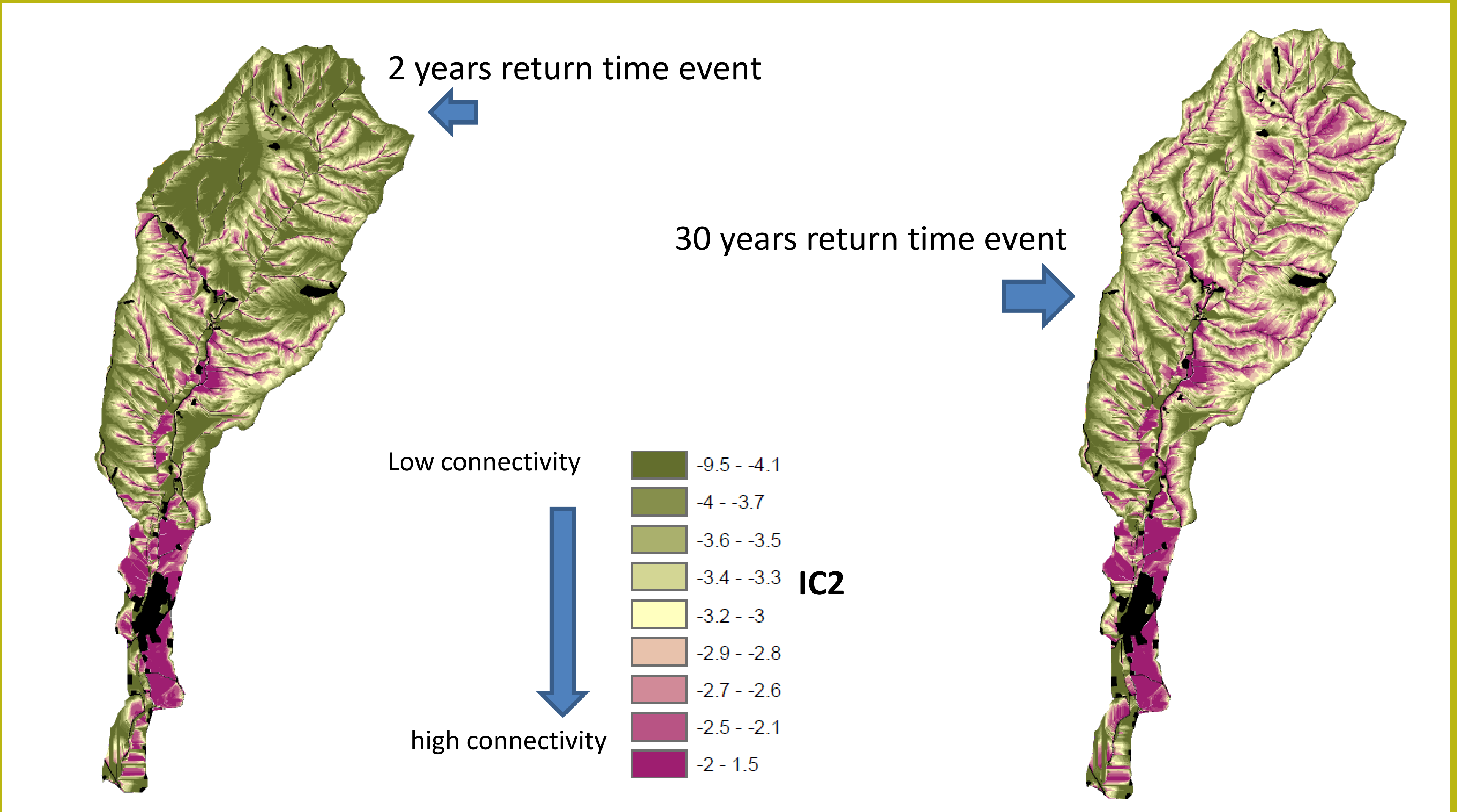
Step 1: computation event runoff coefficent (C_r) (adimensional) , by total infiltration volume (I_{dt}), surface water storage (S) and rainfall volumes (P_{dt}) (all in mm)
Infiltration can be calculated locally by model e.g. model di Morel-Seytuox (1978) for each land units,
S was computed with relationship by Borselli and Torri (2010, Journal of Hydrology), as a function of surface roughness and local slope gradient

$$\frac{1}{f}$$

Step 2 Hydraulic roughness due land use and soil surface characteristics (including vegetation) by Darcy Weisbach (f) friction factor (adimensional)

$$W = C_r * \frac{1}{f}$$

Step 3: Final W calculation
(please note W is still adimensional)



Average Intensity 15.7 mm/h
Duration 2.5 h
Amount 39.2 mm

First application of IC2
Portion of Bilancino watershed

Cassi, 2010 (PhD thesis)

Average Intensity 37.9 mm/h
Duration 1 h
Amount 37.9 mm

EARTH SURFACE PROCESSES AND LANDFORMS
Earth Surf. Process. Landforms **40**, 177–188 (2015)

Published online 17 September 2014 in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/esp.3635

State of Science

Sediment connectivity: a framework for understanding sediment transfer at multiple scales

Louise J. Bracken,[1]* Laura Turnbull,[1,2] John Wainwright[1] and Patrick Bogaart[3]
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[3] Environmental Sciences, Copernicus Institute of Sustainable Development, Utrecht University, Heidelberglaan 2, 3584 CS Utrecht, The Netherlands

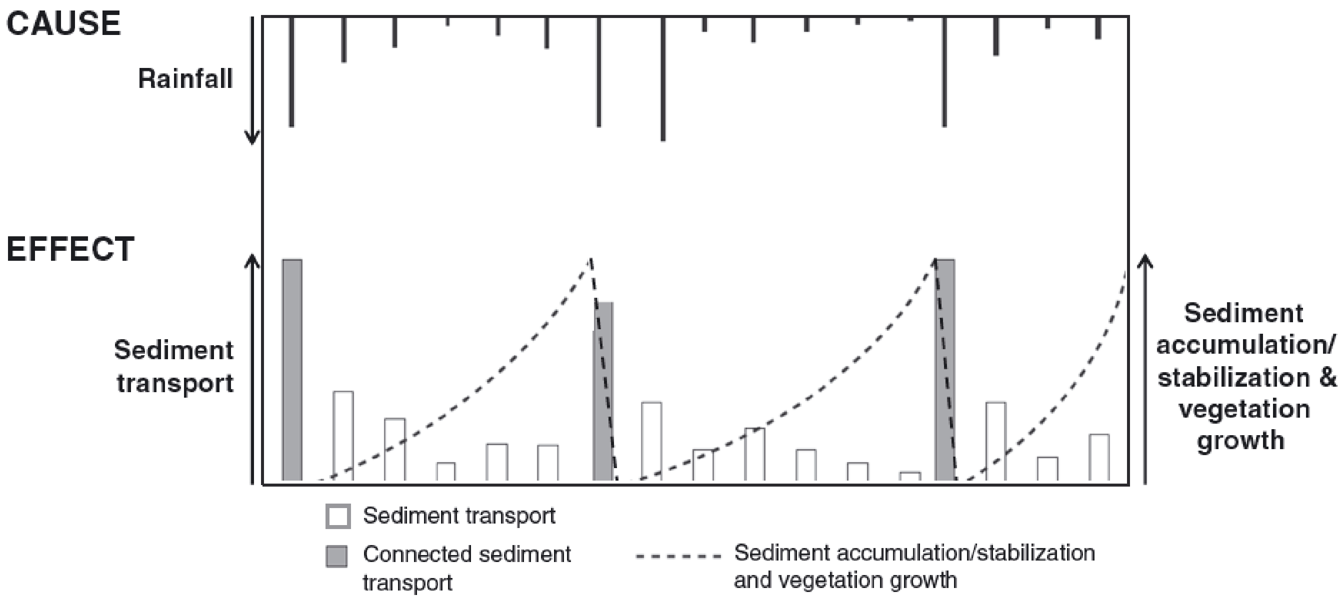


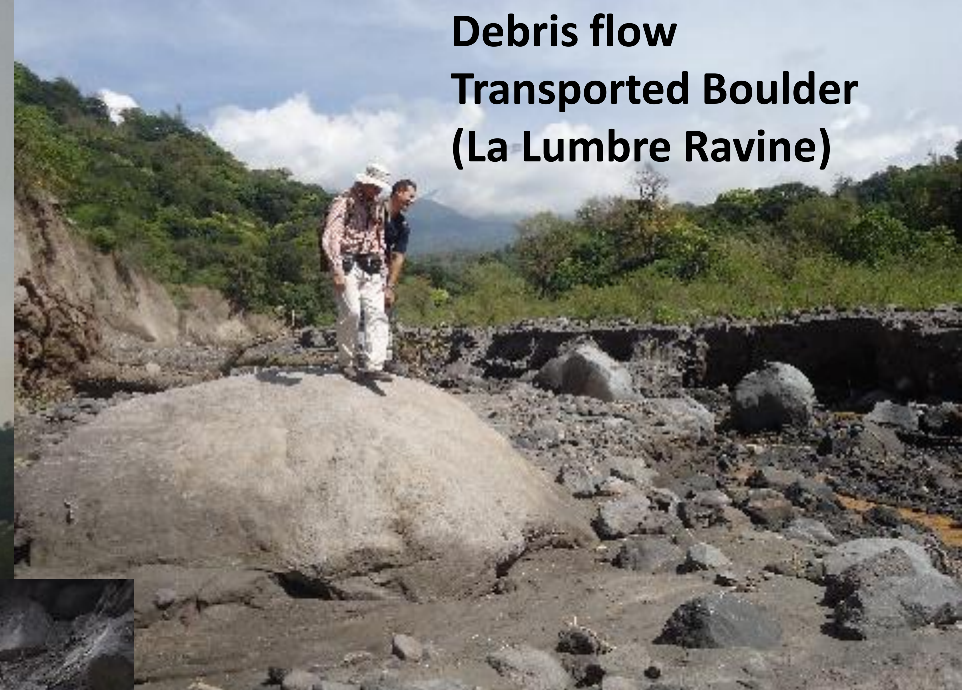
Figure 4. Diagram showing the effect of a major, infrequent event followed by low magnitude, high frequency events, which tend to decrease in magnitude over time as vegetation stabilizes hillslopes and river banks, as well as removing water from sediment transport via transpiration. This pattern continues until another high magnitude event occurs, leading to some form of resetting of the system.

Now …..Connectivity in Mexico…

Project MOPRI (2013-2015)

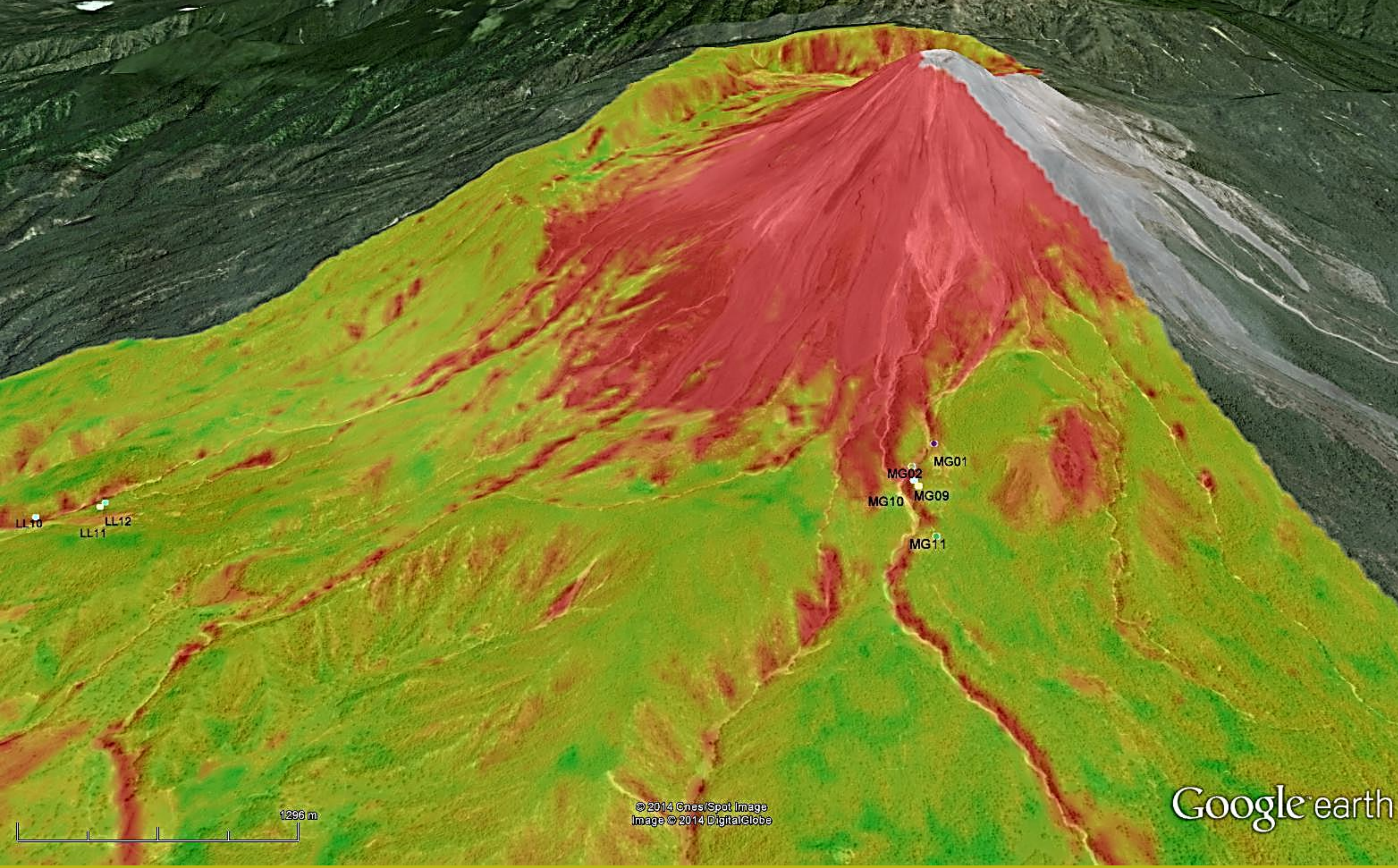
"Modelado de procesos hidrológico, dinámica de hidrofobicidad e infiltración, para su aplicación en la evaluaciones del riesgo debido a inundaciones y lahares: aplicación en la ciudad de San Luis Potosì y en el Volcán De Colima" (2013-2015)(CONACYT-Ciencia Basica-2012-01 -184060)


Colima,
Volcan de
Fuego


Debris flow
Transported Boulder
(La Lumbre Ravine)

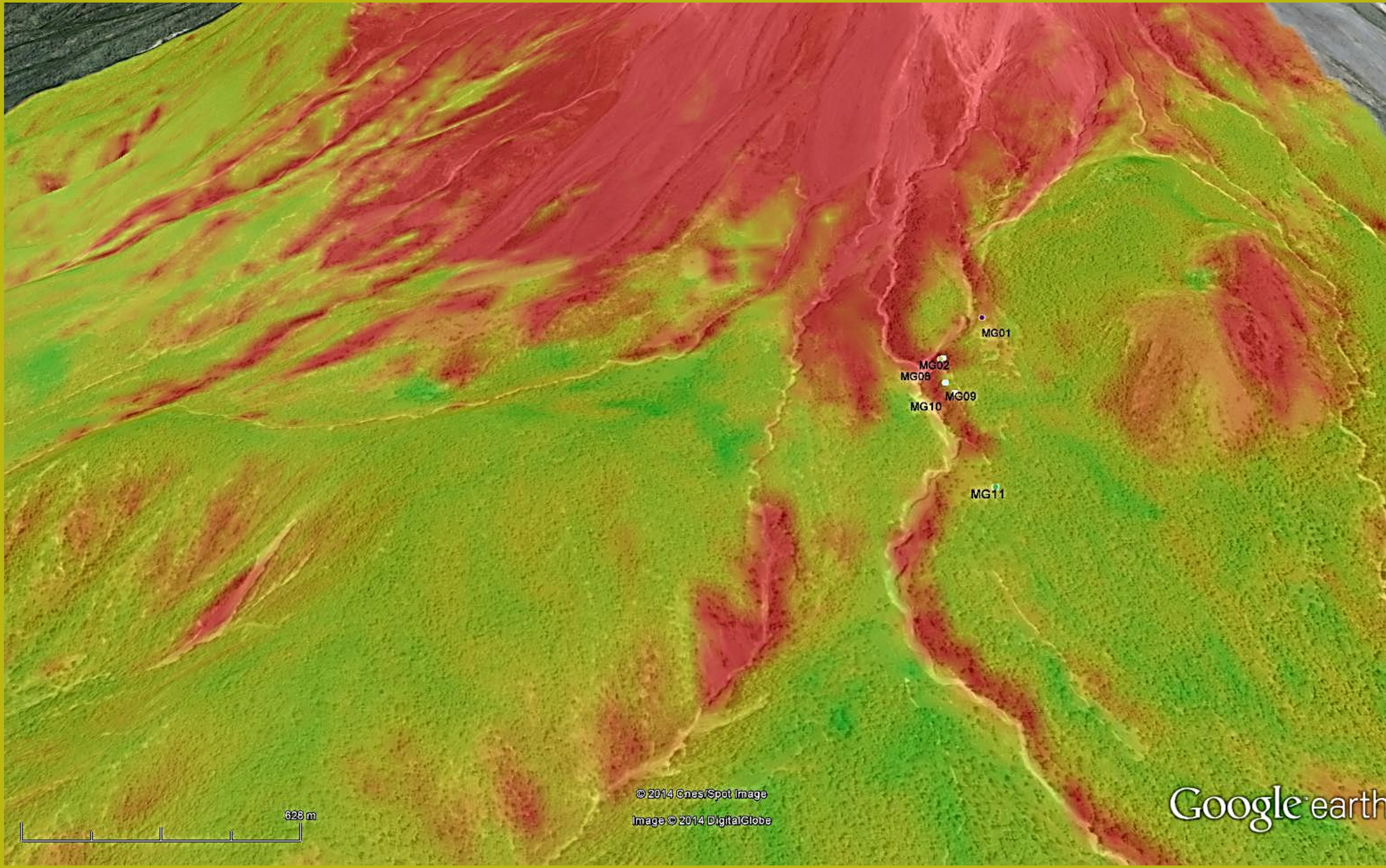

Debris flow
Transported Boulders
(Montegrande ravine)


Infiltration Test
(Montegrande Ravine)



Connectivity map (IC) DEM 5x5m (transparent overlay on Google Earth image 2014)

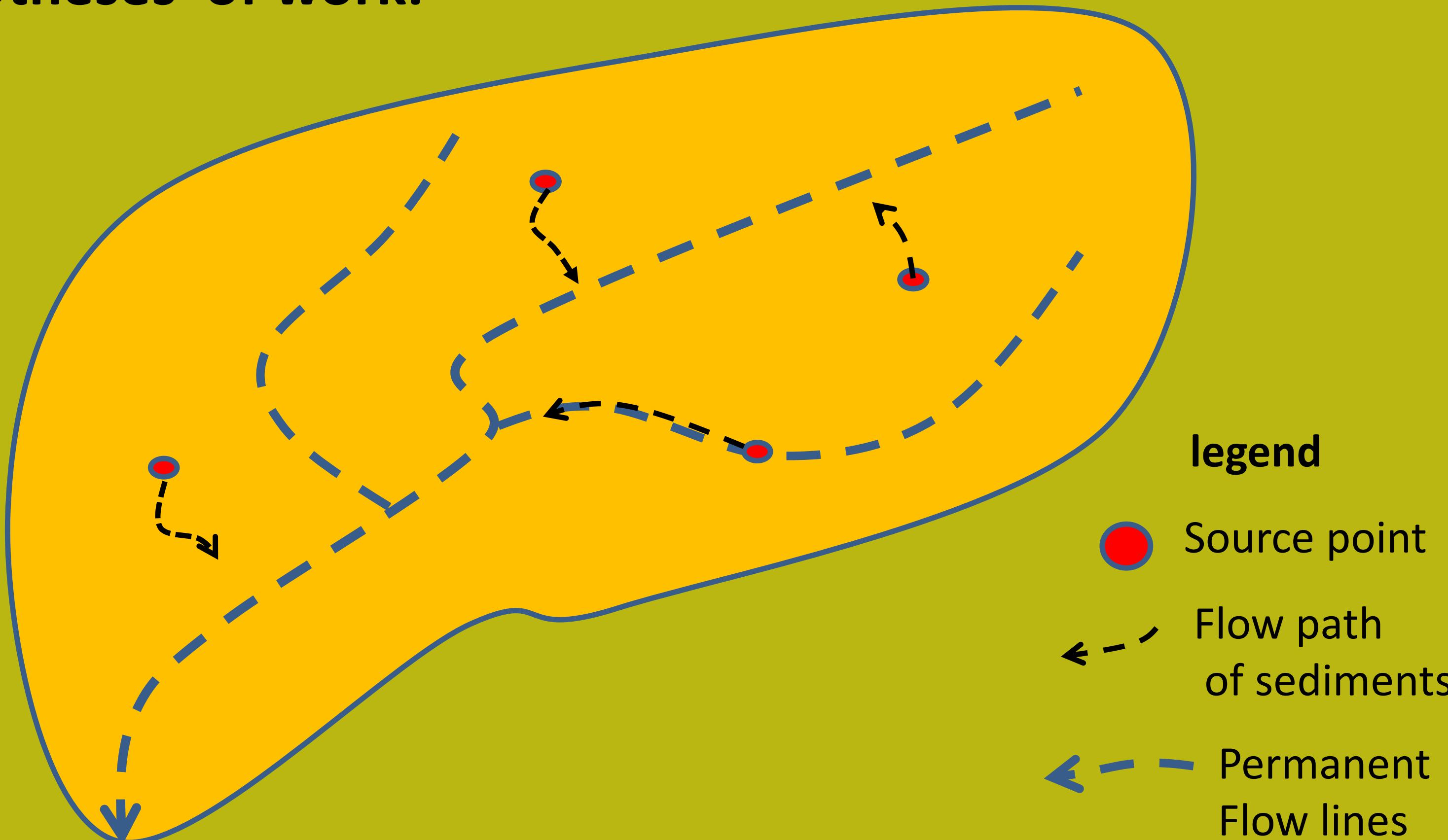
Portion of Colima volcano South flank with several barrancas and main source areas of lahars (above 2500 m a.s.l.); local remobilization, mass movements, and instability of older deposits are in evidence.



Connectivity may help understanding the dynamic of lateral hydrologic contributions that trigger or remobilize the lahars at the beginning of the rain season, when the soil is hydrophobic (Capra , Borselli et al. 2010).

PART II

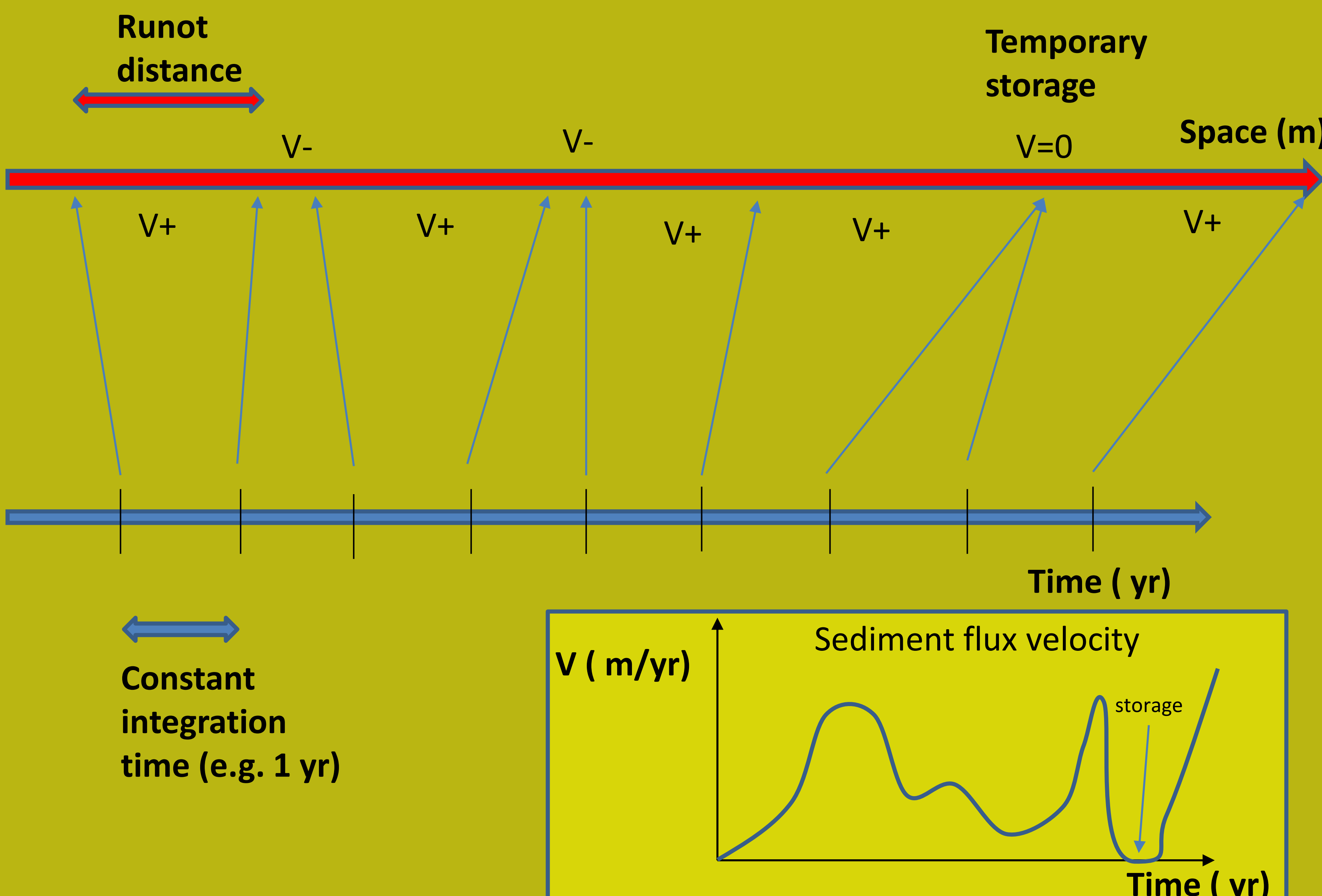
- **Connecting FCA and sediment travel time.. Theory and hypotheses of work.**



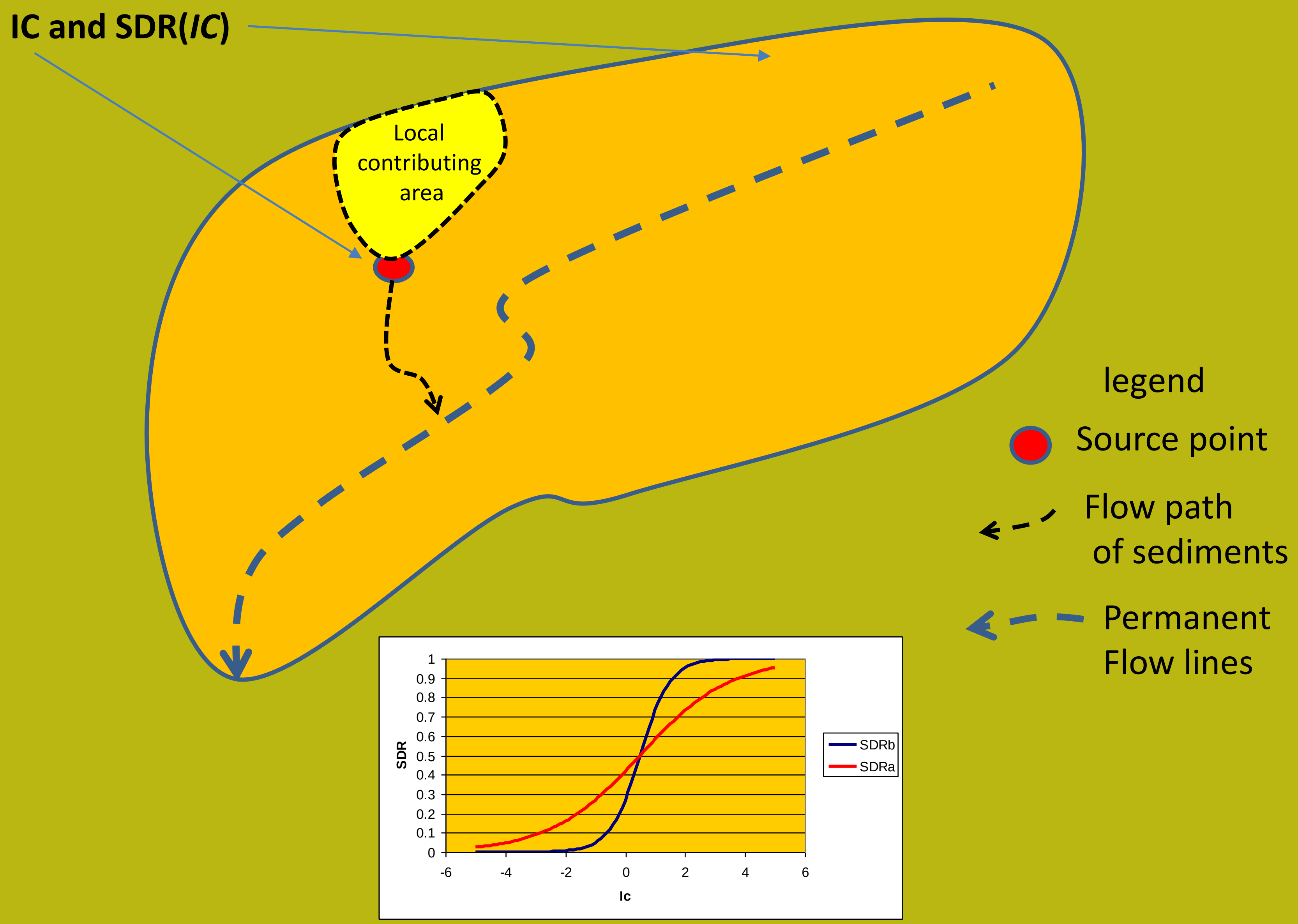
Sediment travel time: time ΔT(s) required to move a given amount of sediments from a source point by a measured distance ΔS(m) along a flow path. An average speed V can be calculated on the same **integrated interval of Time** ΔT.

$$V = \frac{\Delta S}{\Delta T} \quad \left[LT^{-1}\right]$$

- **The local sediment flow can increase or decrease its speed (depending fro many factors : morphology, vegetation, climatic…) also producing a temporary storage (V=0)..**

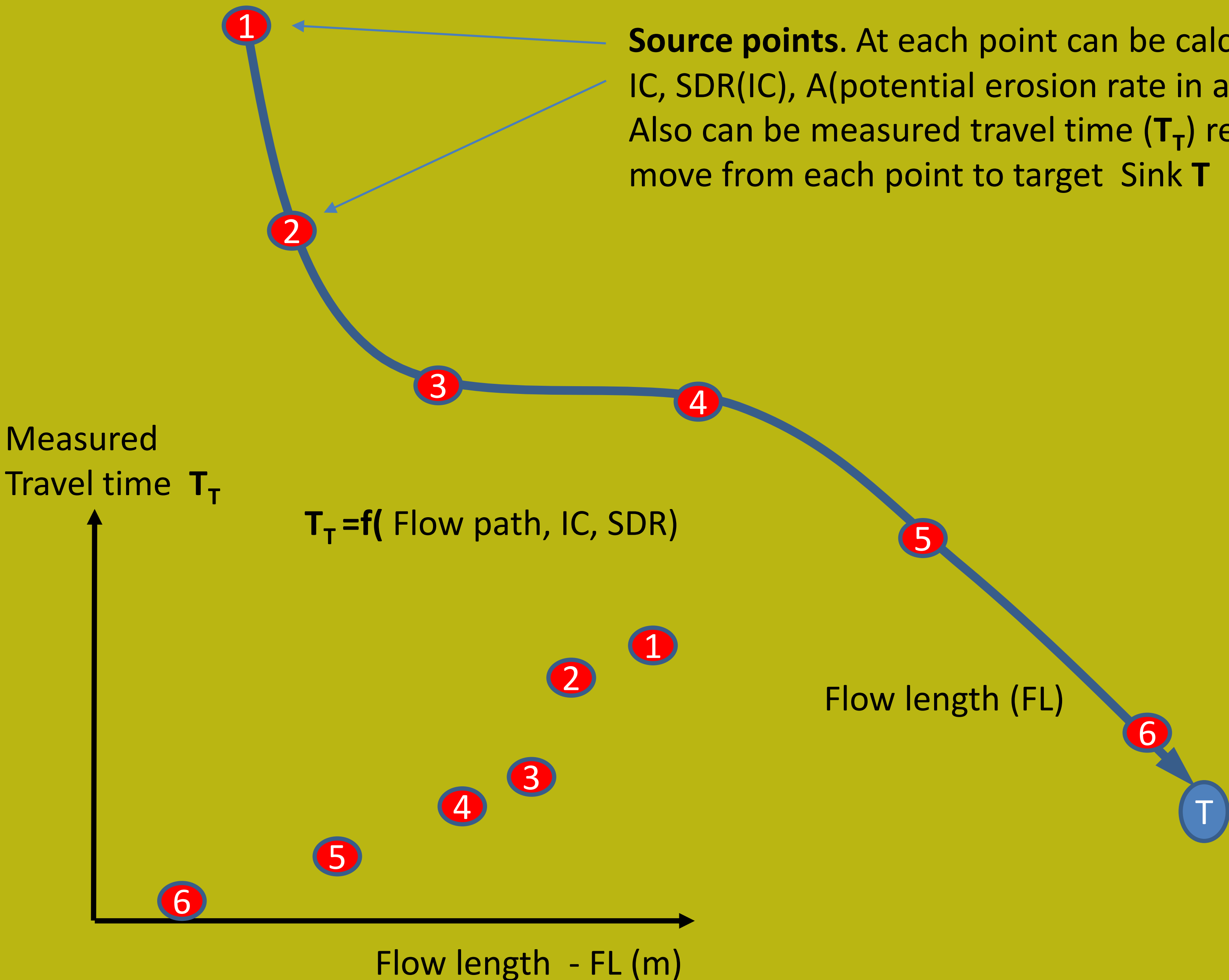


In each source points we can calculate the following parameters:



Flow line

Source points. At each point can be calculated: IC, SDR(IC), A(potential erosion rate in a given ΔT) Also can be measured travel time (**T_T**) required to move from each point to target Sink **T**



Net erosion rate arriving in target (sink) in ΔT

$$E_i = A_i * SDR_i$$

Where:
A_i = potencial erosion rate (Mg ha^{-1} yr^{-1})
SDR= sediment delivery ratio (adimensional)
E_i = Net erosion rate (Mg ha^{-1} yr^{-1})

The travel time $\mathbf{T_T}$ from a single source point i to traget (sink) can be defined as:

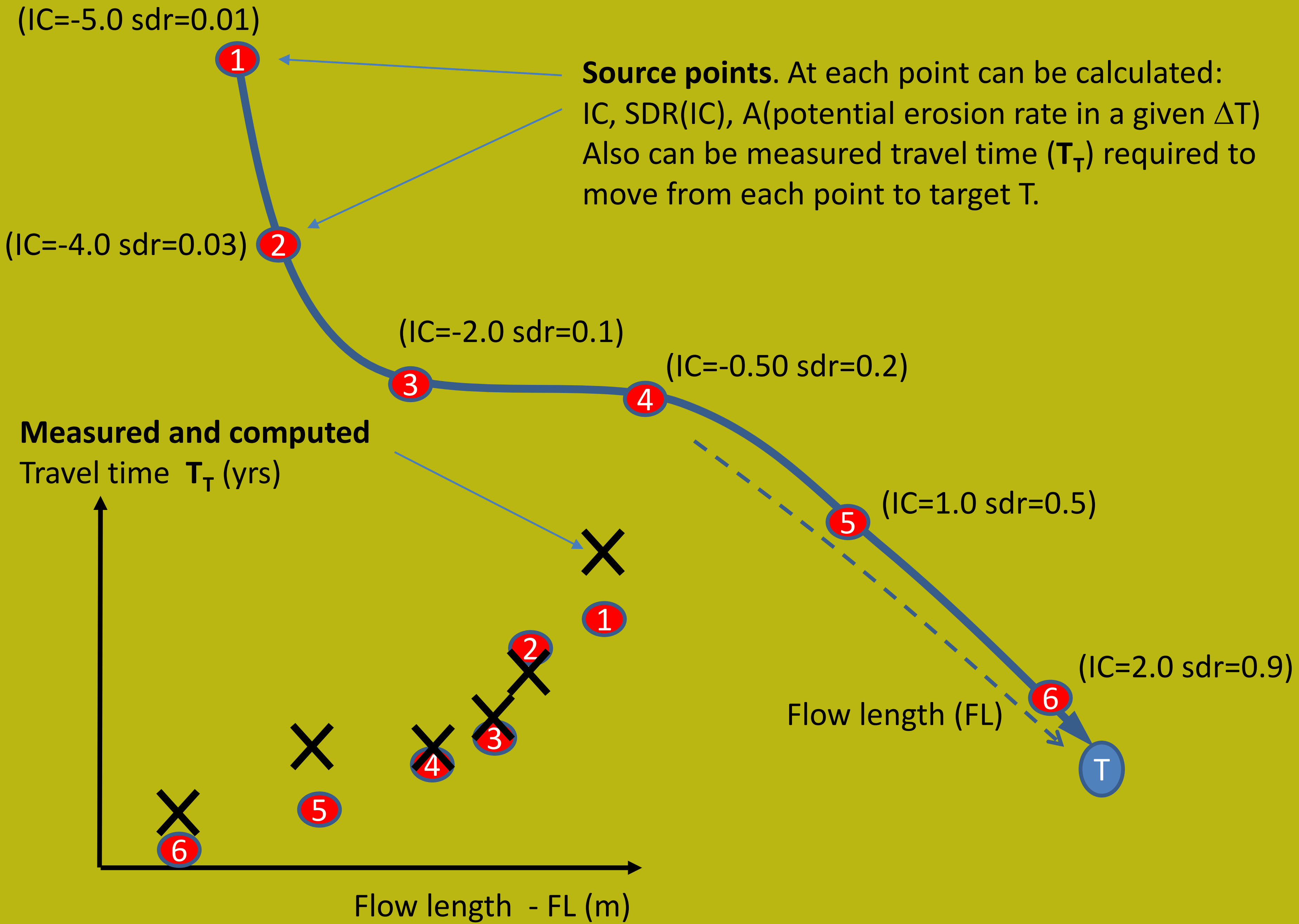
$$T_{T_i} = \frac{\Delta T}{SDR_i}$$

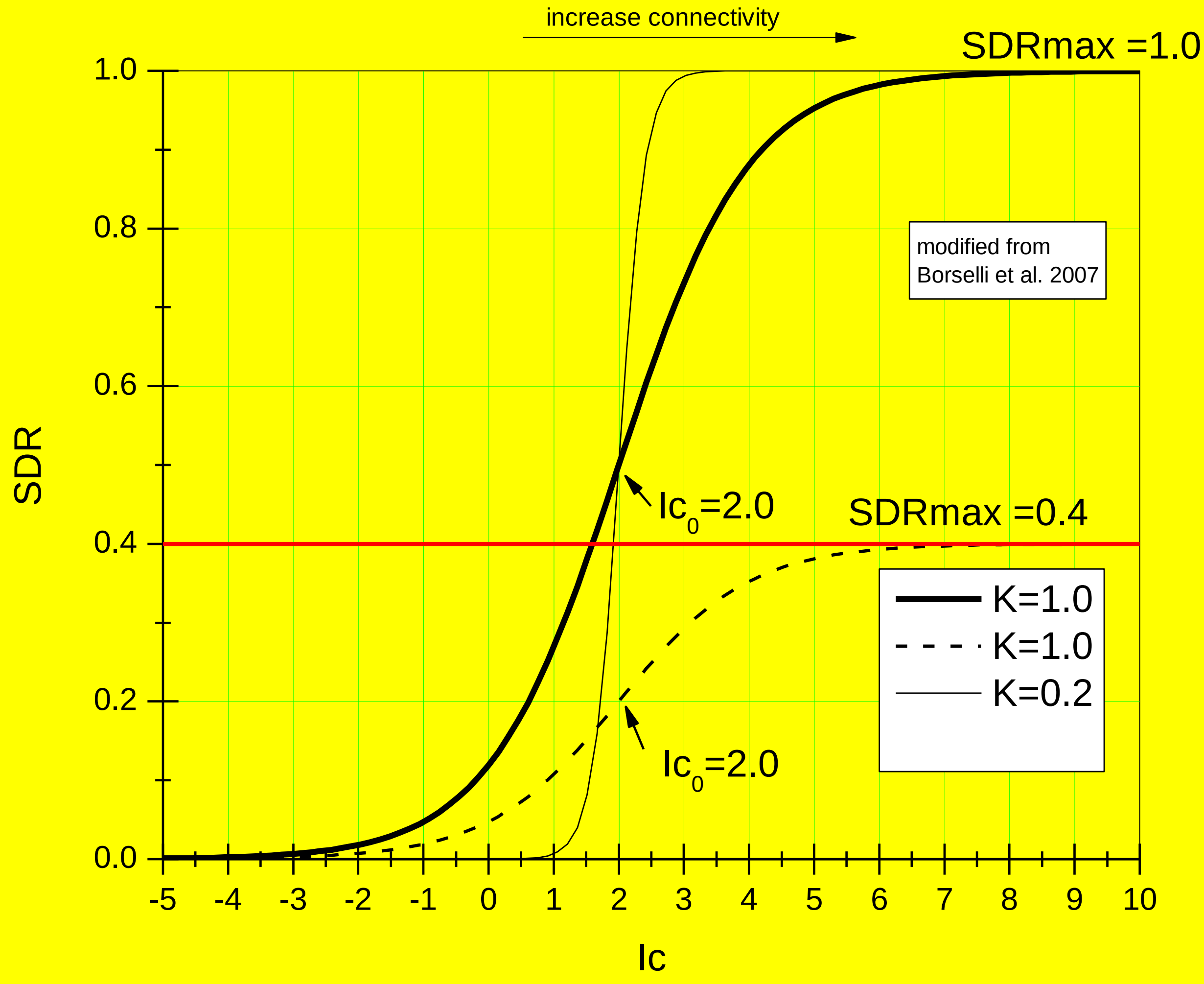
The SDR also represents the probability that in a Integration time ΔT a given mass of sediment Arrives in the target sink.

Usually we asume ΔT=1 yr in most of the USLE-Type models so we have:

$$T_{T_i} = \frac{1}{SDR_i}$$

e.g. If SDR=0.1 → T_T=10 yrs


(IC=-5.0 sdr=0.01)
Source points. At each point can be calculated:
IC, SDR(IC), A(potential erosion rate in a given ΔT)
Also can be measured travel time (**T_T**) required to
move from each point to target T.
(IC=-4.0 sdr=0.03)
(IC=-2.0 sdr=0.1)
(IC=-0.50 sdr=0.2)
Measured and computed
Travel time **T_T** (yrs)
(IC=1.0 sdr=0.5)
(IC=2.0 sdr=0.9)
Flow length (FL)
T
1
2
3
4
5
6
Flow length - FL (m)



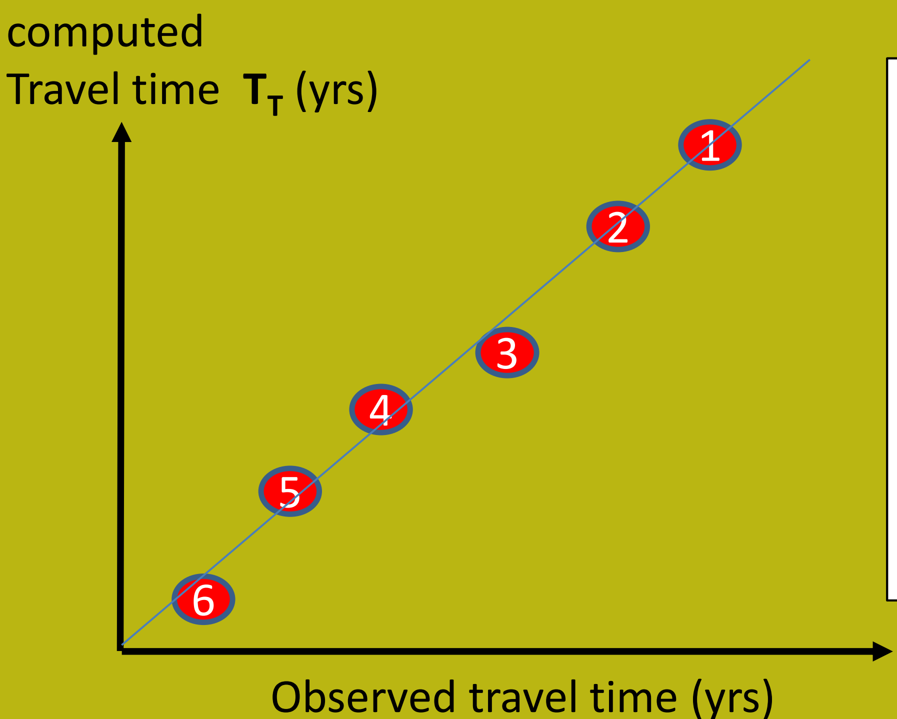
Implementation of *SDR = f (iC)*

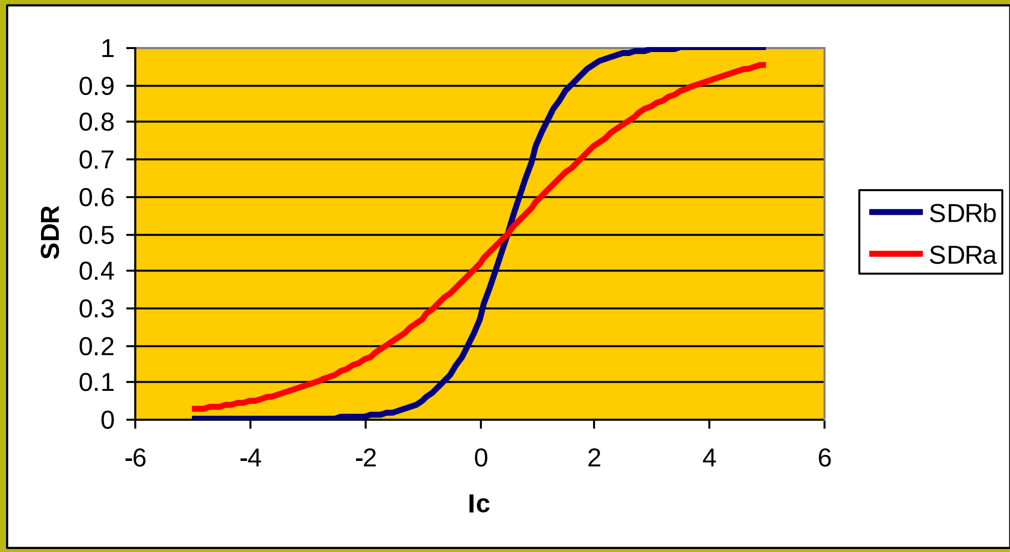
Function Optimization that allows The calibration based on A set of observed experimental source points Instead the use of a set of total gauging stations As used bay borselli et al (2007) and vigiak et al. (2012)

$$SDR = \frac{SDR_{Max}}{1 + \exp\left(\frac{Ic_0 - Ic}{k}\right)}$$

Optimization numerical techniques allows calibrate the apropriate SDR=f(IC)
In our experimental watersheed. Using as objective function the sum of minimum absolute difference between measured and computed travel times.

e.g. minimization by genetc algorithm can by used in efficient ient way
See presentation: [Differential Evolution Application In Earth Sciences(Borselli, 2008)]
At www.lorenzo-borselli.eu

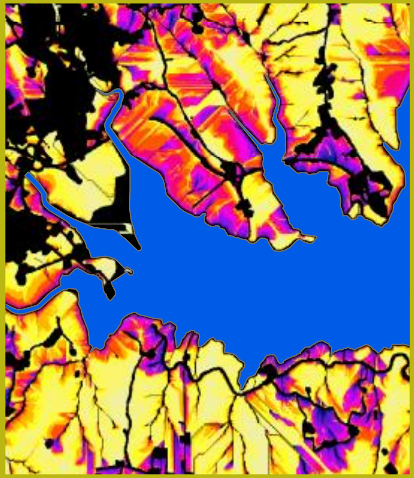




The procedure can be summarized in subsequent steps:

1) To Generate Map of IC , considering also possible variants with respect the original formulation by Borselli et al. (2008)
2) To Use travel times measured in an adequate number of sites representative of existing land units in the studied watershed.
3) To Consider Boltzmann sigmoid type function for Sediment delivery ratio (SDR) to be obtained form IC values ..(see Borselli 2007,2008 and in particular Vigiak et al. 2012)
4) To Calulate travel Time from IC and SDR
5) To Calculate sum of absolute difference between the observed and calculated travel time
6) To Activate a non-linear optimization routine in order to change sigmoidal SDR=f(IC) parameters. (repeating step 3, 4 and 5 until minimum objective function value is found)
7) To Generate final calibrate SDR map..

The final SDR may offer additional information on range of HIGH, MEDIUM an LOW connectivity ranges of IC values in a watershed.



Highlights and speculations - 1

The Connectivity index IC and FCA **provide an estimate of the potential connection index between the sediment eroded from hillslopes and the stream system or other local sinks**;

FCA can put in relation the IC index and SDR. SDR can be used then to correct the USLE-TYPE models (*transport capacity unlimited*) generally used for large catchments modelling and obtain a Sediment yield assessment .

The use of SDRmax limited values (Borselli et al. 2009 and Vigiak el a. 2012) can correct for inconsistencies indicated by some researchers (Kinnell 2004, Parson et al. 2006) in previous SDR assessment.

Highlights and speculations - 2

The IC model have a large set of potential applications such as hot spot identification of primary sediment sources to permanent drainage lines and **verification of impacts of eco-compatible mitigation measures to reduce or increase connectivity**. (without more complex
Soil erosion models) (e.g. indications of Boardman, 2006)

IC can be easily transformed in a more physical based index (e.g. variants by Cavalli 2013 and Cassi 2010)

Potential application of IC to define **SDRL** can help to assessment of Sediment yield contribution due to Landslides and debris flow (PESERA-L model).*(see appendix 1)*

Highlights and speculations - 3

The IC model have potential pplication at various temporal and spatial scale : from small watershed (<1km2) to large watershed (subcontinental scale)
Temporal scale change of IC can be easily obtained by remote sensing. (see. Foerster et al.2014)

IC May be not limited only to soil erosion. E.g.Pesera-L example for shallow landslide, or debris flow watershed classification (Heiser et al. 2015)

Connectivity is a local metric index and it may be an opportunity for a set of new tools oriented to planning and decision making for soil and water conservation and Hydrogeological hazard assessment.

APPENDIX 1
Connectivity: toolbox, software and extensions

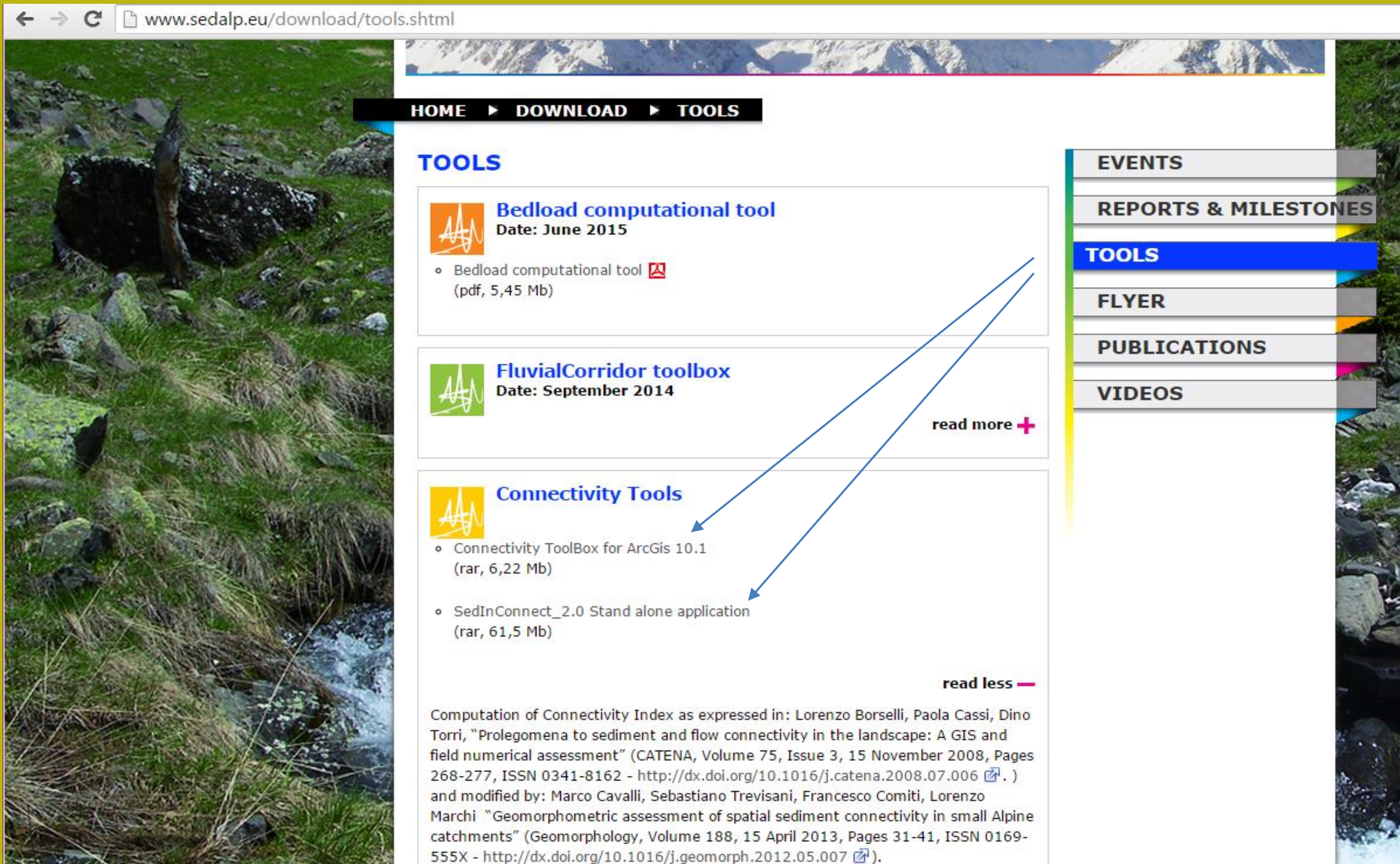
Cavalli's TOOLBOX (2014) for IC index computation

(An ArcGIS implementation for IC calculation and its variants)

From Marco Cavalli 2014

marco.cavalli@irpi.cnr.it

From **Project SEDALP** www.sedalp.eu

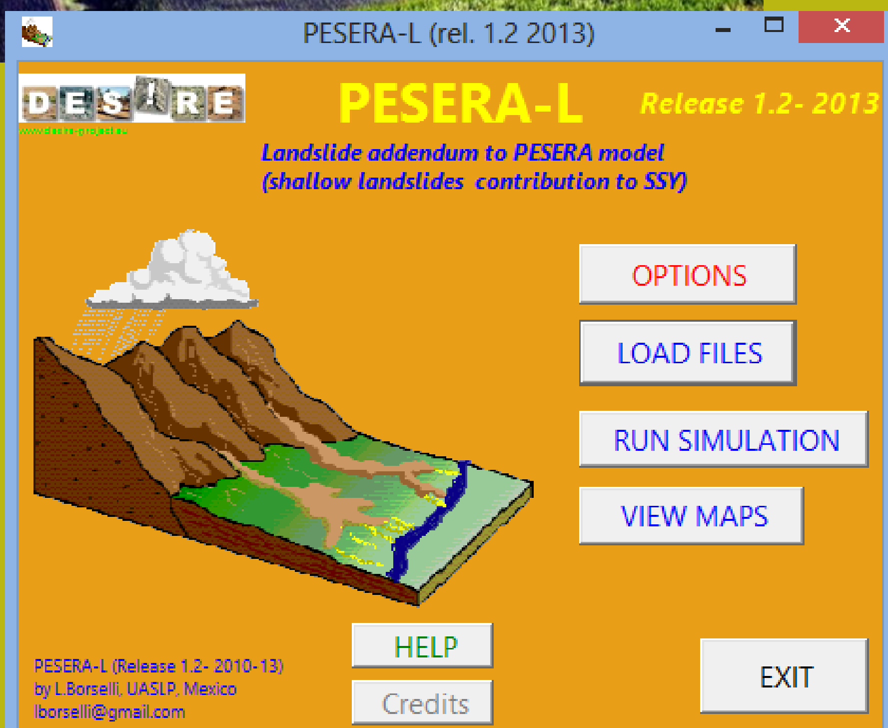


A global initiative to combat desertification

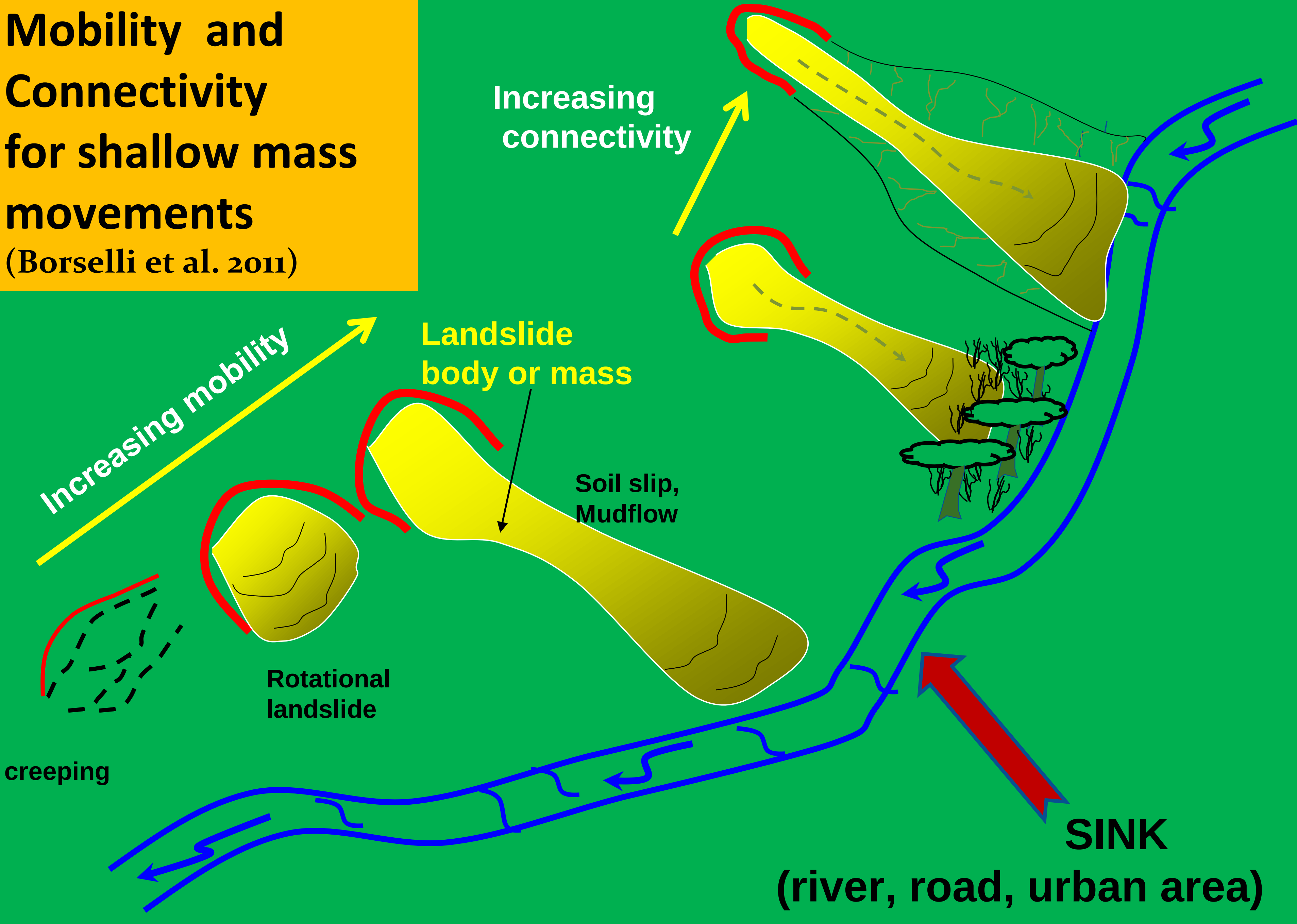
Consiglio Nazionale delle Ricerche

PESERA-L, the shallow landslides contribution to specific sediment yield (SSY), as extensions of the PESERA soil erosion model

See www.Lorenzo-borselli.eu/peseral
For software download and documentation



Mobility and Connectivity for shallow mass movements
(Borselli et al. 2011)



The Sediment delivery ratio for landslides SDRL
And how to obtain SSY (under Pesera-L)

$$V = 10^6 A\ D\ \Psi\ SDR_L$$

$$SSY = \frac{V\gamma_s}{100A\Delta_t} \qquad [Mg\ ha^{-1}yr^{-1}]$$

Where

***V*= <u>net eroded Volume (m3)</u>**

A*= *area of HLU (km2)

D*= *<u>average depth of landslides</u> (m)

Ψ*= *<u>fraction of area potentially unstable</u> (-)

SDR_L= *sediment delivery ratio from landslides* (-)

γ_s= *soil unit weight (Mg/m3)*

Δ_t = *<u>annual frequency</u> (yr)*

***SSY*= *specific sediment yield from hillslope* [Mg/ha/yr]**

Exponential distribution model for sediment delivery

Derived by *Miller and Burnett (2008*) and modified by implementation of a portion of IC

Where:

L$_R$ = landslide average runout (m)

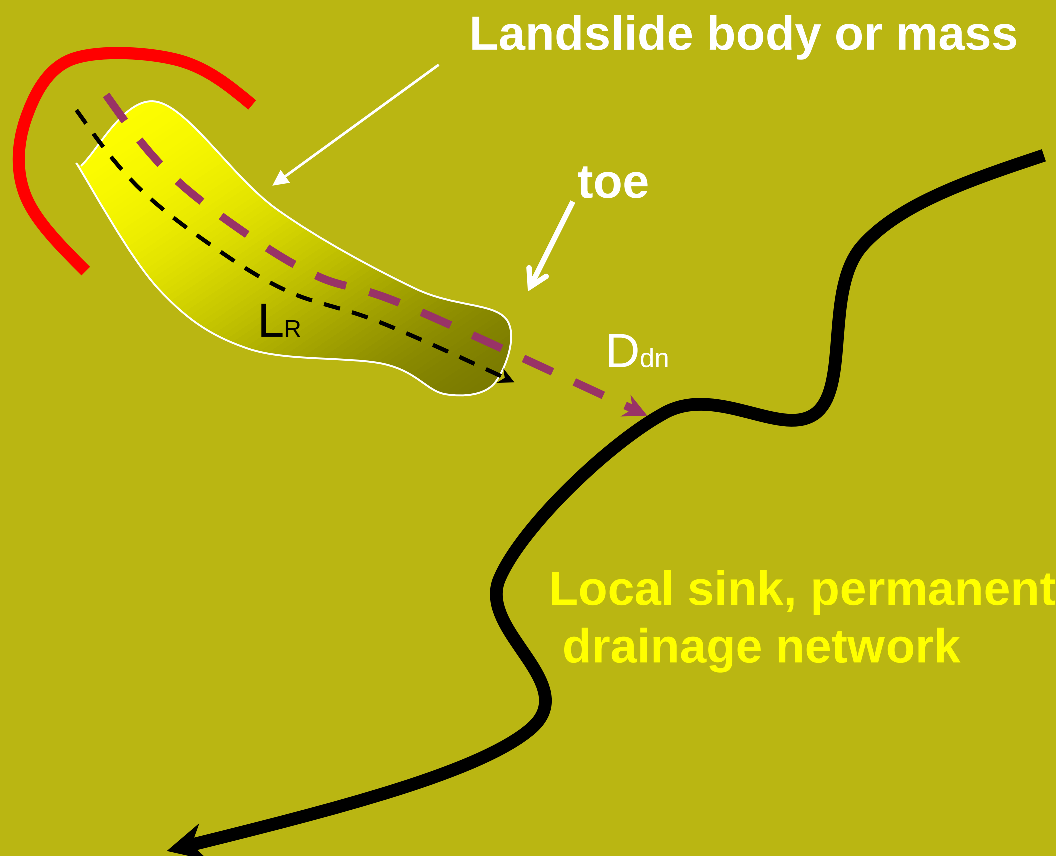
D$_{dn}$= Downslope routing weigthed distance (m)

(downslope component IC model Borselli et al. 2008)

$$SDR_L = e^{-\lambda D_{dn}}$$

$$\lambda = \frac{1}{\overline{L_R}}$$

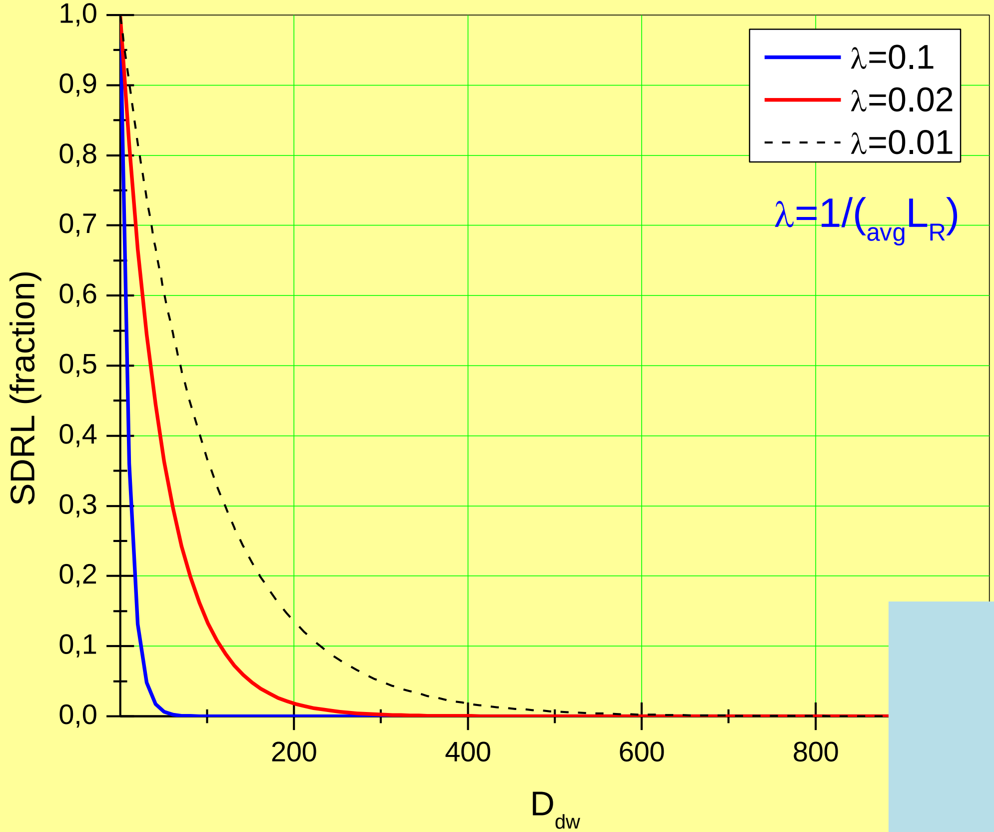
$$SDR_L = e^{-\frac{D_{dn}}{\overline{L_R}}}$$

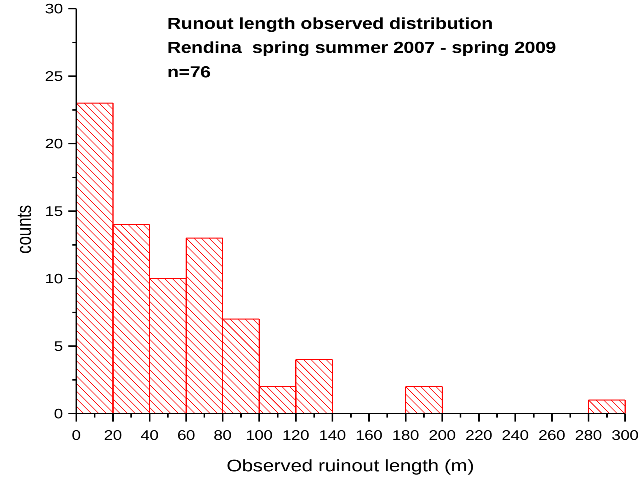


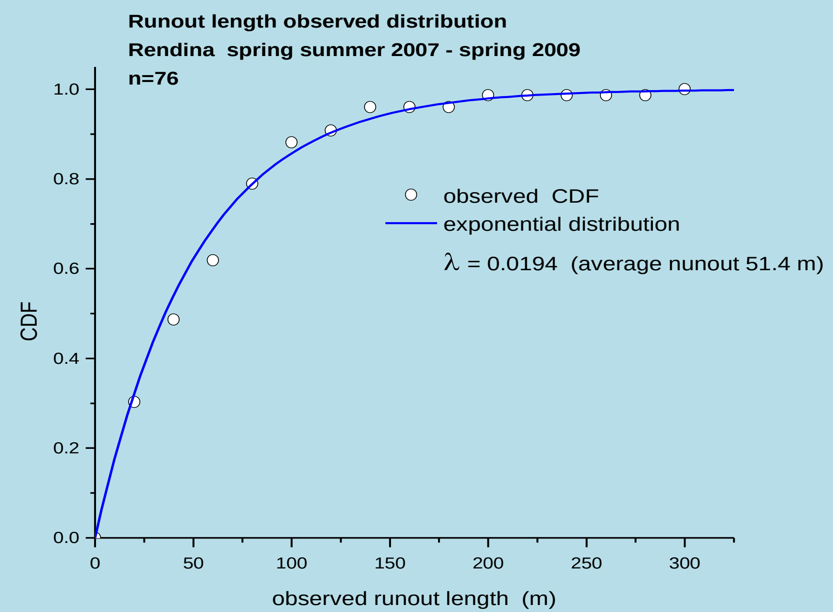
Mobility parameter that depends on average observed runout L_R and local D_{dn}

probabilistic model of landslides and debris flow delivery to stream channels

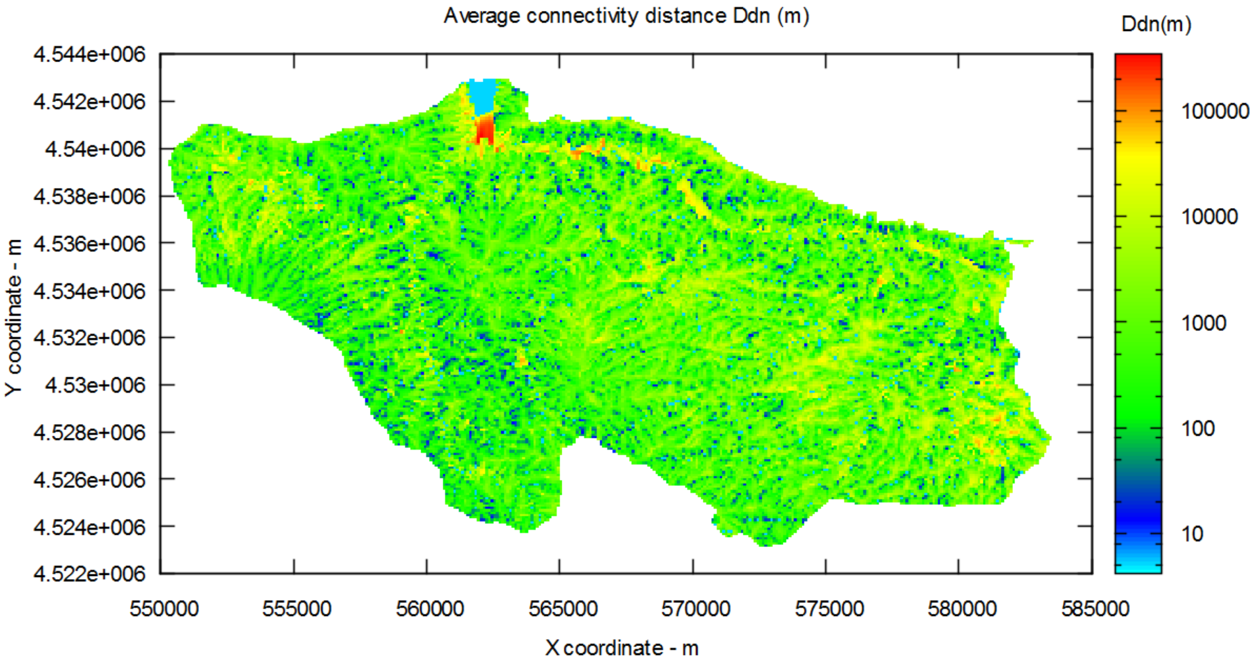
(Miller & Burnett, 2008)







Exponential probability distribution function
depends from the average runout length Lr (measured)
and the local site D_{dn} distance to a sink

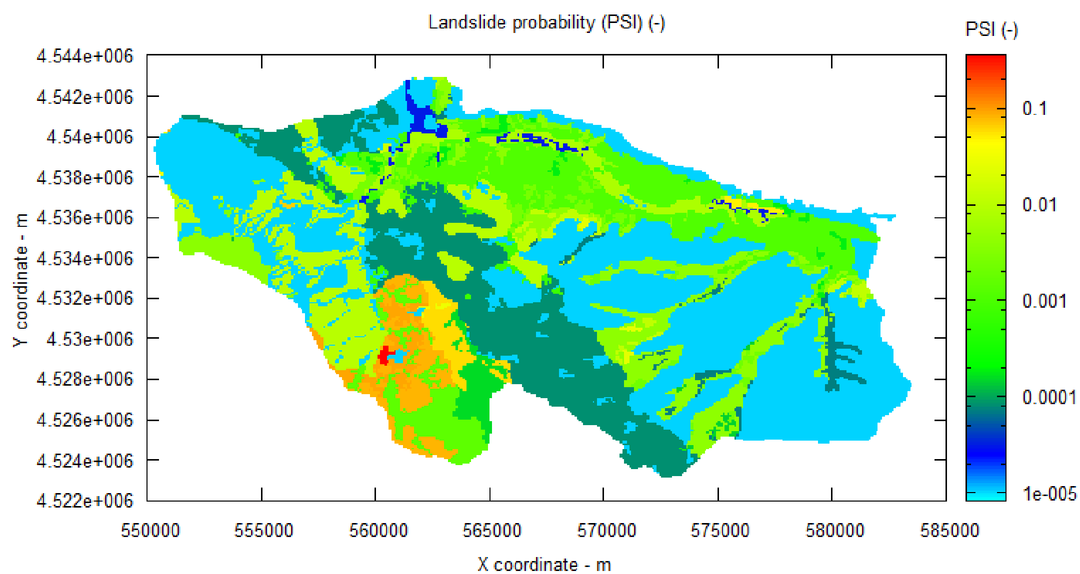


PESERA-L rel. 1.2 (2013) by L. Borselli, lborselli@gmail.com
http://www.lorenzo-borselli.eu/peseral

Application to Rendina watershed
Project DESIRE

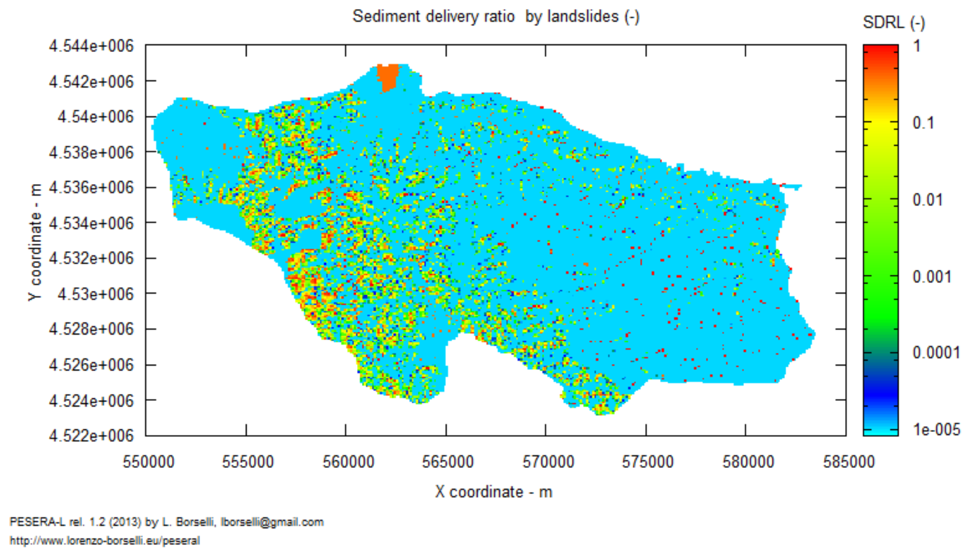
Connectivity average downslope distance

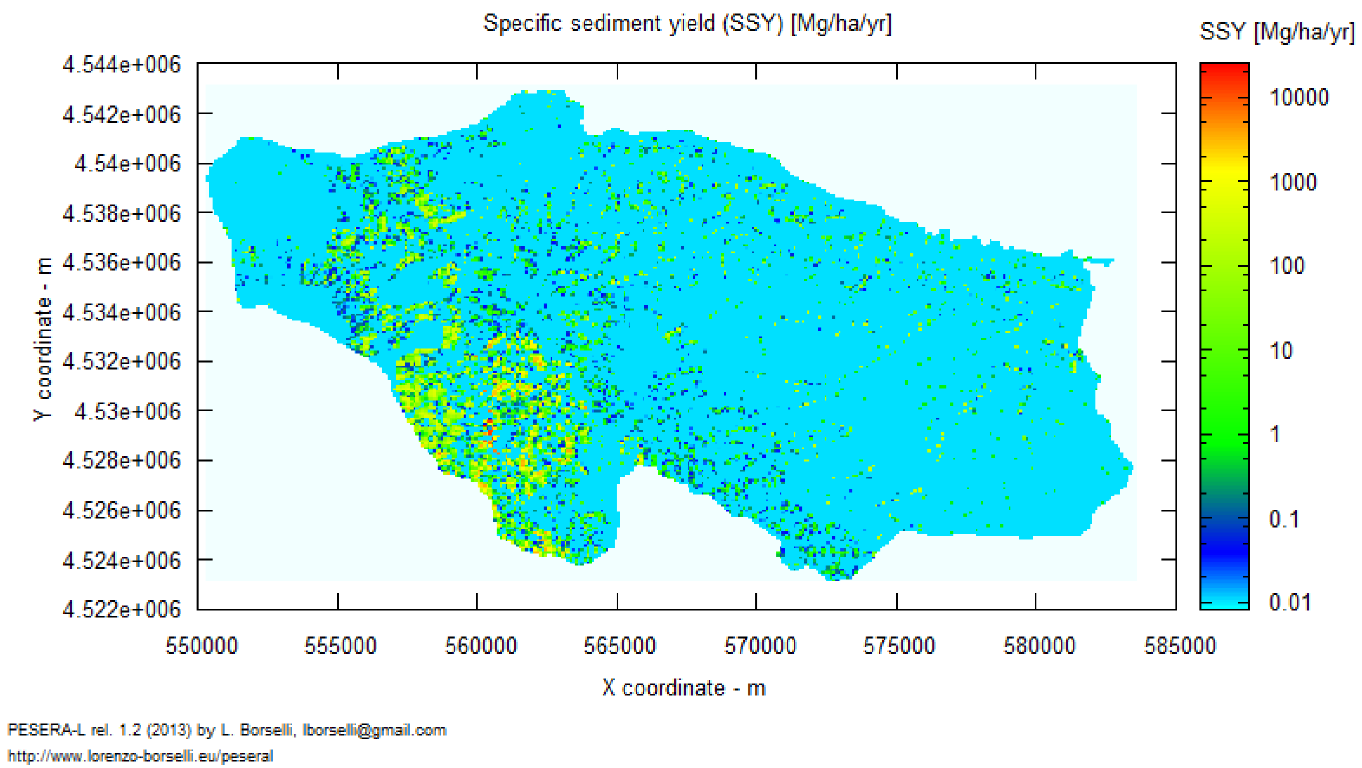
Landslide probability



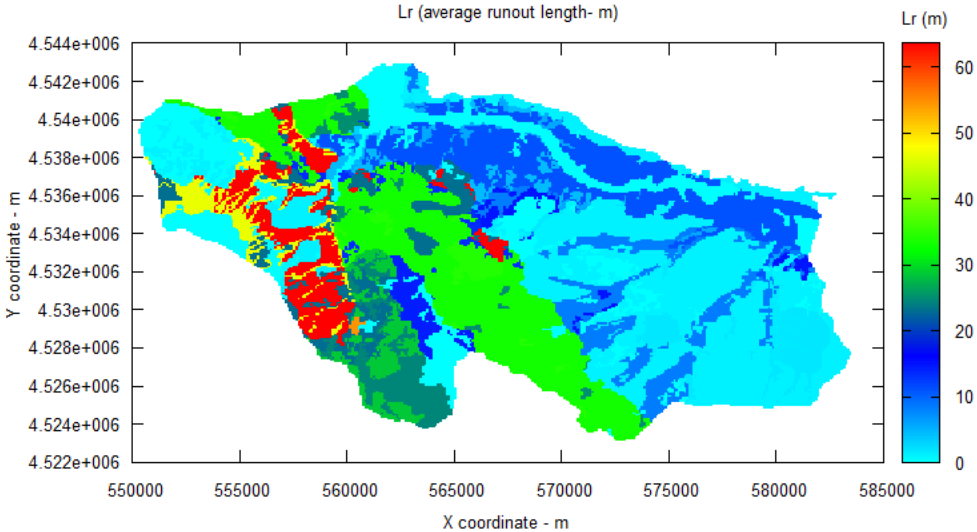
PESERA-L rel. 1.2 (2013) by L. Borselli, lborselli@gmail.com
http://www.lorenzo-borselli.eu/peseral

SDRL
Sediment delivery by
Shallow landslides





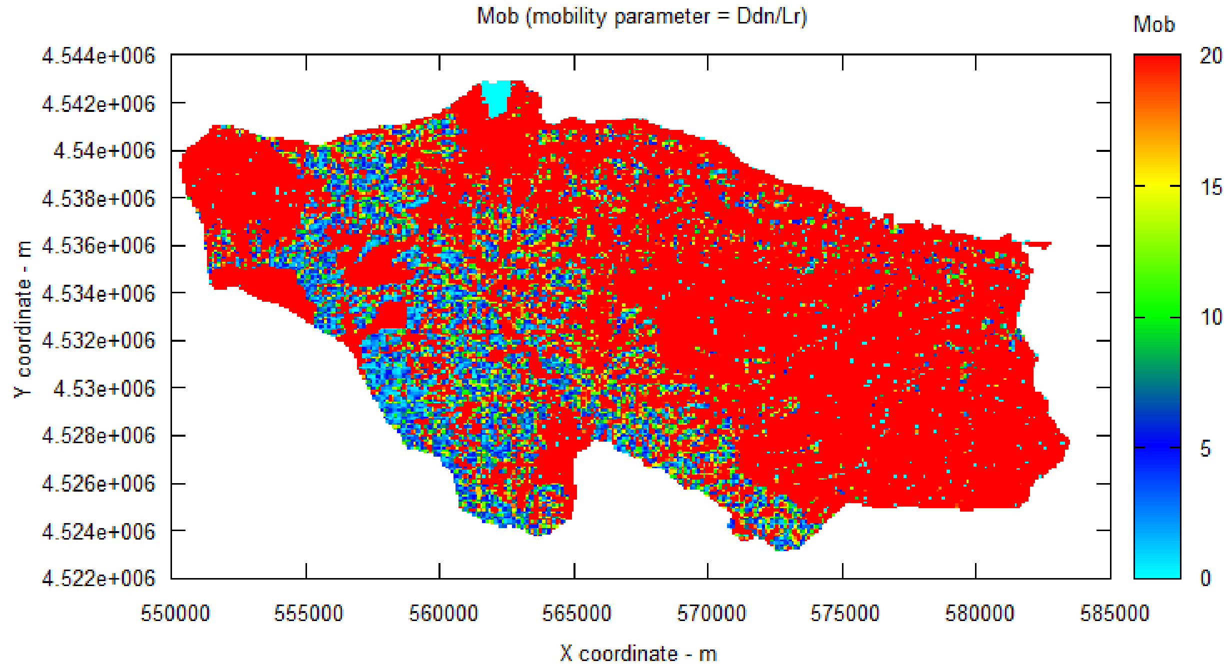
SSY by landlsides



Average run-out length of shallow landslides for each LUS (land unit system) obtained from field survey and multi-temporal aerial photos

Mobily parameter of landslides

$$\frac{\overline{D}_{dn}}{\overline{L}_R}$$



Mass movement type

Flow slide mudflow

Shallow Translational

Shallow Rotational

creeping

$$\frac{\overline{D}_{dn}}{\overline{L}_R}$$

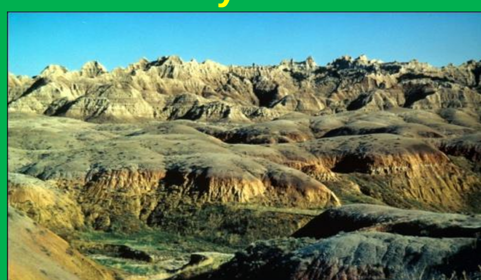
0.1 → **1.0** → **2.0** → **5** → **10**

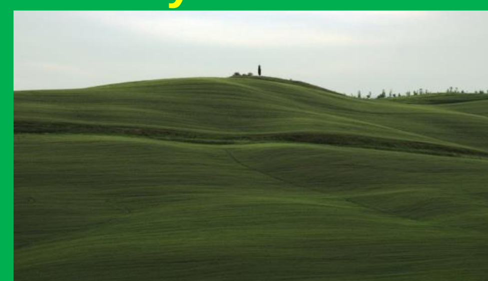
Land unit landforms

Badlands
Clay shale
Deposits
High drainage density

rolling topography
Medium steepness and medium drainage density

Rolling to flat topography





Landslide mobility parameter

And the possible dependence from processes and landforms

APPENDIX 2
Literature Review on IC index Application in soil erosion, geomorphology , hydrology (Until August 2015)

Catena 84 (2011) 1–11

Contents lists available at ScienceDirect

Catena

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

ELSEVIER

Year 2011

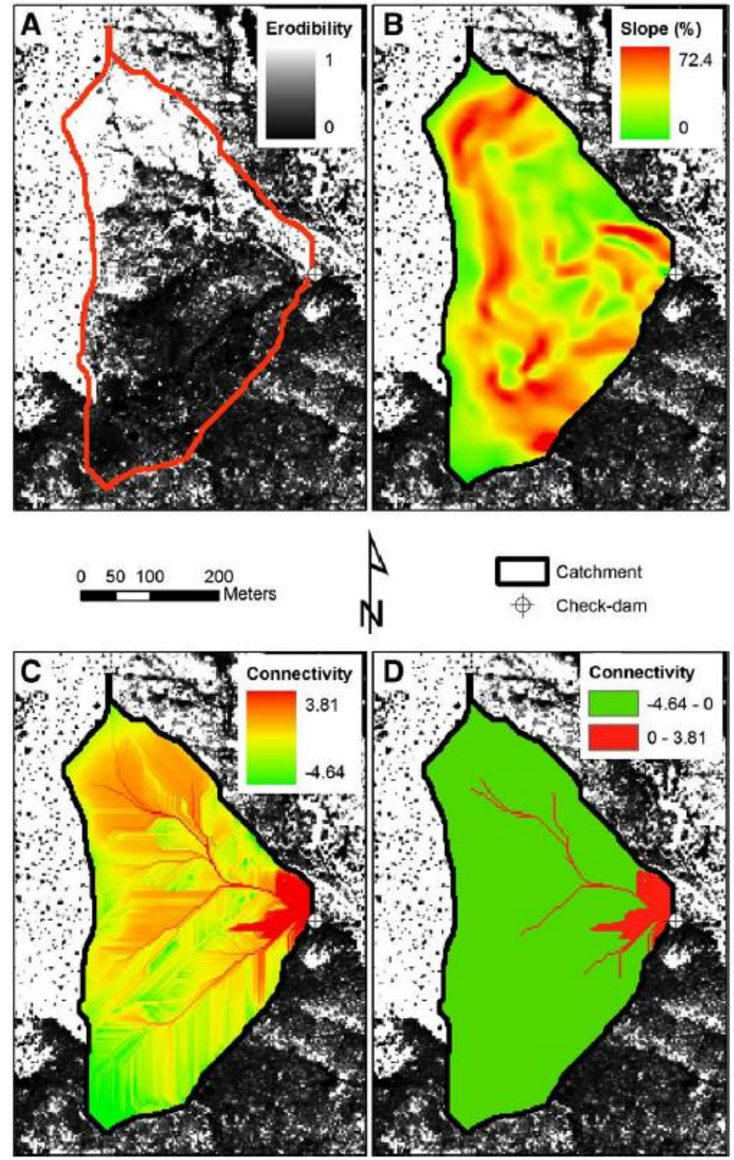
Review

Low erosion rates measured for steep, sparsely vegetated catchments in southeast Spain

N. Sougnez *, B. van Wesemael, V. Vanacker

George Lemaître Centre for Earth and Climate Research (TECLIM), Earth and Life Institute (ELI), Université Catholique de Louvain, B-1348 Louvain-la-Neuve, B

N. Sougnez et al. / Catena 84 (2011) 1–11



Site: Sierra de la Torrecilla and the Sierra de Carrascoy (Murcia, South Spain) – several small catchments of 1-20 ha each.

DTM: 3x3 m from contour lines, topographic Map 1:25.000

aims: to provide an **accurate estimation of catchment-wide erosion rates for a semi-arid mountainous region**. A variety of methods combined to measure and analyze spatial **patterns in vegetation cover; and to evaluate their effect on water and sediment connectivity**

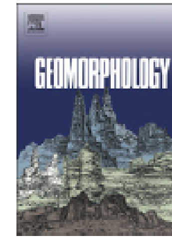
Geomorphology 138 (2012) 74–88

ELSEVIER

Contents lists available at SciVerse ScienceDirect

Geomorphology

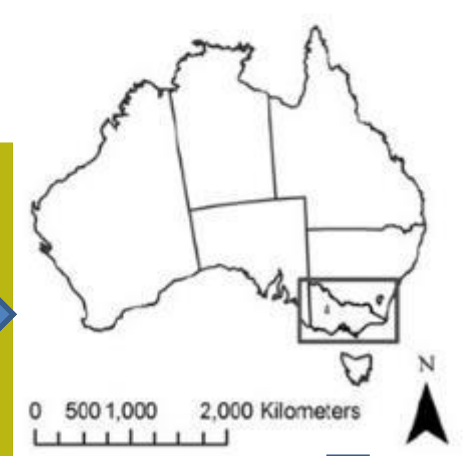
journal homepage: www.elsevier.com/locate/geomorph

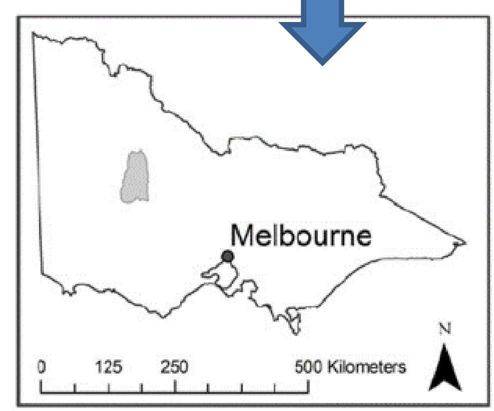


Comparison of conceptual landscape metrics to define hillslope-scale sediment delivery ratio

O. Vigiak [a,*], L. Borselli [b], L.T.H. Newham [c], J. McInnes [a], A.M. Roberts [a]

Site : Avon-Richardson catchment (Victoria, Australia) 3300 km2 .. **DEM:** Raster DEM 20x20 m



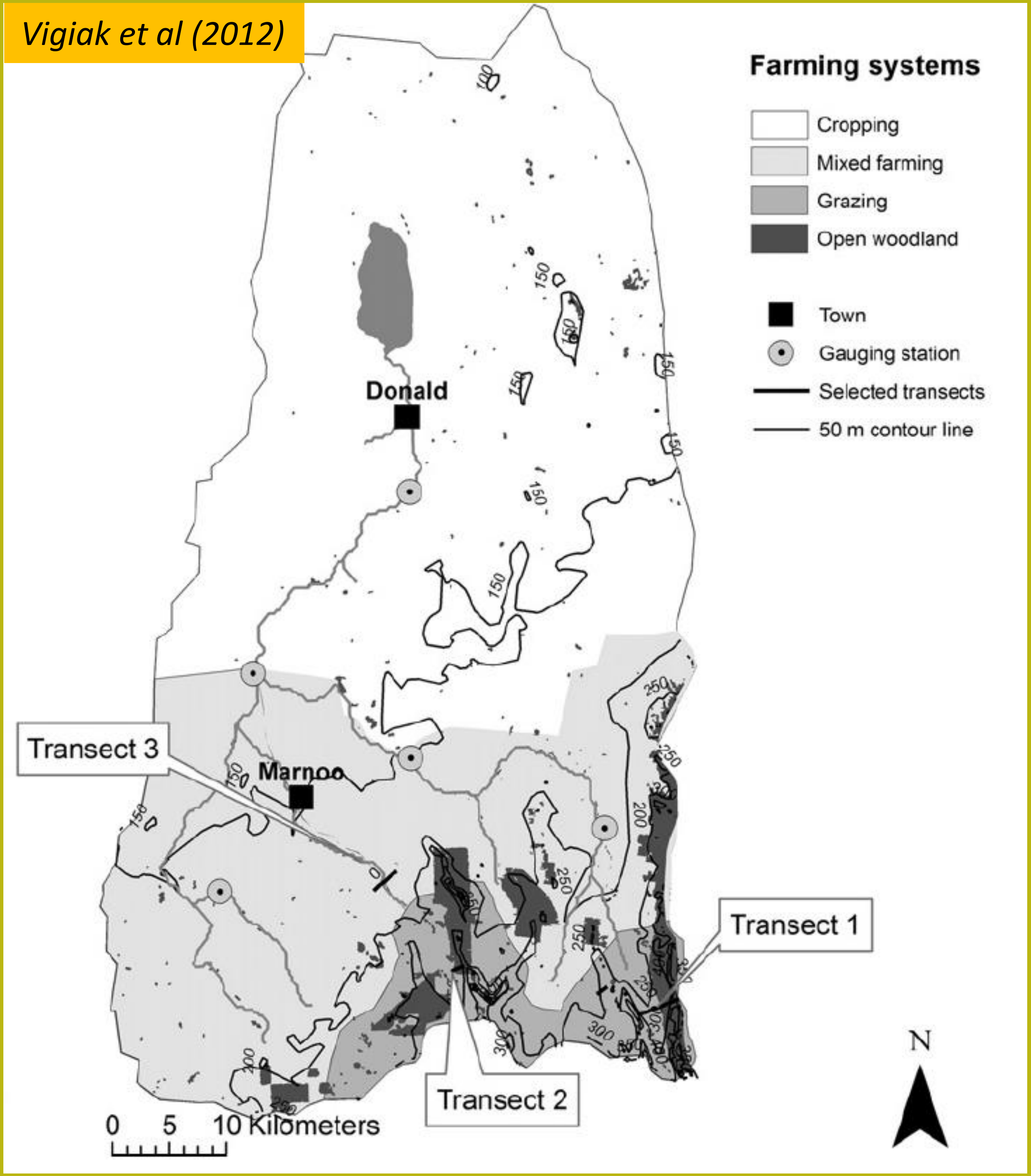


AIMS:

To calibrate and apply a point-to-catchment linked model (**HowLeaky + CatchMODS**) for daily soil loss estimation (developed by Olga Vigiak and collaborators)

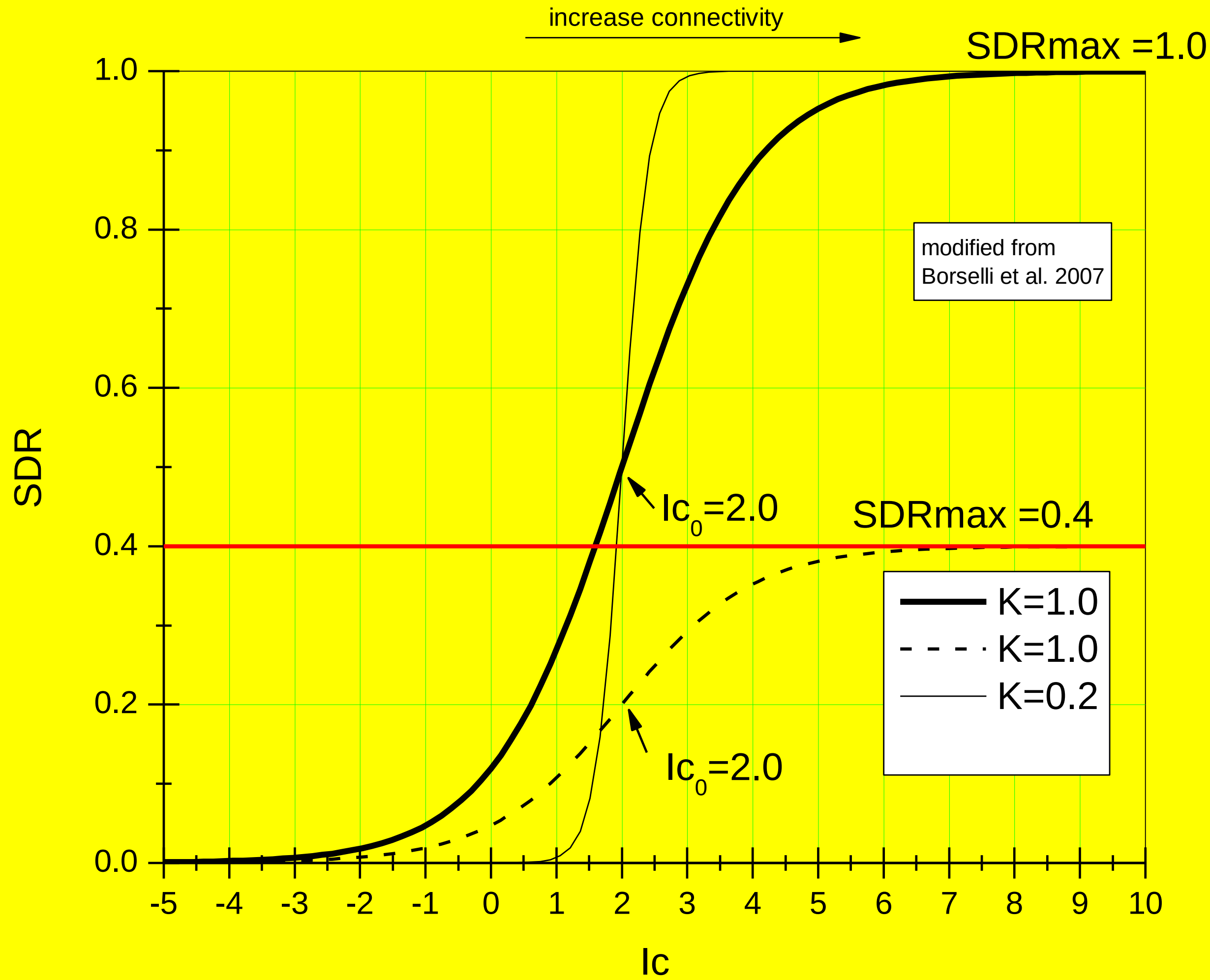
4 metrics for regionalization of SDR were compared in terms of pattern distributions and efficiency in matching sediment yields at 5 monitoring stations (4 indices of connectivity in total, including IC)

- **Avon-Richardson catchment (Victoria, Australia)**



Comparison of 4 connectivity metrics…

Metric	Main concepts
Travel Time (TT, Ferro and Minacapilli, 1995)	(time) distance to the stream
Stream Transport (ST, based on Rustomjii and Prosser, 2001)	Stream transport capacity (Upstream accumulation area and local slope)
Flux Connectivity Index (IC, Borselli et al., 2008) linked to SDR	**Potential for down routing of runoff vs potential for sinks to the stream**
Sediment Residence Time (RT, Lu et al., 2006)	Travel time vs effective storm duration, sediment settling properties

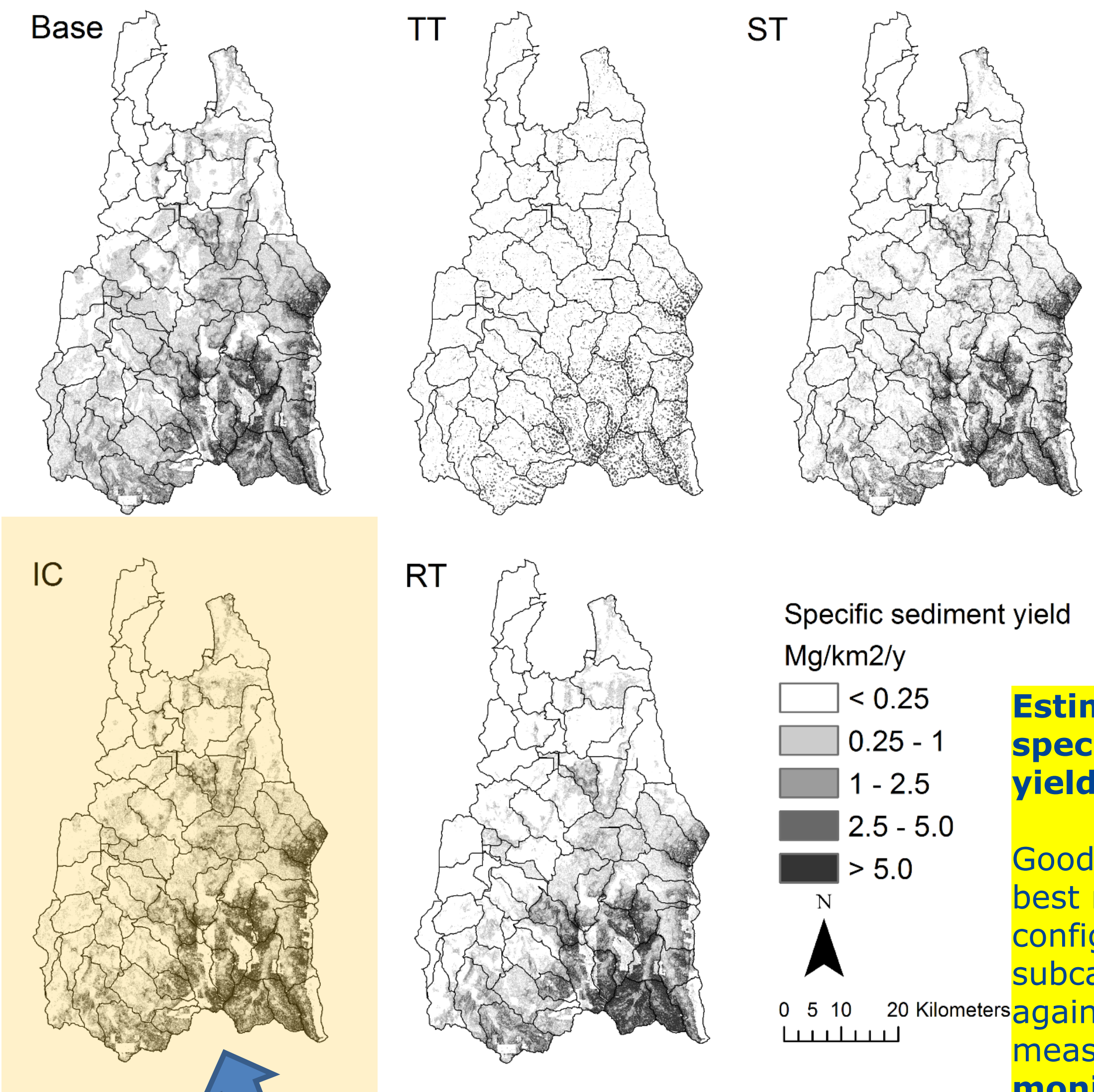


Implementation of ***SDR = f (conn. Index)***
For 4 types of connectivity indexes (including IC…) and optimization of parameters (Ic0 and k) by Observed SSY at a series of Gauging stations

$$SDR = \frac{SDR_{Max}}{1 + \exp\left(\frac{Ic_0 - Ic}{k}\right)}$$

Case of SDR by IC, and optimized IC0 and k
IC0=0.5 and k=2.0

Hillslope erosion patterns (pixel)



IC

By Vigiak et al (2012)

Base = spatially-constant SDR

TT = travel time (Ferro and Minacapilli 1995)

ST = sediment transport (Rustomjii and Prosser, 2001)

IC = flux connectivity index (Borselli et al. 2008)

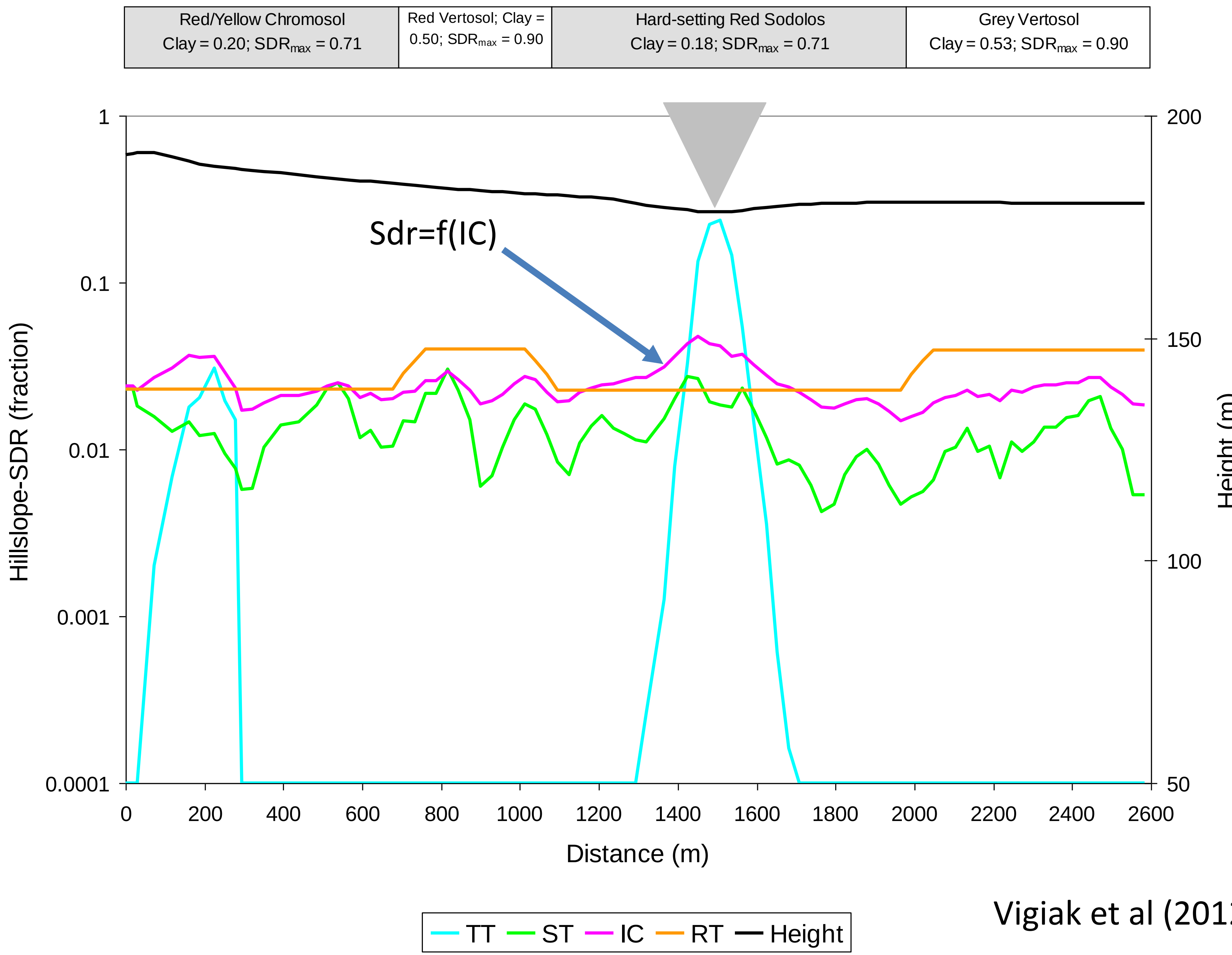
RT = residence time (Lu et al 2006)

Estimation of specific sediment yields

Goodness of fit of best model configurations at subcatchment scale against measurements at **monitoring gauging stations (sample size=7)**

	Nash-Sutcliffe Model Efficiency	AICc
Base	0.48	-52
TT	-0.25	-46
ST	0.55	-50
IC	**0.66**	**-52**
RT	0.61	-54

SDR pattern along a transect



Vigiak et al (2012)

Conclusions (Vigiak et al. 2012)

Regionalisation of hillslope SDR improved the estimation of specific sediment yields at subcatchment scale (less so at pixel scale)

The introduction of all metrics (except RT) did not increase data requirements

The 4 metrics differ in data requirements, dominance of landscape factors, and conceptualization of sedimentological connectivity

IC metric can be recommended in small-medium catchments (homogeneous climatic conditions)

RT metric can be recommended on large catchments (e.g. continental scale; important climatic gradient)

Catena 102 (2013) 62–73

Contents lists available at SciVerse ScienceDirect

Catena

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

Year 2013

Predicting runoff and sediment connectivity and soil erosion by water for different land use scenarios in the Spanish Pre-Pyrenees

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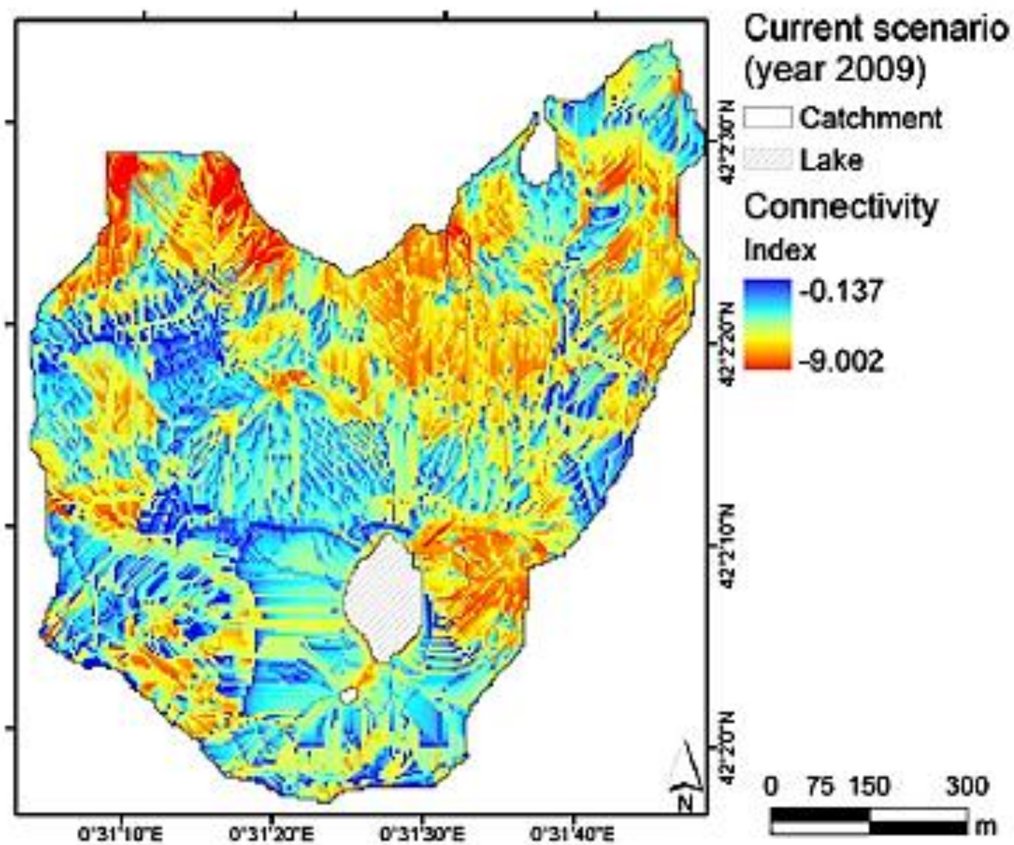
[b] Dept. of Soil and Water, Experimental Station of Aula Dei, CSIC, Postal Box 202, 50080, Zaragoza, Spain

Site: Spanish Central Pre-Pyrenees. 0.74 km2 catchment

DTM: not provided (probably 5x5m)

aims: the study seeks **to assess the effect of agricultural terraces, irrigation channels, trails, sinks, scarps, and land abandonment on the hydrological connectivity** of a small catchment and its **consequences on predicting rates of soil erosion under four different scenarios of land uses**.



Geomorphology 188 (2013) 31–41

Contents lists available at SciVerse ScienceDirect

Geomorphology

ELSEVIER

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

Geomorphometric assessment of spatial sediment connectivity in small Alpine catchments

Marco Cavalli [a,*], Sebastiano Trevisani [b], Francesco Comiti [c], Lorenzo Marchi [a]

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[b] University IUAV of Venice, Faculty of Architecture, Venezia, Italy
[c] Free University of Bozen-Bolzano, Faculty of Science and Technology, Bolzano, Italy

Lithology: mica-schist, gneiss, and phyllite.

Land use: coniferous forest, mountain grassland, bare rock and debris.

Annual rainfall: around 500 mm in the valley floor, strong increase with elevation.

Gadria catchment : area 6.36 km², average slope 79.1%, range in elevation: 1394 – 2945 m.

Strimm catchment : area 8.5 km², average slope 61.8%, range in elevation 1394 – 3197 m.

Sites: Gadria and Strimm catchments (Eastern Italian Alps) - 14.4 km2

DTM: 2.5x2.5 m (high resolution)

aims: development and **adaption of IC index to model sediment pathways dealing with debris flows and channelized sediment transport**, based on the one proposed by Borselli et al. (2008) with *ad hoc* modifications aimed at better exploitation of HR-DTMs

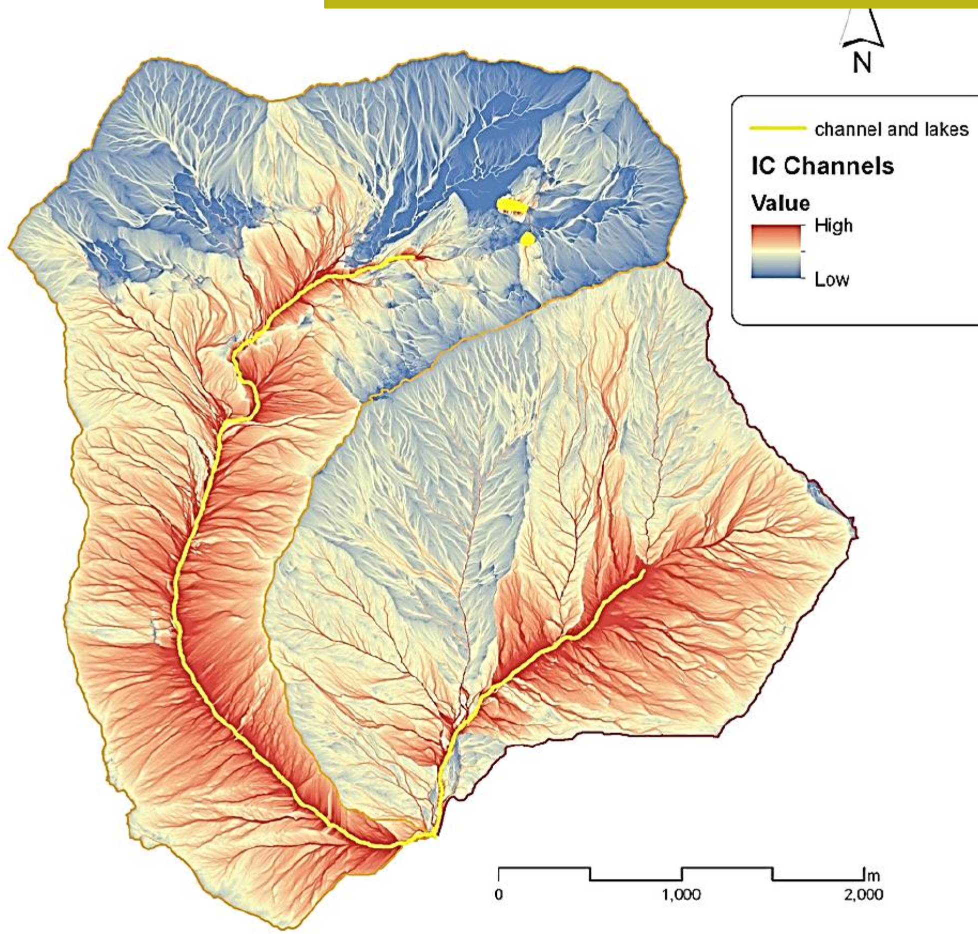
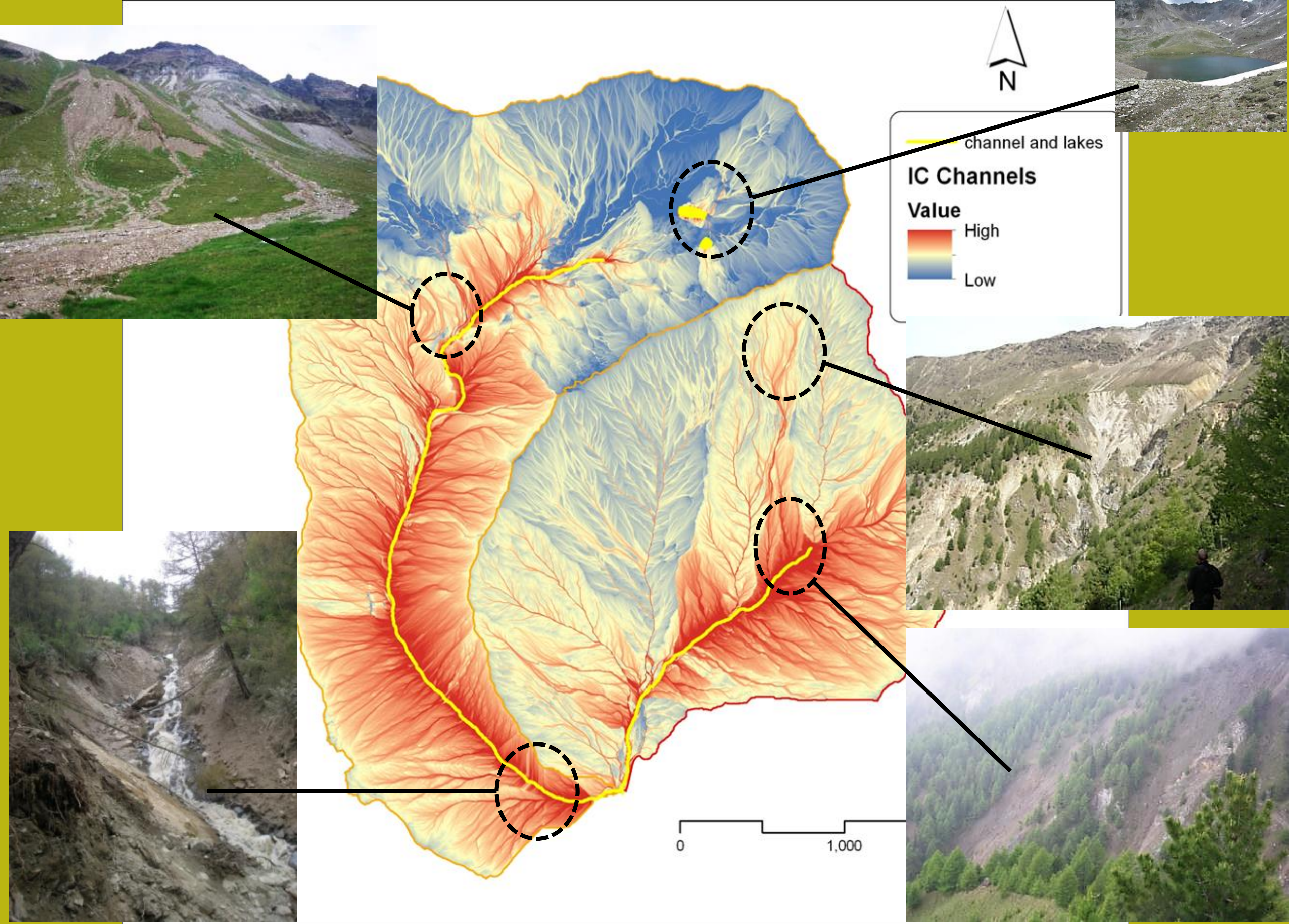


Fig. 5. *IC channels* map: index of connectivity *IC* computed with reference to main channels and lakes.

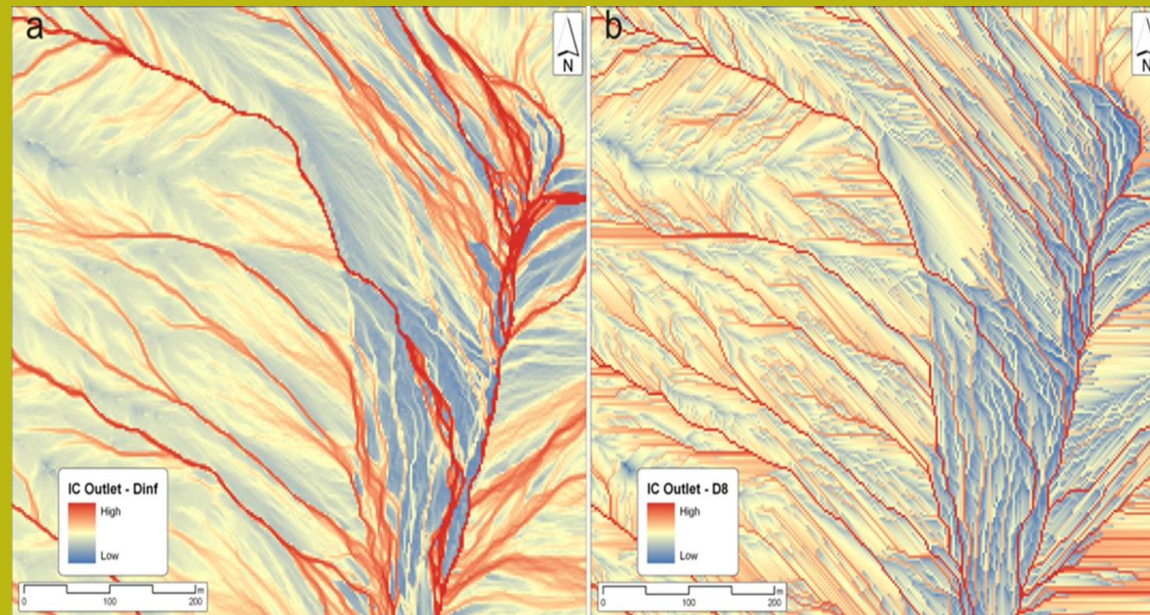

N
channel and lakes
IC Channels
Value
High
Low
0
1,000

Adaptation of the IC to mountain catchments and its use with HR-DTMs (Cavalli et al., 2013)

BEWARE !!!
High resolution DTM is required....

Flow direction

D ∞ method (Tarboton, 1997)



Slope *S* (m/m)

S > 1 -> *S* = 1

Weighting factor *W*

- Related to the impedance to water and sediment fluxes;
- *C* factor of USLE – RUSLE in the original model;
- Replaced by a roughness index (Cavalli et al., 2008).

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

W (m/m) ranges from 0 to 1; minimum value set to 0.01

High *W* : Low roughness and low impedance to fluxes

Low *W* : High roughness and high impedance to fluxes

Application to debris flow and Surface landslide process .. But not only

standard dev of local residual Cavalli (2008)

$$RI = \sqrt{\frac{\sum_{i=1}^{25} (x_i - x_m)^2}{25}}$$

Geomorphology 197 (2013) 64–75

Contents lists available at SciVerse ScienceDirect

Geomorphology

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

A sediment fingerprinting approach to understand the geomorphic coupling in an eastern Mediterranean mountainous river catchment

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Centre for Archaeological Science, KU Leuven, Celestijnenlaan 200E box 2408, B-3001 Leuven, Belgium

Site: Büğdüz River catchment in SW Turkey (262 km2)
DTM: Detailed information not provided.
aims: to elucidate the **spatial variability of sediment sources and geomorphic coupling between hillslope and floodplains**

Cavalli's approach has been used by others Authors e.g.

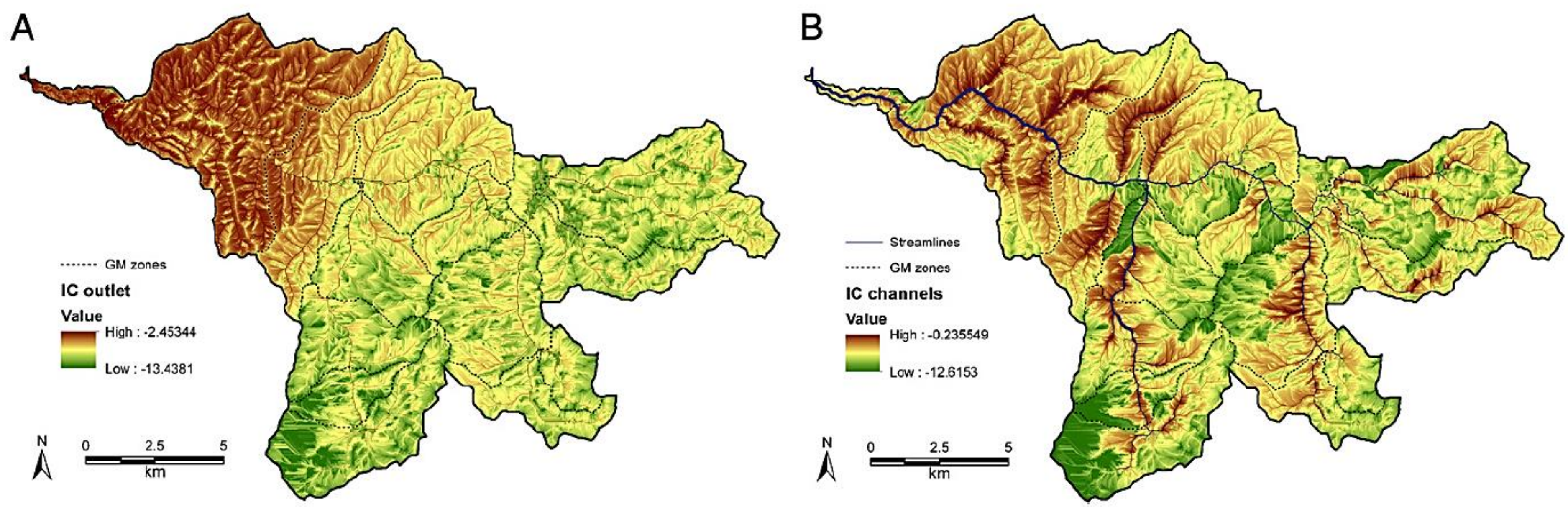

Fig. 4. (A) Connectivity index of Büğdüz catchment with respect to catchment outlet (IC outlet). (B) Connectivity index of Büğdüz catchment with respect to catchment outlet (IC channels).

EARTH SURFACE PROCESSES AND LANDFORMS
Earth Surf. Process. Landforms **38**, 1496–1512 (2013)

Published online 11 February 2013 in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/esp.3384

Initial hydro-geomorphic development and rill network evolution in an artificial catchment

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Received 2 February 2012; Revised 18 December 2012; Accepted 20 December 2012

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Site: open-cast lignite mine Cottbus, 150 km south of Berlin (Germany)
Approx 0.04 km2

DTM: 1x1 m survey in several phases of erosion evolution (during 5 years)

aims: to **characterize and to identify characteristic phases of rill network development in the artificially-created catchment** as an example for initial hydrogeomorphic landform development in temperate climate

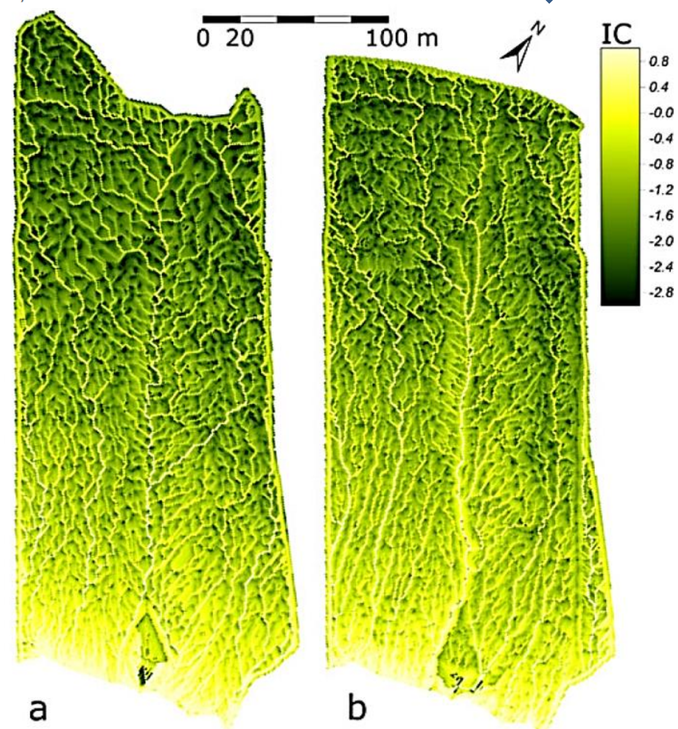

Figure 13. Spatial distribution of DEM cell values of the IC in the erosion-dominated area (as defined in Figure 3b), based on DEMs for (a) November 2005, and (b) March 2010. Grid cell size is 1 m by 1 m. Modification of the surface catchment area in autumn 2009 results in lower IC values in b).

Site: **Fukushima Prefecture** (Japan) Approx 600 km2

DTM: 10x10 m

aims: In post-accidental context, the paper aims to provide alternative **methods to estimate the early dispersion of contaminated sediment during the 20 months that followed the nuclear accident in the mountainous catchments exposed to a succession of erosive rainfall, snowfall and snowmelt events.**

Anthropocene 1 (2013) 23–34

Contents lists available at ScienceDirect

Anthropocene

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

Tracking the early dispersion of contaminated sediment along rivers draining the Fukushima radioactive pollution plume

Caroline Chartin [a], Olivier Evrard [a,*], Yuichi Onda [**,b], Jeremy Patin [b], Irène Lefèvre [a], Catherine Ottlé [a], Sophie Ayrault [a], Hugo Lepage [a], Philippe Bonté [a]

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[b] Center for Research in Isotopes and Environmental Dynamics (CRIED), University of Tsukuba, 1-1-1 Tennodai, Tsukuba, Ibaraki 305-8572, Japan

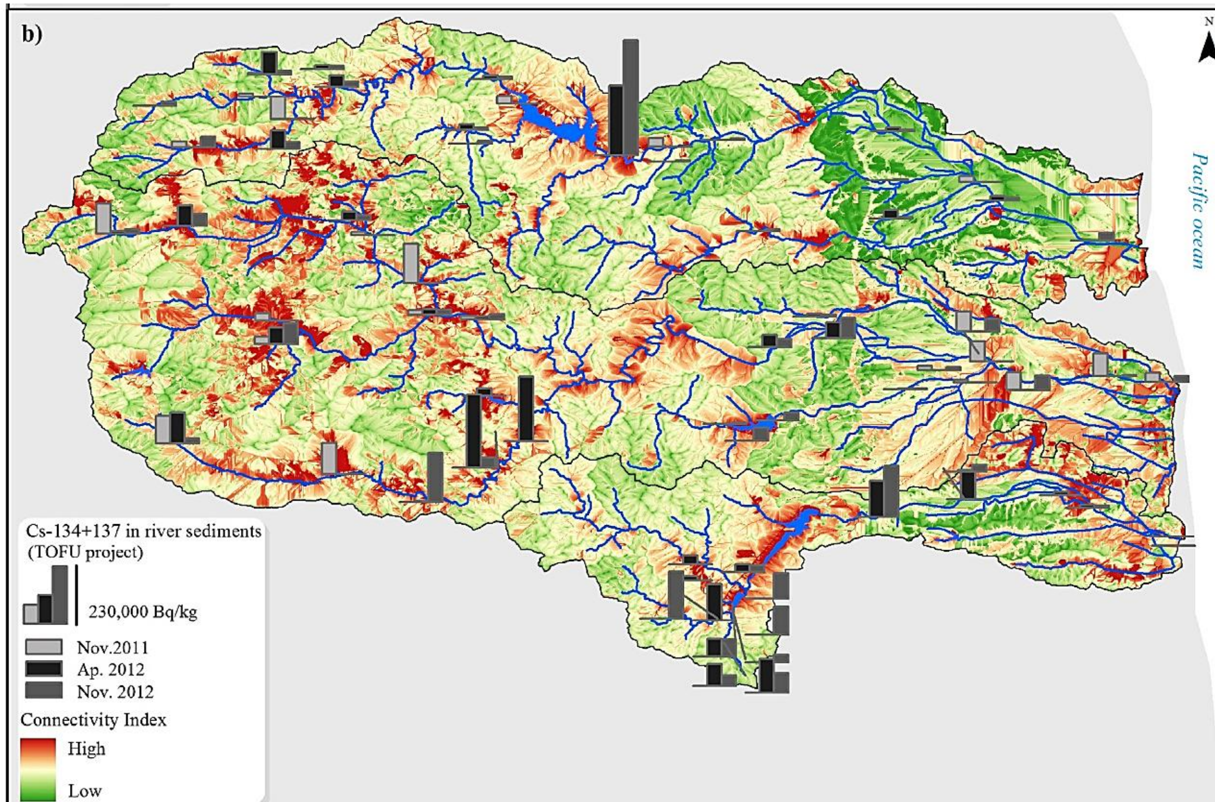

Fig. 6. Dominant land uses in the coastal catchments derived from analysis of satellite images (a) and associated hillslope-to-sinks hydro-sedimentary connectivity index compared to river sediment radiocaesium activities (b). ((M) Mano catchment); (N) Nitta catchment; (O) Ota catchment).

Site: in Swiss National Park (SNP), Engadine region in Switzerland - study area 6.4km2

DTM: LiDAR-based 2x2m

aims: 1) **to evaluate the morphometric GIS modelling results against the field based geomorphic map**, 2) to decipher **key controls on the present-day sediment flux in a small, de-glaciated mountain valley,** and 3) to address the question of whether traditional geomorphic field maps have become indispensable today when studying mountain cascading systems.

Cavalli et al (2013) variant for W factor

Geomorphology 221 (2014) 215–229

Contents lists available at ScienceDirect

Geomorphology

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

Sediment connectivity in the high-alpine valley of Val Müschauns, Swiss National Park — linking geomorphic field mapping with geomorphometric modelling

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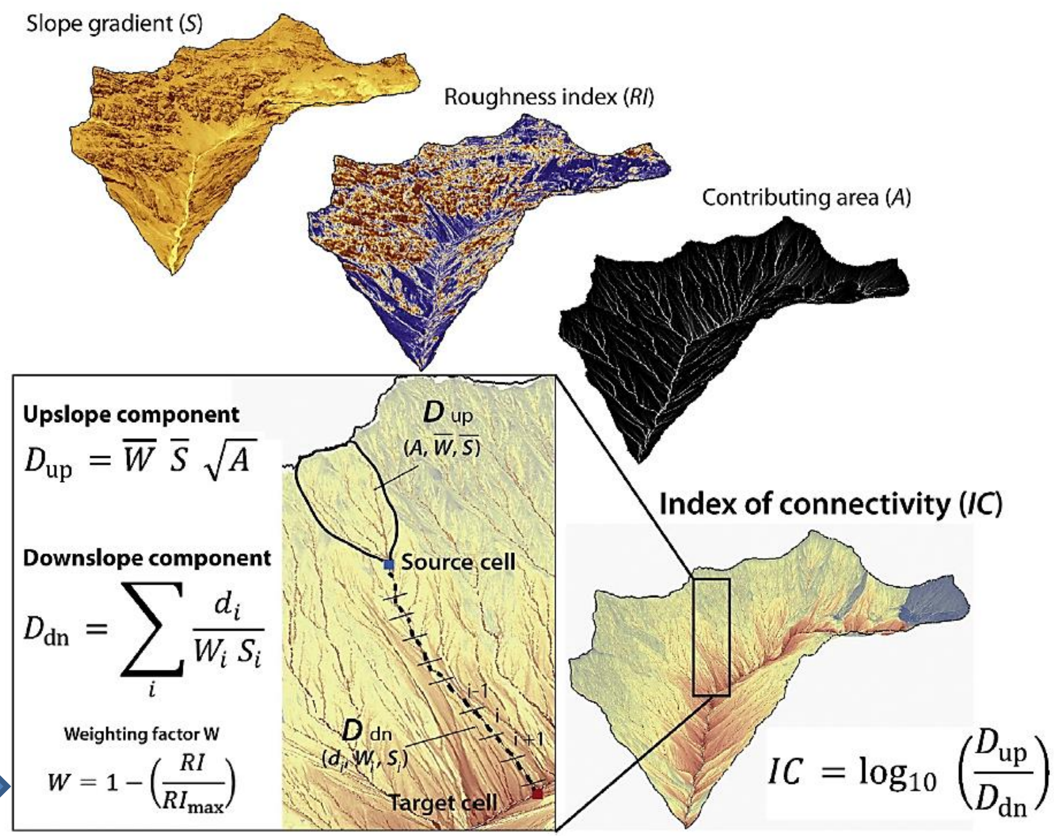

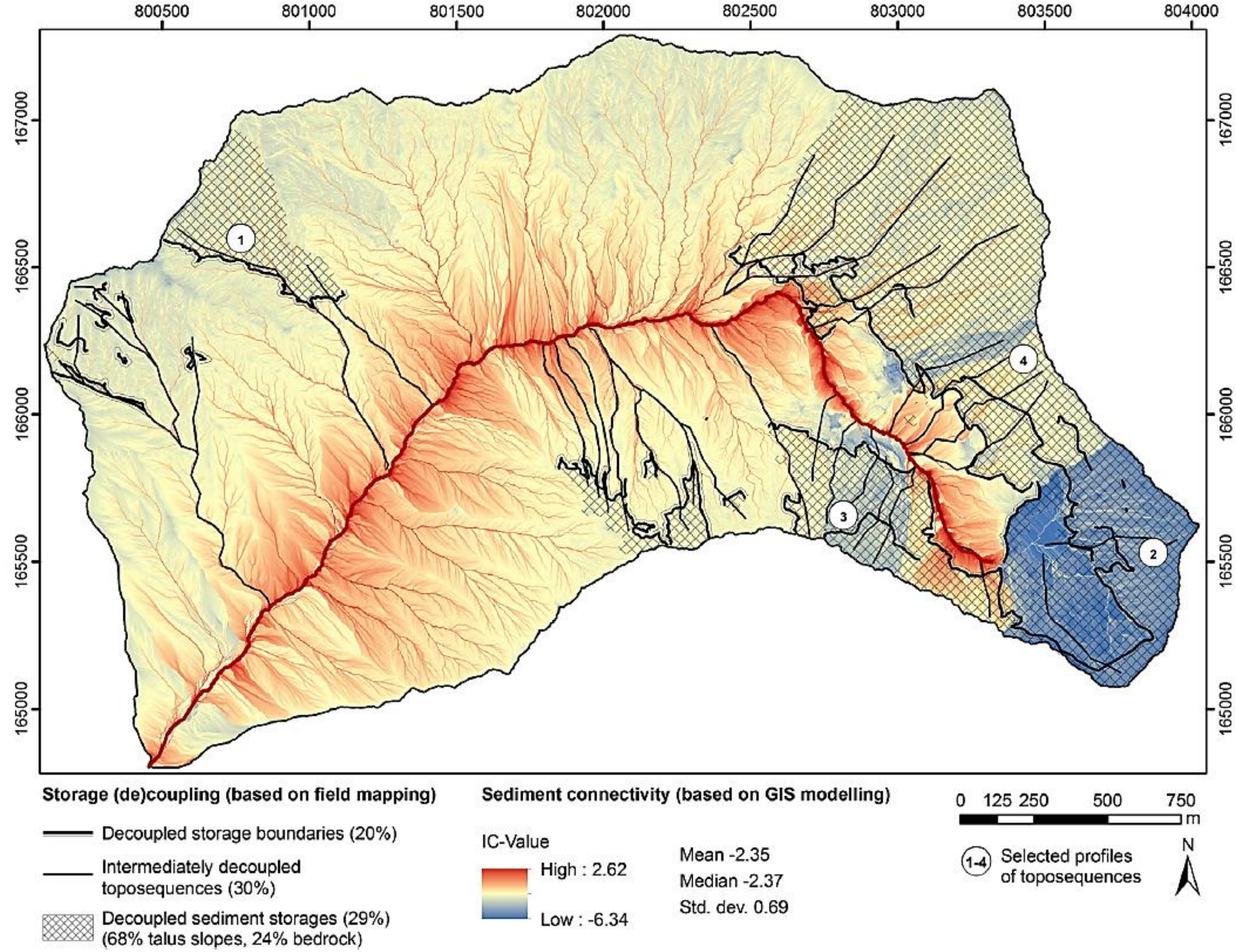

Fig. 9. Storage (de)coupling, according to the field-based analysis of toposequences, and index of connectivity (*IC*), calculated by the GIS modelling approach (2-m DTM, © SwissTopo, in 2013). Thick double lines show storage boundaries qualitatively defined as decoupled due to lacking sediment transfer between adjacent landforms caused by inactivity of geomorphic processes or the occurrence of buffers. As a consequence, around 29% of the basin surface has no connectivity to the fluvial system (crosshatched area). Among them, 68% of the talus slopes and 24% of the bedrock-coverage are affected by this disconnectivity.

IC related to different geomorphological units and processes depending on sediment storage types

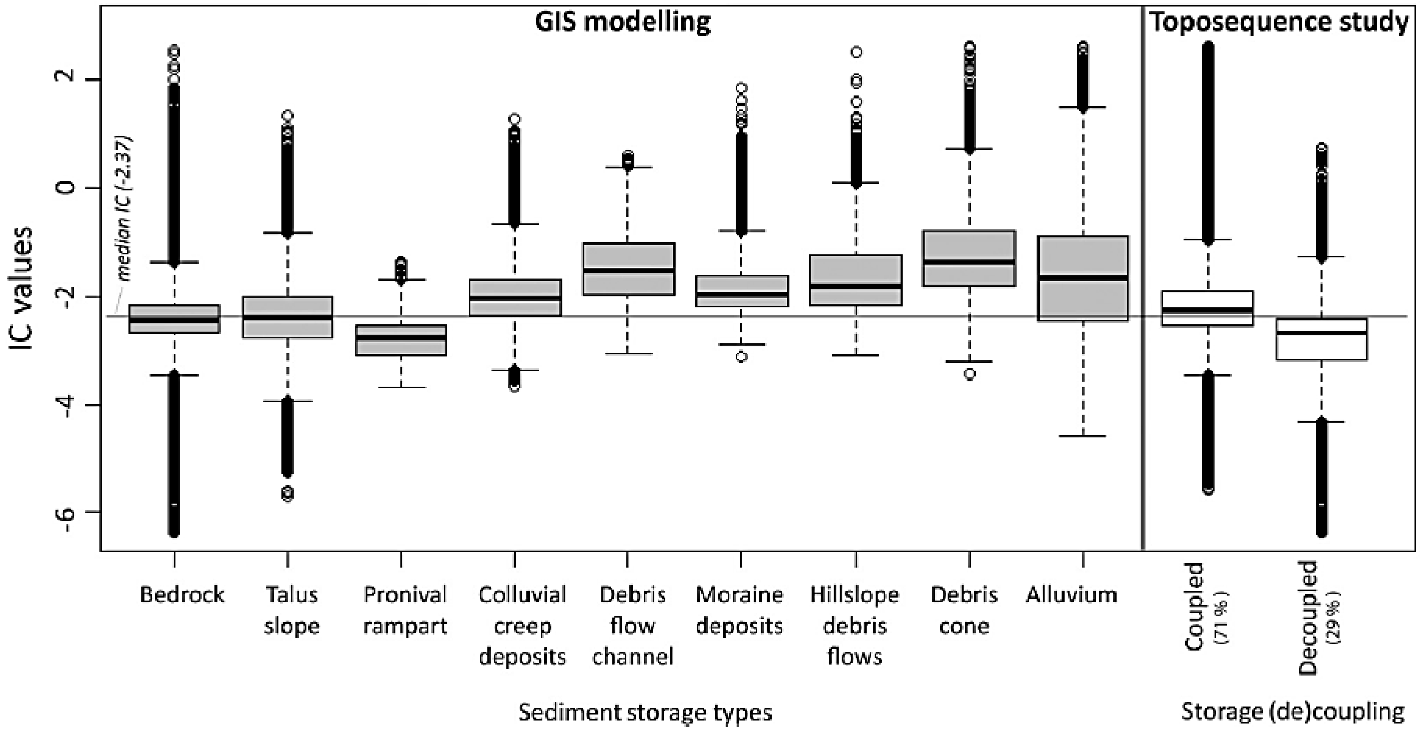

Fig. 10. *IC* values of sediment storage types in Val Müschauns and comparison between the modelling results (grey boxplots, left-hand side) and the field-based mapping results of the toposequence study (white boxplots right-hand side). Around 35% of the basin surface, which has been qualitatively classified as being decoupled, is related to *IC* values higher than the basin's median *IC*.

Site: Kangaroo River State forest, northern NSW, Australia 21.7 km2.

DTM:10x10 m

aims: to apply a **distributed hillslope erosion-SDR approach** in raster data layers **to assess the impacts of vegetation removal** (single tree selection logging) on the **spatial distribution of estimated sediment yields**

HYDROLOGICAL PROCESSES
Hydrol. Process. **28**, 2671–2684 (2014)
Published online 24 April 2013 in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/hyp.9805

Distributed empirical algorithms to estimate catchment scale sediment connectivity and yield in a subtropical region

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[2] *Forestry Corporation of NSW, PO Box 4019, Coffs Harbour Jetty, NSW, 2450, Australia*
[3] *Australian Centre for Agriculture and Law, University of New England, NSW, 2351, Australia*

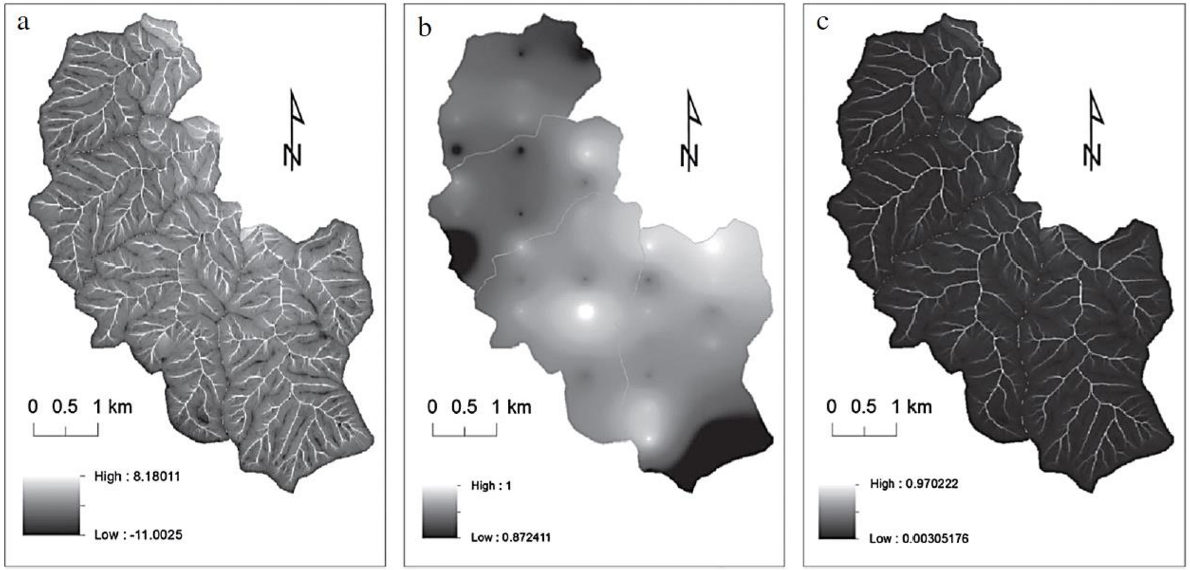

Figure 2. The predicted maps of (a) index of connectivity IC, (b) the maximum theoretical SDR coefficient SDR_{max} and (c) SDR variability within the study area. The IC and SDR maps in this figure were selected for spatial variability in 2007. Catchment boundaries are depicted in Figure 1

$$SDR = \frac{SDR_{Max}}{1+\exp\left(\frac{Ic_0 - Ic}{k}\right)}$$

Use of SDR by IC, and optimized IC_0 and k, by Vigiak et al. 2012
IC_0=0.5 and k=2.0

ARTICLE IN PRESS
GEOMOR-04764; No of Pages 14
Geomorphology xxx (2014) xxx–xxx
Contents lists available at ScienceDirect
Geomorphology
journal homepage: www.elsevier.com/locate/geomorph

Connectivity structure of the Kosi megafan and role of rail-road transport network

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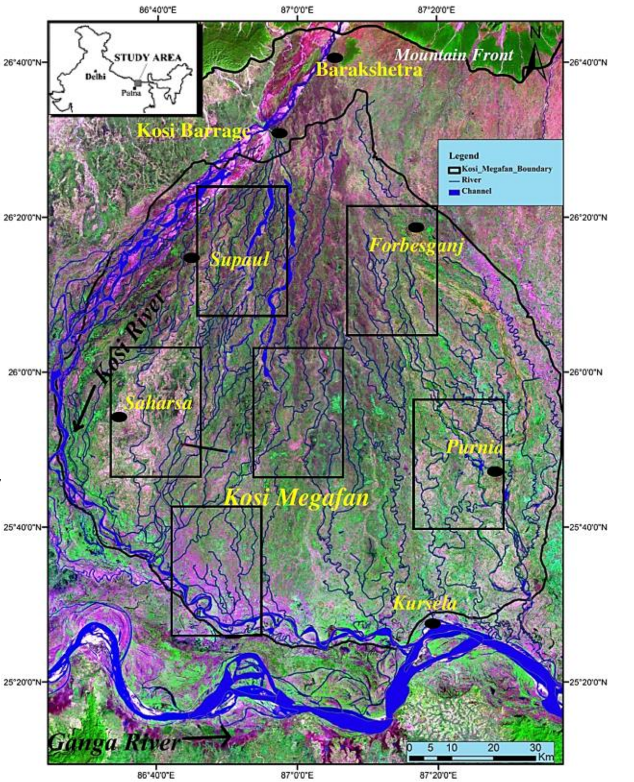
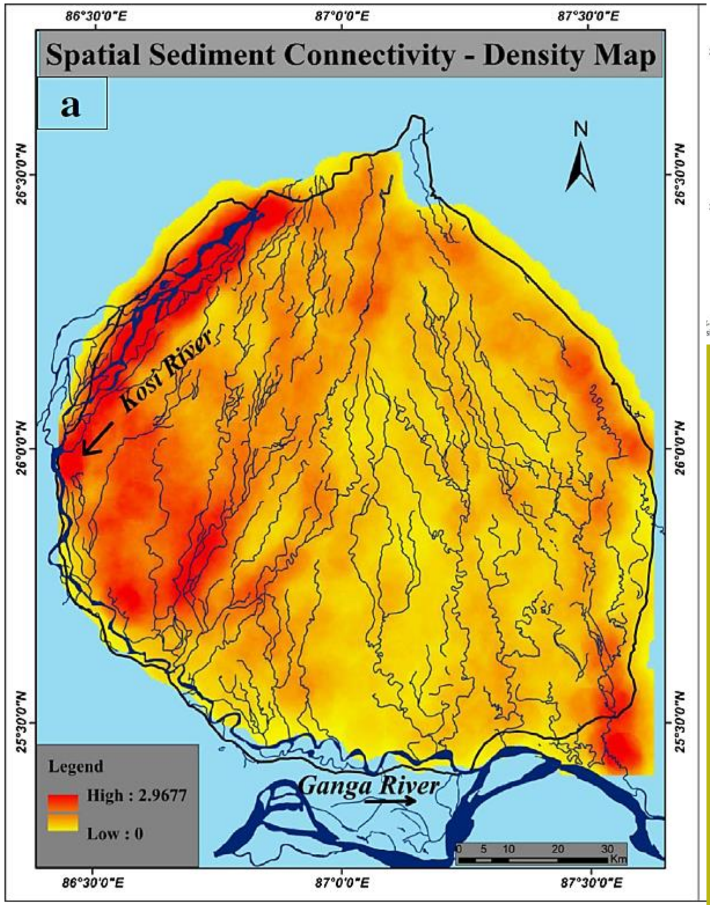
[b] Discipline of Earth Sciences, Indian Institute of Technology Gandhinagar, Ahmedabad, Gujarat 382424, India
[c] UNDP, Disaster Management Unit, 55 Lodi Estate, New Delhi 110003, India
[d] Department of Earth Sciences, Indian Institute of Technology Kanpur, Kanpur 208 01



. 1. Study area showing the Kosi River in the North Bihar, India. The megafan surface has numerous small paleochannels most of which are activated during the monsoon period. The si River debouches into the plains at Barakshetra and joins the Ganga River system at Kursela. Windows for field-based classification of the intersection points have been marked.

Site: Kosi megafan, India Hymalayan region. approx. 7000 km2
DTM: SRTM DEM data of February 2002. http://www.cgiar-csi.org (*resolution not provided*)
Aims: The paper presents the **two-dimensional dis(connectivity) structure** of the Kosi megafan, India, including the lateral and longitudinal dimensions (continued …)



(continued …) of geomorphic connectivity. The quantitatively defined and the **'anthropogenic' impacts on the connectivity structure due to railroad transport network** were also estimated.

J Soils Sediments (2014) 14:1982–2000
DOI 10.1007/s11368-014-0992-3

ANALYSIS AND MODELLING OF SEDIMENT TRANSFER IN MEDITERRANEAN RIVER BASINS

Assessment of sediment connectivity from vegetation cover and topography using remotely sensed data in a dryland catchment in the Spanish Pyrenees

Saskia Foerster · Charlotte Wilczok · Arlena Brosinsky · Karl Segl

Site: Isabena River.Spanish Pyrenees approx. 70km2

DTM: Lidar 4x4 m

Aims:approach to exploit high resolution airborne data for overland flow sediment connectivity estimation. investigate the potential of hyperspectral and LiDAR data for assessing sediment connectivity at the hillslope, subcatchment , catchment scale, using the index of connectivity. The change of IC Values in wet and dry season Depends from wegetation cover…

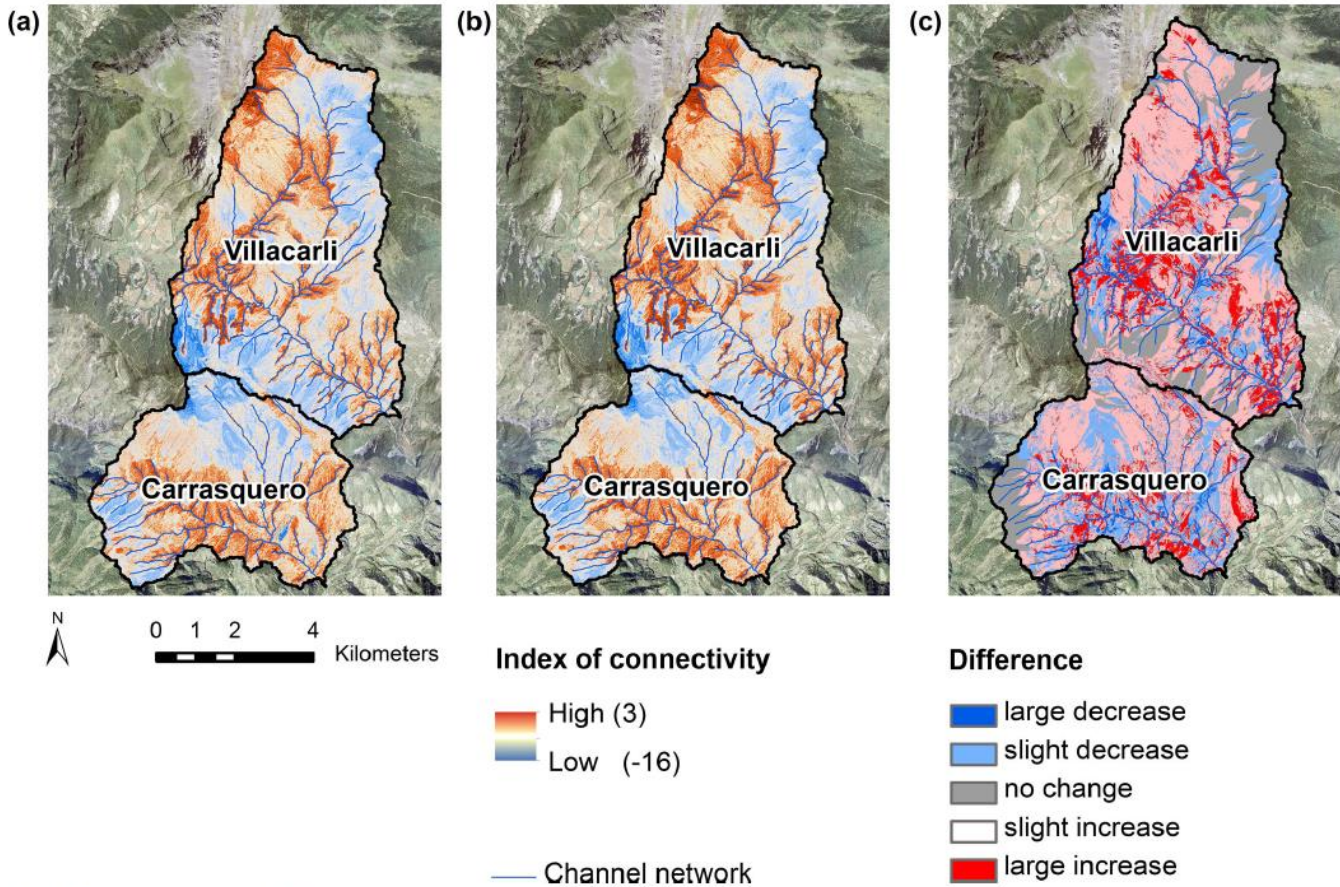


Fig. 10 Connectivity map for the entire study area for April (a) and August (b) and the change from April to August (c)

Geomorphology 232 (2015) 239–247

Contents lists available at ScienceDirect

Geomorphology

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

Process type identification in torrential catchments in the eastern Alps

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[a] Institute of Mountain Risk Engineering, University of Natural Resources and Life Sciences, Vienna A-1190, Austria
[b] Institute of Applied Statistics and Computing, University of Natural Resources and Life Sciences, Vienna A-1190, Austria

Site: Austrian watersheds in alpine areeas

DTM: 5x5 m

Aims: A database of torrential events in Austria (Hübl et al., 2008c) is used to sample prototypical catchments for all defined process types (WFL, FST, and DBF). morfometric parameters and classifcication process Bayesian type.. Identification of debris flow prone dominated by debris flow processes DBF.

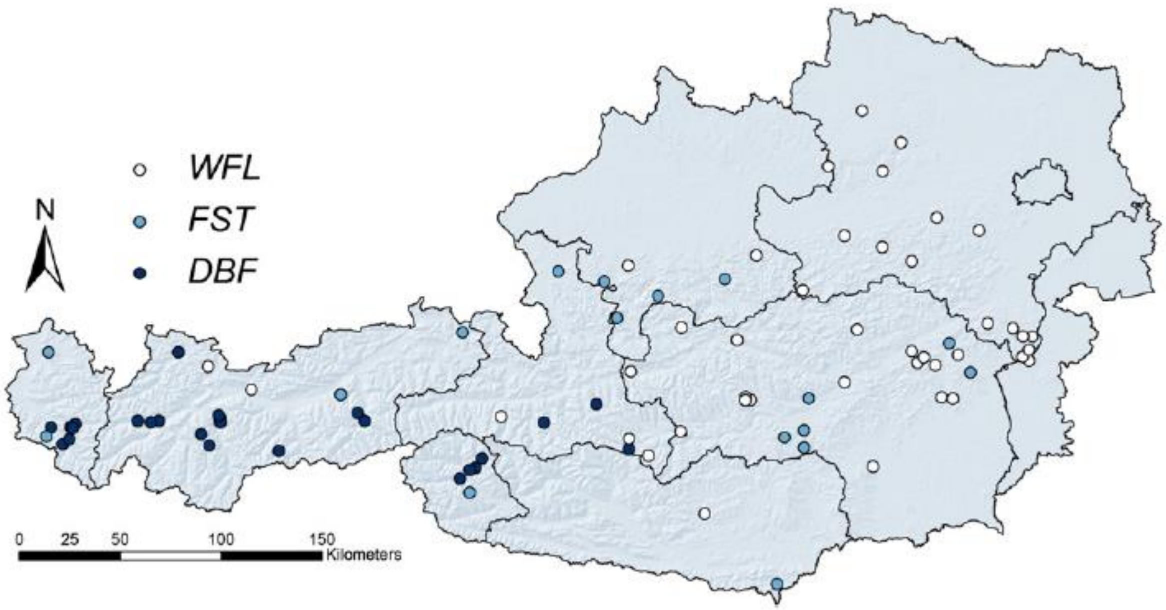
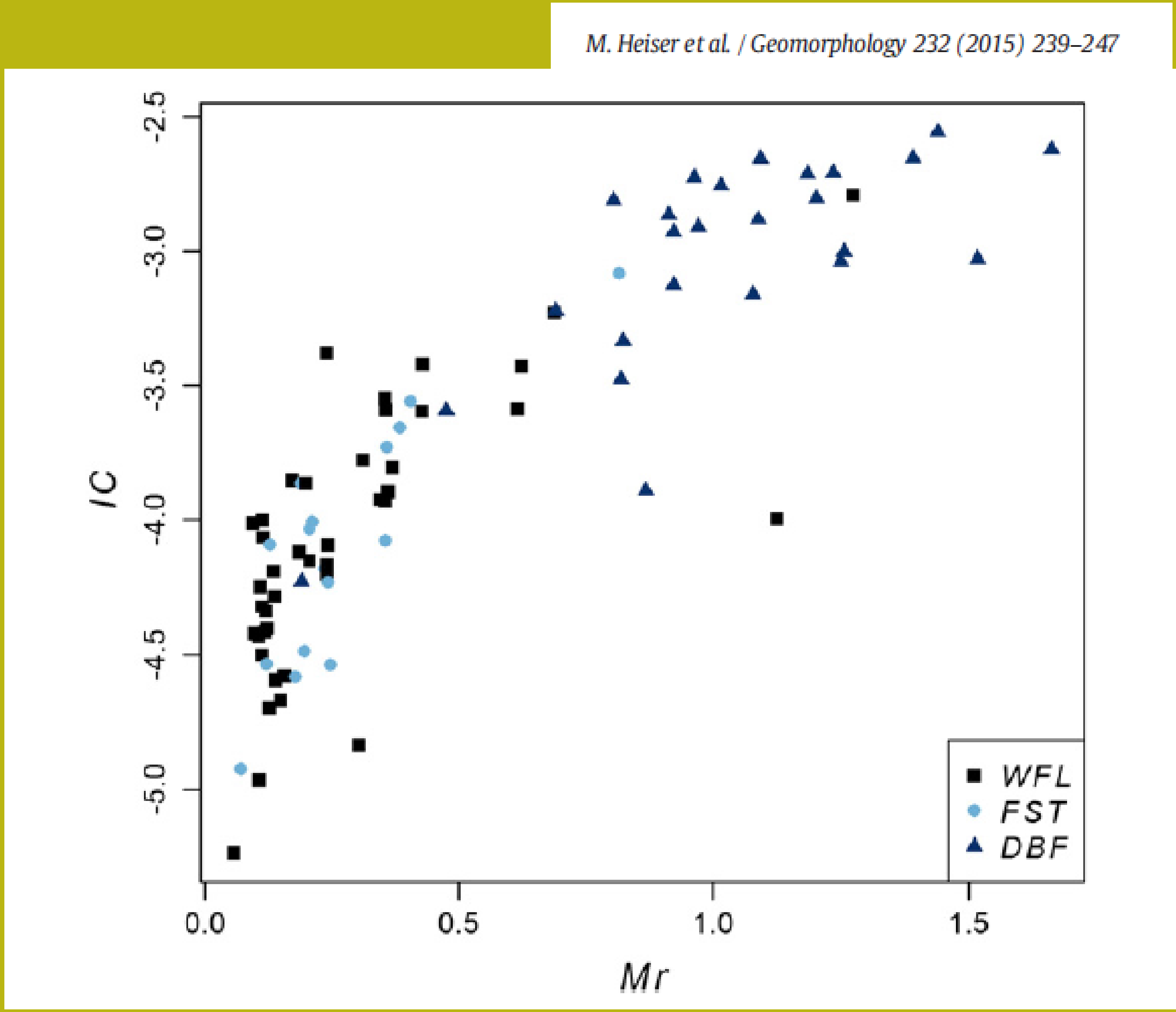


Fig. 2. Spatial overview of the assigned torrential catchments to a defined process type.

Strong relationships between IC index (based on Cavalli 2013 iC calculation variant) and the Melton ratio (Mr) (Melton, 1957) also used to Classify dominant flow process In a watershed. Sediment connectivity was considered by analysing the IC value, which shows a strong correlation to the Melton number (Mr) with a power law relationship between IC and Mr values.



Melton' Number → MR = (ZMax - ZMin) / Sqrt(Area)

J Soils Sediments
DOI 10.1007/s11368-015-1235-y

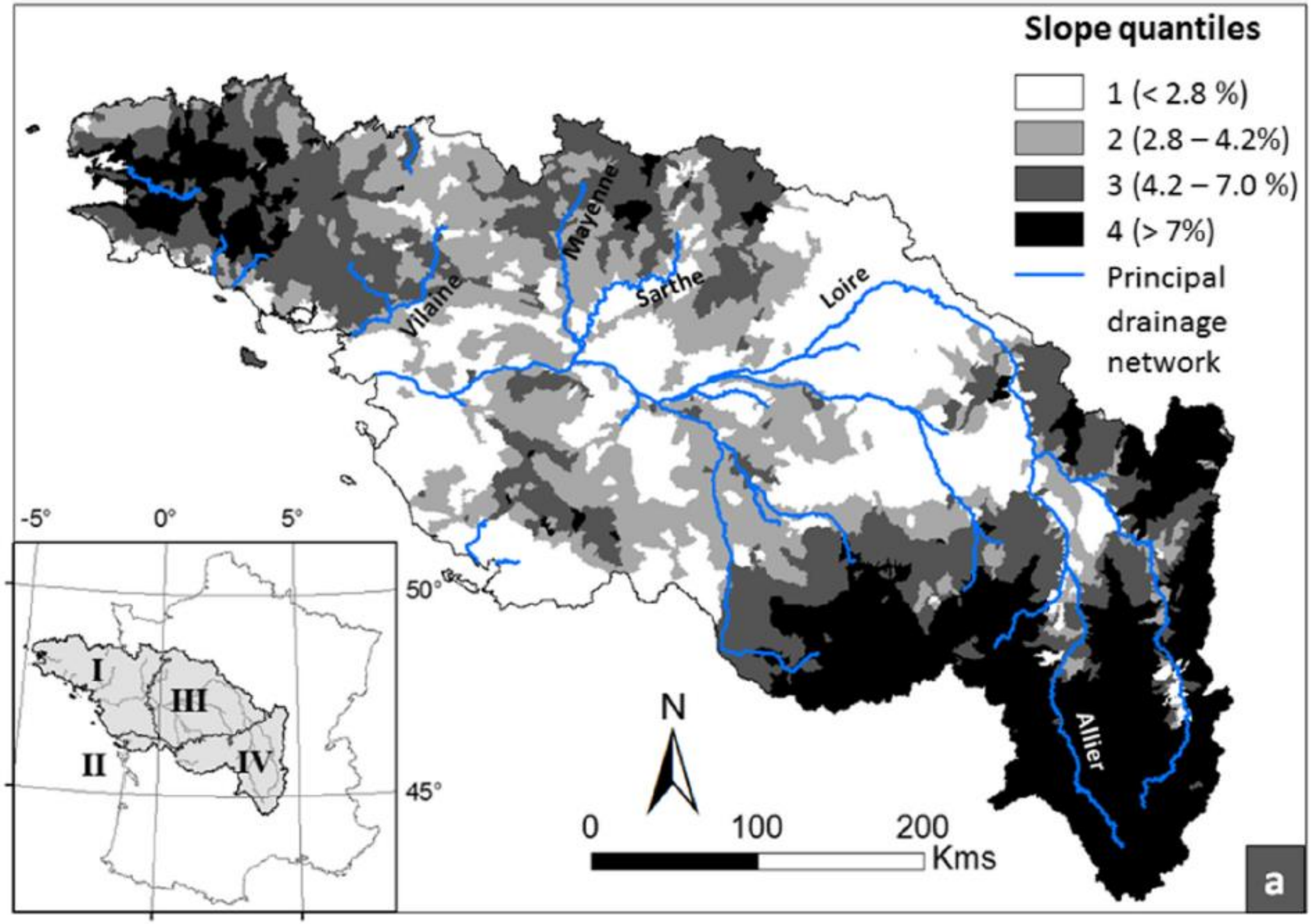
SEDIMENTS, SEC 3 • HILLSLOPE AND RIVER BASIN SEDIMENT DYNAMICS • RESEARCH ARTICLE

Article in press

Application of an index of sediment connectivity in a lowland area

Aurore Gay[1,2] • Olivier Cerdan[1] • Vincent Mardhel[1] • Marc Desmet[2]

Site: The Loire–Brittany River Basin (~155,000 km2).
DTM: Lidar 50x50m
Aims: provide an evaluation of sediment connectivity for a lowland territory. with process and scale constraints: (i) landscape infiltration and saturation properties of lowland areas are integrated in the index and (ii) the assessment is performed over a large river basin (~105 km2) containing both mountainous and lowland areas.



In this study, was introduced a pixel-based parameter (IDPR) related to the drainage density and which accounts for hydrological connectivity in the lowland areas. The Authors propose a IC variants better for Lowlands and for low resolution DTM in big watershed

$$IC_{revised} = log10\left(\frac{\overline{W}\cdot\overline{IDPR}\cdot\overline{S}\cdot\sqrt{A}}{\sum_i\left(\frac{d_i}{W_i\cdot S_i\cdot IDPR_i}\right)}\right)$$

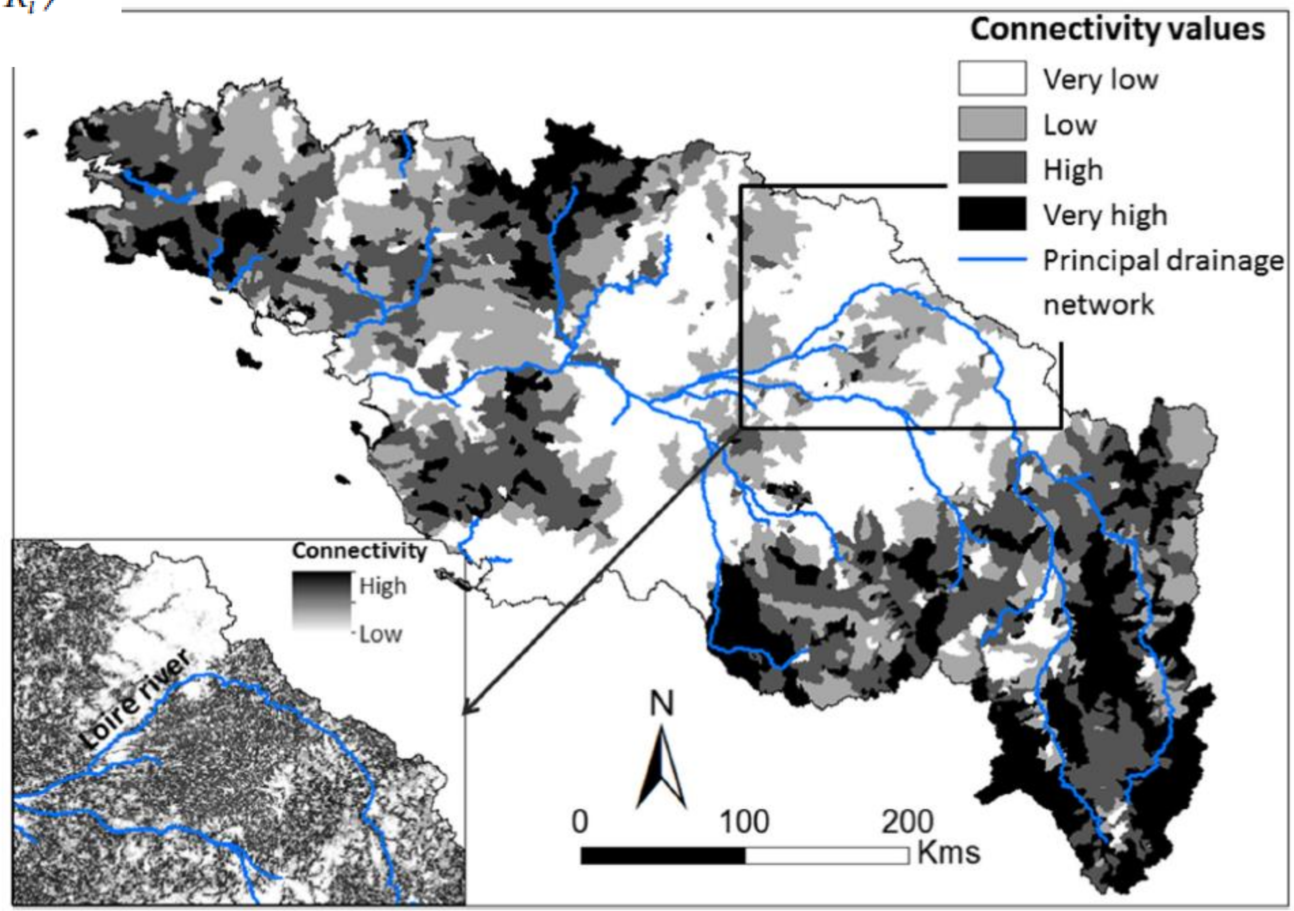


Fig. 5 Map of mean connectivity for each watershed (classification of mean values in quartiles)

This presentation can be downloaded at

www.lorenzo-borselli.eu

Many thanks for Your attention !!!