Connectivity approach for flow and sediment delivery and application to SDR assessment

Lorenzo Borselli *

Paola Cassi*

***National Research Council**

Research Institute for Geo-Hydrological Protection (CNR-IRPI)

Via Madonna del Piano 10,

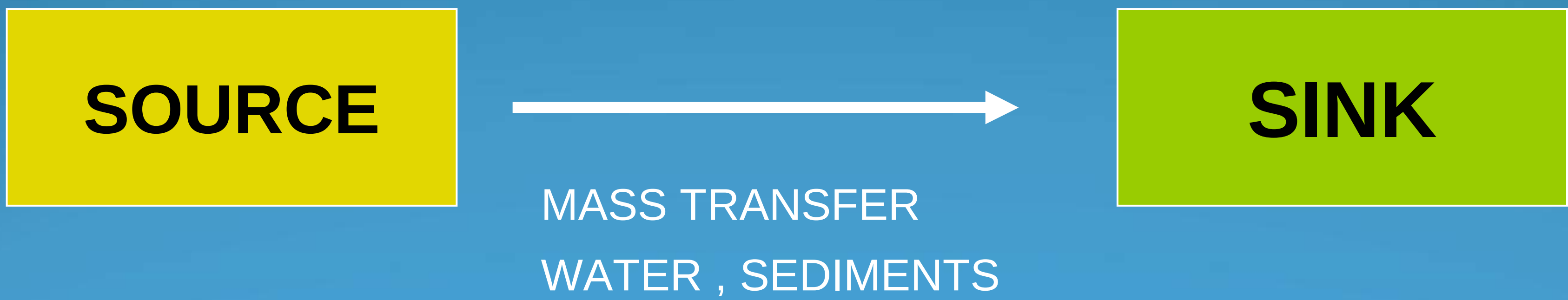
50019, Sesto Fiorentino (Florence), ITALY

borselli@irpi.fi.cnr.it

http://www.irpi.fi.cnr.it/borselli.html

This presentation have as subject the concept of CONNECTIVITY and their application in the context of soil erosion and conservation models: the *flow connectivity approach* (FCA)

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).

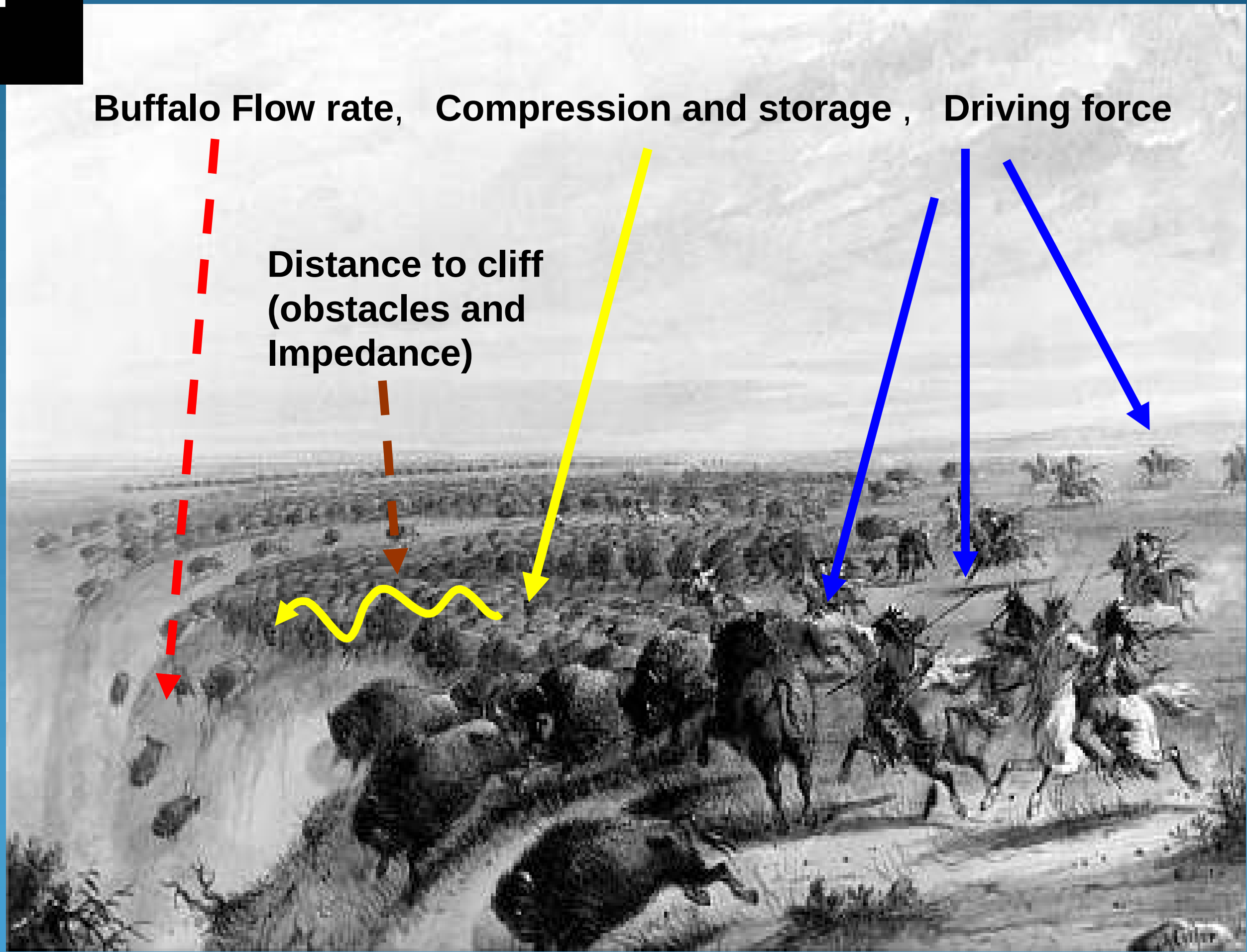


Definition of connectivity for sediment flow:

Connectivity is defined as chances that a particle has to reach the nearest sink
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**

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

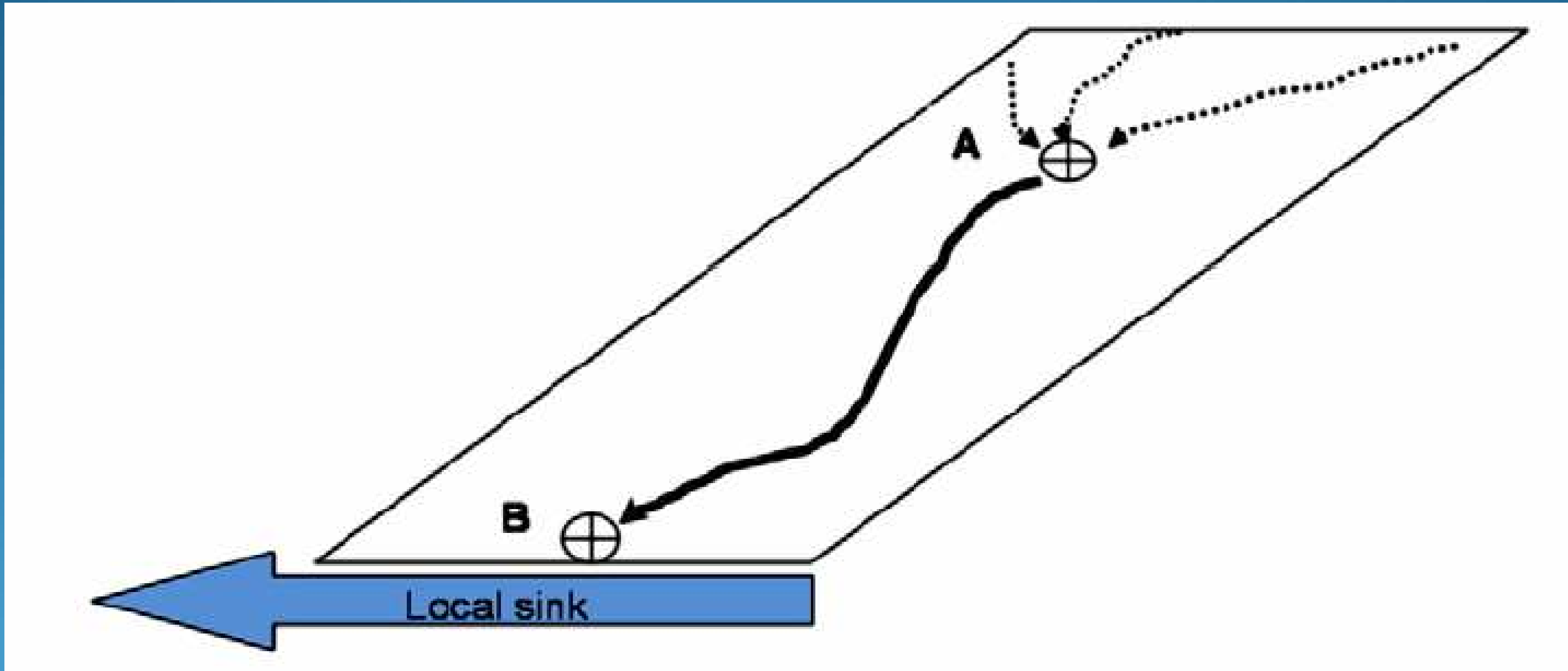
A conceptual example of importance of connectivity



*The **Buffalo jump***
A Native Americans' Hunting technique That Have some similitude with soil erosion /runoff processes
e.g. The chance of each buffalo to fall …. and die.

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

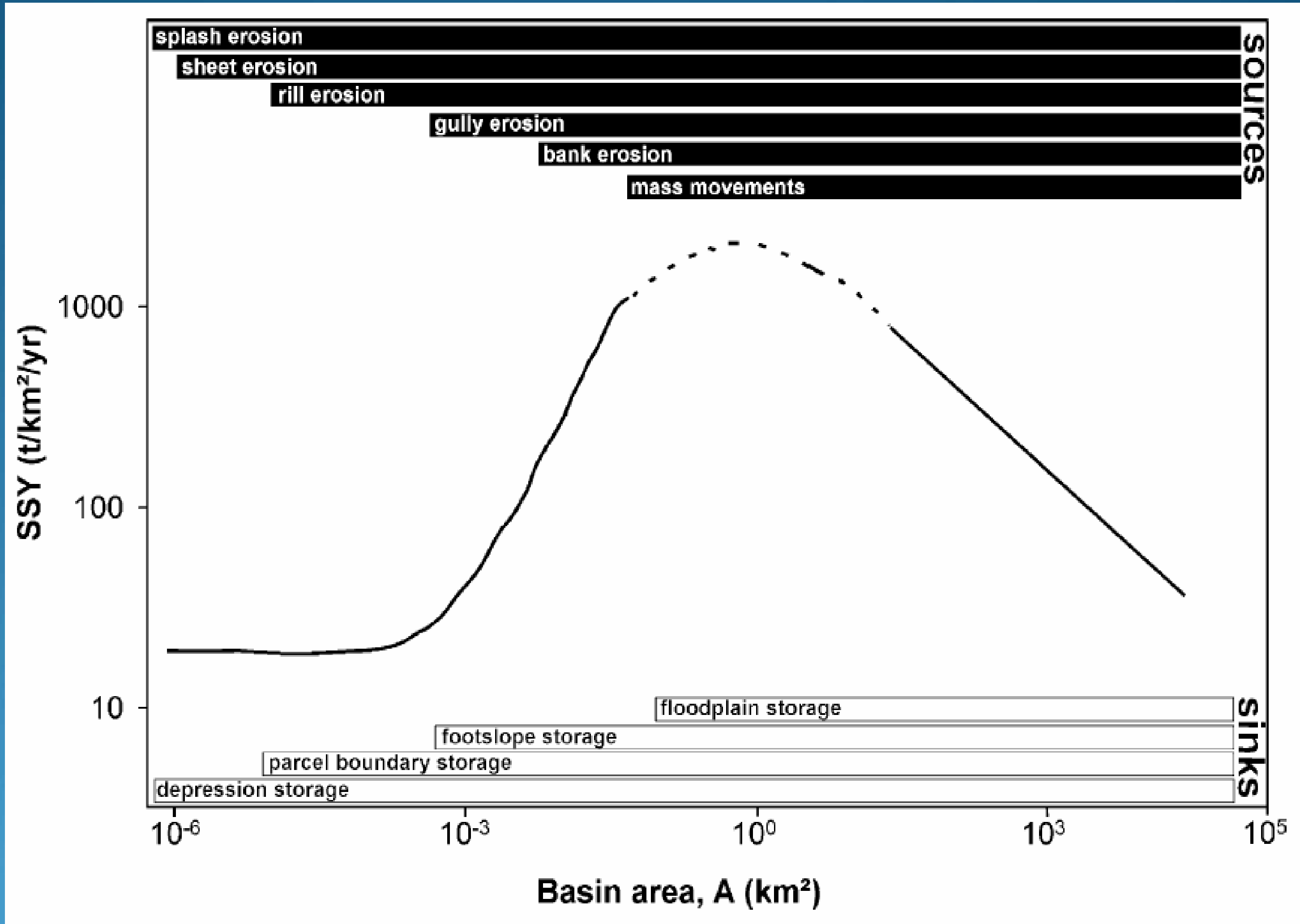
Diffuse connectivity Cammeraat (2002) it is influenced by:
1) soil surface irregularity (roughness), which could be very low on the patch scale, but higher at the hillslope and catchment scales,
2) spatial organization of the vegetation on the hillslope scale and the spatial arrangement between land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



…Influence of Connectivity on sediment yield

SOURCES

SINKS



Conceptual model of sediment yeld at various scale and contributing Sources and sinks (De Vente and Poesen (2005))

... Influence of Connectivity on sediment yield

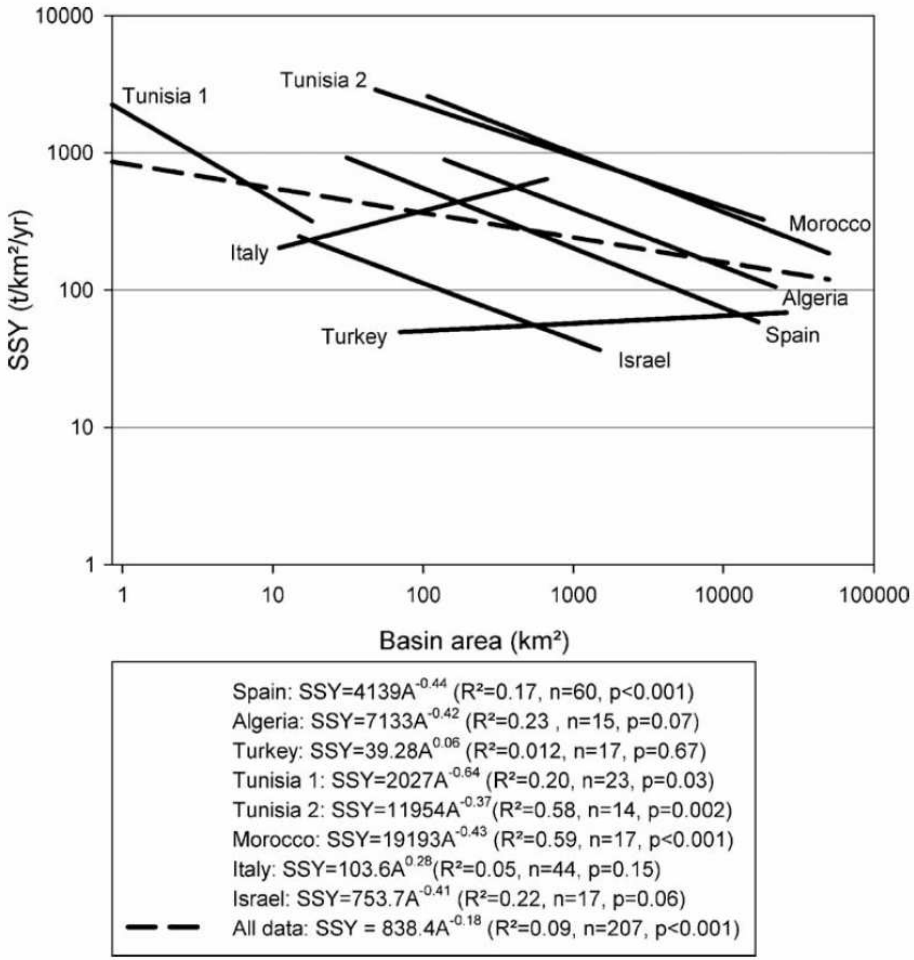


Fig. 3. Relation between area-specific sediment yield (SSY) and basin area for various Mediterranean basins. Source of data: Spain: (Avendaño Salas et al., 1997); Algeria: (Tidjani et al., 1998); Turkey: (Gögüs and Yener, 1997); Tunisia 1: (Albergel et al., 2000); Tunisia 2: (Lahlou, 1996); Morocco: (Lahlou, 1996; Fox et al., 1997); Italy: (Tamburino et al., 1990; Van Rompaey et al., 2003a; Van Rompaey et al., 2005); Israel: (Inbar, 1992).

Sediment delivery at field and watersheed scale

The prediction of sediment yield at basin scale is sometime done coupling a soil erosion model with mathematical function expressing the sediment transport efficiency of the hillslopes and the channel network
(*Kirkby and Morgan 1980; Walling 1983, Ferro and Porto 2000*).

At mean annual temporal scale, the sediment transport efficiency of the hillslopes and the channel network is usually represented by the spatially lumped concept of *basin sediment delivery ratio* (*SDR*) (*Walling 1983*).

Sediment delivery ratio - Definition and link to flow connectivity

***SDR* is used to reduce Gross erosion:**

$$SDR = SSY / A$$

Where: *SSY* is average annual sediment yield per unit area, and *A* is average annual erosion over the same area.

$$SDR = \frac{\text{Net erosion (SSY)}}{\text{Gross erosion (A)}} \quad \text{where SDR [0.0 - 1.0]}$$

At hillslope scale, and at mean annual temporal scale the sediment delivery ratio *SDR* appears to be an estimate of the efficiency with which materials eroded from hillslopes are delivered to the streams system (Boyce 1975).

Many factors influence *SDR* including hydrological inputs (mainly rainfall), landscape properties and complex interactions at the land surface (e.g *vegetation, topography, and soil properties, roads, streams, ponds*..), so CONNECTIVITY.

Role of flow connectivity
Field observations

Models for ASSESSMENT of SDR

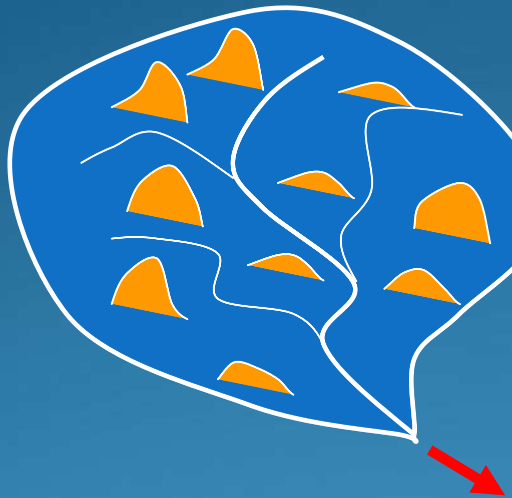
Various algorithms and methods exist for the assessment of sediment delivery ratio (SDR) at field or watershed scale :

- **Geometrical topographical properties of watershed and drainage paths (Greenfield et al. 2001)**
- **Long term transport capacity assessment (Van Rompaey et al. 2001) - SEDEM**
- **Sediment properties and trap efficiency along the flow path (Lu et al. 2003).**

Greenfield et al. (2001) , distinguish between 2 type of algorithms, both dominated by geometrical topographical properties of watersheed and drainage paths:

- **Drainage Area based models (UPSLOPE approach)**
- **Distance and slope models (DOWNSLOPE approach)**

In case of AREA BASED models the SDR is applied to average erosion rate A computed for whole watersheds



UPSLOPE approach

SSY=A*SDR

In case of DISTANCE/SLOPE BASED models the SDR is applied to average erosion rate A_i computed for single pixels or morphological units

$$SSY_i=A_i*SDR_i$$

DOWNSLOPE approach

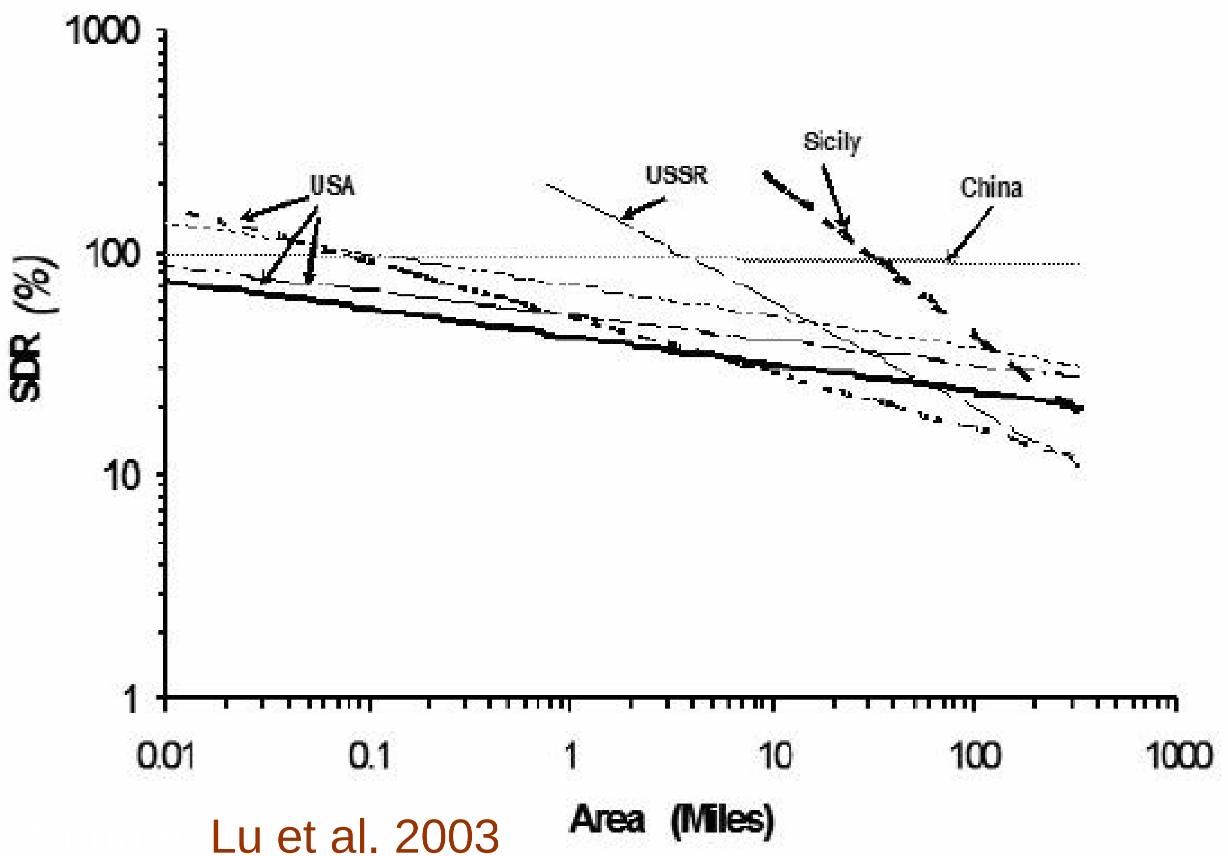
-Spatial disaggregation-

Draninage Area based models

$$SDR = \alpha A^{\beta}$$

ß → [-0.7, -0.01]

(Lu et al. 2003)



Lu et al. 2003

$$SDR = 0.418 A^{-0.135} - 0.127$$

USDA-NRCS. 1983

SDR **generally decreases with increasing basin size, because average slope decreases with increasing basin size, and large basins also have more <u>sediment storage sites</u> located between <u>sediment source areas</u> and the <u>basin outlet,</u> Boyce (1975)**

Area based models

+ relief-length ratio and land use.. a variant

Williams (1977) found the sediment delivery ratio is correlated with drainage area, relief-length ratio, and runoff curve numbers. (Model based on the sediment yield data for 15 Texas basins).

$$SDR = 1.366 \times 10^{-11} (A)^{-0.0998} (ZL)^{0.3629} (CN)^{5.444}$$

Where:

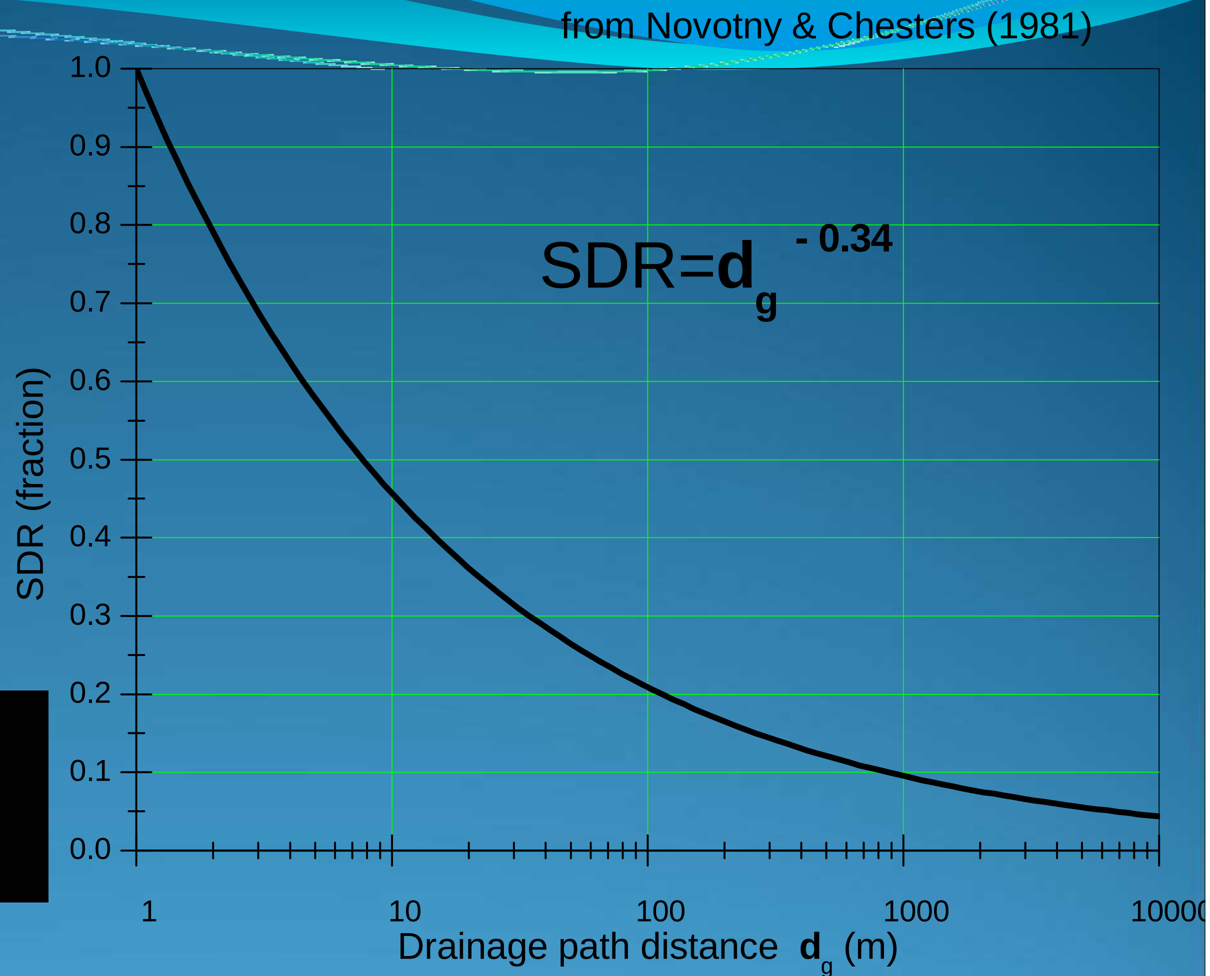
A = the drainage area in km2,

ZL = the relief-length ratio in m/km,

CN = the long-term average SCS curve number.

Travel distance/slope models

Local slope gradient and length of path downslope to the nearest drainage line or sink.



(Sun and McNulty, 1998)
SDR = (1- 0.97*D/L)
Where: L = 5.1 * 1.79*M

Distance and slope-based equation (Yagow et al., 1988)
SDR = exp(-0.4233*L*Sf)
Where: Sf = 0.6 + exp(-16.1*(r/L*0.057))

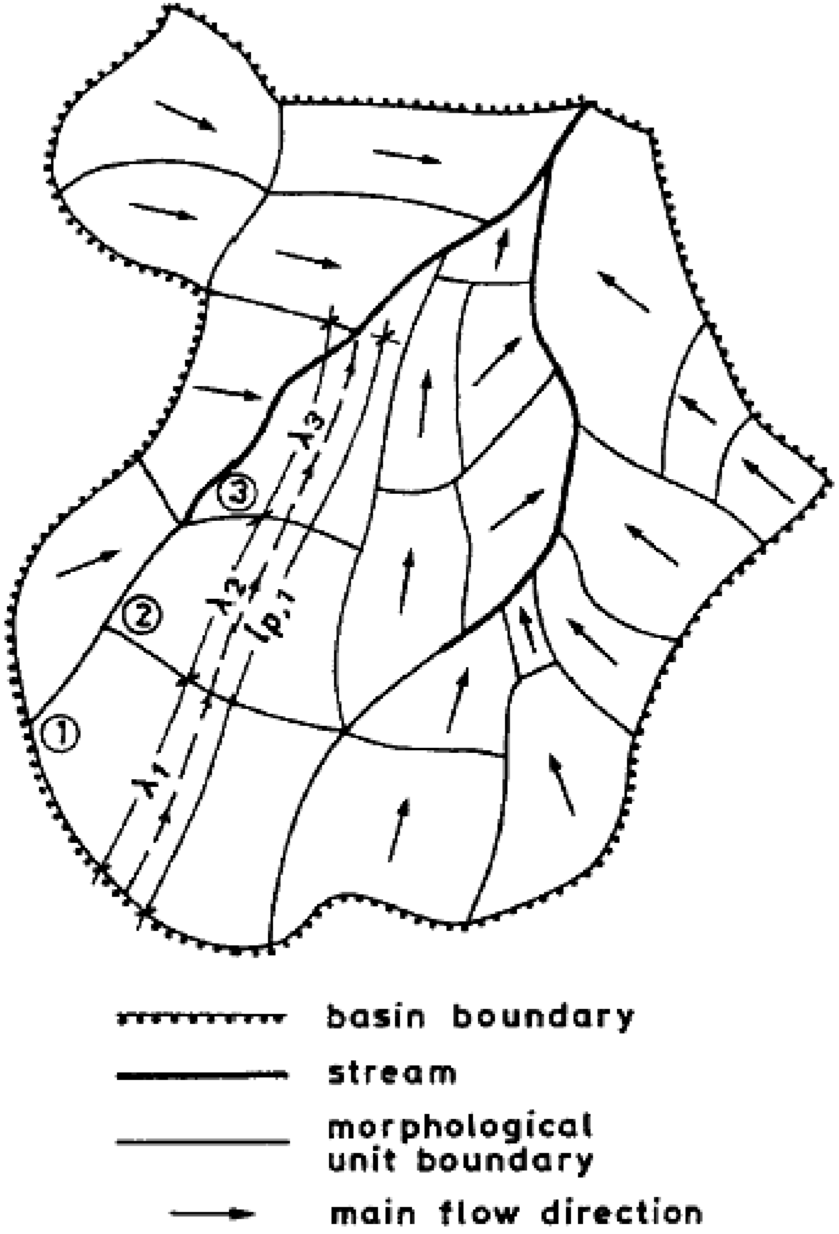


FIG. 1. Scheme of Basin Discretized into Morphological U

Ferro & Porto 2000
(SEDD model)

$$SDR_j = \exp\left[-\beta\left(\sum_{j=1}^{n}\frac{\lambda_j}{\sqrt{s_j}}\right)\right]$$

β = lumped calibration parameter
λ = length along flow path
s =slope along flow path

In this case SDR it is computed and applied at each morphological units to obtain the single sediment yield contibution

How to relate flow connectivity and SDR

Remeber the previous definition...

The chances that a particle has to reach the nearest sink depends on: the distance to the sink, the characteristics of the route, the water available to transport from upslope, the water that is gained/lost along the downslope route.

So the properties of the path to the nearest sink and the properties of the uspslope contributing areas should be CONCURRENT to estabilish the potential connectivity.

Local sinks at field scale

L. Borselli –Rutherglen (Victoria Australia)
Department of Primary Industries (DPI) –
September 25th 2009 –
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INDEX OF CONNECTIVITY (*IC*)

Hillslope sediment delivery processes and channel processes should be considered and modeled separately (Atkinson 1995).

We concentrate on HILLSLOPE DOMAIN and in our schematization we have defined the permanent drainage lines (streams), roads, urban areas, and lakes as total sink .

Land use and slope gradients along the downslope route, and path length, are used to rate the sinking potential. (*first component*)

Upslope catchment's areas, mean upslope and land use are used to rate the potential for down-routing. (*second component*)

Finally the TWO COMPONENTS are then used for defining an INDEX OF CONNECTIVITY (Ic).

best application with a spatial disaggregation defined by a 5X5 m resolution raster GIS

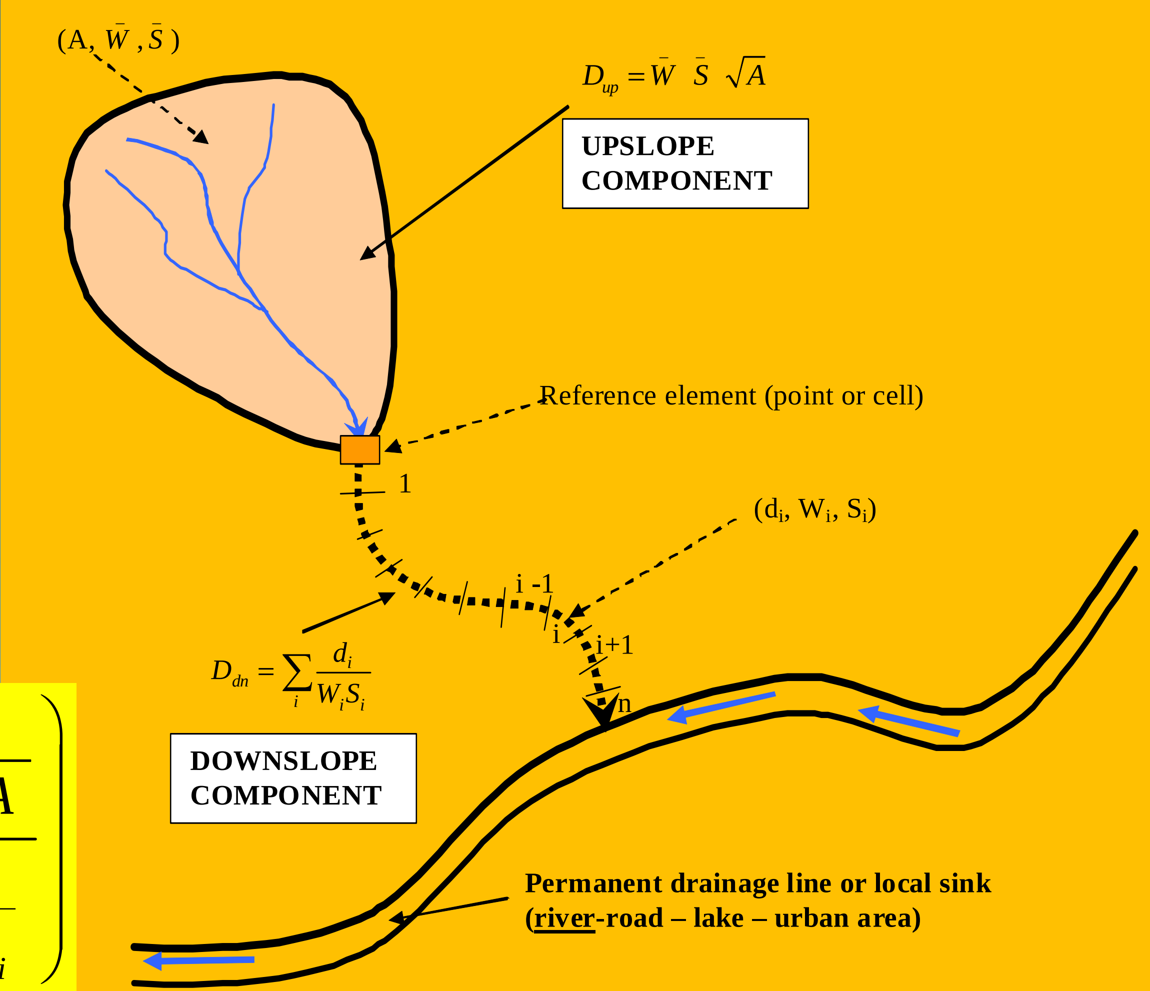
Connectivity index model – IC

Borselli et al. (2008). Prolegomena to Sediment and flows connectivity in the landscape: a GIS and field numerical assessment . CATENA(elsevier)

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

- **Downslope component**: is the sinking potential due to the path length, land use and slope along the downslope route.
- **Upslope component**: is the potential for down routing due to upslope catchment's areas, mean upslope and land use.

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



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

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)

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

UPSLOPE Component

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

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

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

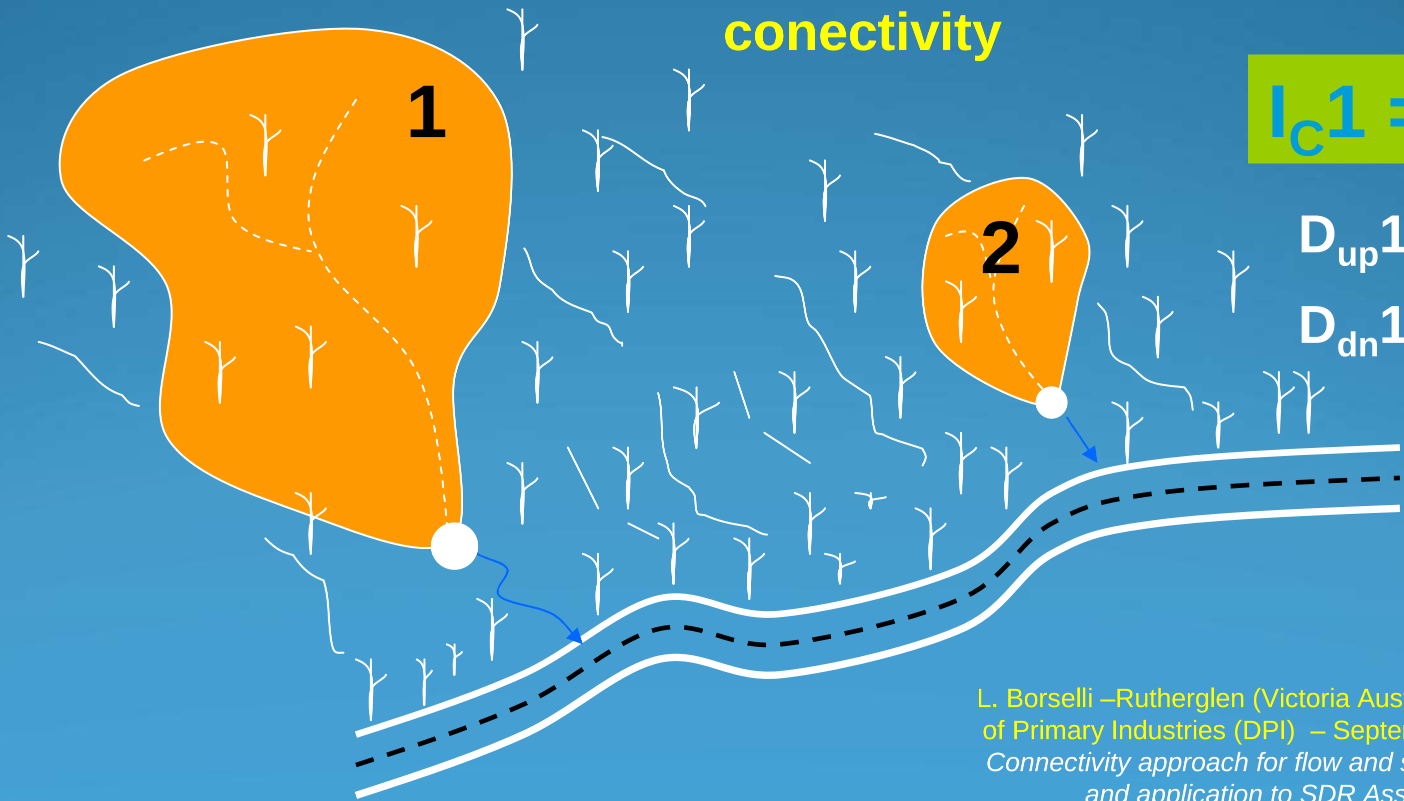
Connectivity index (Ic)

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

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

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 conectivity



$I_C1 = I_C2$

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

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

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Application of connectivity approach.

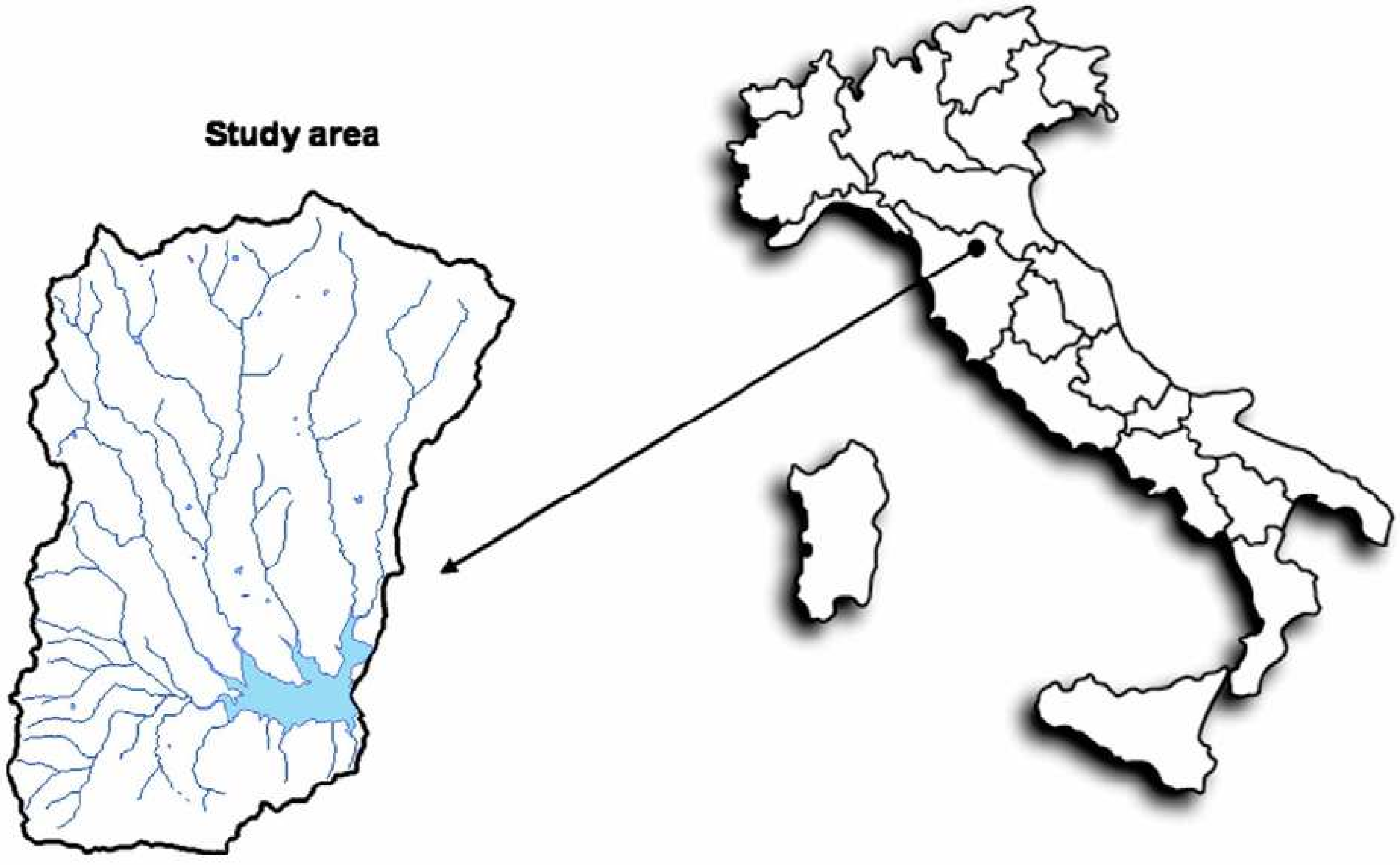
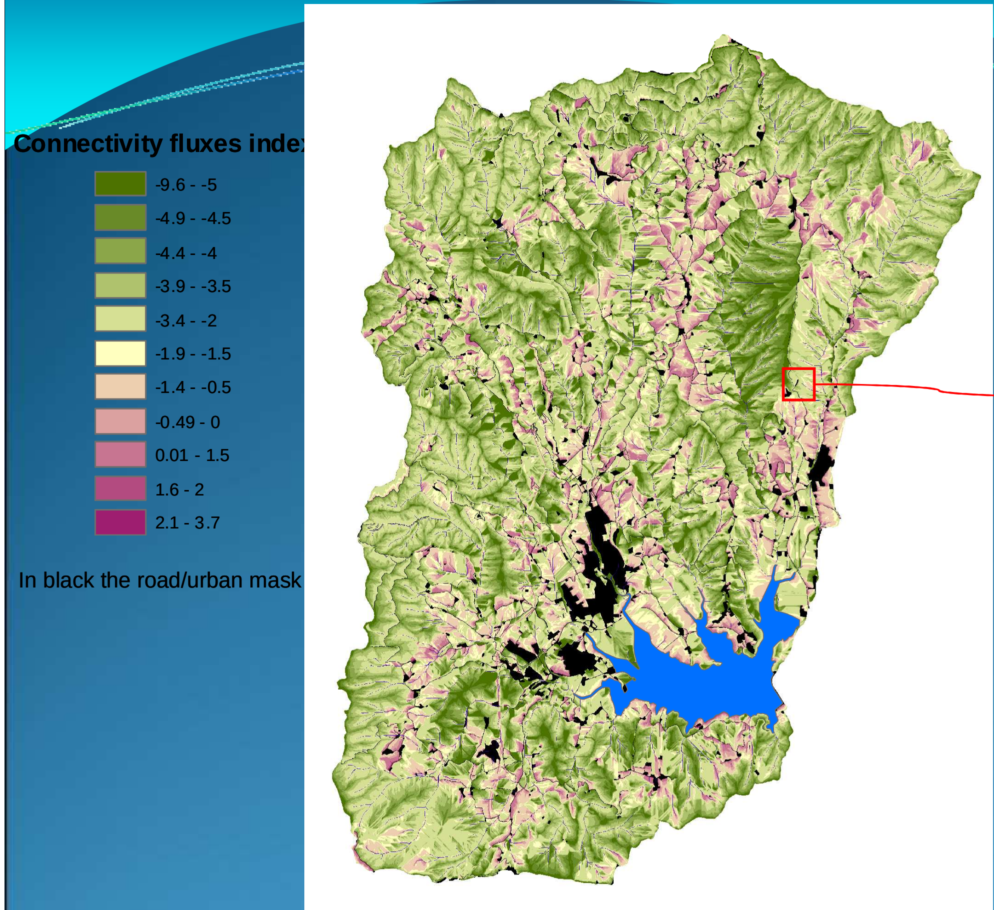
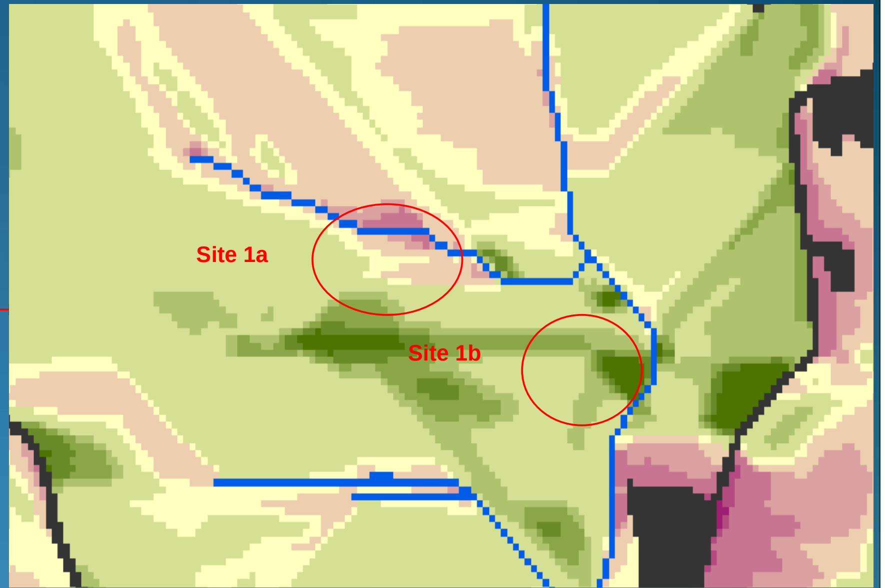
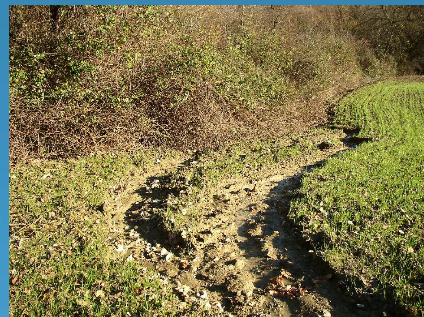


Fig. 3. Study site—Bilancino watershed (Tuscany, Italy).



IC map of deposition and connection areas evidenced in red

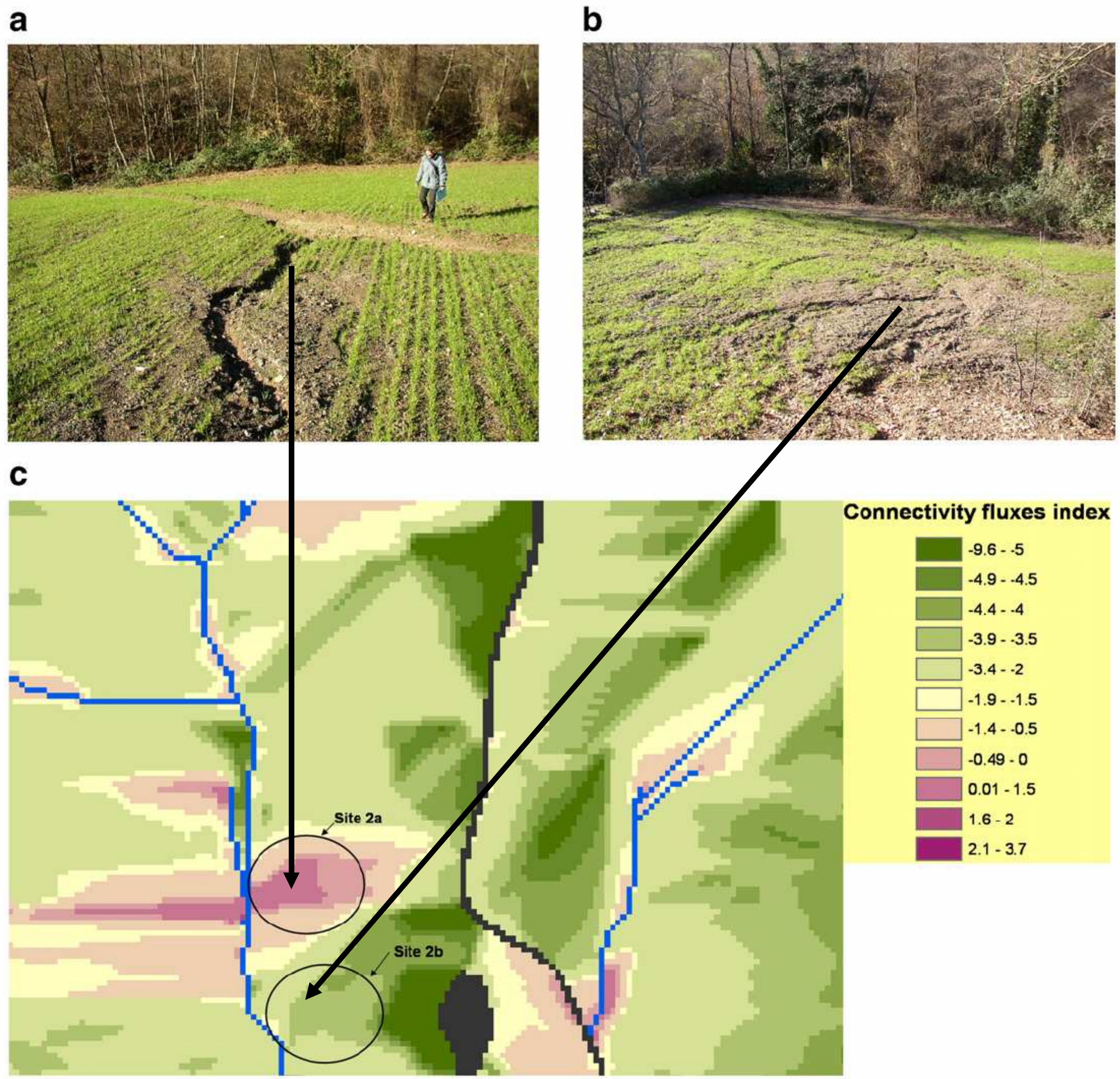




Site1a -Area in proximity of local sink at field bottom: direct connection of rill system without appreciable sedimentation

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. Borselli eta. Al. 2008)



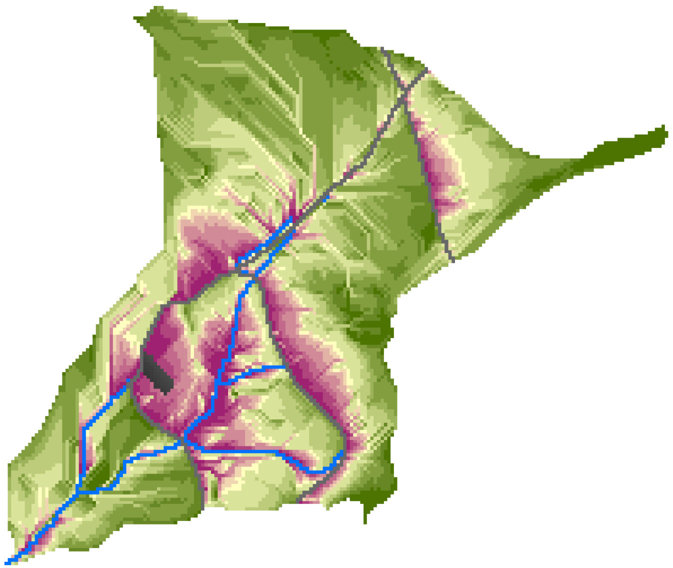
ite 2—Area close to a local sink at the bottom of a field: direct connection of rill system without detectable sedimentation. b: Site 2—Area in proximity of local sink at the bottom of a field: direct connection of rill system with intense sedimentation. c: IC map of Site 2: deposition and connection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

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

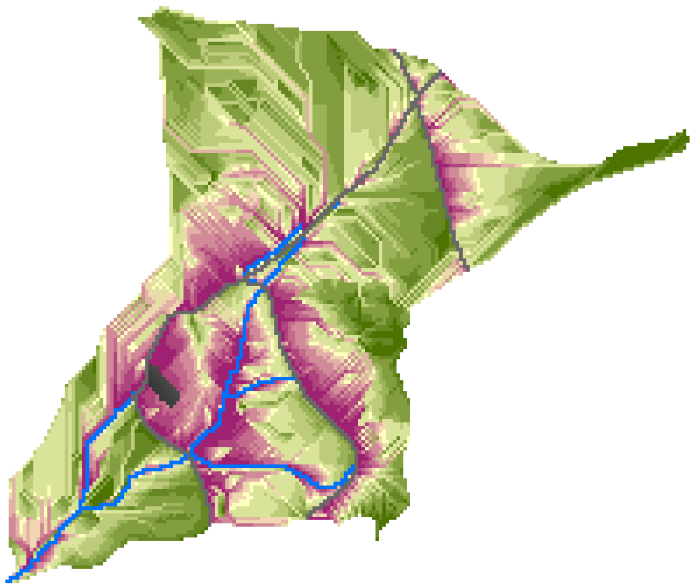
Without strip of bared soil on field border



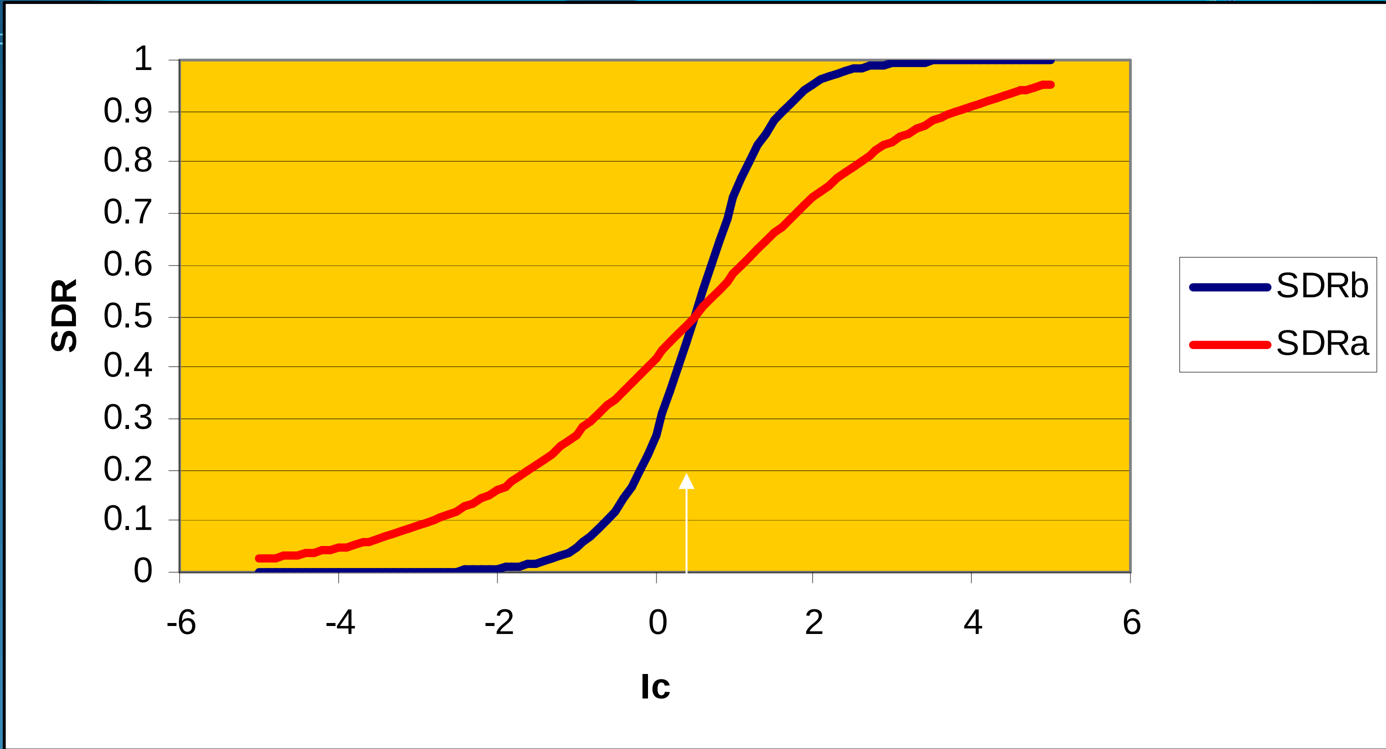
Connectivity fluxes index

- -4.1 - -2
- -1.9 - -1.5
- -1.4 - -1
- -0.9 - -0.8
- -0.79 - -0.5
- -0.49 - -0.1
- -0.09 - 0
- 0.01 - 0.1
- 0.11 - 0.25
- 0.26 - 0.5
- 0.51 - 0.66
- 0.67 - 1
- 1.1 - 1.5

With strip of bared soil on field border



Possible functional relationships between Ic and SDR…



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

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

FIC – THE FIELD APPROACH

The field assessment of connectivity is evaluated using the same approach of Ic, i.e. estimating the upslope and the downslope component. A well defined field connectivity index (*FIC)* can permit an evaluation of the GIS-based *IC*. As *FIC* is strictly related with the event that produced the connectivity evidence, it is also a way of representing ground truth. Hence a comparison between the two indexes will allow for a validation of IC.

$$\mathbf{FIC} = \frac{\mathbf{Su} + \mathbf{Sd}}{\mathbf{2}}$$

FIC is subdivided into an upslope (Su) and a downslope subfactor (Sd); FIC varies between 1 and 100 and increases with connectivity

$$\mathbf{Su = Au + Bu + W_u Cu_1 + (1 - W_u) Cu_2}$$

Upslope subfactor

$$\mathbf{Sd = Ad + Bd + Cd + W_{d1} Dd_{1\_} + (1 - W_d) Dd_2}$$

Downslope subfactor

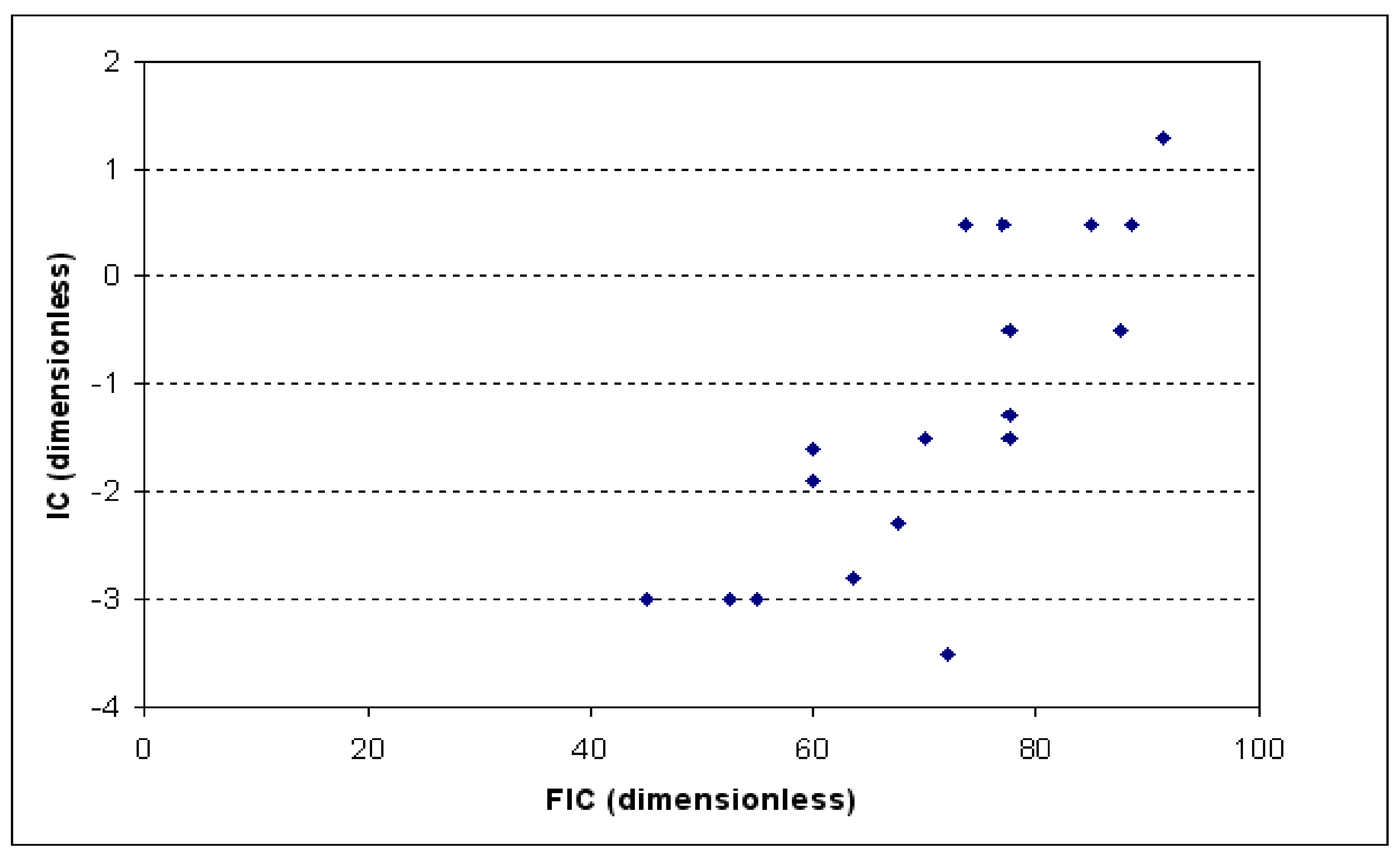
Au and **Ad**- Upslope area and the downslope distance to local sink;
Bu and **Bd** - Presence of sedimentation features along the upslope and downslope flow paths;
Cd presence and wideness of buffer-bush strip area before or along the flow path to the local sink;
Cu1, Cu2, Dd1, Dd2 - Subfactors opposing resistance to fluxes (surface roughness and vegetation cover crop, plant basal area) in the upslope area and the downslope flow path;
Wu and **Wd** – Fraction of arable land in the upslope area and in downslope flow path.

Application at watershed scale (Bilancino Tuscany Italy, 150 km^2)

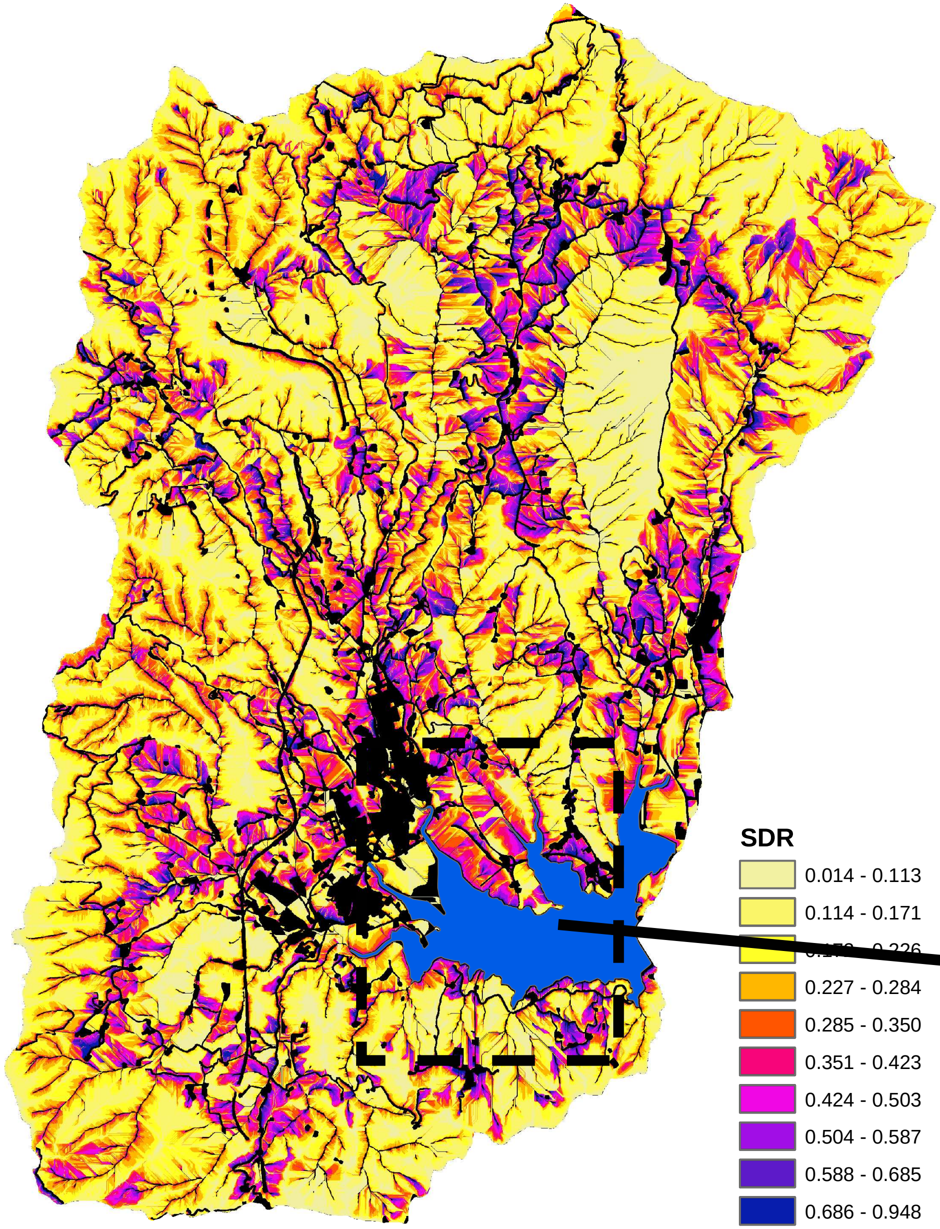
To evaluate the degree to which the map represented real sediment flow connectivity, we compared it with field observations, conducted in autumn–winter 2003-2004 after several rainfall events of medium magnitude for the area.
During the surveys, 18 hot spot areas were identified within the watershed in proximity of the main streams. They are representative of the landuse and management of the basin

	SOIL USDA classification (8th ed.1998)		LAND USE	Rainfall	Season
Site1	Typic Udorthents fine mixed mesic		Wheat crop at the beginning of the growing season	2 events 30 mm/day	Autumn
Site 2	Typic Udorthents clayey skeletal, mixed mesic		Wheat crop at the beginning of the growing season	2 events 30 mm/day	Autumn
Sub Factors	*Component*	**Site 1a**	**Site 1b**	**Site 2a**	**Site 2b**
Au	UPSLOPE COMPONENT	45	45	45	30
Bu		20	5	20	5
Cu1		5	5	10	10
Cu2		-	-	20	-
Wu		1	1	0.8	1
Ad	DOWNSLOPE COMPONENT	40	40	20	20
Bd		20	10	15	10
Cd		20	20	20	10
Dd1		-	-	-	-
Dd2		20	10	15	5
Wd		1	1	1	1
Connectivity indexes					
FIC (eq. 10)		85	67.5	85	45
IC (eq. 7)		0.5	-2.3	0.5	-3

Subfactors for field assessment of connectivity index *FIC*. The last row reports and the corresponding values of *IC*

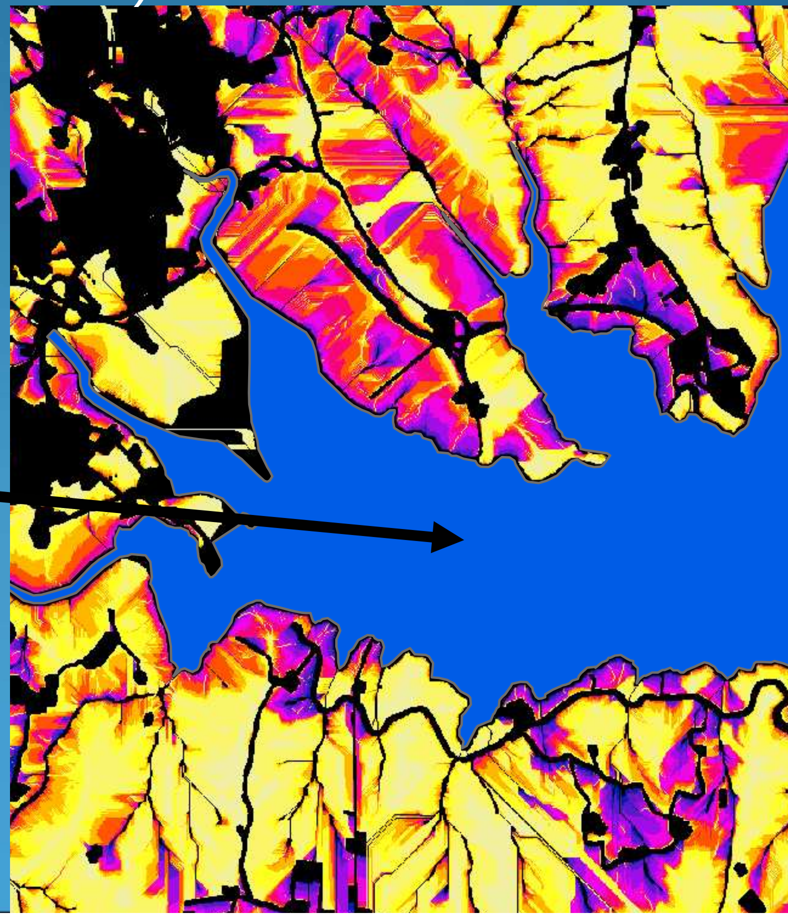


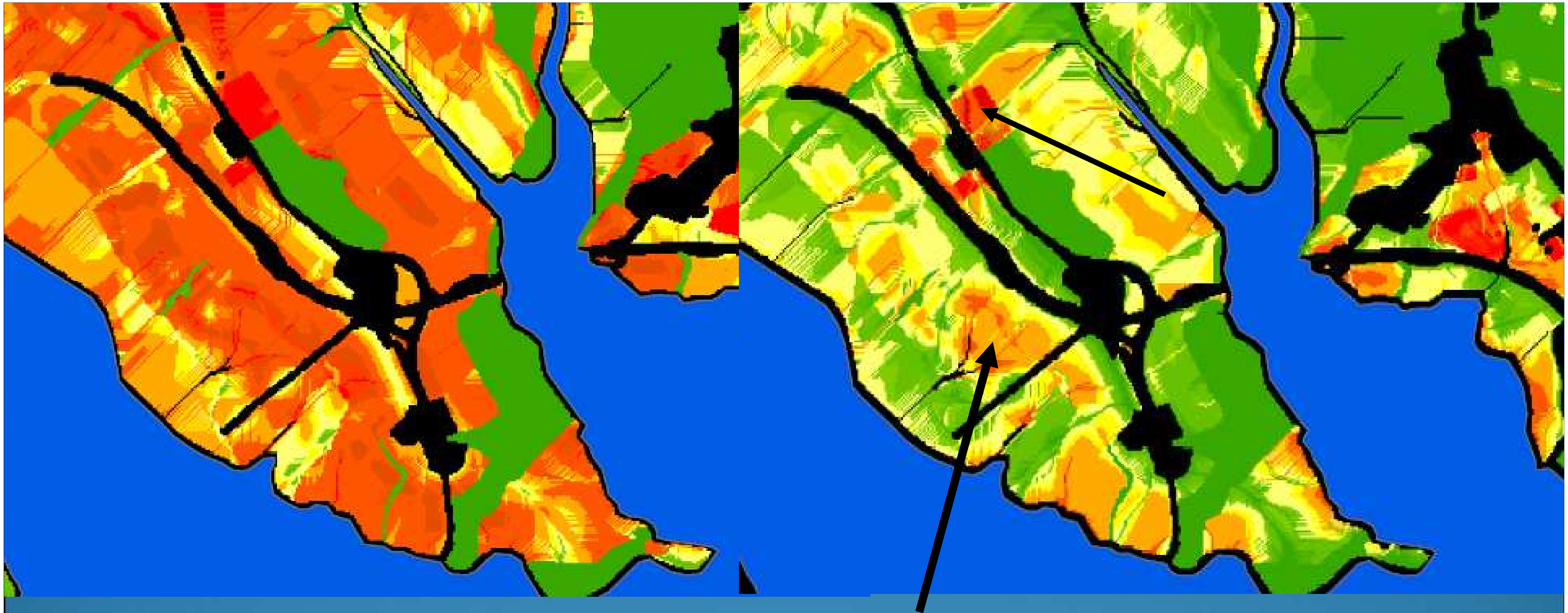
The FIC values have been compared to the IC flux map obtained with the ArcGIS procedure for the entire study site



SDR maps distribution in an entire watersheed for average annual erosion rate correction

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





Local Average erosion rate... Classic RUSLE3D

Average sediment yield Contribution: RUSLE3D corrected according to *Ic* and SDR

SDRmax

SDRmax is the maximum SDR can occurr in a given place and in a given interval of time.

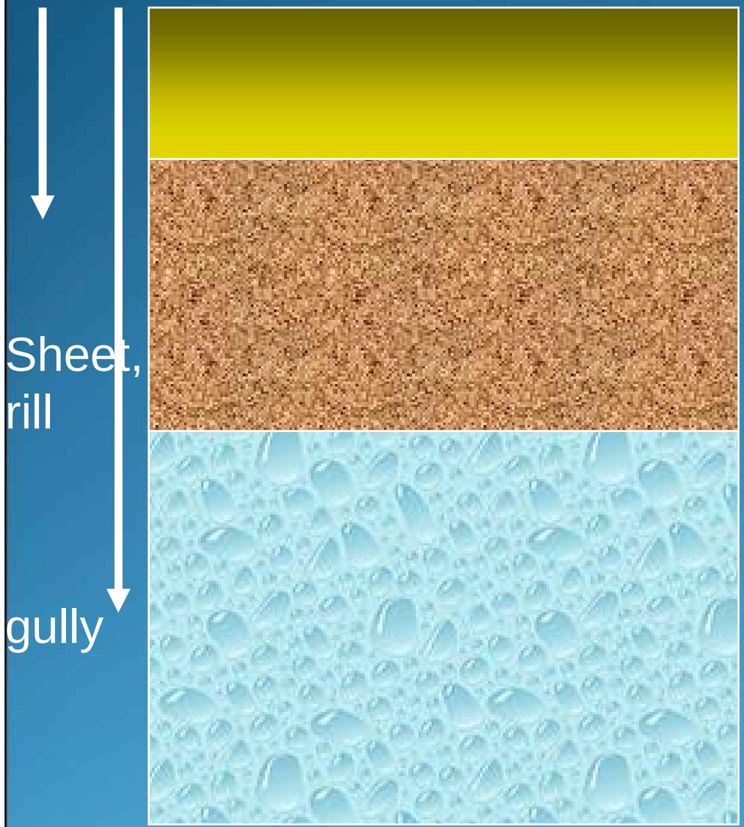
For geological time the SDR is 1.0 everywere!

For much shorter interval of time it may be lower...

DT= 1day, 1 year, 10 year... (it depend form distance and travel speed... Or in other words from the dominant erosion processes

It should depends on different mobility of the textural class of sediments (clay, loam , sand, gravel, boulder) that are in soil profile.. (Lu 2003, 2006)

SDRmax may be obtained by weigthed average of each SDRmax of the differents horizons that can be mobilised by the considered soil erosion processes (e.g. Gully , rill; sheet ..)



30% C; 40% L; 20% S; 10% R → SDRmax=0.8

10% C; 30% L; 40% S; 20% R → SDRmax=0.5

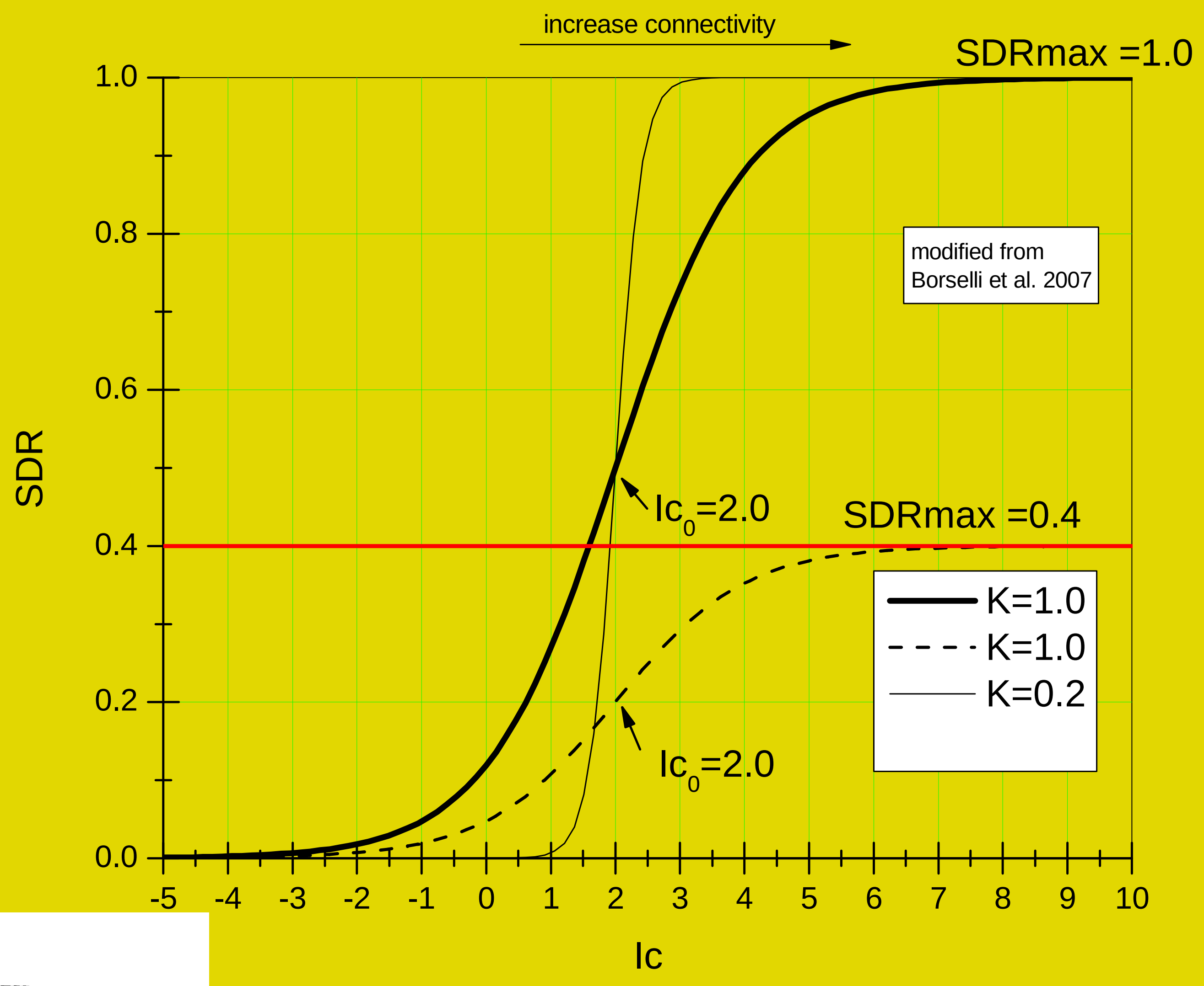
0% C; 5% L; 25% S; 80% R → SDRmax=0.2

Global SDRmax in this case Is about 0.5 (gully ?)

SDRmax for each text.class can be obtained using the Lu (2003,2006) algorithm knowing soil profile data and the defined ΔT .

Genralised functional relationships between Ic and SDR…

The definition of SDRmax



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

Others Possible integrations between soil erosion and connectivity assessment models:

•**<u>Flow connectivity approach</u> (FCA) is easy to apply to large catchments**

•**FCA can identify problematic areas**

•**Models can then be applied only to these spots (saving time and money) and be used for designing <u>conservation strategies</u> (CS)**

And More... Application of connectivity TO LANDSLIDES (work in progress…)


Samoggia Valley
(north Italy)
2 October 2002
(200 mm rainfall
in september)

APPLICATION TO LANDSLIDES: landslides contribution to sediment yield

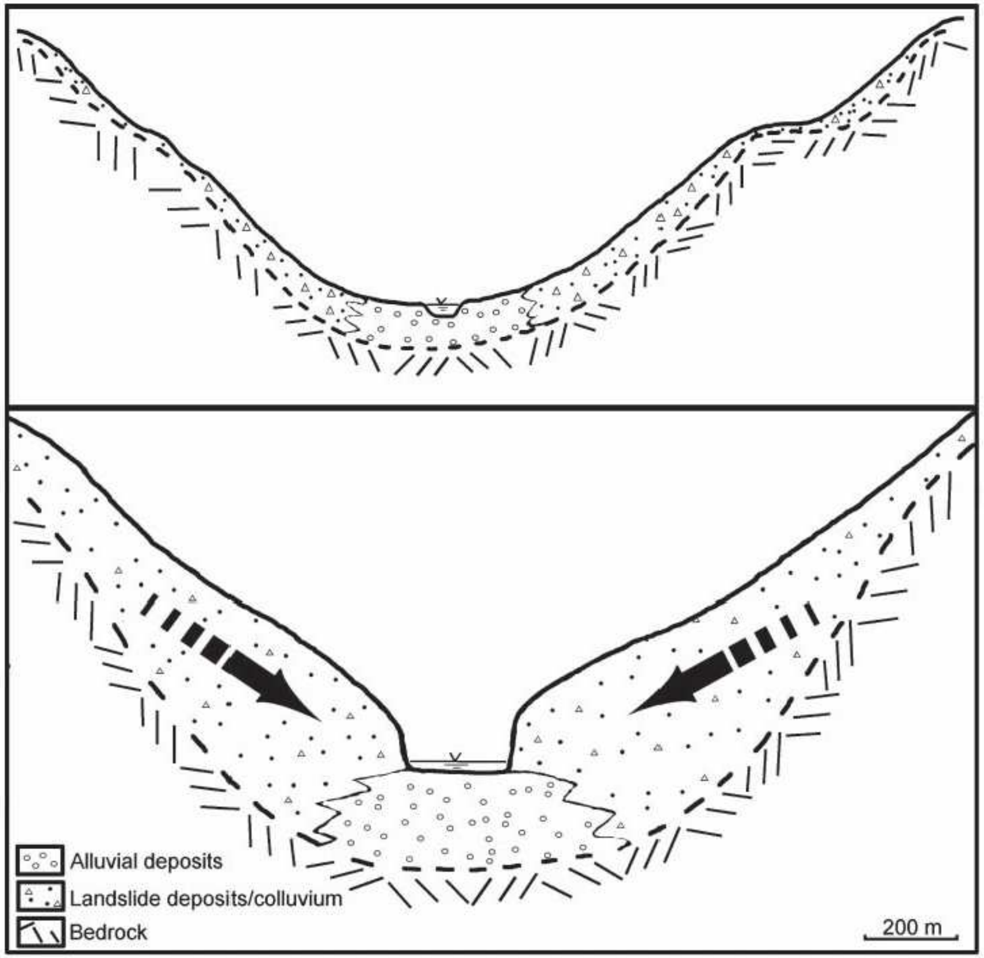


Figure 10. Typical cross-sections of two contrasting valleys. *Top*: valley with no dominant landslides. *Bottom*: valley with abundant landslides that supply lots of sediment to the ephemeral channel.

DIFFUSE SURFACE LANDSLIDE IN A BADLAND AREA

…LANDSLIDE DISTRIBUTION, DEPTH AND VOLUMES.

Application a distributed slope stability model Es. Sinmap, Shalstab or an alternative model like *montecarlo methods* applied to entire watershed

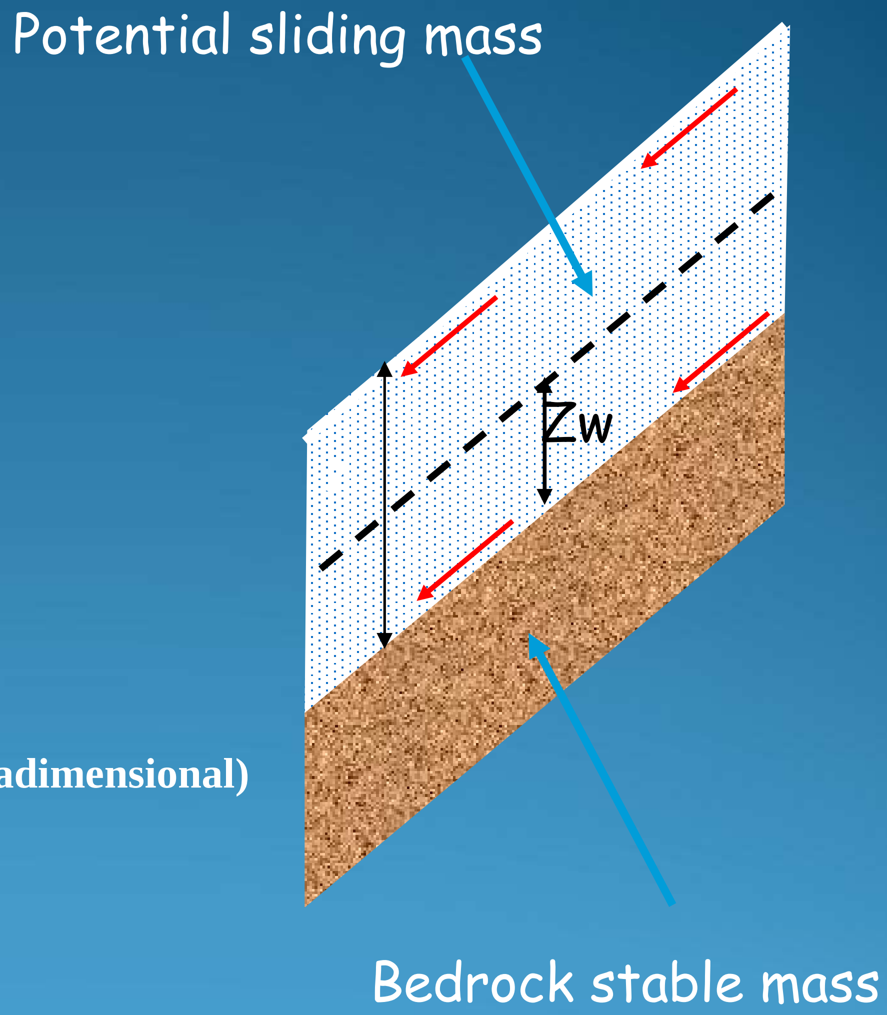
Limit equilibrium - Infinite slope model

$$Fs = \frac{\left(\frac{c'}{\gamma z} + (\cos^2\beta - r_u)\tan\phi'\right)}{\sin\beta\cos\beta}$$

where:

- **β= slope gradient (degrees)**
- **ϕ'= internal friction angle(degrees)**
- **c'= soil choesion+ roots strength (kPa)**
- **γ= soil unit weigth (kN/m^3)**
- **Z= depth of sliding surface (in m)**
- **Zw = depth of water saturated horizon**
- **r_u = coefficient of interstitial pressure (adimensional)**

$$r_u = \frac{9.81 * z_w}{\gamma z}$$



If Fs < 1.0 = unstable condition

Limit equilibrium - Infinite slope model

Fields of application

- Planar uniform slope
- Debris/soil over stable bedrock
- Translational landslides (failure surface parallel to slope)
- Possibility of application in GIS systems (e.g. SHALSTAB,SINMAP)
- Trigger conditions for debris flow and mud slide (Iverson, 2000)

Advantages

- Easy to implements in spreasheets and programs
- Easy and fast computation

Disadvantages

- Static approach (e.g. fixed depth of saturated horizon)
- It Need to iterate the computation for several conditions: (infiltration/rainfall, Z, Zw..), soil properties variability and local gradient β of the slope

Limit equilibrium method, Infinite slope model, and Monte Carlo Method

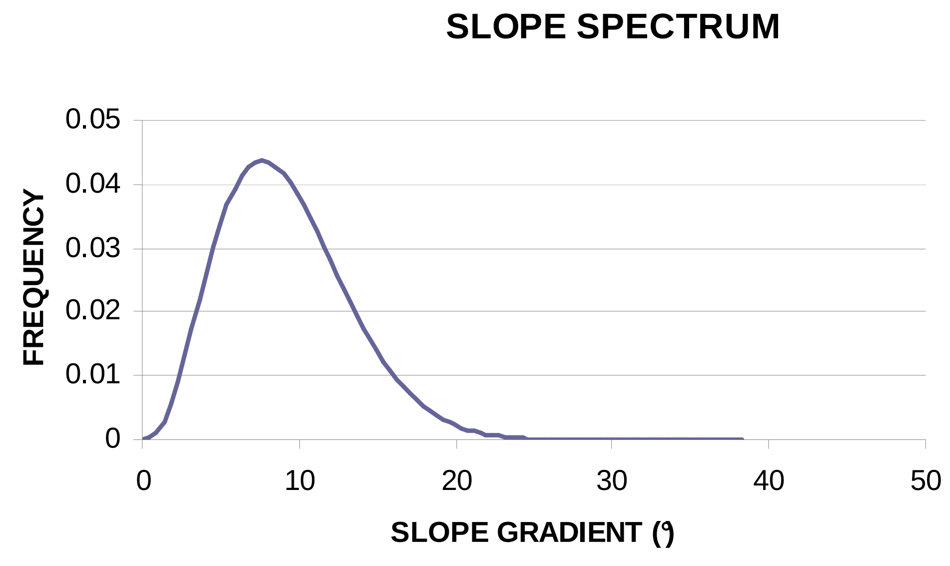
Local variability of soil properties
Local variability of slopes
Groundwater depth

Random variables
e.g. **uniformly distibuted**
Between loower and upper bounds:
10° < ϕ' < 14°
2 < C' < 5

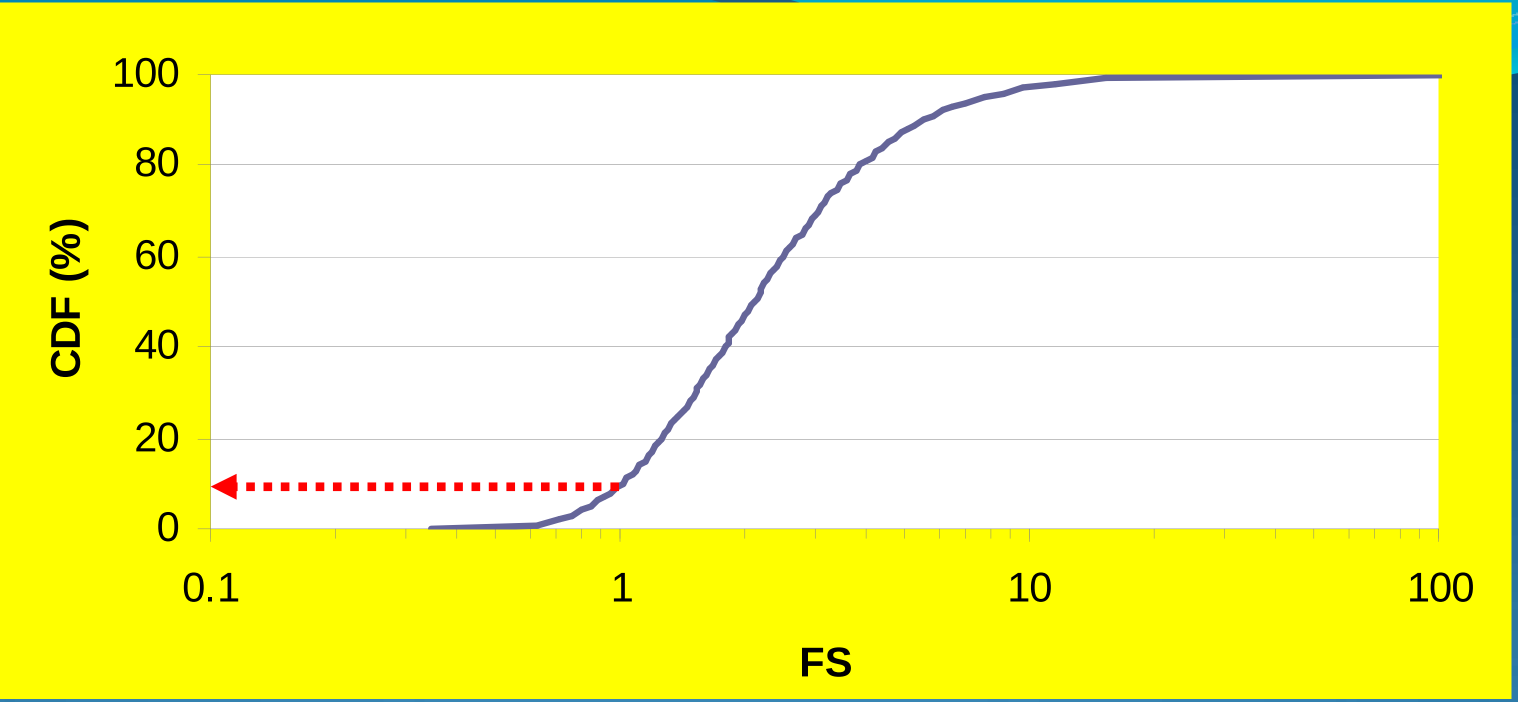
alpha	2.64	0	grad min
beta	10.43	0.79	grad max

	c' (kPa)	ϕ ' (°)	ru	β (°)	γ (kNm^3)	z(m)
min	2	10	0.5	0	17	0.5
max	5	14	0.5	38.3087	19	1.5

The safety factor Fs
Is a random variable
It accounts for local
Variability of the input
Parameters...



L. Borselli –Rutherglen (Victoria Australia) Department of Primary Industries (DPI) – September 25th 2009 –
Connectivity approach for flow and sediment delivery and application to SDR Assessment

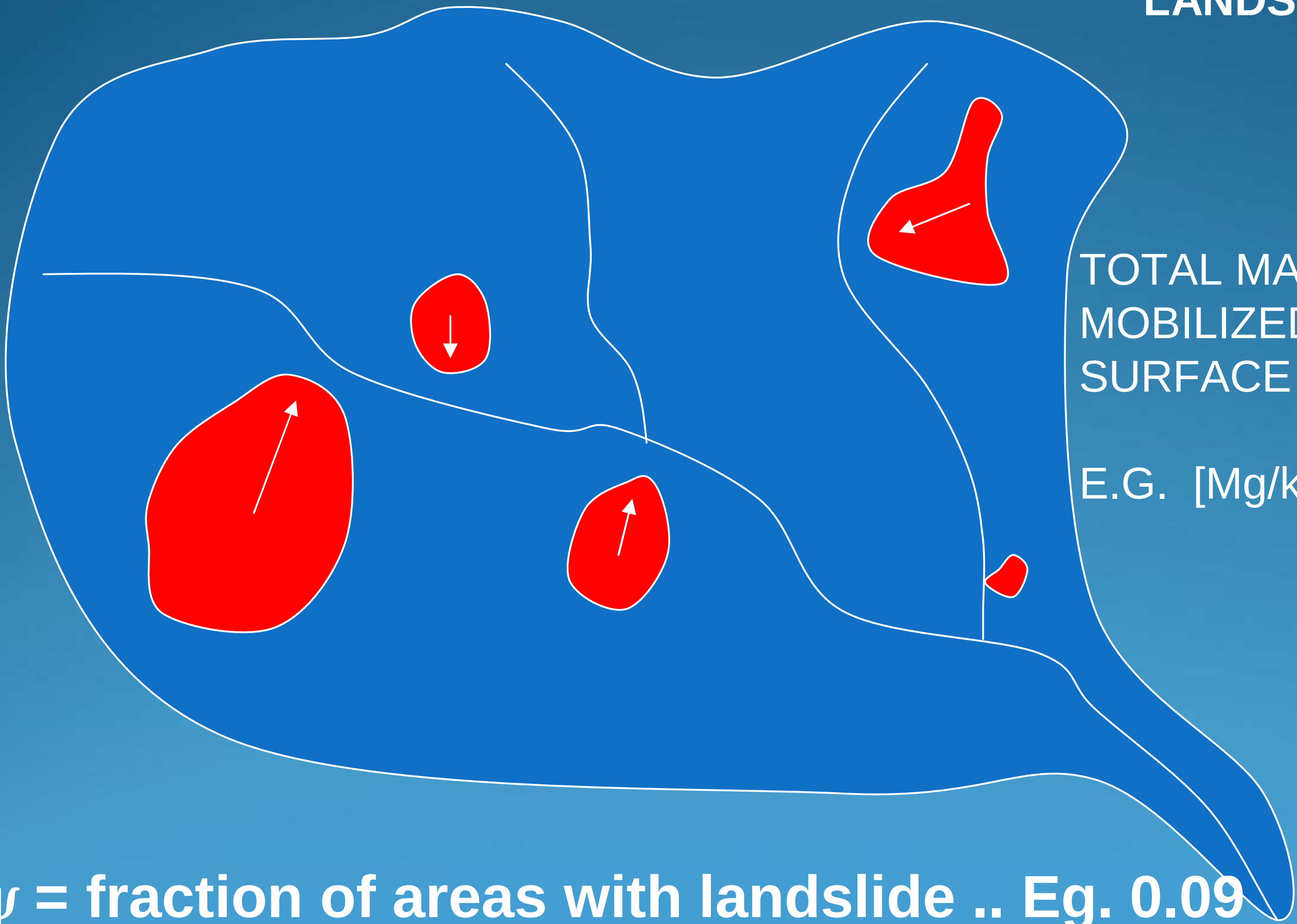


9% of entire watershed has FS<1.0

Using the slope specturm of a entire watershed the % of Fs<1.0 represents the potential fraction of total area affected by landSlides (Ψ)

Total LANDLISDE VOLUME from area and average depth of landslides

IT APPLIES AT SHALLOW LANDSLIDE ONLY..

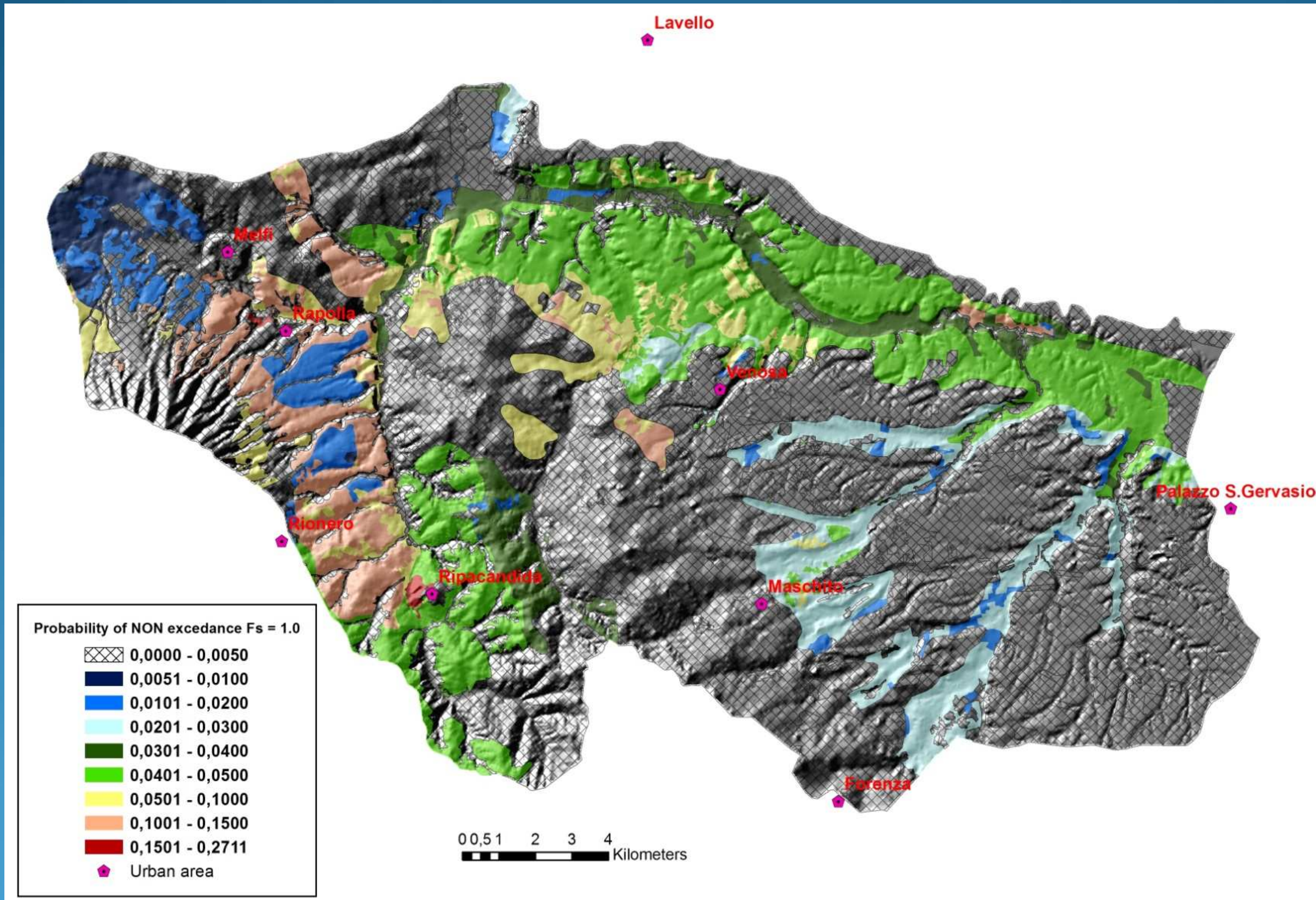


TOTAL MASS THAT CAN BE MOBILIZED FOR SPECIFIC SURFACE IN A WATERSHED

E.G. [Mg/km2]

ψ = fraction of areas with landslide .. Eg. 0.09

Shallow landslides extension to PESERA
It is One of the CNR-IRPI Activities within
DESIRE project – Rendina Dam catchment (south, italy)



…Sediment delivery ratio for landslides:SDRL

The same definition of previous SDR can be applied also to shallow landslides contribution because only a fraction of landslide volume can contribute to sediment yield…

USUALLY SDRL SHOULD BE LOWER THAN SDR… BUT IN EXTREME CONDITION IT IS VERY HIGH (SDRL > 0.5)

case studied

Sestino (Tuscany- Marche border)

Parent material : clay shales and olistrostromes (Eocene)
(structurally complex formations)

Altitude
1000- 1100 m

Mean annual
Precipitation
(snow included)
1200 mm

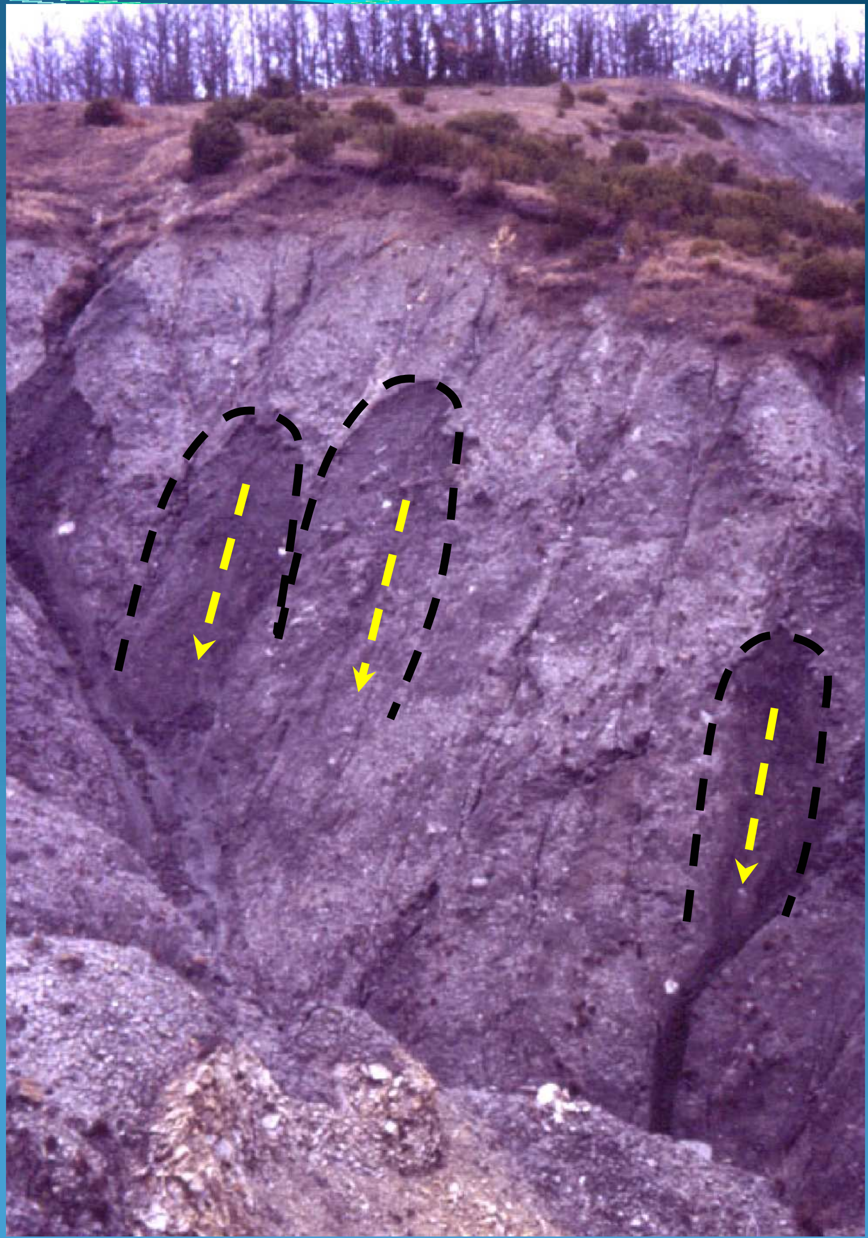
Several
snowmelting
events during the
winter !!

Badaland area where the main Erosion process is shallow landsliding

Translational landslides of wheatered rind formed from clay shales parent material

Temporary accumulation at the valley bottom and subsequent mudflow

(computed average depth erosion rate: 0.2-0.05 m/y)

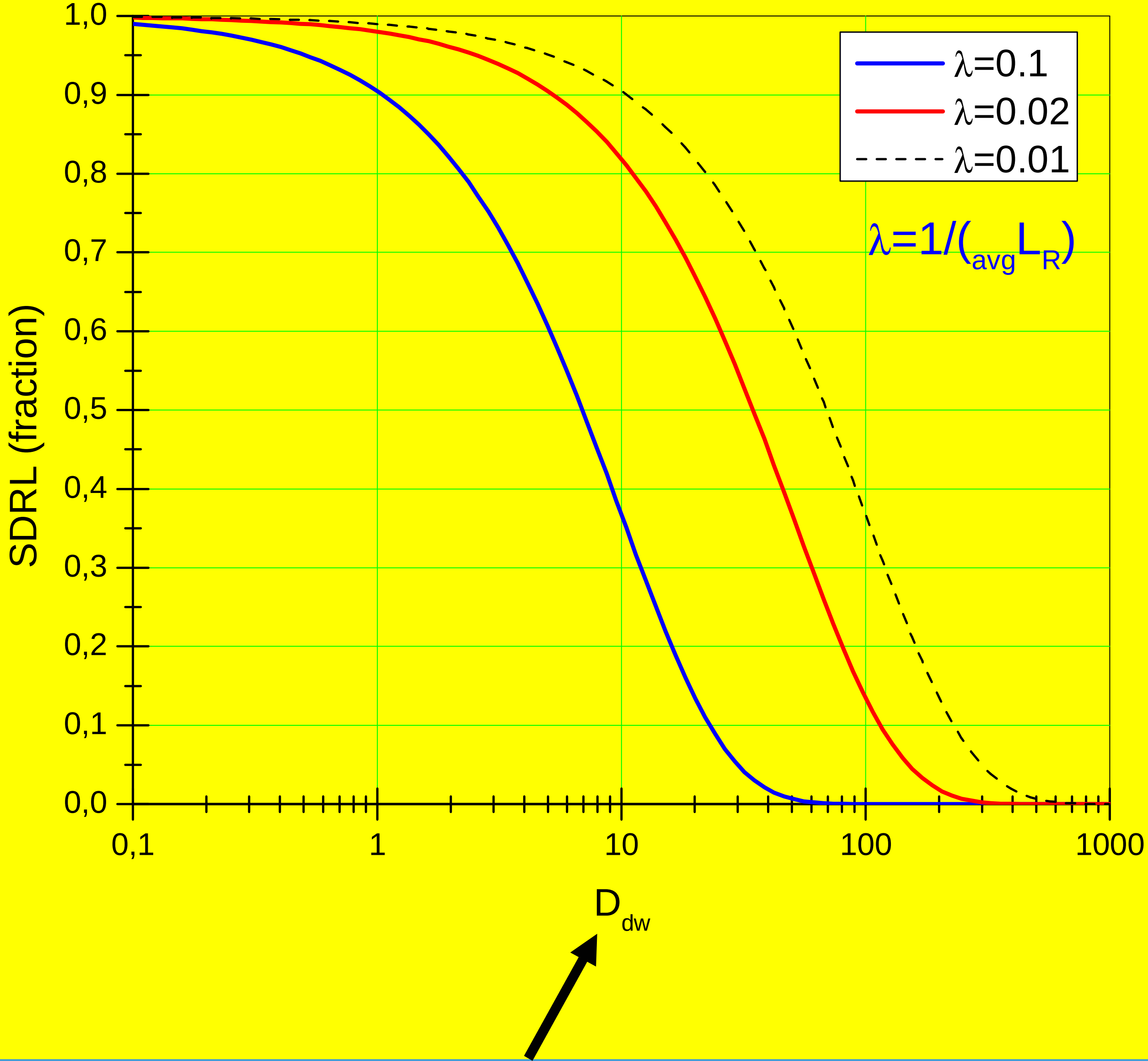



sliding of weathered
rind (20–30cm) from all
the watershed at the
same time, during the
snowmelt phase

Mudflow – gully runout distance

probabilistic model of landslides and debris flow delivery to stream channels

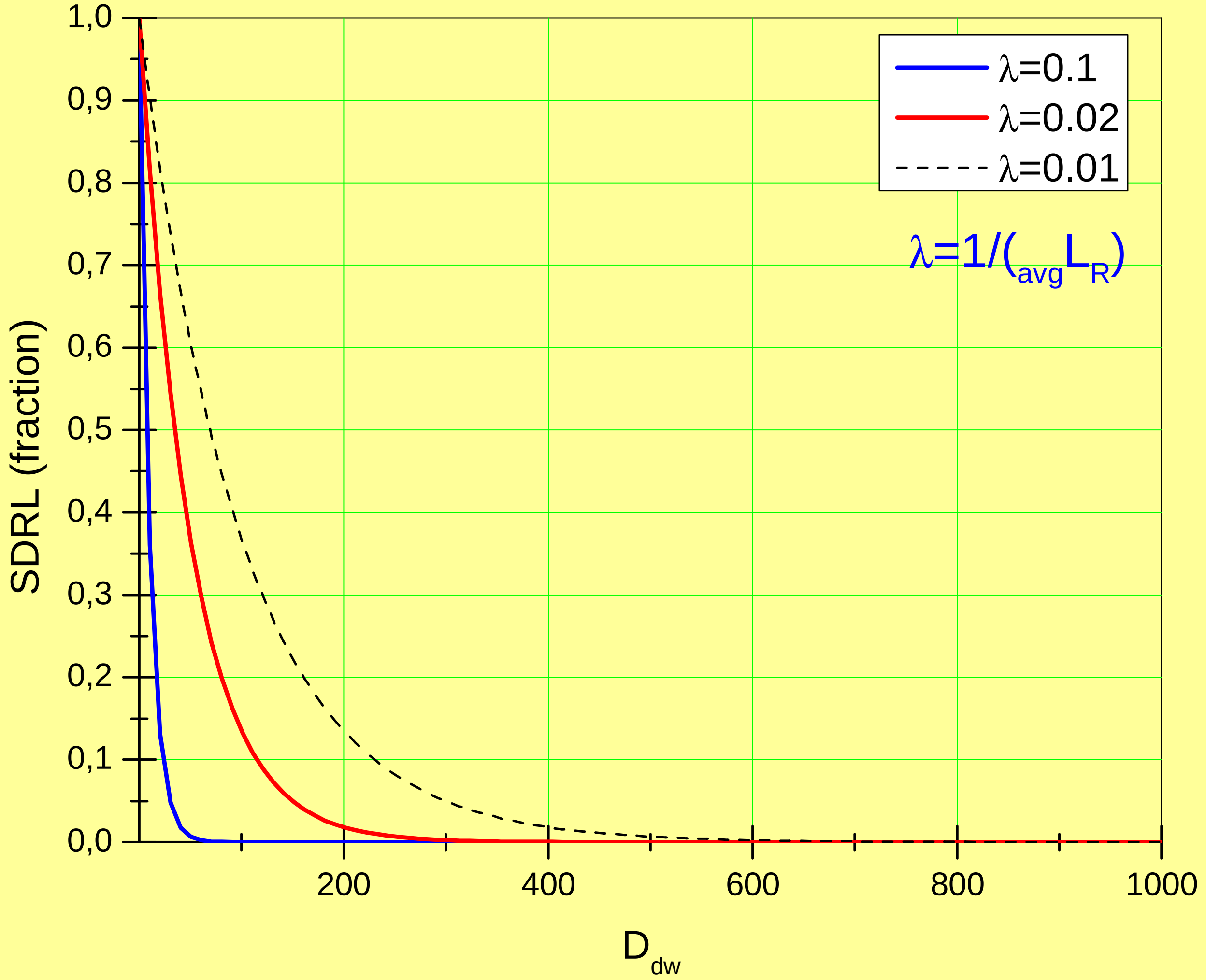
(Miller & Burnett, 2008)



Downsloper component of IC index

probabilistic model of landslides and debris flow delivery to stream channels

(Miller & Burnett, 2008)



Exponential probability distribution functiin
Depends from the average runout length Lr (measured)
and the local site D_{dw} distance to a sink

Ferro & Porto 2000
(SEDD model)

$$SDR_j = \exp\left[-\beta\left(\sum_{j=1}^{n}\frac{\lambda_j}{\sqrt{s_j}}\right)\right]$$

β = lumped calibration parameter
λ = length along flow path
s =slope along flow path

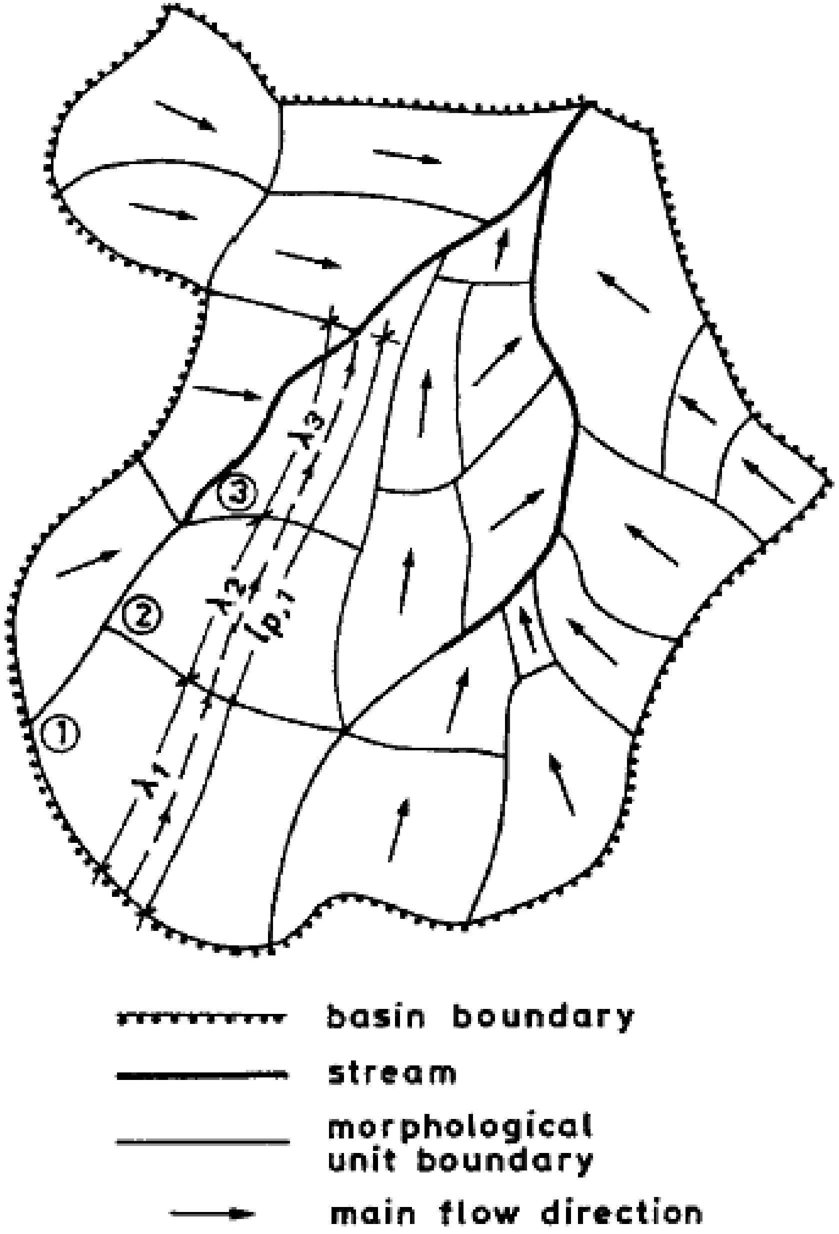
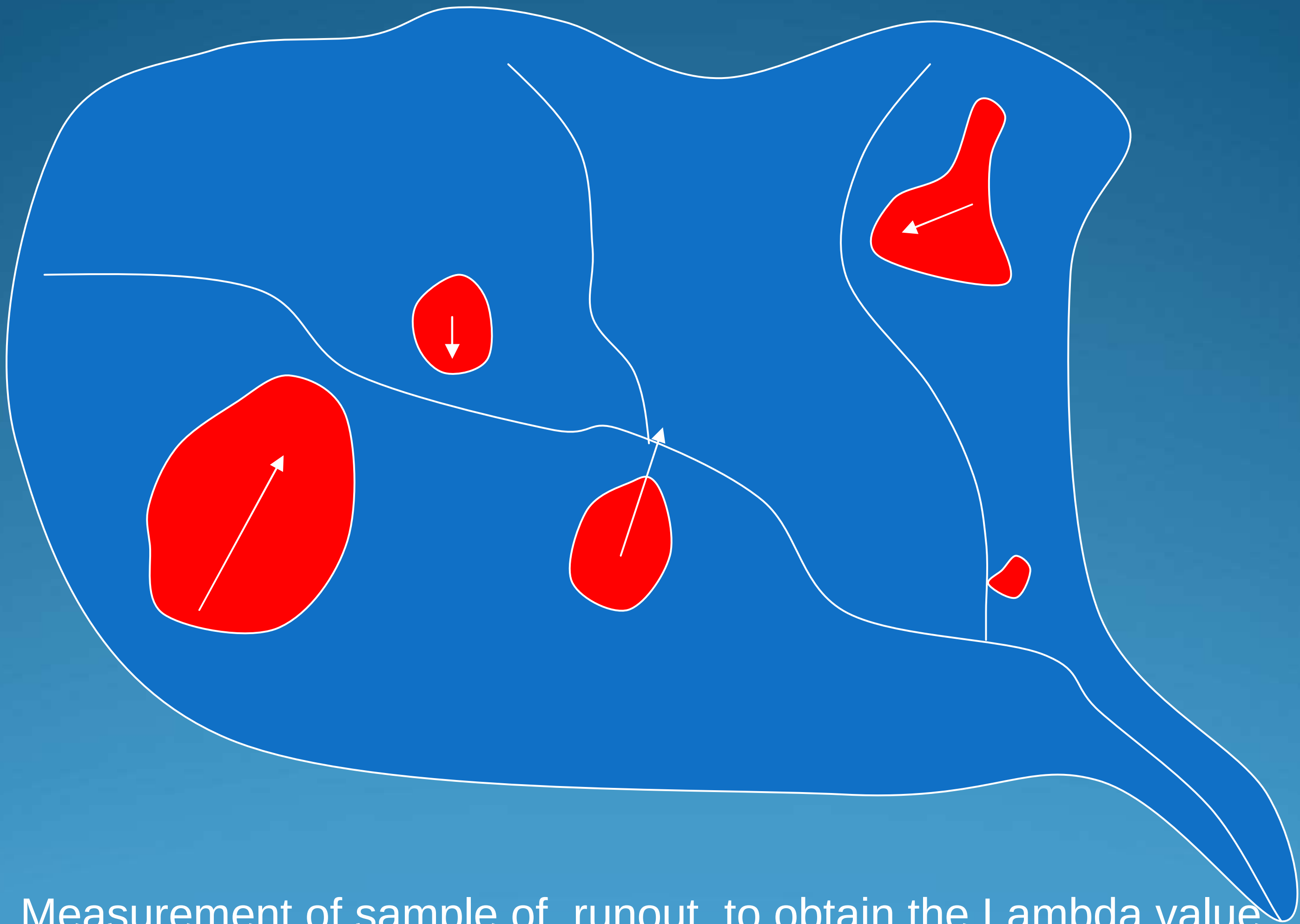


FIG. 1. Scheme of Basin Discretized into Morphological U

In this case SDR it is computed and applied at each morphological units to obtain the single sediment yield contibution



Measurement of sample of runout to obtain the Lambda value

Specific Sediment yield due to landslide only

Two examples of computation

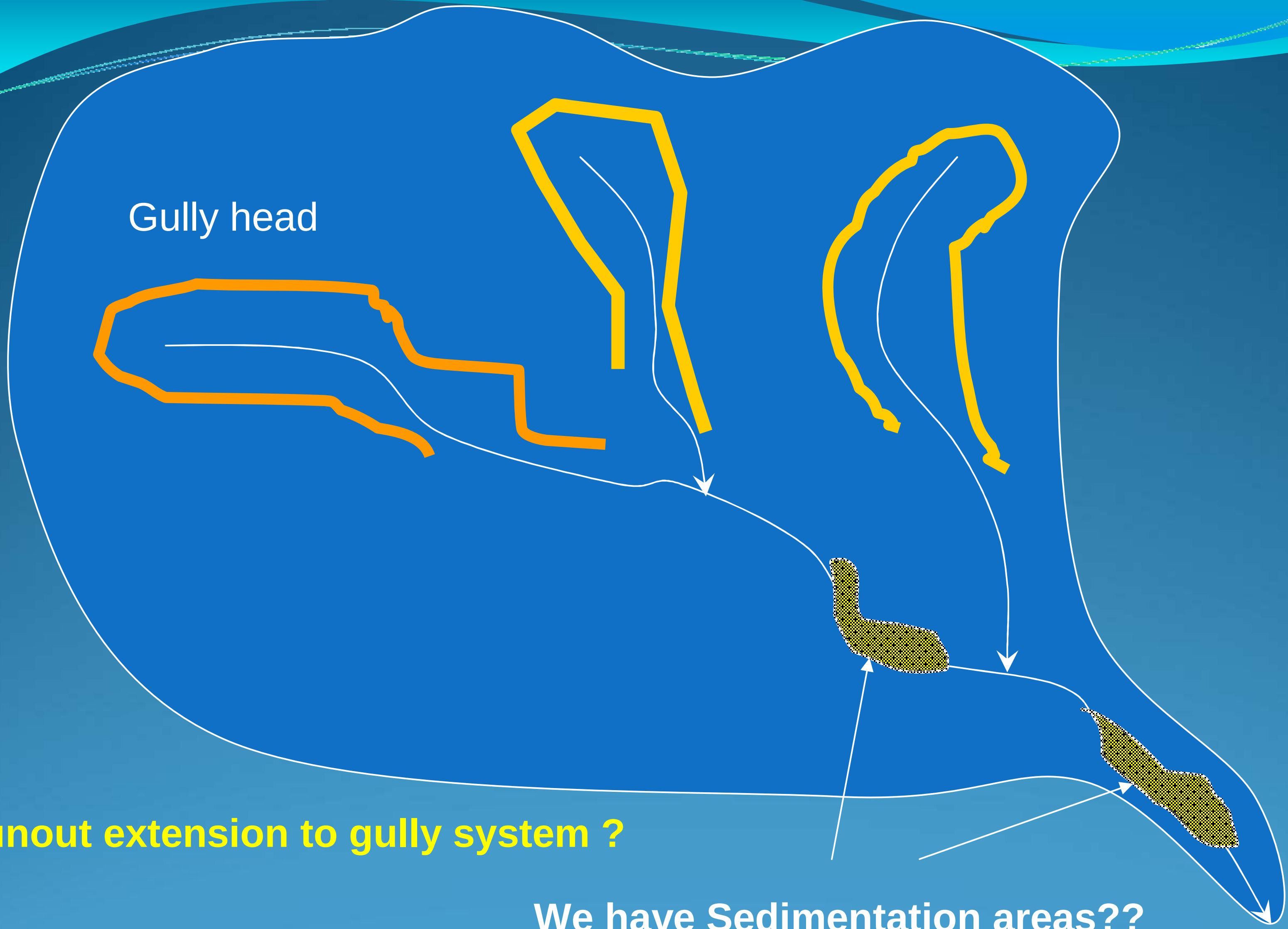
area (km^2)	λ	D(m)	SDRL	γ(Mg/m^3)	ΔT (years)
0.5	0.7	0.1	0.8000	1.5	1
0.5	0.04	1	0.0100	1.5	1

volume(m^3)	A equiv (Mg/ha/yr)	SSY (Mg/km^2/yr)
28000.00	840.00	84000.0
200.00	6.00	600.0

- Fraction of surface affected by landslide (λ)
- Aveage depth of landslide (D)
- Average Sediment delivery ratio from landslide bodies (SDRL)
- Density of soil mass (γ)
- Annual frequency (ΔT): 1 .. each year; 2 … each 2 years; 0.5 two time each year
- Net erosion volume
- Specific sediment yield

The first row represents the situation of Sestino site 840 Mg/km2/yr

The second row represent an area affected of relevant fraction of shallow landslides less connected to drainage system 6 Mg/km2/yr



Runout extension to gully system ?

We have Sedimentation areas??

Integration processes for multi source.. ?

Conclusions

The Connectivity index and FCA **provides an estimate of the potential connection index between the sediment eroded from hillslopes and the stream system**;

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 end obtain a Sediment yield assessment

The use of SDRmax can correct the inconsistencies indicated by somemeone (Kinnell 2004, Parson et a. 2006)

Conclusions-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 effects of eco-compatible mitigation measures to reduce or increase connectivity** . (without more complex Soil erosion models) (e.g. indications of Boardman 2006)

Potential application of IC to define **SDRL** can help to assessment of Sediment yield contribution due to Landslides (*work in progress..) and gullies may be..*

Many
Thanks for your
attention …