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

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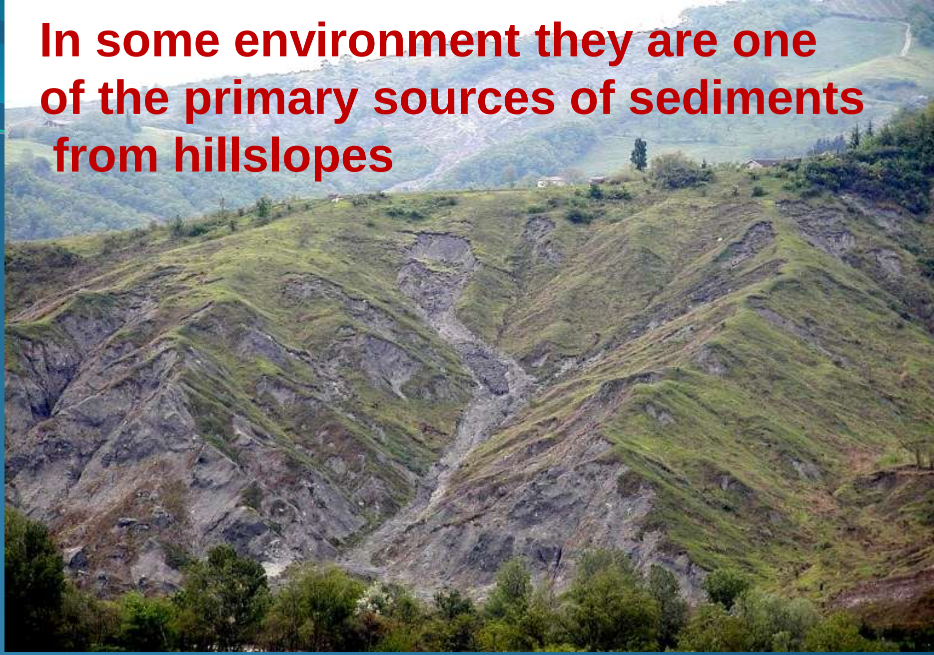
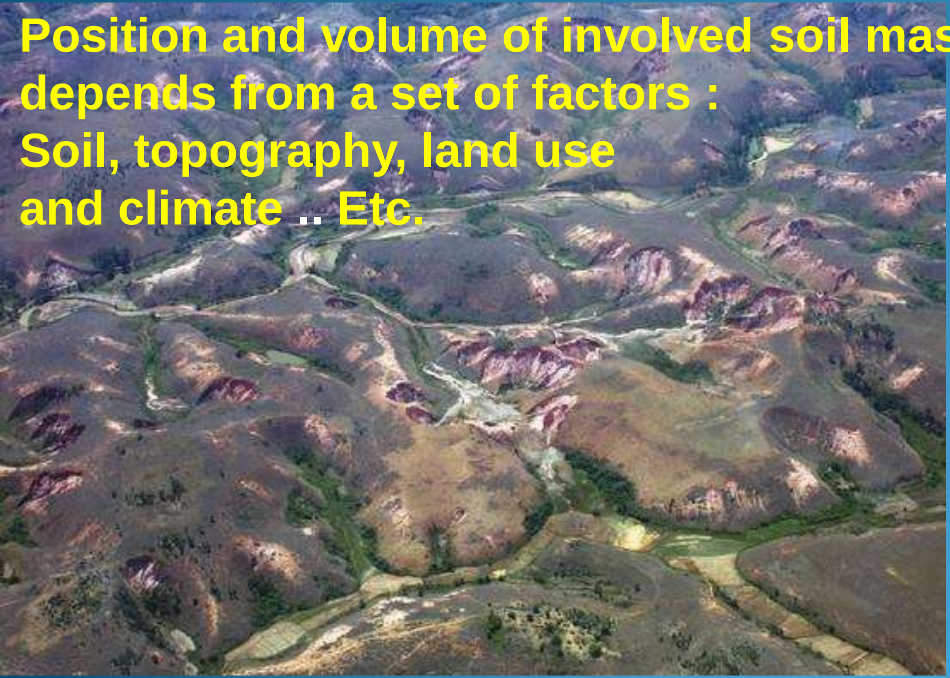
Shallow landslides contribute
Directly to soil loss and ..


In some environment they are one
of the primary sources of sediments
from hillslopes

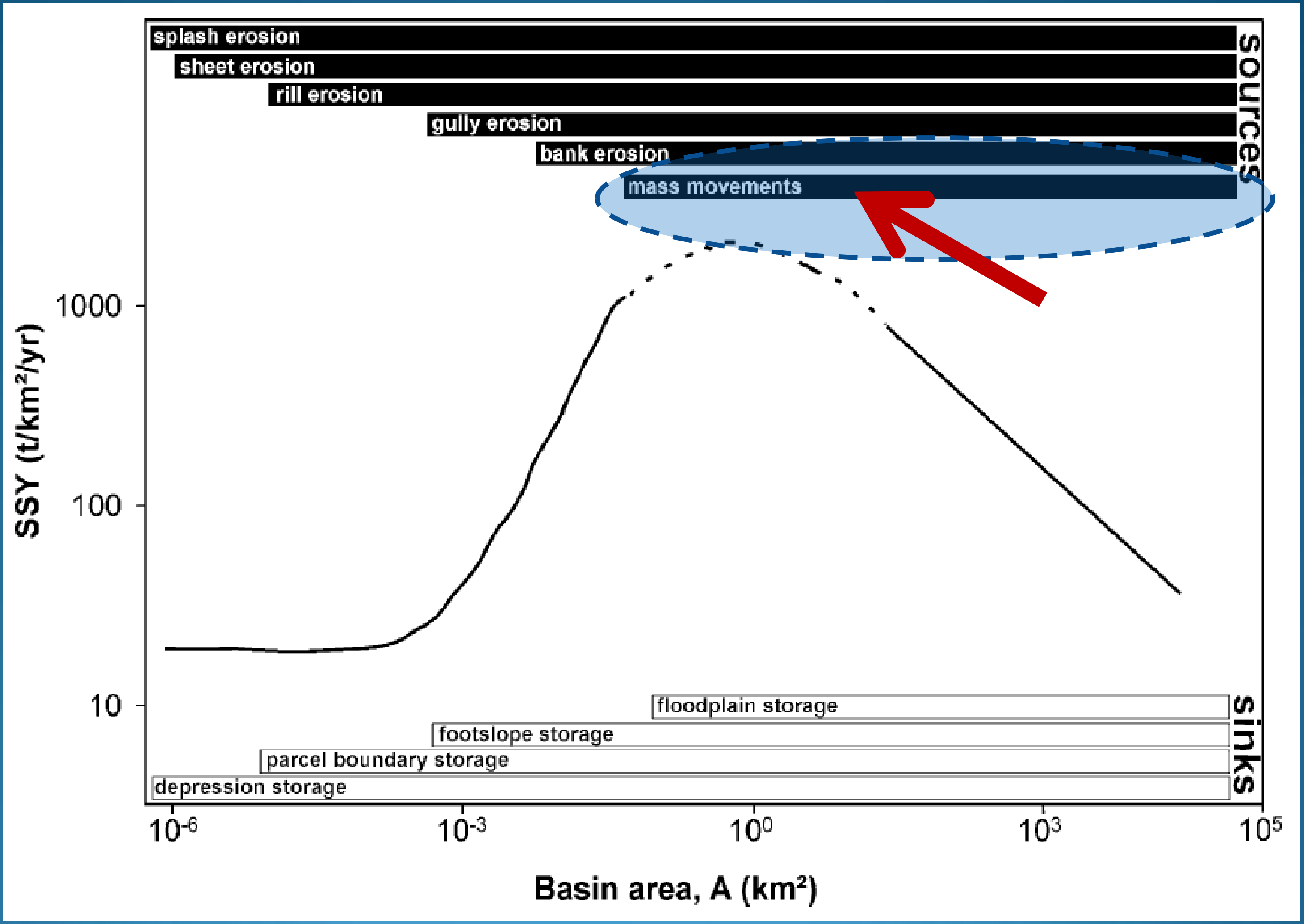

Position and volume of involved soil mass
depends from a set of factors :
Soil, topography, land use
and climate .. Etc.


But how , and how much these volumes
are transformed in sediment yield to
local sink (rivers, roads, Urban area..)
depends from landslide mobility and
flow connectivity

…Influence of Connectivity on sediment yield

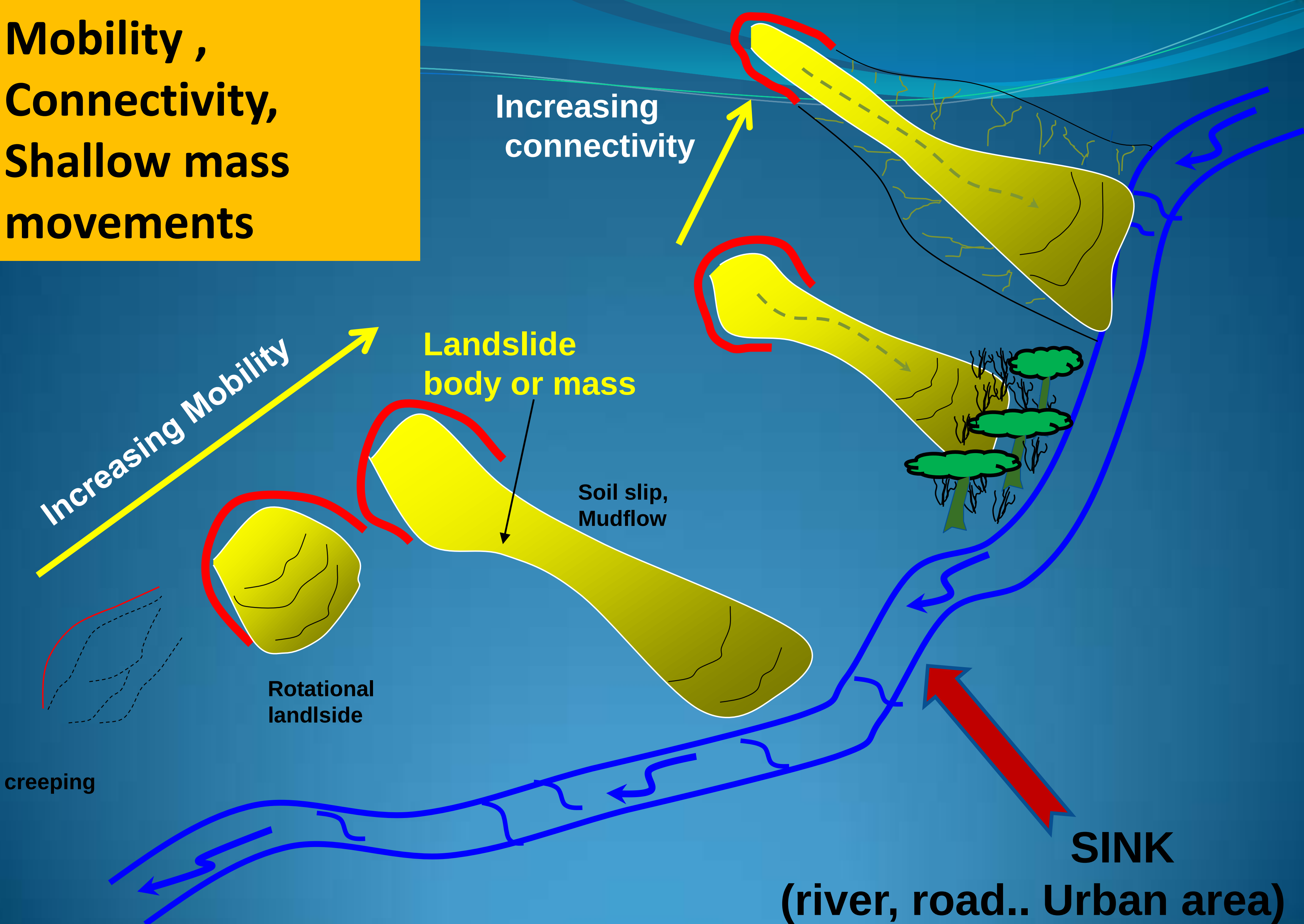
SOURCES

SINKS



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

Mobility, Connectivity, Shallow mass movements



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The PESERA-L model

shallow landslides (*mudflow, flow slides, Slumps*) can contribute significantly to sediments yield in a watershed (Maquarie and Malet, 2006)

PESERA-L has ben developed as an additional component to PESERA model :

- Assessment of fraction of unstable area inside a land unit (LU)
- Assessment of sediment delivery mass from landslide area to the nearest relevant sink (permanent drainage network , river, road ….).

The concept of CONNECTIVITY has several 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).

SOURCE → **SINK**

MASS, ENERGY TRANSFER...

WATER , SEDIMENTS

PESERA-L model uses the FCA approach for the assessment of sediment yield (SY) direct contribution from shallow Landslides

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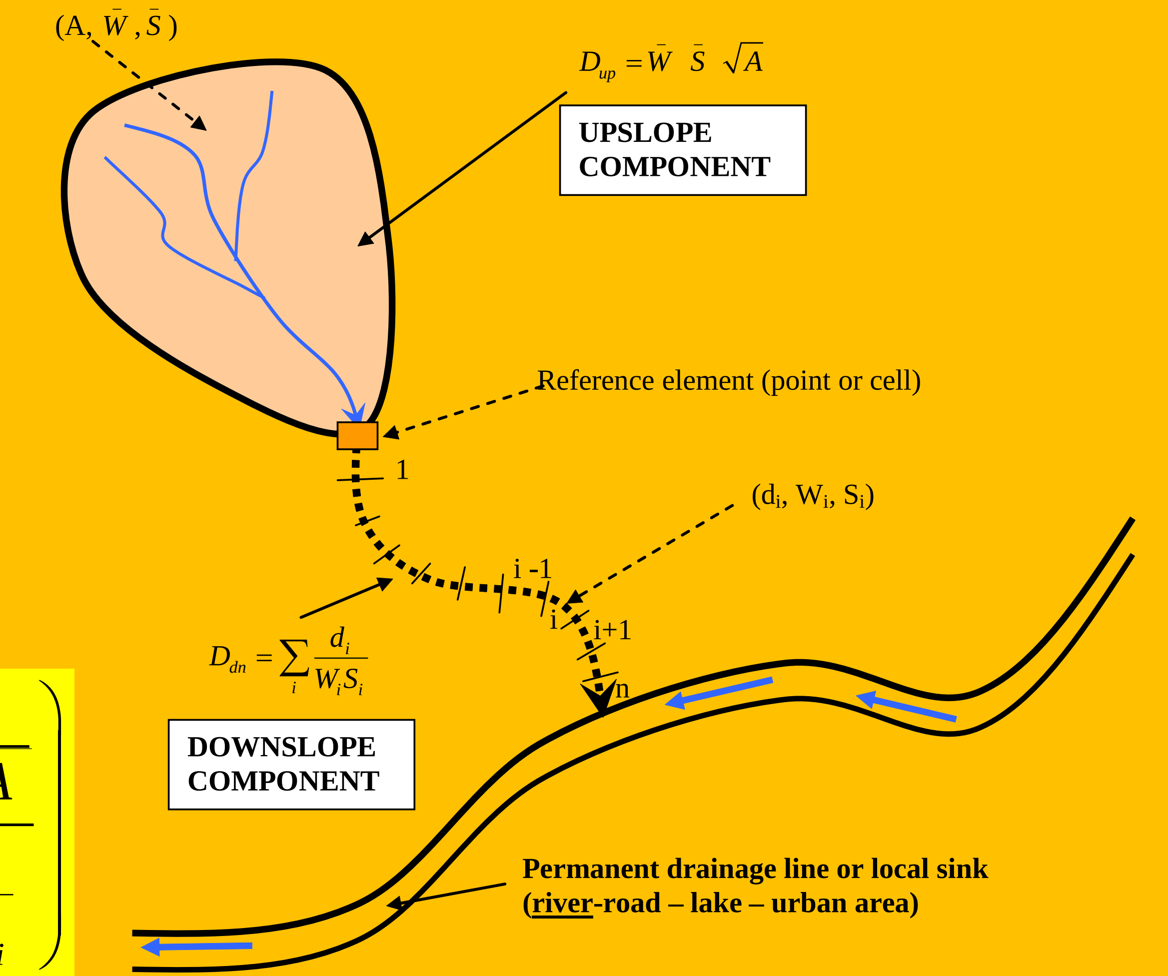
Connectivity index model – IC

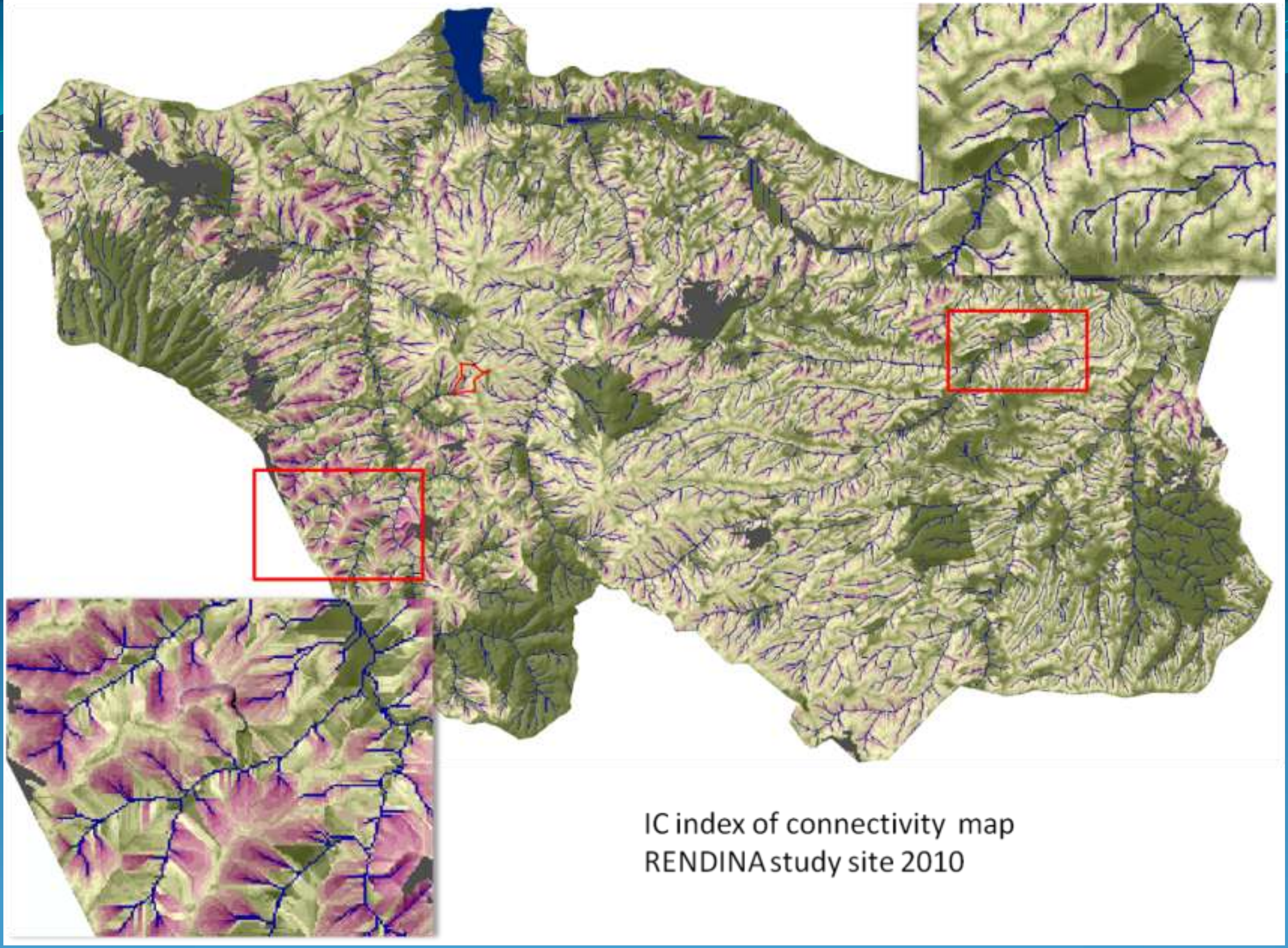
Borselli et al. (2008). Prolegomena to Sediment and flows connectivity in the landscape: a GIS and field numerical assessment . CATENA (elsevier)

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.



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


IC index of connectivity map
RENDINA study site 2010

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

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)**

For shallow mass movements it is important mainly the DOWNSLOPE component

First requirement…for SSY from landslides

Probable LANDSLIDE DISTRIBUTION, DEPTH AND VOLUMES….

Possible approach.

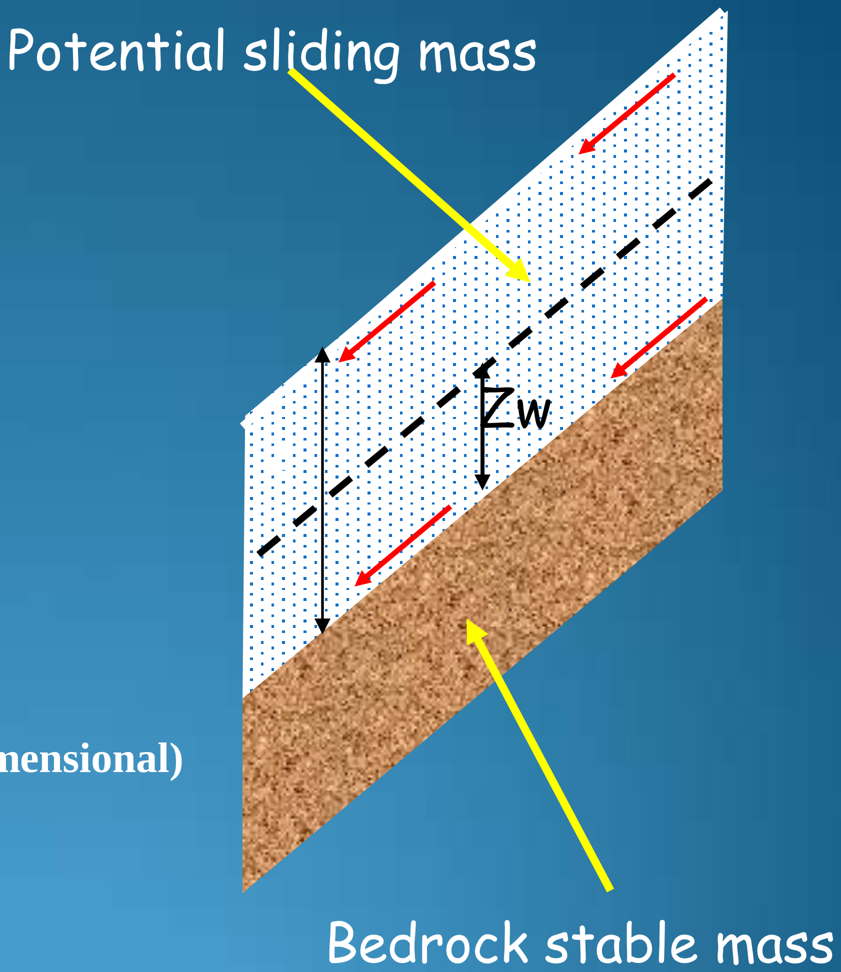
Application a distributed slope stability model Es. **Sinmap, Shalstab (GIS)** or an alternative stochastic model (*montecarlo method)* applied various land unit and thus toan entire watershed

So We are using:

Montecarlo method (stochastic component) with a series of variant adapting it to particular PESERA model stochastic approach.

Limit equilibrium - Infinite slope model required to define (stabel unstable condition

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



where:

- **β= slope gradient (degrees)**
- **ϕ'= internal friction angle(degrees)**
- **c'= soil choesion+ roots strength (kPa)**
- **γ= soil unit weigth (kN/m³)**
- **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 (suitable for distributed
- 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 spreadsheets and programs and GIS
- Easy and fast computation
- Easy to transform in stochastic sense with no loss of his physical significance

Stochastic approach allow to overcome some Disadvantages of deterministic form:

- 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 (Capra and Borselli 2003)

Local variability of soil properties
Local variability of slopes
Saturated depth

e.g. Random variables
uniformly distibuted
Between lower and upper bounds:
$10° < \phi' < 14°$
$2 < C' < 5$

To assign to each Land unit

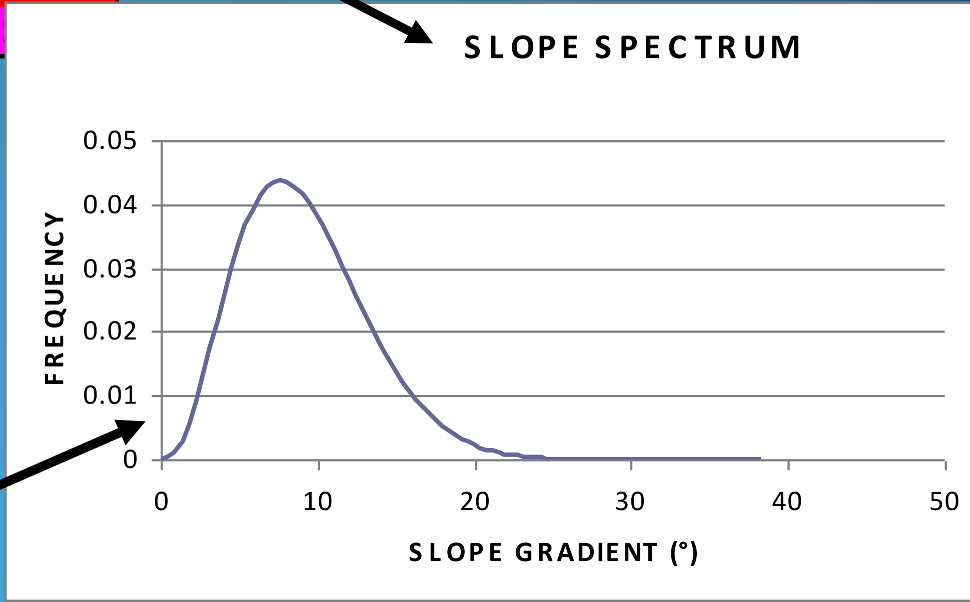
Slope spectrum parameters

alpha	2.64	0	grad min
beta	10.43	0.79	grad max

Soil and hdrologic parameters

	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	

The safety factor Fs may be Considered as a random variable It accounts for local Variability of the input Parameters...



The slope gradient instead Modelised by beta distribution

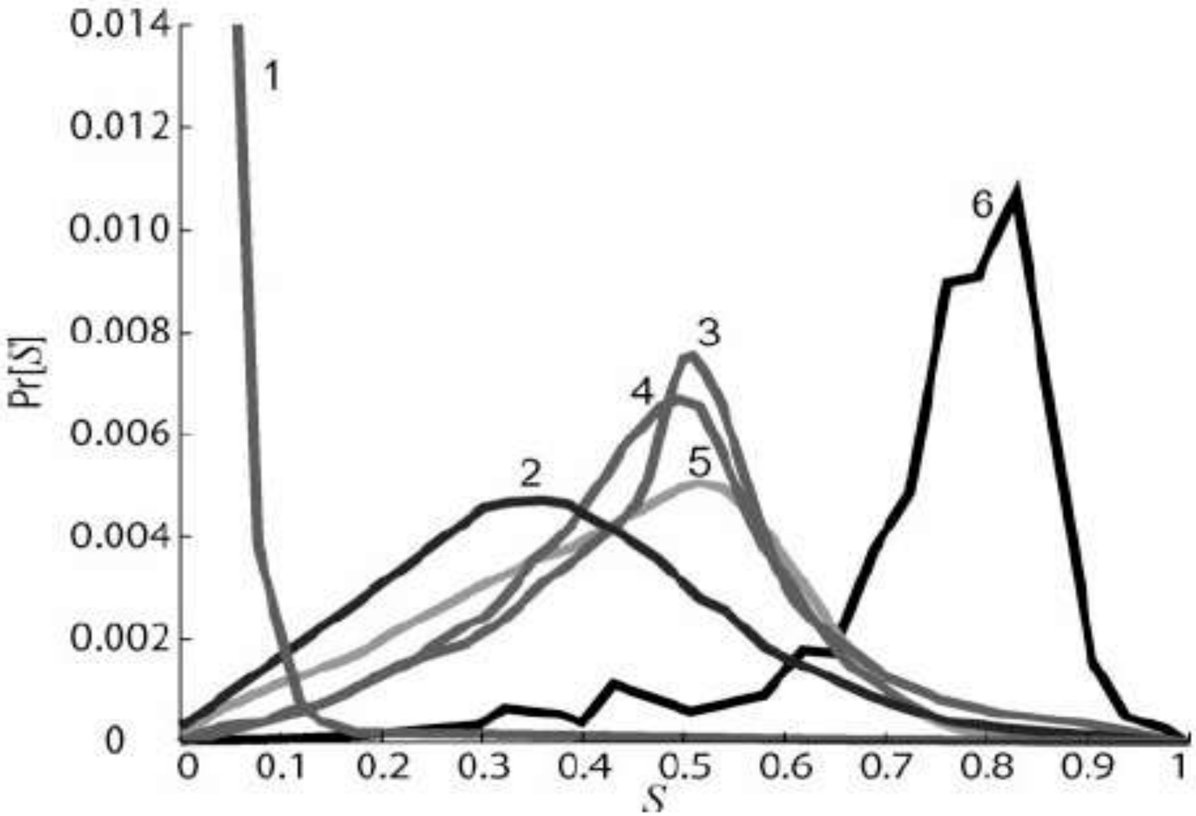
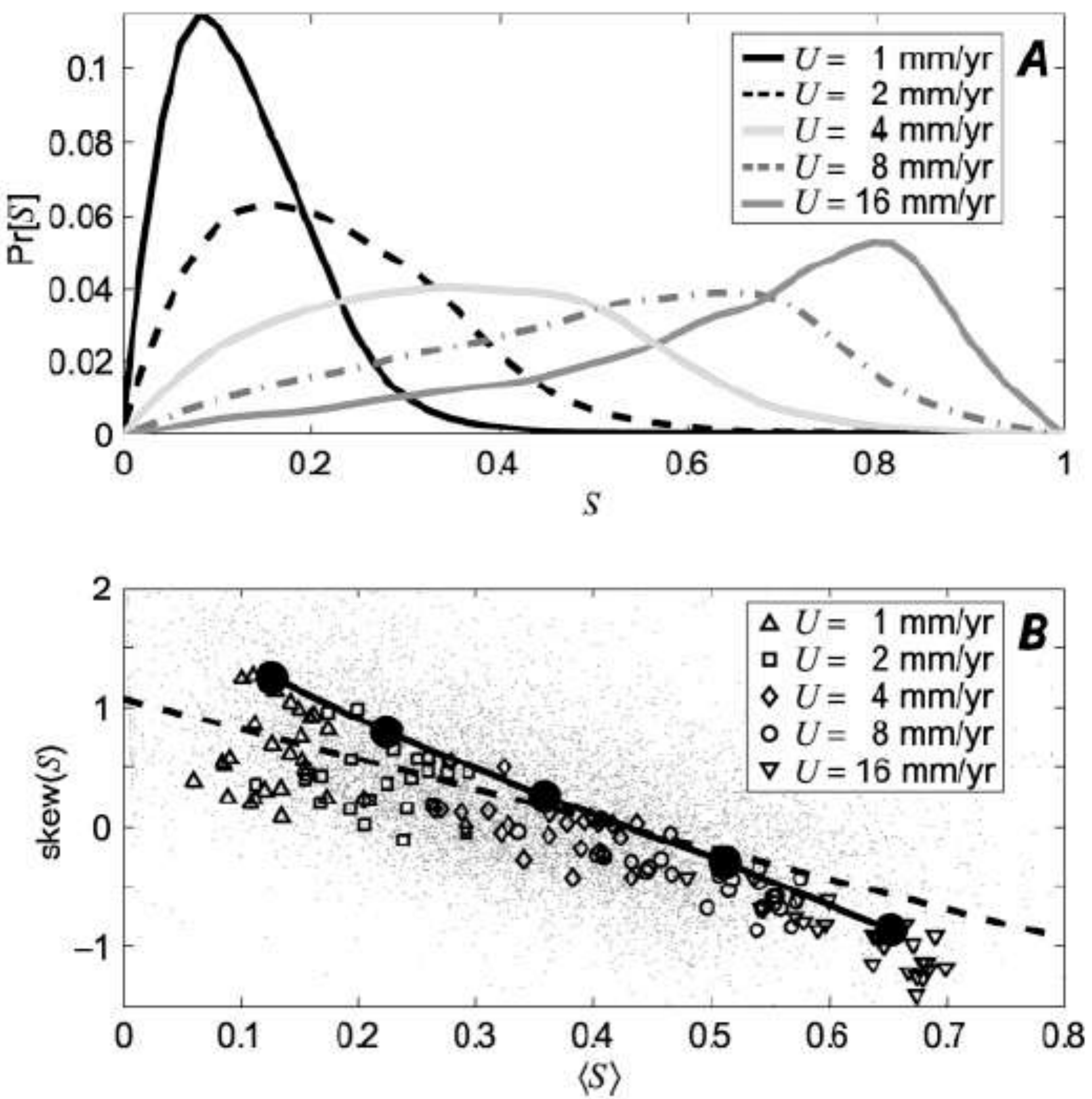


Figure 1. Slope frequency distributions (fraction Pr[*S*] of landscape at given slope *S*) from previous studies (each normalized by its maximum slope). 1—Himalayan foreland basin (Burbank, 1992); 2—Himalayan fold-and-thrust belt (Burbank, 1992); 3—model (Densmore et al., 1998); 4—Higashikubiki—intrusive rock (Iwahashi et al., 2001); 5—Higashikubiki—volcanic rock (Iwahashi et al., 2001); 6—Oregon Coast Range—convex and planar hillslopes (Roering et al., 1999).

the frequency distribution of slope gradient (slope spectrum) Is fundamental to describe the topographic factor for landslide susceptibility

Slope spectrum examples in the world Wolinsky et al. 2005



Example of slope spectrum (Oregon-USA) and Relationship with relief 's denudation rate (Wolinsky et al. 2005)

Average slope gradient and skewness of slope Frequency distribution

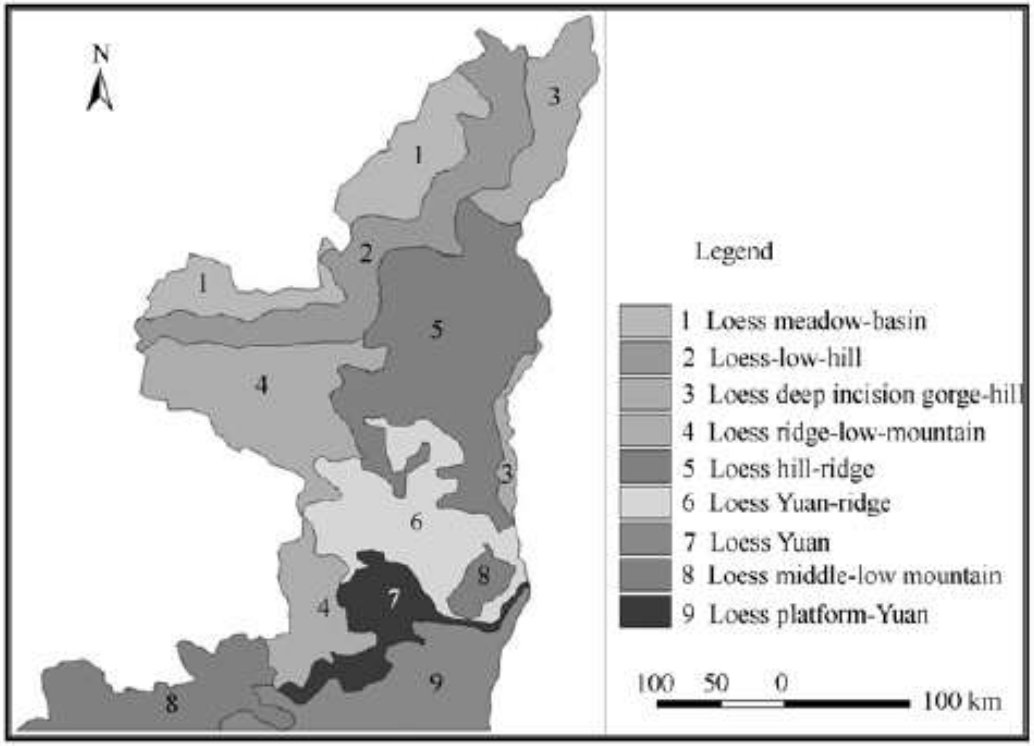
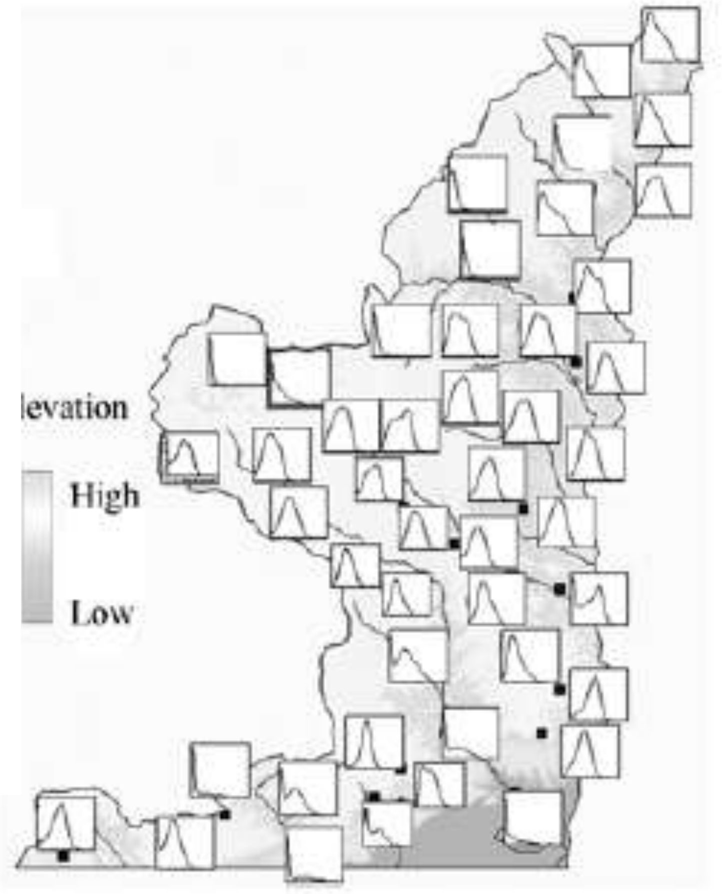
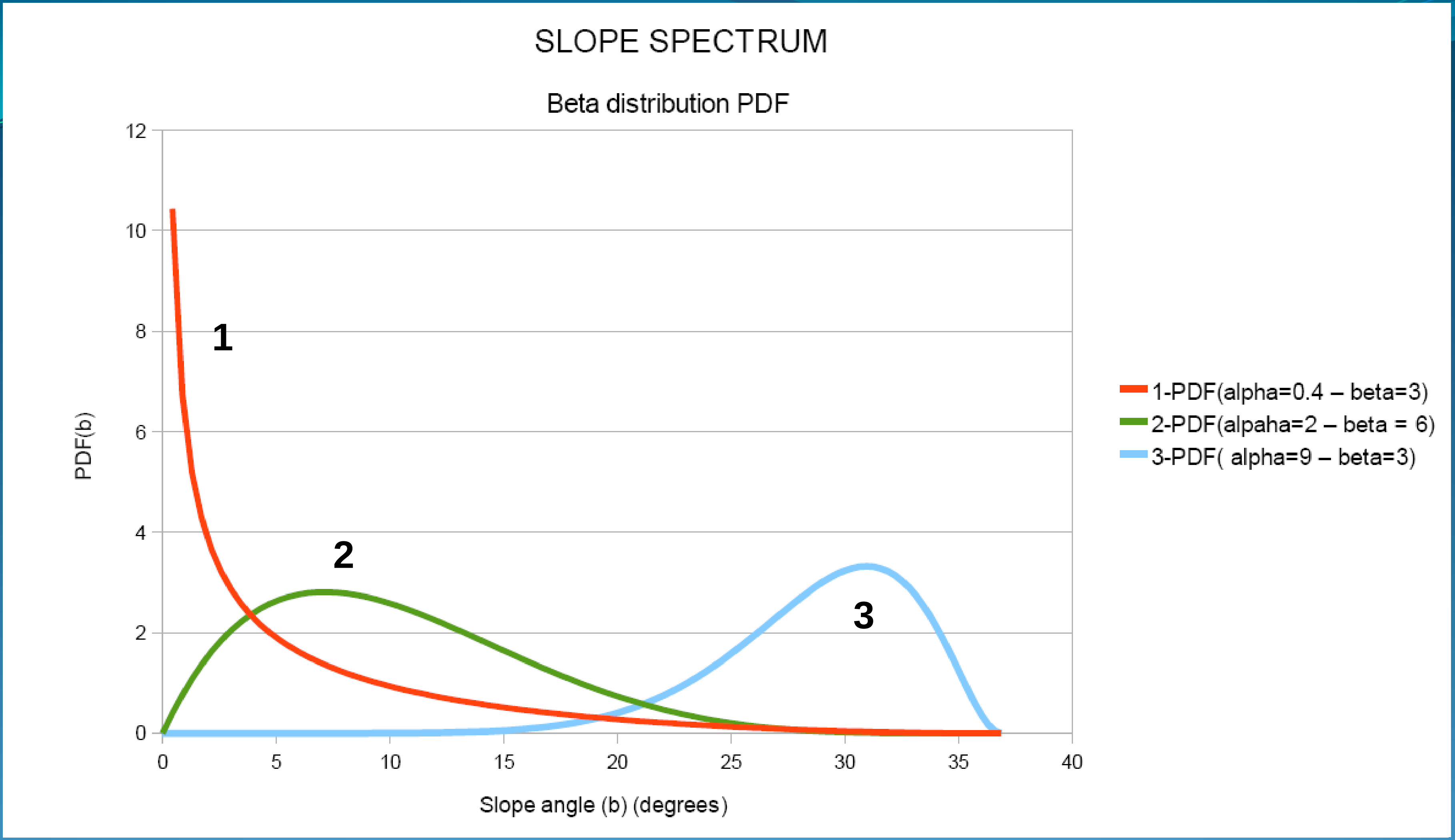


Figure 6 Slope spectrum based landform classification in northern Shaanxi.



the spectrum extracted in northern Shaanxi.

Example of slope spectrum analysis in loess belt (China) (TANG GuoAn et al. 2008)



Example of modelised slope spectrums with Beta distribution

1-exponential type (positive skewenss) (flat areas)

2 – right tailed (positive skewness) – (rolling topography- water erosion)

3 – left tailed (negative skewness) – (landslide areas – badlands)

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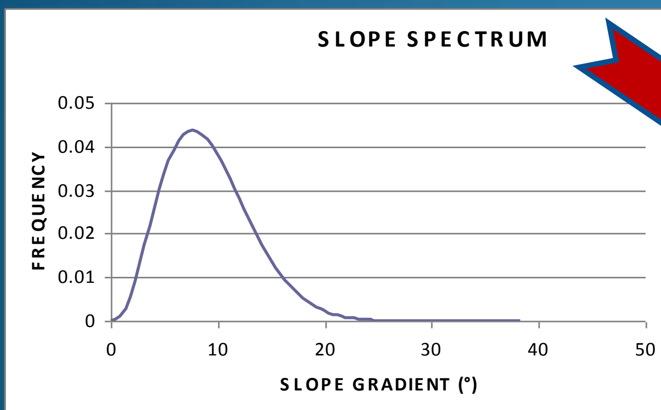
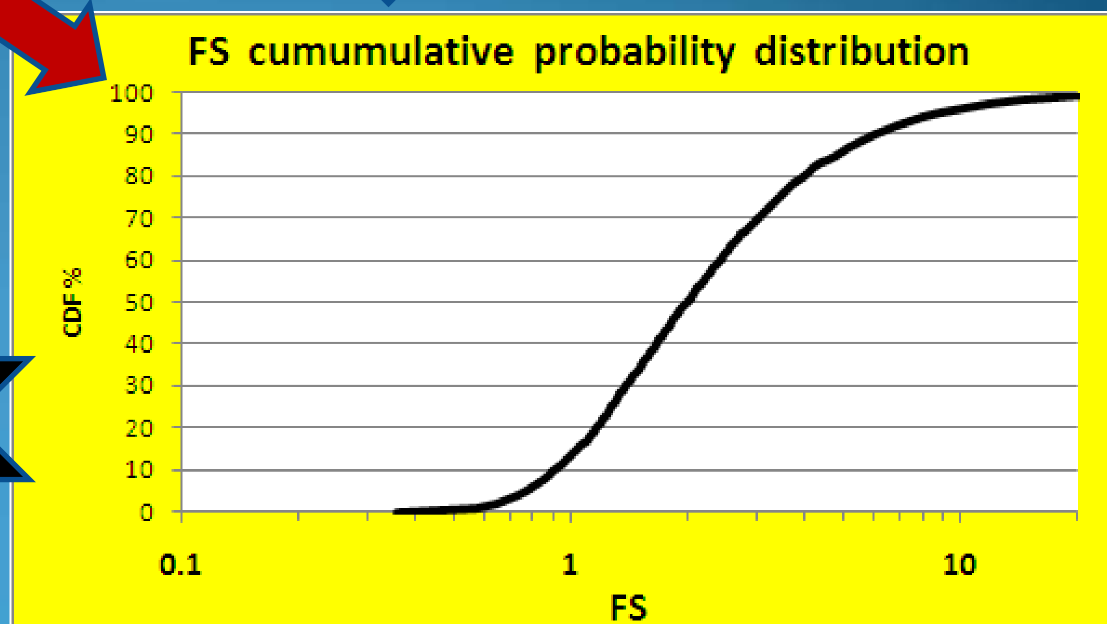
Limit equilibrium method, Infinite slope model, and Monte Carlo Method - OUTPUT

Local variability of soil properties
Local variability of slopes
Groundwater depth

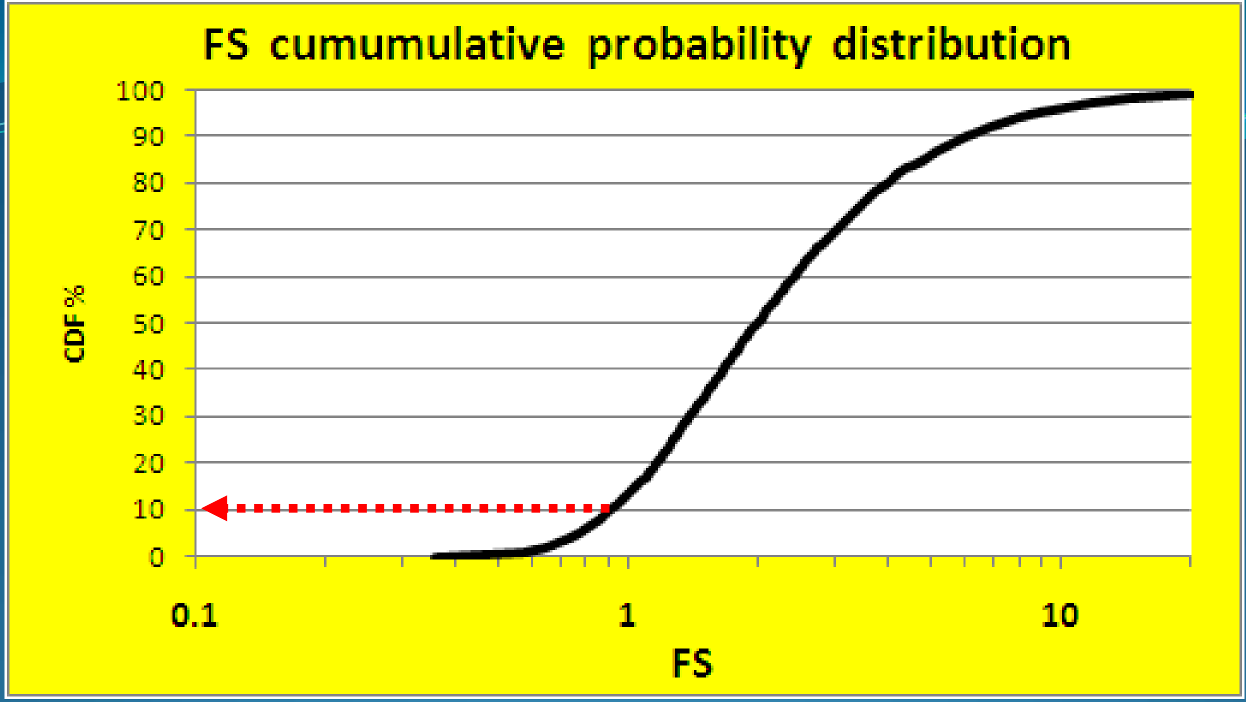
alpha	2.64	0	grad min
beta	10.43	0.79	grad max

	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





for each land unit



e.g. 9% of a specific land unit has FS<1.0 (unstable when condition of soil profile is fully saturated)
Using the slope spectrum of Land Unit (LU) the % where Fs is <1.0 represents the potential fraction (Ψ) of total area in the LU affected by landSlides

Index of sensitivity to desertification (SDI), 2008

- < 1.2 Non affected areas or very low sensitive areas to desertification
- 1.2 - 1.3 Low sensitive areas to desertification
- 1.3 - 1.4 Medium sensitive areas to desertification
- 1.4 - 1.6 Sensitive areas to desertification
- > 1.6 Very sensitive areas to desertification

European Environment Agency (EEA) (2009)

Sensitivity to Desertification

Based on
Medalus methodology
Kosmas et al. (1999)
And
Domingues & Fons – Esteve (2008)

Web ref:

http://www.eea.europa.eu/

Rendina basin(Basilicata, Italy)
Average rainfall 550 mm/yr

Desertification process and Desertification risk

Water erosion

landslides

Land levelling

Tillage erosion

Burning residue

Study site DESIRE EU project (2007-2012)

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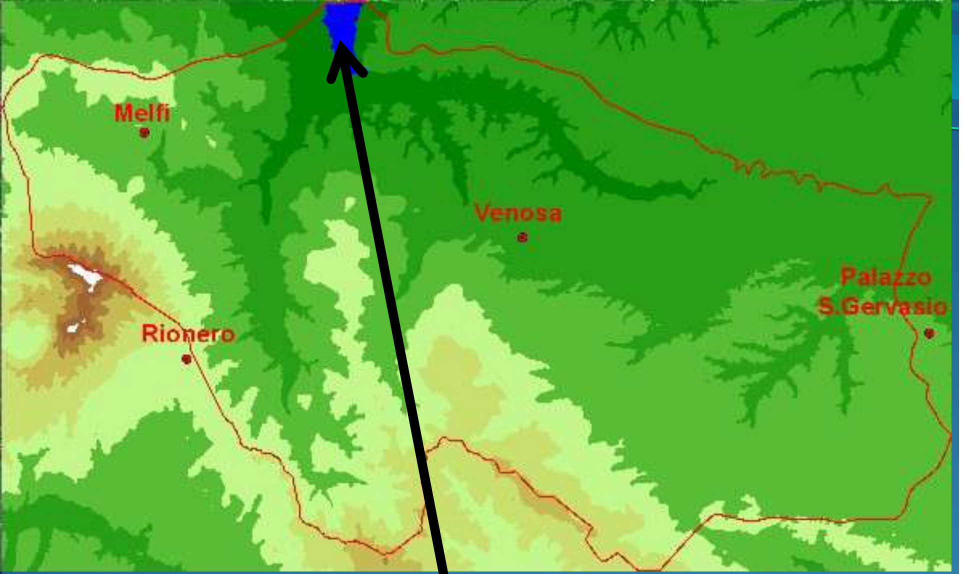
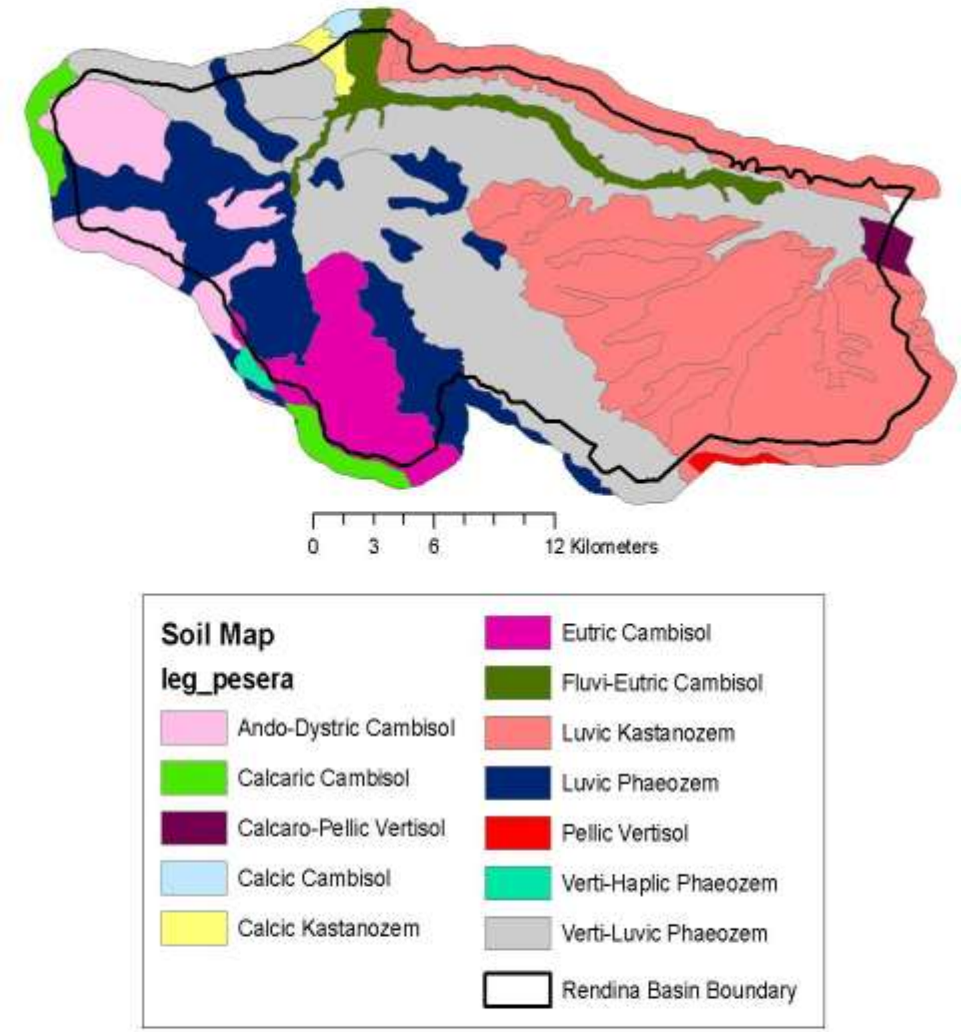
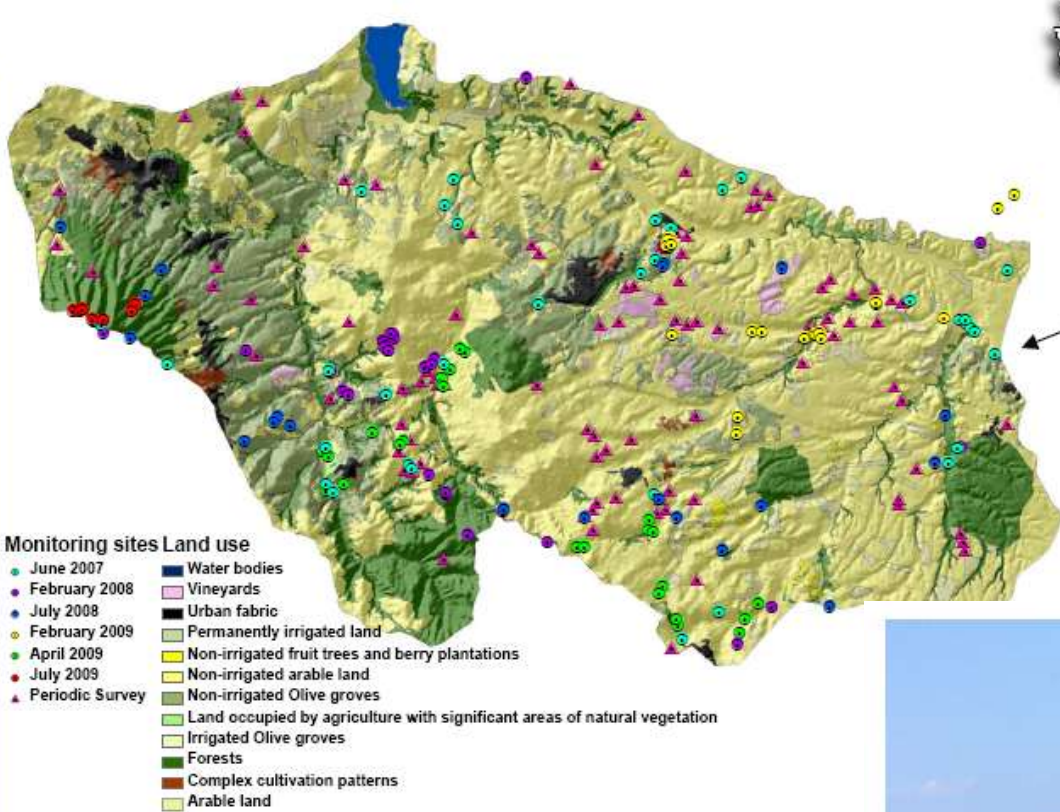


Recent burned area (dark upper part of the slope)close to the Rendina reservoir (sept. 2008)



Rendna Soil map and topography

Measured Specific sediment yield 12 Mg/ha/yr in REDINA dam reservoir (1957-1996) .
But … 1X10^6 m^3 only in 1959 !

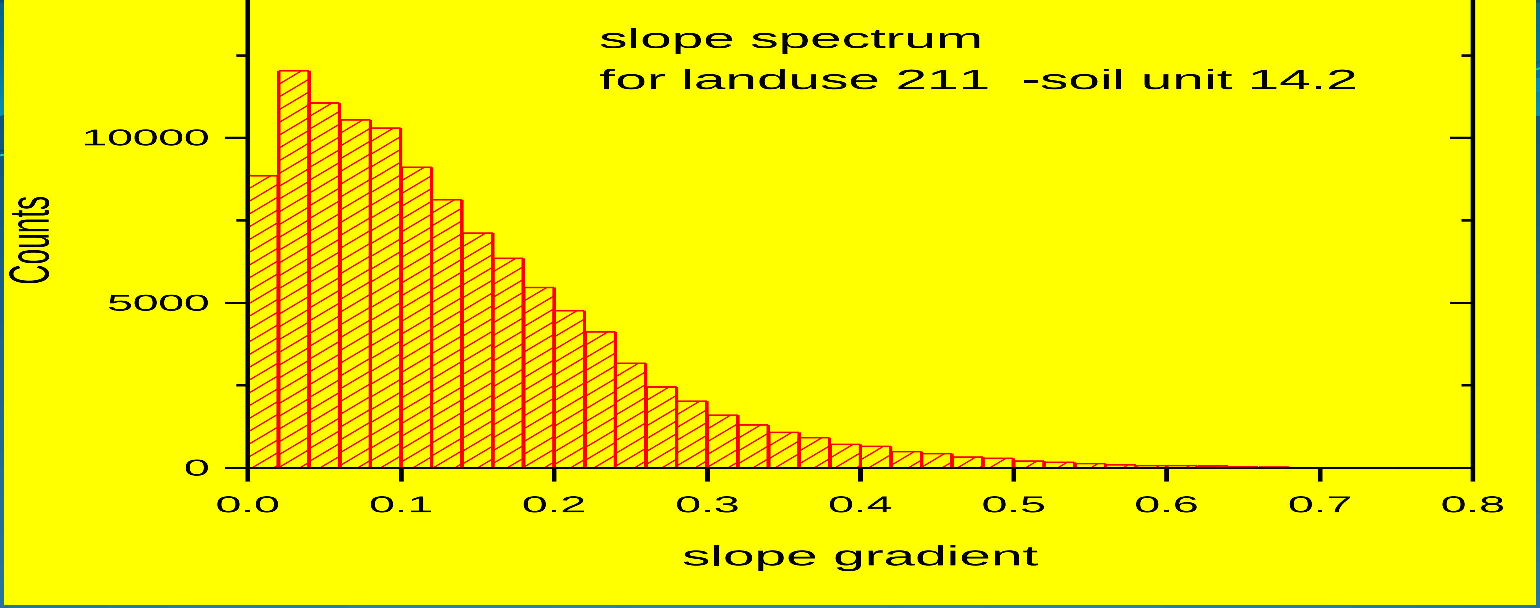


Rendina land use
And perioc monitoring sites

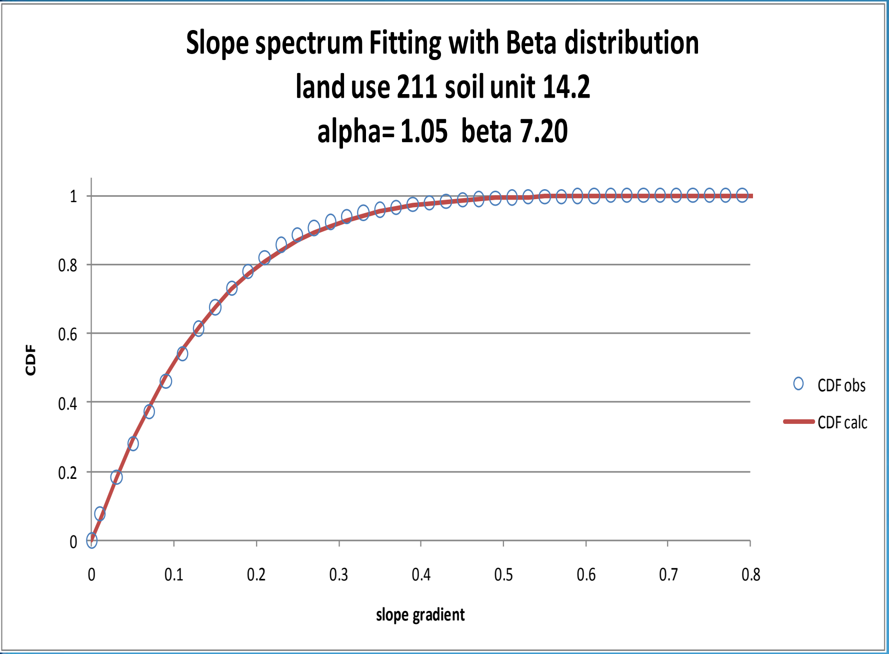
Dominanat ceral crops
durum wheat
in arable lands

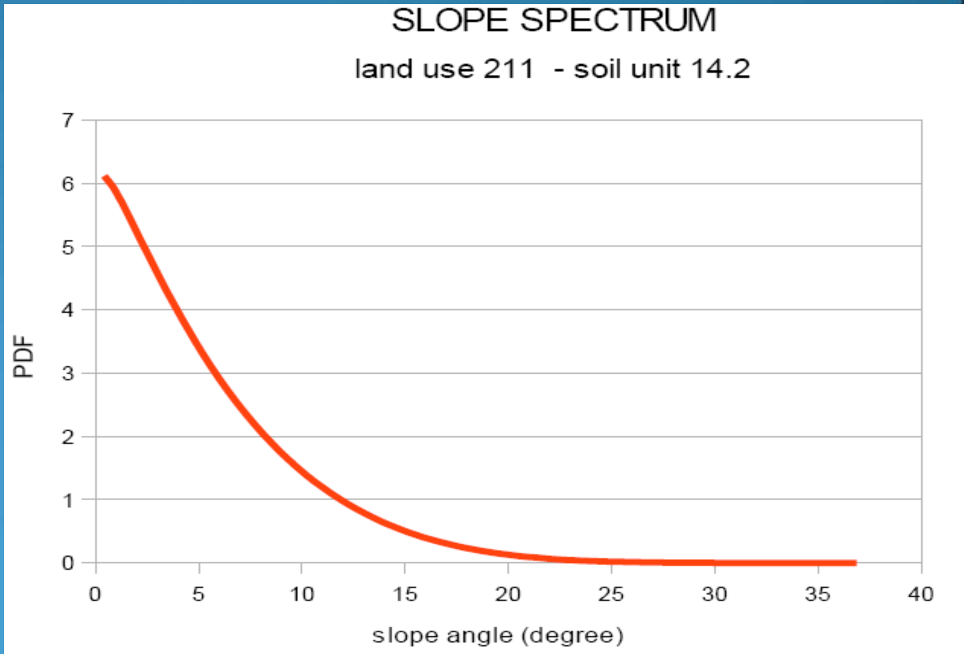
Rendina basin (Italy- Basilicata region): wheat fields and degraded pasture – (Sept. 2008)

Shallow landslides (soil slip and combined gully erosion) at Rendina site



Slope spectrum analysis for a specif land unit - Rendina site (ITALY)





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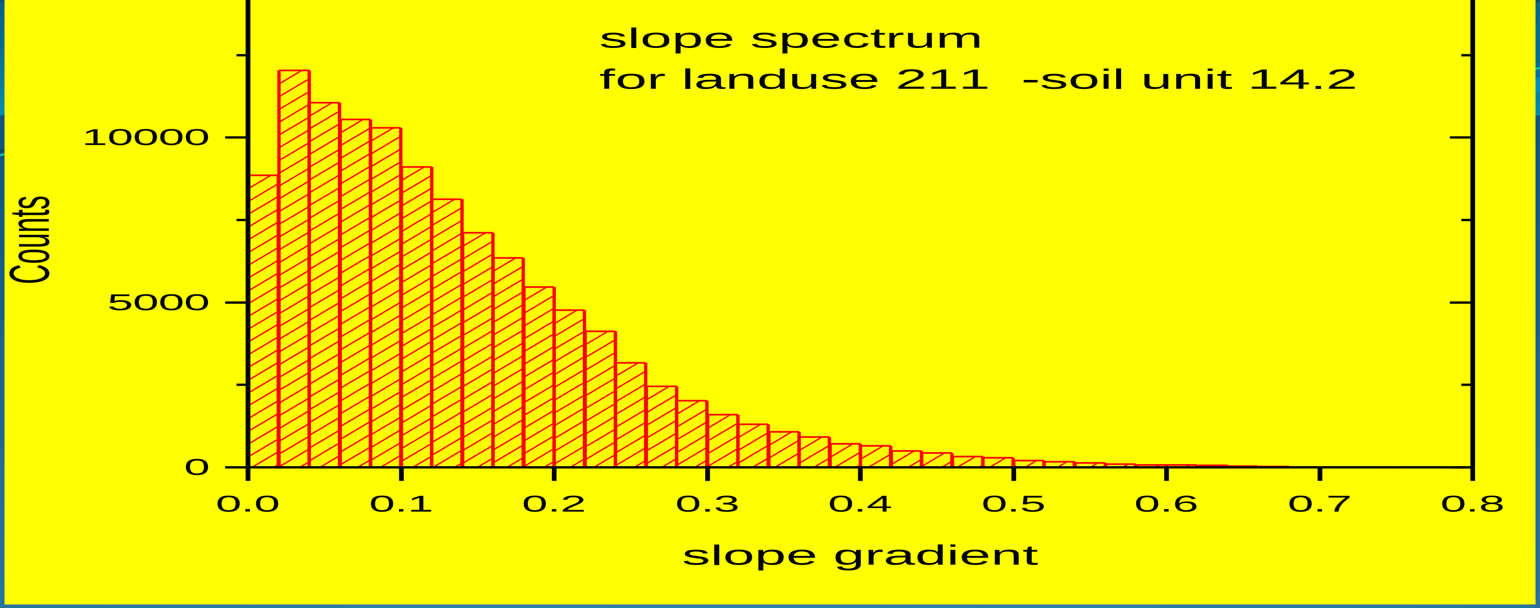
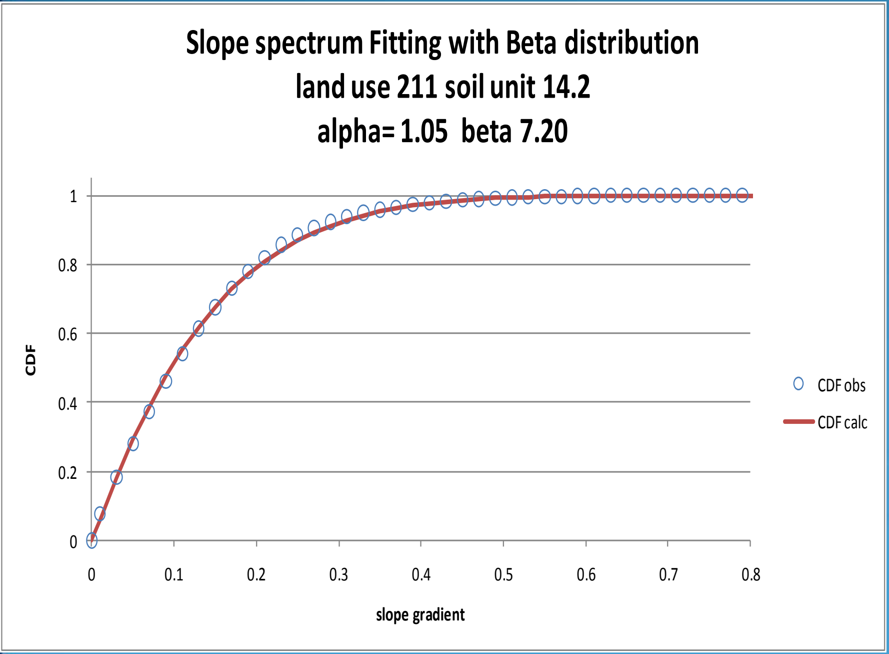
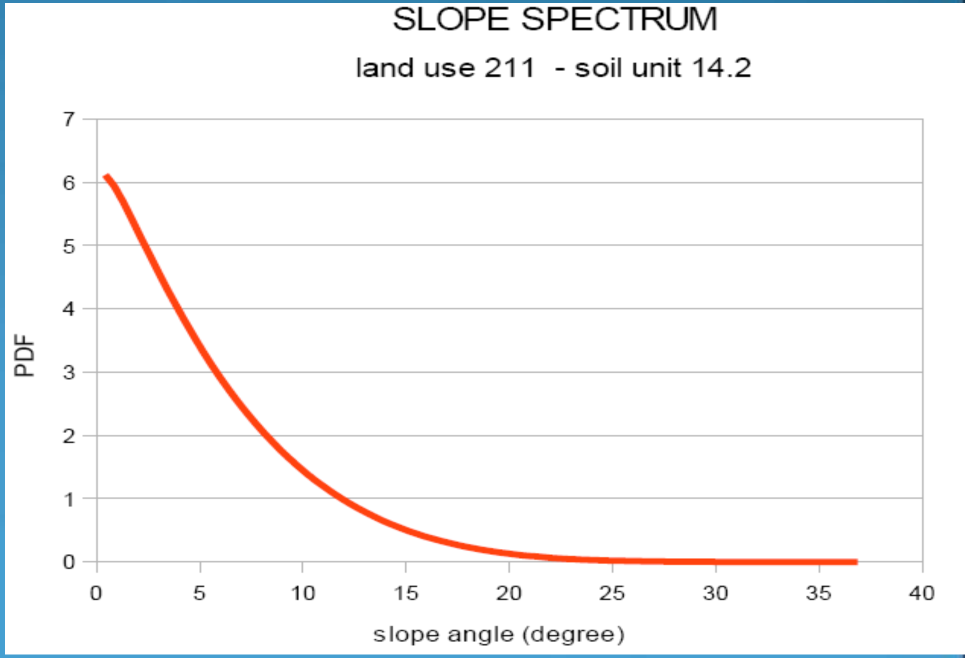
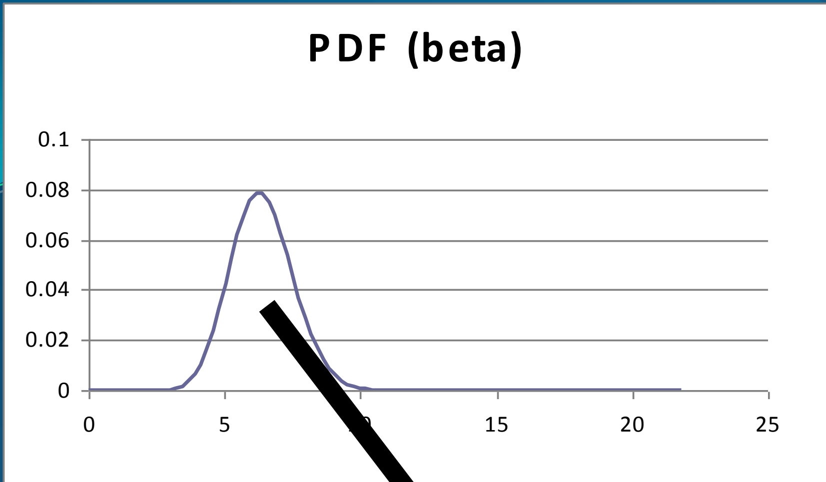
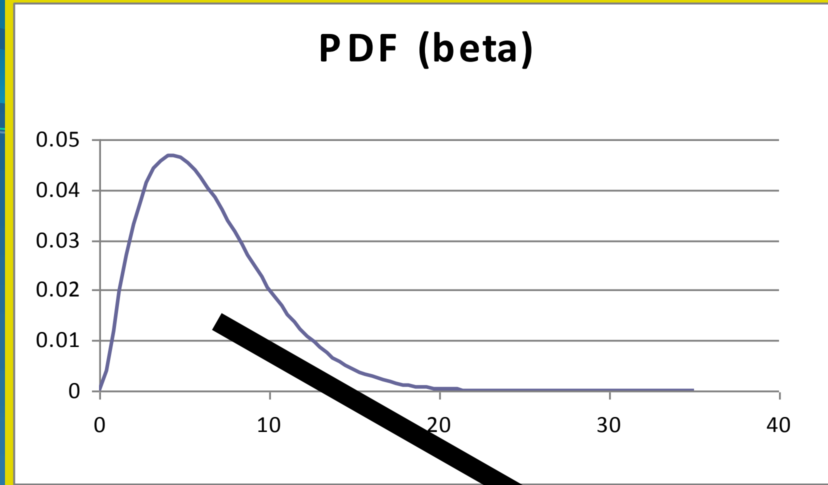


Slope spectrum analysis for a specif land unit - Rendina site (ITALY)





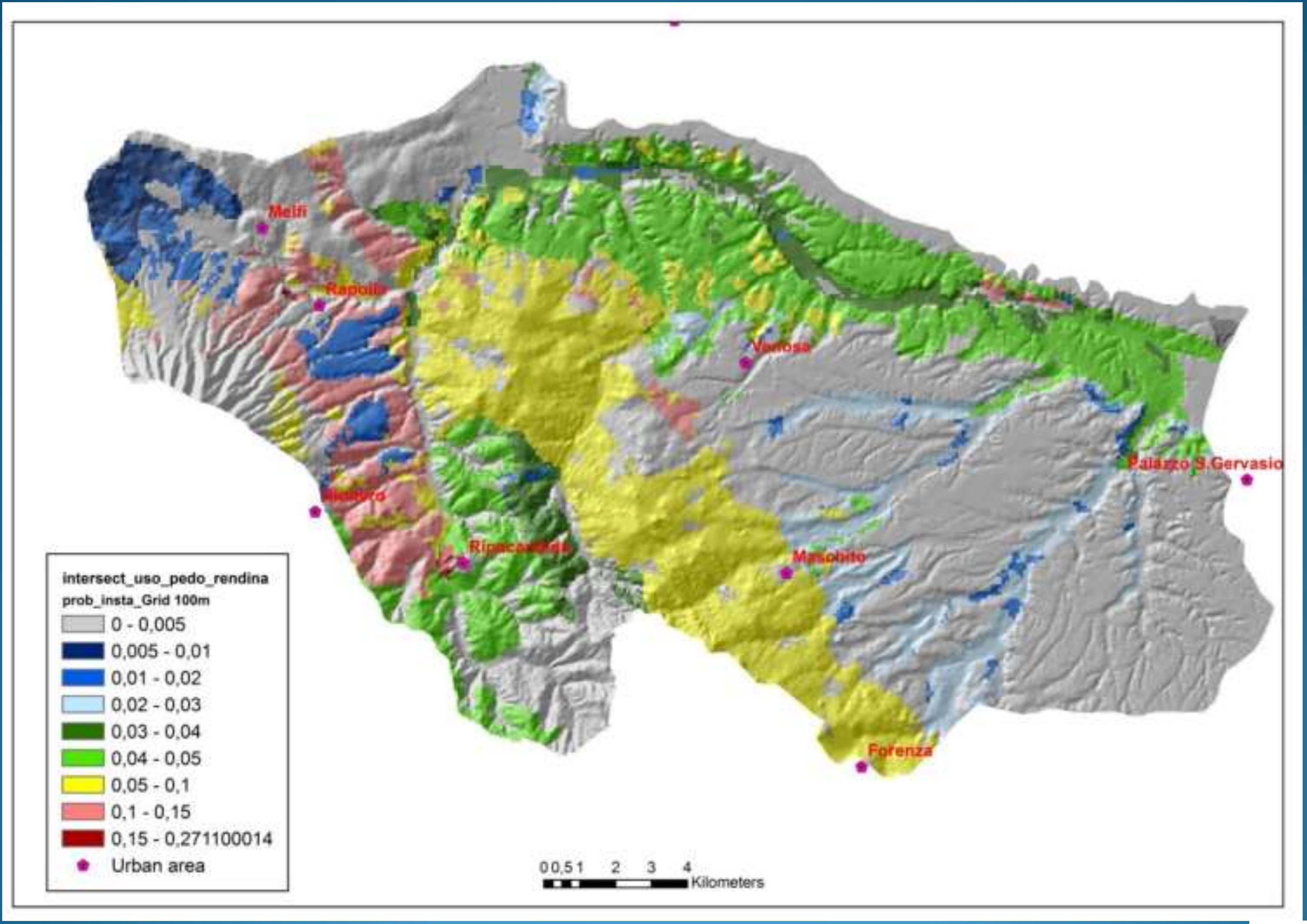




Soil	6_2	6_3	6_4	7_3	7_5	9_1	9_2	9_3
Max	0.403	0.808	0.752	0.791	0.279	0.401	0.984	0.692
Min	0.003	0	0	0	0.002	0.099	0	0
media	0.1912839	0.211361	0.2373963	0.1595235	0.087165	0.2399394	0.1596267	0.1157366
mediana	0.201	0.213	0.236	0.155	0.069	0.231	0.137	0.112
1 quart	0.1225	0.139	0.175	0.113	0.05	0.186	0.081	0.068
3 quart	0.239	0.279	0.296	0.199	0.124	0.309	0.202	0.155
Skewness	0.1161863	0.2513274	0.2845791	0.7367156	0.8548086	0.088239	1.8120818	1.0674365
Kurtosis	-0.3089752	0.3492475	0.5545535	1.8381401	-0.1572921	-0.7457649	4.8425078	4.1549007
Dev.st	0.0989641	0.0990916	0.098731	0.0734925	0.0513878	0.0774213	0.1168277	0.0658305
Num. Punti	155	14060	25319	159441	2369	33	30174	15319
mean (normalized)	0.47071	0.261585	0.315687	0.201673	0.307455	0.466687	0.162222	0.167249
variance (normalized)	0.061212	0.01504	0.017237	0.008632	0.034416	0.065721	0.014096	0.00905
alpha	1.445155	3.097929	3.640677	3.559678	1.594724	1.300678	1.401818	2.406715
beta	1.625007	8.744972	7.891891	14.09105	3.59213	1.486369	7.239528	11.98326

Example of slope spectrums from different LU s (soil units + land use: *arable land -cereals*)

DESIRE project – Rendina Dam catchment (italy) – PERSERA-L 100X 100 pixel – probability of soil slip (condition water saturated soil profile)



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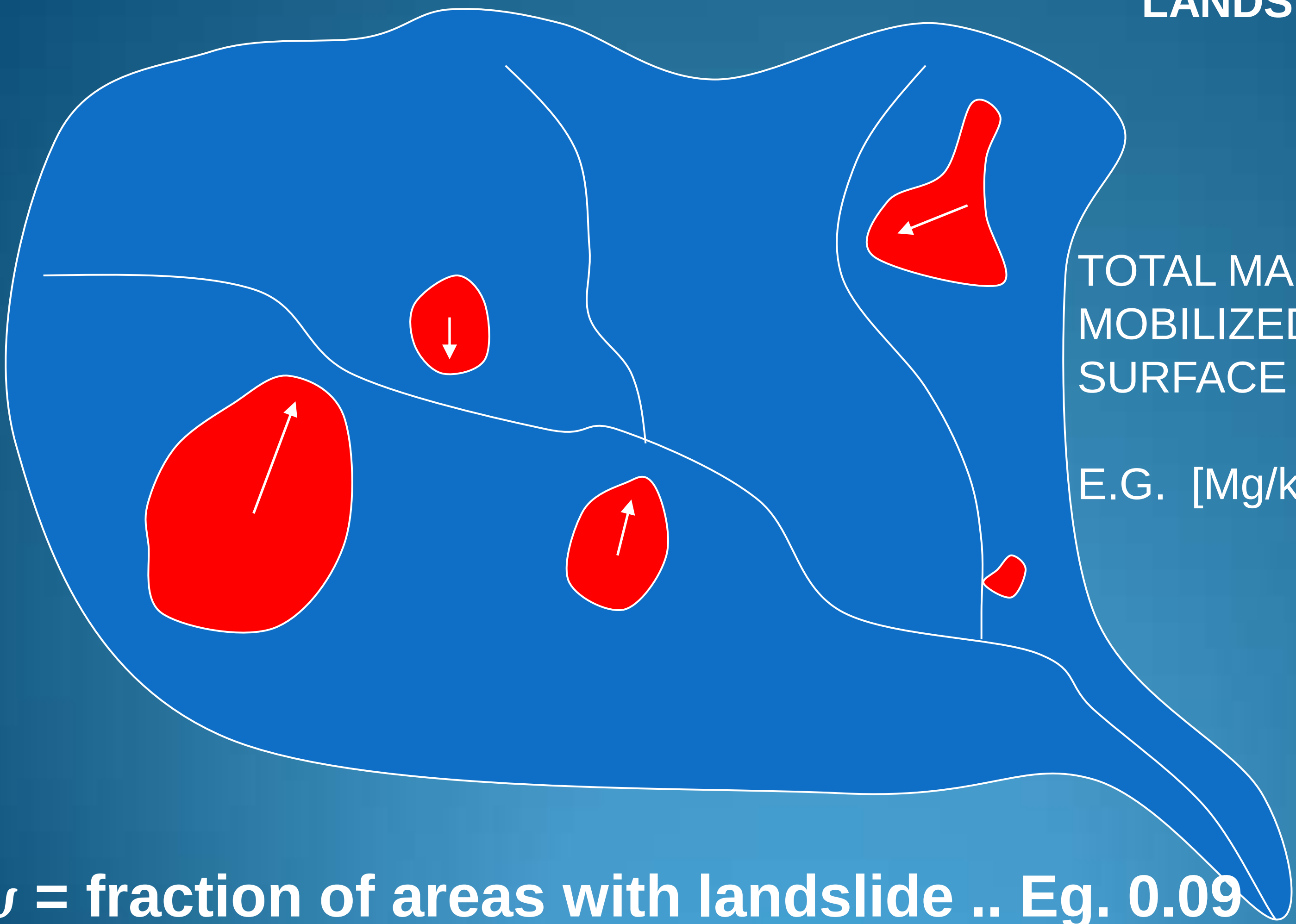
How to obtain LANDLISDE VOLUME from area and average depth of landslides

IT APPLIES AT SHALLOW LANDSLIDE ONLY..



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

E.G. [Mg/km2] or [Mg/ ha]

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

The Sediment delivery ratio from landslides SDRL And How to obtatin SSY ..

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

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

Where

V= net eroded Volume (m3)

A= area of HLU (km2)

D= average depth of landslides (m)

Ψ=fraction of area potentially unstable (-)

SDR_L= sediment delivery ratio from landslides (-)

γ_s=soil unit weight (Mg/m3)

Δ_t = annual frequency (yr)

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

aerea (km^2)	λ	D(m)	SDRL	gamma(Mg/m^3)	DT (years)	volume(m^3)	A equiv (T/ha/y)
1	0.6	0.1	0.7000	1.5	1	42000.00	**630.00**
1	0.01	1	0.0100	1.5	1	100.00	**1.50**

- λ: Fraction of surface affected by landslides
- D(m): Average depth of landslides
- SDRL: Average Sediment delivery ratio from landslide bodies (SDRL)
- gamma(Mg/m^3): Density of soil mass
- DT (years): Annual frequency 1 .. each year 2 ... each 2 years 0.5 two time each year
- volume(m^3): Net eroded volume
- A equiv (T/ha/y): Contribute from landslide to net soil erosion rate

...Sediment delivery ratio for landslides: SDRL

The same definition of SDR can be applied also to shallow landslides contribution because only a fraction of landslide volume can contribute to sediment yield…but we have to consider landslide mobility.

USUALLY SDRL SHOULD BE LOW … BUT IN EXTREME CONDITION IT IS VERY HIGH (SDRL > 0.5)
(e.g. calanchi badland areas in humid or sub humid environments)

Exponential distribution model for sediment delivery

Derived by *Miller and Burnett (2008*)

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

$$\lambda = \frac{1}{\overline{L}_R}$$

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

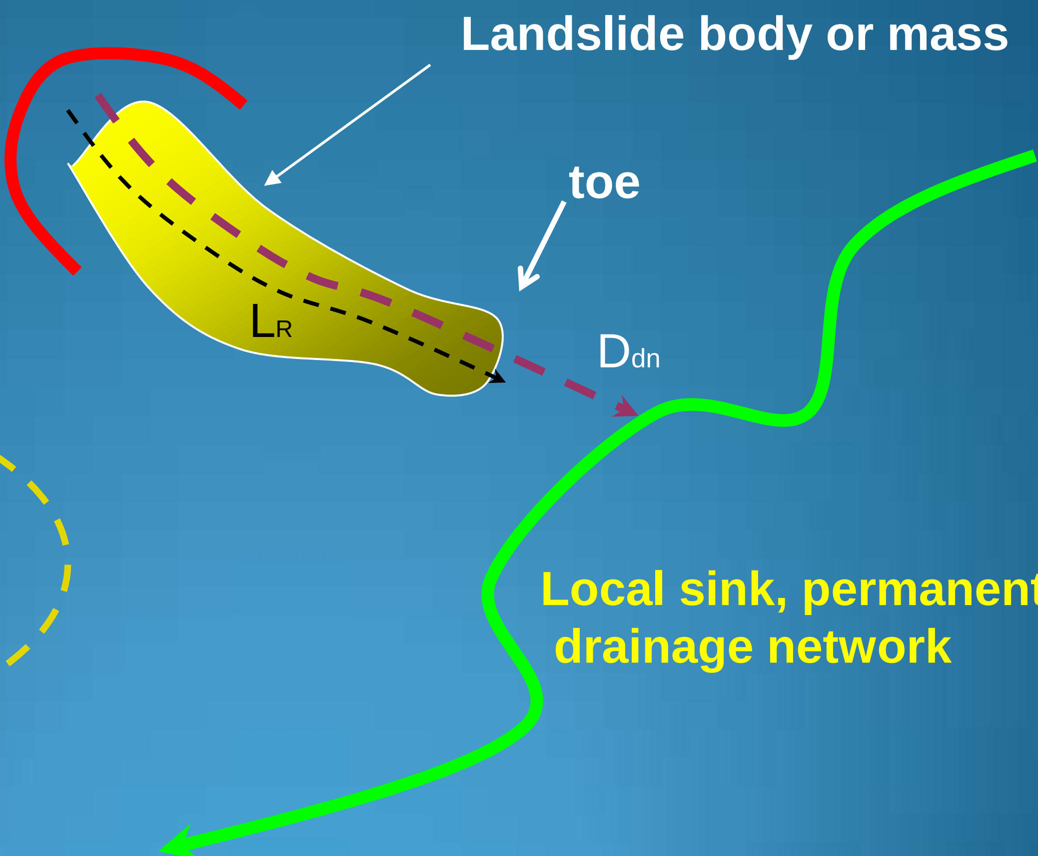
Current form used in model PESERA-L

Where:

L_R = landslide average runout (m)

D_{dn}= Downslope routing weigthed distance (m)

(downslope component IC model Borselli et al. 2008)



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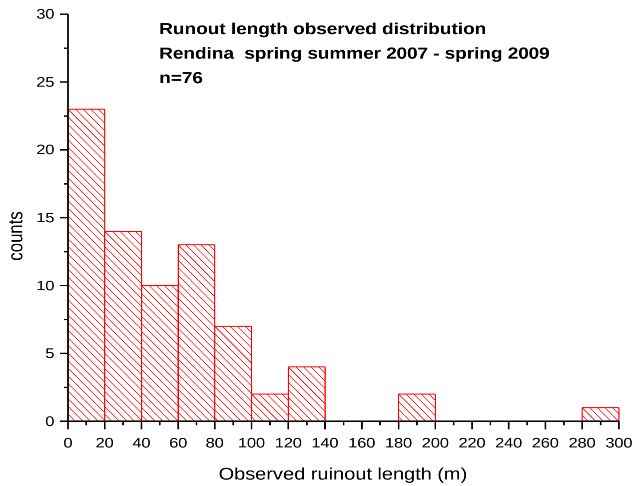
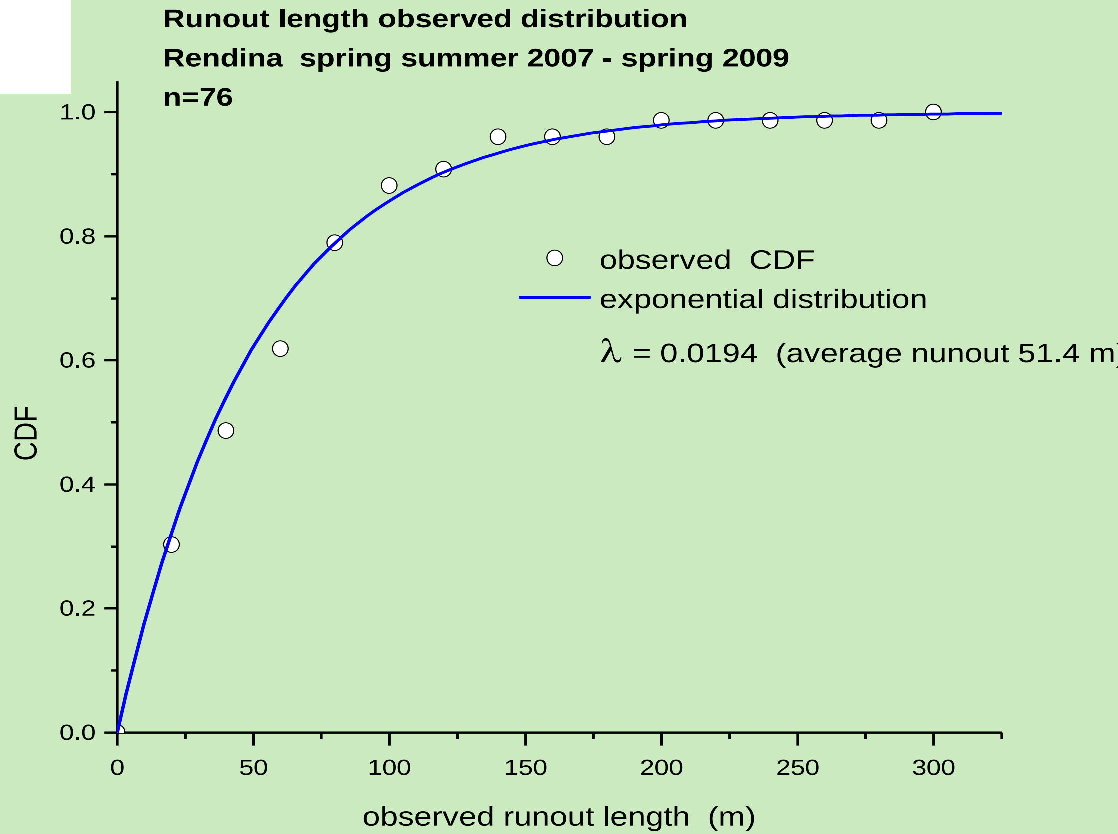
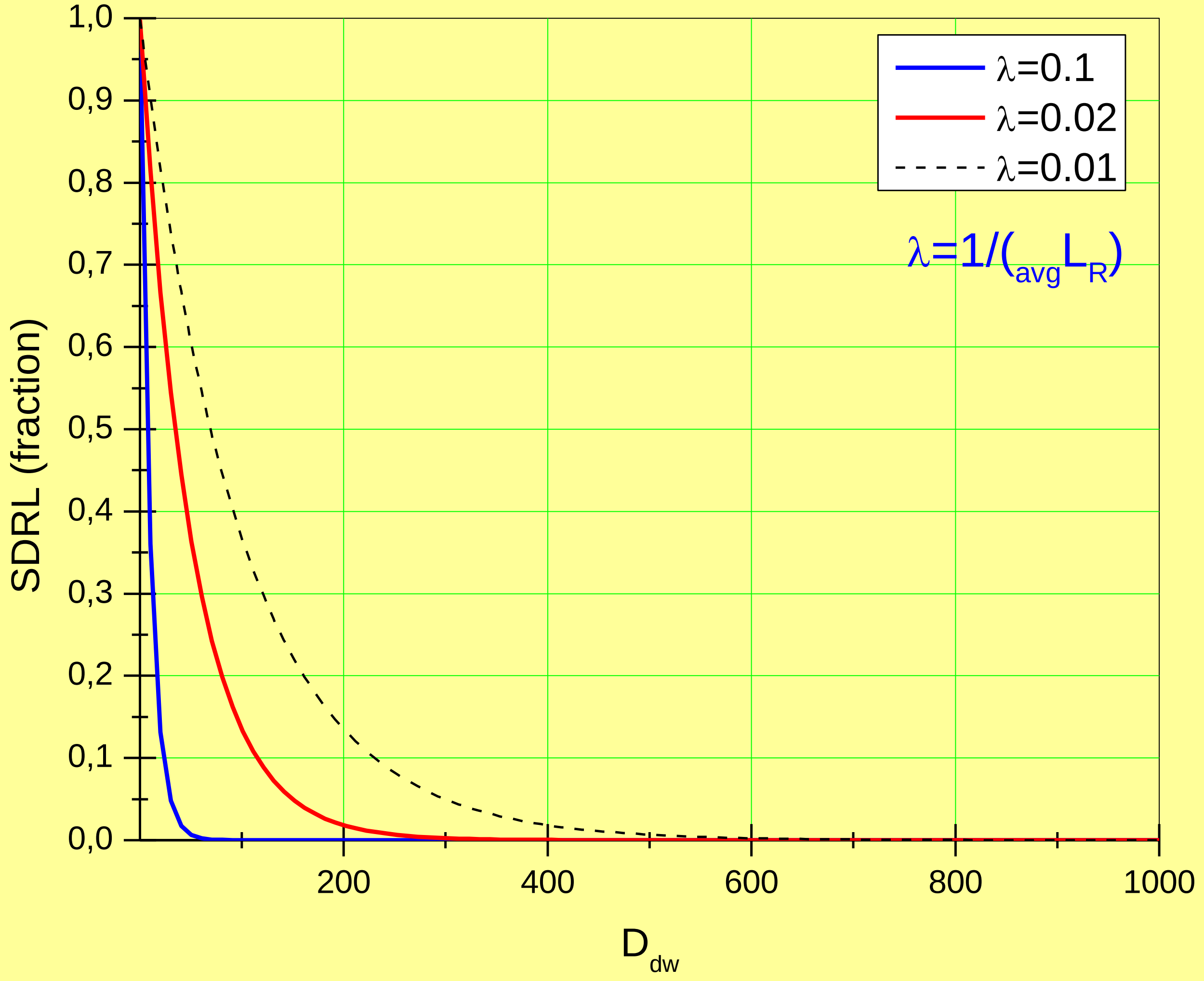
Runout analysis of landslides at Rendina site (subset of 76 landslides in central area of basin 30 km^2) Land unit with highest runout





probabilistic model of landslides and debris flow delivery to stream channels

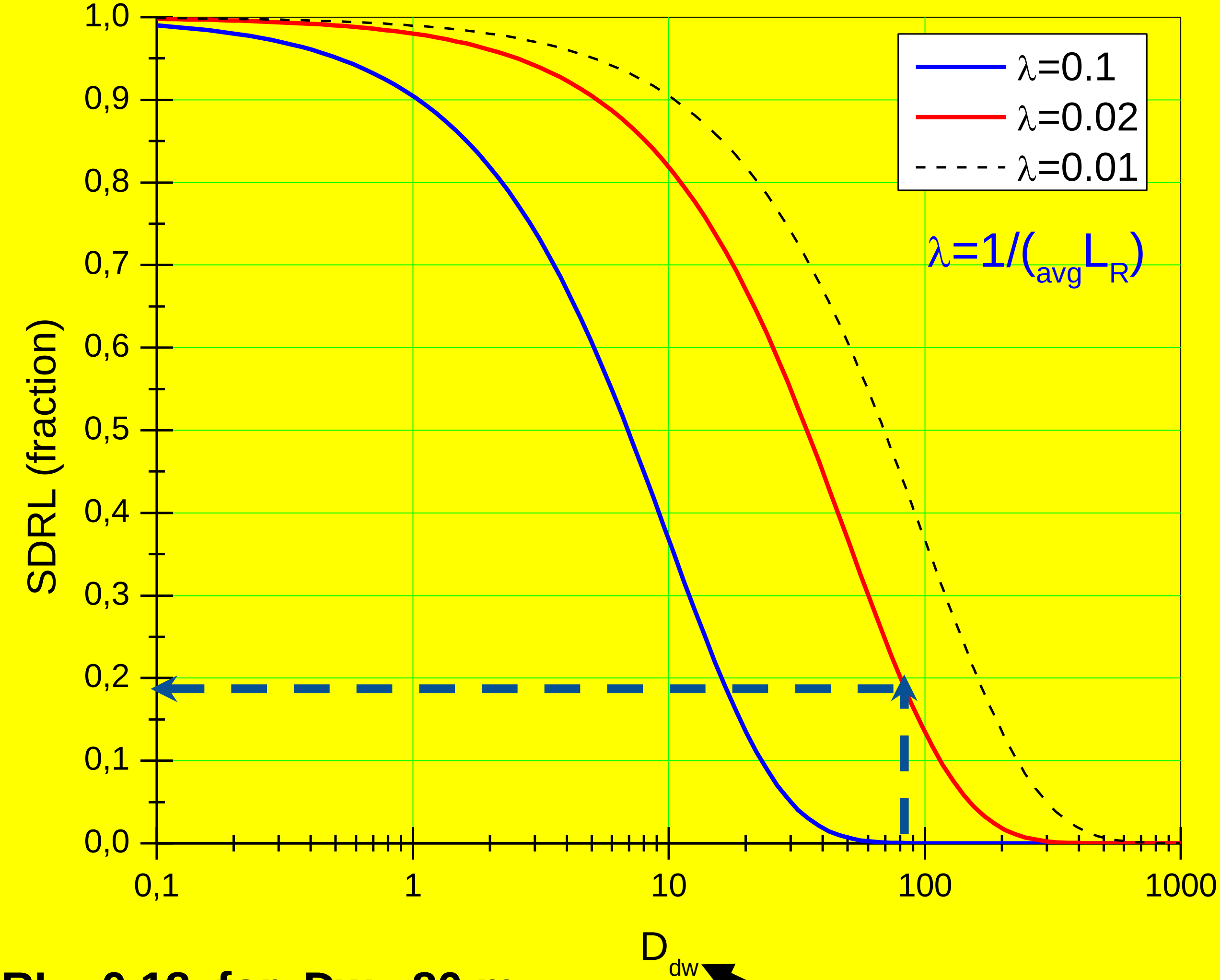
(Miller & Burnett, 2008)



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

probabilistic model of landslides and debris flow delivery to stream channels

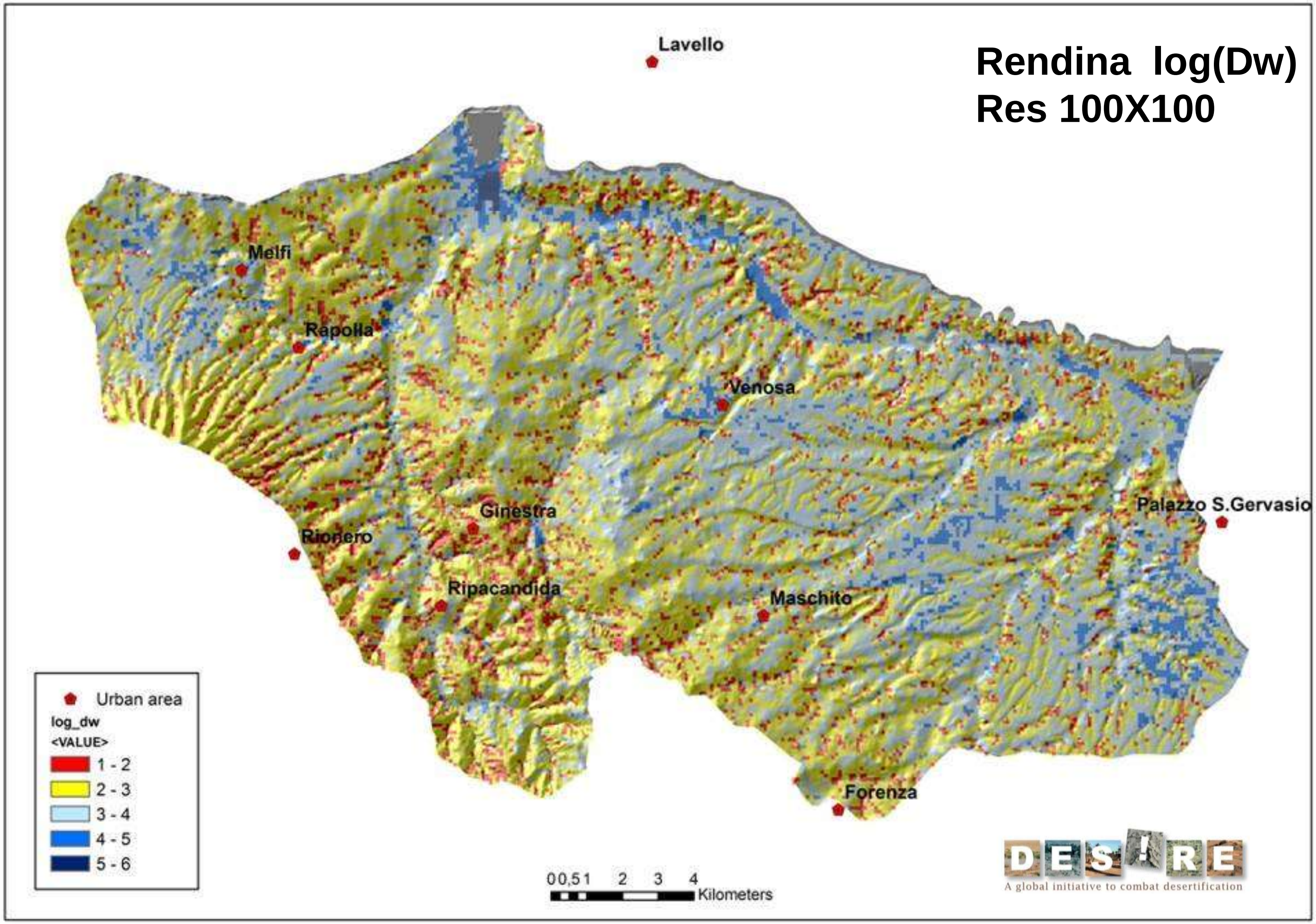
(Miller & Burnett, 2008)



SDRL =0.18 for Dw= 80 m

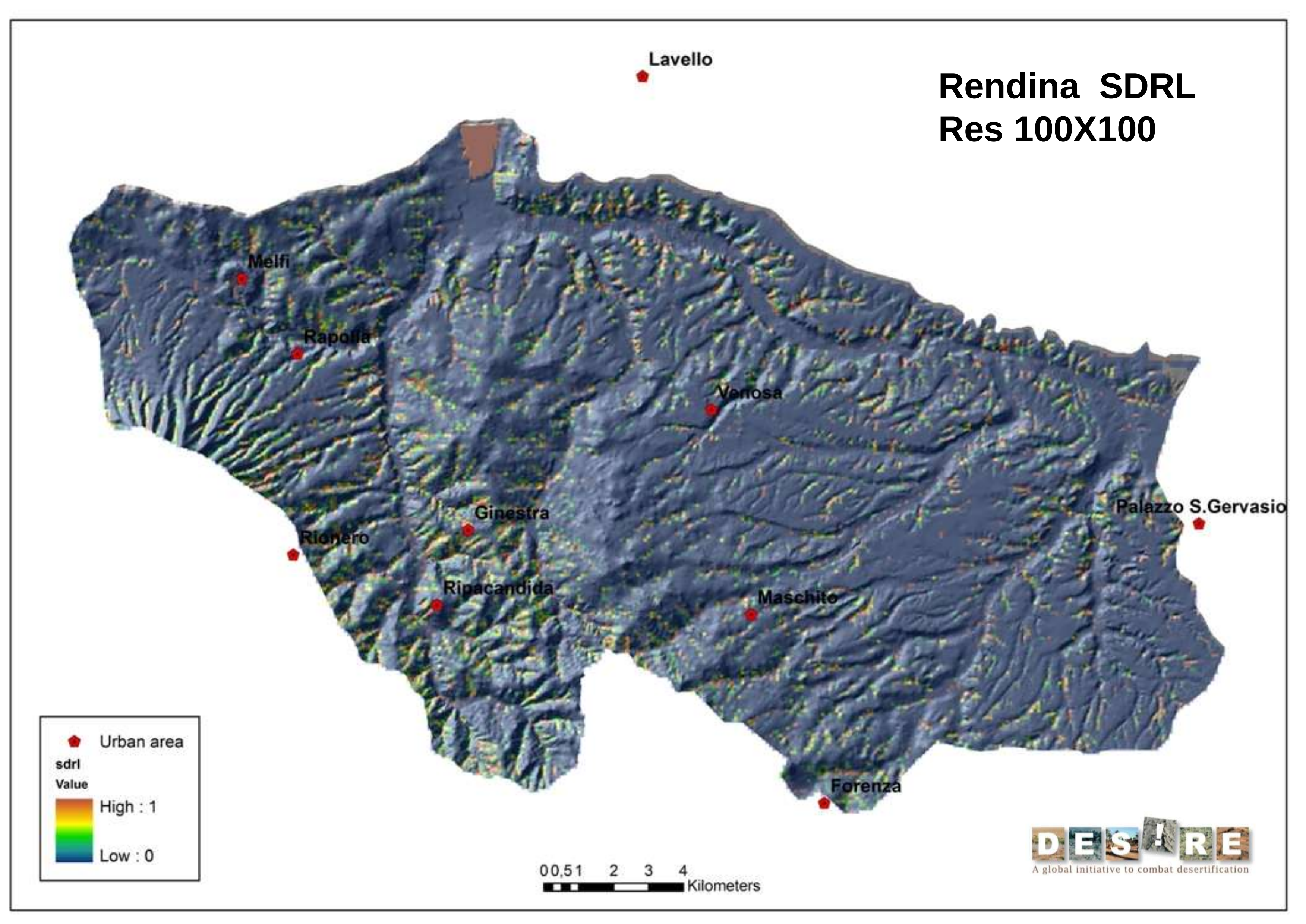
Average runout 50 m (lambda 0.02)

Downslope component of IC index



Logarithm of weigthed downslope distance DW (e.g. 1= 10 m ; 2=100m; 3=1000m …) The RED pixels are most relevant for our application

SDRL - Scenario average runout length LR=50m (pixel 100x100)



Borselli et al. "*PESERA-L, the shallow landslides contribution to specific sediment yield (SSY), as extensions of the PESERA soil erosion model* "

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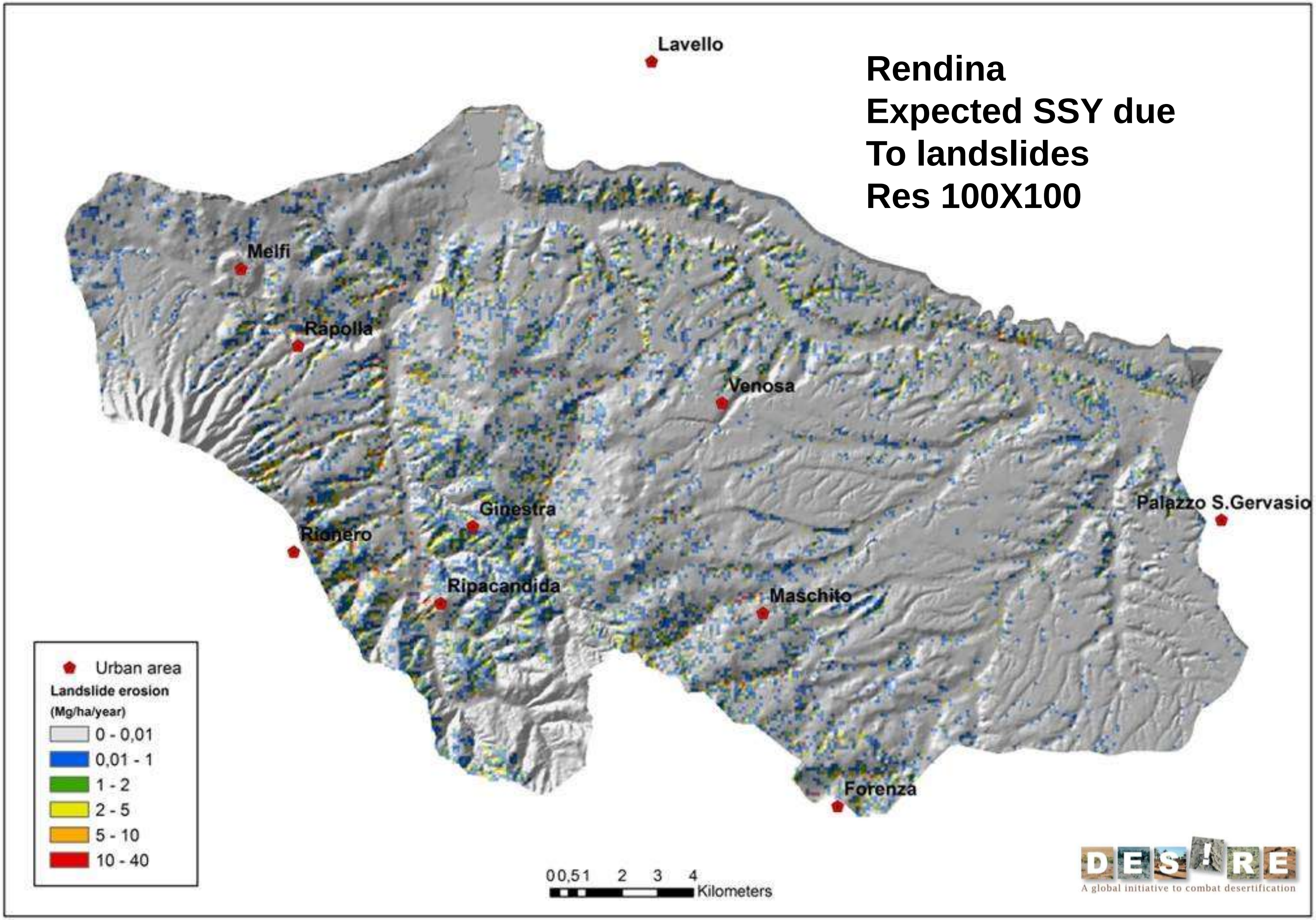
Erosion rate Mg/ha/yr Scenario runout length LR=50m (pixel 100x100)



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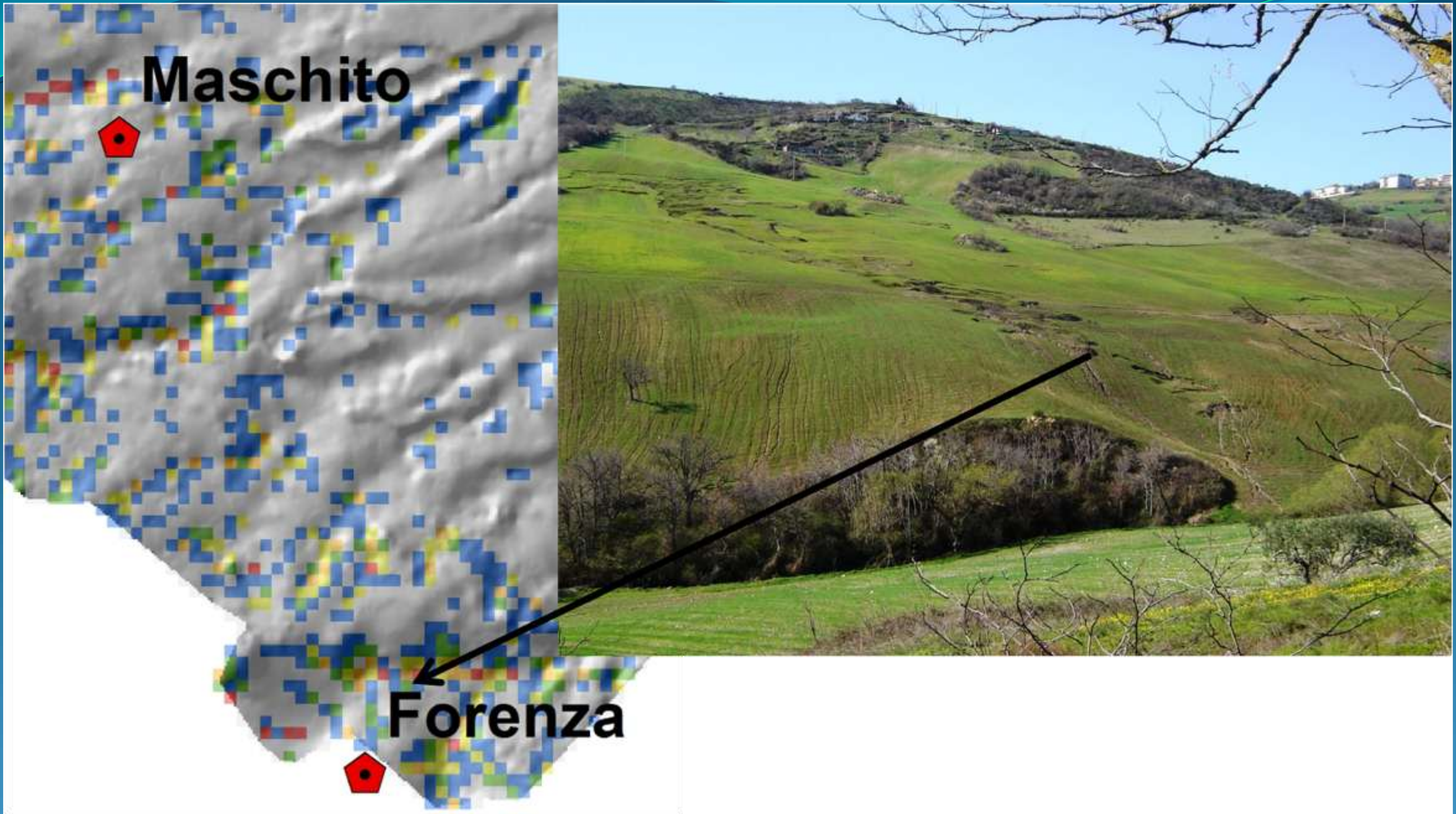
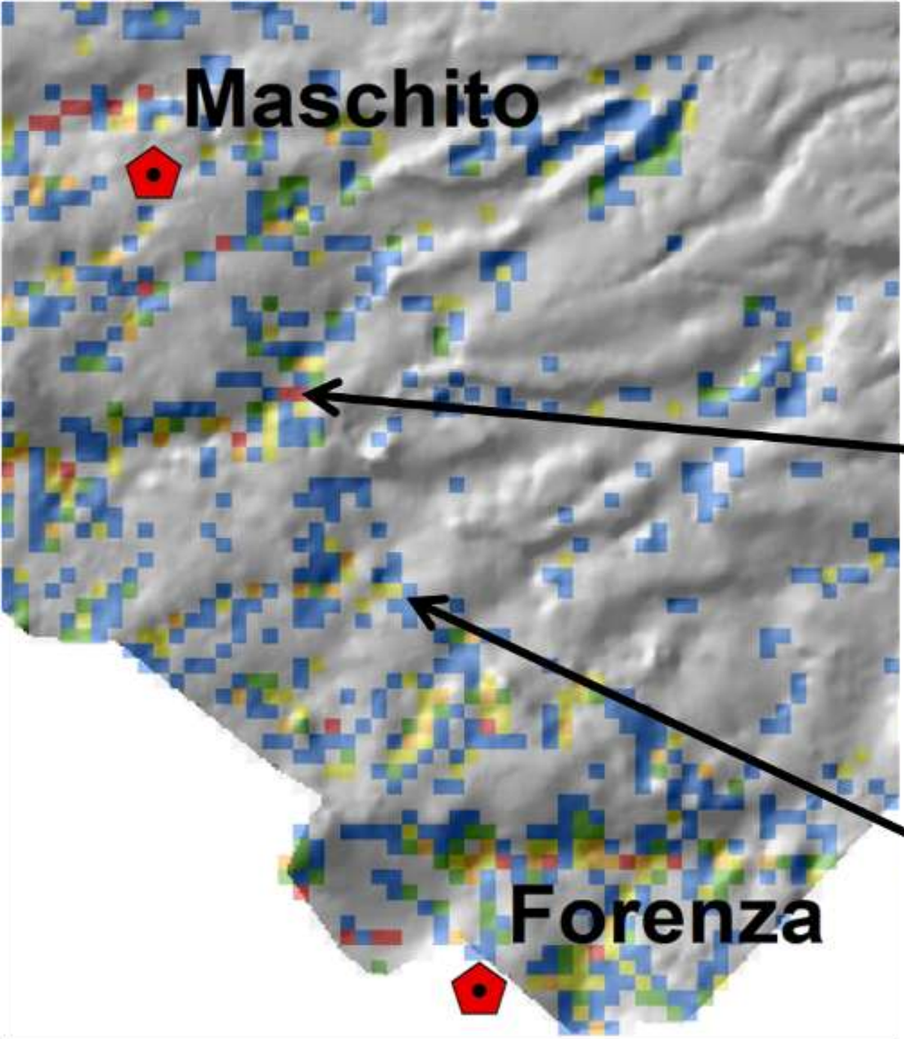


Landslides at rendina site -1



Landslides at rendina site -2

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 units landforms

Badlands
Clay shale
Deposits
High drainage density

rolling topography
Medium steepness and medium drainage density

Rolling to flat topography

Landslides mobility parameter

And the possible dependence from Processes and landforms

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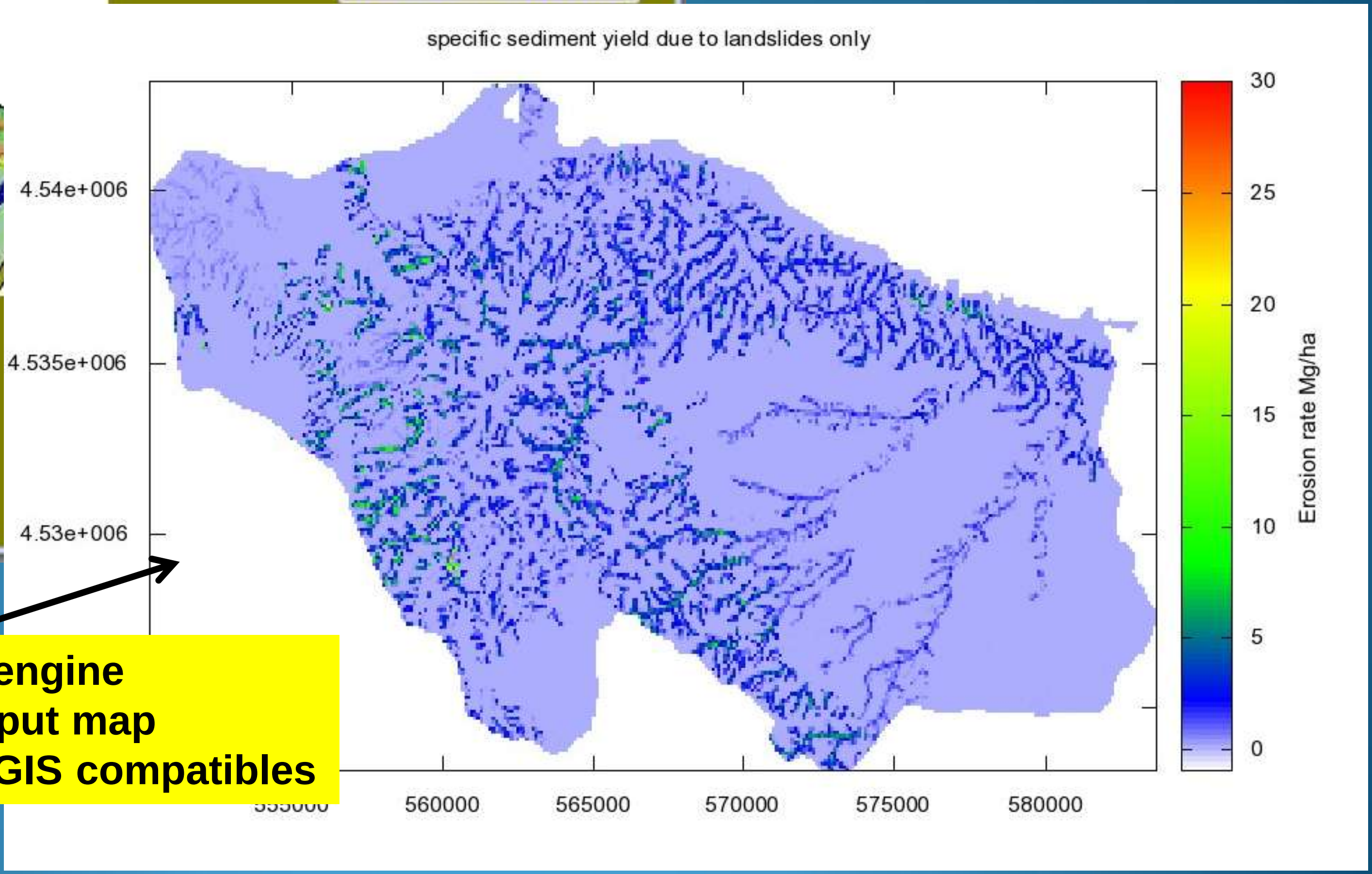
To do list ... For final PESERA _L distribution (freeware)

- A Guide to soil geotechnical parameters*
- Guide and Atlas of slope spectrum and procedure to select alpha and beta values for land units*
- A Guide and atlas to select and or /calculus of LANDLSIDE MOBILITY PARAMETERS *
- Additional testing phase
- user manual editing

** in progress*

PESERA-L
Is developed ysing
OPEN Source platforms

It is still in testing phase



GNUPLOT rendering engine
To plot input and output map
Input/ output are ArcGIS compatibles

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Many thanks for Your Attention !

From CNR-IRPI staff