



REGIONAL SCALE LANDSLIDE EARLY WARNING SYSTEMS

Samuele SEGONI

samuele.segoni@unifi.it

IR0000032 – ITINERIS, Italian Integrated Environmental Research Infrastructures System
(D.D. n. 130/2022 - CUP B53C22002150006) Funded by EU - Next Generation EU PNRR-
Mission 4 “Education and Research” - Component 2: “From research to business” - Investment
3.1: “Fund for the realisation of an integrated system of research and innovation infrastructures”



What is a RSLEWS?

Regional
Scale

WIDE AREA (nation, region...) = thousands of km²
(a.k.a. geographical LEWS, a.k.a. territorial LEWS)

Landslide

Early
Warning
System

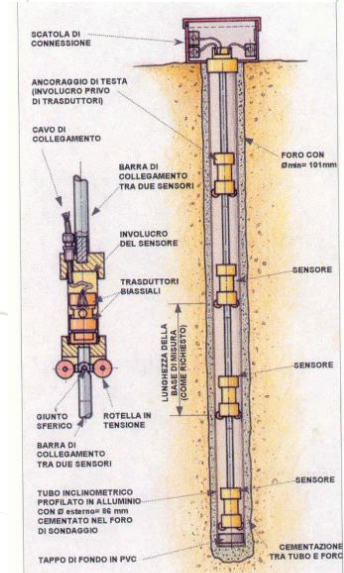
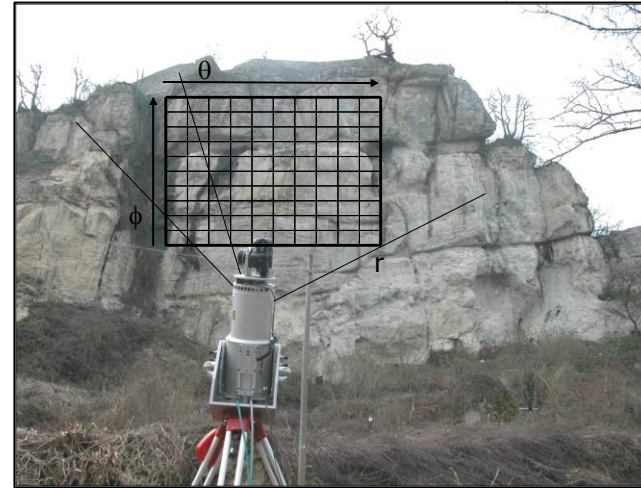
The set of capacities needed to generate and disseminate timely and meaningful warning information to enable individuals, communities and organizations threatened by a hazard to prepare and to act appropriately and in sufficient time to reduce the possibility of harm or loss.

UNISDR, 2009

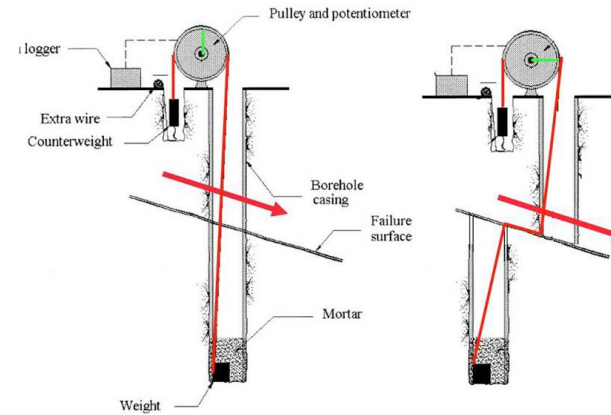
Which approaches?

~~Traditional hillslope monitoring systems~~

MATTER OF "SCALE":
difficult application to a very wide area with ubiquitous landslide phenomena, in which nobody knows where the next one will be triggered.



Schema di sonda inclinometrica fissa biassiale, per il controllo dei movimenti profondi



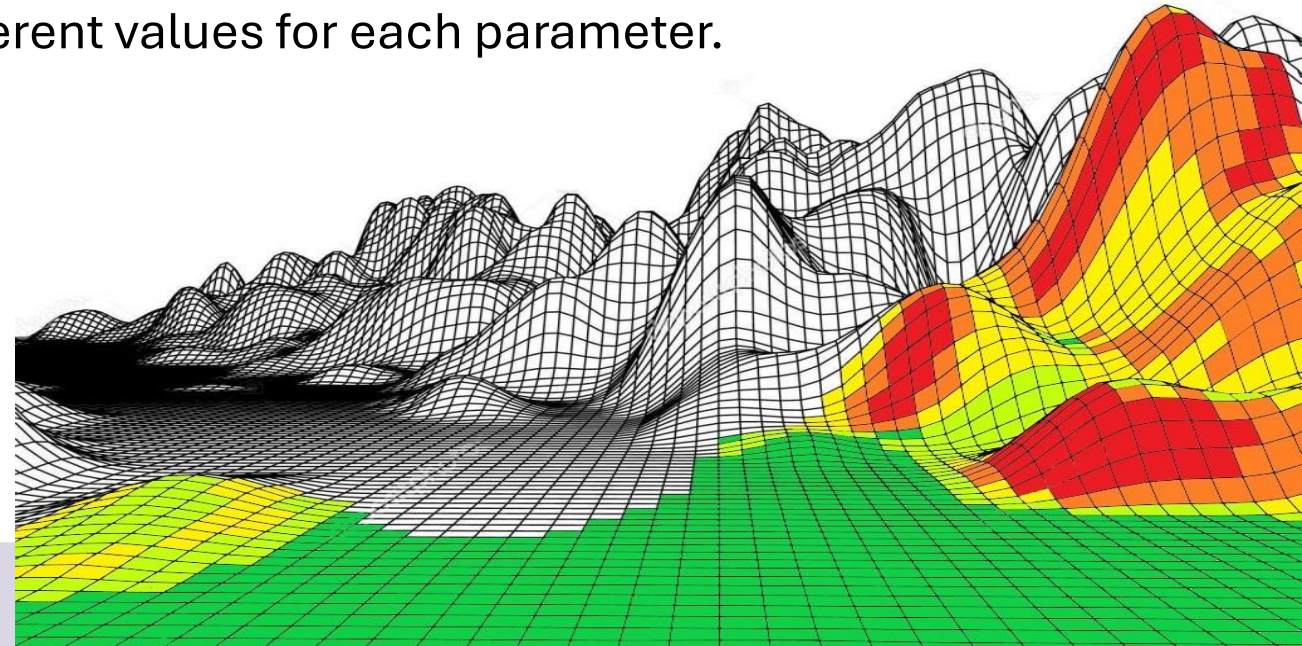
Which approaches?

Distributed physically based models

- Process-based or physically based = all physical processes contributing to trigger landslides are taken into account into mathematic equations accounting for all parameters involved
- Distributed = applied on several computing spatial units (e.g., pixels); in each of them the formulation is applied using potentially different values for each parameter.

All models in a nutshell:

FS = resisting forces / driving forces



Distributed physically based models

The first, the simplest:

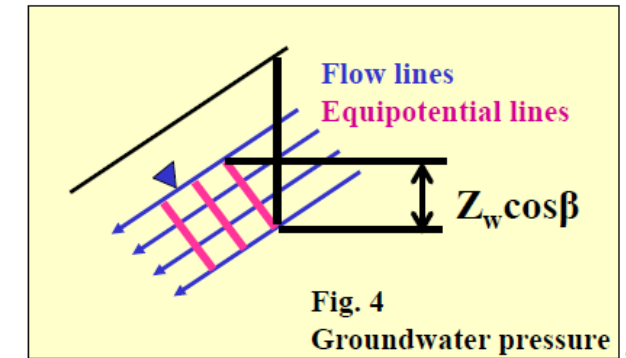
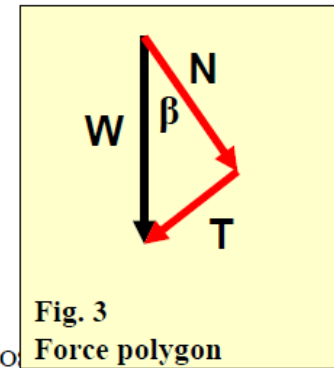
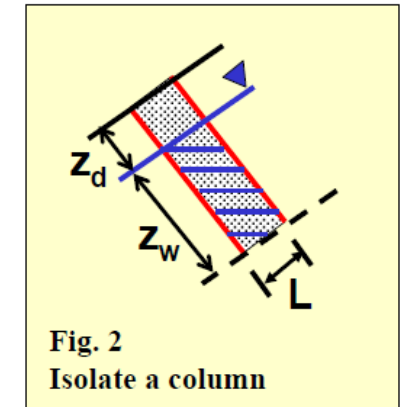
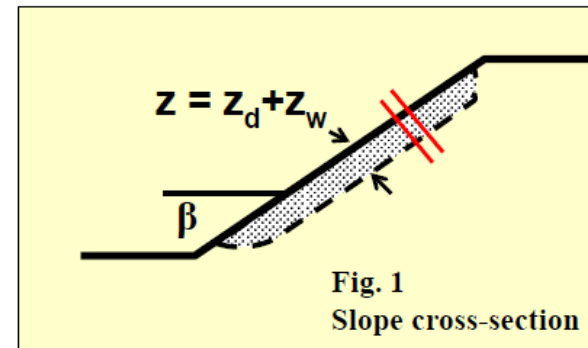
Infinite slope theory (Skempton & DeLory, 1957)

- Rupture and sliding surface is parallel to the slope
- Small depth compared to the landslide length or width

Good assumptions for:

- Shallow translational slides;
- debris flows;
- other landslides with rupture/sliding surfaces influenced by discontinuities (layered rocks, soil/bedrock interface)

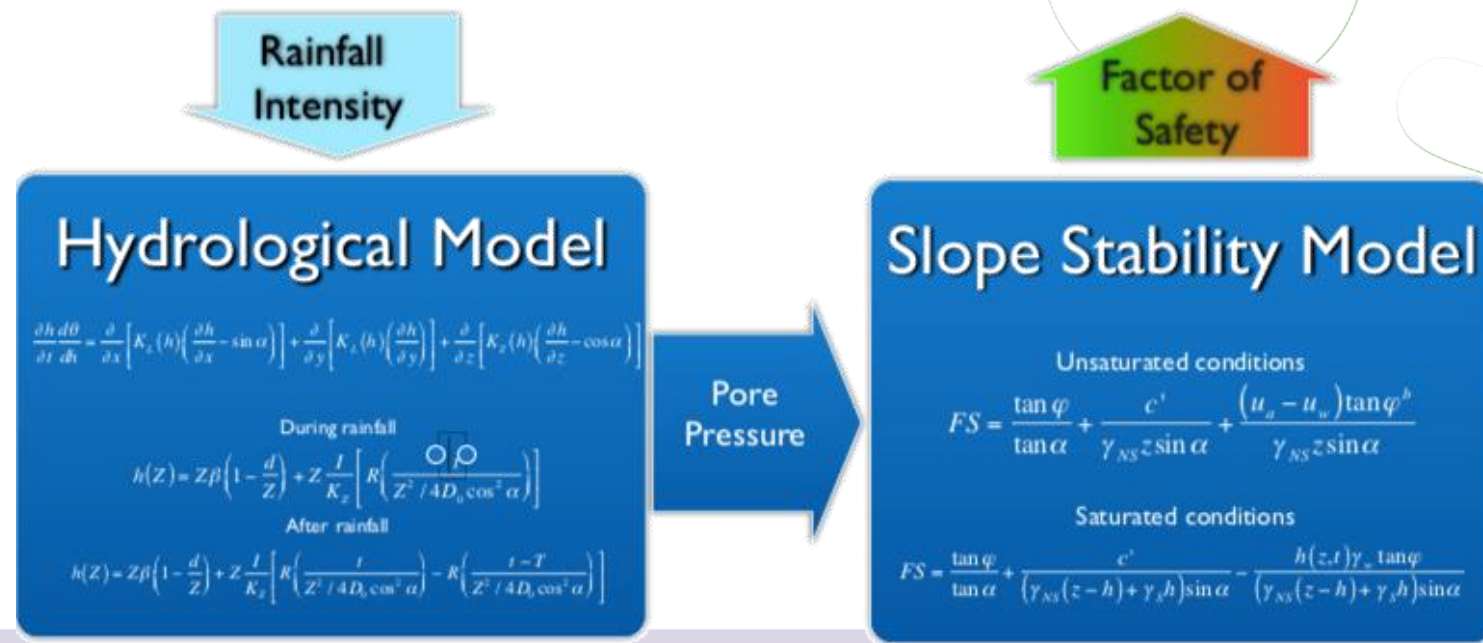
Infinite slope equation



$$F = \frac{c' + (\gamma_d z_d + \gamma_{sat} z_w - \gamma_w z_w) \cos \beta \tan \phi}{(\gamma_d z_d + \gamma_{sat} z_w) \sin \beta}$$

FURTHER IMPROVEMENTS (just two examples):

- The most used worldwide: **TRIGRS** (Transient Rainfall Infiltration and Grid based Regional Slope stability model) (Baum et al., 2002, 2010)
- The one developed by our research grup: **HIRESSS** (Rossi et al., 2013)



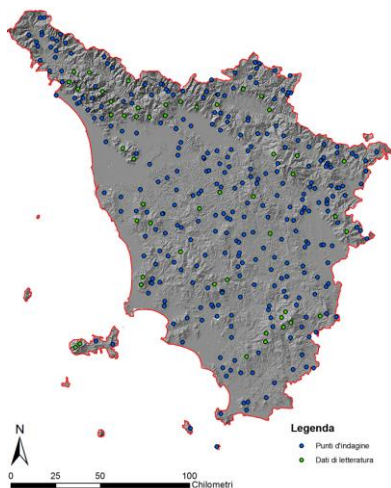
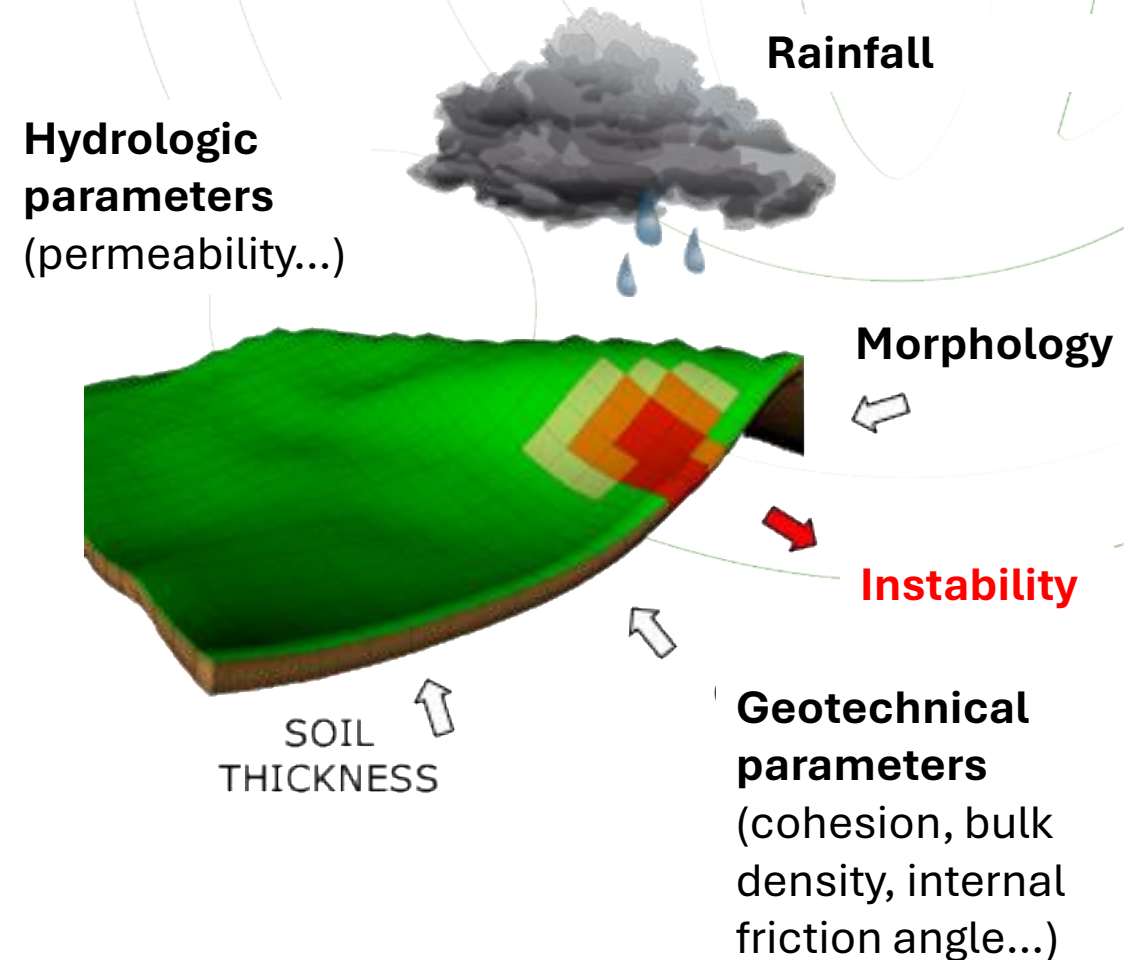
Distributed physically based models






Probabilistic implementation

- Many parameters
- High variability of values
- Complex spatial pattern

SOLUTION: characterization of parameters values; stochastic implementation (e.g. Monte Carlo)

OUTPUT: PROBABILITY of having $FS < 1$

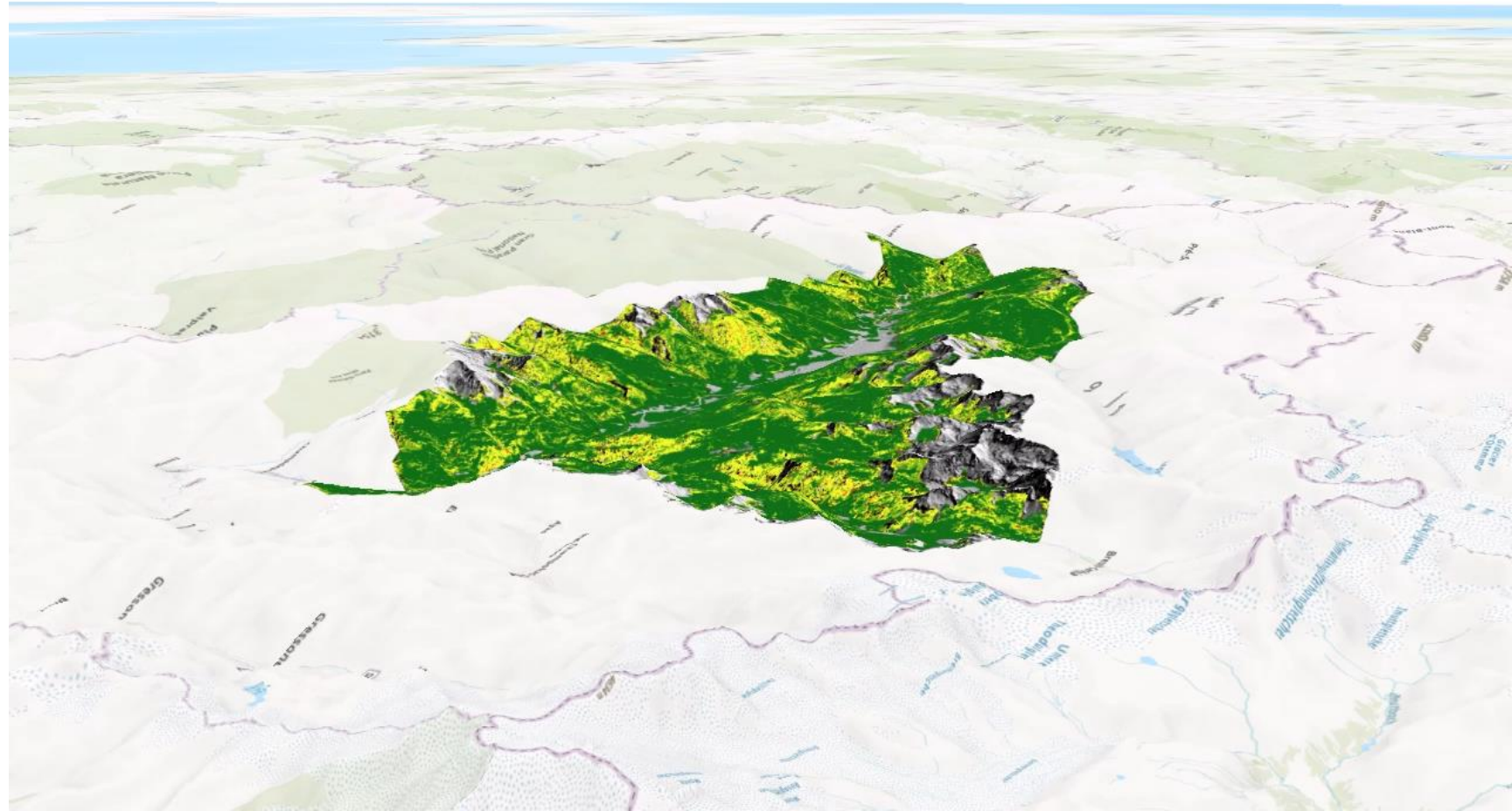


 Prova in situ BST	 Tensiometro	 GPS
 Permeometro a carico costante Amoozometer	 Particolare del Laboratorio di Geotecnica e Geomeccanica, utilizzato nel corso dell'A2	

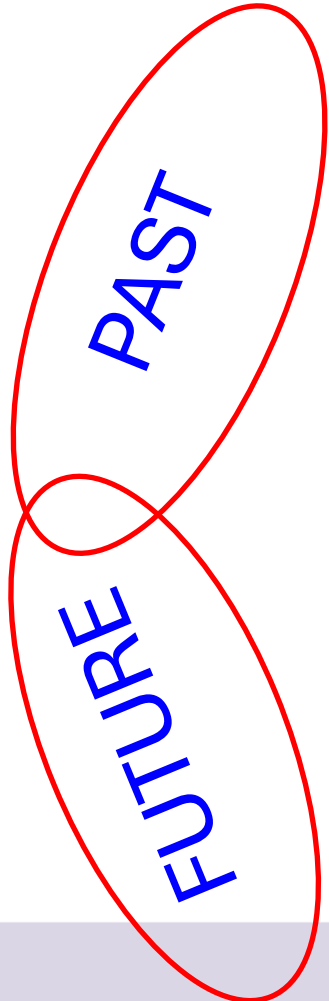
Limitations

- Many data needed
- Computing time
- Pixels: good spatial unit for modeling, bad for warning

At present is used in preliminary or prototype LEWS, usually on small or medium-size areas



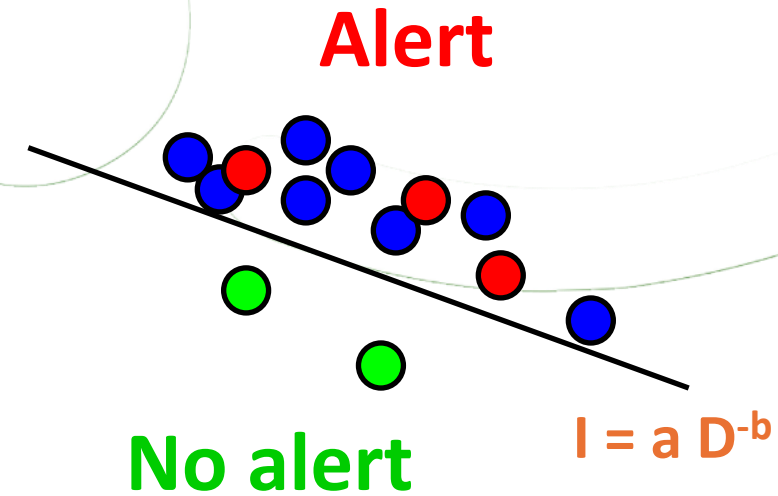
RAINFALL THRESHOLDS



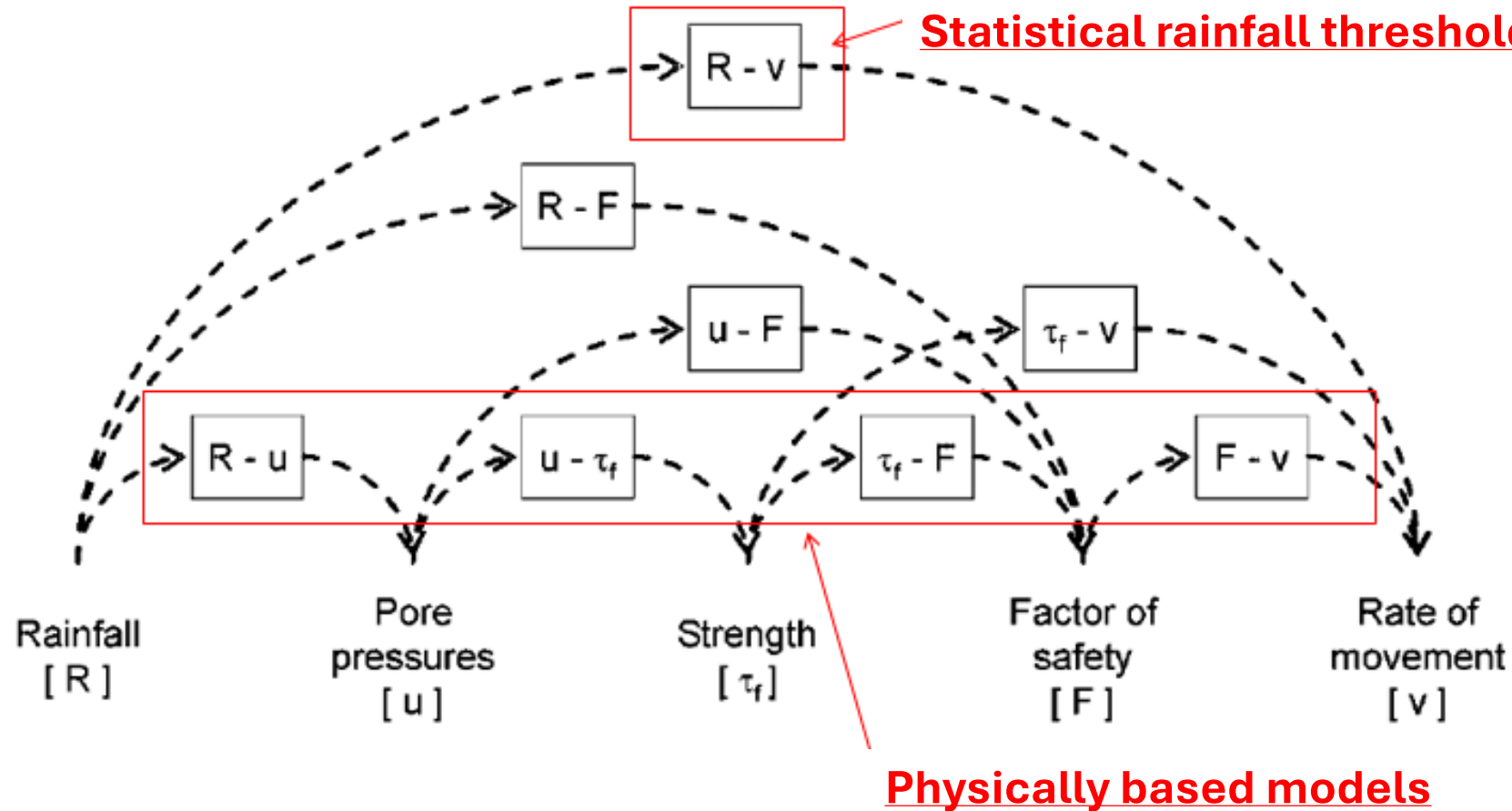
Rainfall conditions that in the past triggered some landslides

Statistical correlation → THRESHOLD
(mathematic equation)

If valid for the future → rainfall used for landslide warning



Conceptualization



«BLACK BOX»
approach

Conceptual schematization of the approaches used to model the kinematic response of landslides to rainfall (Calvello et al. 2008; modified from Leroueil 2001). Different simplifications are needed depending on monitoring scale and data availability.

Conceptualization

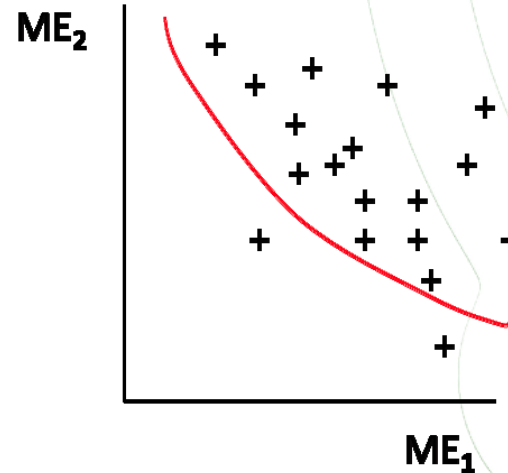
Types of thresholds based on the available classes of meteorological events: (a)

Only landslide occurrences available; (b) only non-occurrences available; (c)

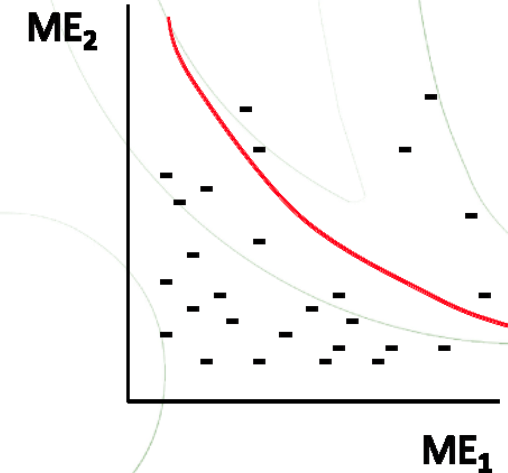
both occurrences and non-occurrences are available.

For simplicity, a threshold based only on two meteorological elements (ME) is shown. The proportion of “landslide” events in relation to “no landslides” events is usually very small and does not correspond to the proportion shown in (c), which is presented for illustration purposes only.

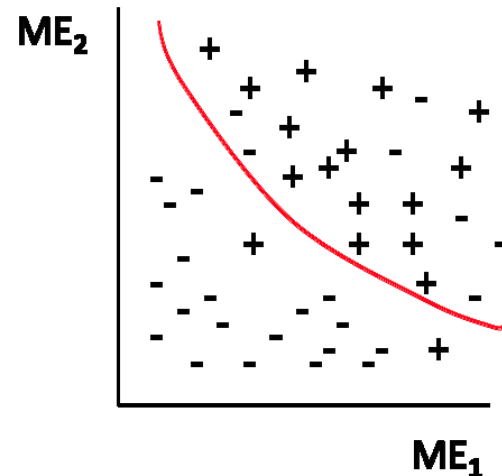
Adapted from Cepeda and Devoli (2008).



(A)



(B)



(C)

ME_1 : Meteorological Element 1
 ME_2 : Meteorological Element 2
+: Meteorological event with observed landslides (LI = "landslides")
-: Meteorological event with no observed landslides (LI = "no landslides")
— : Threshold

Basics: pioneer works and state of the art

Endo, 1969 - Probable distribution of the amount of rainfall causing landslides

Caine, 1980 - The rainfall intensity-duration control of shallow landslides and debris flows

Guzzetti et al., 2007 - Rainfall thresholds for the initiation of landslides in central and southern Europe

Guzzetti et al., 2008 - The rainfall intensity-duration control of shallow landslides and debris flows: an update

Segoni et al., 2018 - A review of the recent literature on rainfall thresholds for landslide occurrence

RAINFALL THRESHOLDS step by step

- **OBJECTIVE**

- Study area (areal extension, characteristics)
- Reason (warning? Other studies?)

- **INPUT DATA**

- Rainfall (records, timeframe, temporal resolution...)
- Landslides (type, triggering and predisposing factors, accuracy/completeness, ...)
- (Altri dati)

- **MODEL**

- Choice of rainfall parameters
- Other contour conditions
- Definition of triggering conditions
- Threshold definition

- **VALIDATION**

- Methods/datasets
- Performance indicators

- **IMPLEMENTATION**

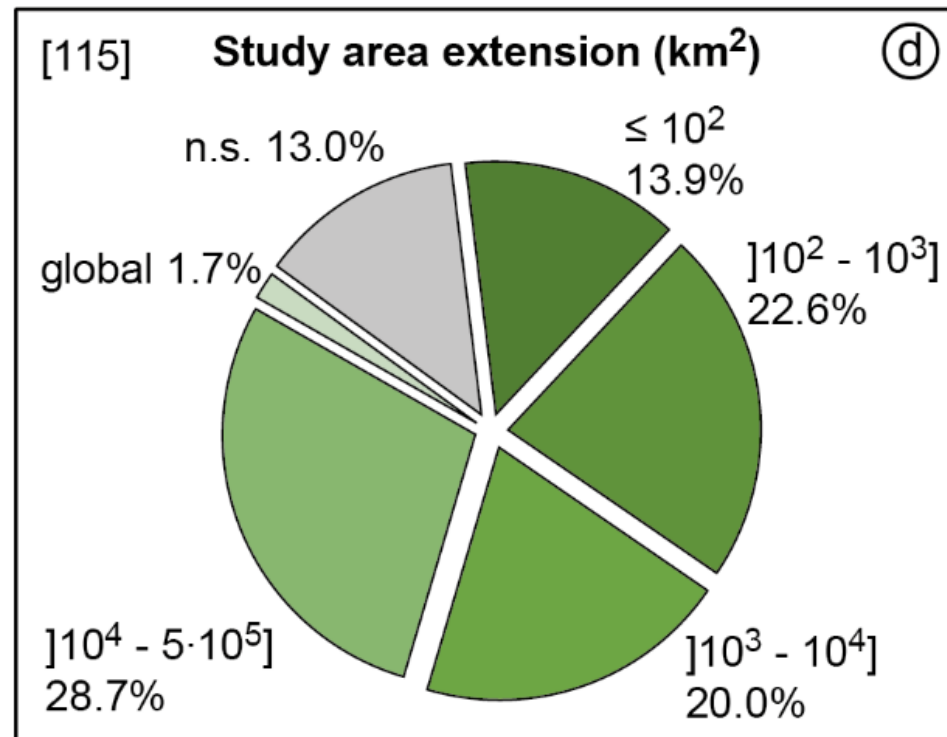
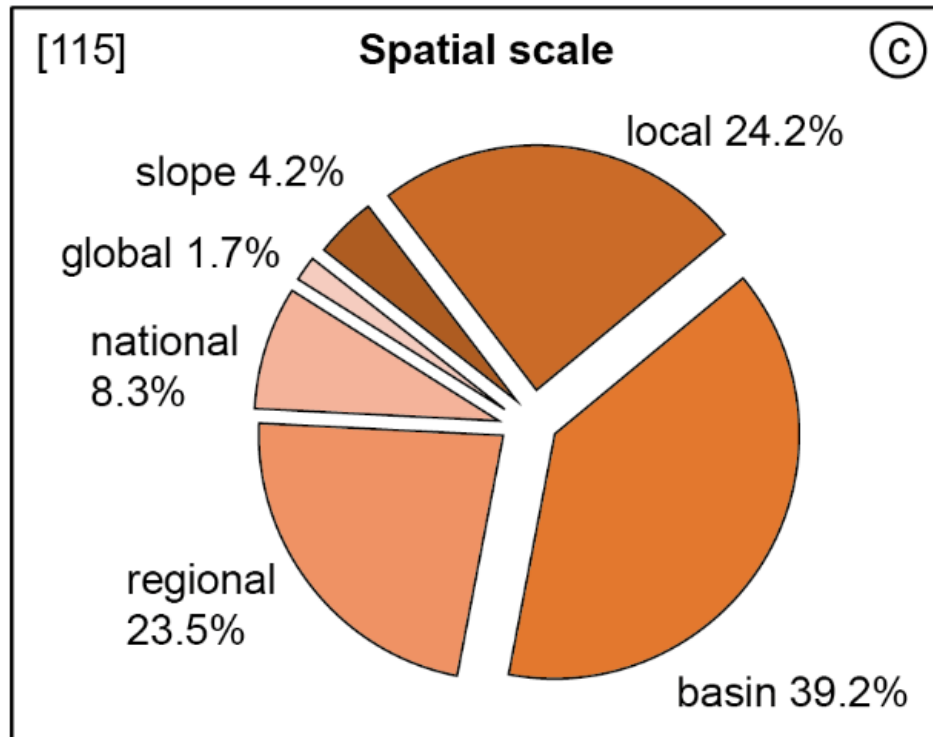
- Operational use
- Automation
- Standardization of warnings
- Dissemination of warnings

- **DEVELOPEMENT**

- Periodic update
- Error analysis
- Correction/redesign/evolution

RAINFALL THRESHOLDS: scale of analysis

- They were born as GLOBAL «minimum condition» thresholds (Caine, 1980)
- Now, they serve specific needs (prediction and warning), typically over large areas



RAINFALL THRESHOLDS: objective

- Minimum condition thresholds
Identify the minimum rainfall condition associated to landslide triggering. Useful for research purpose (e.g., climatic and geomorphologic characterization). Usually, they are very low.
- Warning thresholds
Identify typically safe and unsafe conditions to provide timely warnings. Usually, they find a tradeoff between correct predictions and false alarms

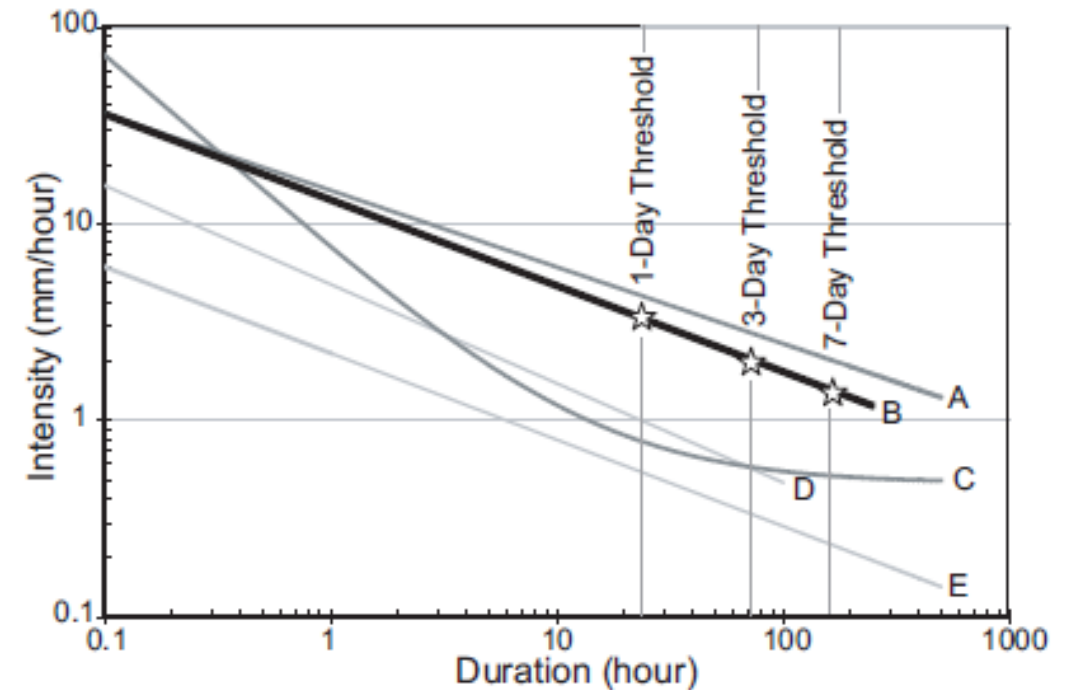
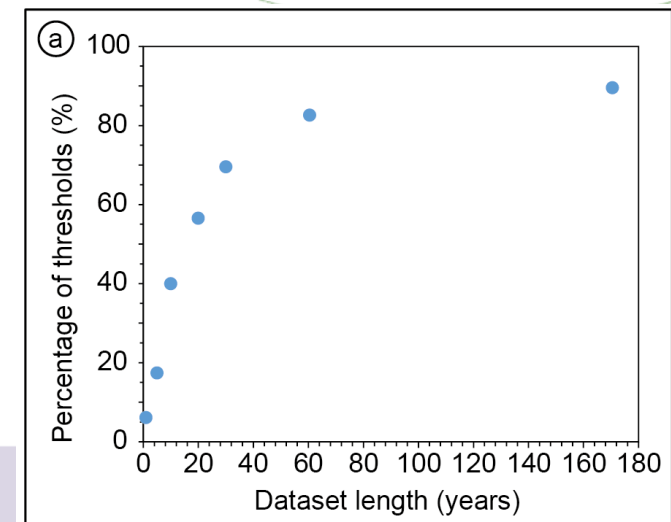
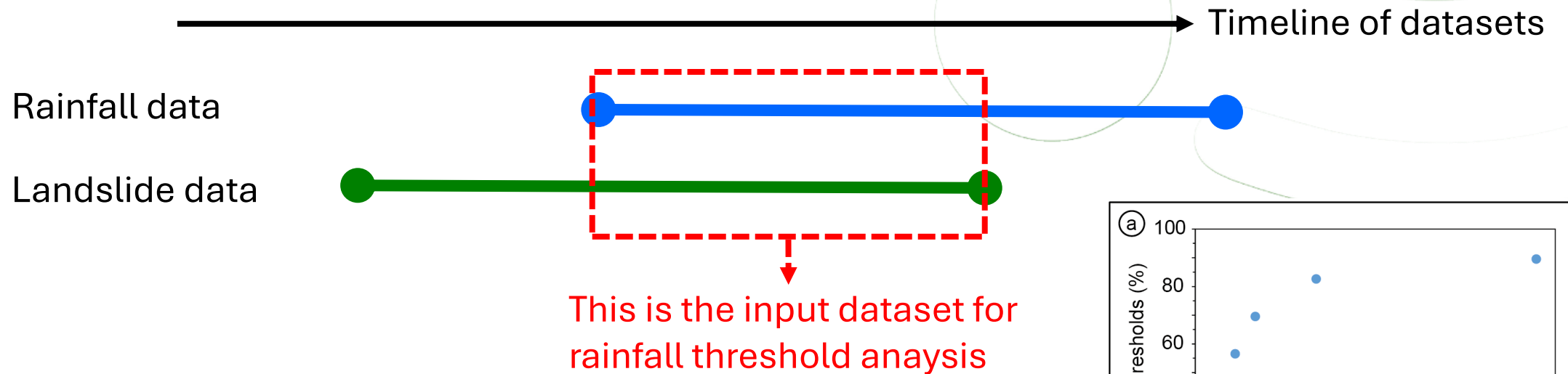


Fig. 2. Global rainfall intensity-duration thresholds: (A) Caine (1980), (B) Hong et al. (2006), (C) Crosta and Frattini (2001), (D) Innes (1983), (E) Guzzetti et al. (2008). The 1, 3, and 7-day durations considered by the algorithm are shown on the graph.

RAINFALL THRESHOLDS: Input data

- RAINFALL
- LANDSLIDES

The technique is based on defining the rainfall conditions associated to landslide events



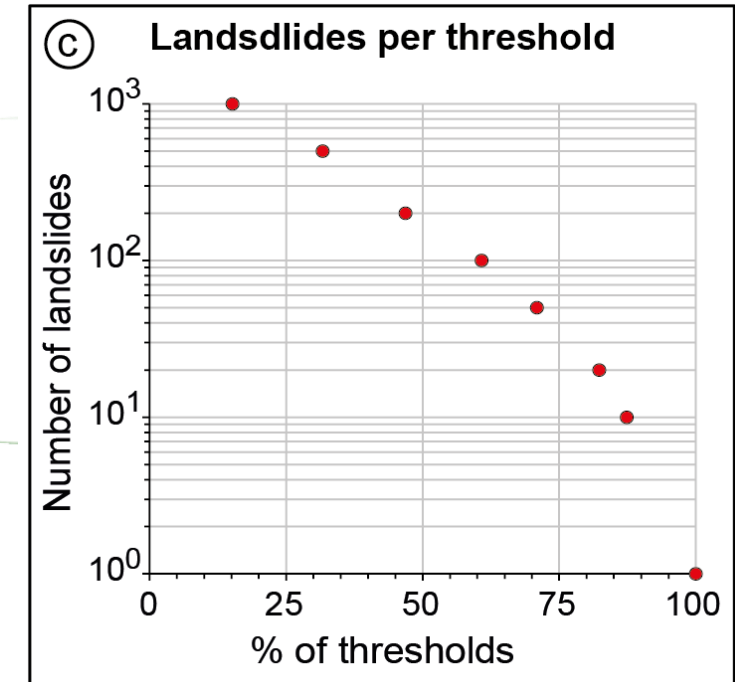
RAINFALL THRESHOLDS: input data

Q: How many events are needed to calibrate a threshold?

A: As much as possible, as complete as possible!

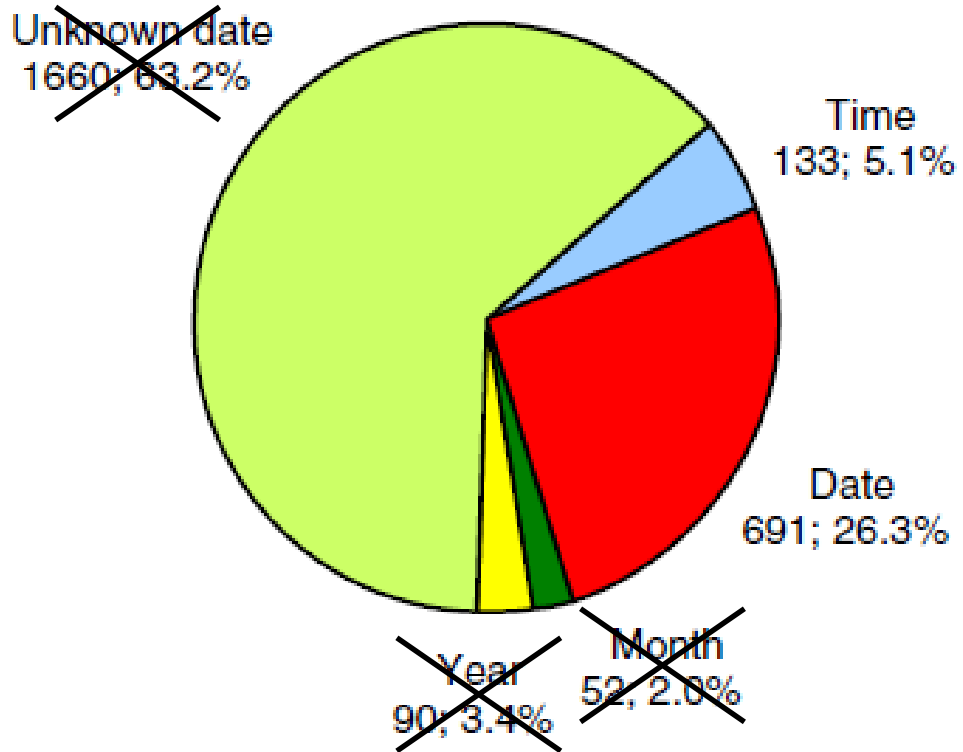
Table 2. Documented increase of the forecasting effectiveness of SIGMA by expanding the calibration dataset.

Work Phase	SIGMA Prototypal Version	First Major Update	Second Major Update
Reference	[28]	[24]	[31]
Calibration period	2000–2003 (highly incomplete)	2004–2007	2004–2010
Landslides used for calibration	180 (only pertaining to a single TU)	888	1652
Performance indicator	Likelihood ratio = 8.38	Likelihood ratio = 16.43	Likelihood ratio = 17.01



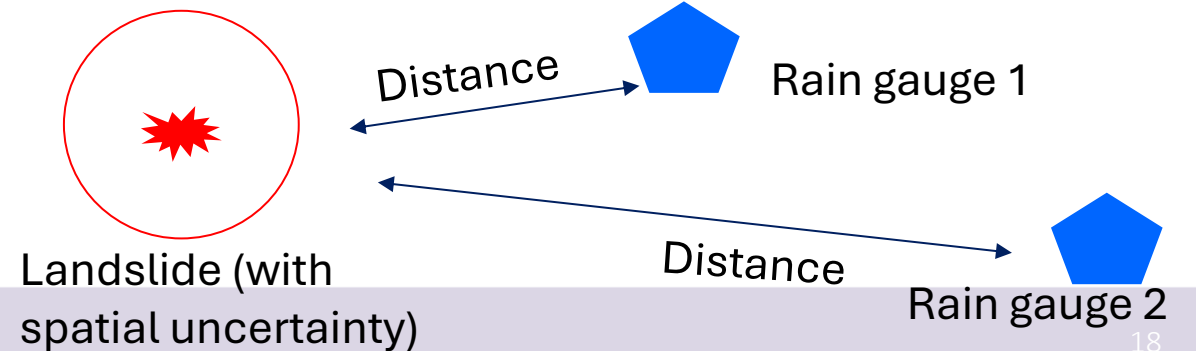
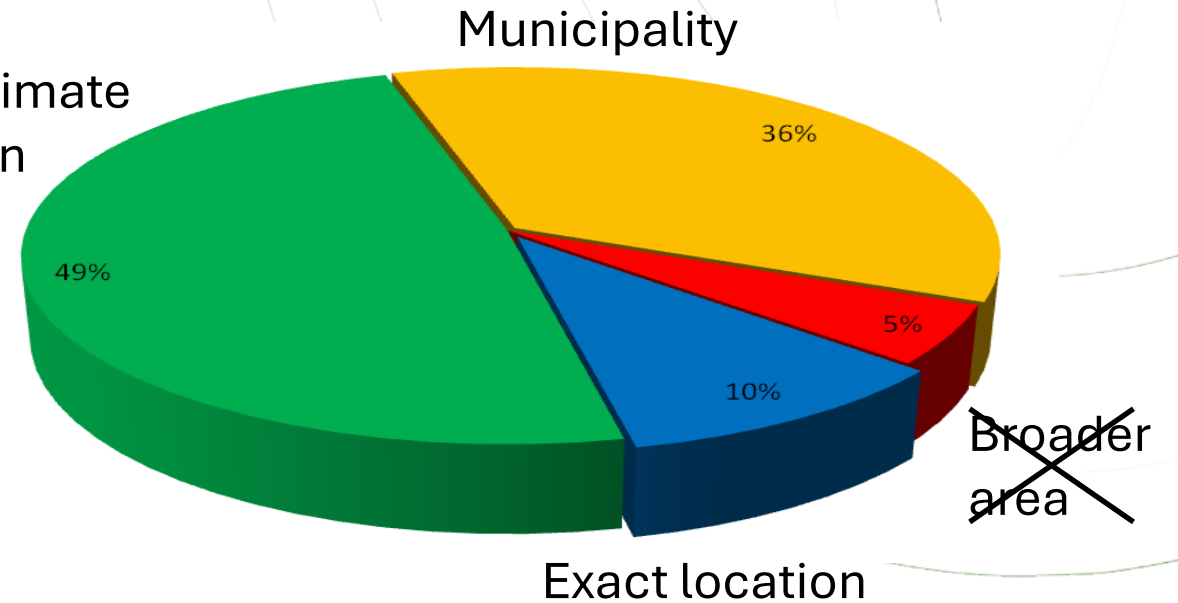
RAINFALL THRESHOLDS: input data (landslides)

Time accuracy



Spatial accuracy

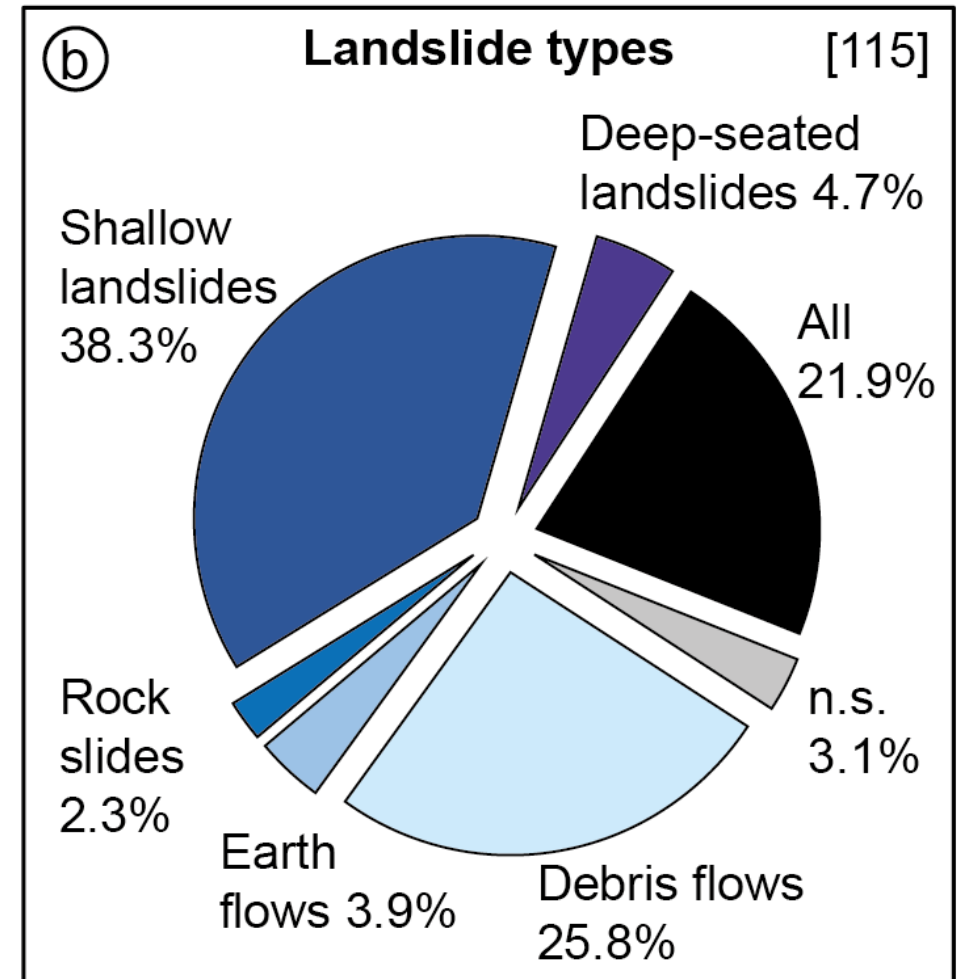
Approximate location



RAINFALL THRESHOLDS: input data (landslides)

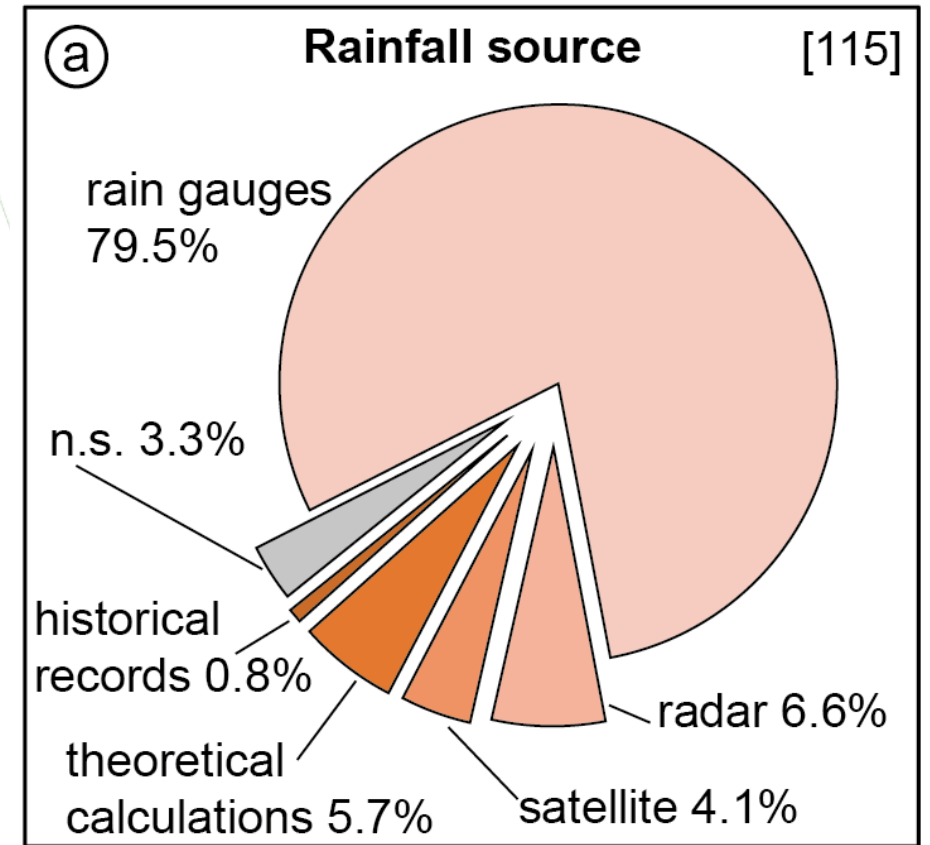
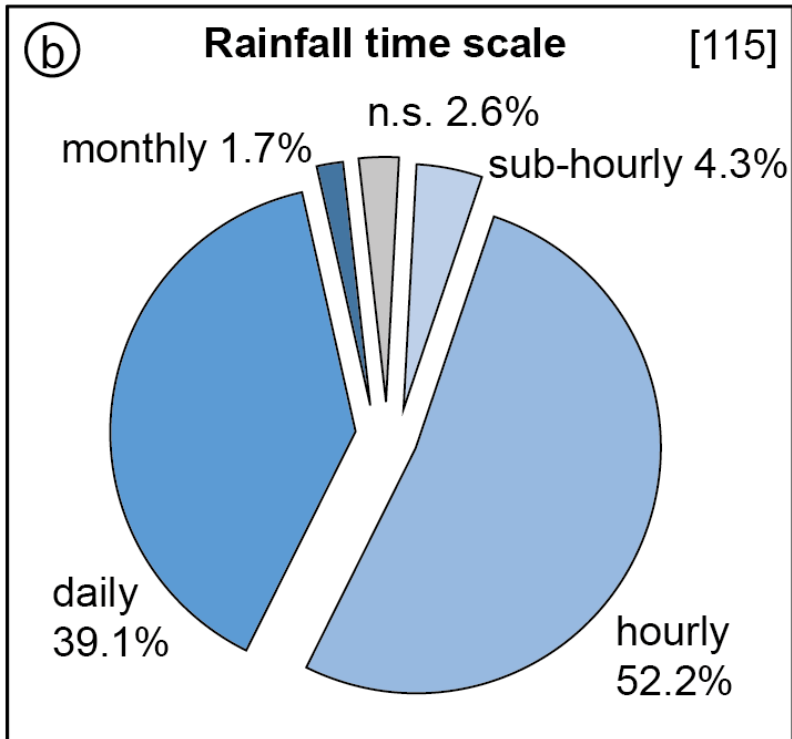
Landslide types

- Initially conceived for shallow landslides (and debris flows)
- Gradually expanded to all kinds of landslides, with specific rainfall parameters:
 - Deep seated landslides: antecedent rainfall
 - Shallow landslides: rainfall intensity and duration
- Different types together: yes but...
 - Nearly same triggering mechanism
 - Small areas with homogeneous geomorphology (one prevailing type)



RAINFALL THRESHOLDS: input data (rainfall)

Important:
if an operational use is expected, the rainfall source used for threshold calibration should be the same used for rainfall monitoring in the EWS



Important:
the temporal resolution of rainfall data influences the approach (e.g.: we can't characterize rainfall intensity properly if we have only daily measurements)

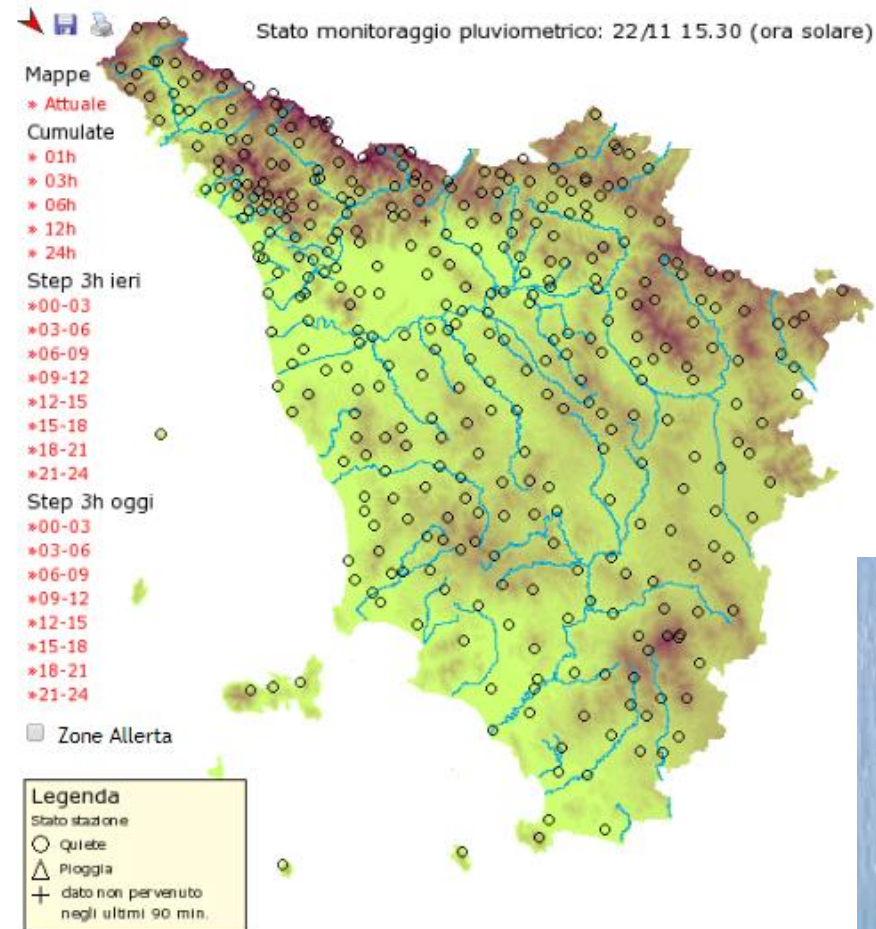
Rain gauges or radar?

RAIN GAUGES

 **DIRECT** rainfall measurement

 Typical precision: 0.2mm

 **PUNCTUAL MEASURE**



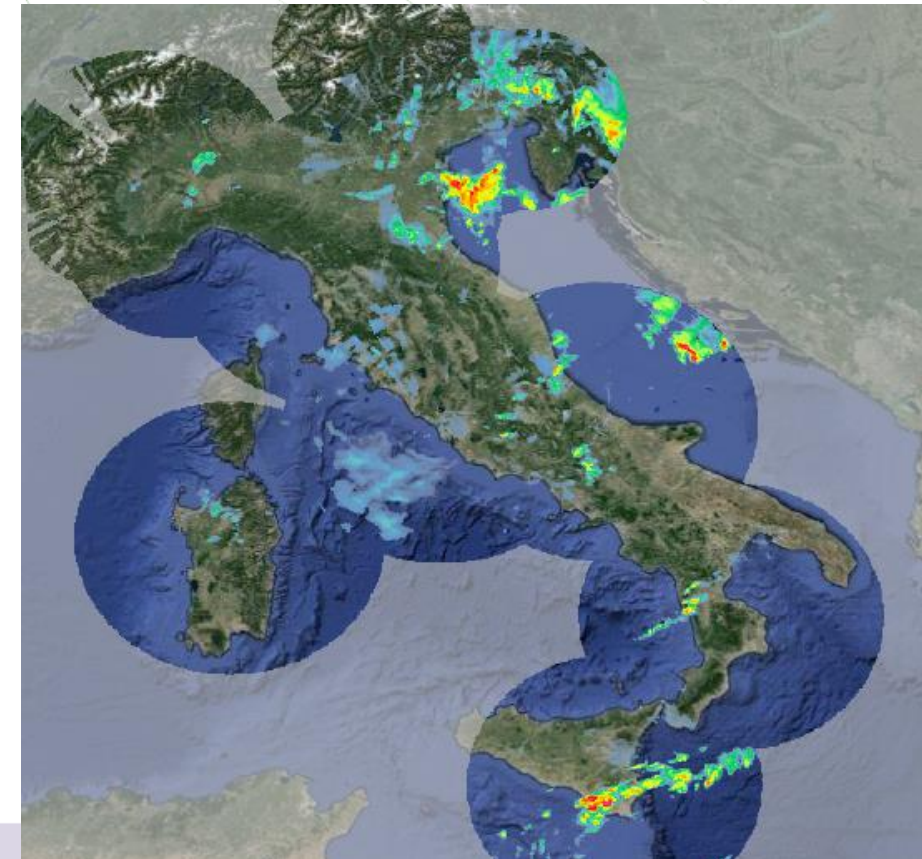
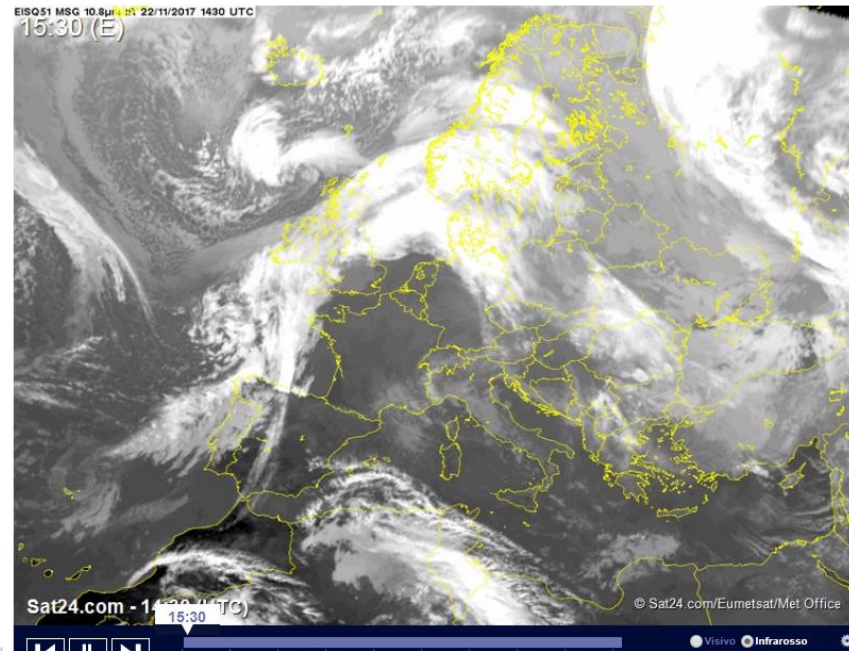
Rain gauges or radar?

RADAR (ground or satellite meteorologic radar)

 **INDIRECT** rainfall measurement

 Typical precision: 0.2mm

 **CONTINUOUS MEASURE**



Rain gauges or radar?

BOTH!

🌐 Radar measures of REFLECTIVITY (Z)

🌐 Proxy for instant rainfall intensity (mm/h)

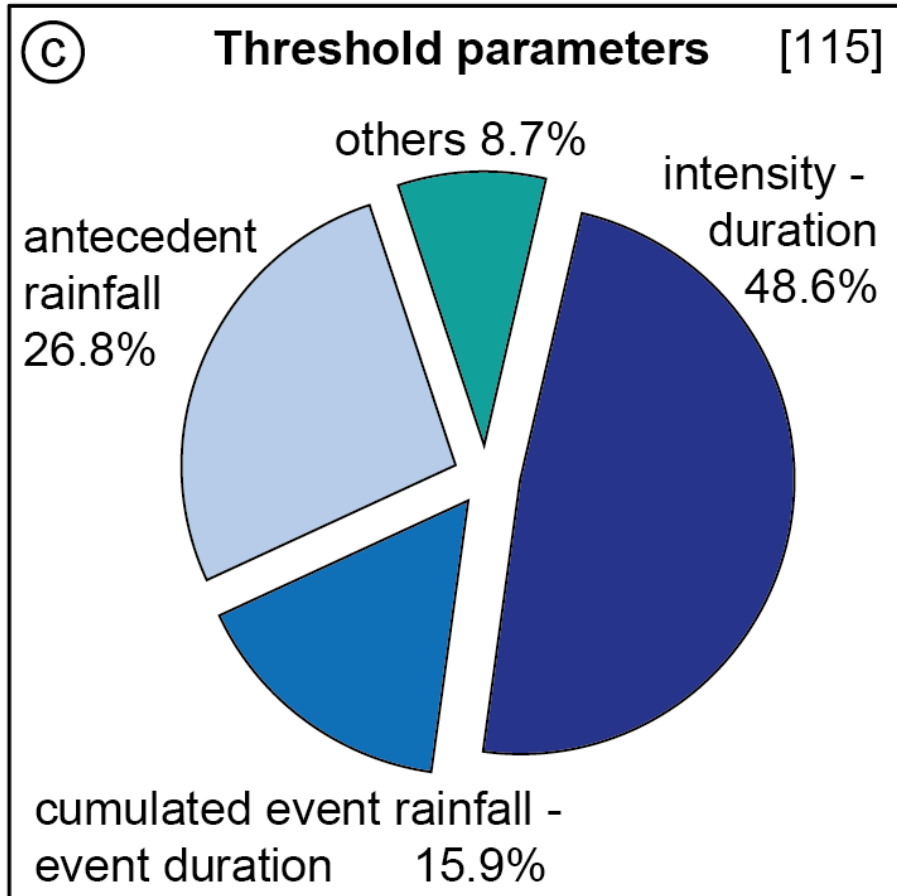
🌐 Z-I relationship

e.g.: $Z = a I^b$ (Cremonini and Bechini, 2010)

🌐 Z-I relationship calibrated with direct measures from RAIN GAUGES

🌐 **SPATIALLY CONTINUOUS** INDIRECT ESTIMATIONS OF RAINFALL INTENSITY CORRECTED BY **DIRECT MEASURES** IN RELEVANT CONTROL POINTS (rain gauges)

Rainfall parameters



The choice depends on:

🌐 Landslide typology

- I - D : shallow landslides
- Antecedent rainfall: deep seated landslides

🌐 Rainfall data characteristics

- Daily rainfall measurements = underestimation of rainfall intensity, good for antecedent rainfall

🌐 Technical constraints

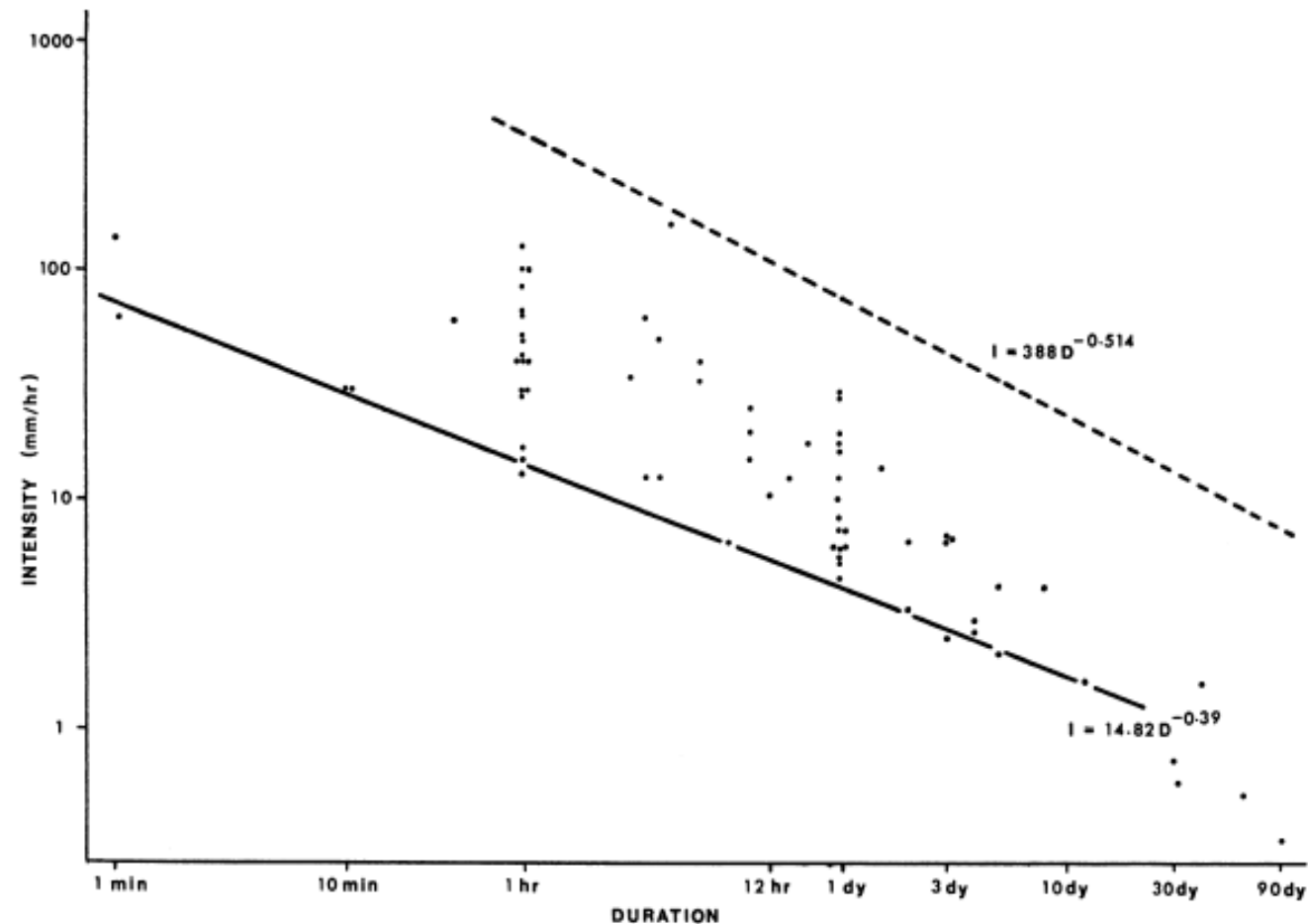
Rainfall parameters

- **THRESHOLDS BASED ON THE TRIGGERING RAINFALL**
 - **I-D (Intensity-Duration) → $I=14.82 D^{-0.39}$ (Caine, 1980)**
 - E-D (Event rainfall-Duration) → $E = 14.82 D^{0.61}$ (Caine, 1980)
 - R (Total event rainfall) → $R > 200\text{mm}$ (Endo, 1970)
 - E-I (total event rainfall - Intensity)
- **STHRESHOLDS BASED ON ANTECEDENT RAINFALL**
 - All rainfall amount before the triggering time
 - Amount of rainfall in x days before triggering time (x may vary from 1 to 365 days)
 - Same as above but weighted based on the temporal distance
- **OTHER**
 - ES: Wilson (2000) debris flow occurrence as a function of the daily rainfall normalized by the 5-year storm rainfall
 - Rainfall anomaly expressed as standard deviation from average antecedent rainfall
 - Return time

Rainfall parameters: Intensity – Duration

Caine, 1980

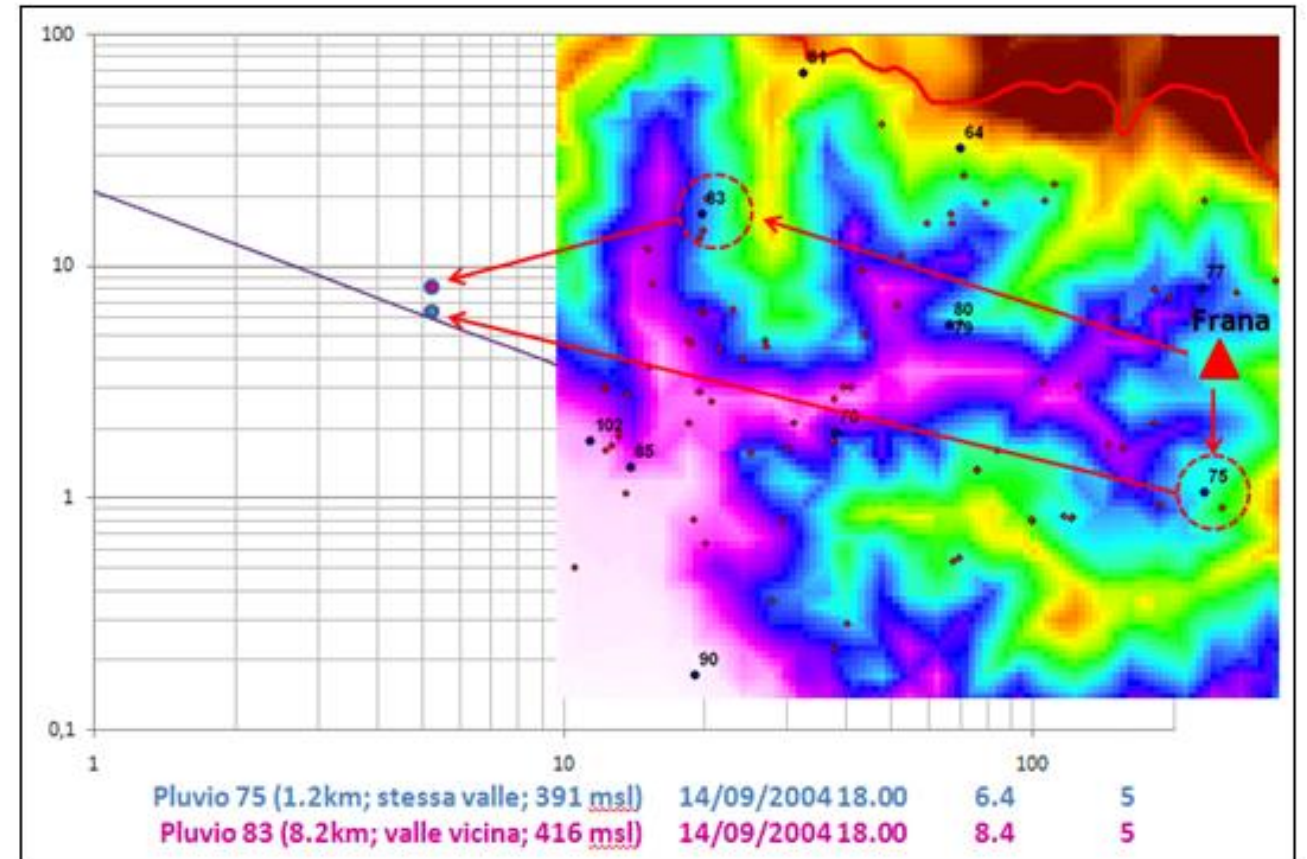
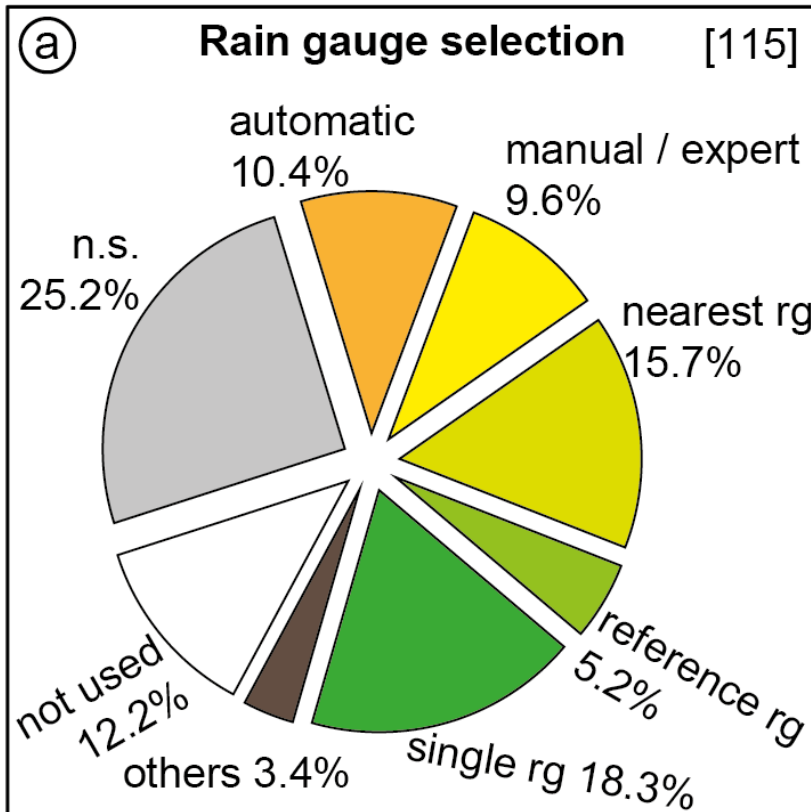
$$I = 14.82 D^{-0.39}$$



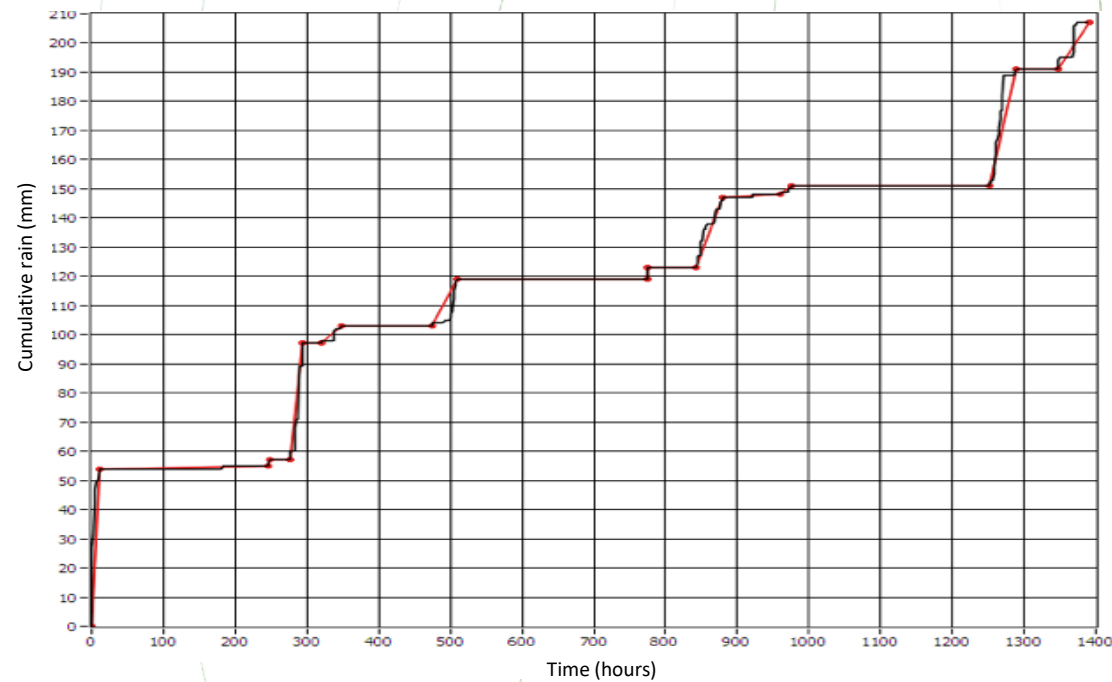
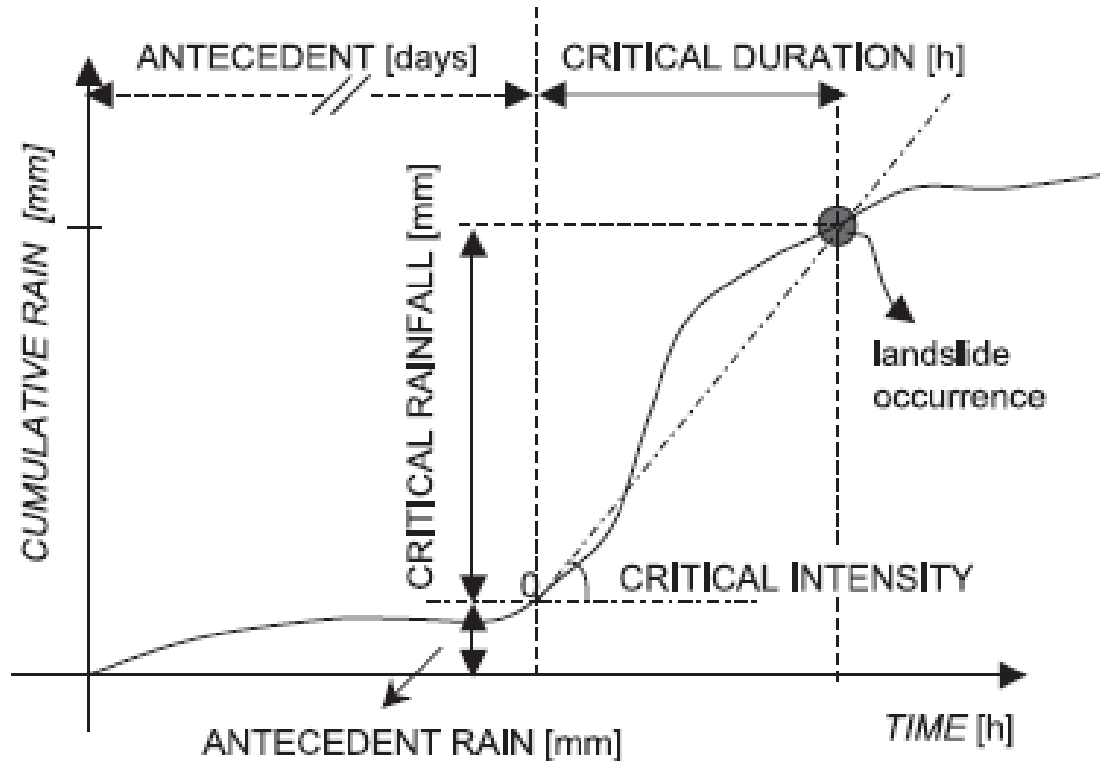
Combinations of intensity and duration for rainfall events which resulted in landslides are usually plotted in logarithmic coordinates and the thresholds are obtained by drawing lower-bound lines to the points. Most commonly, the thresholds are drawn visually, i.e., without any rigorous mathematical, statistical, or physical criterion (Guzzetti et al. 2007).

Landslide – rain gauge association

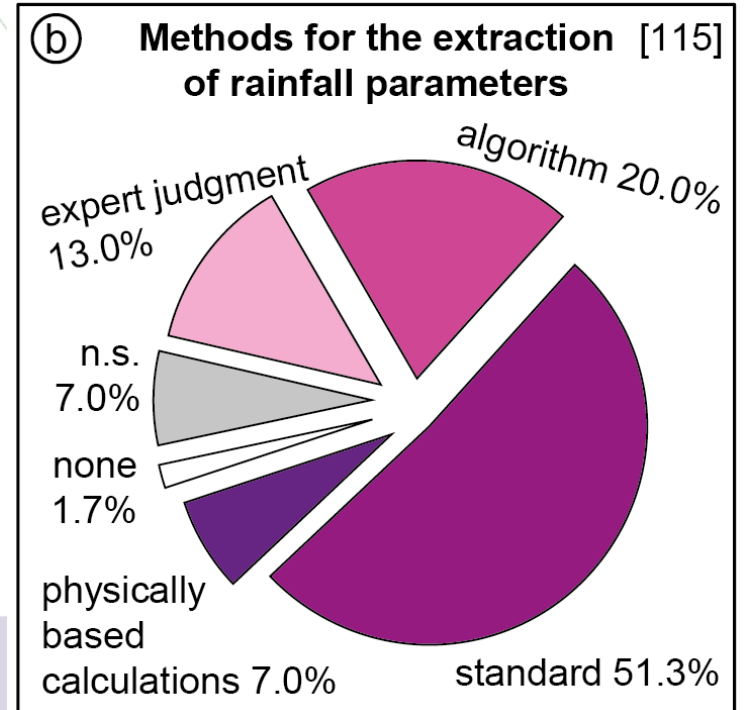
- Not used: radar
- Nearest
- Manual (expert judgment after analysis of pluviograms)
- Reference rain gauge (one among many is selected to characterize the whole area)
- Automatic (e.g. algorithm)



Rainfall parameters from pluviographs

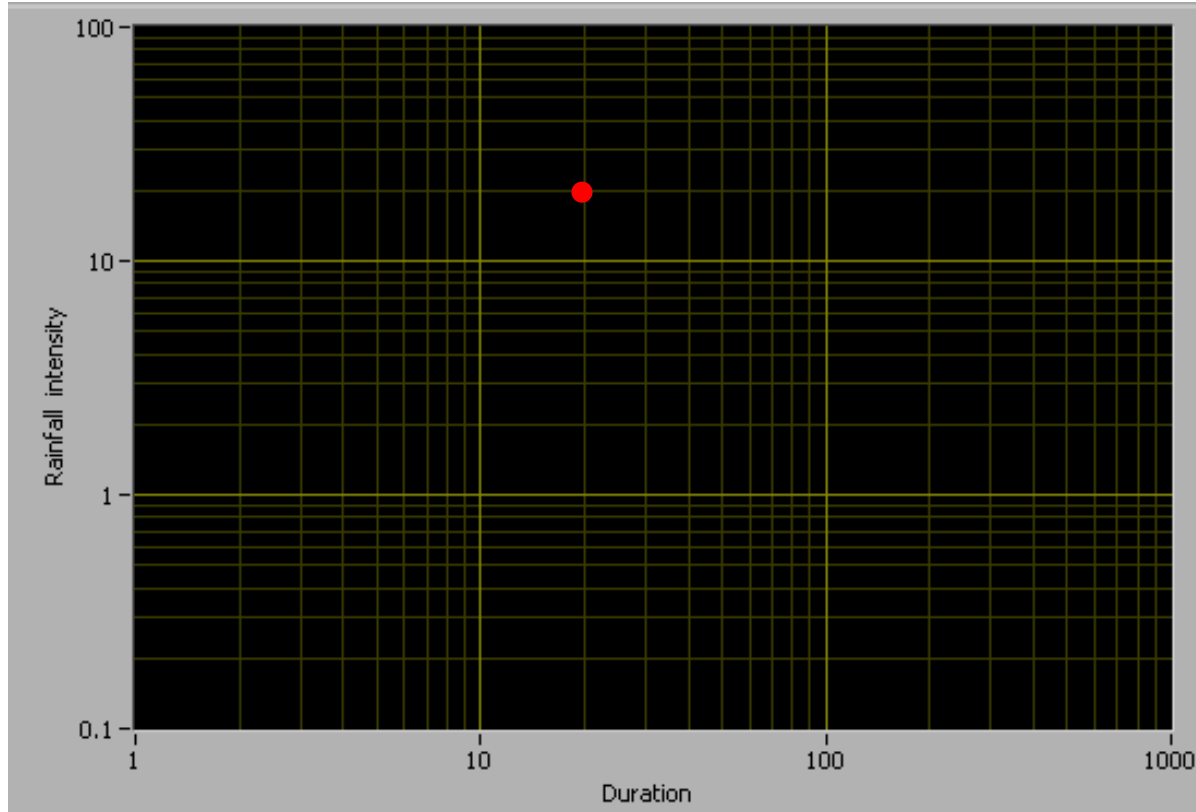


- Start/end
- When are two events separated?
- Is the choice standardizable?
- Is a computer able to replicate it in a EWS?

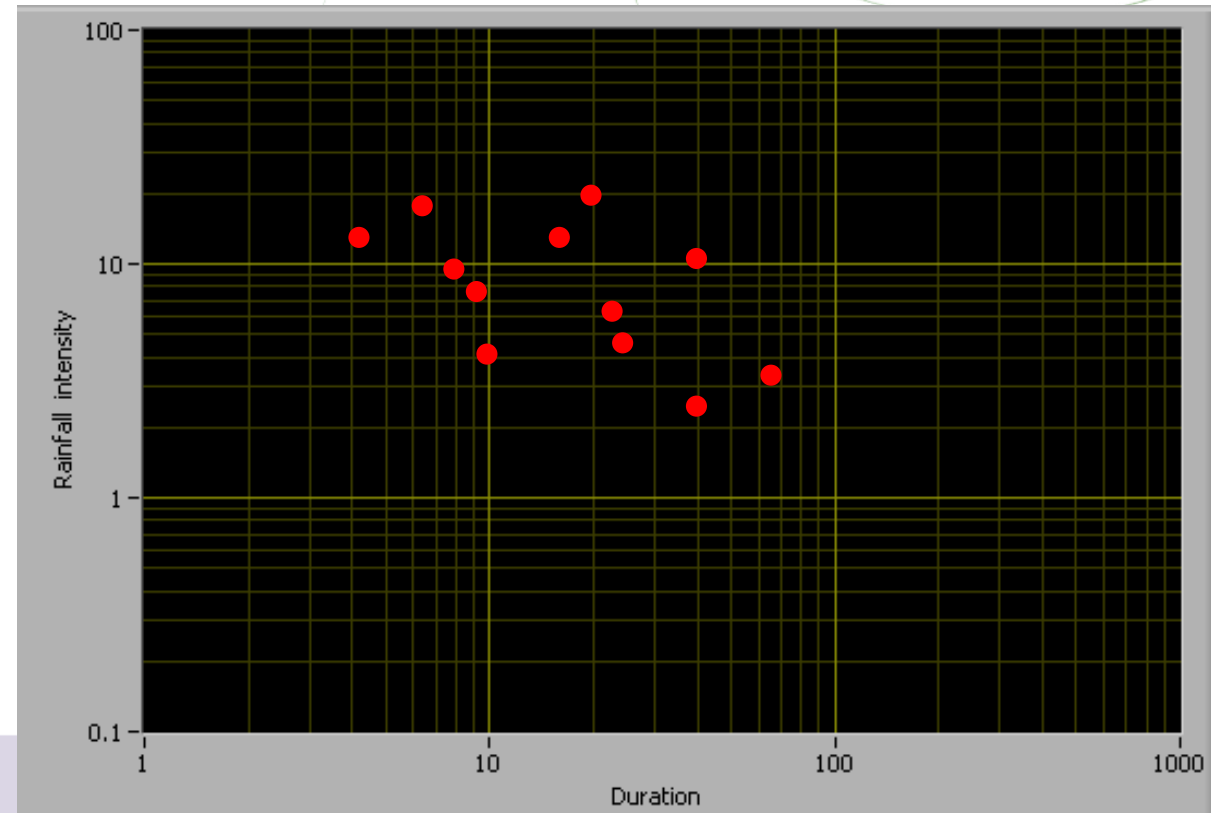


Triggering conditions

The triggering conditions are «summarized» by a point in a graph

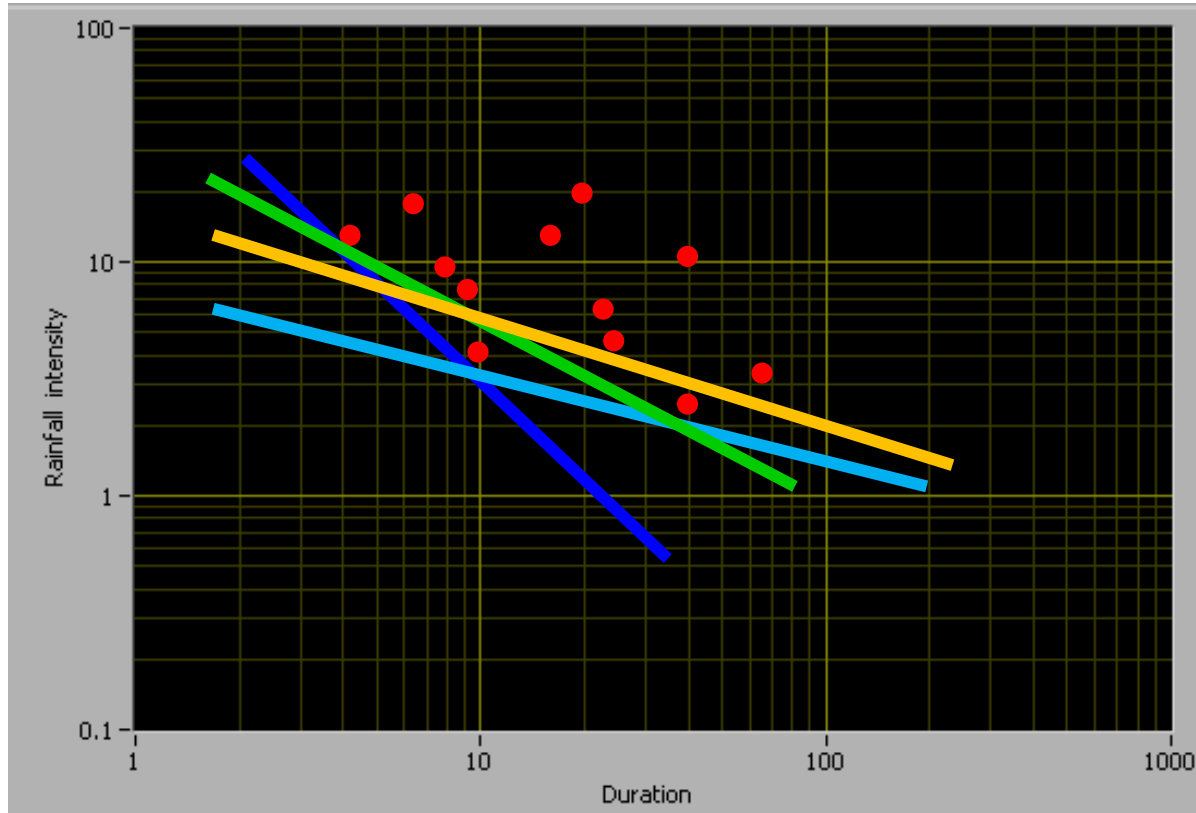


The procedure is replicated for the whole dataset

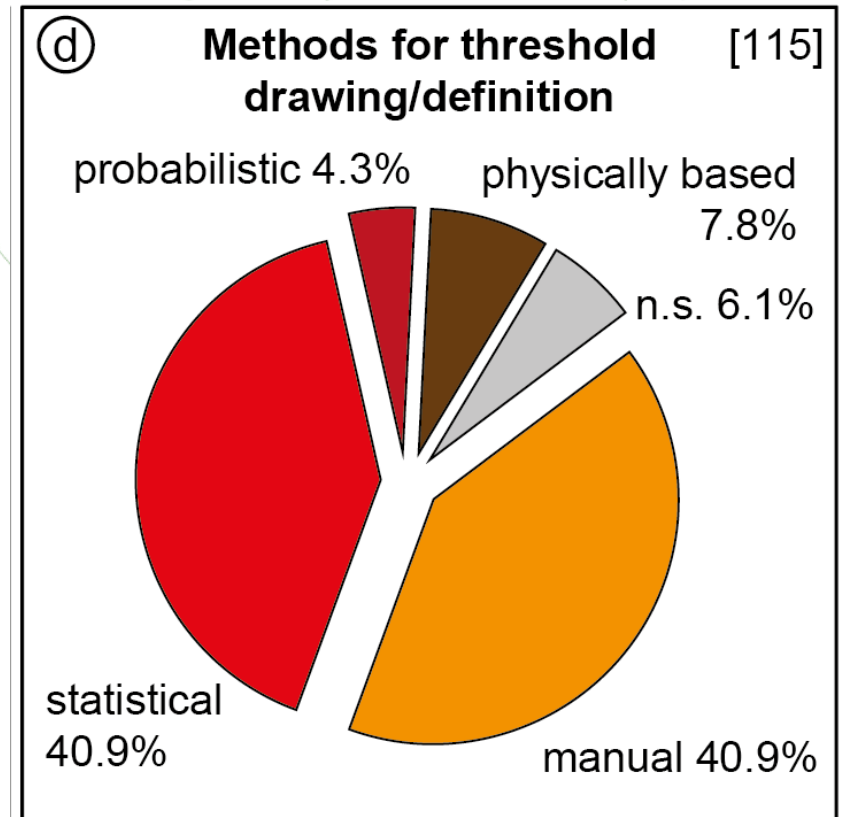


Triggering conditions

Where do you draw the line?



And how?



Triggering conditions

Where do you draw the line?

Statistical methods

- Data are fitted
- The fitting line is shifted upward/downward until a desired level

E.g.: prediction interval technique

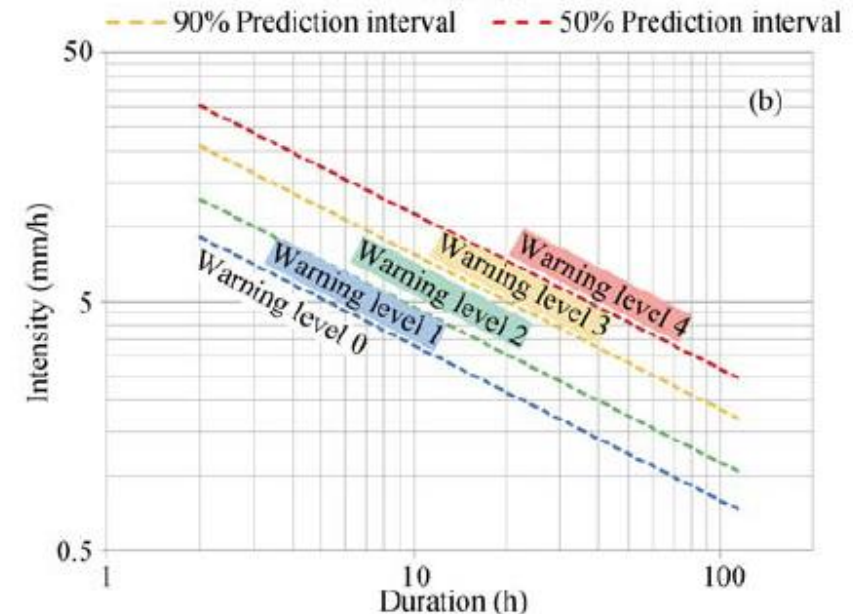
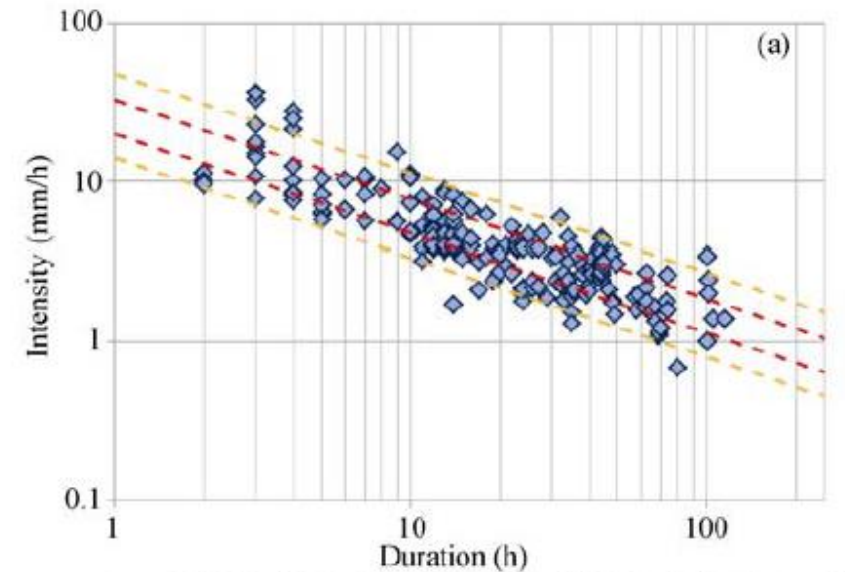
To define each prediction interval the following equations were used (3, 4):

$$X_{n+1} = \bar{X}_n \pm T_a * S_n * \sqrt{1 + \frac{1}{n}} \quad (3)$$

$$T_a = 100 * \left(1 - \frac{p}{2}\right) \quad (4)$$

where n = dimension of the sample; \bar{X}_n = sample mean; X_{n+1} = expected value; S_n = standard deviation; p = percentile used to define the prediction interval.

In this work limits that define 90% and 50% of the data distribution were calculated to define the prediction intervals (Figure 7a).



Triggering conditions

Where do you draw the line?

Probabilistic methods

E.g.: probability of exceedence

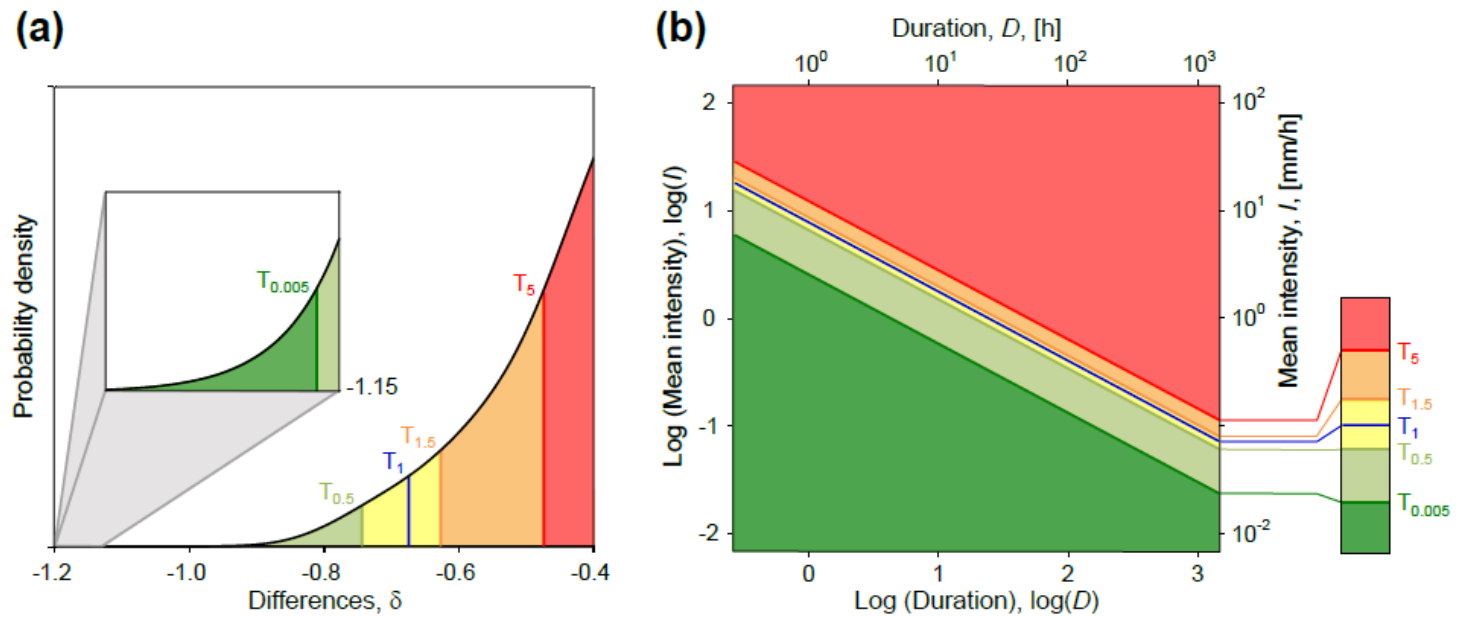
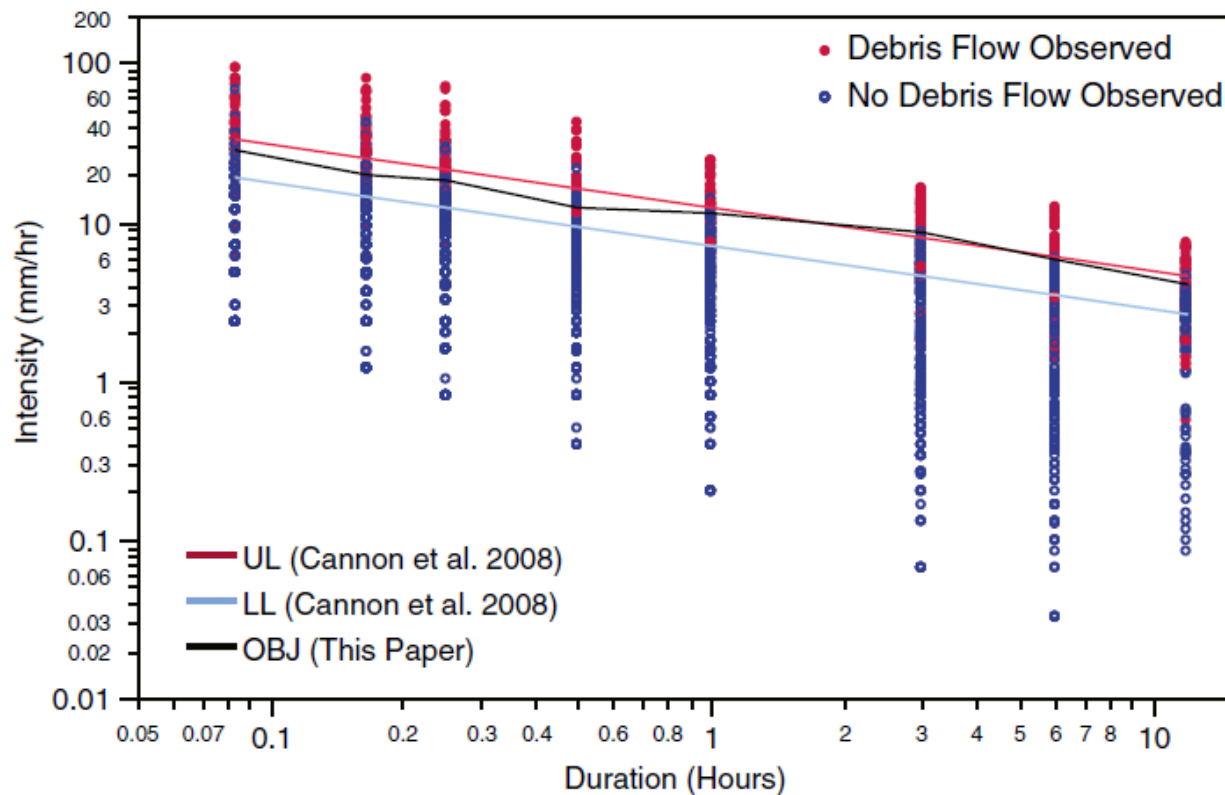


Fig. 5. Critical rainfall conditions defined by thresholds having different exceedance probability shown (a) in the Gaussian curve (see Fig. 2), and (b) in the $D-I$ plane. Legend: dark green, rainfall condition “well below the threshold”; light green, “below the threshold”; yellow, “on the threshold”; orange, “above the threshold”; red, “well above the threshold”.

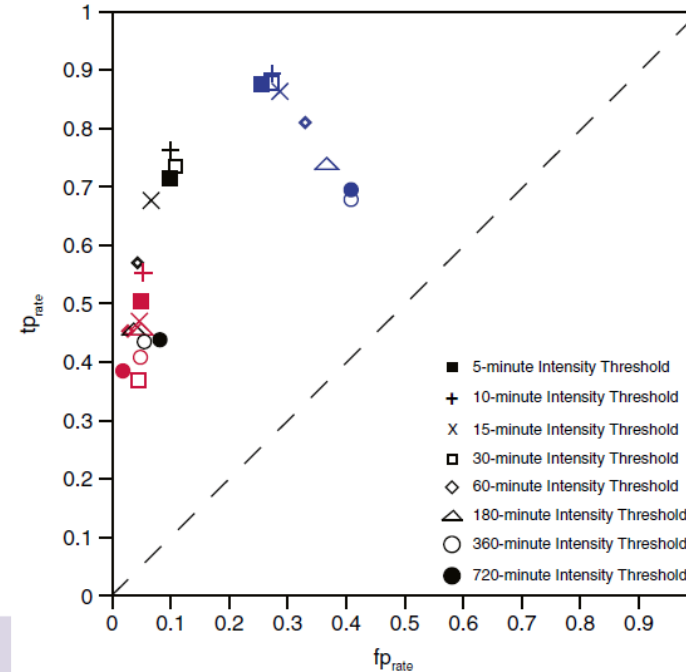
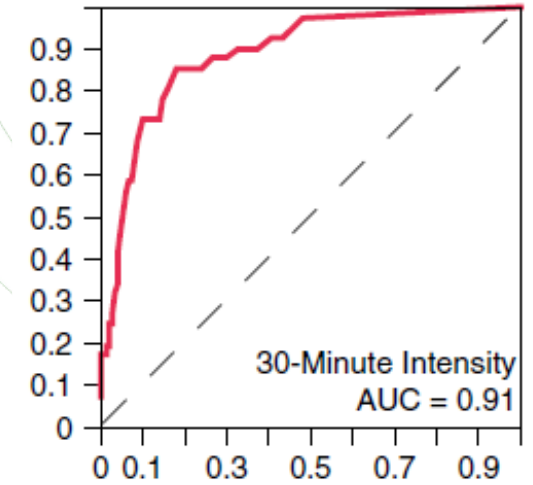
Triggering conditions

Where do you draw the line?

«Best» discriminator



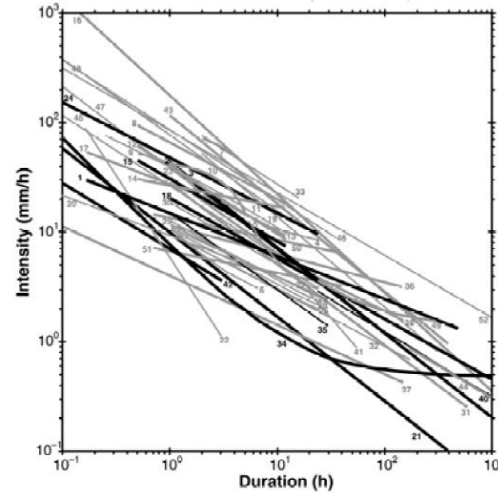
Staley et al., 2012



VALIDATION

R
I
G
O
U
R

- No validation
- Comparison with literature thresholds
- Single case study
- Quantitification of effectiveness (calibration dataset)
- Quantitification of effectiveness (independent dataset)
- As above, comparing alternate approaches/models



VALIDATION

- Validation dataset (not used for calibration)
- Identification of rainfall above and below threshold
- Identification of days with landslides
- Confusion matrix
- Skill scores (or other performance indicators)

		OBSERVED CLASS	
		Debris Flow	No Debris Flow
MODELED CLASS	Above Threshold	True Positive (TP) <i>Above Threshold, Debris Flow Observed</i>	False Positive (FP) <i>Above Threshold, No Debris Flow Observed</i>
	Below Threshold	False Negative (FN) <i>Below Threshold, Debris Flow Observed</i>	True Negative (TN) <i>Below Threshold, No Debris Flow Observed</i>

$$TP_{rate} = \frac{TP}{TP + FN}$$

$$FP_{rate} = \frac{FP}{FP + TN}$$

$$TS = \frac{TP}{TP + FN + FP}$$

Confusion matrix		LANDSLIDE	
		YES	NO
THRESHOLD EXCEEDED	YES	TP	FP
	NO	FN	TN

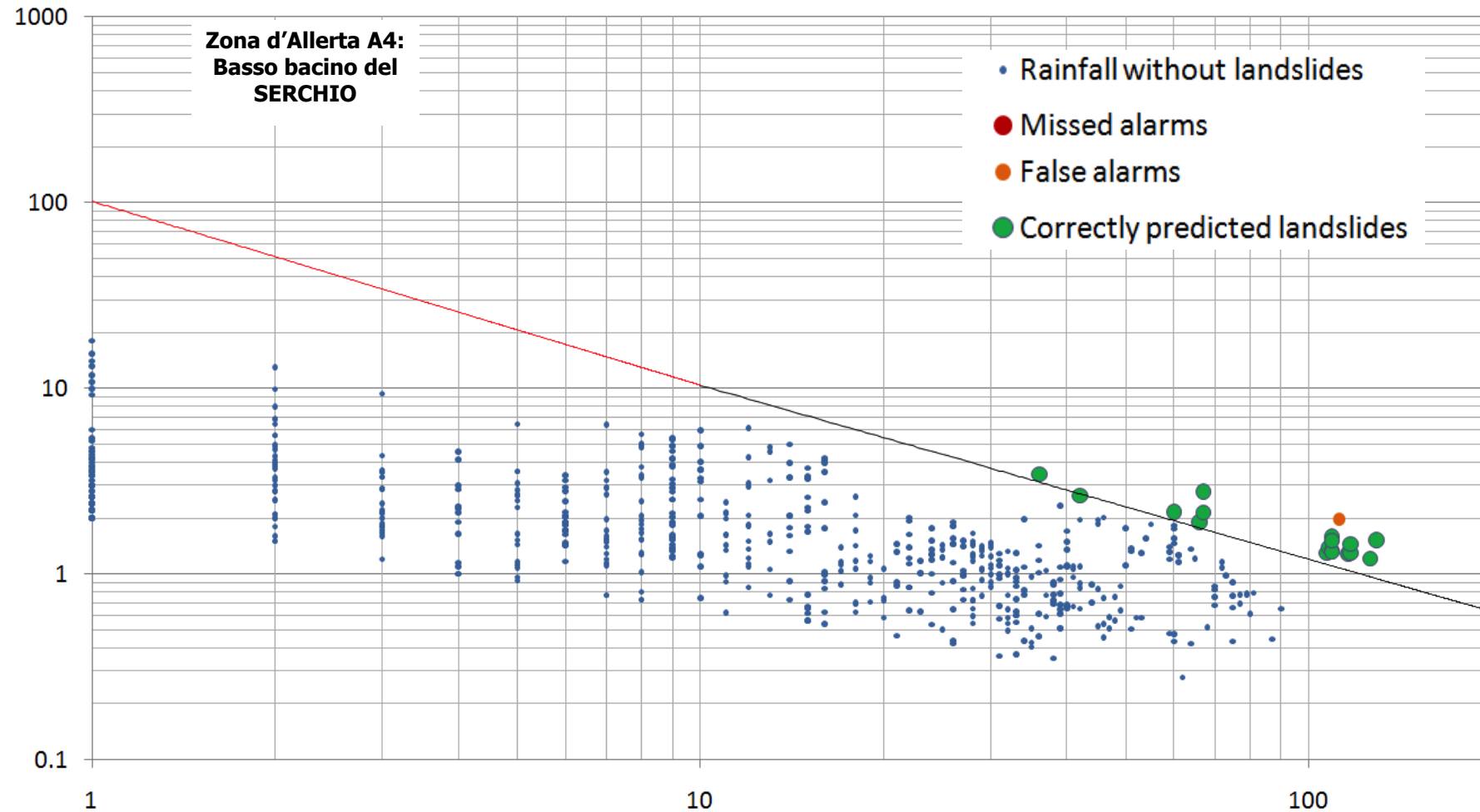
$$\text{Sensitivity} = TP / (TP + FN)$$

$$\text{Specificity} = TN / (TN + FP)$$

$$\text{Likelihood ratio} = \text{Sensitivity} / (1 - \text{Specificity})$$

VALIDATION

Example of visualization of the validation results



VALIDATION

Example of visualization of the validation results

$$I = 41.64 D^{-0.85}$$

JAN	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
FEB	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29		
MAR	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
APR	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	
MAY	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
JUN	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	
JUL	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
AUG	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
SEP	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	
OCT	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
NOV	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	
DEC	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
JAN	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31

True negatives: threshold not exceeded, no landslides

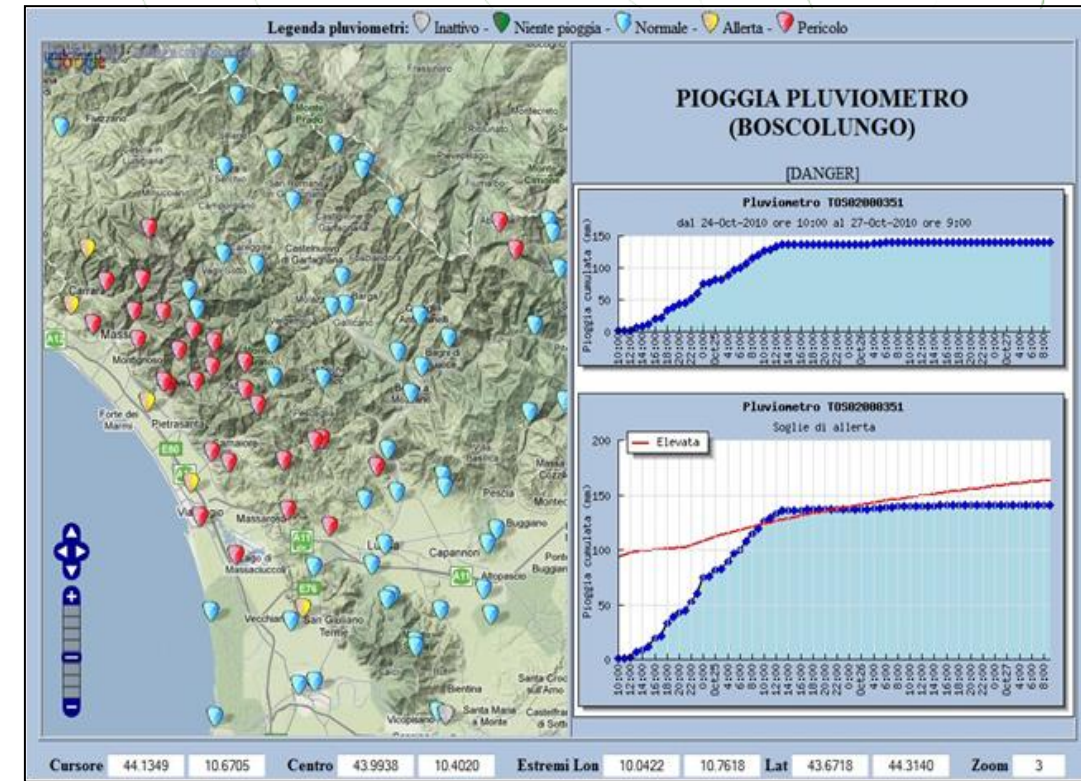
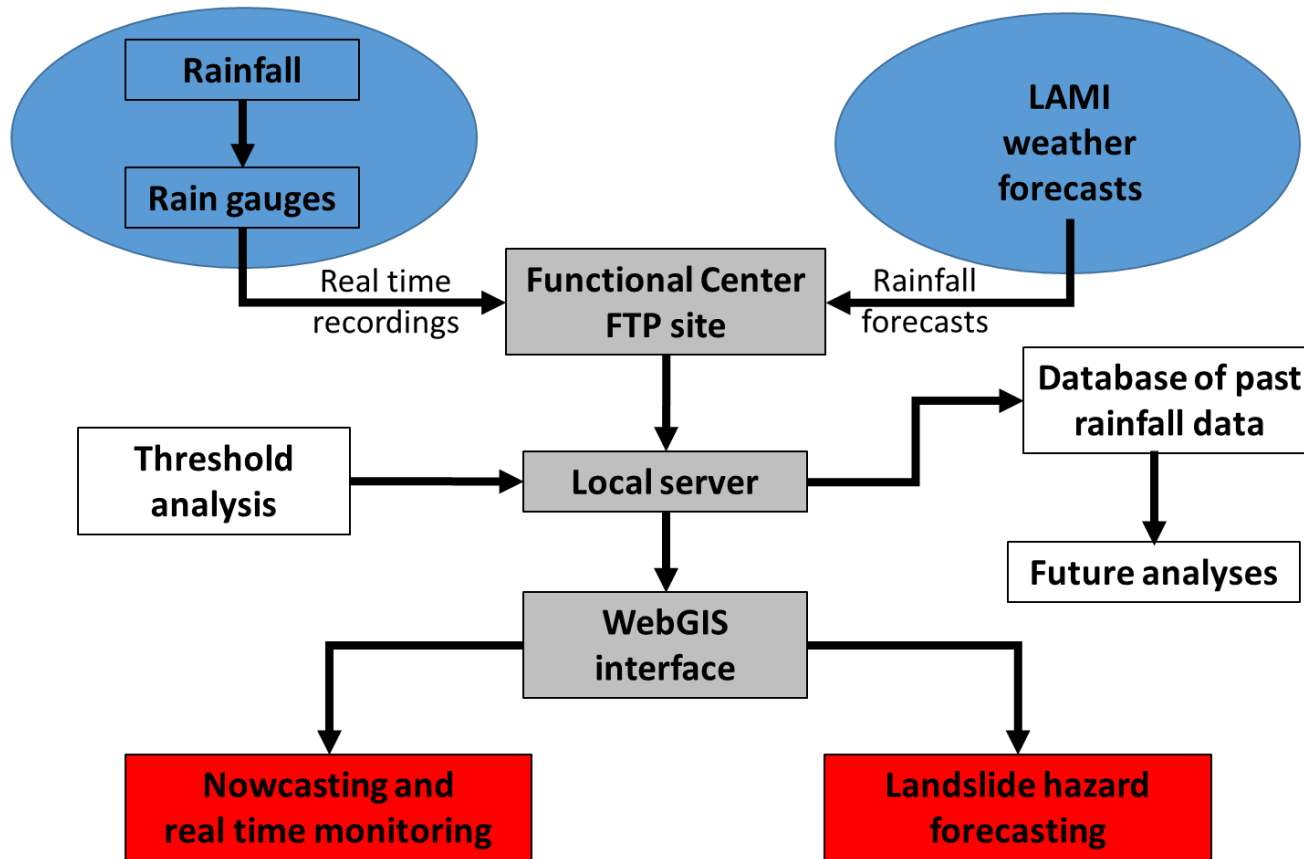
True positives: threshold exceeded, landslides triggered

False positives (false alarms): threshold exceeded, no landslides

False negatives (missed alarms): threshold not exceeded, landslides triggered

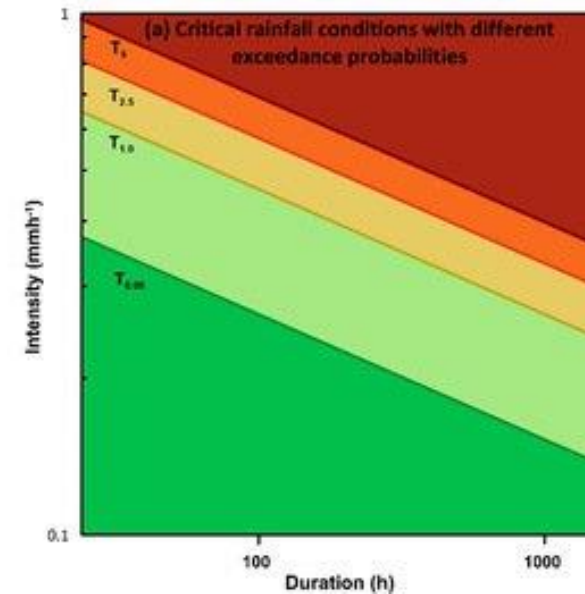
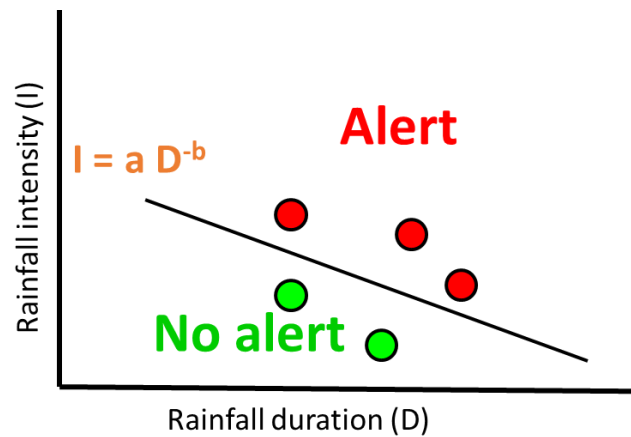
IMPLEMENTATION

From a forecasting model to a EWS: example of implementation scheme



IMPLEMENTATION

Outputs of the EWS:
«state» of the thresholds = alert levels



One threshold
→ two states of the system

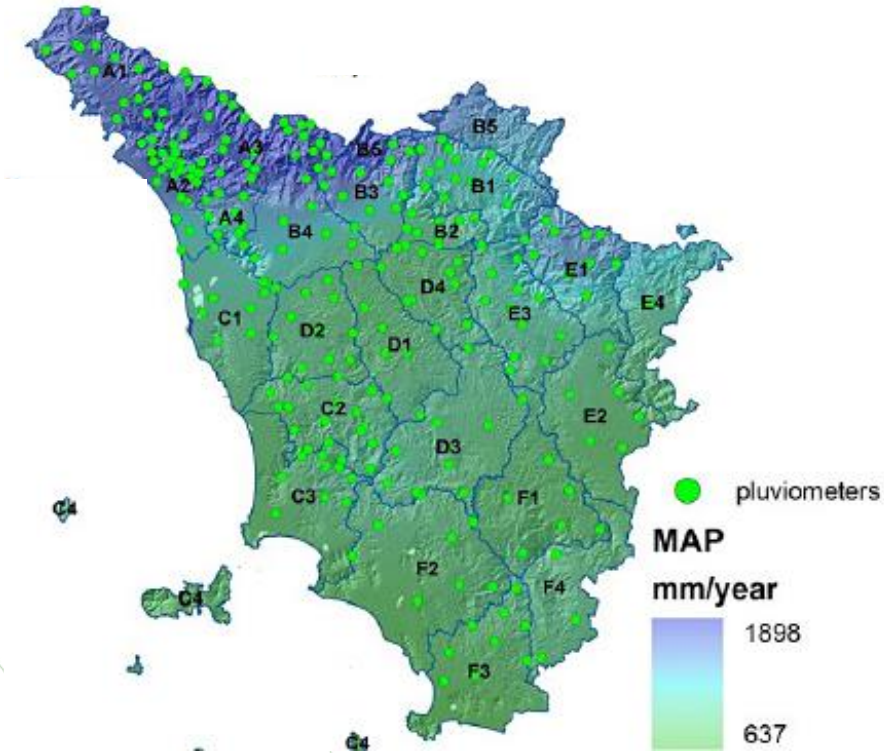
n threshold
→ $n+1$ states of the system

Mosaics of thresholds

Instead of a single threshold for a wide and heterogeneous area
It's better to use a mosaic of relatively homogeneous sub-zones.

- + Reducing the area adopted for issuing a warning (finer spatial resolution)
- + Better hazard management
- + Homogeneous conditions (rainfall; geomorphology) bring to stronger rainfall-landslide correlation
- + Increased forecasting effectiveness
- More data needed

Tuscany: 23,000 km²
25 alert zones (900 km²
each, on average)



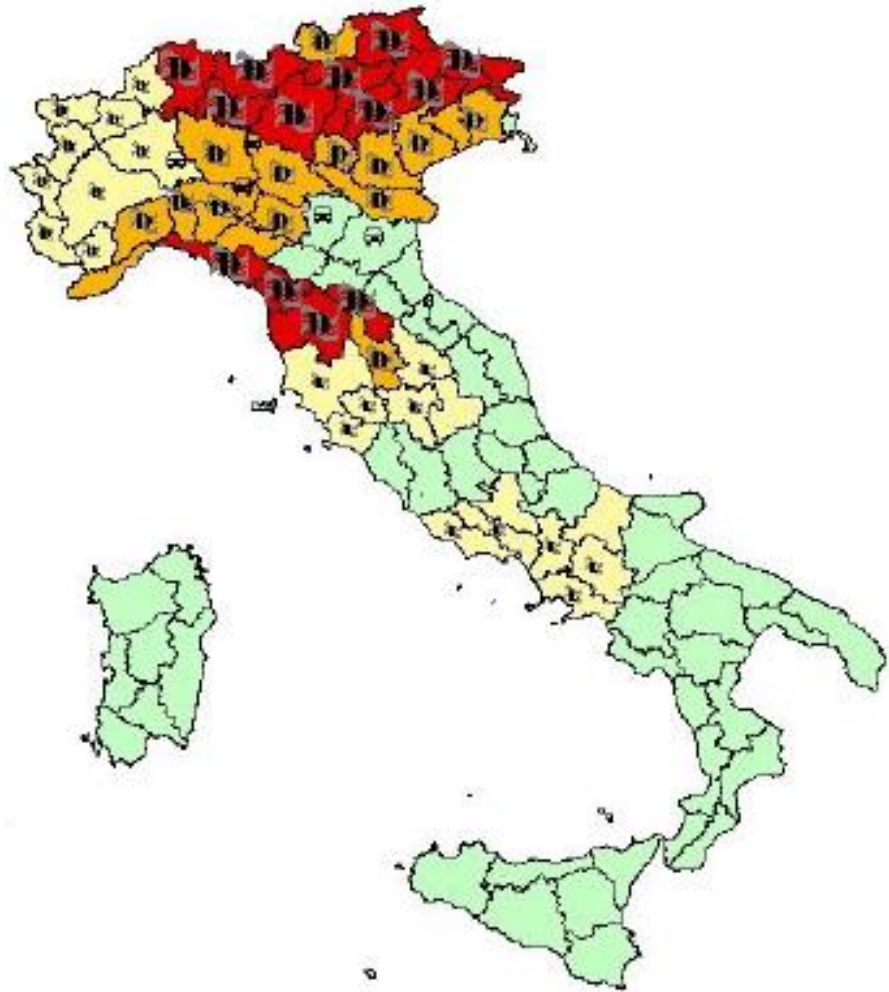
2644

S. Segoni et al.: Analysing the relationship between rainfalls and landslides

Table 4. Validation statistics of the mosaic of thresholds defined in this work, compared with literature thresholds proposed by Rosi et al. (2012) and Brunetti et al. (2010); as explained in the text, TP stands for true positives, TN for true negatives, FP for false positives, and FN for false negatives.

		This work	Regional threshold	National threshold
Sensitivity	TP/(TP + FN)	0.894	0.896	0.958
Specificity	TN/(FP + TN)	0.987	0.732	0.692
Positive predictive power	TP/(TP + FP)	0.797	0.448	0.430
Negative predictive power	TN/(TN + FN)	0.994	0.967	0.986
Efficiency	(TP + TN)/(TP + TN + FP + FN)	0.982	0.764	0.744
Likelihood ratio	Sensitivity/(1-specificity)	67.761	3.347	3.111

USE IN CIVIL PROTECTION



- Italy is divided into 170 alert zones.
- Italy is covered by a radar network and a dense rain gauge network
- In each region a Functional Center is in charge of monitoring and warning
- Outputs are standardized



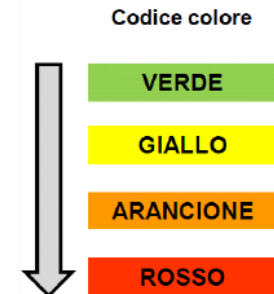
Bollettino di Martedì, 26 Marzo 2019

Codice Allerta Meteo

Situazione di Martedì, 26 Marzo 2019



Situazione di Mercoledì, 27 Marzo 2019

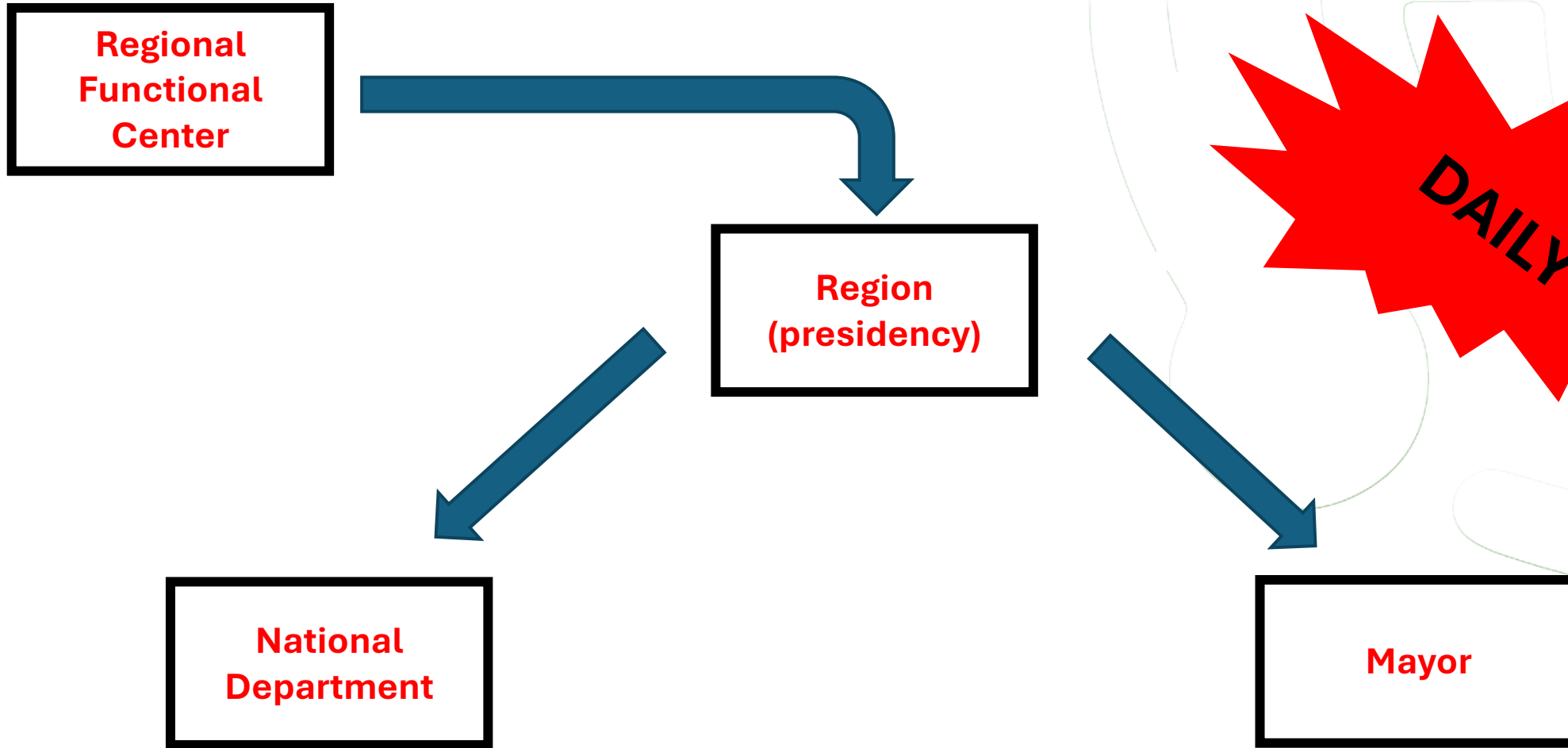


Punti di forza:

- Semplicità e univocità (comunicazione)
- Applicabile a tutti i rischi
- Analogia con altri sistemi
- Uniforme a livello nazionale
- Coerente con EU-MeteoAlarm
- Non dipendente da lingua (48ML turisti/anno)

Codice colore	Criticità	Fenomeni meteo-idro	Scenario d'evento	Effetti e danni	
Verde	Assente o poco probabile	Assenti o localizzati	IDRO/GEO	Assenza o bassa probabilità di fenomeni significativi prevedibili (non si escludono fenomeni imprevedibili come la caduta massi).	Danni puntuali e localizzati.

USE IN CIVIL PROTECTION



Activates the emergency plan and informs the population exposed to risks

Let's practice with rainfall measures

How much is 1 mm of rainfall?

Tomorrow it is expected **10 mm** of rainfall
The critical slope is **1 hectare wide** (100m x 100m)

How many liters of rainfall it will receive?

$$\text{Height} = 10 \text{ mm} = 0.01 \text{ m}$$

$$\text{Base} = 100 \text{ m} \times 100 \text{ m} = 10,000 \text{ m}^2$$

$$\text{Volume} = 0.01 \times 10,000 = 100 \text{ m}^3 = 100,000 \text{ liters}$$

Let's practice with rainfall measures

How much is 1 mm/h of rainfall intensity?

Yesterday it has rained.

The mean rainfall intensity has been 10 mm/h

The critical slope is **1 hectare wide** (100m x 100m)

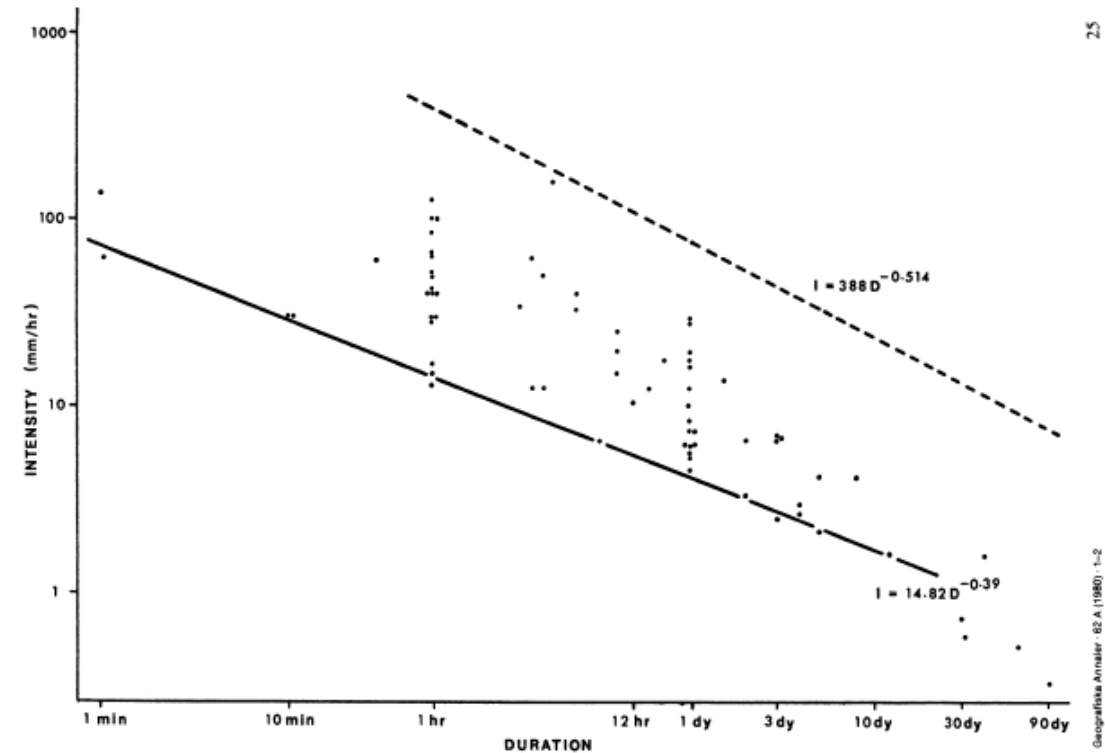
How many liters of rainfall it has received?

Rainfall amount = 10 mm/h x 24 h = 240mm

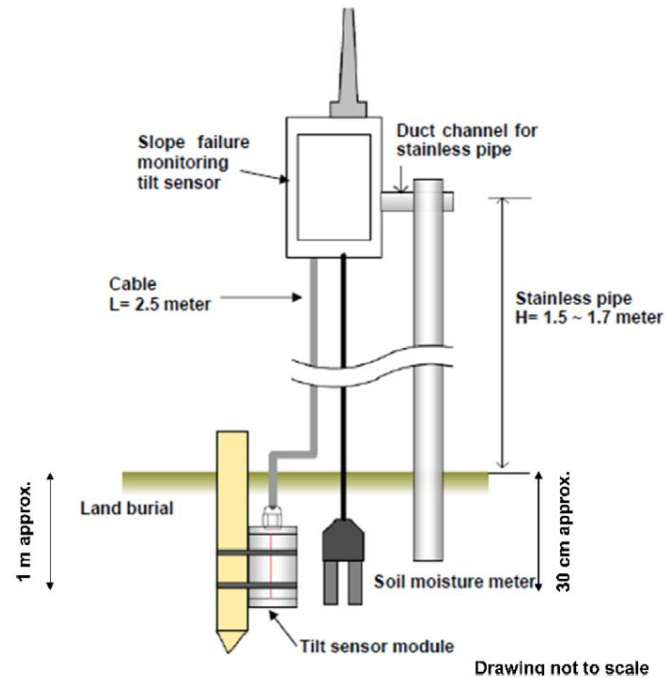
Height = 240 mm = 0.24 m

Base = 100 m x 100 m = 10,000 m²

Volume = 0.24 x 10,000 = 2400 m³ = 2,400,000 liters



Recent advances: hydro-meteorological thresholds



In addition to (or instead of) **rainfall** measured by rain gauges

Soil moisture (or similar parameters) measured by in-situ sensors

Pros:

- Better constraint of soil conditions
 - Conceptual advance

Cons:

- Difficult extrapolation of measures (very site-specific measures)
 - Limited past dataset

VALIDATION (3 years)	SIGMA	SIGMA + hydro	Improvement
😊 TP (true positives)	88	88	=
😞 FP (false positives)	70	38	-46%
😞 FN (false negatives)	3 *	3 *	=
😊 TN (true negatives)	996	1028	

Recent advances: thresholds & susceptibility

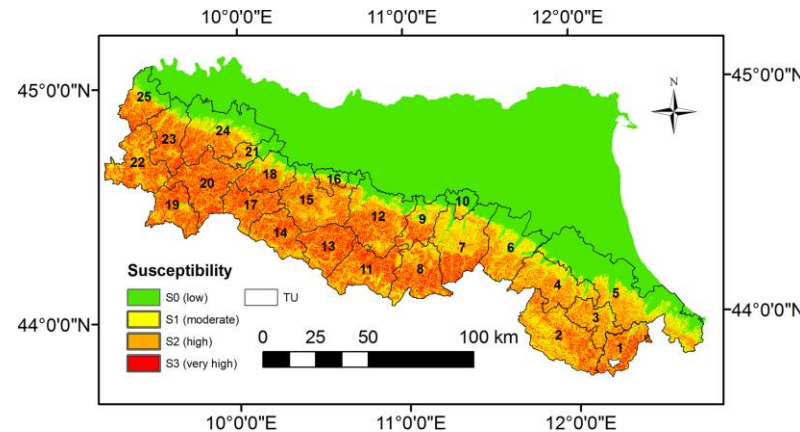
Objective: improving the spatial resolution of the EWS

SUSCEPTIBILITY MAP

Statistical correlation among landslides and PREDISPOSING FACTORS

+ Spatial forecasting (fine spatial resolution)

- Static map (no temporal information)

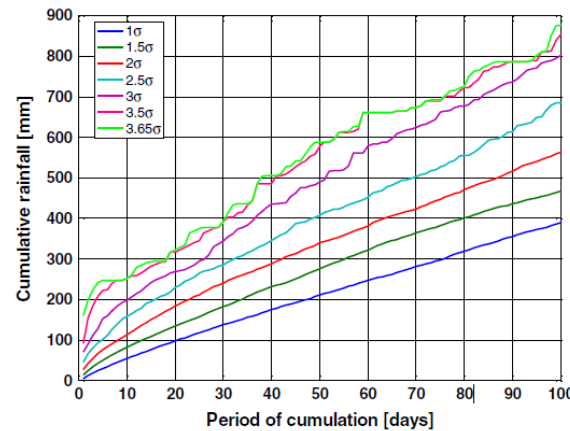


RAINFALL THRESHOLDS

Empirical correlation among landslides and the TRIGGERING FACTOR (rainfall)

+ Temporal forecasting

- Coarse spatial resolution (alert zone)



	S1	S2	S3
R1	H0	H1	H2
R2	H1	H2	H3
R3	H2	H3	H4

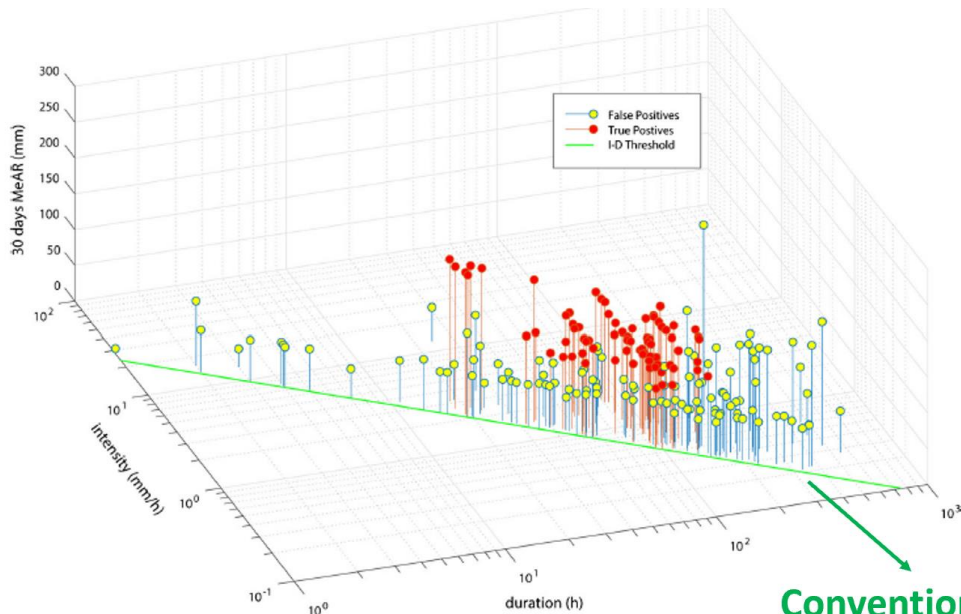
Dynamic hazard matrix

Recent advances: 3 D thresholds

Why working on a plane with a linear threshold?

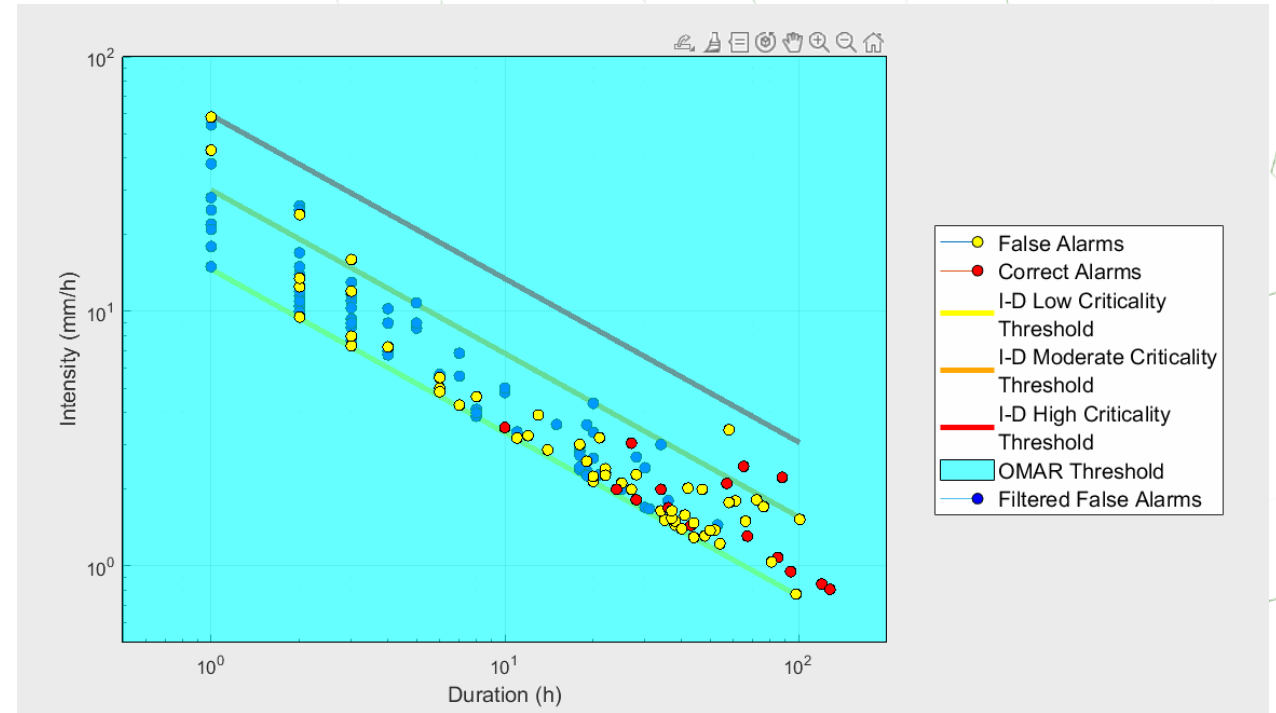
3 rainfall parameters

The threshold is a plane in a 3D space



Conventional I-D threshold

3rd dimension:
Mean Antecedent Rainfall



Recent advances: unlimited dimensions

Predisposing factors (STATIC)

DEM	aspect
Slope gradient	curvature
Lithology	Land cover
Wetness index	ecc...



Triggering factors (DYNAMIC)

Daily rainfall
Antecedent rainfall 1
Antecedent rainfall...
Antecedent rainfall n



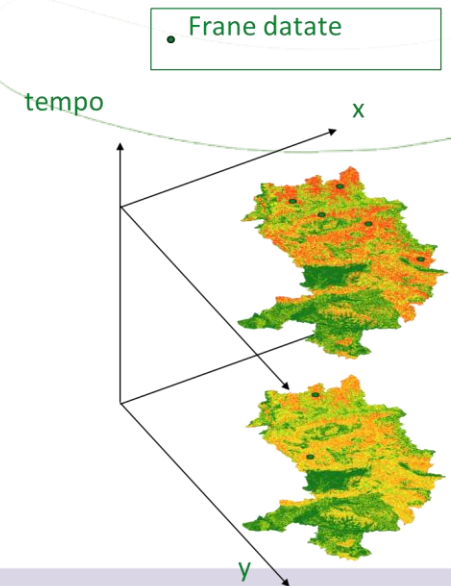
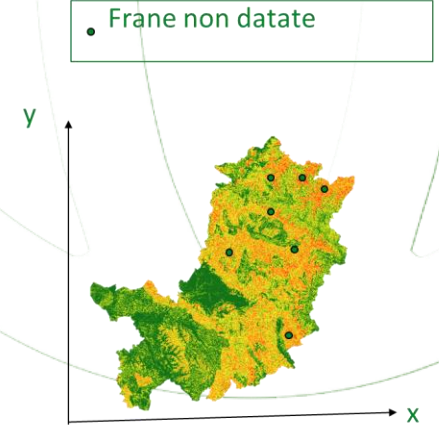
Machine Learning



Dynamic Machine Learning

Landslide susceptibility (Spatial prediction) STATIC MAP

Probability of occurrence (spatio-temporal prediction) DYNAMIC MAP





THANKS!

IR0000032 – ITINERIS, Italian Integrated Environmental Research Infrastructures System
(D.D. n. 130/2022 - CUP B53C22002150006) Funded by EU - Next Generation EU PNRR-
Mission 4 “Education and Research” - Component 2: “From research to business” - Investment
3.1: “Fund for the realisation of an integrated system of research and innovation infrastructures”

