Assessment of landslides susceptibility and reactivation likelihood in the Emilia Romagna region (Italy)

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ANTICIPATION

MODEL 1 (2006)		MODEL 2 (2009)
"NEW" LANDSLIDES (areas outside landslide boundaries)	Target Area	MAPPED LANDSLIDES
Triggering areas susceptibility	Focus	reactivation likelihood
Multivariate statistic analysis (logistic regression)	Methods	Statistic and Heuristic analysis (geomorphologic method)

Extent → entire Emilia-Romagna Apennines (11'000 Km²)

Background: LANDSLIDE INVENTORY MAP - 1:10'000 Scale

From SGSS WebGIS: (http://ambiente.regione.emilia-romagna.it/geologia/cartografia/webgis-banchedati/cartografia-dissesto-idrogeologico)

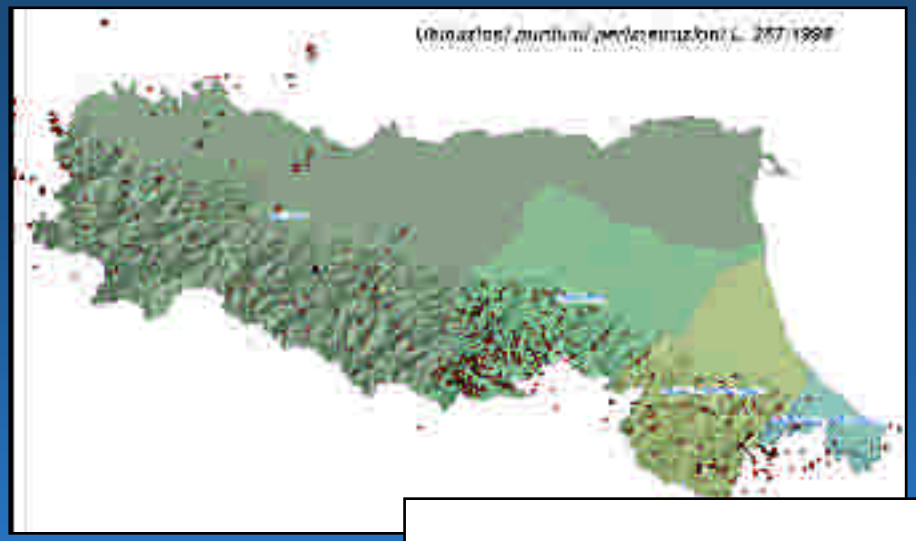
FEATURES

- Derived by '80-'90 field survey for 1:10'000 geological map;
- Coverage ≈ 11'000 Km^2;
- Continuously updated by: aerial photo interpretation, public and private reports, field surveys, InSAR and LiDAR data;
- ≈ 80'000 landslide accumulations (mean Landslide Index ≈ 24%);
- Attended by an historical archive with ≈ 11'000 landsliding events.
- **FEEDBACK: ≈ 80% of recent events > 5'000 m^2 and ≈ 95% > 20'000 m^2 fall totally or partially inside a mapped landslide.**

SHORTCOMINGS

- It is lacking in small landslides, (especially dormant);
- Maps only landslides accumulations (not depletion areas or main scarp);
- There's no natively kinematic classification between slides, earth flows and complex landslides…;
- State of Activity (active/dormant) defined in a subjective, inhomogeneous and diachronic way…;
- It's all but annually updated ➔ active for 20-30 years…
- IT DOESN'T PROVIDE ANY INFORMATION ABOUT AREAS OUTSIDE THE LANDSLIDES OR PREDICTIONS ABOUT THE FUTURE EVOLUTION OF THE MAPPED LANDSLIDES

Background: Land-Use Planning ➔ Hazardous use of Landslide Inventory Map



Apart of the areas interested by L.267/1998 Hazard Zonization… (~3% Apennine) land-use planning is mainly based on mapped Landslide Activity State

➔ ACTIVITY STATE is assumed as an HAZARD Indicator!!!

CAN WE RELY (just) ON ACTIVITY STATE FOR LAND-USE PLANNING ???

NO ! ➔

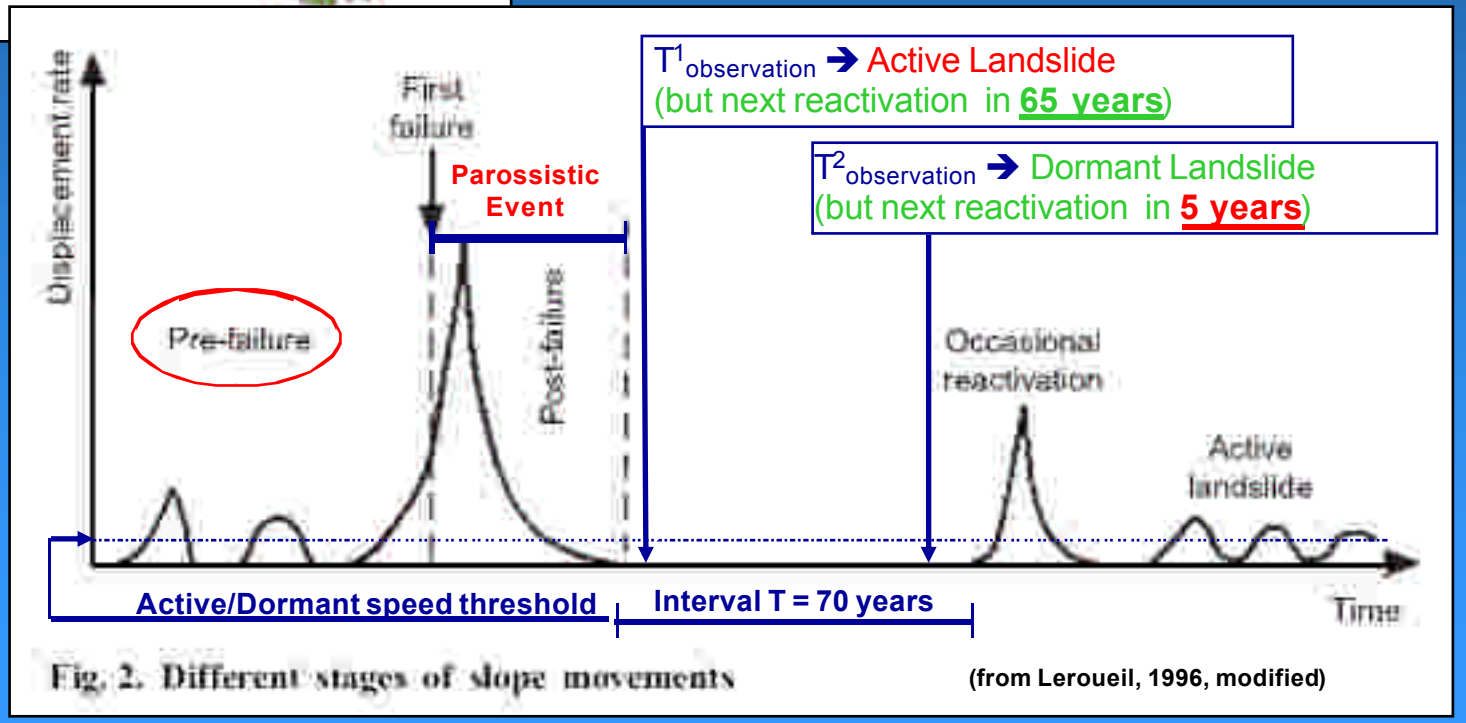
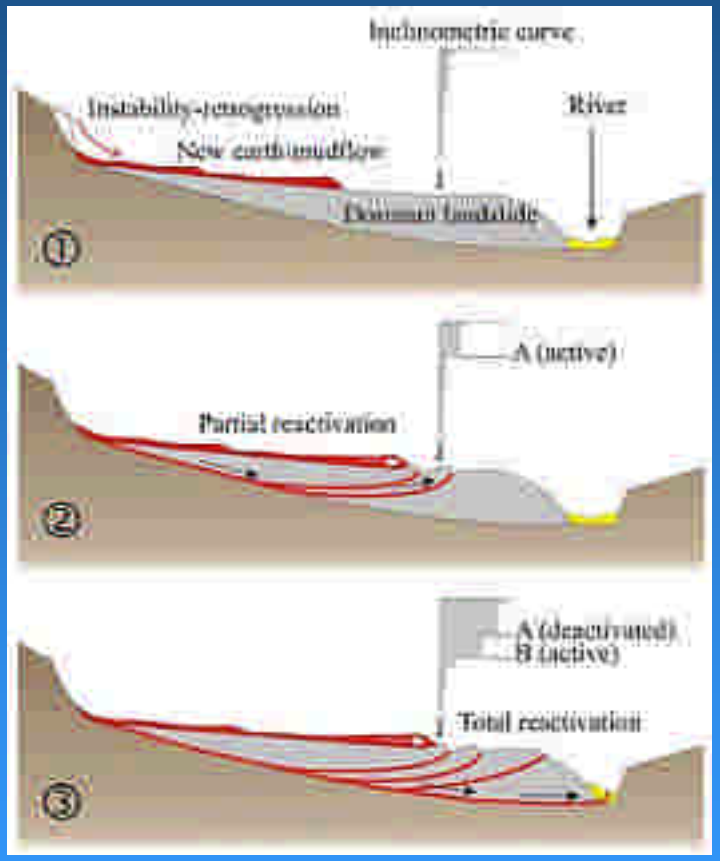


Fig. 2. Different stages of slope movements

(from Leroueil, 1996, modified)

Background: Reference Landslides and LANDSLIDING PROCESS

SLIDES, EARTH-FLOWS, COMPLEX LANDSLIDES → **different evolution for a (often) common triggering process!**



(from Bertolini & Pizziolo, 2008)

Even huge landslides are often reactivated by small and quite shallow landsliding !!!

MODEL 1 ➔ Landsliding Triggering Susceptibility

Conceptual choices

- **Focused on the forecast of shallow landslide initiation**

  ➔ **in the areas outside the mapped landslides boundaries.**

- **Process oriented (landsliding), not on the final product (landslide)**

  ➔ **calibration on depletion areas (not deposits).**

Strategic choices

- **Base unit: DEM 10x10m (ed. 1976) ➔ high level of detail required (scale 1:5'000 or better).**

- **Analysis method: Multivariate Binomial Logistic Regression ➔ main advantages:**

  1) ideal for dichotomous dependent variable: (landslide YES/NO);

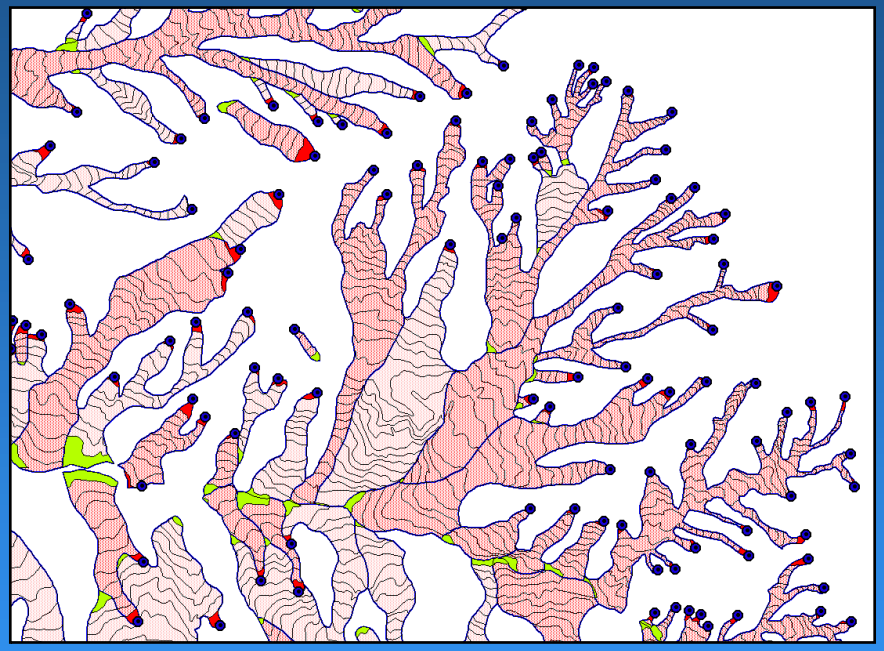
  2) can manage both continuous (slope, etc.) and categorical (litho-technic, etc.) variables;

  3) the results can be directly assumable as landsliding probability.

MODEL 1 ➔ Landsliding Triggering Susceptibility

Modellization process

1. **Choice of stable and unstable areas** - depletion areas are not mapped in LIM ➔ Local TOP



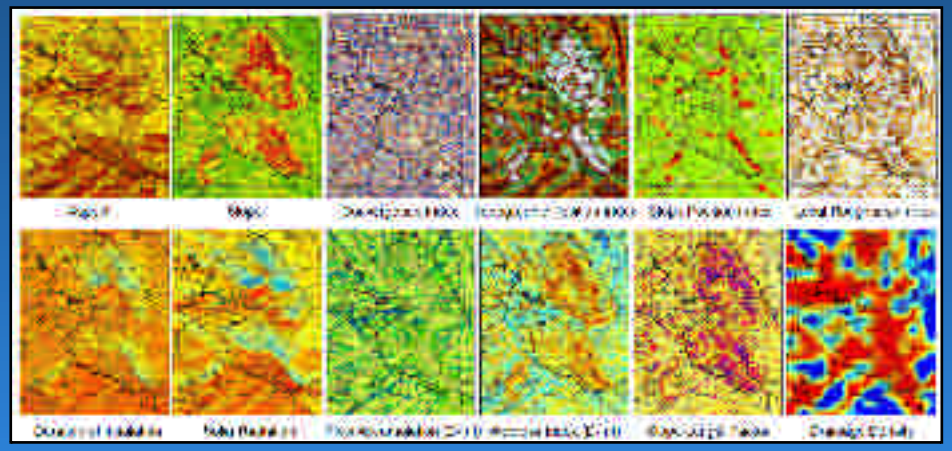
Unstable Areas ➔ ≈ 112.000 apex cells

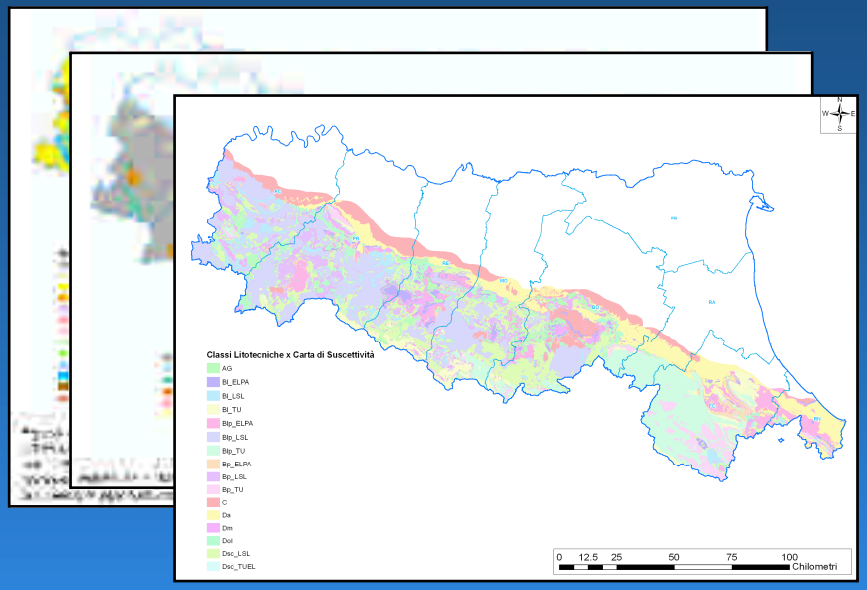
Stable Areas ➔ 130'000 "presumably stable" points randomly sampled "far outside" (>30m) mapped landslides (and slope deposits)

MODEL 1 ➔ Landsliding Triggering Susceptibility

Modellization process

2. **Build of independent variables:**



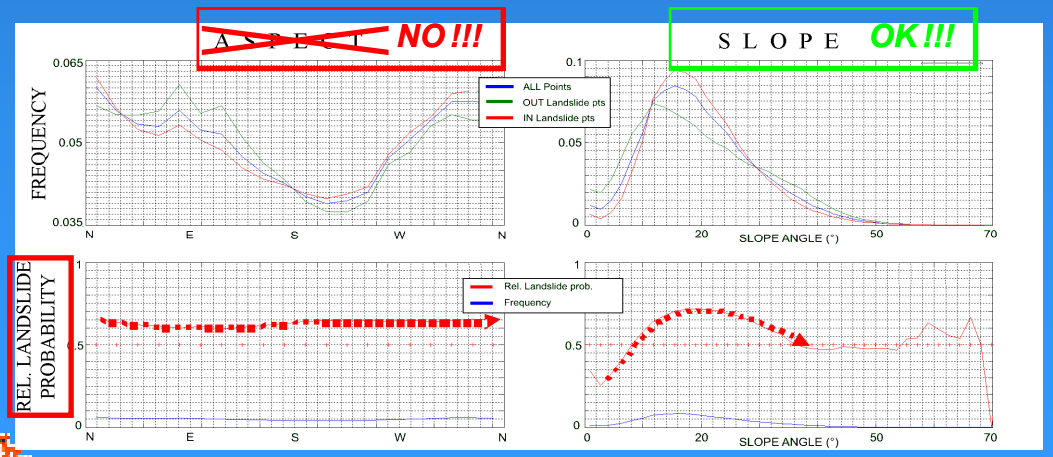


3. **Preliminary analysis of the independent variables:**

   1) cross correlation matrix;

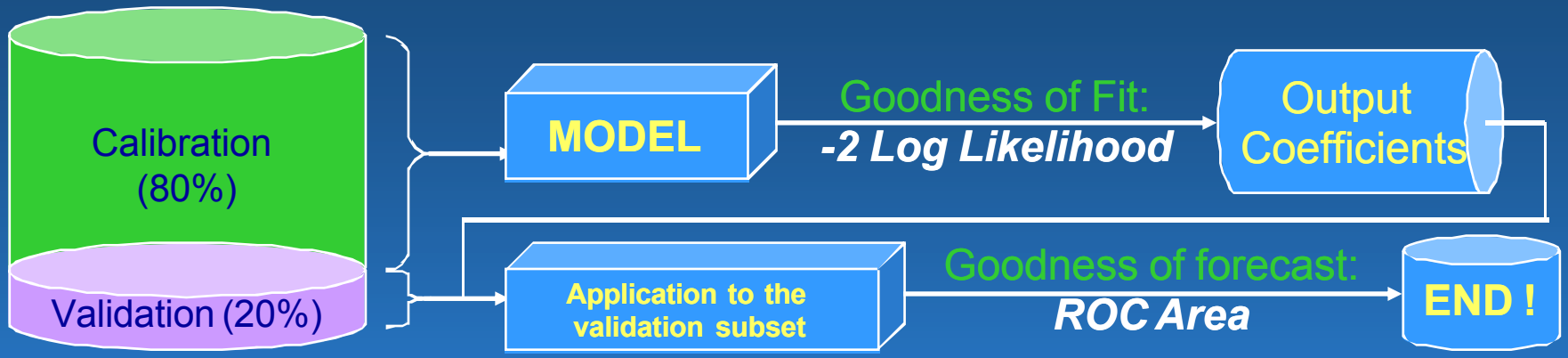
   2) bivariate (bayesian) analysis

   (for single variables effectiveness).



MODEL 1 ➔ Landsliding Triggering Susceptibility

4. Application of the multivariate regression:



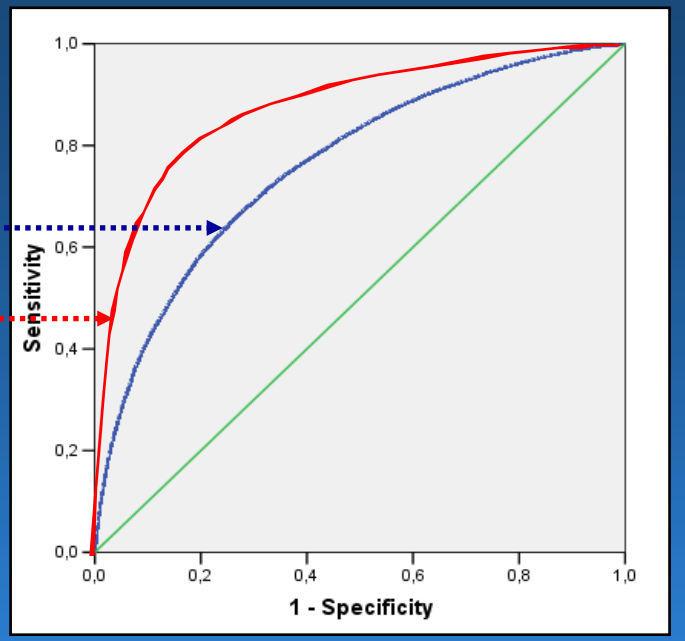
	Model	ROC area
1	$Logit(\pi) = \beta_0 + \beta_1 SLP$	0.573
2	$Logit(\pi) = \beta_0 + \beta_1 SLP + \sum \beta_j LIT_j$	0.696
3	$Logit(\pi) = \beta_0 + \sum\sum \beta_j SLP \cdot LIT_j$	0.708
4	$Logit(\pi) = \beta_0 + \sum \beta_i x_i$	0.748
5	$Logit(\pi) = \beta_0 + \sum \beta_i x_i + \sum\sum \beta_{ij} x_i LIT_j$	0.769
6	$Logit(\pi) = \beta_0 + \sum\sum \beta_{ij} x_i LIT_j + \sum\sum \beta_{ij} x_i USE_j$	0.780

COMPLEXITY ↓ — GOODNESS OF FORECAST ↓

7 Continuous DEM derivative + 2 Categorical:
(Lithotechnical Map and Land-Use 1976 classes)

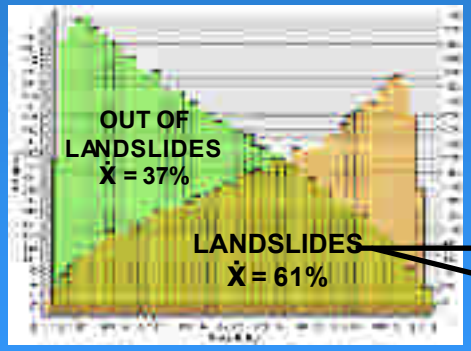
MODEL 1 ➔ Landsliding Triggering Susceptibility

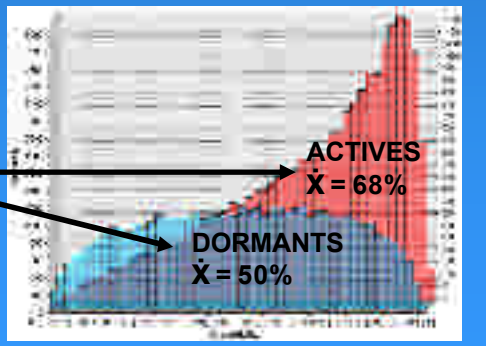
Calibration Subset	Model Reliability
ALL Landslides (A + D)	78%
ACTIVE Landslides Only	85%



Advantages in calibrating the model on the ACTIVE LANDSLIDE only:

1. **Better landslide mapping accuracy** (especially in the upper portion of the accumulation);
2. We can be more confident that the **independent variables are representative of the pre-failure conditions** (land-use ’76 is more likely independent from recent/active landslides than from old/dormant ones);
3. Other…



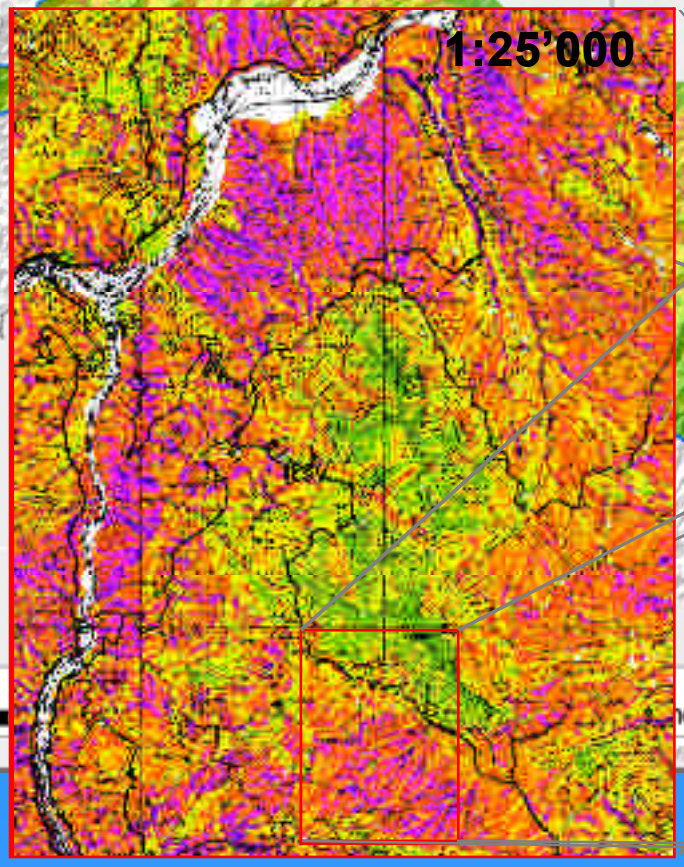


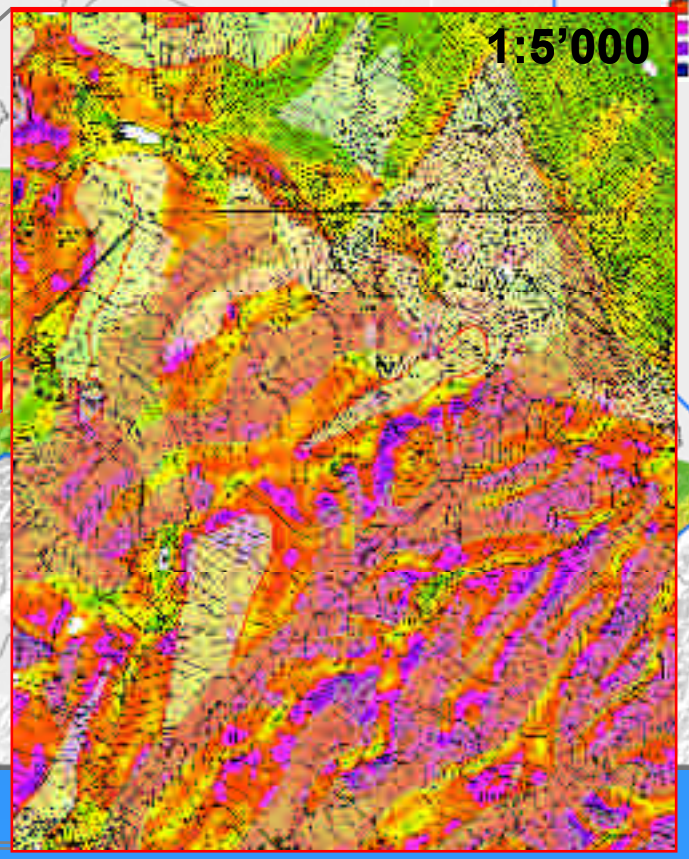
MODEL 1 ➔ Landsliding Triggering Susceptibility

5. Results:

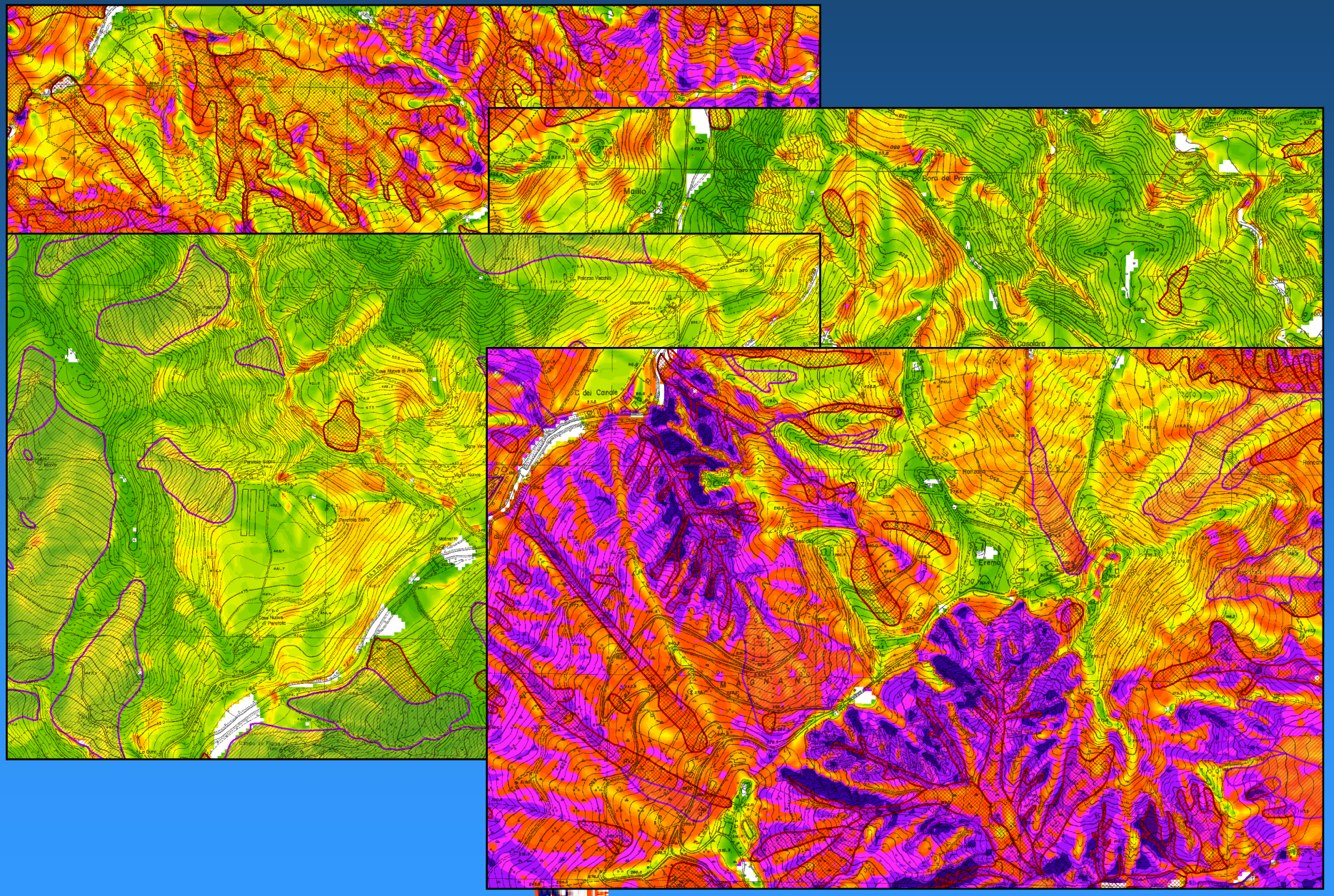
Cells calculated : 113.840.217

Mean Susceptibility: 38.2%



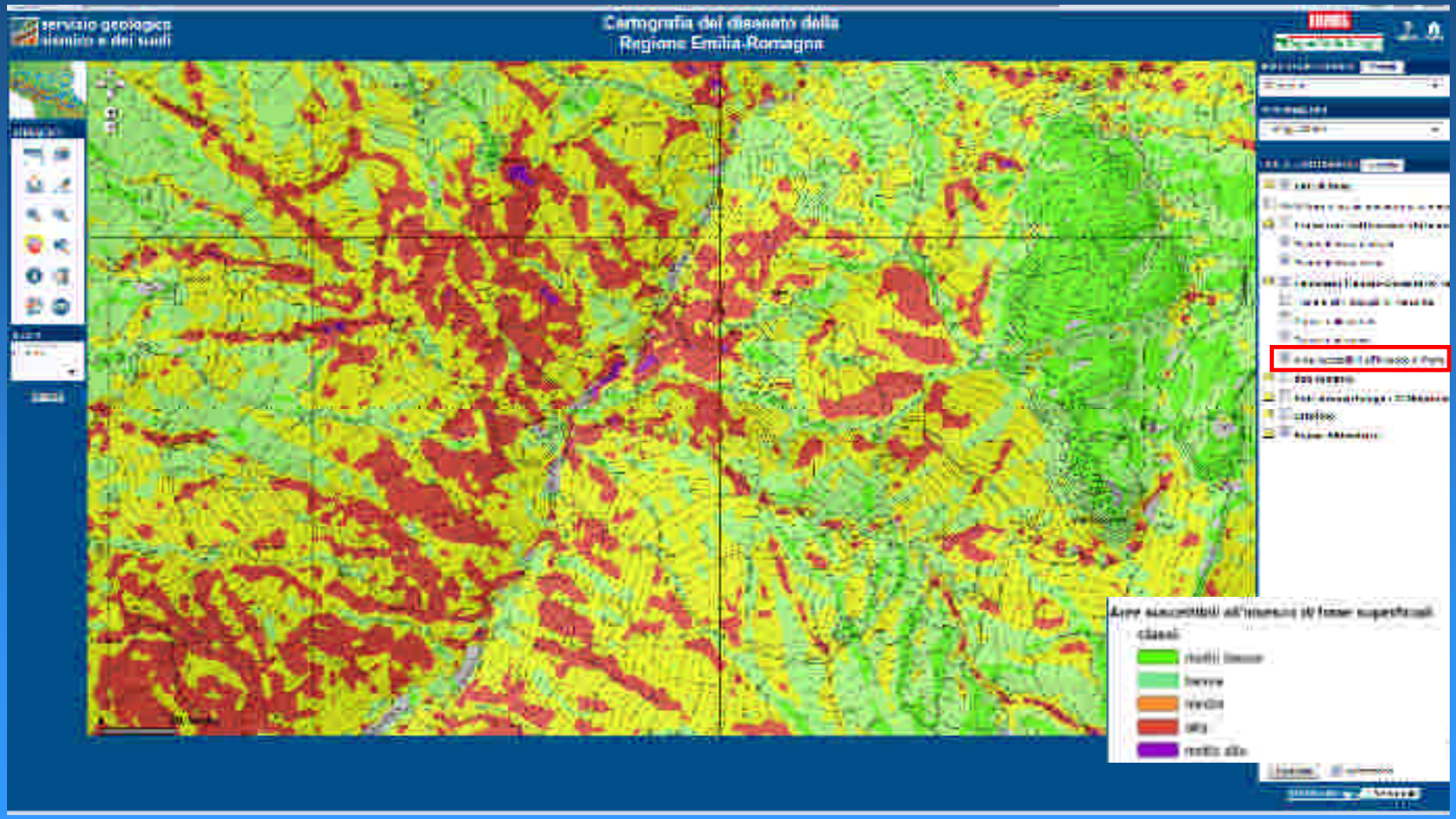


MODEL 1 ➔ Landsliding Triggering Susceptibility



MODEL 1 ➔ Landslide Triggering Susceptibility

http://ambiente.regione.emilia-romagna.it/geologia/cartografia/webgis-banchedati/cartografia-dissesto-idrogeologico



What about the mapped landslides?

The evaluation of the reactivation likelihood of the "existing landslides" is a crucial issue for Emilia Romagna region because they are the great most of the areas yearly affected by landsliding events.

HAZARD ASSESSMENT:

80'000 landslides

Reactivations:
1. **Total**
2. **Partial 1**
3. **…**
4. **Partial n**

- **Magnitude**
- **Return Period**

f (*Climate, Land-Use changes*) **=**

We changed questions and wandered:

1) For Land-Use Planning are there actual differences between active and dormant landslides? If yes, can they be quantified?

2) Dormant landslides are all similar with each other or there are some of them "really dormant" and other more "active like" ?

MODEL 2 ➔ Mapped Landslides Reactivation Likelihood

PURPOSE: Assess the "reactivation likelihood" of the mapped landslides (with a particular attention to the dormant landslides).

IDEA: Identify and Quantify the "boundary conditions" that promote the landslide reactivation (*expert knowledge method*).

CONCEPTUAL FRAMEWORK

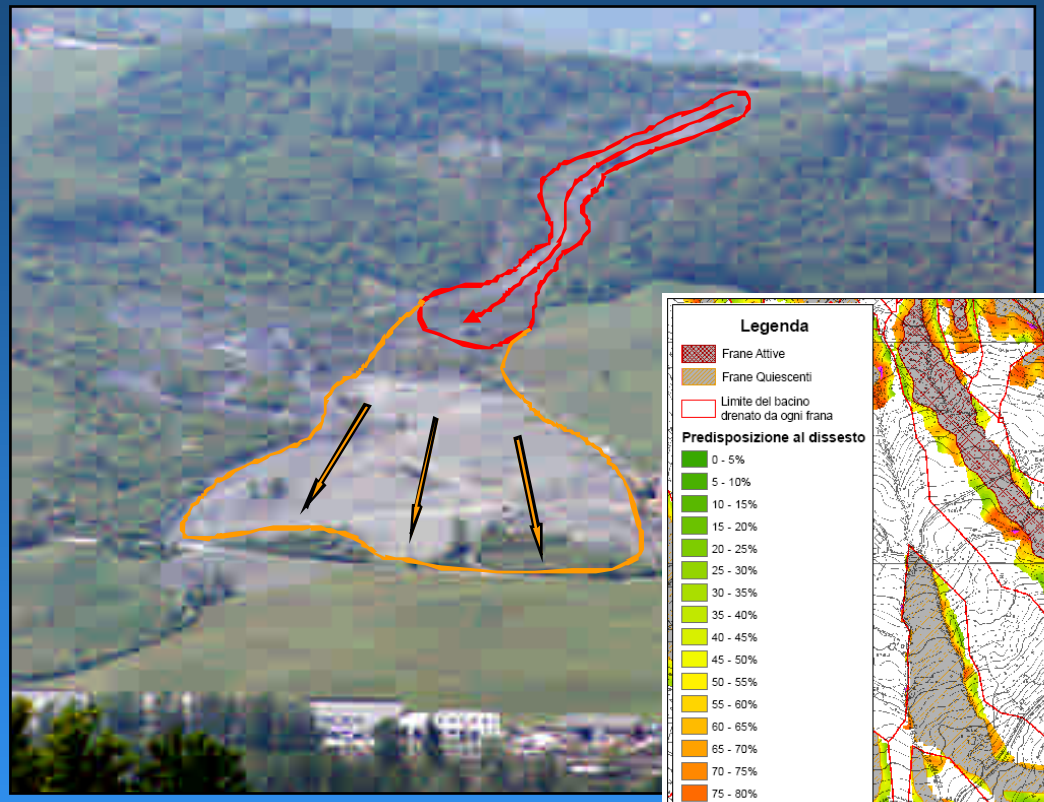
Reactivation predisposal factors:

1. Landsliding susceptibility in the landslide's upslope surrounding areas;
2. Influence of the geometrical relationship "active/dormant" landslides;
3. Presence of past events in the historical landslide database.

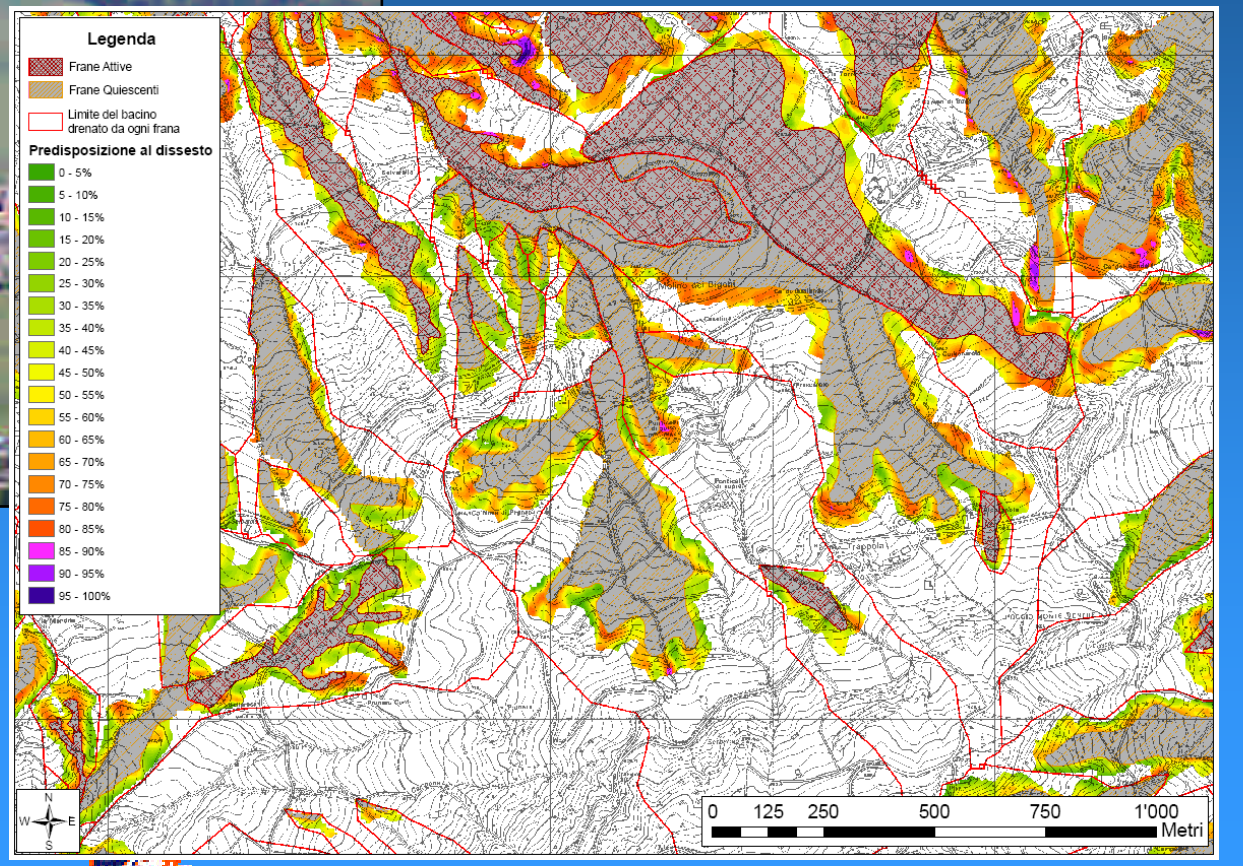
METHOD ➔ Geomorphologic and Heuristic analysis

MODEL 2 ➔ Mapped Landslides Reactivation Likelihood 1/3

1. Landsliding susceptibility in the landslides upslope surrounding areas!



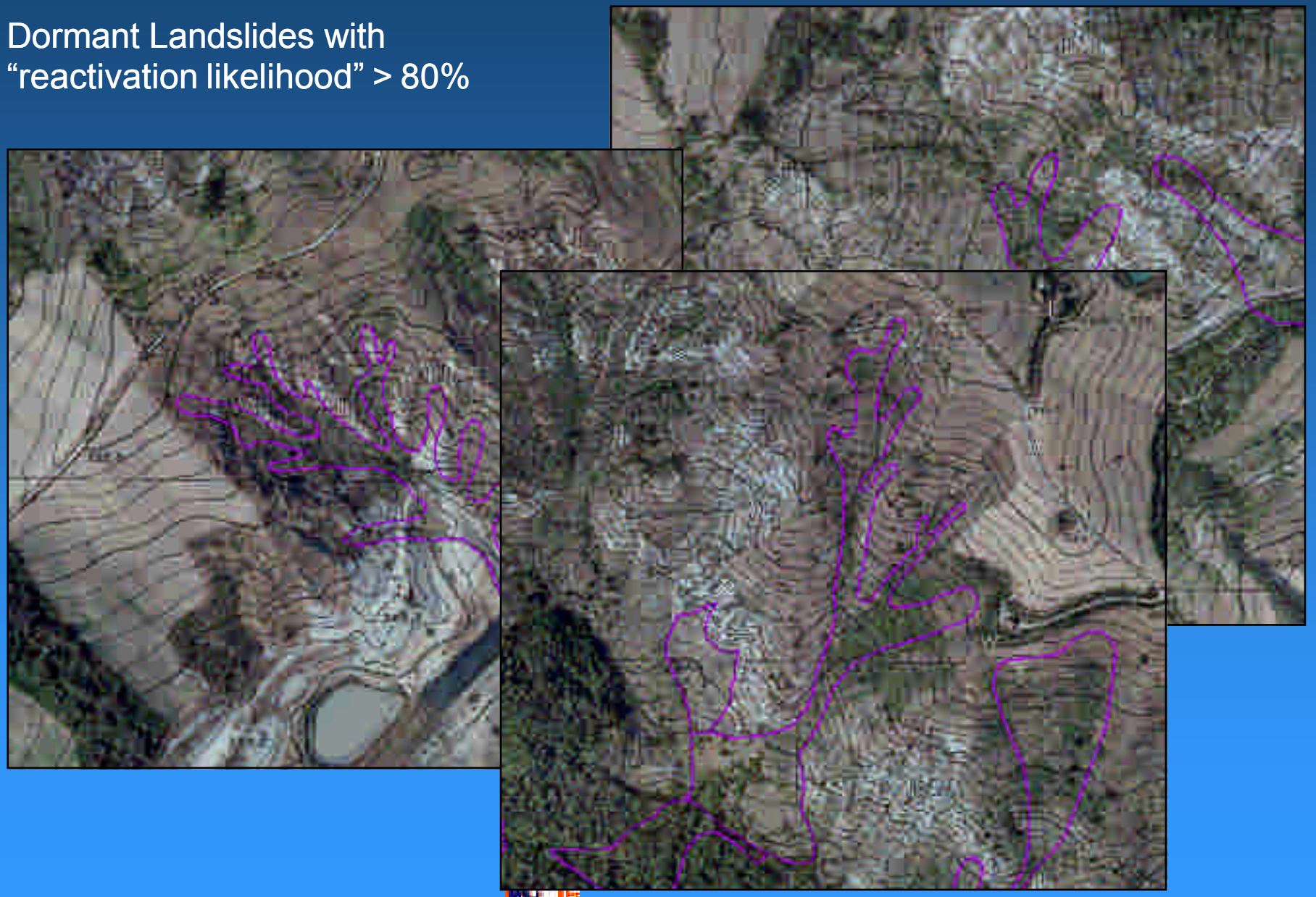
Assumption: the higher is the susceptibility value in the upslope surrounding a mapped landslide, the higher will be the reactivation likelihood of that landslide.



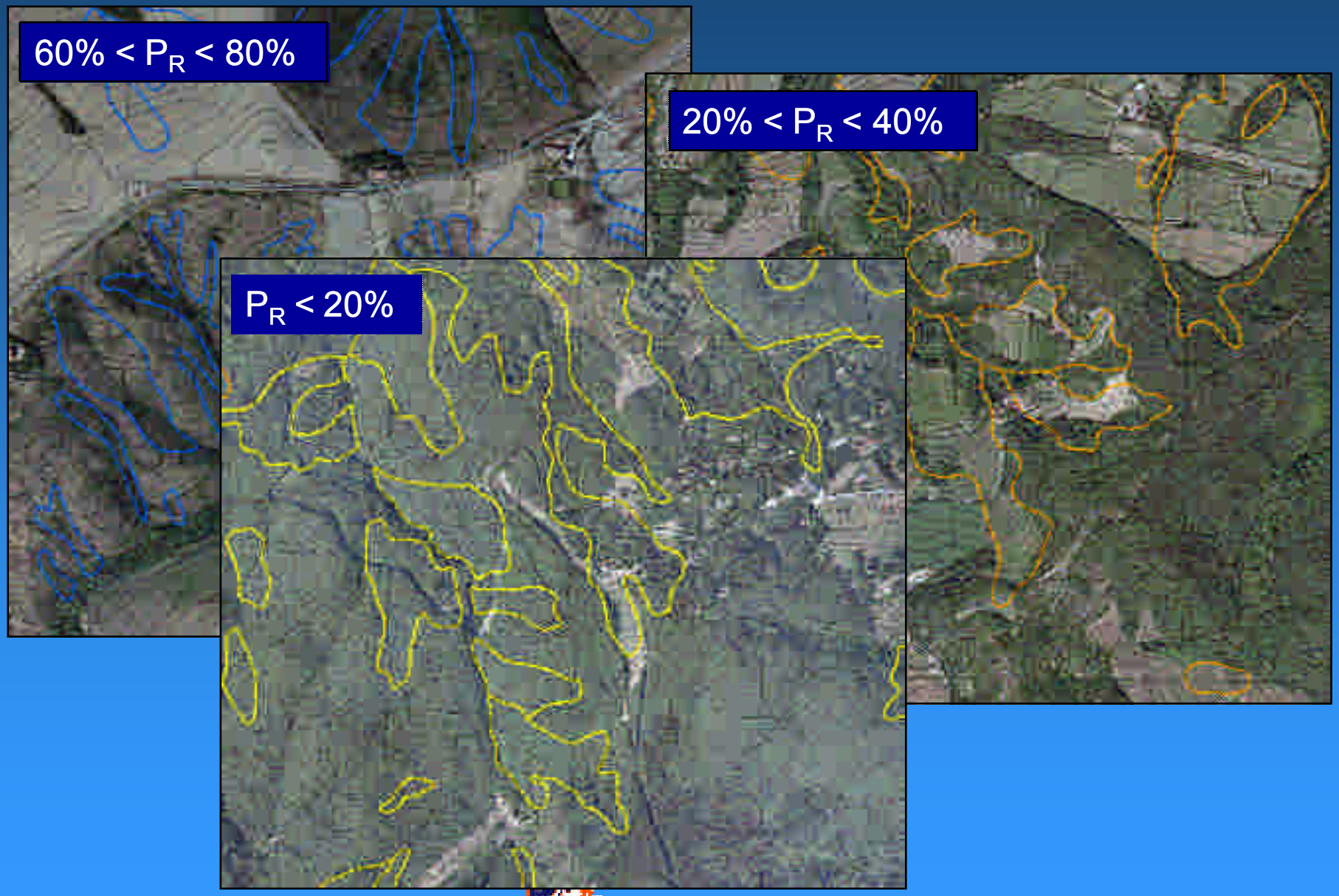
➔ we calculated the mean susceptibility in the landslide upper surrounding for a distance ≤ 50 m along the flow lines.

MODEL 2 ➔ Mapped Landslides Reactivation Likelihood 1/3

Dormant Landslides with
“reactivation likelihood” > 80%



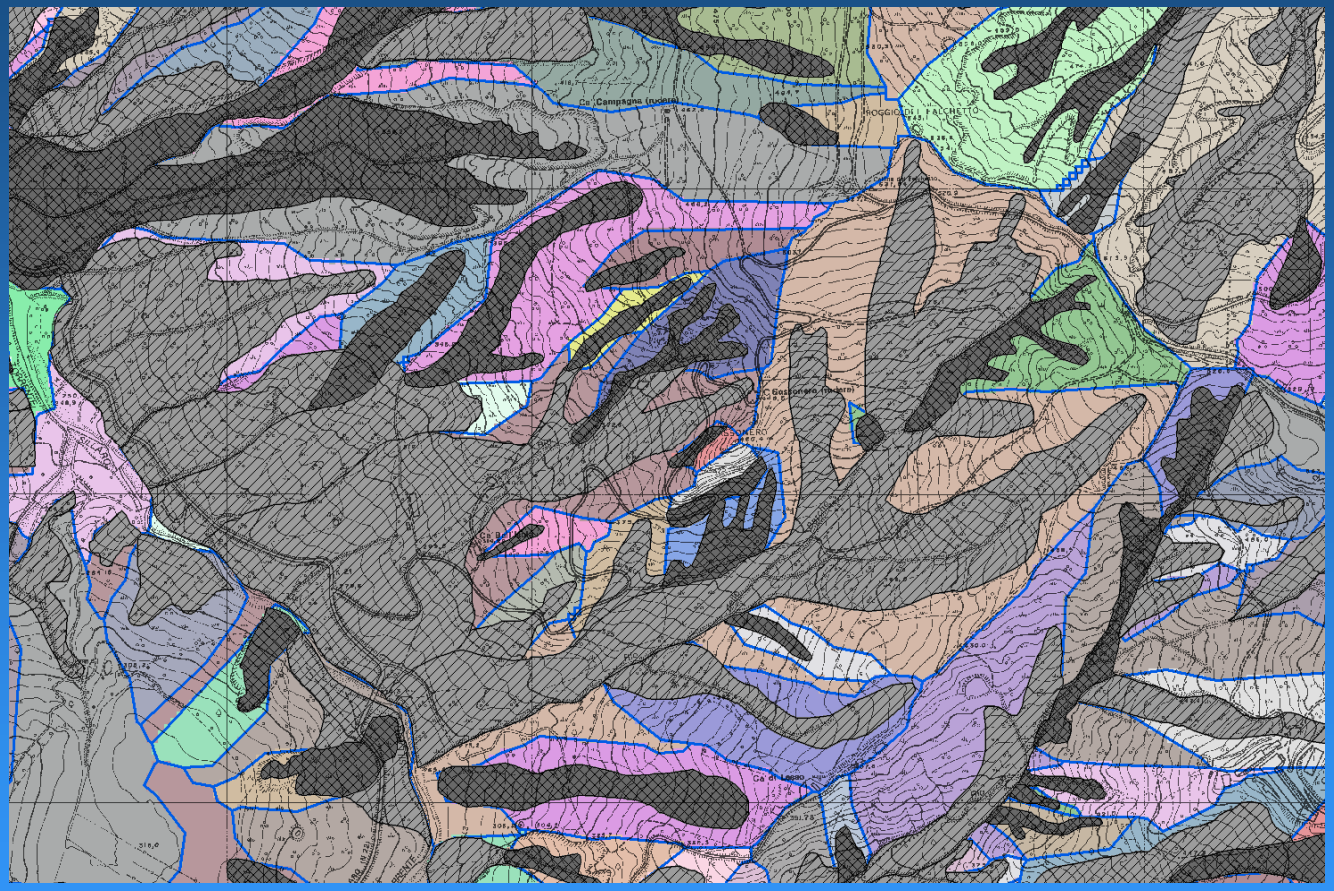
MODEL 2 ➔ Mapped Landslides Reactivation Likelihood 1/3



MODEL 2 ➔ Mapped Landslides Reactivation Likelihood 2/3

…but there's a problem:

37% of dormant landslides are "touched" by (at least) one active landslide !!!



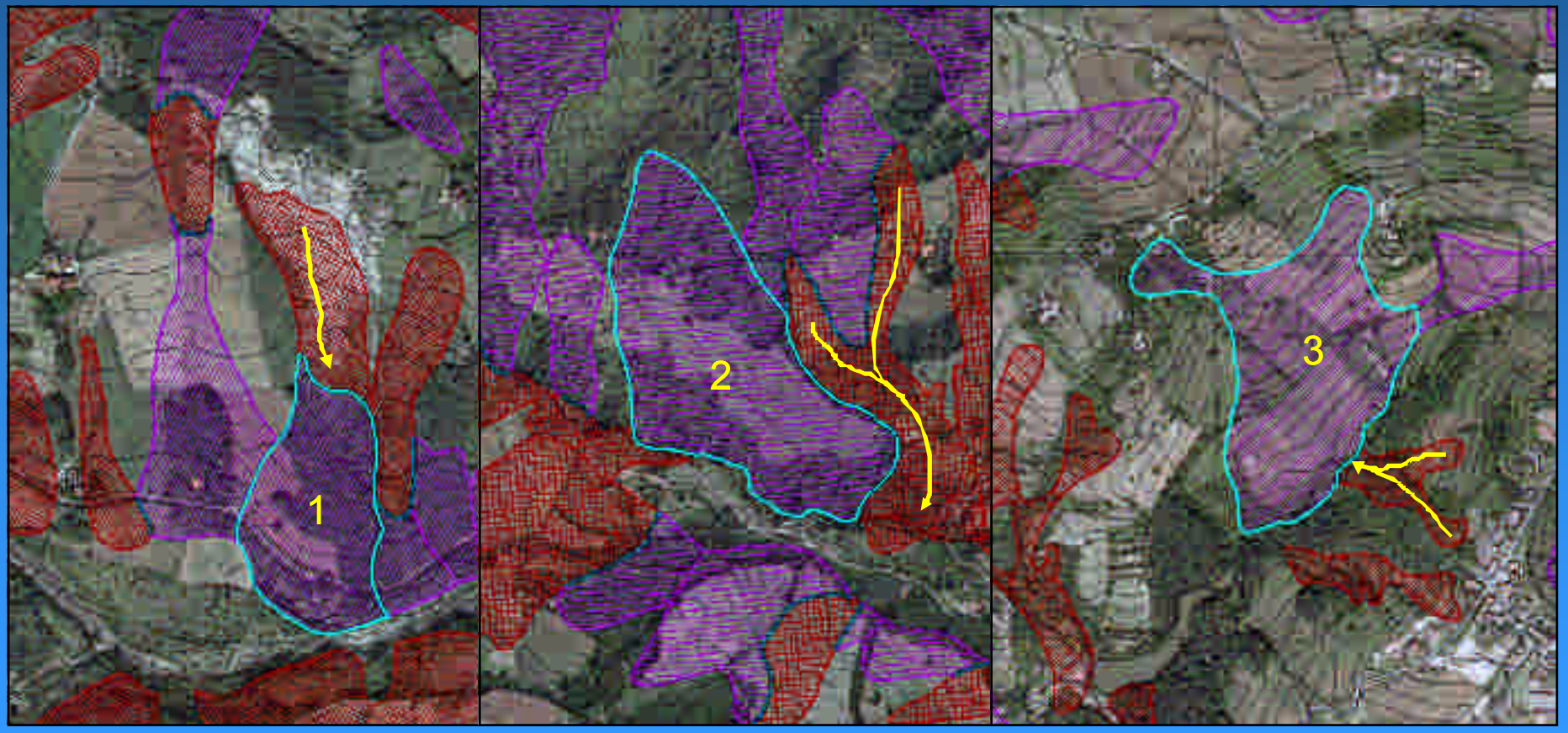
- **They have a reduced or no basin (for the susceptibility calculation);**
- **If an active landslide "load and push" a dormant one, may reactivate it…**

MODEL 2 ➔ Mapped Landslides Reactivation Likelihood 2/3

2. Influence of active landslides on the dormants accumulations!

➔ **Codify the "geomorphologist intuition" or "expert knowledge"**

Example: what a geomorphologist would say about these three dormant landslides?

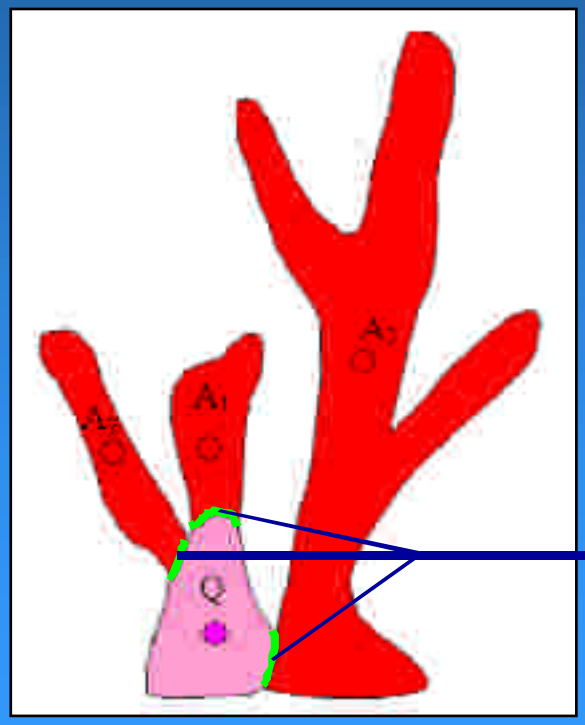


MODEL 2 ➔ Mapped Landslides Reactivation Likelihood 2/3

➔ We analyzed the geometric relationship between landslides to (empirically) quantify the relative influence of Active vs Dormant landslides!

ADVANTAGES

1. To reduce subjectivity through an homogeneous judgment criteria for the whole region;
2. To automate the relative influence evaluation all over the RER Landslide Inventory Map.

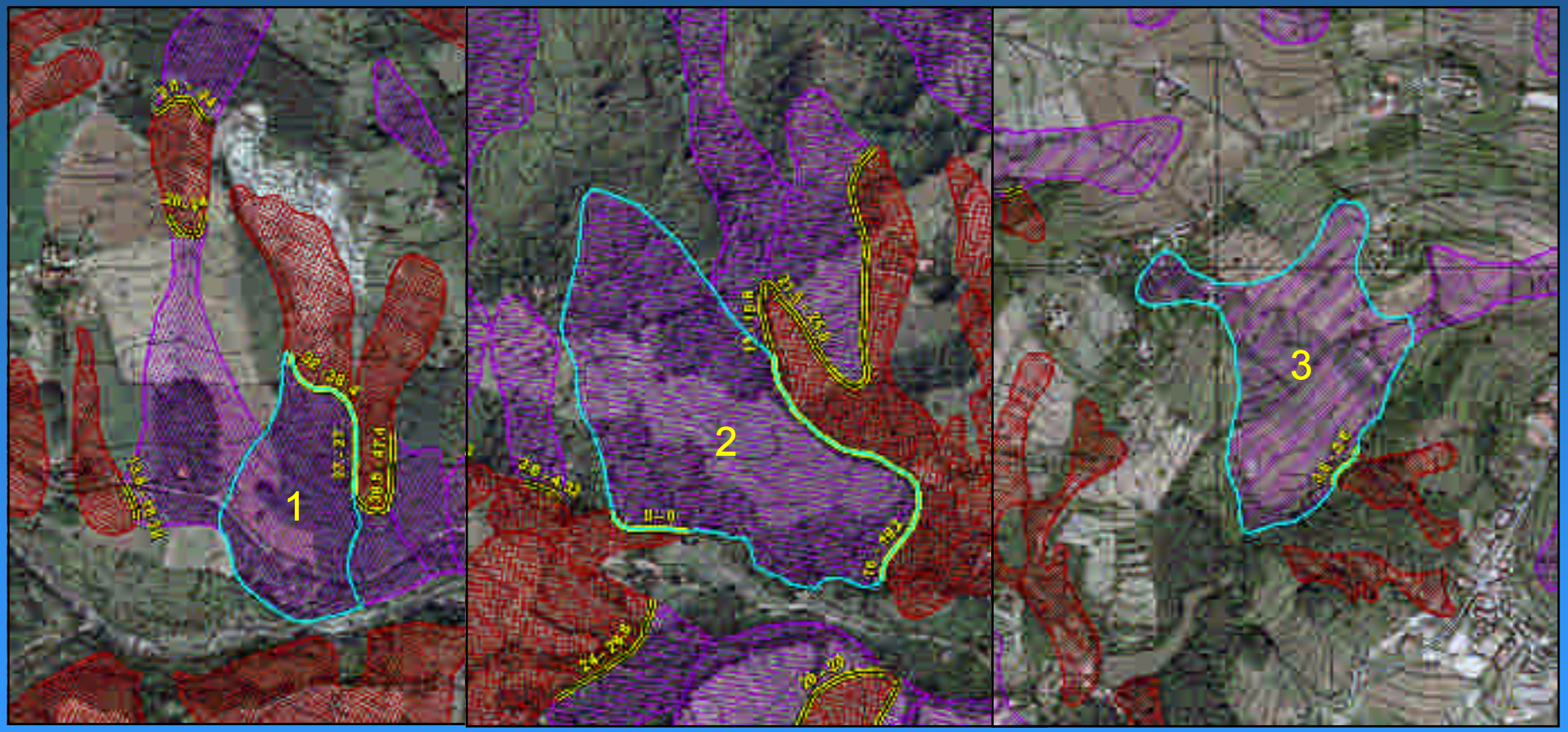


N°	Parameters
1	Mean Aspect difference
2	Centroids height difference (Q_{FR1} - Q_{FR2})
3	Areas ratio (A_{FR1}/A_{FR2})
4	Mean slopes ratio (SLP_{FR1}/SLP_{FR2})
5	Contact boundary mean curvature
6	Length of contact zone vs dormant landslide perimeter ratio
7	Relative position of the contact zone respect the dormant landslide perimeter
8	Number of active landslides in contact with the dormant
9	Type of landslide movement in contact with each other

MODEL 2 ➔ Mapped Landslides Reactivation Likelihood 2/3

➔ Additive and Multiplicative scores Synthesis ➔ **INFLUENCE INDEX: A➔D**

Let's see the QUIZ results…



MODEL 2 ➔ Mapped Landslides Reactivation Likelihood 3/3

3. Historical Reactivation records: The Historical Landslide Events Database!

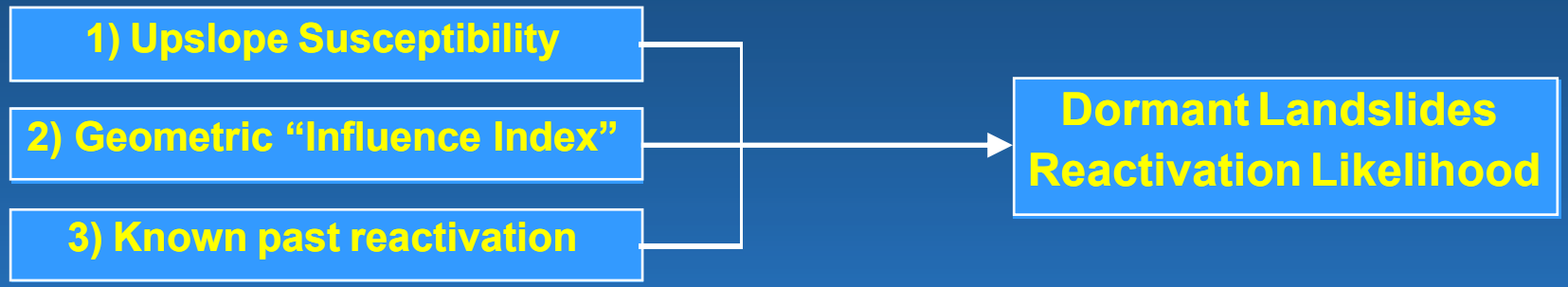
So far it counts ~11'000 events with this data:

- event date (variable precision);
- location;
- main descriptive features;
- triggering causes;
- damages;
- historical documentation (eventual).

Model statement: If a certain landslide has been activated in a known past, it will likely reactivate again!!!

MODEL 2 ➔ Mapped Landslides Reactivation Likelihood

Waiting for future model development, so far the combination of the three sub-models:



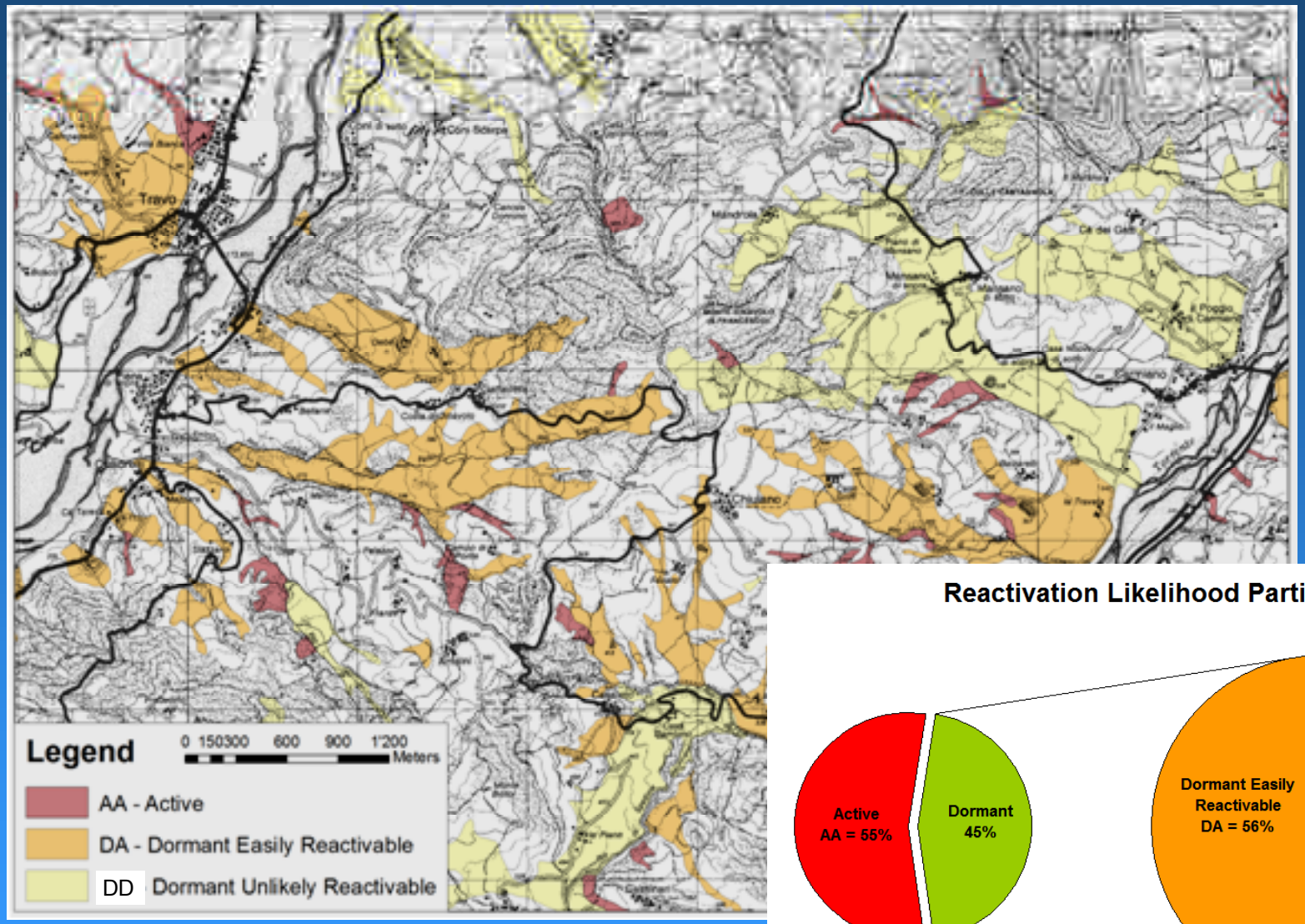
is performed in an easy way:

Dormant accumulations that have "at least one" of these conditions:

1. Upslope mean susceptibility higher than a threshold (mean = 48%)
2. Are touched by at least one active landslide with an Influence Index higher than a threshold (I.I. = 20);
3. Have at least one historical reactivation record…

Will be classified as DA = Dormant with High Reactivation Likelihood

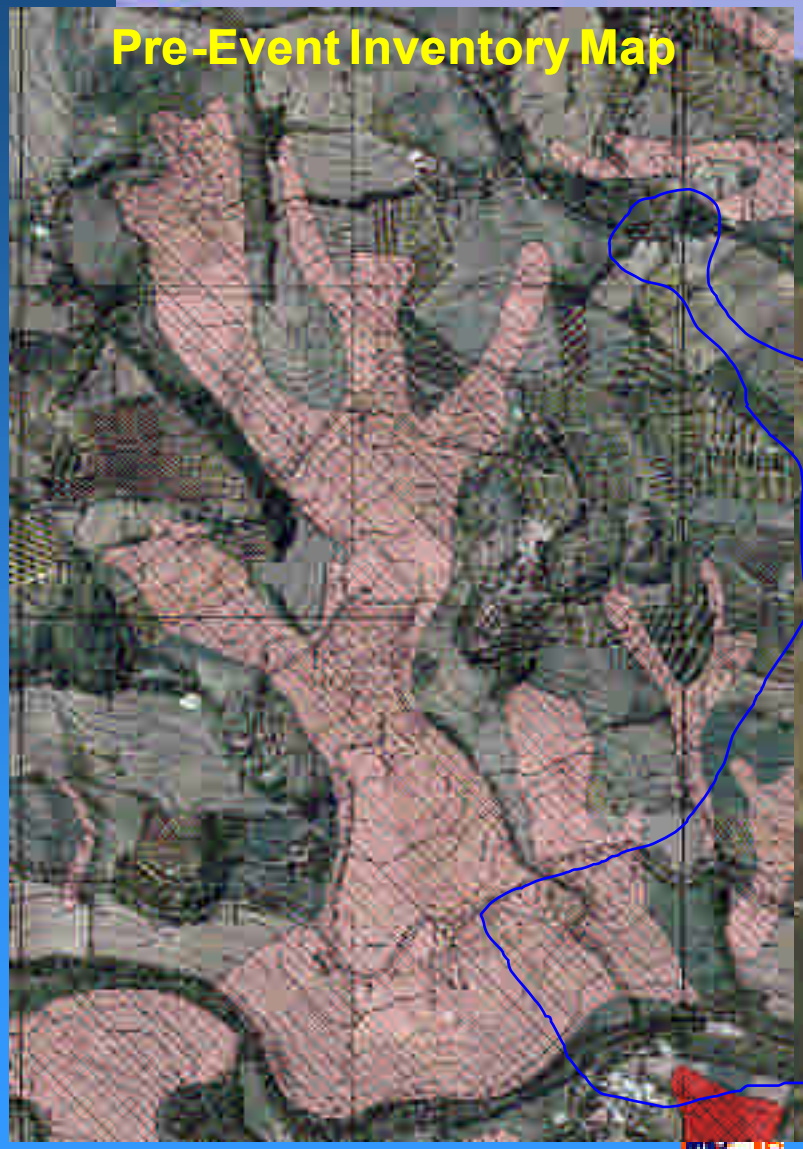
MODEL 2 ➔ Mapped Landslides Reactivation Likelihood



MODEL 2 ➔ Mapped Landslides Reactivation Likelihood

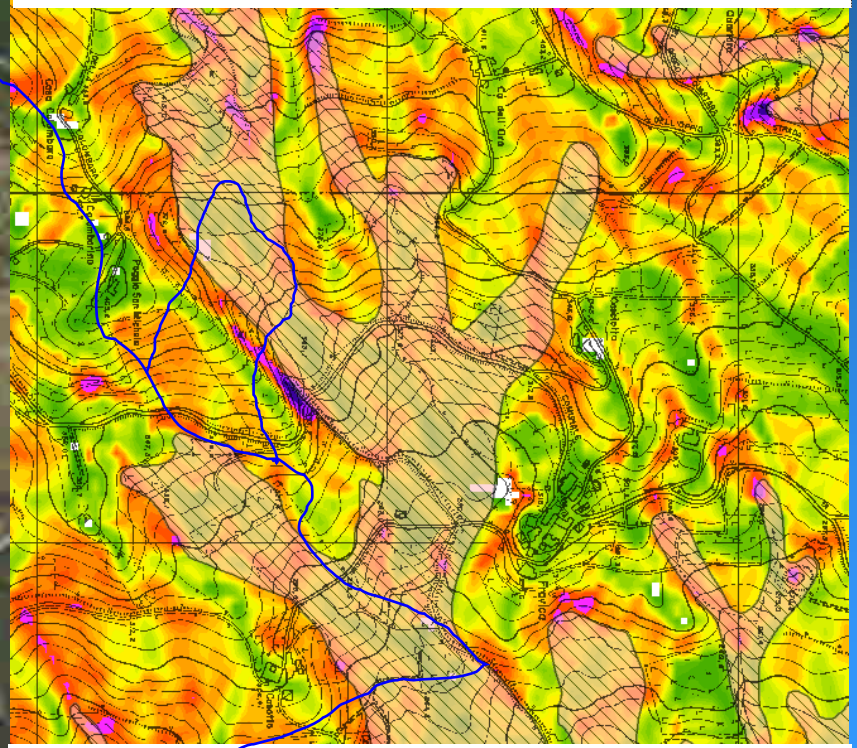
Example 1: - Fravica Landslide - Pianello Val Tidone (PC) - Last reactivation: January-April 2009

Pre-Event Inventory Map



Model components:

1. Mean Upslope Susceptibility = 56%
2. No active landslides in contact
3. N°2 previous known partial reactivation (1964-1965)



➔ High Reactivation Likelihood!

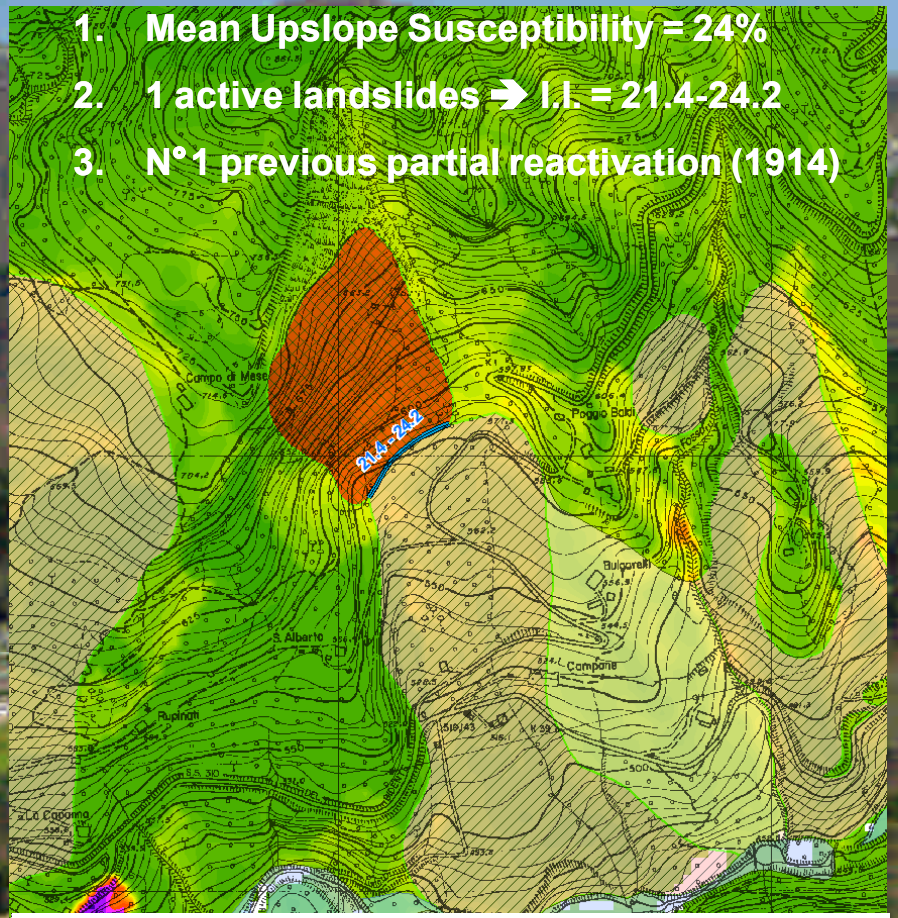
MODEL 2 ➔ Mapped Landslides Reactivation Likelihood

Example 2: Poggio Baldi Landslide - Corniolo - Santa Sofia (FC) - Last reactivation: 19 March 2010

Pre-Event Inventory Map

Model components:

1. Mean Upslope Susceptibility = 24%
2. 1 active landslides ➔ I.I. = 21.4-24.2
3. N°1 previous partial reactivation (1914)



➔ High Reactivation Likelihood!

MODEL 2 ➔ Mapped Landslides Reactivation Likelihood

Future development:

1. Improvement of the upslope susceptibility assessment (to account also for high susceptibility values inside the landslide perimeter);
2. Use of the historical landslide database to calibrate, by statistical regression, the actually empirical coefficients for the Influence Index.
3. If you have other suggestions we'll be glad to collaborate…

➔ the mandatory requirement for the good models performance is a complete, update and high quality Landslide Inventory Map