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Linking highly sophisticated debris flow modules and vulnerability analysis to risk mapping

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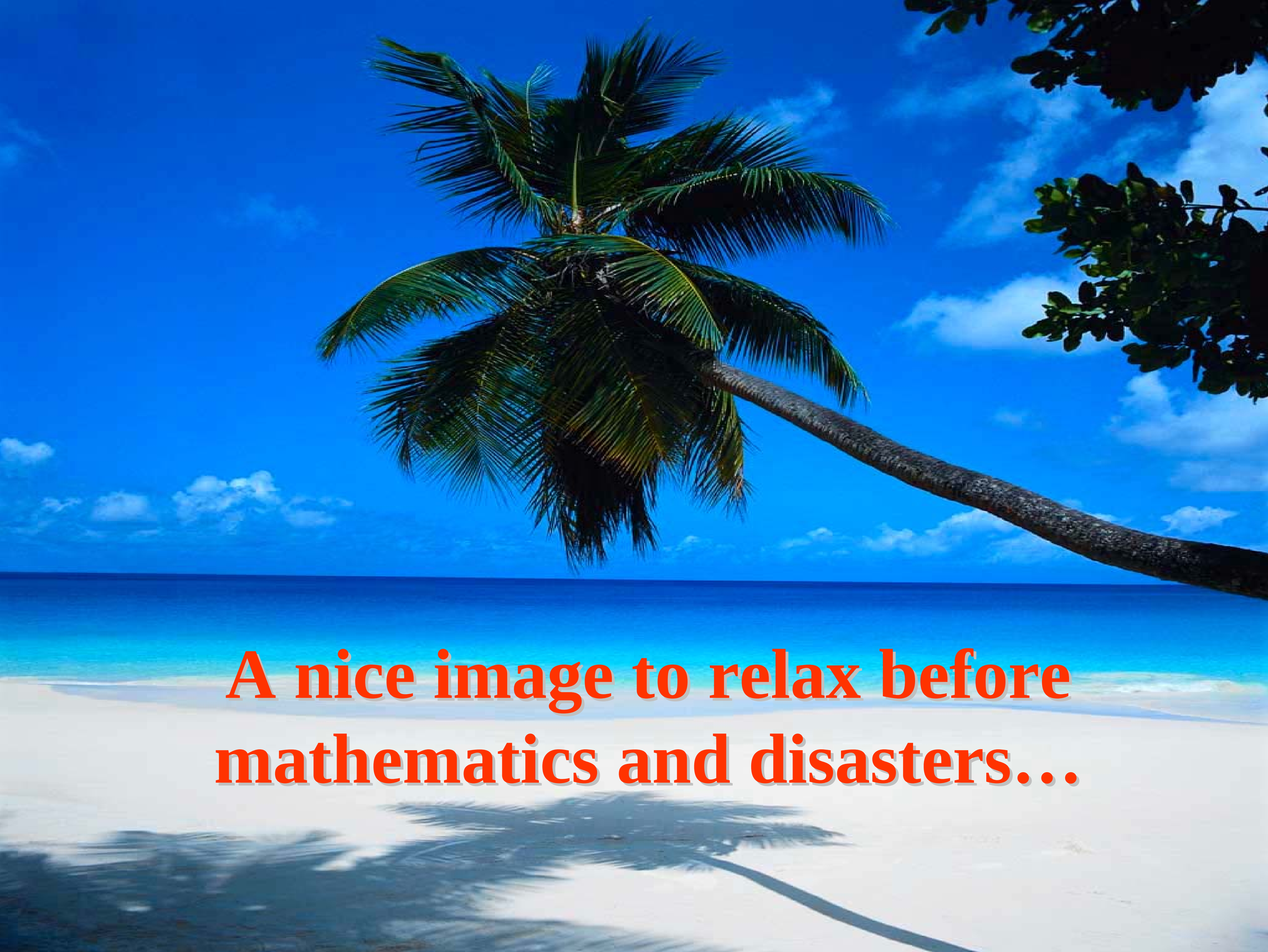
Objectives

1. Link debris flow modeling and risk mapping
2. Back analysis of a debris flow event to gather intensity values
3. Address a vulnerability curve as function of intensity based on real damages occurred


A nice image to relax before
mathematics and disasters…

model TRENT-2D

Transport in Rapidly Evolutive Natural Torrent

- general assumptions:
  - ✓ solid and liquid streamlines coinciding
  - ✓ depth integrated variables (shallow water), with hydrostatic pressure distribution and uniform velocity profile
  - ✓ dynamics of debris flow and evolving morphology coupled
- equations:
  - ✓ mass balances for both liquid and solid constituents
  - ✓ momentum balance along each coordinate direction

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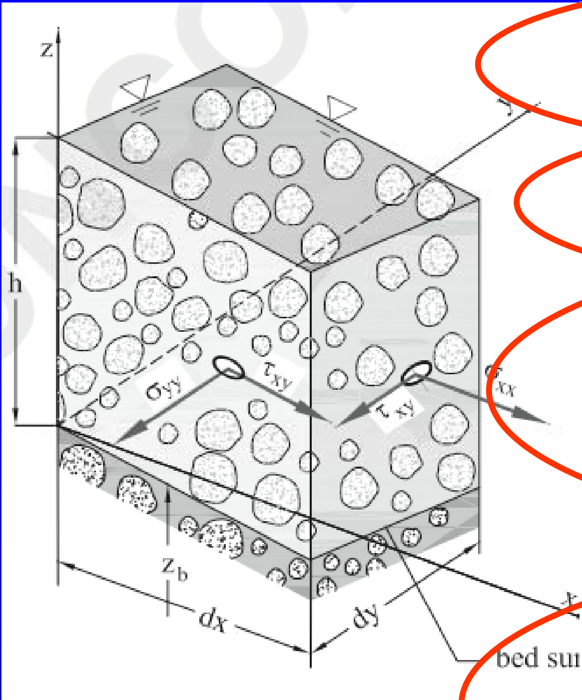
The pde's:



$$\frac{\partial}{\partial t}(z_b + h) + \frac{\partial}{\partial x}(hu) + \frac{\partial}{\partial y}(hv) = 0$$ Liquid mass

$$\frac{\partial}{\partial t}(c_b z_b + ch) + \frac{\partial}{\partial x}(chu) + \frac{\partial}{\partial y}(chv) = 0$$ Solid mass

$$\frac{\partial}{\partial t}((c\Delta+1)hu) + \frac{\partial}{\partial x}\left((c\Delta+1)\left(\tfrac{1}{2}gh^2 + hu^2\right)\right) + \frac{\partial}{\partial y}((c\Delta+1)huv) + (c\Delta+1)gh\frac{\partial z_b}{\partial x} = -\frac{\tau_{bx}}{\rho_w}$$ Momentum along x

$$\frac{\partial}{\partial t}((c\Delta+1)hv) + \frac{\partial}{\partial x}((c\Delta+1)huv) + \frac{\partial}{\partial y}\left((c\Delta+1)\left(\tfrac{1}{2}gh^2 + hv^2\right)\right) + (c\Delta+1)gh\frac{\partial z_b}{\partial y} = -\frac{\tau_{by}}{\rho_w}$$ Momentum along y

Fraccarollo & Capart (2002), Leal et al. (2006)

4 equations
6 variables: c, τ, z_b, h, u, v

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Closure relations:
1) *the bed shear stress*

- grain-inertial behavior
- Solid and liquid streamlines aligned

$$\frac{\vec{\tau}}{\rho_w} = \frac{25}{4}\frac{\rho_s}{\rho_w} a \sin\phi_d \frac{\lambda^2}{Y^2}|\vec{u}|\vec{u}$$

Bagnold – Takahashi formulation in vectorial framework

where:

$\lambda = \left[(c_b/c)^{1/3} - 1\right]^{-1}$ linear concentration

ϕ_d dynamic friction angle of the solid bulk

$Y = h/d$ Flow depth over grain size ratio (assumed constant in this model)

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Closure relations: *2) depth-average concentration*

•Hypothesis: immediate adaptation of c to local and instantaneous flow conditions

- Using formulation of Ashida & Michue (1972)

$\tau_c << \tau$

$$\left|\vec{q}_s\right| \approx \frac{8}{g\Delta}\left(\frac{\left|\vec{u}\right|^2}{\rho_w}\right)^{\frac{3}{2}}$$

- Assuming that: $\left|\vec{\tau}\right| \propto \left|\vec{u}\right|^2$

$$c = \frac{\left|\vec{q}_s\right|}{\left|\vec{u}\right| h} = c_b \frac{\beta}{g} \frac{\left|\vec{u}\right|^2}{h}$$

β is a grain mobility parameter

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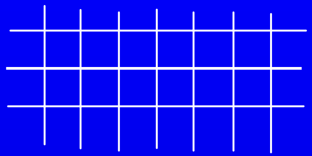
Numerical modeling

- Finite volume scheme on a Cartesian orthogonal grid
- The discretized system becomes:



$$\tilde{U}_{i,j}^{n+1} = U_{i,j}^{n} - \frac{\Delta t}{\Delta x}\left(F_{i-\frac{1}{2},j}^{n} - F_{i+\frac{1}{2},j}^{n}\right) - \frac{\Delta t}{\Delta y}\left(G_{i,j+\frac{1}{2}}^{n} - G_{i,j-\frac{1}{2}}^{n}\right) - \int_{\Delta t}\int_{A_{i,j}} \gamma\left(\frac{\partial f_x}{\partial x} + \frac{\partial f_y}{\partial y}\right) dA \cdot dt$$

Conservative fluxes

- Godunov approach with initial values of Riemann problem
- Accuracy: second order both in time and space through MUSCL-Hancock strategy (Van Leer, 1977)

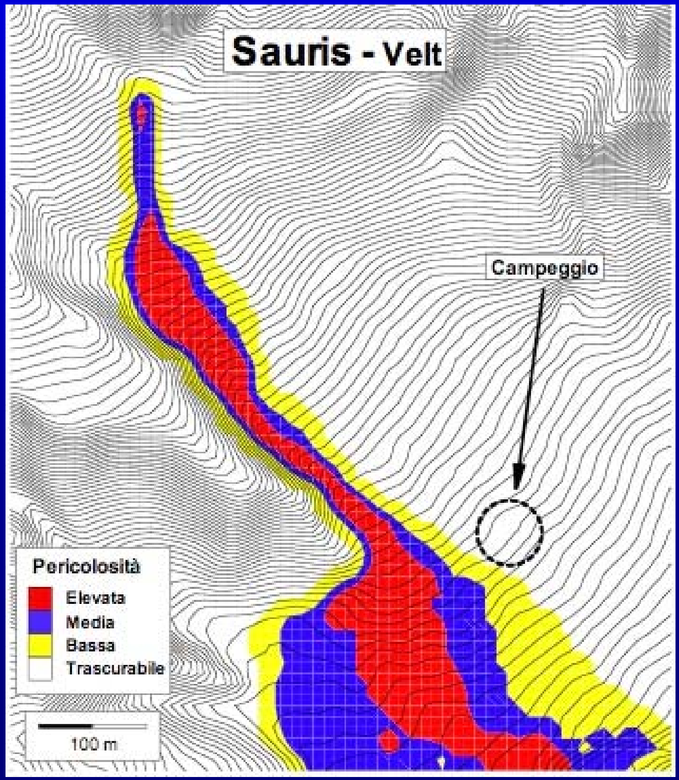
Non-conservative fluxes:

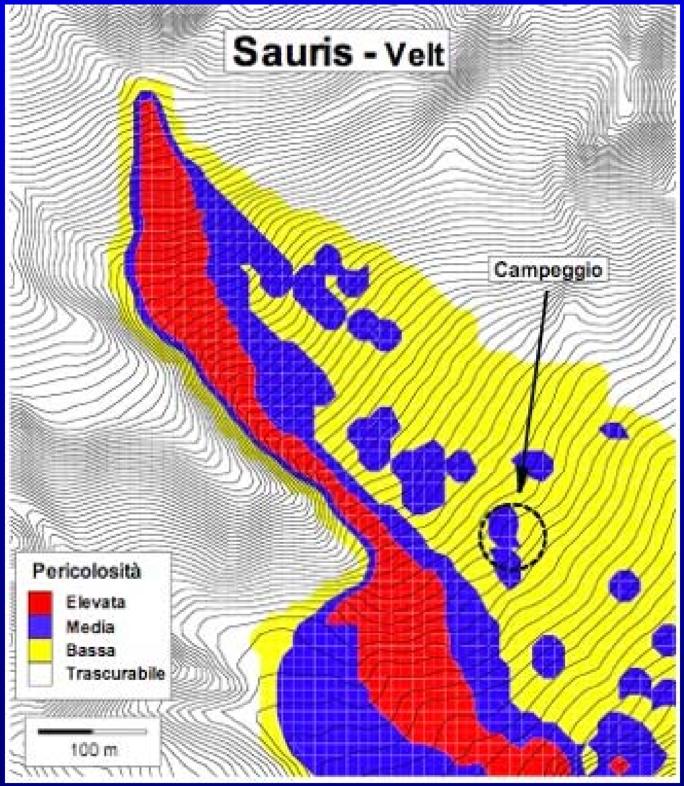
- Explicit discretization of the non conservative term over the cell
- Discontinuity in the bottom evaluated through an LHLL solver (Fraccarollo & Capart, 2002)

$$F_{L,R}^{LHLL} = F^{HLL} - \frac{S_{L,R}}{S_L - S_R} g\bar{h}\left(z_b^R - z_b^L\right)$$

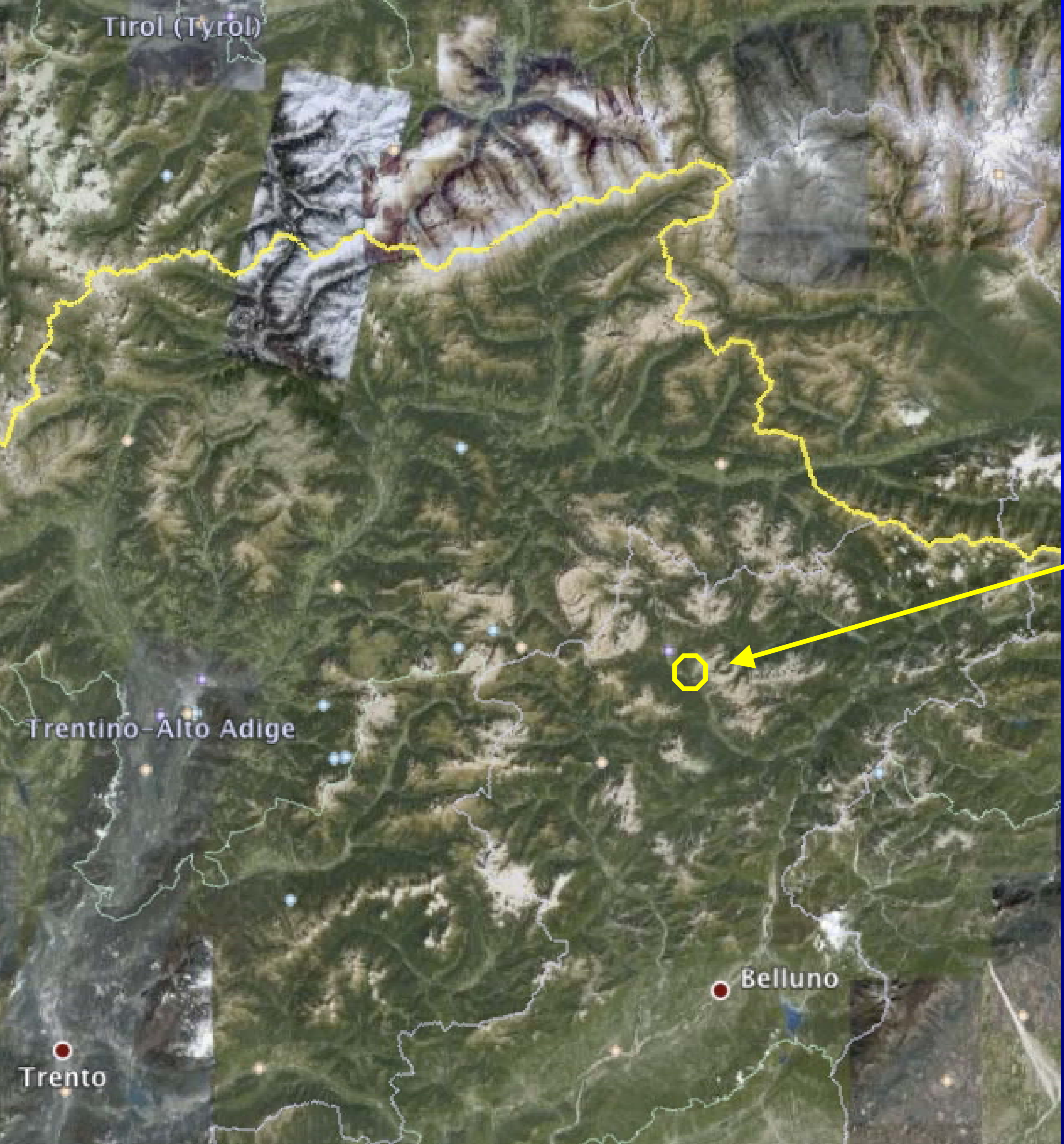
Potentials

- scour/deposit and velocity field evaluation
- hazard maps
- evaluation of effectiveness of countermeasures
- cost/benefit analysis
- export of results in GIS format





The location



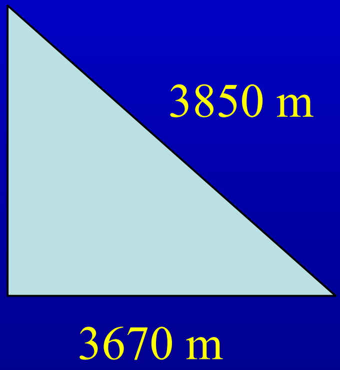
- CANCIA, Dolomites (Italy)
- 46.26˚N, 12.13˚E, 974m a.s.l
- MAP=1108 mm

Aerial photo of the channel

Morphology

The area exposed to the phenomenon extends about 550.000 m^2 (Centeleghe MsS thesis, 2000)

Forcella Salvella, 2451 m



Boite river, 880 m a.s.l.

Steepness: ~36° near the top, ~12° upstream the tank

Morphology

Source of the debris channel

Morphology

Bottom of the channel at 1680 m

Morphology

The channel immediately upstream of the village Corte di Cadore

Morphology

Downstream retention tank at 1010 m

A long story of events…

27 luglio 1868: Cancia.**(foto: Ghedina)**

A long story of events…

- ***2 May 1730*** **Debris flow impacted the village of Chiappuzza, 50 persons died**
- ***19 June 1736: 12 casualties***
- ***21 April 1814: tremendous rock avalanche / debris flow 260 casualties***
- ***27 luglio 1868: 12 casualties***
- ***4-5 novembre 1966: 25000*** m^3
- ***2 luglio 1994: 25000*** m^3 ***mobilized***
- ***7 agosto 1996: 60000*** m^3 ***mobilized***

The event 07/08/1996

Accumulated debris
(Photo: Zanfron)

The event 7/08/1996

Bed erosion
(Photo: Zanfron)

The event 7/08/1996

Smashed auto inside the garage (Photo: Zanfron)

The event 7/08/1996

Debris inside the cellar of a house (Photo: Zanfron)

The event 07/08/1996

Demolished building due to load on the roof due to the flow (Photo: Zanfron)

The event 02/07/1994

Deposits of the flow among the houses (Photo: Zanfron)

The event 02/07/1994

Access road to Corte full of debris. On the right a huge boulder trasported by the flow (Foto: Zanfron)

The event 02/07/1994

Cars dragged away by the flow (Photo: Zanfron)

The event 02/07/1994

Damaged building (Foto: Zanfron)

The event 02/07/1994

DAMAGES:

- **19 damaged buildings**
- **1 collapsed due to roof damages**
- **30 buildings invaded by debris**
- **30 cars spoiled**
- **No human casualty**
- **30 rabbits, 1 cat**

Total 1.400.000.000 Lire (about 700.000 Euro)

The Simulation

Characteristics of the numerical simulations:

Computational area: 550m x 1000 m

Computational cells: 5m x 5m

$\beta = 0.698$

$h/d = 32.8$

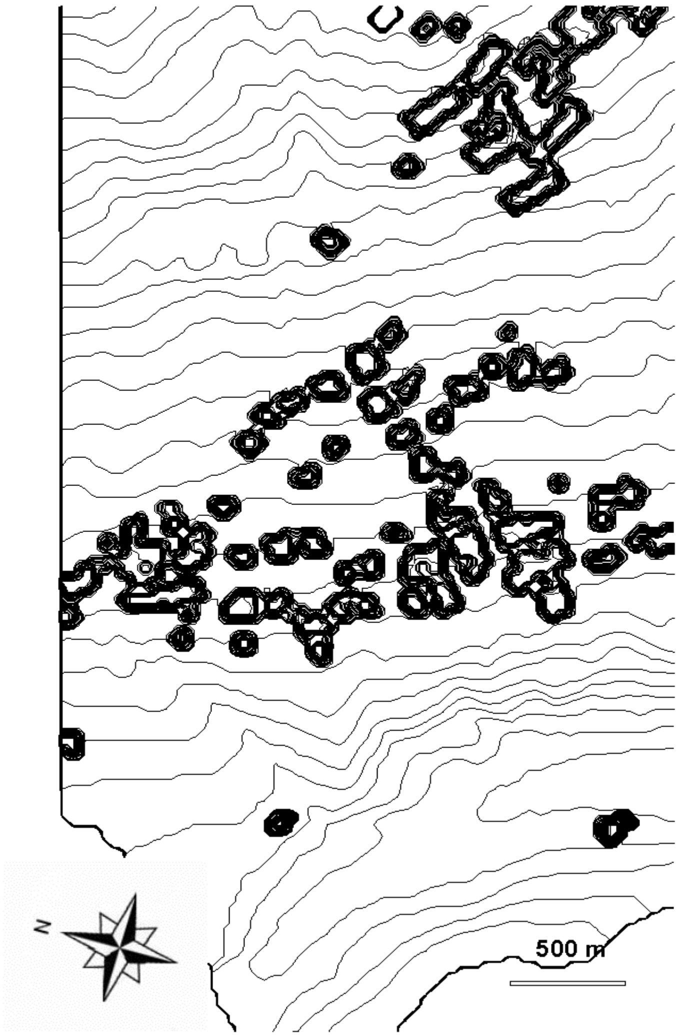
Characteristics of the basin:

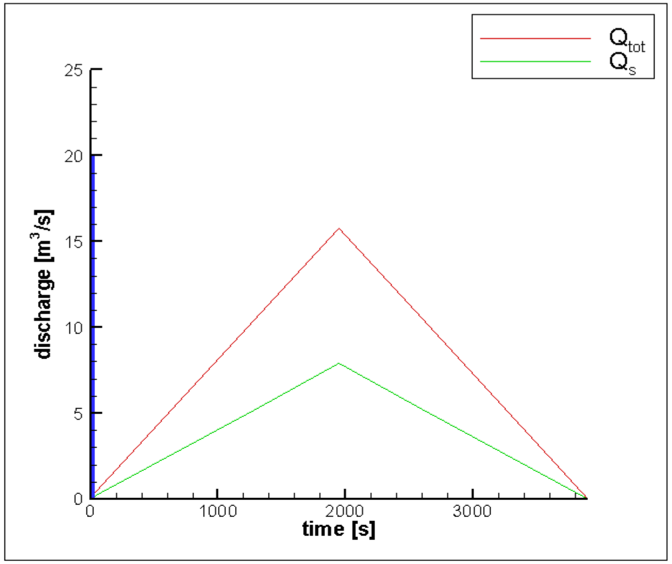
Area: 1km^2

Slope: from 70% upstream to 20% downstream

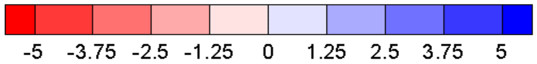
CANCIA DEBRIS FLOW

SEDIMENT VOLUME 30000 m^3





Scour and deposit [m]

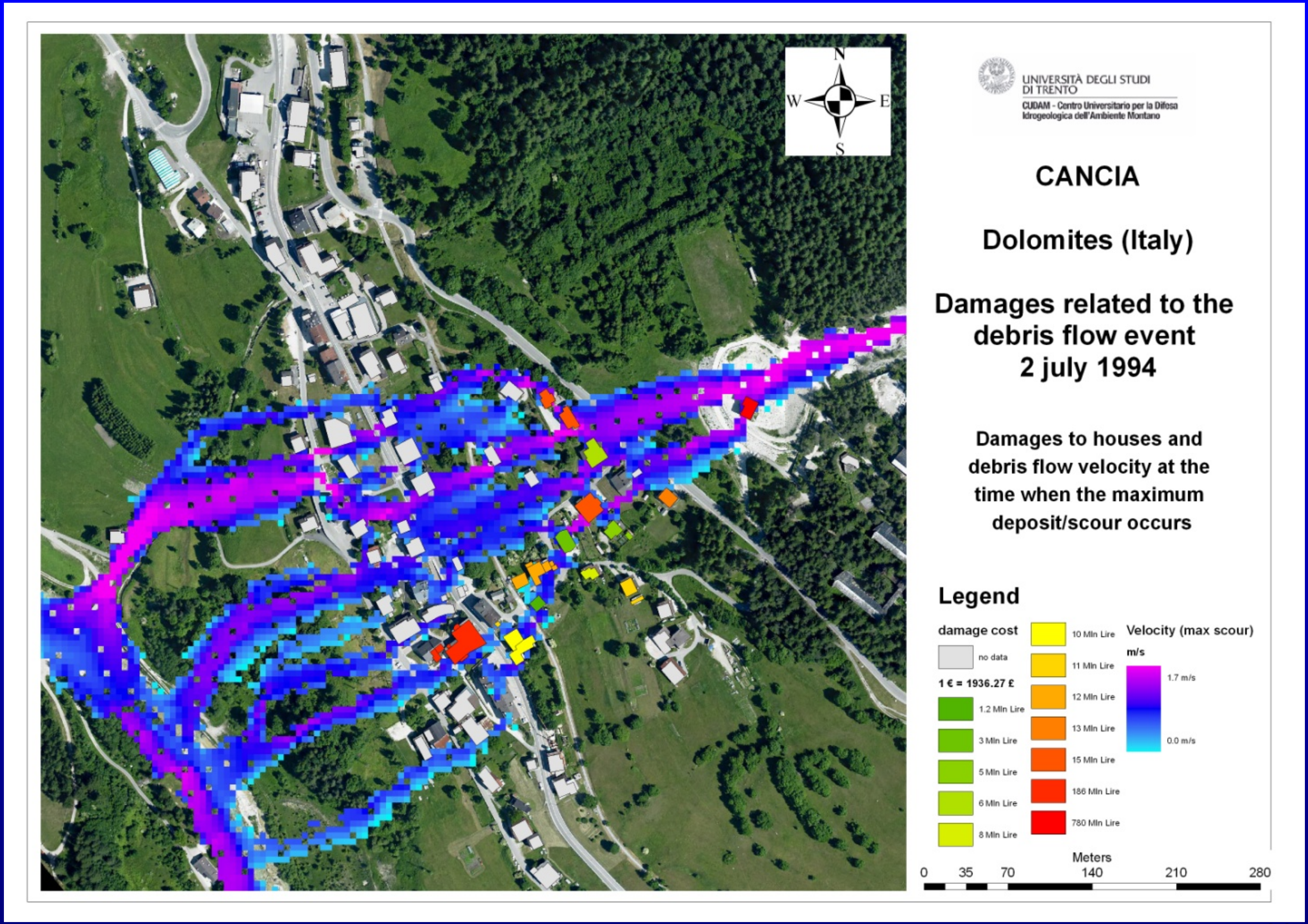


Concentration: c = 0.5

Transport parameter: beta = 0.698

h/d = 32.825

Results



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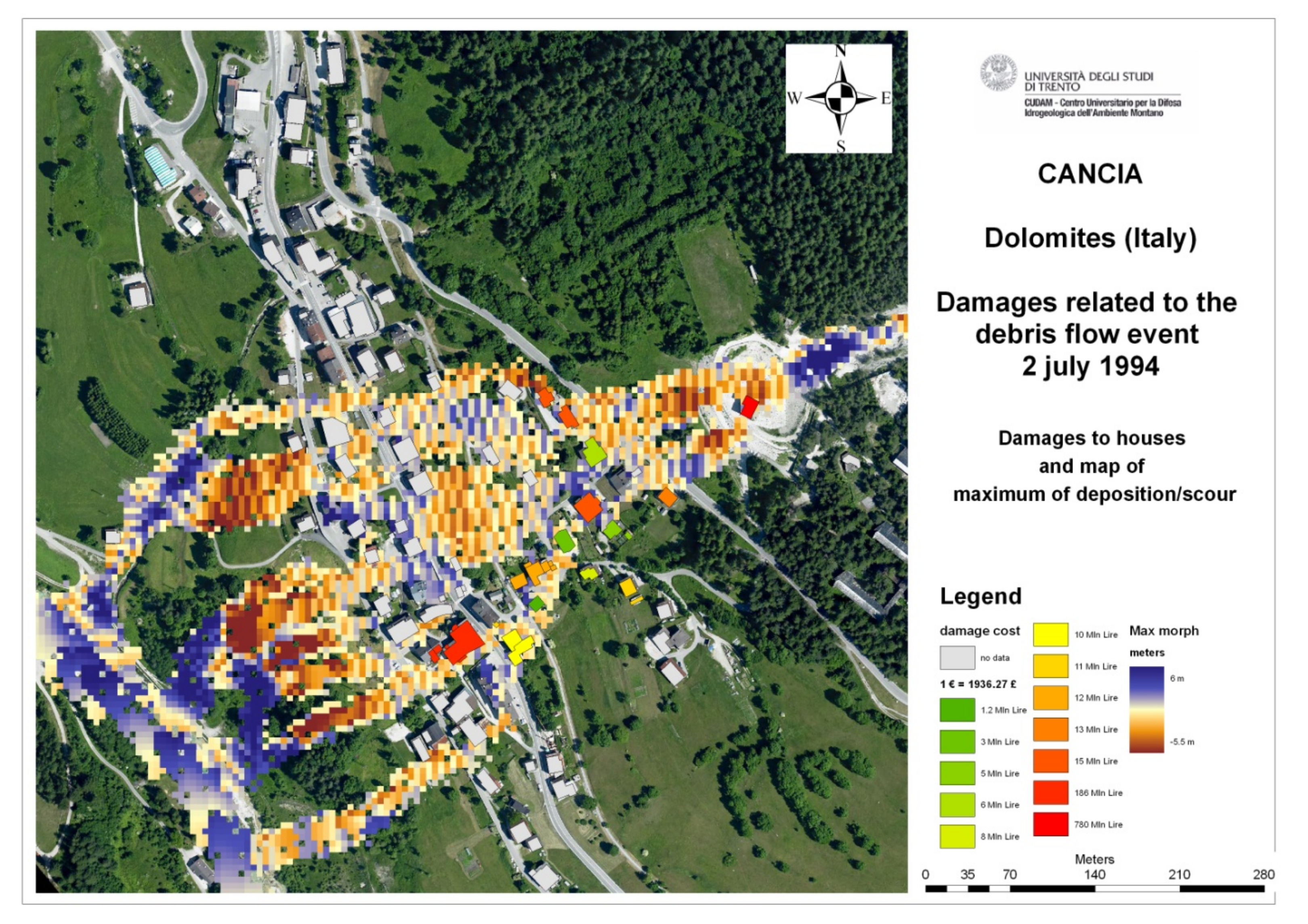
CANCIA
Dolomites (Italy)
Damages related to the debris flow event 2 july 1994
Damages to houses and debris flow velocity at the time when the maximum deposit/scour occurs
Legend
damage cost
no data
1 € = 1936.27 £
1.2 Mln Lire
3 Mln Lire
5 Mln Lire
6 Mln Lire
8 Mln Lire
10 Mln Lire
11 Mln Lire
12 Mln Lire
13 Mln Lire
15 Mln Lire
186 Mln Lire
780 Mln Lire
Velocity (max scour)
m/s
1.7 m/s
0.0 m/s
Meters
0 35 70 140 210 280

Results



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CANCIA
Dolomites (Italy)
Damages related to the debris flow event 2 july 1994
Damages to houses and map of maximum of deposition/scour
Legend
damage cost
no data
1 € = 1936.27 £
1.2 Mln Lire
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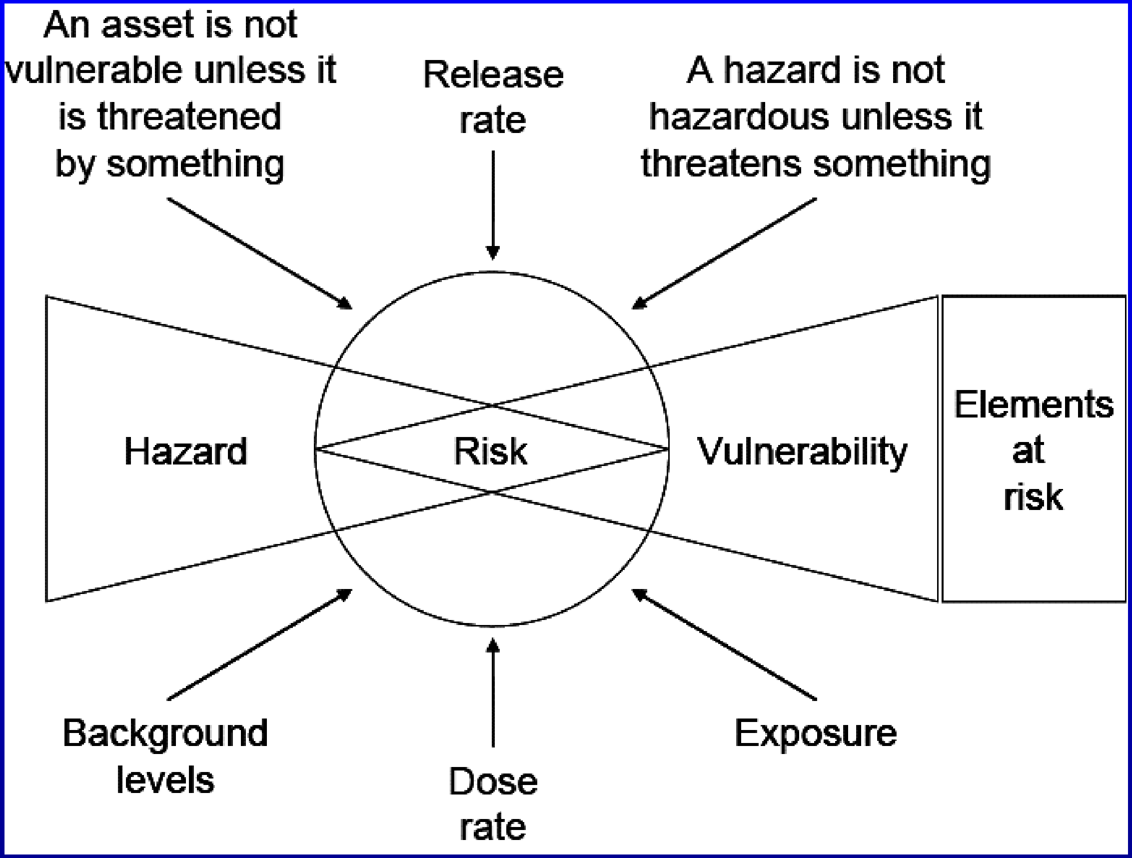
13 Mln Lire
15 Mln Lire
186 Mln Lire
780 Mln Lire
Max morph
meters
6 m
-5.5 m
Meters
0 35 70 140 210 280

The concept of vulnerability

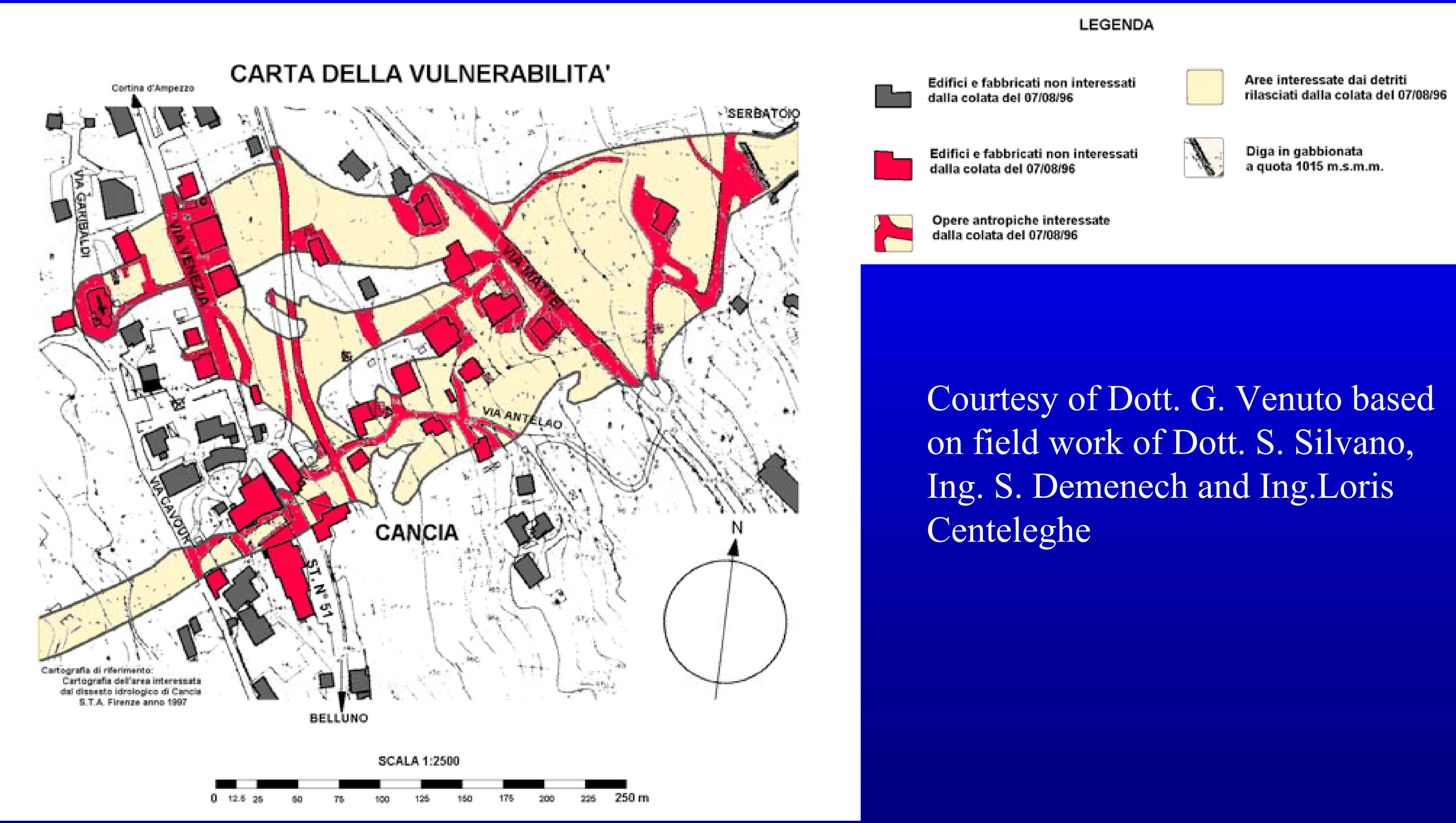


Modified from Alexander (2005)

- Vulnerability: **the expected degree of loss** for an element at risk as a consequence of a certain event (Varnes 1984; Fell 1994);
- from 0 (no damage) to 1 (complete destruction);
- Despite some overviews (e.g. BUWAL 1999, Glade 2003), detailed studies on vulnerability values and functions are missing so far.

Within IRASMOS, the quantification was carried out for Austrian watersheds, and for Cancia is work in progress…

Vulnerability analysis: 1st attempt



Courtesy of Dott. G. Venuto based on field work of Dott. S. Silvano, Ing. S. Demenech and Ing.Loris Centeleghe

Vulnerability analysis

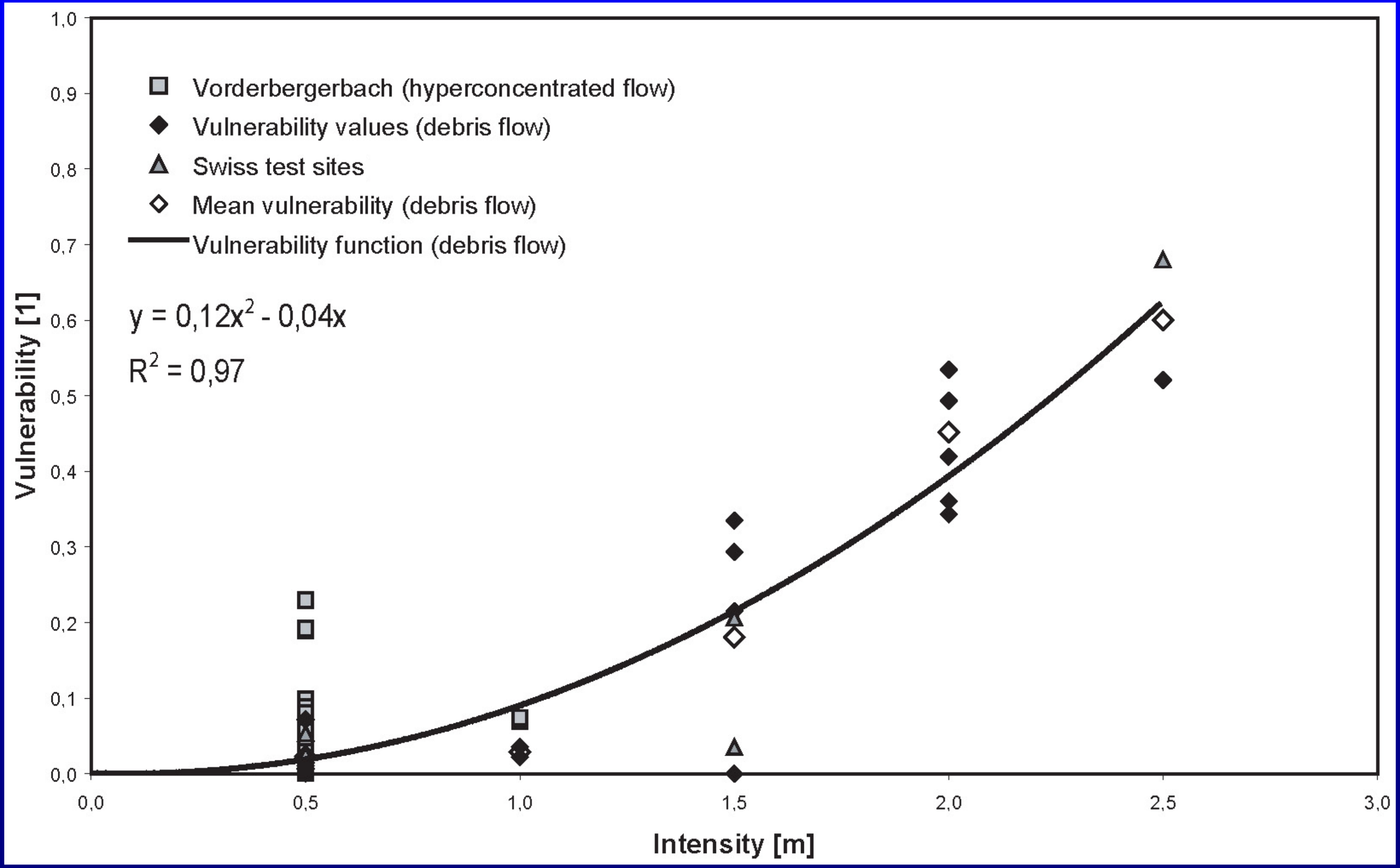
- **Analysis of values at risk**:
  - Spatially explicit analysis of buildings
  - Assessment of values according to Keiler et al. (2006)
    (classification, floor space, height, reconstruction value, real estate appraisal)

- **Analysis of losses**
- Categories of damages:
  - cars (interior + exterior)
  - houses (interior + exterior)
  - debris removal

$$v = \frac{loss}{value}$$

Vulnerability

Vulnerability function



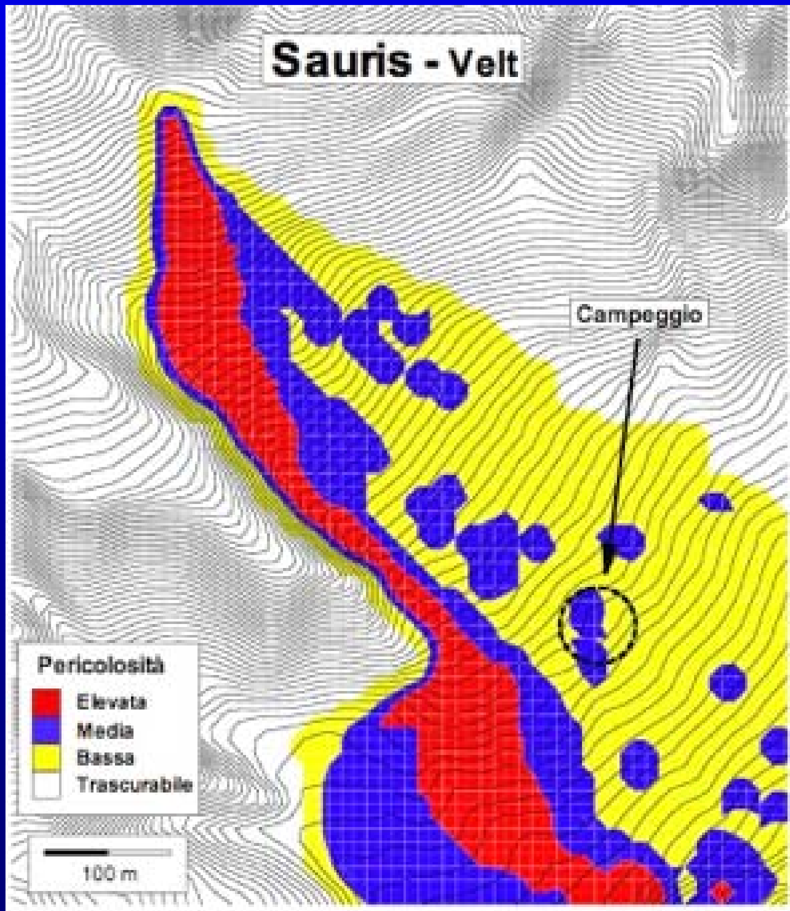
(Fuchs et al. 2007)

Future developments

- By the implementation of the modeling results, an inclusion of vulnerability function developed within IRASMOS will be possible. Hence, an improved quantification will be possible;
- Sensitivity analysis to derive the a vulnerability of the various objects based on risk scenarios
- Risk Map

$$R_{i,j} = f\,(p_{Si}, A_{Oj}, v_{Oj,\,Si})$$

$R_{i,\,j}$ = risk
p_{Si} = probability of scenario *I* *(magnitude/intensity)*
A_{Oj} = value at risk of object *j*
$v_{Oj,\,Si}$ = vulnerability of object *j*, dependent on scenario *i*



Conclusions

- The model has shown promising results related to the case study in Cancia, in particular since the values do not only indicate intensities, but also flow velocities;
- Shadowing effects of buildings located on the torrent fan modeled accordingly, which is an substantial improvement compared to other (debris flow) models
- The link to vulnerability has not yet been implemented, but this will be done in early summer

Two planets…

Planet Modelers

Is the link possible

?

Planet Users

- Mathematical formulation
- Physics and numeric
- Highly complex and high potential

- High practical experience
- Simplified phenomenology
- Scarce attention to research advances

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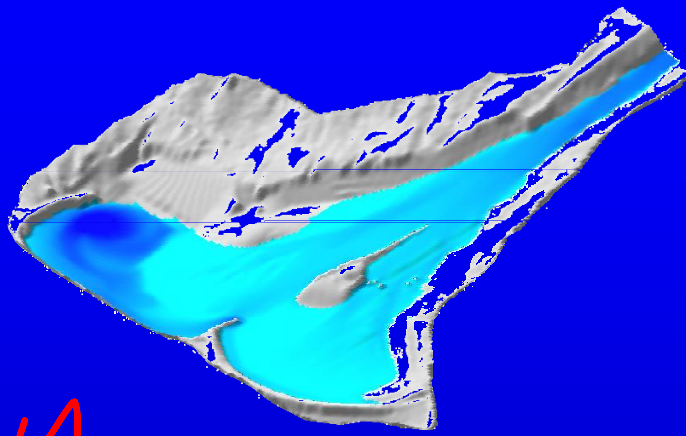
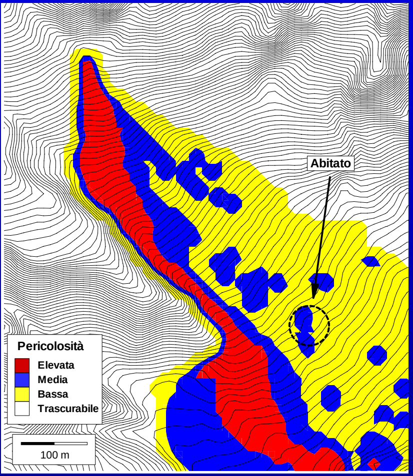
The end

Thank you for attention





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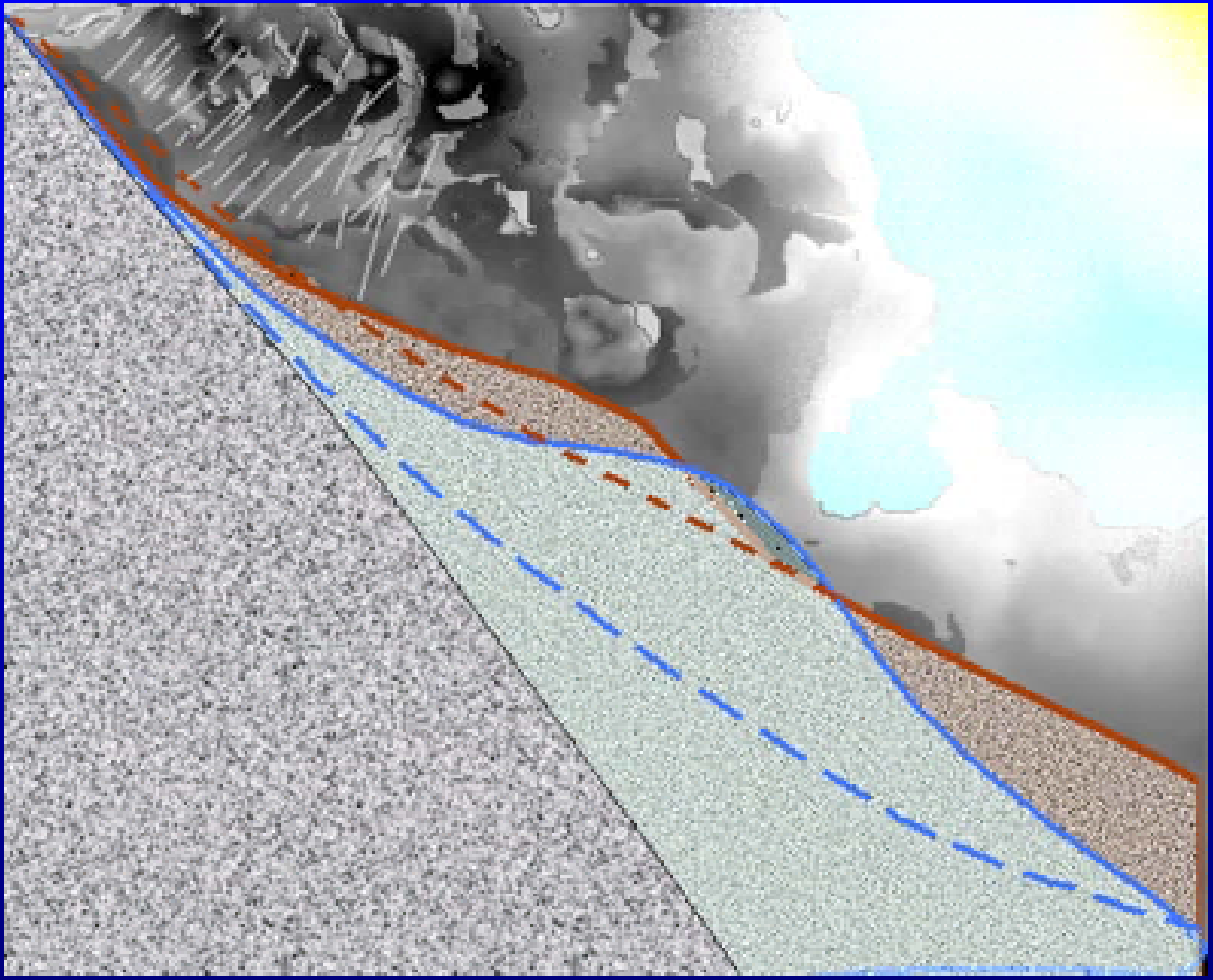
Risk analysis

- **Risk dependent on**
  - **the probability of occurrence** of a specific process and
  - the height of the **damage potential exposed**

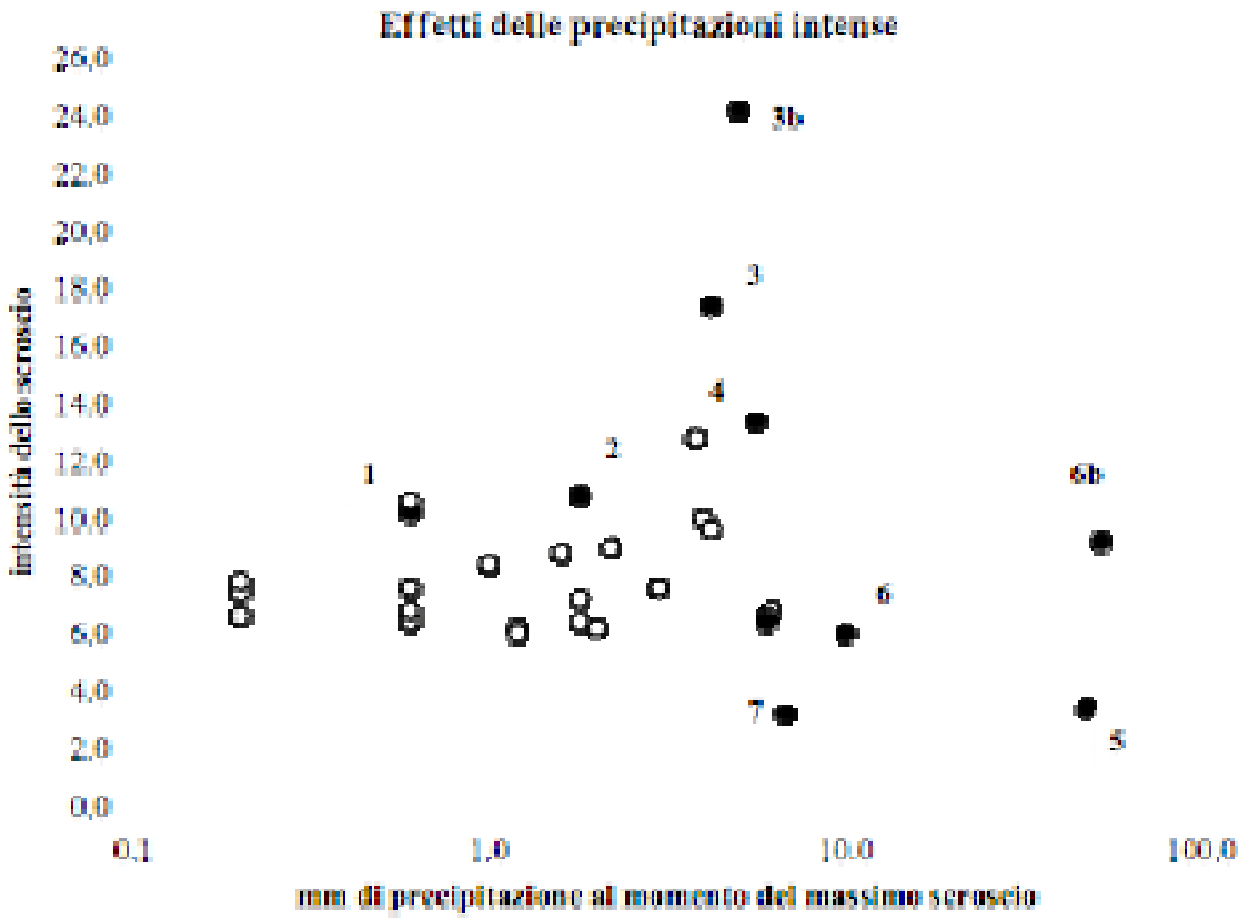
$$R_{i,j} = f\,(p_{Si}, A_{Oj}, v_{Oj,\,Si})$$

$R_{i,\,j}$	=	risk	✓
p_{Si}	=	probability of scenario *i*	*(magnitude/intensity)*
A_{Oj}	=	value at risk of object *j*	✓
$v_{Oj,\,Si}$	=	vulnerability of object *j*, dependent on scenario *i*	?

Triggering mechanism



Presence of thresholds



Source term and primitive variables

- Operation-splitting approach: from the solution of the homogeneous system, we can solve the ODE related to the source term (Euler implicit method)

$$U_{i,j}^{n+1} = \tilde{U}_{i,j}^{n+1} + \Delta t\left[\left(S_x\right)_{i,j}^{n+1} + \left(S_y\right)_{i,j}^{n+1}\right]$$

where

$$S_x = \begin{bmatrix} 0 \\ 0 \\ -\frac{\tau_{bx}}{\rho_w} \\ 0 \end{bmatrix} \qquad S_y = \begin{bmatrix} 0 \\ 0 \\ 0 \\ -\frac{\tau_{by}}{\rho_w} \end{bmatrix}$$

- Translation to the primitive variables

$$\begin{cases} h + z_b = \tilde{U}_1 \\ \beta g^{-1} c_b |\vec{u}|^2 + c_b z_b = \tilde{U}_2 \\ \left(\beta g^{-1} c_b \Delta |\vec{u}|^2 + h\right) u = \tilde{U}_3 - \Delta t\, \Psi(|\vec{u}|, h) u \\ \left(\beta g^{-1} c_b \Delta |\vec{u}|^2 + h\right) v = \tilde{U}_4 - \Delta t\, \Psi(|\vec{u}|, h) v \end{cases}$$

From the first two equations:

$$|\vec{u}|^2 = \frac{U_2 - c_b\left(U_1 - h\right)}{\beta g^{-1} c_b}$$

Non-linear system solved by Newton-Raphson

$$|\vec{u}|^2 \left(\beta g^{-1} c_b \Delta |\vec{u}|^2 + h + \Delta t\, \Psi(|\vec{u}|, h)\right)^2 = \tilde{U}_3^2 + \tilde{U}_4^2$$

where $\frac{\tau}{\rho_w} = \Psi(\vec{u}, h) \cdot \vec{u}$ and $\Psi = \frac{25}{4} \frac{\rho_s}{\rho_w} a \cdot \sin\phi_d \frac{\lambda^2}{Y^2} |\vec{u}|$

Upstream boundary conditions

- ✓ uniform flow hypothesis
- ✓ 2 conditions from outside the flow domain: Q_{liq} , Q_{sol}
- ✓ 1 inner condition: the bed elevation

} Coherent with characteristic analysis

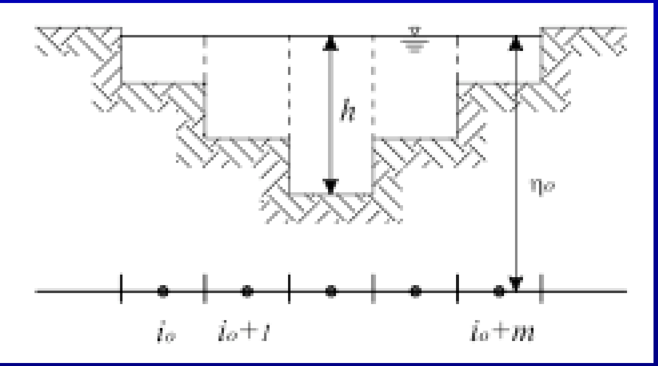
- Guessed η_0 it is possible to derive how many cells are affected and resolve the equation of the uniform flow to calculate u

$$[c(u)\cdot\Delta+1]ghi_f-\frac{25}{4}\frac{\rho_s}{\rho_w}a\cdot\sin\phi_d\frac{(\lambda(c))^2}{Y^2}\left|\vec{u}\right|^2=0$$

Newton Raphson

- Then the error related to this measure is calculated and through an iterative procedure we arrive at convergence

$$err=\sum_{i=i_0}^{i+m}u_{i,j_0}^n h_{i,j_0}^n dy-Q^n$$



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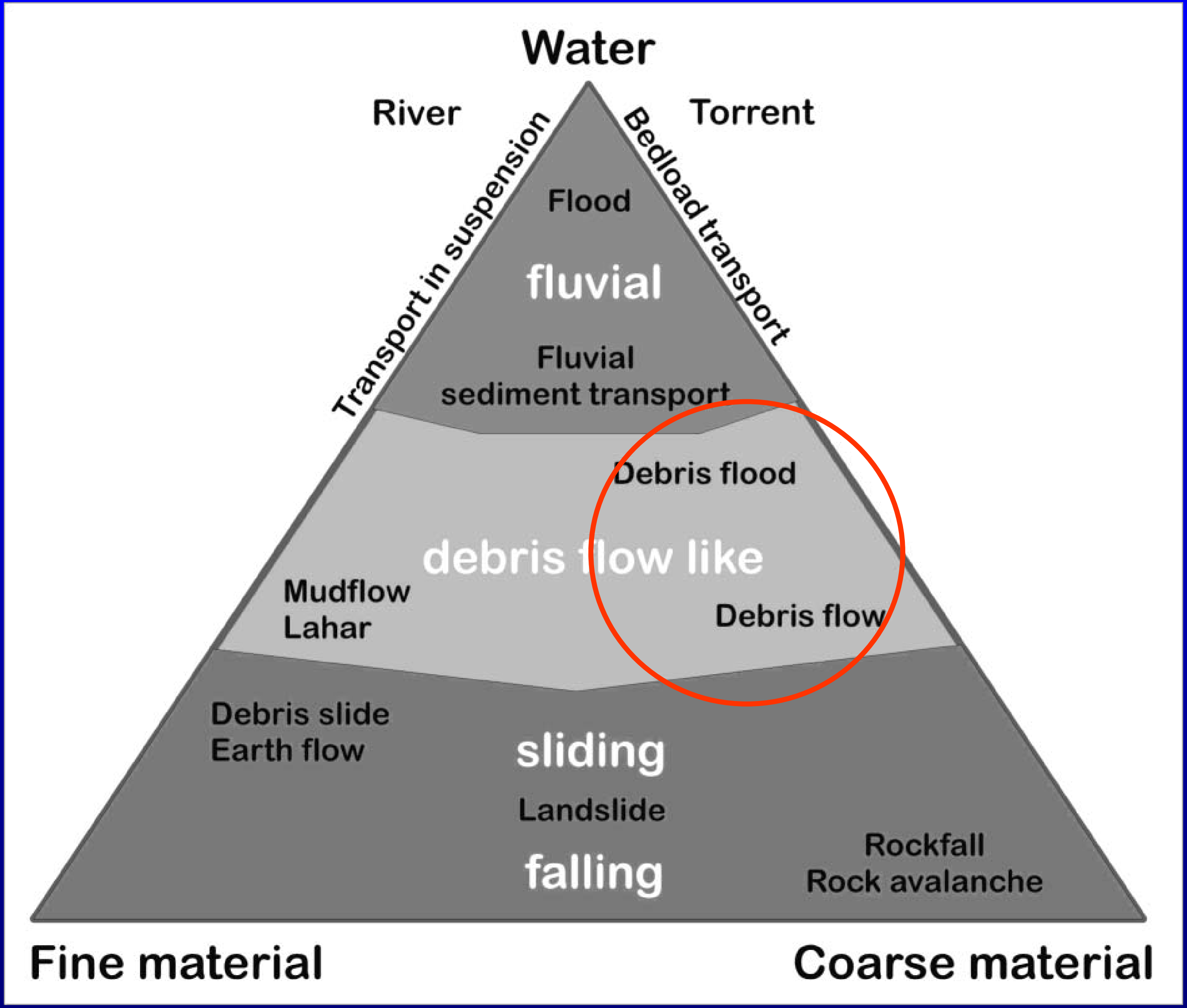
Debris flow hazard



Phillips and Davies 1991