Hydrologic design and debris flow hazard assessment in an alpine region using JGRASS geomorphologic modules

Ing. Andrea Salvetti
Cantone Ticino Land Department
Bellinzona - Switzerland
andrea.salvetti@ti.ch

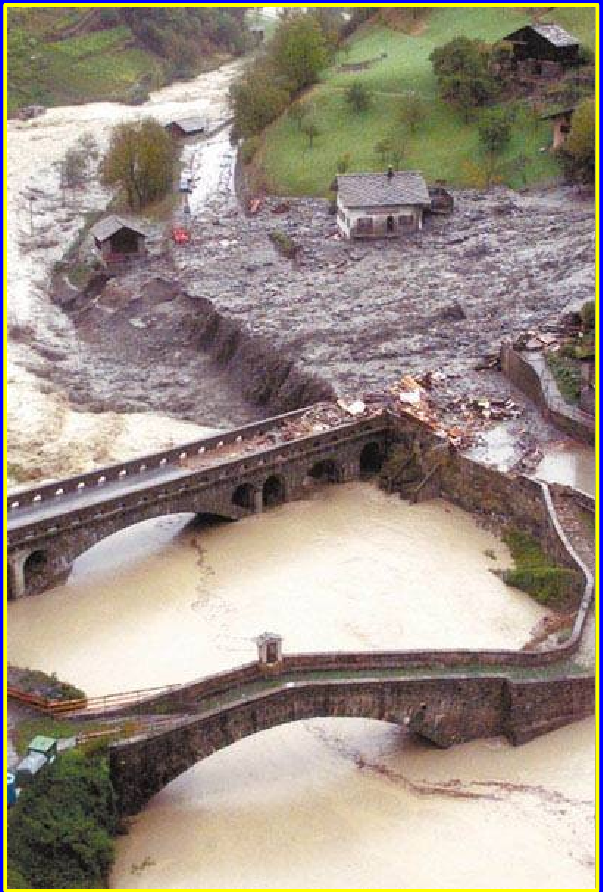
Topics: Flash Floods & Debris Flows

- **Introduction**
- **Definition of Case Study Areas**
- **Geo- morphological & hydrological analysis with JGrass**
- **Debris Flows: triggering factors & mobilization criteria**
- **Results**
- **Outlook**

Flash Flood

- A flash flood is a rapid increase of water stage and runoff in rivers and stream, potentially flooding the surrounding areas, that is caused by intense rainfall associated with a thunderstorm, or multiple training thunderstorms.
- Flash floods are the most dangerous kind of floods, because they combine the destructive power of a flood with incredible speed and unpredictability.
- Flash flood waters move at very fast speeds. They have the power to move boulders, tear out trees, destroy buildings, and obliterate bridges. They generally carry a huge amount of debris with them.

Flash Flood: some pictures



Debris Flow

DEFINITION

- A Mud Flow is a mass of water and fine-grained earth materials that flows down a stream or gulch. If more than half of the solids in the mass are larger than sand grains- rocks, stones, boulders—the event is called a Debris Flow.
- Debris and mud flows are a combination of fast moving water and a great volume of sediment and debris that surges down slope with tremendous force. They are similar to flash floods and can occur suddenly without time for adequate warning.

CHARACTERISTICS

- When the drainage channel eventually becomes less steep, the liquid mass spreads out and slows down to form a part of a debris fan deposit. In the steep channel itself, erosion is the dominant process as the flow picks up more solid material.
- They are common events in the steep terrain of the Swiss Alps and vary widely in size and destructiveness.
- Cloudbursts provide the usual source of water for debris flow in Switzerland.

Debris Flow (2)

SEVERITY OF THE PROBLEM

- Debris Flows become a serious threat to man-made works and human life when man inadvertently chooses to live in active debris flow areas (debris fan).

CONSEQUENCES

- The consequences of improper utilization of and debris-fan areas range from occasional inconvenience to human inhabitants to loss of life and total destruction of all works of man in the area affected.
- In general, the more hazardous mud flow and debris flow areas should be avoided. In less severe cases, careful mitigation measures and compatible kinds of development are recommended.

Debris Flow: some pictures

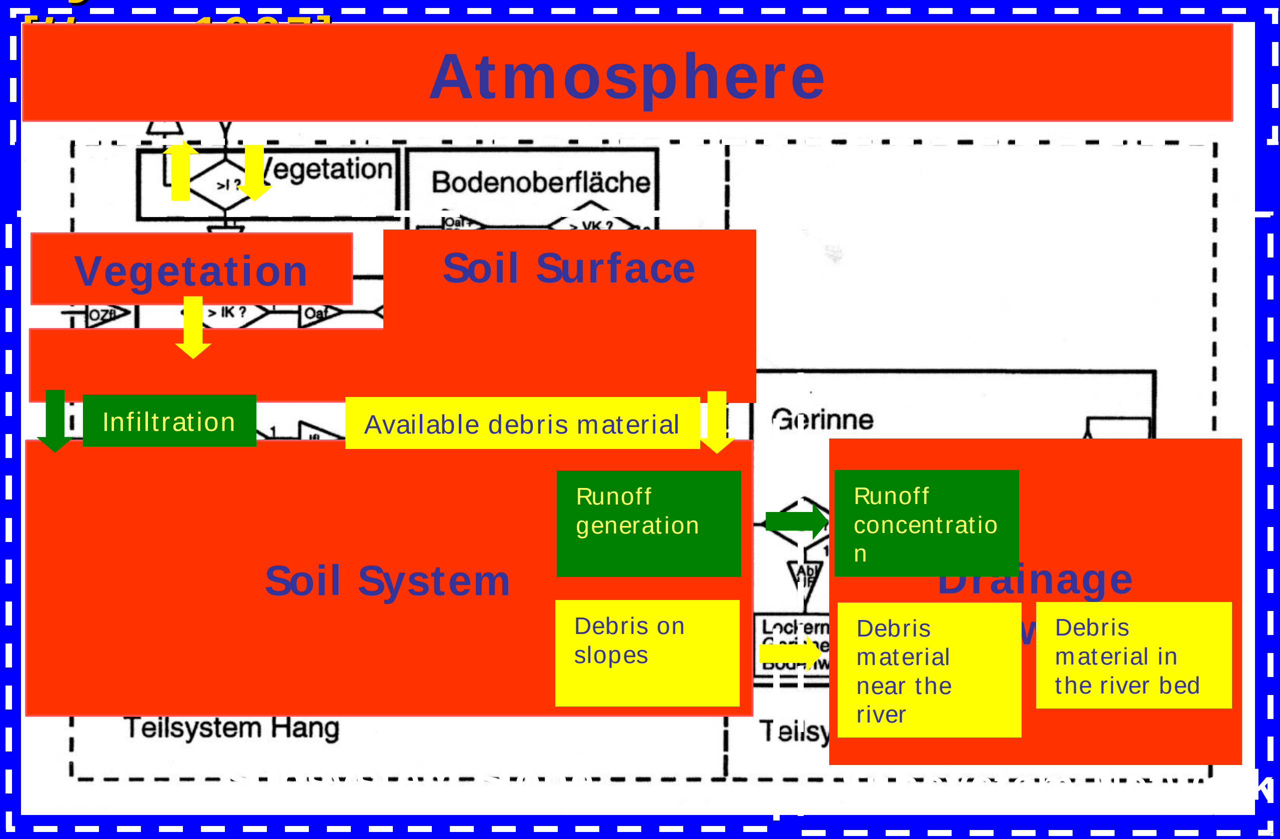

Kummerbach, Davos [Eberle, 1998]


Brienz, Switzerland [Swiss Army, 2005]

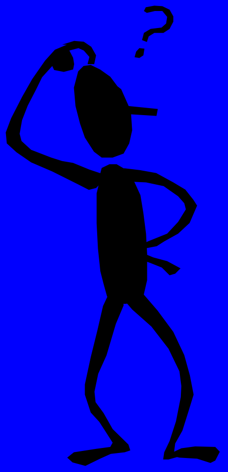

Acquarossa, Switzerland [Cantone Ticino, 2003]

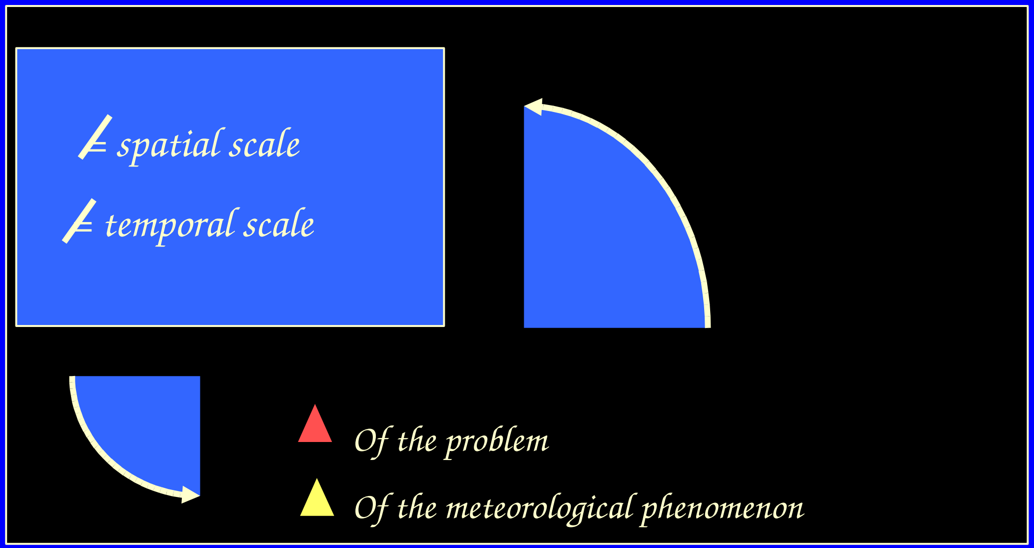

Brione Verzasca, Switzerland [Cantone Ticino, 1982]

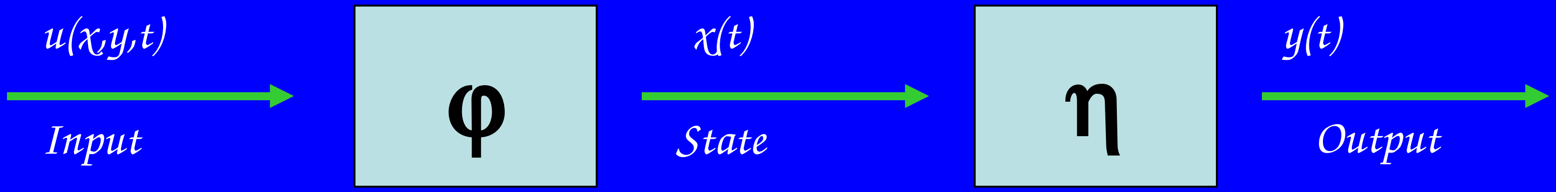
The Torrent Process System



Design flood estimation & debris flow hazard

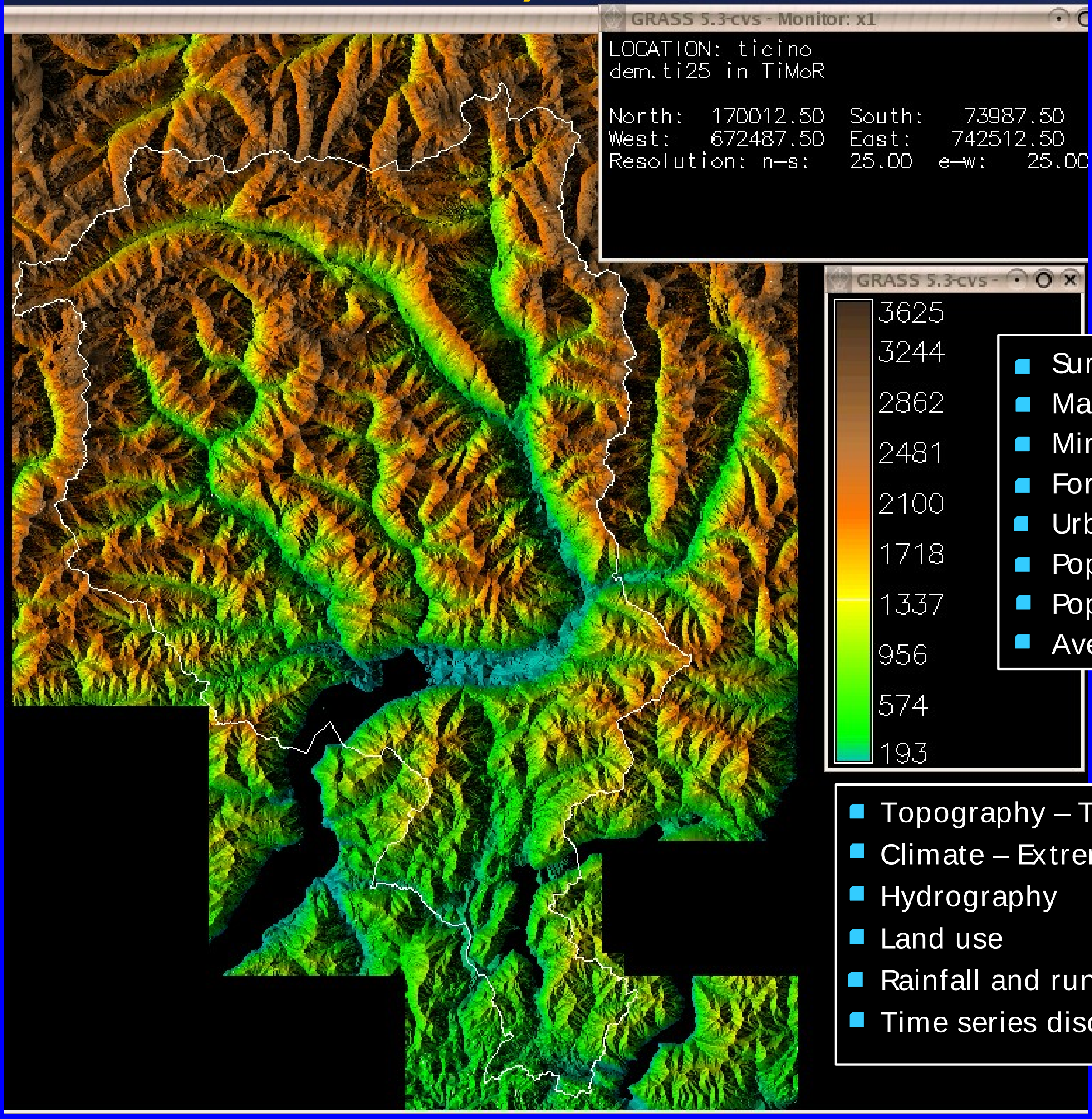






$$x(t) = \varphi\left(t, \tau, x(\tau), u(\ )_{[\tau,t)}\right) \qquad y(t) = \eta\left(x(t), t\right)$$

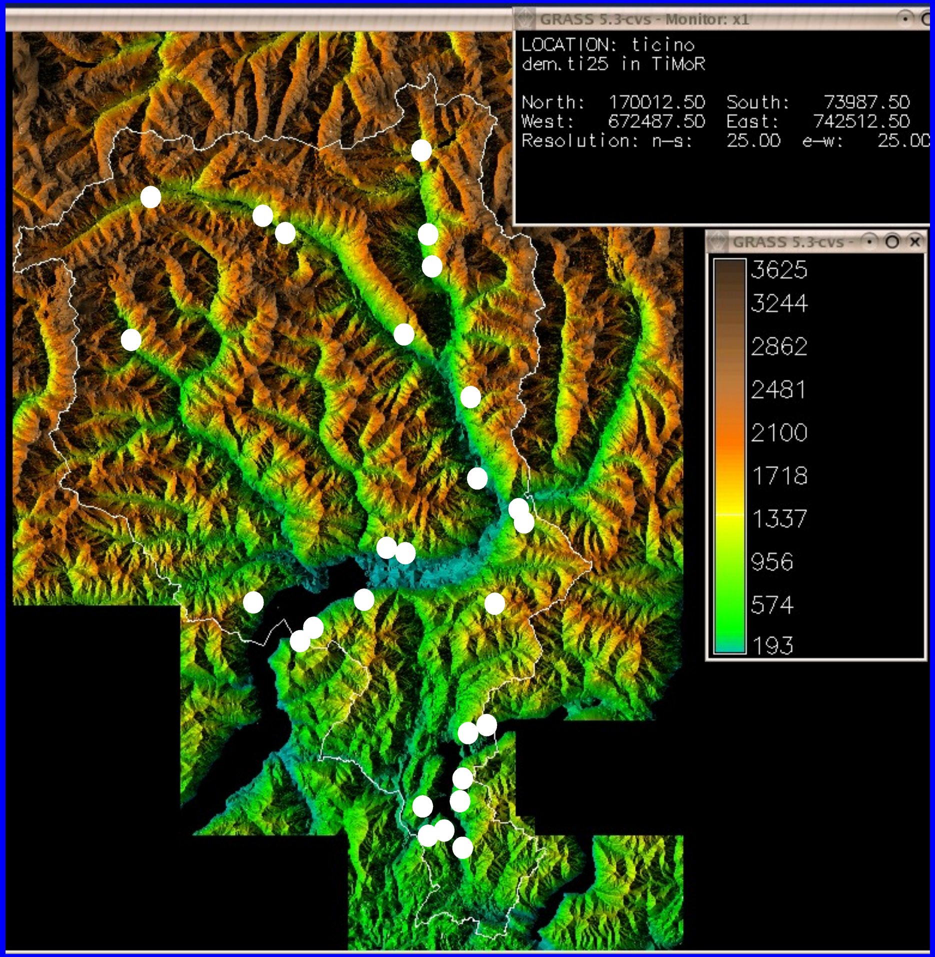
Ticino Canton, Switzerland



- Surface = 2812 km²
- Max. Altitude = 3402 m a.s.l.
- Min. Altitude = 193 m a.s.l.
- Forest cover = 1374 Km² (ca. 50%)
- Urban areas = 102 Km² (3.6%)
- Population = 282'000 inhabitans
- Pop. Density = 100 inhab./km²
- Average Rainfall = 1900 mm/year

- Topography – Terrain morphology
- Climate – Extreme events
- Hydrography
- Land use
- Rainfall and runoff data availability
- Time series disomogeneity

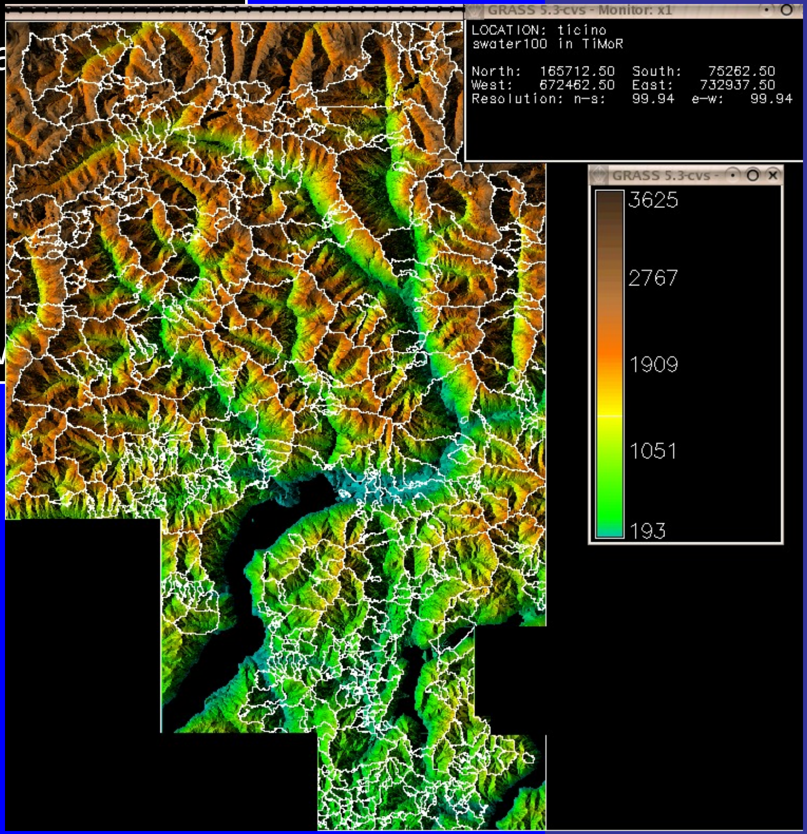
Available data set (36 possible study areas)



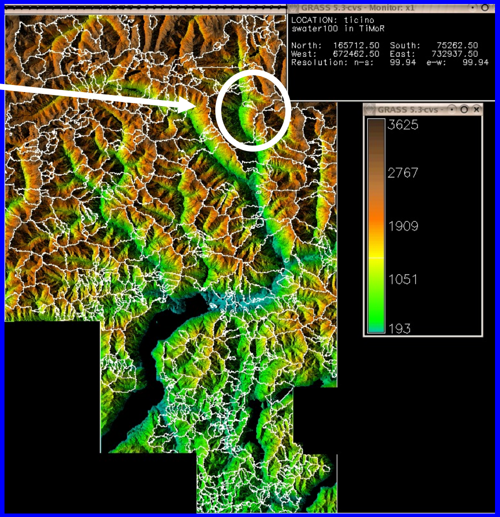
- All the different geological region are represented
- Historical cases with different quality of information
- Different typology: mud, sediment and debris flows
- Different climatic regions (rainfall characteristics: mean annual rainfall and extreme rainfall events)
- Different hydrological response of the soil
- Different anthropogenic influence and urbanization degree

Watershed selection criteria

- Basin surface < 5 km^2
- Different litology and morphology
- Availability of historical events with magnitude da
- Availability of airplane photographs
- Interesting case for applied research
- Existing vulnerability of urban areas and/or highw



Presented study area

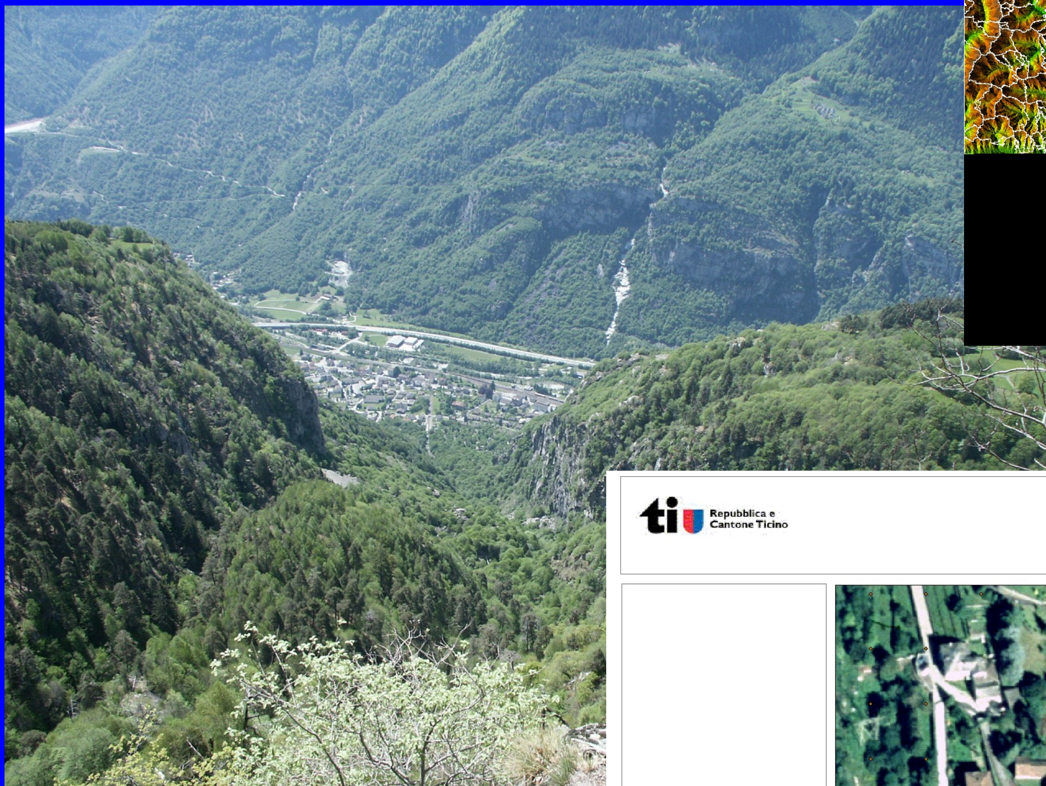


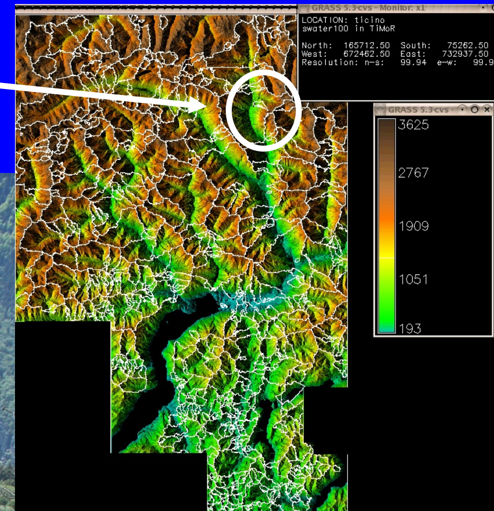
Test Basin & alluvial fan:

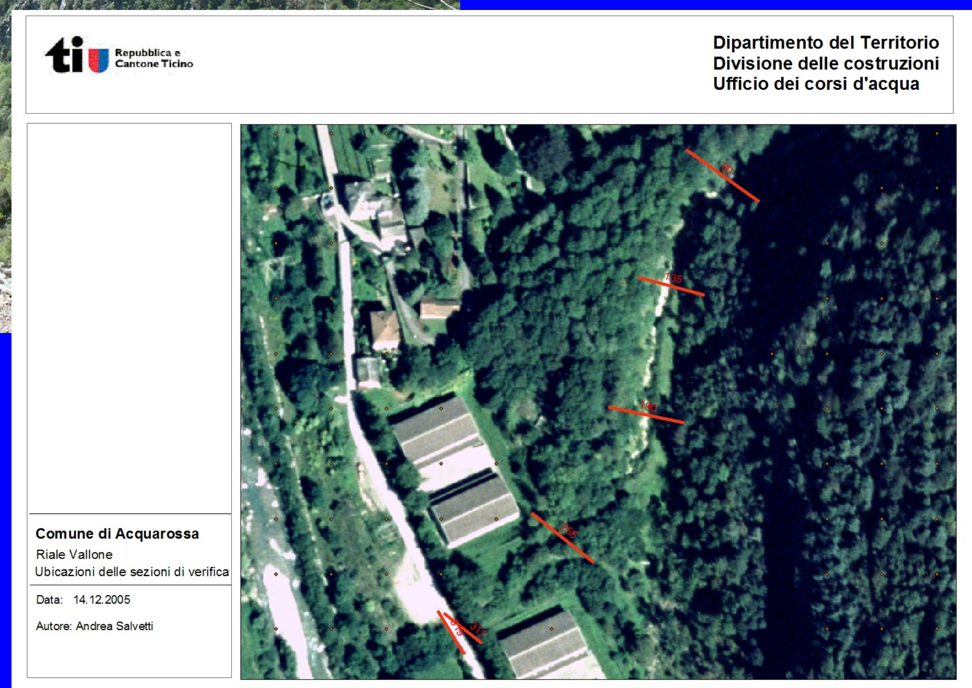
Acquarossa Creek, Blenio Valley TICINO

- **Watershed area: < 2 km²**
- **Max altitude: 2600 (m a.s.l.):**
- **Min altitude: 520 (m a.s.l.):**
- **Mean basin slope [%]: 76.7**
- **Litology: gneiss (+ debris and morains)**
- **Swiss Army Infrastructures and Building to protect**
- **Roadway**

Presented study area







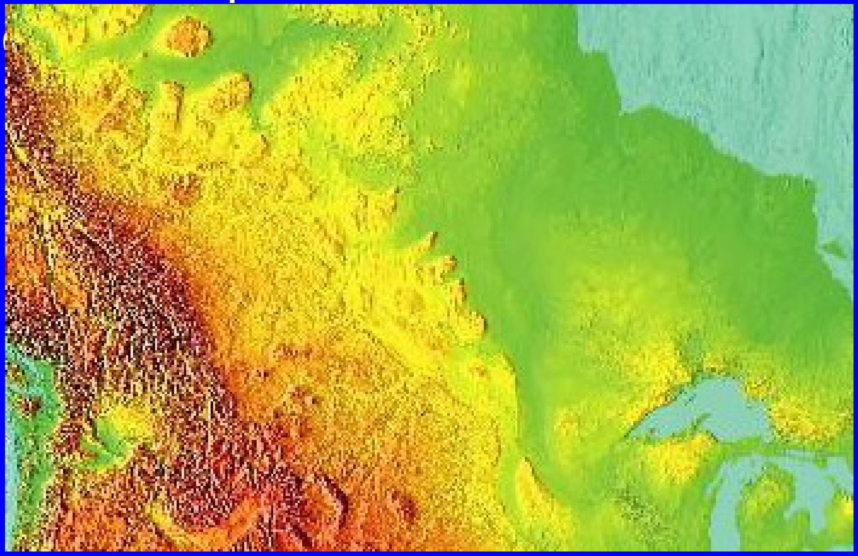
Morphology - Geomorphometry

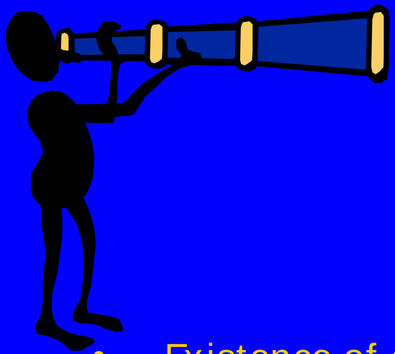
JGRASS

- Geomorphometry is characterizing quantitatively the morphology of the Earth's surface, of the topographical forms and of the basins, in order to deduce from them:

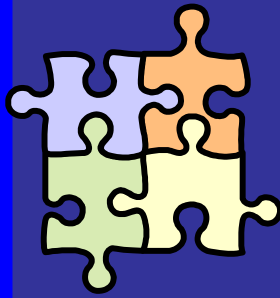
1. Some indicators of hydrologic and erosive

   processes
2. Some instruments for a correct parameterization of the hydrologic simulati





Morphology - Hydrology



- Existence of a link between morphology and hydrologic response is always implicitly assumed by a number of empirical formulas (*Concentration time as a function of basin size, length or slope*)
- *Rinaldo and Rodriguez-Iturbe* [1996]: geomorphological theory of the hydrologic response an coherent general framework

Needs for models which include:

- *Space-time representation of rainfall field*
- *Interaction between precipitation and hillslopes (runoff generation)*
- *Transport dynamics in the river network*

Hyp.: Linear systems

Linearity and stationairty

$$U\left[p(t-\tau)\right] = k \cdot q(t-\tau)$$

Unit hydrograph theory

$$a_n \frac{d^n q(t)}{dt^n} + a_{n-1} \frac{d^{n-1} q(t)}{dt^{n-1}} + \ldots + a_1 \frac{dq(t)}{dt} + a_0 q(t) = p(t)$$

GIUH Theory

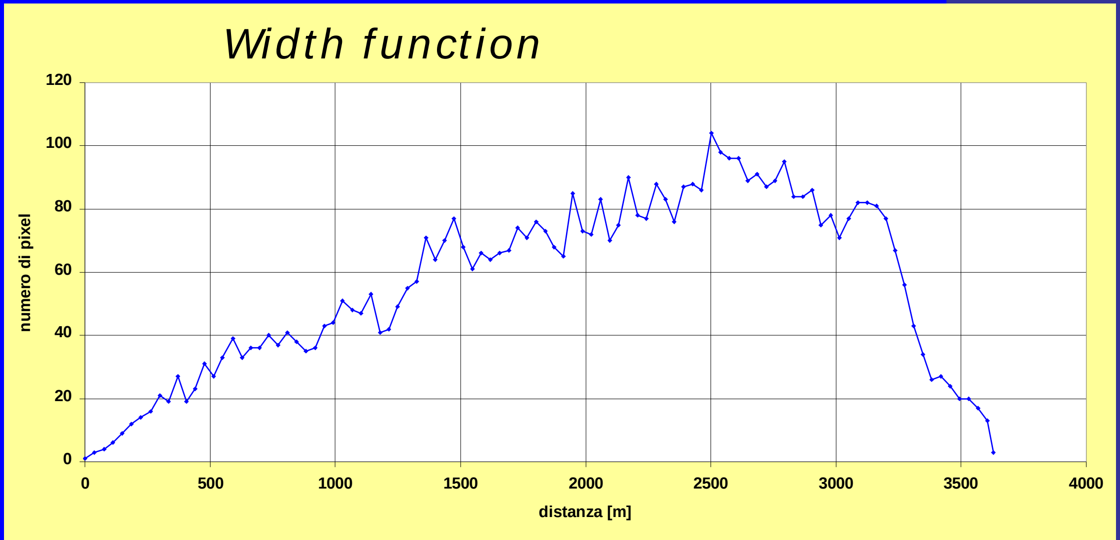
$$I_k(t) = \begin{cases} 1 \text{ se } t < T_k \\ 0 \text{ se } t \geq T_k \end{cases}$$

Probabilistic interpretation of the distribution of residence time in the watershed.

$$Q(t) = \int_0^t IUH(t-\tau) \cdot p_{eff}(\tau) \mathrm{d}\tau$$

Convolution integral

$$W(x) = \frac{1}{A_T} \mu\{a : d(a) = x\}$$



$$GIUH(t) = \int_A f(t \mid x; \vartheta) \cdot W(x) \mathrm{d}x$$

Geomorphologic Instantaneous Unit Hydrograph

GIUH Theory

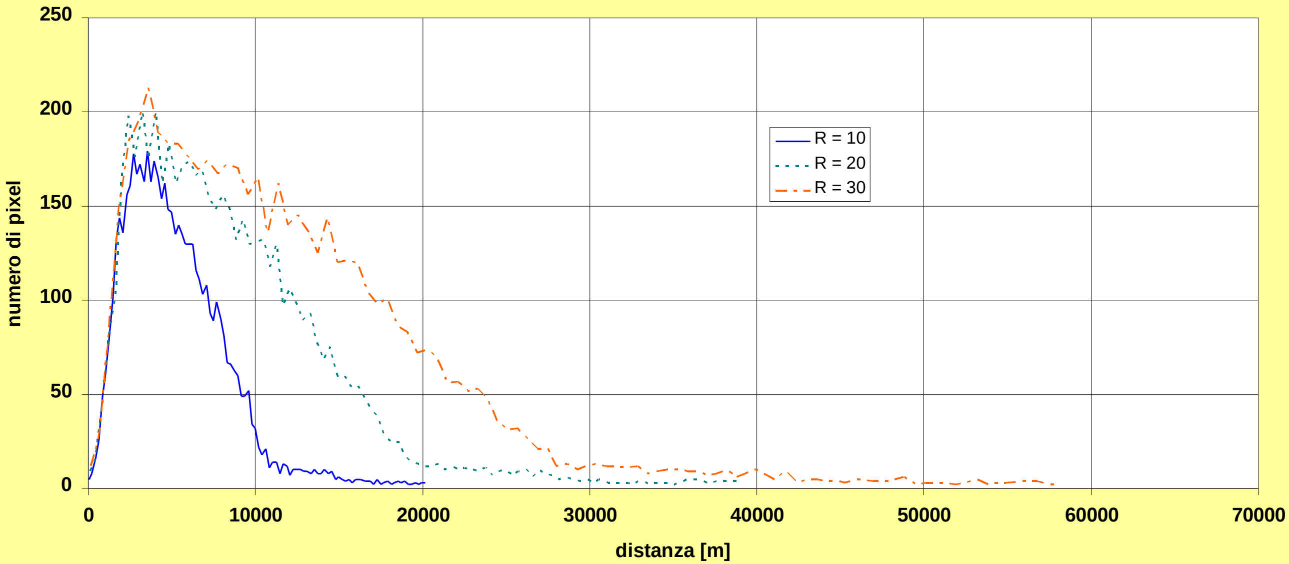
$$GIUH(t) = u \cdot W(u \cdot t)$$ *Kinematic approach*

$$\text{con } x = u \cdot t$$

$$x' = x_c + r \cdot x_h$$ *Rescaled distance (different travel time for hillslope and channel*

$$con\ r = \frac{u_c}{u_h}$$

Rescaled width function



JGRASS in general

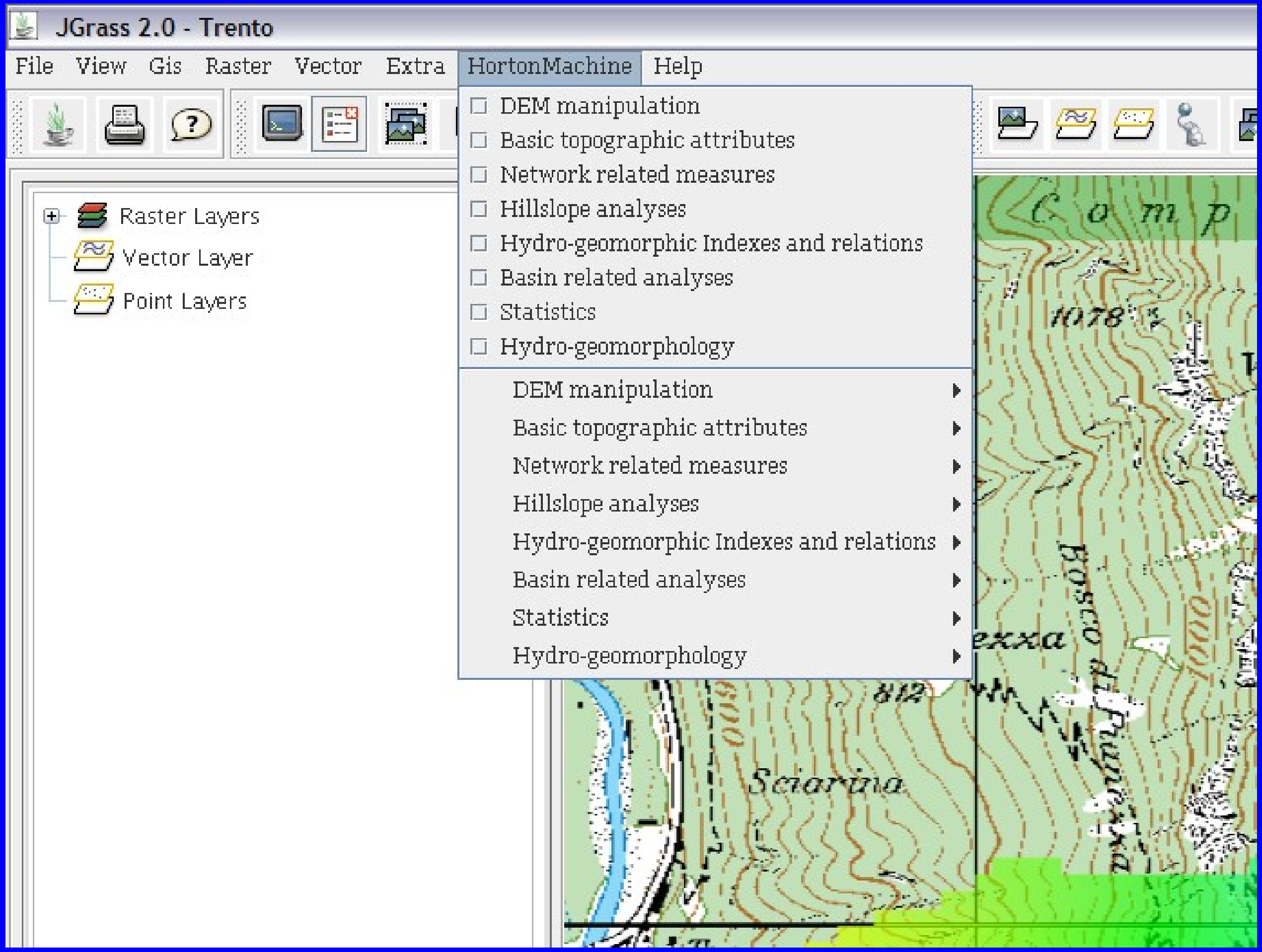
- JGrass, a Java based framework for the GRASS Geographic Information System
- The software is being entirely developed by HydroloGIS with the collaboration of the Civil Engineering and Environmental Department of the Trento University in Italy and the International Centre for Environmental and Nuclear Sciences of Kingston in Jamaica.
- Jgrass is essentially a GIS in which territorial analysis algorithms are integrated and include the hydrologic modelling and the geo-morphologic variables computing routines.

More info:

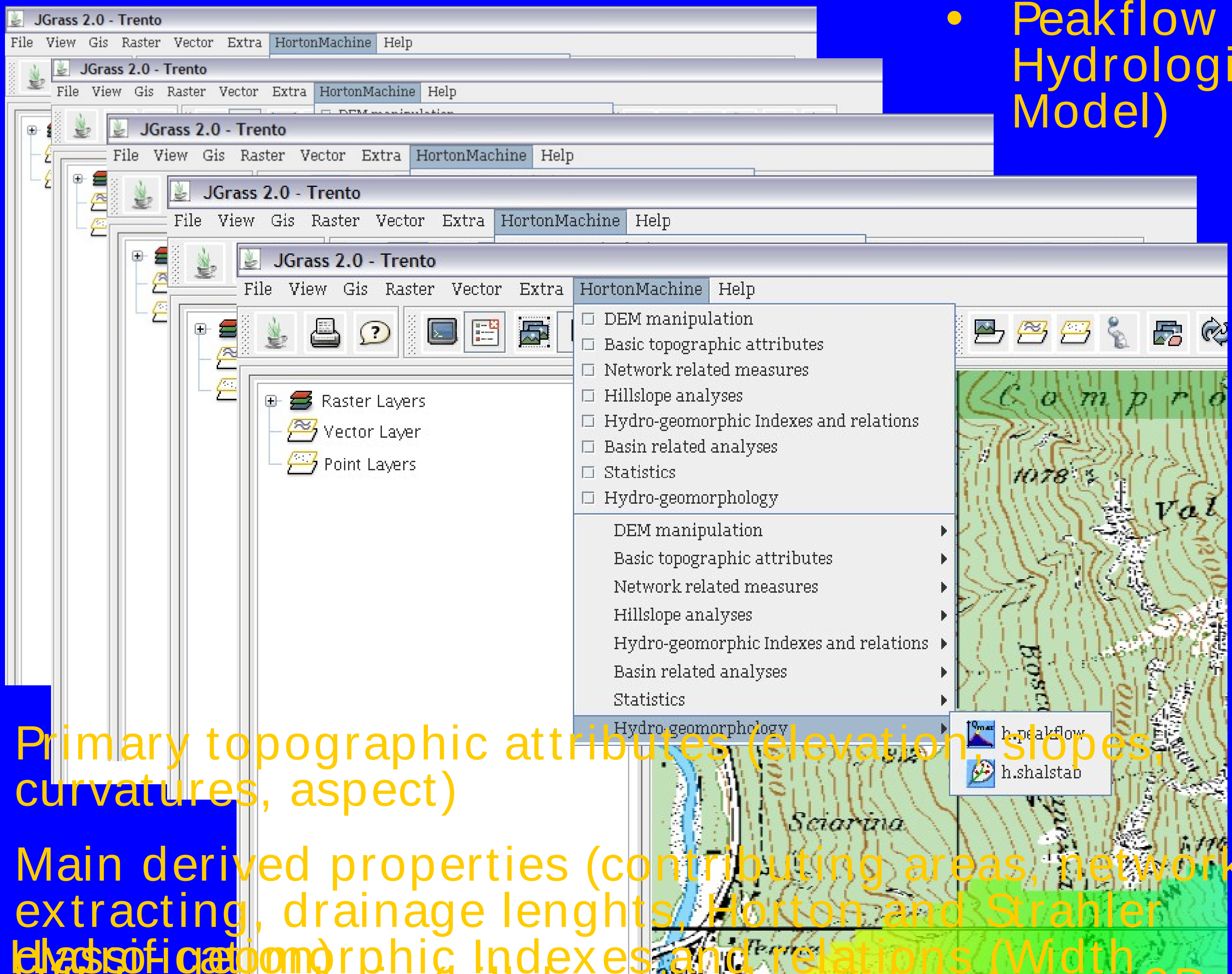
- A. Antonello, J. Preston, R. RIgon FOSS/GRASS Users Conference, Bangkok 2004
- www.hydrologis.com

JGRASS Horton Subroutine

- The suite of HORTON programs is composed of a set of applications, which carry out several operations on DEM.



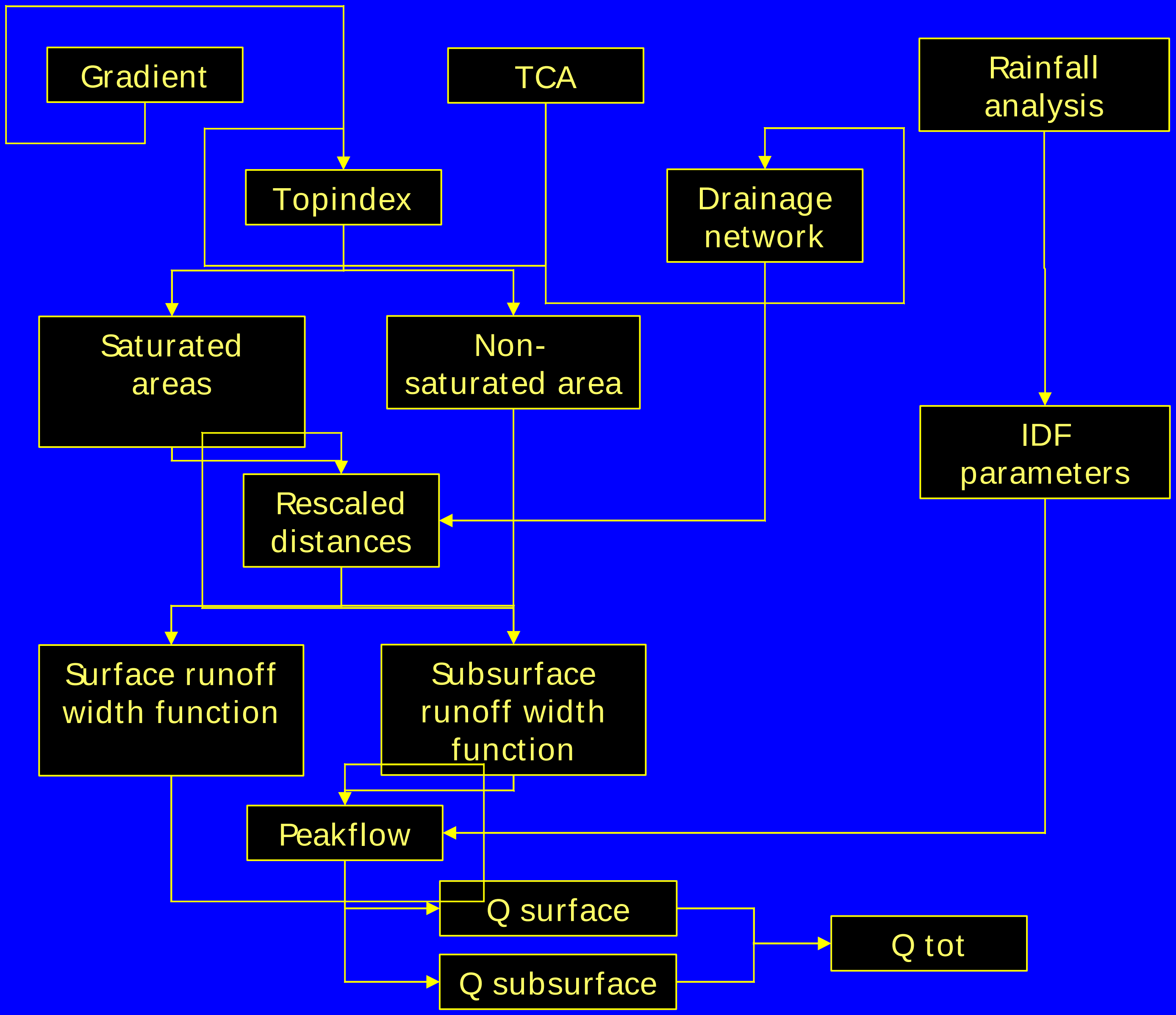
JGRASS Horton Subroutine (2)



- Peakflow (GIUH Hydrological Model)

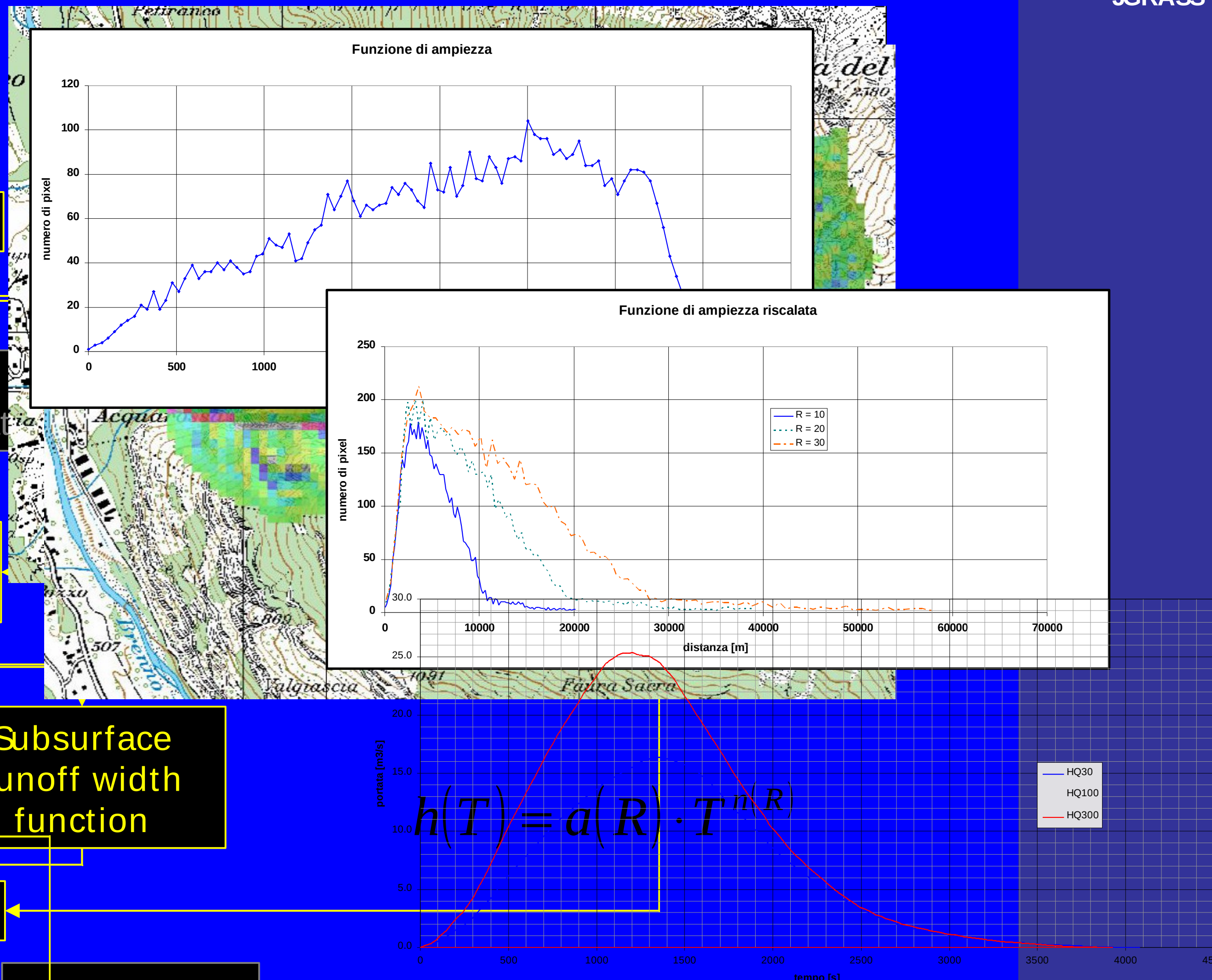
- Primary topographic attributes (elevation, slopes, curvatures, aspect)
- Main derived properties (contributing areas, network extracting, drainage lenghts, Horton and Strahler classification)
- Hydro-geomorphic Indexes and relations (Width function, Topographic index)
- Hillslope analysis (hillslope to channel distance, 2D e 3D; tangential shear stress, …)

Procedure from DEM to Peakflow



Procedure from DEM to Peakflow

- Gradient
- Topindex
- Saturated areas
- sat...
- Rescaled distances
- Surface runoff width function
- Subsurface runoff width function
- Peakflow
- Q surface
- Q subsurface
- Q tot



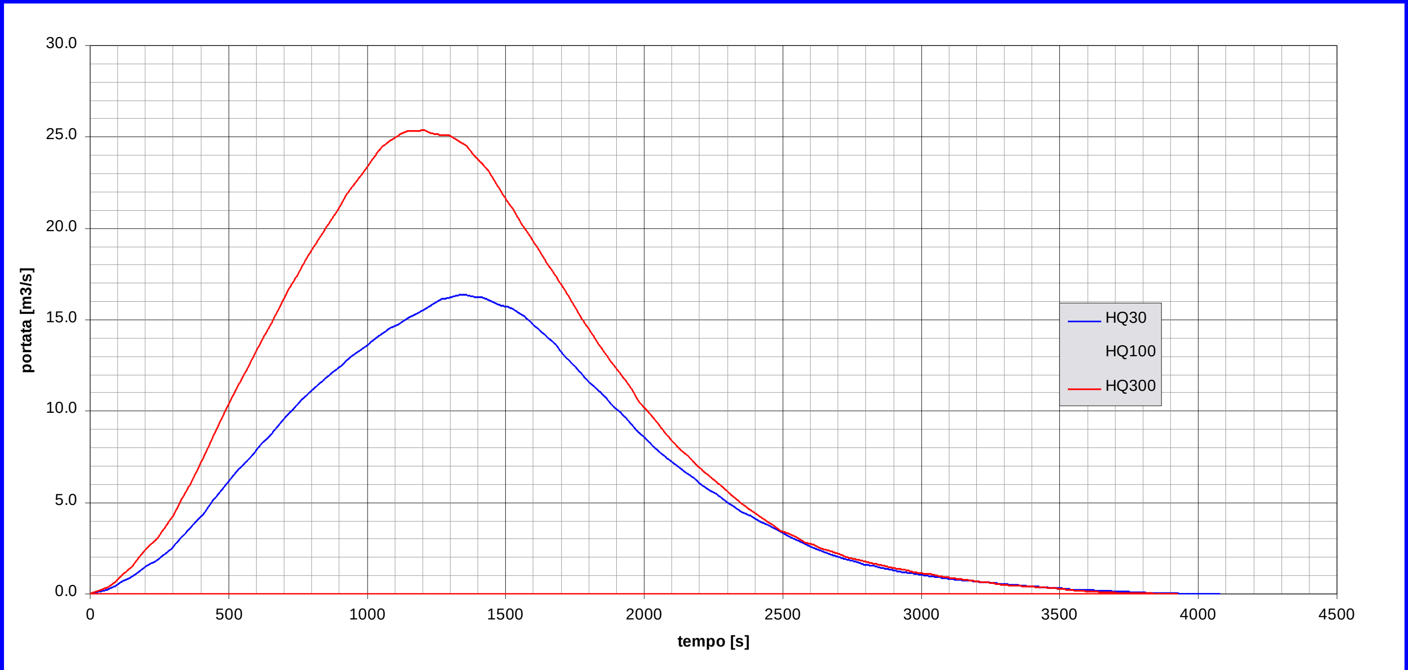
$$h(T) = a(R) \cdot T^{n(R)}$$

Calibration – Scenarios of peakflow parameters

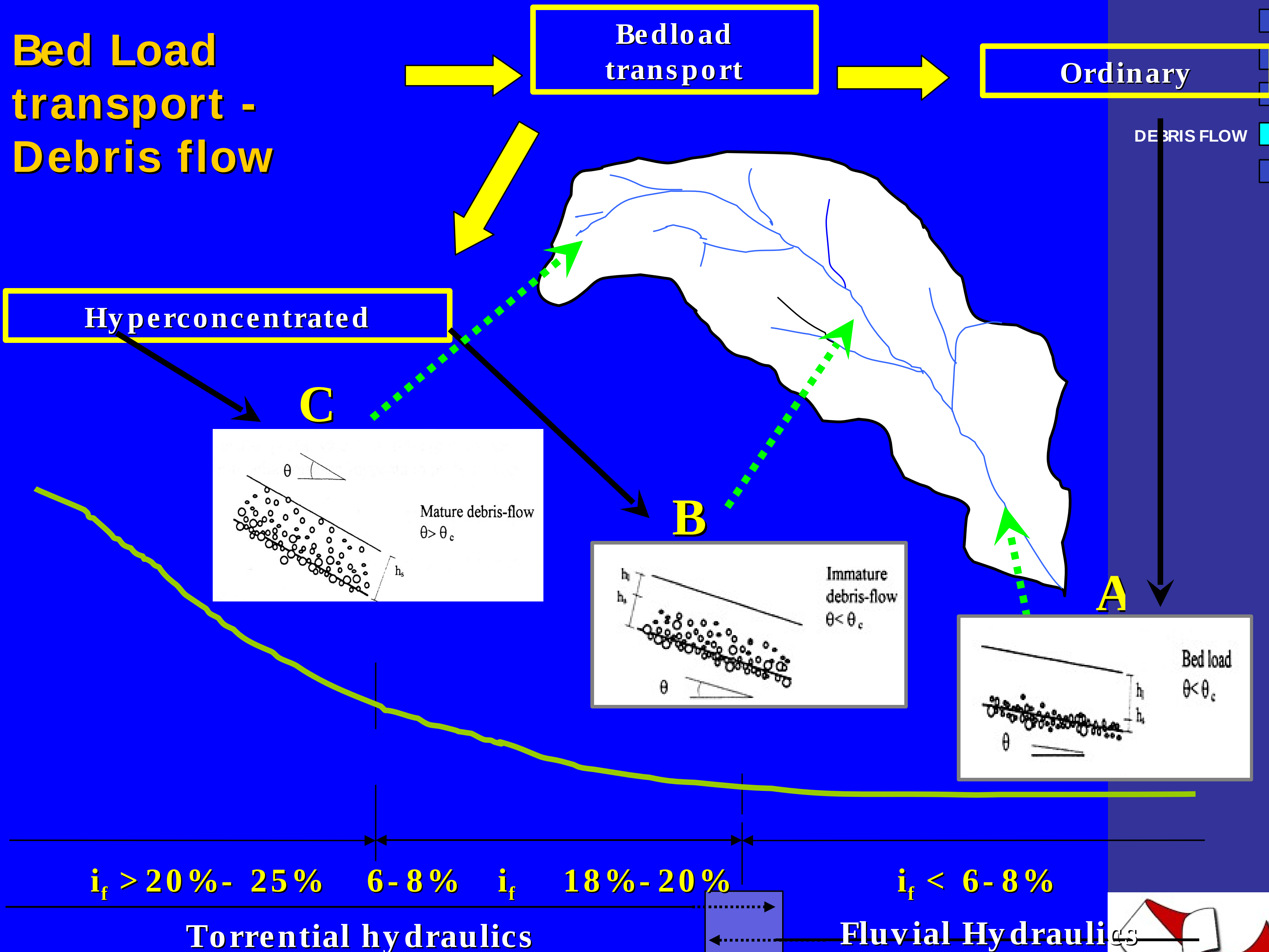
- Different %of saturation in the basin (antecedent soil moisture condition)
- Different r ratio (rescalled width function)
- Different v (channel velocity)
- Different rainfall return period

- JGRASS scripting

- Independent validation by using different approach (time concentration formulas)

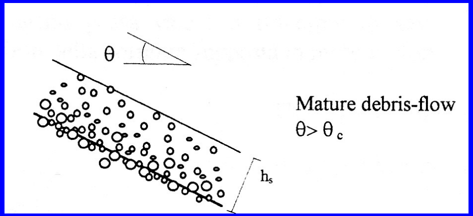


Bed Load transport - Debris flow



Debris flow – initiation mechanism

Three types of debris flow initiation are relevant:



[Takahashi, 1991]

- The first type is due to erosion of a channel bed. As a consequence of intense rainfall, surface runoff appears on a steep channel bed, in which a large amount of material was accumulated; the water destabilizes and entrains the available debris to form the debris flow.

- The second type of initiation is due to landslide: the slid soil mass transforms into debris flow.

- The third type is the destruction of natural dams. A previous landslide, which dams up a creek, is suddenly destroyed by the water over-topping the dam, which abruptly collapses. The mechanism to disperse the materials in flow depends on the properties of the materials (grain size, friction angle), channel slope, flow rate and water depth, particle concentration, etc., and, consequently, the behaviour of flow is also various.

Class of variables involved: geo- litology - morphology - hydrology

- Bedrock geology, weathering mechanisms (debris grain size, friction angle,…).

- Morphological properties (in the watershed and locally): local slope, channel width, drainage network density, width function, hillslope and channel length, …

- Hydrological properties: peak runoff, water depth, rainfall intensity and depth, (influence of landuse, soil properties, …)

Tognacca criterion

$$q_c^* = \frac{A}{(\tan\Theta)^B}$$

- q_c^* is the a-dimensional Threshold-runoff for sediment transport initiation [*Whittaker & Jäggi*, 1986]
- *A* and *B* are empirical parameters
- Tognacca [1999] extended this approach to debris flow, with proper values of *A* and *B*.

g =	9.8	m/s^2	*g* force
ρ_s =	2.65	g/cm^3	debris density
ρ_w =	1	g/cm^3	water density
d_m =	0.2	m	average diameter
Θ =	0.29	rad	average bed slope (initiation zone)
Θ =	16.7	°	
$\tan\Theta$ =	0.3		
b =	8	m	Average river bed width
$Q_{crit., bed load transport}$	3.0	m^3/s	
$Q_{crit., debris flow}$	11.8	m^3/s	

Magnitude assessment – Definition of Scenarios

- Hystorical documents
- Field surveys: Identification of unstable
- areas

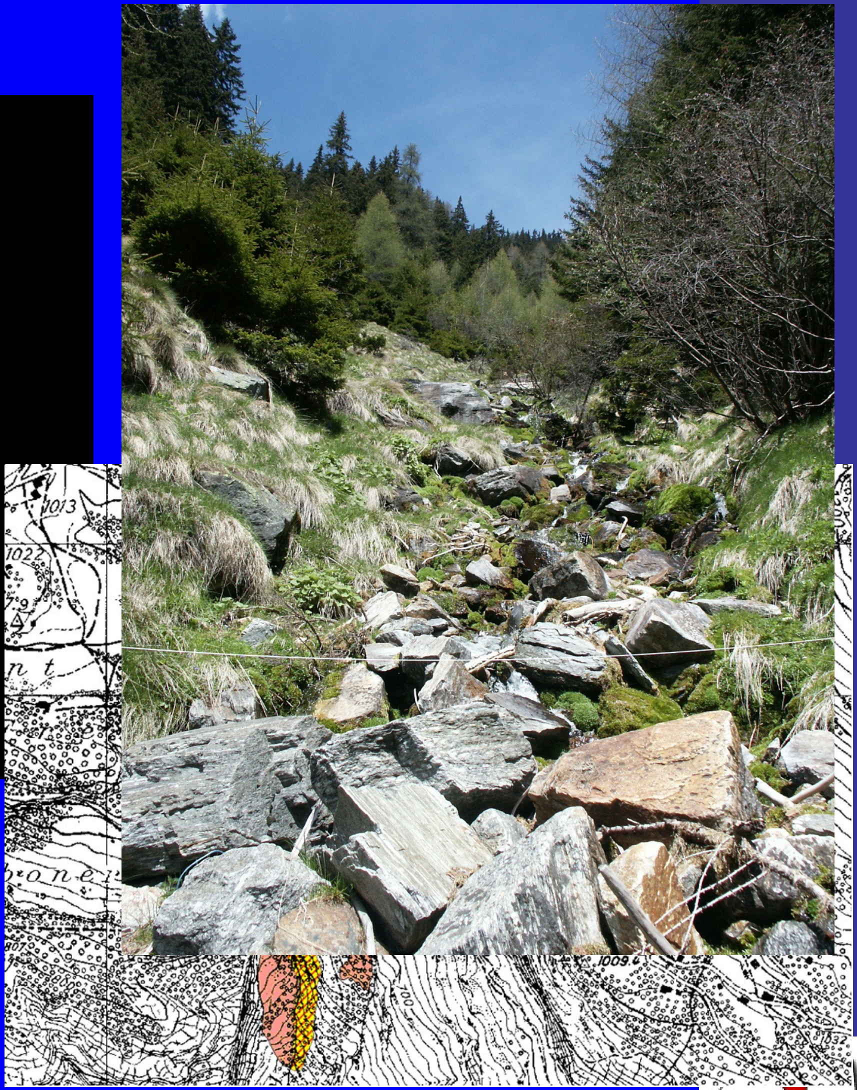
Assessment of Debris Availability:

- Debris Cover on slopes

Sediment depth in the riverbed

- *Possible erosion sources*

Classification of the different processes: sediment transport – debris flow



Geomorphological Evidences

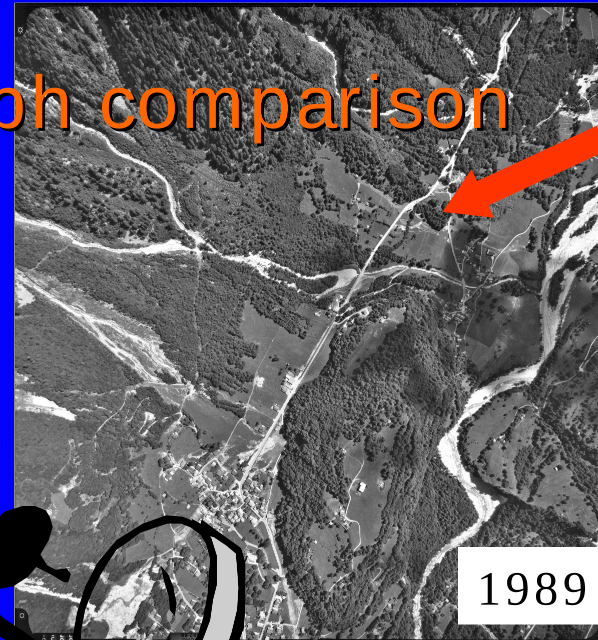
DEBRIS FLOW

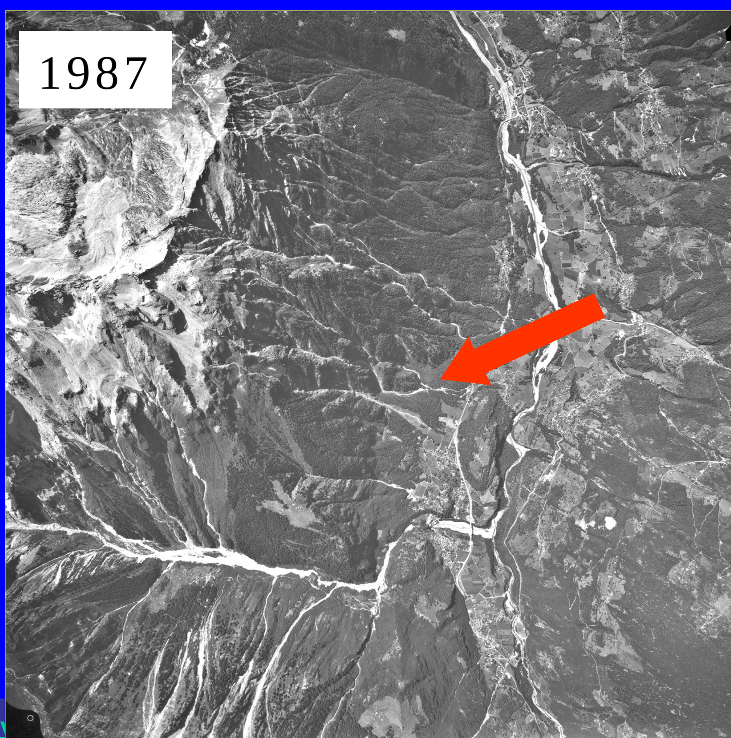
Upper part of the basin
(sediment availability in the river bed)

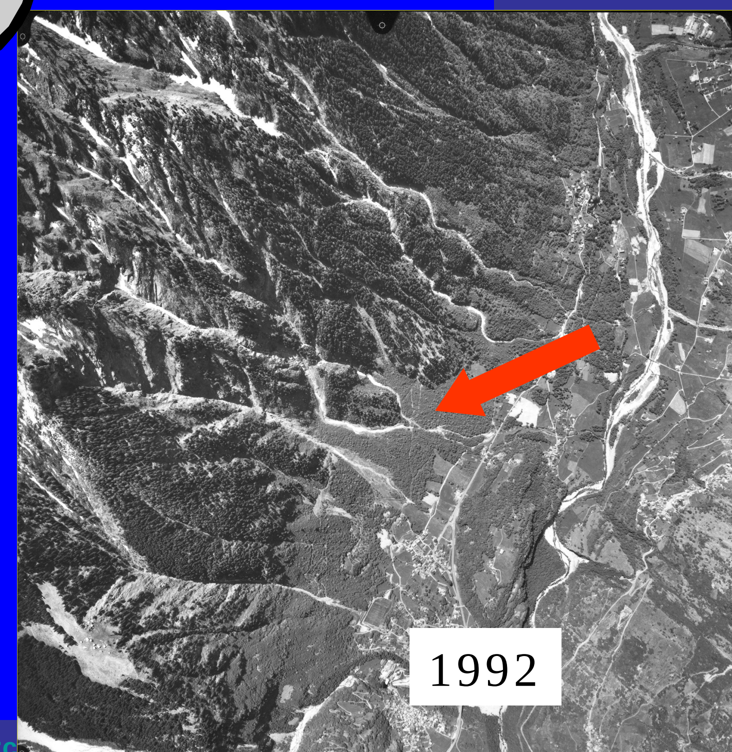
Lateral levee with inverse sedimentation

Areal photograph comparison

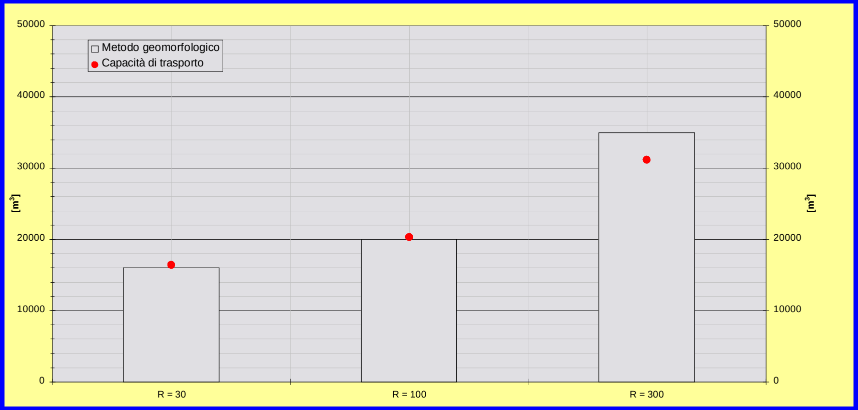
DEBRIS FLOW

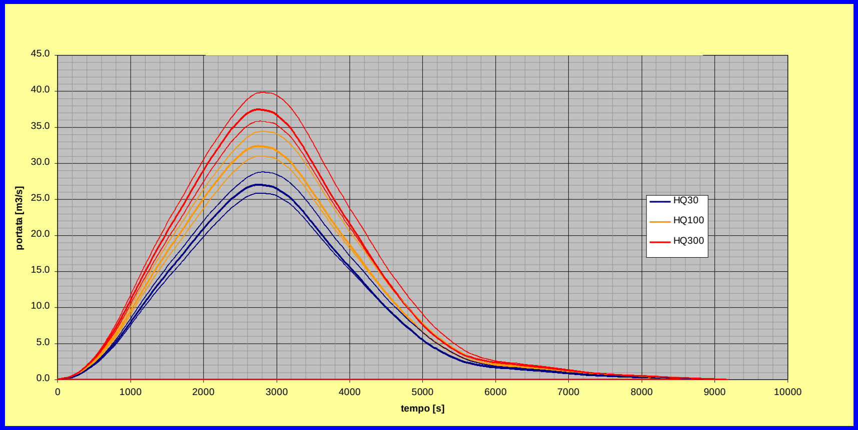






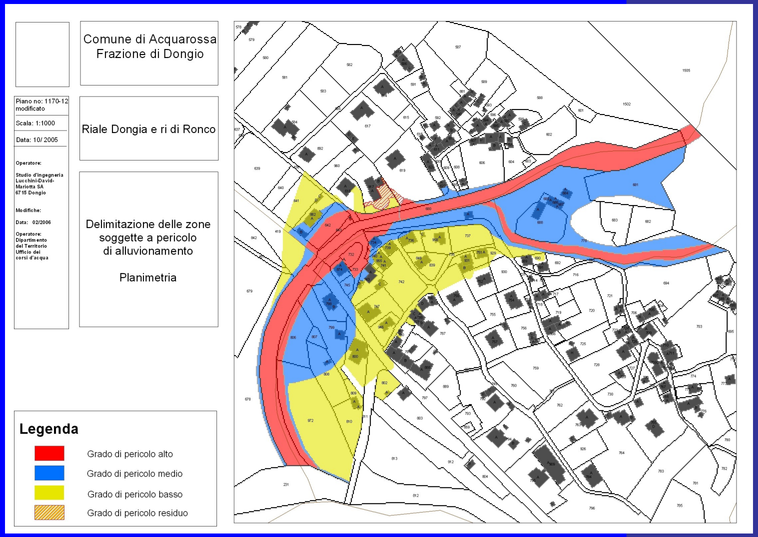
Geomorphological approach vs. transport capacity





Solid Hydrograph

Hazard Maps



Outlook

OUTLOOK

- Grass – JGRASS scripting for more procedure automatization

- Grass – JGRASS module for GIS- embedded detachment of initiation hazard assessment (different hazard level as screening procedure, without or with reduced field work)

- Grass – JGRASS module for simplified 2D- debris modeling within drainage network and on alluvial fan