Looking for a new method of estimating solid discharges in small alpine watersheds

Riccardo RIGON, Andrea COZZINI, Silvano PISONI

Dipartimento Ingegneria Civile e Ambientale, Universita' di Trento, via Mesiano 77,
tel. 0461-882610, fax 0461-882672, e-mail riccardo.rigon@ing.unitn.it

Abstract
A quantitative method for the gross estimation of landslide areas, volumes and solid discharge in extreme events is proposed. The method is based on the use of digital elevation models (DEM) in a GIS environment. First the SHALSTAB model has been used (Dietrich, 1994) to evaluate the area subject to landsliding according to specified hydrological conditions, then we have coupled SHALSTAB with soil depth model to get landslides volumes. However, landslides from hill-slopes are not the only source of solid discharges in Alpine watersheds. Major damage is in fact produced by the failure of sediment accumulated in unchannelized valleys and channel beds. These sources produce, after geo-mechanical instability triggered by subsurface water flow, solid movements called debris flows which are a mixture of variable concentration of sediments and water. We propose to assume that, at least for events of medium to large return time in small watersheds, the solid discharge total volume can be derived evaluating liquid discharges with a new method. Used methodologies are partially implemented in GRASS and partially use new codes which are being ported to GRASS.

Introduction
Mountain areas cover nearly two thirds of the Italian territory and have been considered marginal areas up to few years ago, mainly because of their scarce relevance for the economy of the country. Starting from the sixties, the increasing of the birth rate and the increased prosperity allowed a great development of tourism and handicraft. In a few ten years these regions have taken on an important economic role. This transformation changed the fragile hydrological equilibrium of mountain regions: there has been not only an increase of natural catastrophes because of the new anthropic pressure, of the progressive abandon of soil maintenance practices and of the climate change, but also a uncontrolled increase of costs of the damages of the properties and of human lives.
Differently from what happens in plans, the hydrological risk of mountain and piedmont regions depends on the solid supply and the intensity of the solid discharge implies that it is not possible to approach the two components separately. It is possible to think that the intense run-off activate the sediments and debris along the hillslope and the bed of the torrents creating large solid discharges, which could be (for small basins) even ten times the liquid discharges (in form of debris or mud flows). The solid phase starts to deposit in the alluvial fans causing over-flooding phenomena that damage anthropic settlements. Furthermore, the finest part of the solid discharge flows down into piedmont rivers, causing an increase of the water level that often lead to over-flows because of the reduction of the discharge capacity as the events of Versilia and Garfagnana (Italy) in 1996 and Venezuela in 1999 teach.

Traditional studies of the above issues make use of empirical formulas (e.g. Arattano et al., 1999) and field work by geologists, engineers and forest scientists. Formulas usually depend on numerous geomorphological parameters that could be measured only locally till some years ago but that now can be derived in quantitative and distributed form from more and more accurate DEMs. Moreover, also the conceptual understanding of hillslopes and catchments hydrology have recently been largely improved with the introduction of simple distributed techniques which let to obtain fast and reasonably well approximated evaluations of liquid discharges.

In this note a set of consistent quantitative techniques is presented for estimation of liquid discharges, solid discharges and landslide initiation zones by means of GIS , DEMs and simple modelling. Other important issues as landslide and debris flow initiation time and run-out will not be investigated in this note. We believe that, after the necessary verification and enhancements, these techniques could become routine methods integrating field surveys and monitoring.

The proper registration and relation with human settling is an obvious corollary of the techniques presented which make further necessary the use of a GIS system.

A short review of SHALSTAB.

The model of shallow landslide initiation we used has been introduced by Dietrich and his collaborators (1993,1995) and applied to many case studies (e.g. Montgomery, 1998) and it is called as SHALSTAB. It has recently been adopted by USGS as an operational tool.

The underlying assumption in SHALSTAB is that a steady-state subsurface flow model mimics the pore pressure distribution generated by the saturation excess mechanism of runoff. This seems reasonable if we are interested in finding those critical zones where water accumulation due to topography convergence dominates the hydrological fluxes even if it is unrealistic for determining the landslides initiation time (e.g. Iverson, 2000). Under the hypotheses well stated in Iverson (2000) the most relevant results are:

$$\begin{aligned} \psi &= (z-d)[\cos\theta - (\tfrac{I_z}{K_z})] \\ h &= -x\sin\theta - d\sin\theta - (z-d)(\tfrac{I_z}{K_z}) \end{aligned} \qquad [1]$$

where ψ is the groundwater pressure head, h is the difference between the groundwater pressure head and the elevation head, θ is the slope angle, z and x are the vertical and longitudinal coordinates, K_z is the normal hydraulic conductivity, d is the water table depth measured normal to the ground surface and I_z the average effective infiltration rate.

If we also assume that $I_z/K_z << \cos\theta$, then we obtain (Iverson, 2000):

$$\delta - d = h_w = \frac{I_z}{K_z}\frac{A}{b\sin\theta} \qquad [2]$$

where δ-d is the water table height above the reference δ and b is the width of the slope element over which the discharge is measured.

The above simplified model can be coupled with the infinite slope stability model of Skempton and DeLory (1957) with the result that landslides start where the safety factor:

$$F = \frac{c}{\gamma z \sin\theta\cos\theta} + \frac{\tan\phi}{\tan\theta} - \left(\frac{\gamma_w h_w}{\gamma z}\right)\frac{\tan\phi}{\tan\theta} \qquad [3]$$

is less than 1. In the above formula ϕ is the soil friction angle, c is the soil cohesion, γ is the depth-average soil unit weight and γ_w is the unit weight of groundwater. The first part can be seen as due to soil cohesion, the second to geology and the third to hydrology.
According to the rearranging equation (3), as illustrated in Dietrich (1995), we have the landscape partitioned into four classes:
zones unconditionally instable, for which:

$$\tan\theta > \tan\phi \qquad [4]$$

i.e. having slope larger than the Coulomb friction angle;
those unconditionally stable (stable for any subsurface flow condition or for which the necessary –yet not sufficient- condition of instability is the formation of a positive water depth at the surface):

$$\tan\theta < \left(1-\frac{\gamma_w}{\gamma}\right)\tan\phi \qquad [5]$$

The remaining part of the landscape is further subdivided into two regions according to the inequality:

$$\frac{A}{b} > \frac{\gamma}{\gamma_w}\left(1-\frac{\tan\theta}{\tan\phi}\right)\frac{T}{I_z}\sin\theta \qquad [6]$$

where A is the total contributing area uphill a given point. For points where the inequality is verified the landscape is conditionally unstable, otherwise is said to be conditionally stable. In this equation a geotechnical parameters, such as ϕ, geomorphological parameters, that can be determined from DEM, such as A, b and θ, and a hydrological index such as $I = T/I_z$ (where T is the trasmissivity), appear.
The result of the analysis of the case study of the Renanchio (Quincinetto, TO) torrent basin is presented in Figure 1.

Exploring some extensions of Dietrich theories
We need to get the soil depth available in any point of the landscape in order to obtain landslide volumes estimation. One possibility is to make measurements of soil depth in many points of the basin and to extrapolate the measurements for the whole area. This is in any case impossible without modeling. Assuming that the soil depth is in equilibrium with soil production (which is certanly false in the case of points recently affected by landslides which thus should be mapped by historical inventory) as, for instance in Heimsath et al. (1997) we can obtain the equilibrium soil depth given by:

$$h = -\frac{1}{m}\ln\left(-\frac{k\nabla^2 z}{P_0\frac{\rho_r}{\rho_s}}\right) = \frac{1}{m}[\ln(-\nabla^2 z_{cr}) - \ln(-\nabla^2 z)] \qquad [7]$$

where m is a parameter which gives the rate of soil production and $\nabla^2 z_{cr}$ is a critical curvature. The model works only on those convex parts of hillslopes which are soil mantled and implies the esclusion of those parts which are denudated or above the critical angle. Automatic identification of areas subject to different geomorphic processes is discussed in Rigon and Cozzini (2001).

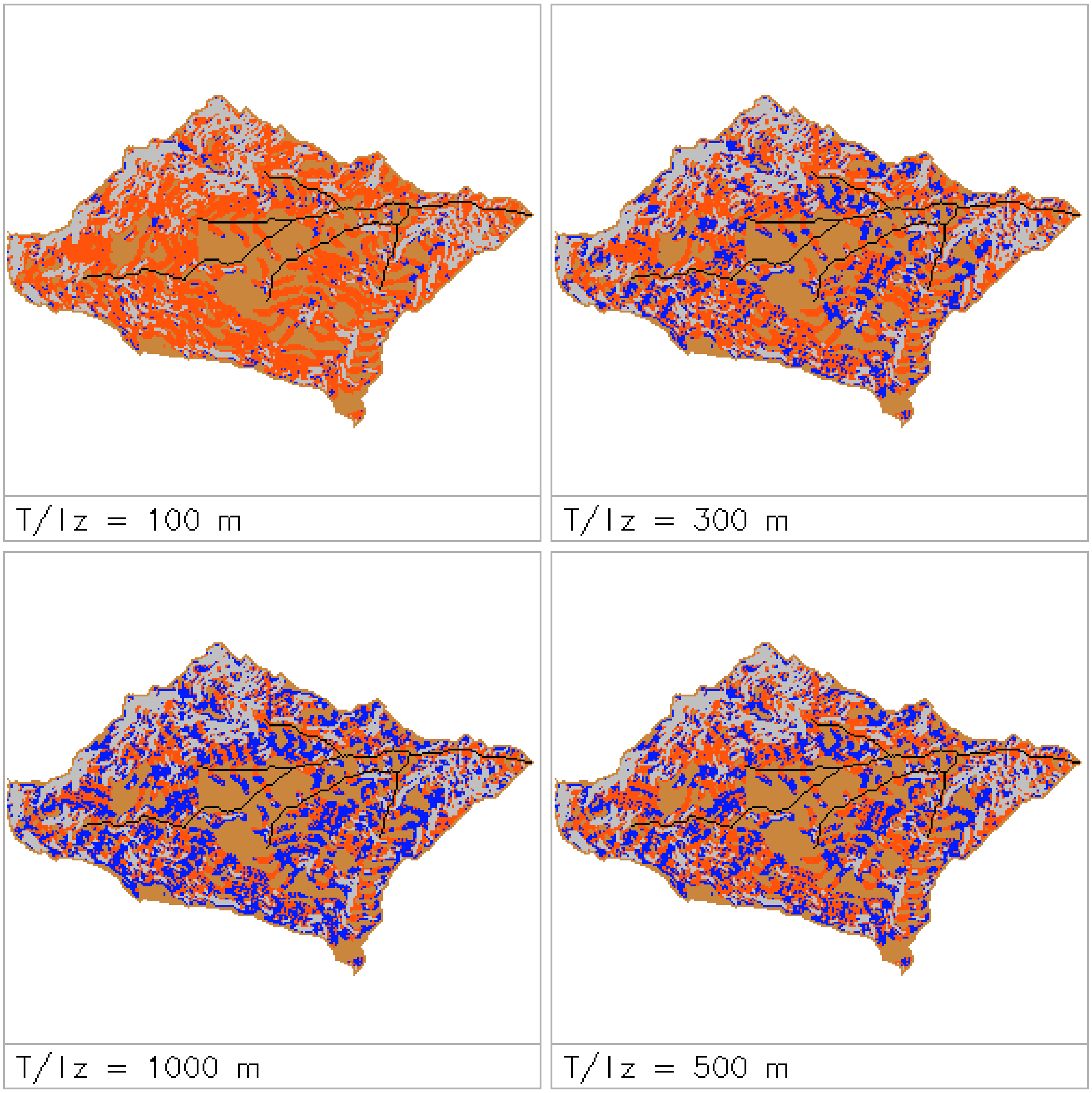

Figure 1 – The outcome of the SHALSTAB model applied to the Renanchio watershed for different values of I. In the original application of the model the value of T and I_z were measured in the field. A practical "effective" way to determine it can be to map old landslides and then to superimpose the computed landslide to the observed ones in a GIS system. An alternative could be to estimate T by means of pedotransfer functions (e.g. Odeh et al, 1989; Romano e Santini, 1997) and to use rainfall measurements to have I_z. Our application differs actually from Dietrich model by implementation details which are discussed elsewhere (Rigon e Cozzini, 2001).

According to the above model and assumptions we are able to plot the volumes subject to landslide against the adimensional ratio K/I_z as shown in Figure 2.

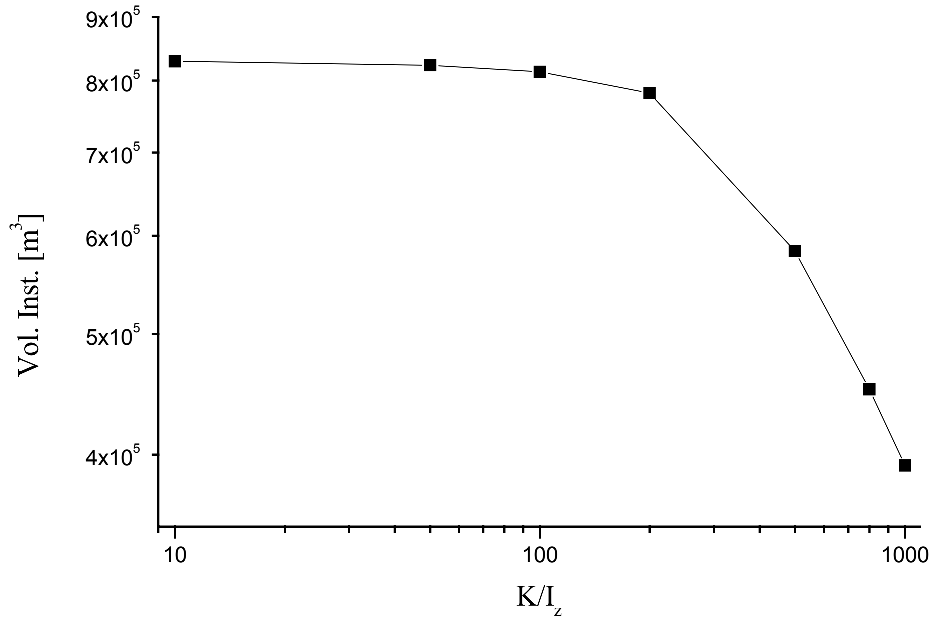

Figure 2 - Volumes of potential landsliding against K/I_z. for the Renanchio watersheds. Reasonable ratios of K/I_z cover the range from 100 to 1000 according to rainfall intensities registered in the basin for rainfall duration of 24 hours

Estimating of the effective infiltration I_z and the hydraulic conductivity for a given catchment we are able to get the potential landsliding volumes. Such volumes are clearly a function of the rainfall amount and can be labeled with an appropriate return time (Borga et al., 1998). For instance, assuming a rainfall with one hundred years of return time (2.35 10^{-6} m/s) and an average hydraulic conductivity of 10^{-3} m/s as representative, the ratio is 426. The resulting volume of about 5.5 10^5 m^3 of soil potentially landsliding must greatly decrease once a small cohesion is introduced. The case shown could be representative of the situation of the basin after a fire destroying the whole basin vegetation cover.

Nothing we can say about the concave parts of the basin (unchannellized valley and channels), about, without numerical modelling. However, at least for design purposes, we can assume that water discharge is governing the geomechanical instability and henceforth that if we are able to estimate the watheshed maximum discharges we could also make guess the maximum solid discharges and volumes.

An evaluation of the maximum solid discharges

According to Takahashi (1981), the solid discharge which is destabilized by a liquid discharge, Q, is:

$$Q_{df} = Q\frac{C^*}{C^* - C_{df}} \qquad [8]$$

with:

$$C = \frac{\tan\theta}{\Delta(\tan\phi - \tan\theta)} \qquad [9]$$

where C^* is the solid close packing degree and C_{df} is the maximum solid packing degree.

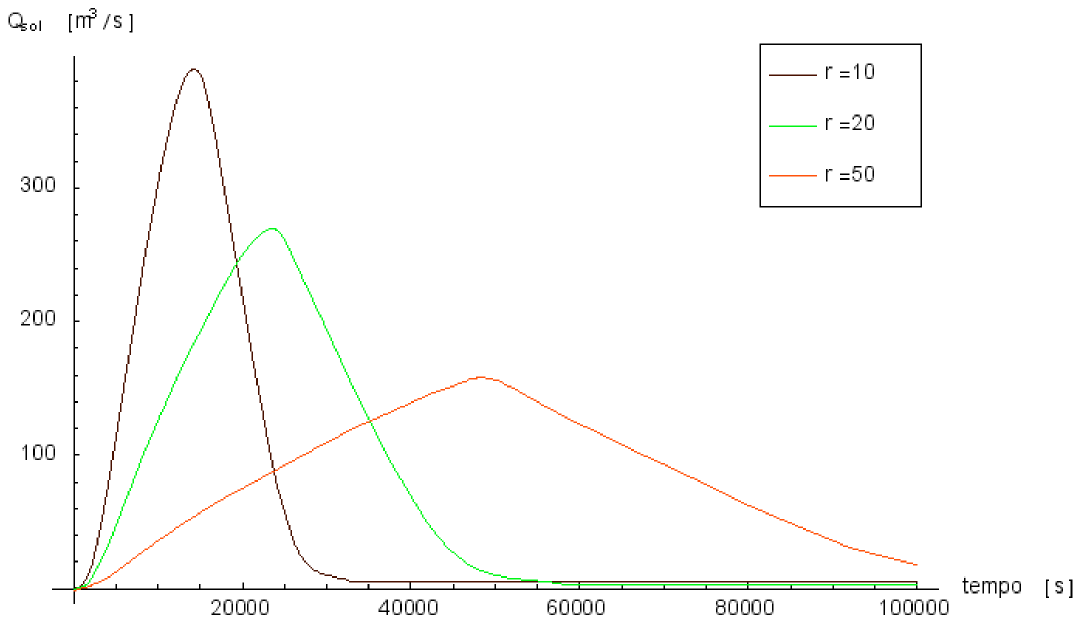

Figure 3 – The maximum solid discharge possible in the Renanchio watershed as a function of flood wave celerity. This is not the real discharge which is, as shown by videos of events and reported by observers, affected by intermittency in time. These phenomena, possibly due both to dynamical cause and the formation of obstacles along the flow paths, could not be described in the framework of the theory presented here and for their randomness possibly require a stochastic modeling. However, at least the peak discharge is of the same order of magnitude of the discharge measured in experimental alpine watersheds of the same size in French and Switzerland. Doing the same operation on the subcatchments, it is possible to get automatically the maximum solid discharge for virtually any point in the basin and the whole plot becomes more realistic the smaller the upstream catchment.

That discharge is obviously the maximum discharge possible and applies only if the sediment supply is continuous. By estimating liquid discharges according to Rigon and D'Odorico (2001) as:

$$Q(t;c,r) = A_T \int_0^t WGIUH(t-\tau;c,r) J_{eff}(\tau) d\tau \quad [10]$$

where *WGIUH* is the width function based on the istantaneous unit hydrograph (Rodriguez-Iturbe and Rinaldo, 1997; Rigon et al. 2001) we obtain the maximum possible solid discharge for a time characteristic of the basin which also depends on the choice of the celerity of flood waves. Such celerity can be evaluated as first approximation either by calibration against measured data or by estimation of the bankfull discharge, given the geometry and roughness of the main torrent channel at the outlet. According to the discussion in the caption of Figure 3, the total volume transported is usually only a fraction of the volumes under those discharge curves, the determination of which is being studied. A comprehensive discussion of *WGIUH* construction is in Rigon et al (2001b).

Conclusion

We have shown a set of techniques, covering both landslide and debris flow volumes, able to asses the amount of potential debris in alpine watersheds. These techniques have been derived from a simplified, yet realistic, description of the hydrology driving the destabilization of masses. As shown in Rigon et al. (2001b), liquid and solid discharges can also be estimated under a variety of less critical initial hydrological conditions which eventually return smaller values of discharges. The method proposed is waiting for field confirmation as a whole, but the single parts of the procedures illustrated have already been validated by the authors and other researchers. The estimation of maximum solid discharges reasonably agree with those measured in Alpine watersheds during the first year of activity of the project THARMIT.

Aknowledgments

This work has been partially supported by the project Torrent Hazard control and Risk MITigation assessment (THARMIT) funded by EC in the Fifth Framework Programme and by the project ASI: Osservazione, modellazione e controllo delle frane con l'ausilio di dati telerilevati. We thanks Ing. Michele Larcher and Prof. Aronne Armanini for their suggestions and advice.

Bibliografia

Arattano, M. et al. (1999) - *Condivisione di metodi e conoscenze sui processi di lave torrentizie per la difesa dei centri abitati* - Relazione generale INTERREG. II 1994-1999 Italia-Confederazione Elvetica

Borga, M., G.D. Fontana (1998) *Modellazione distribuita dei franamenti superficiali innescati da eventi meteorici intensi* - Technical Report Universita di Padova, Dipartimento Territorio e Sistemi Agroforestali

Dietrich, W.E., R. Reiss, M.L. Hsu, D.R. Montgomery (1995) - *A process-based model for colluvial soil depth and shallow landsliding using digital elevation data* - Hydrological Processes, 9: 383-400

Dietrich, W.E et al. (1993) - *Analysis of erosion thresholds, channel networks, and landscape morphology using a digital terrain model* - Journal of geology, 101: 259-278

Heimsath, A.M., W.E. Dietrich, K.Nishiizumi, R.C. Finkel (1997) - *The soil production function and landscape equilibrum* - Nature, 388: 358-361

Iverson, R. M (2000) - *Landslide triggering by rain infiltration* - Water Resources Research, 36: 1897-1910.

Odeh, I.O. A., A.B. McBratney e D.J. Chittelborough (1989) - *Spatial prediction of soil properties from landform attributes derived from a digital elevation model* - Geoderma ,63: 197-214

Rigon R. Cozzini A. (2001) - *Exploring the complexity of mountain landscape: a digital perspective* - 5th International Congress on Geomorphology (Tokyo, 23-28 August 2001)

Rigon R., S. Pisoni e A. Cozzini (2001) - *The construction of the rescaled width function* - 2nd meeting degli utenti italiani di Grass (Trento, 2-3 Febbraio, 2001)

Rigon R. e P. D'Odorico P. (2001) - *Some analytical results on peak discharge in small watersheds* - Submitted for publication.

Rodriguez-Iturbe, I and A. Rinaldo (1997) - *Fractal River Networks: chance and self-organization* - New York.

Romano, R e A. Santini (1997) - *Effectivness of using pedo-transfer functions to quantify the spatial variability of soil water retention characteristics* - Journal of Hydrology, 202: 137-157

Skempton, A., De Lory, F. (1957) – *Stability of natural slopes in London clay* – Proceedings, 4th International Conference on Soil Mechanics and Foundation Engineering, 2: 378-381

Takahashi, T. (1981) - *Debris flow* - Ann. Rev. Fluid Mech, 13, 57-77