ON THE SIMULATION OF HYDROGEOLOGICAL HAZARDS INDUCED BY CLIMATE CHANGE

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ABSTRACT

Some notes on the structure of flood and shallow landslide modelling for hydrogeological hazard assessment are presented in the framework of climate change analysis. A short description of the rainfall-runoff model structure, together with a breif discussion of regional rainfall-thresholds for the initiation of shallow failures is given. A continuous infiltration-redistribution approach useful in this type of modelling is also examined.

INTRODUCTION

Problems linked with climate change have been widely discussed in the scientific literature. One of the most important effects of this change could be the increase of precipitation within particular periods over European areas, that has been emphasized but whose reliability remains to be further supported. It is expected that modifications in the rainfall fields over a given basin will affect its hydrological and geomorphological behaviour.

Landslides and floods are among the most disruptive natural phenomena. They occur in different climatological and geological environments claiming lives and causing billions of dollars in damages (Alexander 1989; Sehmi 1989; Starosolszky and Melder 1989; Swanston and Schuster 1989). The assessment of landslide and flood hazard has been the subject of investigation for Government and Research Institutions world-wide for decades, with various degree of success.

Floods and landslides, despite being commonly caused by the same triggering event (i.e., heavy and/or prolonged rainfall) affect river basins in different ways and in locally mutally exclusive areas. Mass movements occur on slopes whereas inundations affect valley bottoms. Debris flows (Pierson and Costa, 1987; Guzzetti et al., 1992) are a notable, highly hazardous, exception. They initiate on slopes as ground failures and may travel into the drainage system, becoming part of the total discharge volume. Geomorphological and hydrological settings prone to landslides and floods may also differ. Catchments that exhibit a higher drainage density have a larger probability of producing overbank flow with flooding but, through a reduced infiltration, they favour the stability of slopes.

Flood-hazard affects a relatively narrow portion of a catchment, mostly along or close to the channel network. Areas potentially affected by inundations can be identified on the basis of topographic (altitude of channel, levees, and surrounding terrain) and hydrological (water levels and discharge) considerations. Failure or overtopping of natural or artificial levees can be modelled in both open and urban areas provided reliable rainfall-runoff models are available. Currently, these models can be effectively used in real-time flood forecasting, in which generally the adaptive estimate of parameters has a major role in obtaining reliable results even if rainfall is correctly assessed, and in flow simulation with parameters estimated *a posteriori*. This suggests that in order to examine the effects of climatic change on hydrological hazards it is necessary, due to the lack of adaptiveness, to build models closer to physical reality, involving parameters explicitly linked with basin characteristics.

Landslide hazard is more difficult to define. Ground failures can occur virtually everywhere on the slopes of a catchement, with different geometrical and typological characteristics. Factors controlling the initiation of mass-movements are generally poorly understood or difficult to acquire at the catchement scale. Moreover, slope strength is not time-invariant. The shear stress at any point within a slope is continually changing, subject to contrasting internal and external forces of different magnitude such as gravity, seismic shaking and the changing pore-water pressure due to rainfall and infiltration. Deterministic modelling is therefore very difficult to apply at catchment scale. Up to day, and despite their limitations (Carrara et al., 1992), only multivariate statistical methods have proved to be successful in the assessment of landslide hazard over wide areas (Carrara et al., 1991).

In the present note we discuss the main lines along which to address the above issues. The Upper Tiber River basin, together with a few of its sub-basins, will be used in the future as study area for developing and testing hydrological and geomorphological models and for assessing landslide and flood hazard.

A SHORT ANALYSIS OF THE RAINFALL-RUNOFF MODEL STRUCTURE

Because the model can not be in the adaptive form, with the basin behaviour assumed linear and time-invariant, the direct flow at time t, Q(t), at the basin outlet, may be written as:

$$Q(t) = \sum_j \int_0^t Q_j(\tau)\, g(t-\tau; x_j)\, d\tau + \int_0^t L(\tau; x)\, g(t-\tau; x)\, d\tau \tag{1}$$

with

$$Q_j(t) = \int_0^t E_j(\tau)\, h_j(t-\tau)\, d\tau \tag{2}$$

where the subscript j refers to the jth sub-basin; E_j and h_j are the effective rainfall and the instantaneous unit hydrograph, respectively; L is the lateral inflow along the stream network not incorporated in the sub-basins; x is the distance from the basin outlet and g is the diffusion routing function (Troutman and Karlinger, 1985) given by:

$$g(t; y) = y\left[4\pi D_r\, t^3\right]^{-1/2} \exp\left[-(4D_r\, t)^{-1}(c\,t - y)^2\right] \tag{3}$$

where y=x or $y=x_j$; D_r and c are the diffusivity and celerity, respectively, both considered invariant. Equation (1) is linked with a semi-distributed scheme, but really in order to give physical significance to the parameters involved in the model a distributed scheme should be used in a few sub-basins.

Equation (1) can be used provided the effective rainfall pattern is known. Effective rainfall is computed by input data of rainfall rate, r, assessed by the climatic model and using a reliable approach for infiltration rate, f, such as those of Mein and Larson (1973) or Smith and Parlange (1978). These are "single storm" approaches and should not be applied for a single flood event produced, for example, by different storms separated by no-rainfall periods. Smith et al. (1993) and Corradini et al. (1994) have recently proposed a new approach which gets over this limitation through a reliable continuous representation of infiltration and soil water redistribution starting from an initial moisture content, θ_i, invariant with depth. The climatic model incorporating a simple soil water balance equation will give the time evolution of surface water content, θ_0, which is then used as initial condition θ_i for application of Eq.(1). Further, climatic models which do not rely upon primitive equations could incorporate directly the approach by Smith et al. (1993) and Corradini et al. (1994) for which a synthetic description is given below.

Within a regular rainfall period with r greater than the saturated hydraulic conductivity, the increase of θ_0 with time is described by:

$$(I-K_i t)-\frac{(I-K_i t)^2}{2(f-K_i)(\theta_0-\theta_i)}\frac{d\theta_0}{dt}=\frac{G(\theta_i,\theta_0)(\theta_0-\theta_i)}{\alpha}\ln\left[1+\frac{\alpha K(\theta_0)}{f-K(\theta_0)}\right] \tag{4}$$

with I cumulative infiltration depth; α parameter explicitly linked with the soil hydraulic conductivity, $K(\theta)$; K_i stands for $K(\theta_i)$; $G(\theta_i, \theta_0)$ is an integral capillary drive expressed by:

$$G(\theta_i,\theta_0)=\frac{1}{K(\theta_0)}\int_{\theta_i}^{\theta_0} D(\theta)\,d\theta \tag{5}$$

being $D(\theta)$ the soil water diffusivity. Equation (4) was obtained by integrating the Richards' equation which was then simplified by considering mainly applications to fine textured soils. Up to the time of surface ponding the integration of Eq. (4), in which f=r, gives $\theta_0(t)$, then with θ_0 equal to natural saturation, θ_s, and $(d\,\theta_0/dt)=0$ it gives f as a function of time.

Decreasing of θ_0 for redistribution of soil water content is described by an ordinary differential equation derived through integral forms of the mass balance equation and Darcy's law. The soil moisture profile shape is assumed distorted with its area expressed by a fixed fraction, β, of a rectangle. The equation is:

$$\frac{d\theta_0}{dt}=\frac{\theta_0-\theta_i}{I-K_i t}\left[q-K_i-K(\theta_0)-\frac{\beta(\theta_0-\theta_i)pG(\theta_i,\theta_0)K(\theta_0)}{I-K_i t}\right] \tag{6}$$

where p is a factor linked with the surface flux, q.

If an irregular rainfall pattern is considered the model is more complex. Specifically at time t=t*, after a rainfall hiatus, a compound profile scheme is adopted if the rainfall rate is appreciably greater than the downward redistribution rate, that is if:

$$r(t_*^+)>>q-K_i-\frac{I-K_i t_*^-}{\theta_0(t_*)-\theta_i}\frac{d\theta_0}{dt}\bigg|_{t_*^-} \tag{7}$$

Namely, up to t* the soil moisture variation with depth is represented by a simple distorted profile. After t* an additional profile is formed and will advance alongside the pre-existing profile until merging occurs (see Fig. 1). Redistribution of a compound profile is applied to the additional profile until merging, then to the single profile. Further, for simplicity at most two distorted rectangular profiles are used. This is accomplished by reducing the existing compound profile to a single profile when a further additional profile should be formed.

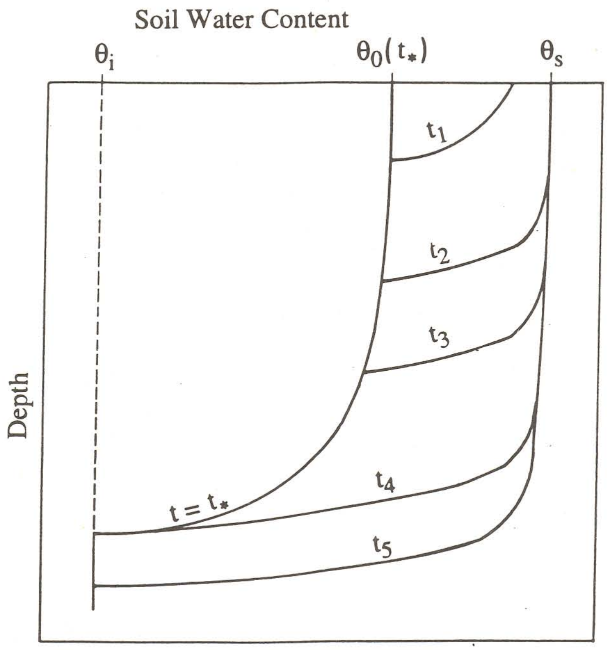

Figure 1. An example of model operation for successive times t_1, ..., t_5 during reinfiltration; t^* denotes the end of a redistribution interval.

RAINFALL THRESHOLDS FOR THE INITIATION OF SHALLOW FAILURES

Whether a given slope will fail depends on the balance between the shear strength of the slope material and the downslope component of the gravitational force. The shear strenght, s, at any point within a slope is expressed as (Terzaghi, 1943)

$$s = c' + (p-u_w)\tan \phi' \tag{8}$$

where, c' is the effective cohesion, ϕ' is the effective friction angle, p is the total stress normal to the potential slip suface, and u_w is the pore water pressure. The stability of a slope and the position of the sliding surface thus depend on strenght characteristics (c', ϕ'), the geometry of the slope, and the distribution of pore water pressure within the slope. Where these variables are known standard methods for the evolution of slope stability can be applyed (Chowdury, 1978).

At the basin scale these variables are difficult to get; nevertheless, with few simplyfing assumptions (Keefer et al., 1987), they can be reasonably estimated. Geometrical characteristics (i.e., terrain slope and curvature) can be derived from a digital terrain model; geotechnical data (c', ϕ'), although highy variable, can be measured at few sites or broadly estimated from geometrical and lithological data; the critical pore water pressure u_w, for an infinite slope of cohesionless material (c'=0) can be calculated as (Skempton and DeLory, 1957)

$$u_w = z\gamma_t\left(\frac{\tan \omega}{\tan \phi}\right) \tag{9}$$

where z is the depth of the slip surface, γ_t is the total weight of the slope material, and ω is the terrain gradient.

The increase in pore water pressure that initiates shallow landslides results largely from the infiltration of rainfall during a storm. Where the infiltration from the surface, plus the upslope throughflow, exceeds the downslope throughflow and percolation beneath the sliding plane, a perched water table is formed. The increase of the pore pressure reduces the stability of the slope (Campbell, 1975).

A number of authors published estimates of the intensity and duration of rainfall required to trigger shallow slope movements, i.e., soil slips and debris flows (Caine, 1980; Moser and Hohenseinn, 1983; Cannon and Ellen, 1985; Wieczoreck, 1987). These thresholds are purely empirical, based on the collection of rainfall data (i.e., intensity, duration, cumulative and prestorm rainfall) linked to observations of landslide occurrence. Most of the proposed rainfall thresholds relate the minimum rainfall intensity for triggering mass-movements r (mm h^{-1}) to the duration of rainfall d (h), with the general form:

$$r = a\, d^{-b} \tag{10}$$

where a and b are constant values. Other empirical relations take into account antecedent conditions, mostly prestorm rainfall (Campbell, 1975; Mark and Newmann, 1988). Constructed as lower bounds of failure occurrence, intensity-rainfall thresholds are valid only for the regions and the meteorological conditions for which they were defined. This is confirmed by the large numerical differences existing between them (Wilson, 1989).

A different approach was recently proposed for the Upper Tiber River basin, where the occurrence of mass-movements was related to hydrological characteristics of the triggering events. Historical data on landslides and inundations, gathered through an extensive bibliographical and archive inventory project (Guzzetti et al., 1994) were compared to mean daily discharge values at the Ponte Nuovo gauging station for the period 1925-1941 and 1951-1980. More than 530 meteorological events, broadly defined as a series of consecutive days with mean daily discharge exceeding 100 $m^3 sec^{-1}$, were identified. For each event an estimate of the total discharge and flood volume were also computed.

The relationship between mean daily discharge and flood volume with the occurrence of inundations and landslides is shown in Figure 2. For all the events that exceeded 400 and 700 $m^3 sec^{-1}$, 50% and 90%, respectively, triggered landslides or caused flooding somewhere in the basin. Virtually all events with a total flood volume greater than 250 million m^3 triggered mass movement. These values can be, tentativelly, considered as preliminary hydrological thresholds for the occurrence of mass-movements in the study area.

Both approaches for the estimate of rainfall or hydrological thresholds for the initiation of slope failures have advantages and limitations. The former allows for precise, distributed estimates, but requires very dense rainfall data and accurate spatial and temporal inventories of failures, usually not available (Brand, 1984). Moreover, it does not explicitly account for infiltration. The latter, allows for the use of historical records and, considering the basin as a unique complex system, it implicitly incorporates infiltration. Its major limitation lays in the lack of spatial resolution.

FINAL REMARKS

The assessment of hydrological and geomorphological hazards in the framework of climate change can not leave aside from the development of a specific hydrogeological modelling which incorporates only parameters having physical significance. A common basic component in flood and shallow landslide modelling is that of infiltration. Its estimate at the scale of the entire basin and its sub-basins will improve the reliability of hydrological models as well as allow for a more accurate assessment of shallow-landslide hazard.

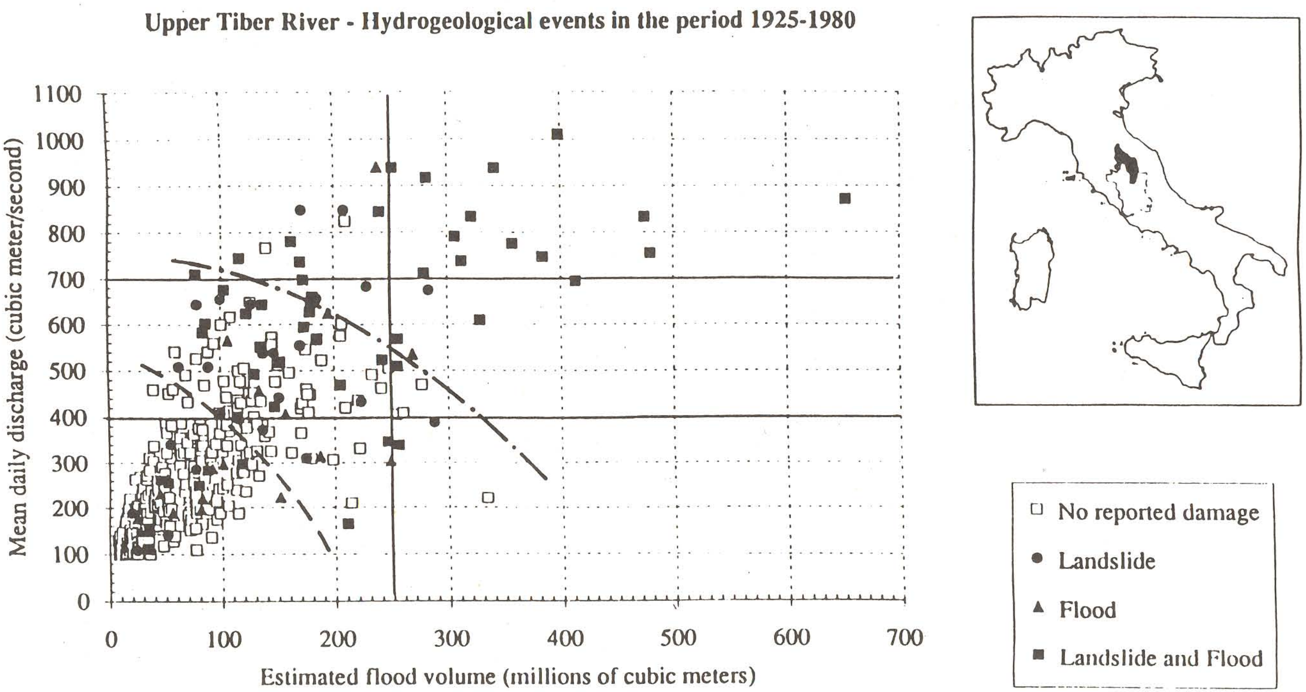

Figure 2. Relationships between the hydrological characteristics of 532 meteorological events and the occurrence of landslides and/or floods in the Upper Tiber River basin. Dashed-dotted and dashed lines separate hydrometeorological conditions that can cause, respectively, with high and low probability, shallow landslides and/or floods. After Guzzetti et al., 1994.

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