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A view on some hydrological triggering systems in landslides

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Abstract

In this paper different types of hydrological triggering systems for debris flows, shallow and deeper landslides are described. The generation of surface run-off and high peak discharges in first order alpine catchments is an important triggering mechanism for debris flows. Failure conditions in shallow landslides can occur when at a critical depth, which is determined by the cohesion of the soil and the slope angle, the moisture content in the soil becomes close to saturation, resulting in a considerable reduction of soil strength. Deeper landslides (5–20 m depth) are in most cases triggered by positive pore pressures on the slip plane induced by a rising ground water level.

The assessment of meteorological threshold conditions for shallow landslides (1–2 m) needs more detailed meteorological information than for deeper landslides. In the analyses of the hydrological triggering systems of deeper landslides the presence of a permeable top layer and fissures has to be taken into consideration. © 1999 Elsevier Science B.V. All rights reserved.

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1. Introduction

Precipitation is commonly known as one of the major landslide triggers. It is also well known that the temporal occurrence of landslides and movement activities is controlled by rainfall patterns with different types of resolution. Relations between precipitation and temporal landslide frequency are in many cases analysed by statistical techniques. Where sufficient precipitation data and dated landslide events are available, thresholds for critical daily rainfall and antecedent rainfall, which trigger landsliding can be assessed (Crozier, 1986; Terlien et al.,1996). One may obtain good results if such procedures are carried out in more or less homogeneous areas with one type of landslide having more or less the same dimensions. A distinct threshold for a given area is difficult to assess, where these studies are carried out in a complex area, with different types of landslides, with varying dimensions, and different types of lithology. Both the frequency of movement and landslide type may be related to entirely different meteorological threshold conditions. Under the same meteorological conditions, the hydrological characteristics and systems within and outside the potentially unstable areas, determine the landslide frequency and play a fundamental role in the development of landslides of different types and sizes.

In order to analyse landslide frequency in response to precipitation patterns more reliably and to understand better the hydrological triggering system,

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more detailed studies pertaining to one region are needed. These investigations must be focused on geomechanical and hydrological characteristics of landslides, which are representative types for the study area. By means of deterministic slope stability models, hydrological threshold conditions for failure can be established. In combination with more or less deterministic hydrological models, which describe the hydrological response system in an appropriate manner for a given landslide type, one can arrive at critical meteorological thresholds for the area under study. Conclusions can be drawn about the future development of the stability of these areas, for example in response to climatic change or land use changes. In this paper different hydrological triggering systems have been selected for varying landslide types, which are related to different types of precipitation input patterns.

2. A hydrological triggering system for debris flows

The generation of surface run-off and high peak discharges in first-order alpine catchments is an important triggering mechanism for debris flows. Surface run-off supplies water to debris masses which have accumulated in channels. This increases the pore pressure within the debris mass which may initiate a debris flow. In such catchments thin soil mantles and bare rocks are present. Hortonian and saturation overland flows are the main processes producing run-off. Sukamoto et al. (1982) also mentioned the importance of pipe flow in thin permeable regoliths as a triggering mechanism debris flows. These processes have to be modelled in order to quantify the occurrence of debris flows in response to precipitation. The infiltration capacity of the soil and the steepness, shape and roughness of the slopes in the catchment determine the height of the peak discharge, and hence the maximum fluid pressure which will be generated in the debris. Other important factors are the sediment content, density and viscosity of the overland flow, and the friction angle and porosity of the debris material.

Blijenberg (1998) monitored the initiation of debris flows and carried out measurements of rainfall and peak discharges in a small catchment in the Bachelard valley in the French Alps. His observations showed that high intensity rainstorms initiate debris flows in summer and autumn. Using logistic regression, he correlated the probability of debris flow initiation with peak discharges. These peak discharges were modelled with both a simple, lumped tank model and a more sophisticated physically based, distributed catchment model.

The logistic regression analysis suggested that the use of the hydrologic tank model could produce better results than a simple rainfall index based on 5-min peak intensities and total rainstorm rainfall, provided sufficient data are available, especially infiltration characteristics. The inclusion of antecedent precipitation did not give significantly better results. This case study showed that the assessment of debris-flow initiation thresholds in this Alpine area, strongly depends on the availability of high-resolution (minute-by-minute) precipitation data, especially requiring information on short-duration (5–10 min) peak rainfall intensities and duration of individual rainstorms. In this case good results can be obtained also by using only precipitation indices instead of hydrologic models. However, it can be desirable to run a distributed hydrologic model, because the use of such a model gives more insight into the relative importance of parameters such as catchment shape, slope angle, soil type and bedrock distribution and debris mass thickness.

3. A soil water percolation system for triggering shallow landslides

Shallow landslides are one of the most common types of landslides, which occur frequently in all climatic zones. These soil slips develop on steep slopes and their depths is generally not more than 1–2 m. In these shallow soils the soil water balance is controlled by infiltration of rain water, unsaturated percolation and a rapid response of the rise of groundwater on single storm events (Haneberg and Onder Gocke, 1994).

Characteristic for the water balance in these shallow soils is the quick response of soil moisture content to the alternation of wet and dry periods during which percolation and evapotranspiration cause a vertical redistribution of soil water. The threshold conditions for failure of these shallow soils are not necessarily determined by the development of positive pore pressures on a potential slip plane. Failure conditions can also occur when, at a critical depth, which is determined by the cohesion of the soil material and the slope angle, the moisture content in the soil becomes close to saturation, resulting in a considerable reduction of soil strength (Van Asch and Sukmantalya, 1993).

3.1. An example of long and short term forecasting of shallow slides

Terlien (1996) carried out tensiometer measurements in a small catchment, covered with volcanic ash near Manizales (Colombia). The catchment was affected by shallow landslides with a depth of 1 m. Terlien also simulated the pressure heads during a 4-month period in the rainy season (March/April 1993) at different depths using a soil water balance model (HYSWASOR). The model is appropriate to describe the vertical flux of soil water in the unsaturated zone using three important functions, the soil water retention curve, the hydraulic conductivity as a function of moisture content and a water root uptake function (Dirksen et al., 1993). The root water uptake function is expressed as a fraction of the maximum root uptake, which in turn is a function of the potential evapotranspiration. Terlien (1996) used the model to calculate the depth of the wetting front, which is related to intensity, and duration of individual storms. The more or less saturated wetting front causes a reduction of the cohesion and hence the strength of the wetted material which can lead to failure at a certain critical depth depending on the cohesion and slope angle. The infinite slope model was used to calculate the stability condition of the slope for a given depth of the wetting front. He used the combined hydrological and slope model in a GIS to make short term and long term forecasts about the effect of rainstorms on the stability of the slopes. He selected, as an example, rainstorms of different intensities and duration, with a return period of 5 years and calculated for these storms the distribution of the depth of the wetting front (which is the depth of the potential slip plane). The calculated variation in depth of the wetting front and the variation in cohesion, angle of internal friction and bulk density were introduced as stochastic parameters in the infinite slope model. This delivers a distribution of the safety factor for each pixel with a given slope angle from which a distributed map was derived giving for each pixel the probability of failure (which is the probability that the safety factor is lower than 1).

For short-term forecasting, failure probabilities were calculated for an expected rainfall event taking into account the initial vertical pressure head distribution. The rainstorm of the 13th of May 1993 was selected for failure probability calculations because this rainstorm produced a soil slip in the area. Knowing the distribution of the initial soil moisture and using the stochastic input of the strength and bulk density values a map was produced which for each location (pixel) shows the probability of failure caused by this 13th of May rainstorm. Fig. 1 shows a part of the map with a cluster of pixels with high calculated failure probability and the location of a soil slip which actually occurred that day. The map cannot actually predict the location of failures. It is simple a probability map showing areas with relatively high failure probability, where in fact no soil slips developed that day.

The detailed investigation showed that on thick soils (mean thickness of the ash was 6 m), shallow landslides (around 1 m depth) on steep slopes can develop by the mechanism of a percolating wetting front, without the creation of positive pore pressures. Only the decrease of cohesion, caused by the wetting of the soil matrix, proved to be sufficient to trigger this soil slip. The depth of the wetting front is controlled by the rainfall intensity and duration of individual storms and by the initial vertical soil moisture distribution in the topsoil, which itself is controlled by the root water uptake and hence the evapotranspiration between the rainstorms.

3.2. An example of the effect of land use on shallow landslide frequency

The same concept of hydrological triggering of shallow landslides (1–1.5 m depth) by a percolating wetting front was applied in a small catchment in the Puriscal area (Costa Rica) (Terlien et al., 1996). K_{sat} measurements where carried out at different depths all over the catchment area and despite the variation in soil types in this area and different kinds of

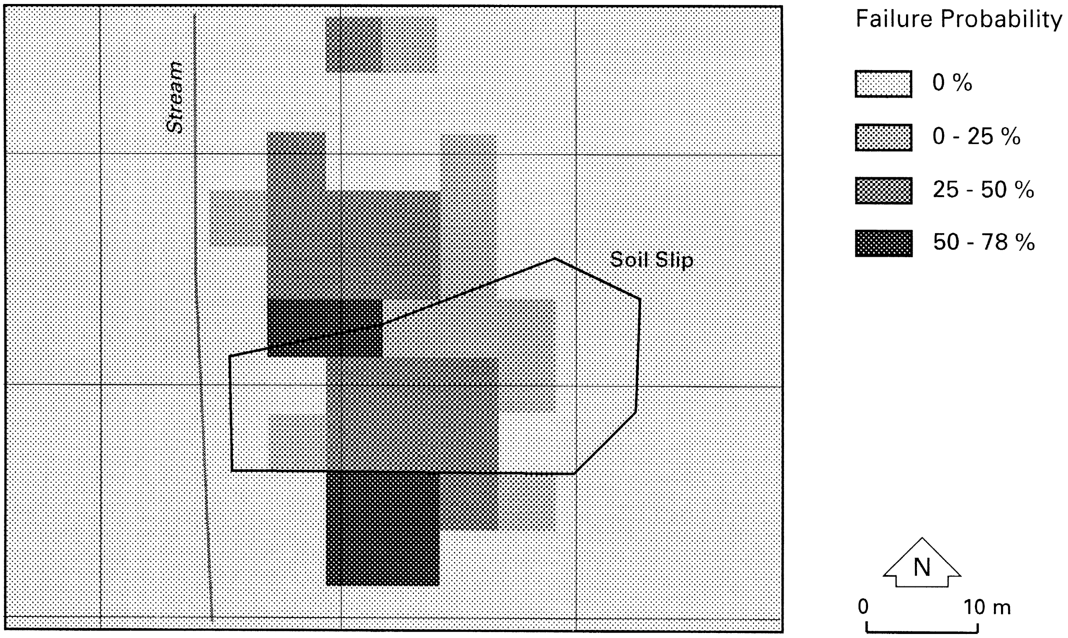

Fig. 1. Comparison of calculated failure probabilities and the location of the soil slips which developed after the rainstorm of May 1993 (after Terlien, 1996).

agricultural land use, no statistically significant differences in saturated hydraulic conductivity between the land units and between different soil layers could be established. Therefore a stochastic simulation with HYSWASOR was proposed, in which the soil profile was considered as heterogeneous with respect to K_{sat}. Heterogeneous K_{sat} profiles with 10 layer units of 15 cm were randomly selected from the K_{sat} distribution curve, while the initial soil moisture content over 5 depths in the profile was taken from a log-normal initial soil moisture distribution. It was assumed that initial soil moisture is an independent variable, because the vertical variation in K_{sat} was not distinct enough to influence the vertical distribution of the soil moisture content. In this way failure probability maps could be made for different rainstorms with a given intensity and duration and return period.

Hydrological simulation for several kinds of crops were carried out for a period of 2 months, during the rainy season in this Puriscal catchment, using daily precipitation figures. The model output did not show significant differences in moisture distribution at the depth of the potential slip plane and hence the strength and stability of the soil (Hetterschijt, 1994). Different crops give different fluctuations of soil moisture content in the root zone because of different evapotranspiration potentials of these crops, which could be measured and simulated. However these differences in fluctuation of the moisture content in the topsoil have small effects on the ultimate moisture content in the subsoil (1–1.5 m depth), where the potential slip plane is expected to develop after rainstorms.

4. The groundwater triggering system

Deeper landslides (5–20 m depth) are in most cases triggered by positive pore pressures on the slip plane induced by a rising groundwater level. The classic slope stability models teach us, that it is the relative porewater pressure — that is the ratio between pore pressure and the total normal stress on the (potential) slip plane, which determines the stability of the slopes. This means that deeper landslides need larger absolute amounts of water for triggering conditions than shallower landslides.

Therefore it can be expected that larger windows of antecedent precipitation periods have to be considered, to establish successfully a correlation between landslide events and precipitation. These windows may vary between several days (Reid, 1994; Matsukura, 1996) to several months of a rain season (Iverson and Major, 1987). It would be a coincidence, caused by special combinations of other stability factors (such as slope, soil strength, and hydraulic conductivity) that one will find one single threshold of antecedent precipitation for landslides that vary significantly in depth.

A second aspect that is often neglected in hydrological studies of landslides is the fact that the slope is never a homogeneous soil mass. Angeli (1992) studied the effect of an increasing hydraulic conductivity with depth on pore pressure distribution at the slip surface. High pore pressures in excess of hydrostatic pressure were generated at the toe of the landslide caused by the confining effect of the less permeable top layers. In many cases it consists of a permeable topsoil followed by a significantly less permeable subsoil. The permeable topsoil may have a great influence on the groundwater fluctuations in the subsoil.

A third aspect, which has to be considered, is the two types of flow in the landslide: matric flow and bypass flow through existing fissures. These two types of flow are important in understanding the relation between rainfall and the triggering of landslides (e.g., Rogers and Selby, 1980). A number of selected examples will highlight the above mentioned aspects of the triggering groundwater system for landslides.

4.1. The importance of subsurface drainage for the groundwater balance

Van Beurden (1997) computed a yearly water balance for the top 2 m of a part of the Hau earthflow in the Widentobel catchment (Switzerland) to show the importance of permeable topsoil for shallow lateral drainage of incoming water. On the Hau earthflow he measured a decrease in K_{sat} with depth ranging from 10^{-5}–10^{-6} m/s (at 0.2 m) to 10^{-7}–10^{-8} m/s at (1.25 m). The first 0.2 m of soil especially is at least 10 times more permeable than the subsoil. Van Beurden (1997) computed two versions of the water balance based on field observations. In the first version the groundwater is at the soil surface, while in the second version the groundwater is at a depth of 0.2 m below the surface and no lateral flow is taken into consideration in the water balance in the top 0.2 m. The lateral drainage from the area in the first version is 37% of the yearly precipitation input. In the second version, with no flow in the 0.2 m. top layer, the lateral drainage amount of the groundwater body out of the landsliding area reduces to 1%. This shows the important contribution in lateral drainage of the permeable 0.2 m. topsoil in the water balance.

The importance of a two layer system for landslide hydrology appears also in other case studies, but in these cases the effect of bypass flow through fissures was also taken into consideration.

4.2. The importance of fissure flow

The groundwater system in landslides in varied clays in the French Alps is a good example of a complex cascading groundwater system (Van Asch et al., 1996). The rainwater is stored as a perched groundwater table in the permeable top layer consisting of morainic and colluvial material. This perched water table supplies water to the fissures in the underlying varved clays, which are assumed to be connected with the slip plane. The varved clays are nearly impermeable in the vertical direction but from the water filled fissures, the water is able to infiltrate in a more or less horizontal direction in the silt laminae of the varved clays. (Van Asch et a1., 1996). Computations show that the permeable colluvial cover plays a crucial role in the storage time of the water, standing in the fissures, and hence the possibility of infiltration of water from the fissures into the varved clays. If the permeable topsoil (in this case with a depth of 2 m) is filled with groundwater above a certain critical level, the fissures will fill rapidly with rain and snowmelt water during days of precipitation. Rapid drainage during dry periods is then prevented, due to a continuous supply of water from the perched water table in the topsoil.

Fig. 2 shows a scattergram where for a simulation period of 13 years (1975–1988), using daily rainfall figures from the station near La Mure (French Alps), the level of the perched groundwater table in the

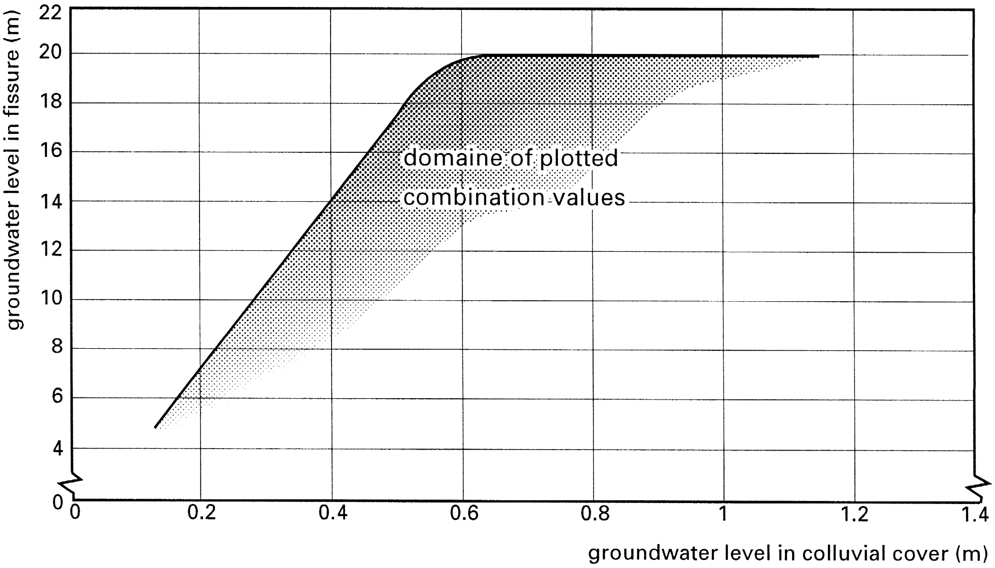

Fig. 2. Scattergram of fissure water level to colluvial cover (2 m depth) groundwater level, calculated on a daily base over the period 1975–1988 for fissures 20 m in depth in varved clay (after Van Asch et al., 1996).

colluvial cover is plotted against the water level in the fissures for each day. One can deduce from this figure, that if the water level of the perched water table exceeds 0.6 m the fissures remain completely filled with water. The left boundary of the scattergram gives an indication, how one can reduce the maximum rise of the water level in the fissures by reducing the maximum rise of the perched groundwater table through an effective drainage system in the permeable topsoil. In this way the stability of the landslide, which proved to be mainly controlled by the water level in the fissures, can be increased (Van Asch et al., 1996).

Since the stability of the landslide is controlled by the height of the water level in the fissures, the response time to be considered for triggering the movement is not more than 5 days. This is the response time of the fluctuation of the perched groundwater table feeding the fissure system. Therefore daily precipitation figures are required in this case and windows of about 1 week have to be considered in order to make good correlations between rainfall and the frequency of movements.

The hydrological system of a landslide which developed in a colluvial cover of the Terres Noires (black marls) with a depth of 6–8 m. can also be explained by a multi layer concept (Van Asch and Buma, 1996). The profiles show a rather permeable top layer of 1.8 m with a K_{sat} ranging from 5 to 30×10^{-7} m/s. A second layer to a depth of 7 m has a K_{sat} ranging from 1 to 8×10^{-8} m/s. The residence time of a perched groundwater table in the top layer proved again to be crucial for the amount of water supplied to the lower groundwater body. This lower body develops on top of the in situ unweathered Terres Noires, by a vertical flux mainly through the rather impermeable second layer. Bypass flow through macro pores and fissures, which were observed in the in the first layer, has a great effect on the fluctuation of the lower groundwater table. This could be shown by sensitivity analyses of a hydrological model, which was developed in the framework of the EC TESLEC project (Van Asch and Buma, 1996). It became clear that the maintenance of a perched water table supplying water to the deeper groundwater body in the second layer depends on long periods of rainfall. In the case of the Terres Noires landslide maximum critical peak heights of the lower groundwater table were reached only in wet seasons (colder seasons with lower evapotranspiration) with high precipitation for at least 6 consecutive months. (Van Asch and Buma, 1996).

Sensitivity analyses with the model developed for the Terres Noires landslide also showed the great influence of a change in effective precipitation. Especially for landslides which are triggered by rainfall over longer periods, the cumulative effect of the water loss by evapotranspiration on the soil water balance cannot be ignored as was the case with the shallow landslides described above which are triggered by a percolating waterfront during individual rain storms.

The effect of the development of fissures in steep slopes on groundwater table fluctuations was explicitly shown in a dynamic hydrological model, linked to a GIS, which was developed for the Alcoy area in Spain. In this area landslides occur on steep unsaturated slopes in marly deposits at the boundary between the regolith and the bedrock (1–2 m depth). Given the low matrix permeability of the marls, it was assumed that preferential flow along a distinct set of fissures might account for the observed response time of landslide events to rainfall. Sensitivity analyses for different fissure scenarios and initial soil moisture contents were performed for a period of 60 days using measured daily precipitation's during a relatively wet season. The simulations show the rapid drainage by fissures of the groundwater body above the potential slip plane during the dry periods. This has a stabilising effect with respect to the extent of the unstable areas compared with simulations carried out for regoliths without fissures. The total number of pixels, which were declared unstable during a part of the simulation period, appeared to be less for the applied fissure scenarios. Probably, the drainage by fissures results in a lower spatial average height of the groundwater table in the catchment. However in the areas which were declared unstable, the instability is initiated earlier and more often in a fissured regolith than in a continuous regolith. A more rapid access of rainwater to the groundwater body in a regolith with fissures and a more rapid drainage of the groundwater by the same fissure system cause this higher temporal frequency instability.

5. Conclusions

One has to be careful in assessing general meteorological thresholds for landslide initiation simply because of the theoretical fact that the absolute amount of water, which is needed to trigger a landslide, increases with the depth of the landslide.

Depending on the depth of the landslide, the hydrological system and the hydrological conductivity of the materials, deeper landslides require less detailed meteorological information ranging from daily to monthly precipitation figures. Indications about evapotranspiration figures, especially for landslides, which are triggered by long periods of rain, cannot be ignored. The assessment of meteorological threshold conditions for shallow landslides (1–2 m) needs more detailed meteorological information such as the intensity and duration of individual rainstorms. However these shallow landslides, which are triggered by a percolating waterfront during individual rainstorms, seem to be not very sensitive to changes in evapotranspiration conditions. Therefore changes in agricultural land use have small effects on the stability of these shallow regoliths.

Most landslides have an important natural shallow drainage system, formed by more permeable topsoil with cracks and macro pores, which may reduce the maximum rise of the groundwater table. The residence time of a perched watertable in this topsoil determines the amount of water, which is supplied to the deeper groundwater table or fissures in the subsoil.

The effect of fissures on groundwater fluctuations cannot be ignored in the hydrological analysis of a landslide. On the one hand the fissures give rapid access to the lower groundwater system, decreasing the response time of triggering and increasing the frequency of triggering. On the other hand the presence of fissure systems in the slope facilitate the drainage of the groundwater body in the matrix during dry periods, which may reduce the extent of potential unstable areas in a catchment.

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