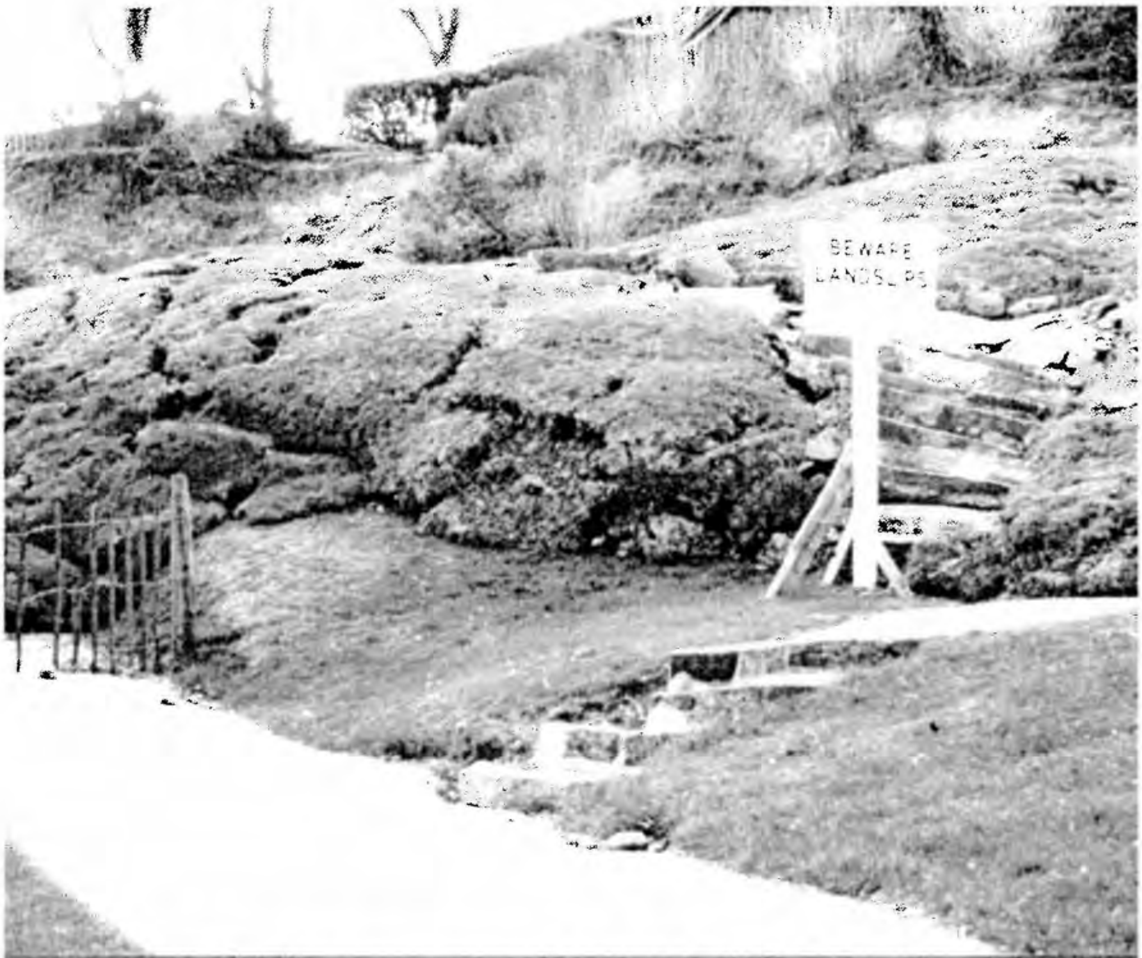

LANDSLIDES

RAINFALL AS A LANDSLIDE TRIGGERING FACTOR: AN OVERVIEW OF RECENT INTERNATIONAL RESEARCH

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Rainfall as a Landslide Triggering Factor: An.Overview of Recent International Research

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INTRODUCTION

Rainfall is the most common cause of landslides. The cost of *Rainfall Triggered Landslides* (RTL) is not well documented and often unobtainable. In areas where they do not pose a threat to life, great damage is caused to farmland and communication infrastructures and pasture bio-mass production is heavily reduced (Table 1). In Japan more than 10,000 RTL are reported every year which claim the lives of some 400 persons (Fukuoka, 1980); a single event has killed 100 persons and inflicted property damages estimated at 300 billion yen Shimizu (1988).

Given the importance of the topic, some 138 papers dealing with RTL were selected and key information was collected in a database. Nearly 82 % of all records are local investigations carried out in 23 countries. Italy provides the largest sample as for authors' nationality and widespread proneness to landslides; followed by United States (15 %), Hong Kong (8 %), Japan and United Kingdom. About 21 % of all selected papers are methodological research or syntheses and comparisons of different methodologies. Investigations refer to widespread landsliding (69 % of AD) (that is the *Available Data* number for each database field), the remainder corresponds to single or few landslides. A landslide classification proposed by Hutchinson (1995) and based on the maximum depth of failure (Vm), is adopted in this work. About 40 % of AD are intermediate or deep-seated landslides (Vm > 10 m), which include all reactivations, the rest are shallow or superficial landslides, generally first-time movements. The most frequent types are: flows, translational and rotational slides, slips, avalanches and creep, decreasing order (Cruden & Varnes 1996) with soil or debris generally constituting the landslide bodies. Daily (54 % of AD), hourly (28 %), monthly (15 %) and yearly (4 %) rainfalls are used as input. Roughly 49 % consider cumulative rainfall (a rain water height obtained adding regularly monitored rainfall) of different duration. The prevalent approach is empirical, statistical or hydrological-qualitative; one out of four is partially physical and often uses numerical modelling. About 10 % combine rainfall effect characterisation with geotechnical stability analysis. The results of research in progress have been summarised.

HYPOTHESES, APPROACHES AND TRIGGERING MECHANISMS SETTING

The more customary assumption is that the landslide body becomes saturated from below when rainfall infiltration starts (Lumb, 1975) but slope saturation is not always that simple phenomenon. Debris slides can burst explosively out of a slope if groundwater flowing in pedological horizons is discharged quickly to the surface (Govi et al. 1985). If high water pressure is locally generated near a spring, little displacements can be induced in the soil and small areas can liquefy and flow downslope. If landslides triggered by *High-intensity Short-duration Rainfall* (HSR) are considered, the intensity grows exponentially as duration decreases and landslides are mainly shallow soil slips and debris flows at higher intensity,

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whereas lower intensity results in larger and deeper debris avalanches and slumps. Wieczorek & Sarmiento (1988) observed that the return period of rainfall which triggers debris flow in California is two years. Church & Miles (1987) suggested that general figures could be misleading, as debris slides were caused by locally HSR which were not necessarily observed by a widespread rain gauge network. Haneberg (1991) and Anderson and Thallapally (1996) carried out investigations at some experimental sites with different approaches, using piezometers, tensiometers and rain gauges but also numerical modelling. They drew some conclusions that can be generalised: a) piezometric variations are due to recent rainfalls along slopes and to antecedent or seasonal rainfalls near slopes foot; b) the groundwater flow is mainly slope-parallel between two storms and vertical during a storm; c) the piezometric response time of slope to rainfall depends on hydraulic conductivity, effective porosity and depth; d) previous soil saturation increases with depth and decreases with distance from slopes foot.

A common feature of most RTL approaches is to operate in terms of triggering and non-triggering events but this boundary is never sharp. It is often useful to consider a minimum and a maximum threshold. The minimum threshold is the minimum rainfall which triggers at least a landslide whereas the maximum threshold is the minimum value which always triggers a landslide (Crozier 1986).

The most widely used climatic variables are rainfall and temperature. McSaveney & Griffiths (1987) provide a good example of the role played by temperature. The movement recurrence of a deep-seated landslide is quite similar to the combined return period of an arid summer-rainy winter (900 years), that is a well-known triggering mechanism in the area, just like summer spontaneous fires.

Location	A	Date	T	D	I	L	V	Reference
Micronesia	tens	4/97	520	4		>30	19	Harp & Savage, 1998
Hong Kong	1050	5/92	>350	24	25-0.08	>300	3	Brand, 1993
Hong Kong	1050	8/76	500	24	82-1	314	57	Brand et al, 1984
Hong Kong	Abt 200	11/93	575	12		>800		Wong et al., 1996
Japan	Abt 12	7/83	500	10		Hundreds	100	Shimizu, 1988
Japan	140	9/71	559	62	122-1	7760	56	Fukuoka, 1980
Italy	Abt 450	6/96	446	24		142	0	Paronuzzi et al., 1998
Italy		11/94	350	62	54-1	180/sqkm	70	Bandis et al., 1996
Italy	Abt 100	5/98	96	48		>100	161	Del Prete et al., 1998
Puerto Rico	Abt 1500	10/85	>560	24	70-1		0	Jibson, 1989
Virginia	Abt 100	6/95	770	16	64-5	Hundreds	0	Morgan et al., 1997
Virginia	Abt 400	8/69	>750	12		Hundreds	>150	Kochel, 1987
California	Abt 10	1/82			107-1	74	0	Wieczoreck, 1987
California	Abt 500	1/69			>50-1	Hundreds	12	Campbell, 1975

Table 1. Some impressive cases of rainfall-landslide events. A) hit area (sqkm), T) event total rainfall (mm) and D) duration (hr), I) maximum rainfall intensity (as water height-duration reported by authors, mm-hr), L) triggered landslides number and V) victims number.

Two approaches can be defined: 1) the spatial analysis and 2) the temporal analysis of landslide occurrence and climatic variables. The former applies to areas characterised by widespread proneness to landsliding, the latter applies to a single site or small areas. In the first case, the area should be homogeneous, in the second one the phenomenon should be stationary (Cascini & Versace 1986, Crozier 1986). The homogeneity concerns geomorphological and hydrological characteristics, as well as the stationary status refers to geotechnical and hydrological parameters. The last condition is a crucial problem in many cases. The factors that influence stability often change over time. Hence, also rainfall-landslide relationships are likely to change over time, as a result of earthquakes, fires, human agency, and climatic oscillations or as a result of landslide activity itself. Some slopes constituted by regolith may become resistance to the event: the triggering threshold may increase if after the landslide occurrence more resistant lithotypes outcrop. Landslide remoulding can worsen the soil geotechnical characteristics and lower the rainfall threshold. If rainfall events are separated by long intervals, there may by sufficient time for the soil layer to recover resistance, a process known as slope ripening (Crozier 1986).

RTL ANALYSIS METHODS

Seven main groups of RTL analysis methods can be distinguished: 1) rainfall duration-intensity threshold methods, 2) *Cumulative and Antecedent Rainfall* methods (CR and AR), 3) long cumulative rainfall methods, 4) actual rainfall methods, 5) simplified hydrogeological or soil water balance methods, 6) rainfall-stability analysis coupled methods and 7) complete slope methods. They are gradually less empirical, qualitative and statistical and more physical, hydrological, hydrogeological and geotechnical.

About the first group methods, the empirical relationship between rainfall intensity, rainfall duration, and slope instability has been thoroughly documented, and scientists have put a great deal of work estimating rainfall thresholds also as a part of landslide warning systems (Clark 1987, Jibson 1989, Keefer et al. 1987, Neary & Swift 1987, Wieczorek 1987, Wieczorek & Sarmiento 1988). Based on the analysis of 73 events in different geological and climatic settings, Caine (1980) suggests a general threshold that works for time periods between 10 minutes and 10 days. In terms of rainfall intensity (I, mm/hr) and duration (D, hr), the relation can be expressed as:

$$I=14.82\ D^{-0.39}$$

Therefore, Caine's relation does not take into account the slope adjustment to climatic conditions. In a region with high *Mean Annual Precipitation* (MAP), slopes tolerate higher precipitation intensities than in a drier area. Hence, the lowest intensity threshold is in Hong Kong and the highest in Puerto Rico (Jibson 1989).

The MAP importance was highlighted by Govi et al. (1985). They plotted hourly intensity against cumulative precipitation of the event as a MAP percentage and identified an instability field which helped isolate the events according to the season of occurrence. Cannon & Ellen (1985) obtained different threshold curves corresponding to high and low MAP areas, which represented a combination of rainfall intensity and duration. *Normalised Storm Rainfall* (NSR), that is the ratio of total storm rainfall to MAP, can help gauge the relative impact of a storm on a local area (Pierson et al. 1992). In Hong Kong a disastrous event is almost certain if NSR is 20 to 30 % when comparing the spatial density to critical rainfall (Au 1998). Studies carried out elsewhere stressed a value of critical rainfall greater than 0.3 (Pierson et al. 1992).

In California, after a dry season, at least 267 mm of rain may be need to bring the soils to field capacity: thereafter an intensity of 5-6 mm/h can trigger debris flows (Campbell 1975). It has been shown that antecedent rainfall must typically exceed a critical for RTL occurring after a storm.

This evidence paved the way to the second group methods, in which rainfall intensity and duration together with AR or CR of not a very long duration were considered. Lumb (1975), according to the number of slips occurred in a day, classified landslide events in four groups: *disastrous* (>50); *severe* (10 to 50); *minor* (<10) and *isolated* (individual slip). By comparing 24-hour rainfalls and the previous 15 days CR, predictive areas for different types of event were outlined.

The effectiveness of rainfall intensity shows an upper limit, represented by the value which exceeds the infiltration rate, after which only runoff occurs. A suitable measure can be the duration of rain occurring at a rainfall intensity known as the intensity-duration parameter (ID) (Wieczorek & Sarmiento 1988). It was found that a minimum AR value of 279 mm was required to trigger debris flows in California. The most significant ID value to indentify landslide triggering storms, once the AR had been met, is:

$$ID_{5.1mm/hr} > 3h$$

In Hong Kong, when the 24-hour AR is below 100 mm, only few minor events occur, but when it exceeds 200mm, 70mm/h is the threshold for a severe landslide event (Brand et al., 1984). Church & Miles (1987), in British Columbia (Canada), found that 24 hour AR of 50-150mm is not sensitive enough to be used as a threshold because localised intensities of up to 20mm/h seem to be important triggers. When peak hourly intensity is characterised by a low return period, only the combination with very wet previous conditions can explain the occurrence of widespread landslide events (Nearly & Swift 1987). In Hong Kong area, the AR effect seems to be not so prominent as in other parts of the world (Brand et al. 1984, Brand 1993, Au, 1998). This effect is reduced where HSR prevails. On the contrary, Wieczorek (1987) reported that AR is an important factor in slope stability in the San Francisco Bay (California), where soils shows low permeability.

A method of the third group was probably first used in the Bohemian region (Czech Republic). Deep-seated landslide displacements were expected at the end of the rainy season and when the CR of the previous ten months exceeded a defined water depth. It was observed that mean rainfall of antecedent three years affected significantly the RTL frequency (Zaruba & Mencl 1969). Cascini and Versace (1986) proposed to study rainfall thresholds of *Daily Cumulative Rainfall* DCR of not beforehand-defined duration, ranging from 1 to 180 days. Determining the return period and the probability classes of DCR the actual role of rainfalls in reactivating intermediate and deep-seated landslides in southern Italy can be assessed (Polemio 1997, Polemio & Sdao 1999). If instead of rainfall depth, which is closely related to local climatic conditions, the DCR return period is taken into account, the method results can be readily assessed and compared to non homogeneous areas. Capecchi and Focardi (1988) defined a precipitation coefficient as a function of two variables referred to the same duration: a daily cumulative modified rainfall and a CR of assigned return period. The rainfall modification is obtained by a coefficient, depending on the draining capacity of the soil involved and on the hydrology of the area, which reduces the weight of antecedent rainfall.

Hutchinson (1970) describes a 6m thick London Clay coastal mudflow and considers the monthly rainfall minus the potential evapotranspiration observing the relationship between it and the landslide movements. The obtained variable does not differ from the actual rainfall in a humid climate area. A more recent application of the fourth group methods is landslides from superficial to deep-seated in laminated clays in the French Alps (Van Ash et al. 1996). In this case, actual rainfall is the input for a model of combined reservoirs used to simulate water fluctuations in the colluvial cover and the clay fissures.

The common characteristics of simplified hydrogeological or soil water balance methods (the fifth group methods) is the assessment of pore pressure response to rainfall using a physically based simplified approach to study RTL. The aim may be achieved in different ways. A soil water balance method utilises daily rainfall and piezometric data (Barton & Thomson 1986). It was applied to a coastal gravel cliff in England. It consists of two models: a soil moisture deficit model to estimate the actual infiltration, and a model to predict the groundwater response. The latter evaluates the aquifer discharge using a decay function as a simplification of the groundwater flow problem. Therefore, piezometric data need to calibrate the model. Sangrey et al. (1984) obtained similar results by discussing and simplifying Darcy law for a sloping aquifer. Shimizu (1988) utilises the tank model to forecast widespread shallow landslides in Japan. Three tanks simulate, from the top, surface hydrology, unsaturated and saturated subsurface hydrology. Each tank has a different maximum storage height, a bottom outlet to control percolation rate, and a lateral outlet to control outflow discharge.

A method of the sixth group generally includes two models. The model to predict pore pressure changes due to rainfall is coupled to a model to evaluate slope stability. Anderson & Howes (1985) coupled a general one-dimensional soil water infiltration model with an infinite slope stability model to understand why many Hong Kong slopes have a safety factor less than one. They demonstrated that it is due to the fact that suction is generally neglected.

Complete slope methods (the seventh group) are numerical models of all physical processes that affect slope stability. They solve transient water flow for both surface and subsurface, and consider pore pressure also in a not saturated soil during and after a storm. The hydrogeological output serves as an input for the stability analysis. Naden et al. (1991) used a hydrological distributed parameter numerical model and a limit equilibrium method. The hydrological model can simulate catchment hydrology using connected two-dimensional vertical planes and a finite element solution of differential flow equations. The hydrological distributed model THALES was applied to investigate purposes to two catchments, in Australia and in the United States, each with different dominant hydrological responses (Grayson et al. 1992). These models may be used as a universal tool to characterise the slope hydrological answer to rainfall infiltration during a storm. However, also at experimental sites with field data available, problems of verification and validation of such models remain.

CONCLUSIONS

One of the results of research in progress is a classification of all analysis methods of rainfall triggered landslides. This study highlighted also the extreme complexity of the phenomena that govern the effects of rainfall upon slope stability. The lack of spatial homogeneity and of time-depending stationary status is the main limitation to a wide use of research results. New efforts are needed to overcome these shortcomings.

REFERENCES

Anderson M.G. & Howes S. (1985) Development and application of a combined soil water-slope stability model. Q. J. Eng. Geol. London. 18: 225-236.

Anderson S.A. & Thallapally L.K. (1996) Hydrologic response of a steep tropical slope to heavy rainfall landslides. Landslides, Senneset (ed.). Balkema, Rotterdam: 1489-1495.

Au S.W.C. (1998) Rain induced slope instability in Hong Kong. Eng. Geol., 51: 1-36.

Bandis S.C., Del Monaco G., Margottini C., Serafini S., Trocciola A., Dutto F. & Mortara G. (1996) Landslide phenomena during the extreme meteorological event of 4-6 November 1994 in the Piemonte Region N Italy. Landslide Senneset (ed.) Balkema, Rotterdam: 623-629.

Barton M.E. & Thomson R.I. (1986) A model for predicting groundwater level response to meteorological changes. In Cripps et al Ed., Groundwater in Engineering Geology, Geol. Soc. Spec. Pub., 3: 299-311.

Brand E.W. (1993) Landslides in Hong Kong caused by the severe rainfall event of 8 May 1992. Landslide News, 7: 9-11.

Brand E.W., Premchitt J. & Phillipson H.B. (1984) Relationships between rainfall and landslides in Hong Kong. Proc. IVth. Symp. on Landslides, Toronto, 1: 377-384.

Caine N. (1980) The rainfall intensity-duration control of shallow landslides and debris flows. Geografiska Annaler. 62A, 1-2: 23-27.

Campbell R. (1975) Soil slips, debris flows and rainstorms in the Santa Monica Mountains and vicinity, Southern California. USGS Professional Paper, 851: 51pp.

Cancelli A. & Nova R. (1985) Landslides in soil debris cover triggered by rainstorm in Valtellina (Central Alps - Italy). Proc. IVth Int. Conf. and field Workshop on Landslides. Tokyo, 1: 267-272.

Cannon S.H. & Hellen S.D. (1985) Rainfall conditions for abundant debris avalanches, S. Francisco Bay region, California. California Geology, 38, 12: 267-272.

Canuti P., Focardi P. & Garzonio, C.A. (1985) Correlation between rainfall and landslides. Proc. 27th I.G.C., Moscow Bull. IAEG, 32: 49-54.

Capecchi F. & Focardi P. (1988) Rainfall and landslides: research into a critical precipitation coefficient in an area of Italy. Proc. 5th Symp. on landslides, Lausanne: 1131-1136.

Cascini L. & Versace, P. (1986) Eventi pluviometrici e movimenti franosi. Atti Conv. Naz. di Geotecnica, 3, Bologna, Italy: 171-184.

Church M. & Miles J.M. (1987) Meteorological antecedents to debris flows in south western British Columbia; some case study. Geological Society of America, Reviews in Engineering Geology, VII: 63-79.

Clark G.M. (1987) Debris slide and debris flow historical events in the Appalachians south of the glacial border. Geological Society of America, Reviews in Engineering Geology, VII: 125-138.

Crozier M. (1986) Climatic triggering of landslide episodes. Landslides: causes, consequences and environment. Croom Helm: 169-192.

Cruden D.M. & Varnes D. (1996) Landslide types and processes. Special Report 247, Transp. Res. Board, National Research Council. National Academy Press, Washington DC: 36-75.

Del Prete M., Guadagno F.M. & Hawkins A.B. (1998) Preliminary report on the landslide of 5 May 1998, Campania, southern Italy. Bull. Eng. Geol. Env., 57: 113-129.

Fukuoka M. (1980) Landslides associated with rainfall - Geotechnical Engineering, v. 11: 1-29.

Govi, M., Mortara G.& Sorzana P.F. (1985) Eventi idrologici e frane. Geol.Appl. & Idrogeol. XX, 2: 359-375.

Grayson R.B., Moore I.D. & McMahon T.A. (1992) Physically based hydrologic modeling. A terrain-based model for investigative pourposes - Water Res. Research, 28, 10: 2639-2658.

Haneberg W.C. (1991) Observation and analysis of pore pressure-fluctuations in a thin colluvium landslide complex near Cincinnati, Ohio. Engineering Geology, 31, 2: 159-184.

Harp E.L. & Savage W.Z. (1998) Landslides triggered by the April 1997 tropical storms on Pohnpei, Federated States of Micronesia. Landslide News 11: 29-32.

Hutchinson J.N. (1970) A coastal mudflow on the London Clay cliffs at Beltinge, North Kent. Geotechnique, 20: 412-438.

Hutchinsons, J.N. (1995) Deep-seated mass movements on slopes. Mem. Soc. Geol. It. 50: 147-164.

Jibson R.W. (1989) Debris flows in southern Puerto Rico. Geological Society of America. 236: 29-55.

Keefer D.K., Wilson R.C., Mark R., Brabb E.E., Brown W.M.III, Ellen S.D., Harp E.L., Wieczorek G.F., Alger C.S. & Zatkin R.S. (1987) Real time landslide warning during heavy rainfall. Science. 238: 921-925.

Kochel R.C. (1987) Holocene debris flows in central Virginia. Geol.Soc.Am., Rev. in Eng.Geol., VII: 139-155.

Lumb P. (1975) Slope failure in Hong Kong. Q. J. Eng. Geol., 8: 31-65.

McSaveney M.J. & Griffiths G.A. (1987) Drought, rain, and movement of a recurrent earthflow complex in New Zealand. Geology, v. 15, 7:. 643-646.

Morgan, B.A., Wieczorek, G.F., Campbell, R.H., and Gori, P.L. (1997) Debris-flow hazards in areas affected by the June 27, 1995 storm in Madison County, Virginia. Open File Report: 97-438.

Naden P.S., Calver A. & Reed D.W. (1991) Rainfall analysis and hydrological hillslope modelling for slope stability in mountainous areas. Proc. Symp. Movimenti franosi e metodi di stabilizzazione. Potenza, 16-17 January - 21 March 1991: 77-88.

Neary D.G. & Swift L.W. (1987) Rainfall thresholds for triggering a debris avalanching event in the southern appalachian mountains. Debris flows-avalanches processes, Recognition and Mitigation. Reviews in Engineering Geology, (7): 81-92.

Paronuzzi M., Collolo A. & Garlatti G. (1998) Eventi climatici critici e debris flows nei bacini montani del Friuli. L'Acqua. 6: 39-50.

Pierson T.C., Ellen S.D. & Iverson R.M. (1992) Spatial and temporal distribution of shallow landsliding during intense rainfall, southeast Oahu, Hawaii. Proc. of Sixth Int. Symp. on Landslide, Christchurch, 2: 1393-1398.

Polemio M. & Sdao F. (1999) The role of rainfall in the landslide hazard: the case of the Avigliano urban area (Southern Apennines, Italy). Engineering Geology (53), 3-4: 297-309.

Polemio M. (1997) Rainfall and Senerchia landslides (Southern Italy). 2nd Panamerican Symposium on Landslides, Rio de Janeiro, November 1997, 1: 175-184.

Sangrey D.A., Harrop-Williams W. & Klaiber J. A. (1984) Predicting groundwater response to precipitation. J. Geotech. Eng.ing, ASCE, 110 (7): 957-975.

Shimizu M. (1988) Prediction of slope failures due to heavy rains using the tank model. 5th Int. Symp. on landslides, Lausanne, 1: 771-777.

Van Asch Th.W.J., Hendriks M.R., Hessel R. & Rappange F.E. (1996) Hydrological triggering conditions of landslides in varved clays in the French Alps - Engeneer Geology, 42: 239-251.

Wieczoreck G.F. & Sarmiento J. (1988) Rainfall, piezometric level and debris flows near La Honda, California, in storms between 1975 and 1983. Ellen & Wieczorek eds., USGS Professional Paper 1434: 43-62.

Wieczoreck G.F. (1987) Effect of rainfall intensity and duration on debris flows in central Santa Cruz Mountains, California. Geol. Soc. of America, Review in Eng. Geol., Vol. VII: 93-104.

Wong H.N., Chen Y.M. & Lam K.C. (1996) Factual report on the November 1993 natural terrain landslides in three study areas in Lantau Island (3 vol.) Special Projects Report SPR10/96, GEO, Hong Kong.

Zaruba Q. & Mencl V. (1969) Landslides and their control. Elseiver-Academia Prague, 214.