Summary

The report describes different approaches to use rainfall data as a tool for warning of landslides based on available international literature. The landslides examined are typically shallow debris flows in steep terrain triggered by intense rainfall. To establish statistical correlations between rainfall and triggering of landslides, recordings of historical landslides and rainfall are necessary. Both long-term (1 day or more) and short-term rainfall (typically 1 hour) have significance in the triggering processes, as the critical hourly intensity is reduced as preceding accumulated rainfall increases.

The investigations give rise to the following conclusions:

- There is no formula that is generally applicable for predicting landslides based on rainfall. This because each region has its own characterises with respect to precipitation pattern and soil cover.

- On local basis, the use of statistical correlations seems to provide a useful tool, given that the correlations are appropriately validated and updated with available information.

- Out of the 4 main approaches that have been studied in this report, it is concluded that the most promising approach is to base the critical threshold values by on the following two parameters: rainfall intensity expressed in mm/hour and accumulated precipitation in mm/24 hours or mm/96 hours.

Contents

Review and reference document

1 INTRODUCTION

A major component in the institutional cooperation project between INETER and NGI on Protective Measurs to Reduce the Landslide Risk in El Salvador is the development of an early warning system for predicting landslides. This system, which is a pilot project, is based on the assumption that there are certain threshold values for rainfall that trigger slides.

There is a vast amount of literature on this subject, but the experience from different part of the world is somewhat scattered and inconsistent. This report is prepared on the basis of a review of the international literature, with main focus on debris flows. The report contains the following elements:

- A summary of different approaches used to identify the important parameters for assessing critical rainfall situations.
- An analysis of the approaches together with their limitations
- Recommendations

2 APPROACHES USED FOR DETERMINING CRITICAL PARAMETERS

The approaches referred to in the literature for critical rainfall that trigger debris flows can be grouped in the following four categories:

- Cumulative rainfall versus time
- Rainfall intensity versus duration
- Normalized rainfall intensity versus duration
- Rainfall intensity versus precedent rainfall

The release mechanism for a rainfall-induced debris flow is the reduction in the soil strength due to an in increase in the pore pressure in subsoil (or a reduction of suction in unsaturated soils) and/or surface erosion cause by high rainfall intensity. The parameters above are basically measures of these two mechanisms.

2.1 Approach A: Cumulative rainfall versus time

Examples of using cumulative rainfall as an indicator of debris flow hazard have been reported by Wilson and Wieczorek (1995) and Kanji et al (1997).

Kanji et al (1997) used data sets from two rainfall episodes at Cubatão in Brazil and found a curve representing the minimum triggering condition. Their equation reads:

$$P = 21.1 \times t^{0.48} \quad (1)$$

where P is cumulative rainfall (mm) in period t (hours). Re-arranging (1) substituting P= I x D where I is average intensity (mm/hr) and D is duration (hr) gives:

$$I = 21.1 \times D^{-0.52} \quad (1b)$$

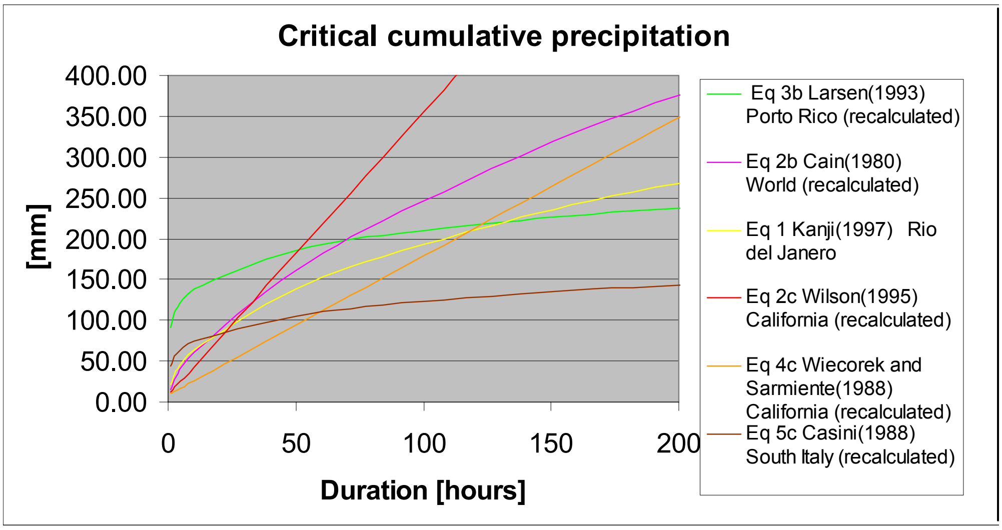

Figure 1 Cumulative rainfall versus duration

As can be seen from Fig. 1 the different ways of prediction seem to be fairly consistent for typical durations of 24 to 48 hours of rain. The range of critical values may be summarized as shown in Table 1:

Table 1 Key data for Approach A

Duration of the rainfall	Critical cumulative precipitation
24 hours	60-180 mm
48 hours	100- 200 mm

2.2 Approach B: Critical Intensity versus duration

Critical rainfall intensity as a function of duration has been reported by Cain (1980), Larsen and Simon (1993), Wiecorek and Sarmiente (1988) and Casini and Versace (1988). Cain (1980) used worldwide data and derived an equation for the lower bound of the data set.

$$I = 14.82 \times D^{-0.39} \quad (2)$$

where I is rainfall intensity in mm/h and D is duration (hrs.). Rewriting (3) into cumulative rainfall gives:

$$P = 14.82 \text{ x } D^{0.61} \quad (2b)$$

Larsen and Simon (1993) derived a similar local equation for Puerto Rico.

$$I = 90.46 \text{ x } D^{-0.82} \quad (3)$$

with the same notation as Cain (1980). Rewriting (4) into cumulative rainfall gives:

$$P = 90.46 \text{ x } D^{0.18} \quad (3b)$$

Wiecorek and Sarmiente (1988) published a curve for California near La Honda. In this data set, rainfall episodes with preceding precipitation less than 280 mm were filtered out. Rainfall episodes with less than 280 mm showed no debris activity.

$$D = 9.0/(I-1.7) \quad (4)$$

This can be rearranged into:

$$I = 1.7 + 9.0 \text{ x } D^{-1} \quad (4b)$$

Or:

$$P = 1.7\ D + 9.0 \quad (4c)$$

Casini and Versace (1988) published an equation for landslides in Southern Italy:

$$\log I = 1.65 - 0.78 \log D \quad (5)$$

that in a rewritten form reads:

$$I = 45 \text{ x } D^{-0.78} \quad (5b)$$

and

$$P = 45 \text{ x } D^{0.22} \quad (5c)$$

A comparison of the different prediction equations is shown in Fig. 2 below.

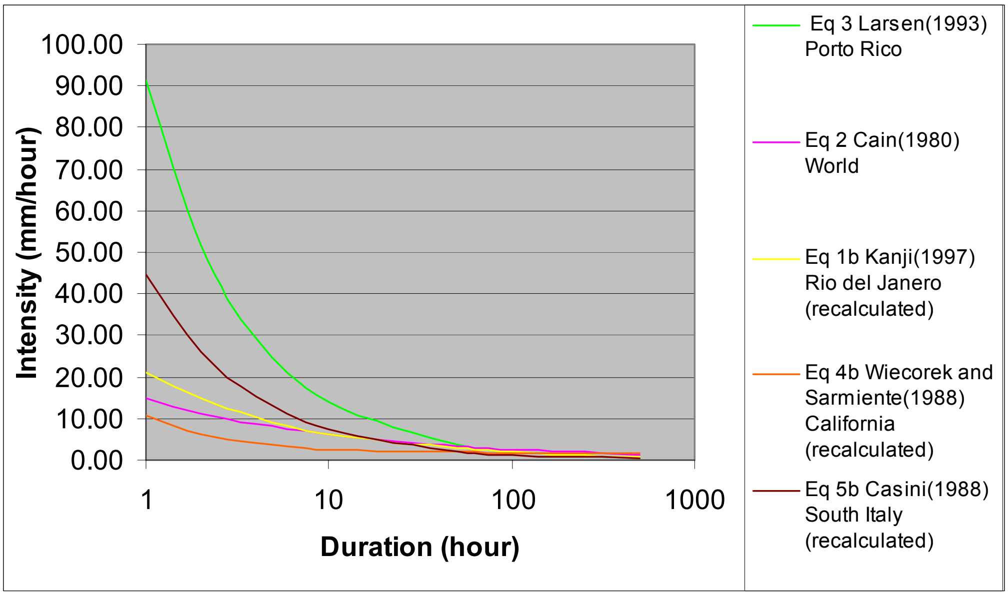

Figure 2 Critical rainfall versus duration

From Fig. 2 it can be concluded that the spread in prediction is high and the chart of this type is not very useful for prediction on a general basis. On a local basis, however, this approach may be valuable as discussed in Section 3.

2.3 Approach C: Normalized critical intensity versus - duration

Normalized intensity is used in order to fit data in larger regions. The basic idea is that an area with high annual precipitation adjusts to a different state of geomorphic equilibrium than an area with lower annual precipitation. Normalizing based on the mean annual precipitation (MAP) was suggested by Govi and Sorzana (1980). MAP values are governed by orographic effect and distances from coastline, Cannon (1988) applied this kind of normalization in California:

$$D = 46.1 - 3.6\text{x}10^{-3}\ \text{In} + 7.4\text{x}10^{-4}\ \text{In}^2 \qquad (6)$$

where D is duration and In is normalized Intensity, defined as rainfall per hour divided by MAP. Mark and Newman (1988) demonstrated the good correlation between the rainfall in the storm of January 3-5 1992 in the San Francisco Bay region as percentiles of MAP. Sandersen et al (1996) normalized the cumulative precipitation in a rainfall period with duration D:

$$P = 1.2 \text{ x } D^{0.6} \qquad (7)$$

In Eq. (7) P is hourly rainfall as percentile of MAP and D is duration in hours.

Jibson (1989) compared 16 equations for threshold rainfall intensity versus duration published from locations in Japan, China, California, Brazil, Hong Kong, Indonesia and Puerto Rico. By using MAP from the different locations, Jibson calculated Normalized Rainfall Intensity to see if the same In – D relationship could be used for the different regions. This analysis showed different relationships between In and D in the regions, and introduction of normalization did not improve the prediction of landslides. It appears that if the normalization by MAP is to give an improved geographically correlation with debris flow activity, then the rainfall distribution during the year should be similar for the different locations.

A way to account for the different distribution of rainfall was suggested by Wilson (1986). Here the normalization factor is called rain-day normal (RND) defined as MAP divided by numbers of rain days during the year.

An improved method would perhaps be to normalize the intensity within the wettest month of the year or the rainfall during the rainy season. The reason for this is that the debris flow activity normally is restricted to the rainy season.

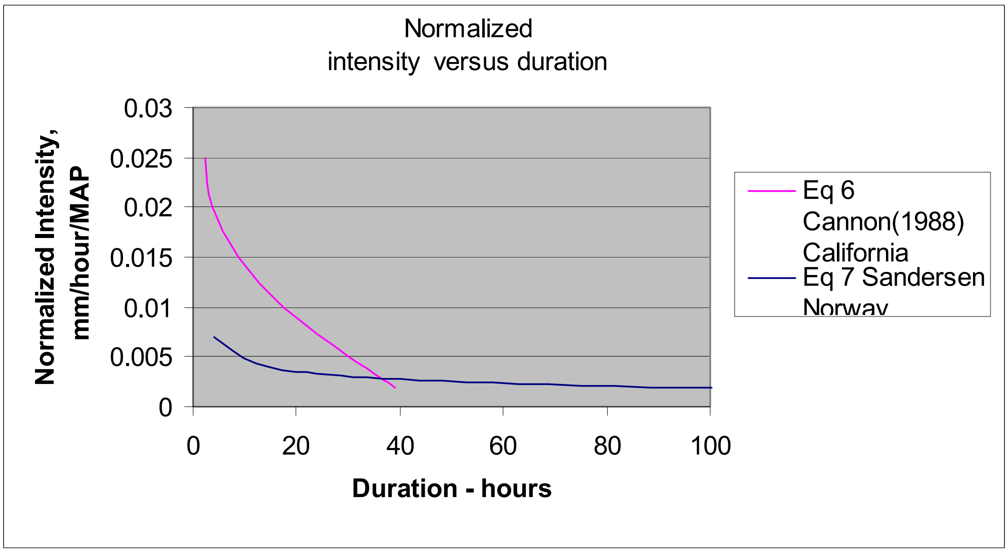

Figure 3 Normalized critical rainfall

Judging from Fig 3, it is difficult to find arguments that the normalized approach offers a significant improvement over the previous approaches.

2.4 Approach D: Rainfall intensity combined with accumulated rainfall

d'Orsi et al (1997) plotted the accumulated rainfall the last 96 hours (R_{96}) against the last hourly rainfall (I_c) before initiation of debris flows in Rio de Janeiro. The critical intensity could be derived from:

$$I_c = \exp(-1.14 \ln(R_{96}) + 9.17) = e^{9.17} R_{96}^{-1.14} \qquad (8)$$

A similar equation (9) was proposed by Heyerdahl et al. (2003):

$$I_c = 258 \times R_{96}^{-0.32} \tag{9}$$

with the same notation as for Eq. (8).

Chleborad (2000) used the variation of precedent rainfall as the criterion for release of landslides. Here the 3-day precipitation (inches) prior to the initiation of landslide was considered against the 15-day precedent precipitation (inches) prior to the 3-day total. There is a lower bound at ~1 inch.

$$Y = -0.67X + 3.5 \tag{10}$$

where Y and X are respectively the 3-day and the 15-day accumulated precipitation (inches).

Jibson (1989) also used the dataset mentioned above to plot rainfall intensity versus cumulative rainfall and thereafter plotted the same equations as normalized rainfall intensity against normalized cumulative rainfall. The latter relationship seemed to give higher correlation than the first relationship. The reason is probably that areas with high annual rainfall also have higher cumulative rainfall in rainfall events.

Another approach is proposed in Manual for Zonation on Areas Susceptible to Rain Induced Slope Failure (1997). The weighted product of accumulated rainfall R and rainfall intensity r, $R^m r^n$ is a factor which depends on the type of hydrological regime (*h*), geotechnical (*gt*) and geometrical effects (*geo*). m and n are dependent on type of failure:

$$R^m r^n = f(h, gt, geo)$$

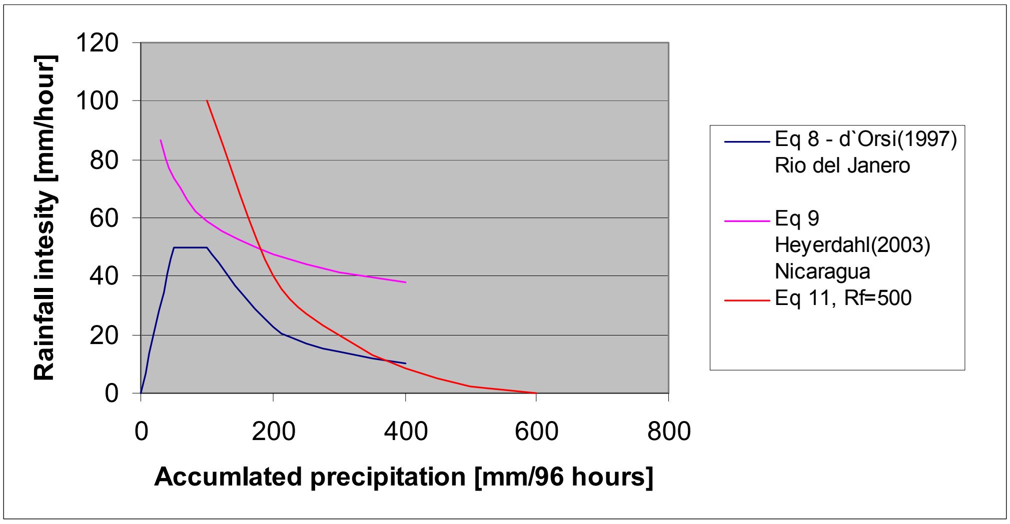

Figure 4 Critical rainfall intensity combined with accumulated values

A classification system based on local conditions was established to generate the factors.

The predictions illustrated in Fig 4 show as the threshold values shown in the Table 2:

Table 2 Key data for Approach D

96 hours accumulated precipitation	Critical hourly rainfall in mm
100 mm	50-100
200 mm	25-50

2.5 Other quantified relations

One of the most comprehensive databases for rainfall intensity combined with accumulated rainfall has been gathered in Hong Kong (Geotechnical Control Office, 2001). The plot of data is shown in Fig. 5 below. The different lines in the diagram mark the difference in terms of the severity of the landslide that could be expected. This plot is conceptually the same type as illustrated on Fig 4, but with the difference that the Hong Kong approach is to use accumulated 24 hours rainfall and not the 96 hours value.

Other quantified relationships are for instance reported by Sasaki et al (2001). They define the following three parameters: Rainfall Index, Effective Rainfall and Effective Rainfall Intensity. Effective Rainfall is defined as the amount of rain that falls after a limit of intensity is reached. The reason to do this is to get a clear definition of when a rainfall period starts. The Rainfall Index consists of weighted components of cumulative rainfall (R) and hourly rainfall intensity (r):

$$R_f^2 = (R_1 - R)^2 + a^2(r_1 - r)^2 \qquad (11)$$

R_1 and r_1 are calibration constants and a is a weighting parameter (Sasaki et al, 2001 calibrated R_1 = 600 mm, r_1= 100 mm, a=5). The Rainfall index will represent curves that can be presented in a plot of Rainfall Intensity versus accumulated rainfall. In Fig. 4 a curve of type (11) is plotted for R_f = 500.

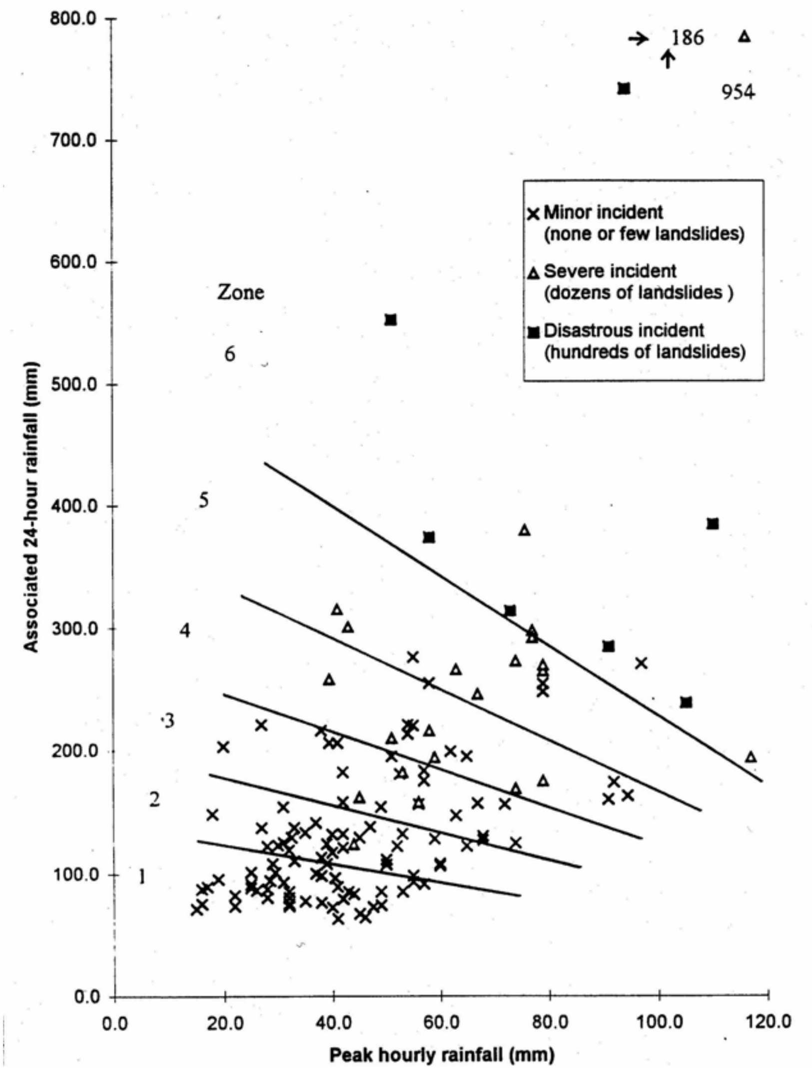

Figure 5 Critical rainfall values based on Hong Kong experience

2.6 Other non-quantified Approaches

Bandari, Seneanayake and Thayalan (1991) discuss examples of pitfalls in the prediction on landslides through rainfall data in Sri Lanka. When daily precipitation exceeds 250 – 300 mm/day, the occurrence of landslides seems imminent. Cumulative precipitation up to the event and precipitation recorded in the event are normalized by MAP. Cc = CPR/MAP, where CPR = Cumulative Precipitation Record up to the day of the event and Ce=PRE/MAP, where PRE = Precipitation record of the event and MAP is mean annual precipitation.

The probability of landslides is categorized as:

Ce > 20 % - Catastrophic landslides may occure

Ce =10- 20 % - High probability of landslides
Ce = 5-10 % - Fair probability of landslides
Ce< 5 - Low probability of new slides

Bhandari and Virajh Dias (1996) studied rainfall and slope movements in Sri Lanka. They plotted intensity (mm/day) against duration of the period with continuous rainfall (days). Based on a large number of observations a zone of exceptional events was defined. No predictive equation was derived, but the zone is well defined. The boundary of the zone is approximately at 300 mm/day for a 2-days event and 200 mm/day for a 4-day event.

3 ASSESSMENT OF THE DIFFERENT APPROACHES

3.1 Consistency in the data

When comparing the work done by different researchers, there are some general problems that should be highlighted, e.g.:

- Debris flow is not a unique type of landslides and the cases that have been used represent probably quite a broad range of slides.
- Location of the rainfall stations relative to the actual slide areas might differ significantly from case to case in the comparison and the possible orographic effects are probably not accounted for.
- Frequency of rainfall recordings might be different from case to case and many of the references do not have hourly recordings available.
- The comparisons represent also different climatic regions of the world from tropical to cold climates, that all have their specific characteristics in terms of rainfall amount, intensity and distribution over the year.
- The relationship between the critical short term and long term rainfall intensities is different for the different climatic zones.
- Characteristics for the soil cover including vegetation pattern differ significantly for the cases that have been studied.

3.2 Comparisons of the different approaches

Some key features for the different approaches that have been investigated are summarized in Table 3 below:

Table 3 Comparison of the four approaches

	Approach	Comments
A	Cumulative rainfall versus time	Seems to be applicable at least for duration in the range of the 24 to 72 hours for many parts of the world. However, the method will not work in areas that are very sensitive to short term high-intensity rainfall conditions.
B	Critical intensity versus duration	This approach seems to suffer from several limitations. One being that the effect of accumulated rainfall is not accounted for. However, for hillsides with very thin soil cover that are exposed to erosion, this approach might be a fairly representative model.
C	Normalized critical intensity versus duration	Is not considered to add significant value to Approach D
D	Rainfall intensity combined with accumulated rainfall	Considered to be the most promising method given that it is calibrated to the local conditions

4 CONCLUSIONS AND RECOMMENDATIONS

It is apparent that the use of statistical approaches for correlation of rainfall conditions and landslide occurrence has its limitations. This is specially the case when doing comparison between regions with different rainfall characteristics, both with respect to rainfall amounts and rainfall distribution over the year.

However, in a specific region, it is concluded that such correlations might be very useful and can serve as a basis for landslide warning. The level of prediction depends on the number of landslides that have been analyzed, and updating of the statistical correlations must constantly be considered as new experience is gained.

When it comes to which method and parameters to use in such a warning system, the investigations carried out for this report may suggest that Approach D is the most promising method. This conclusion might not be generally valid for all part of the world, but it seems to hold in areas such as Hong Kong, Rio de Janeiro and Central America.

When establishing an early warning system it is highly recommended to monitor the rainfall hourly and secure that there are enough stations to get the spatial variation covered. In Norway the rainfall threshold for activating debris flow is in the order of a 50 years precipitation event. This seems logical based on the basic idea that an area is in geomorphologic balance with its climate. The limiting climatic factor is not the mean annual precipitation, but the extreme events. When adequate rainfall recordings are lacking, the first approach to establish a warning system could be to use a statistical analysis of rainfall recordings from climatic regions with similar rainfall characteristics (roughly the same annual rainfall and distribution of rain through the year).

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