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THE MODELLING OF SOIL SLIP EROSION IN THE UPPER KOMERING AREA, SOUTH SUMATRA - PROVINCE, INDONESIA

Summary: VAN ASCH TH. W.J. & SUKMANTALYA KESUMAJAYA I.N., *The modelling of soil slip erosion in the upper Komering area south Sumatra, province Indonesia* (IT ISSN 0391-9838, 1993).

Field observations and back analyses of soil slips in the tuff area of the Komering river basin showed that the triggering mechanism of soil slips in deep weathered tuffs is the downward percolation of a more or less saturated wetted zone to a critical depth.

A combined infiltration and stability model gives the possibility to calculate the probability of failure per area and hence the amount of soil displacement, using a stochastic approach. An estimate of soil slip erosion was done for three different situations of landuse: ladang (recently prepared), coffee field, secondary forest.

A first tentative simulation with the model gives already an insight in the main factors which contribute to the increase in danger for soil slipping in case of deforestation and a transverse into ladang fields. The most sensible parameters in the stability system appeared to be the initial moisture content of water in the soil and the depth of the rootzone.

KEY WORDS: Landslides, Soil slips, Sediment yield, Landuse change, Sumatra (Indonesia).

Riassunto: VAN ASCH T.W.J. & SUKMANTALYA KESUMAJAYA I.N., *Il modello di erosione per scivolamento superficiale nell'Alto Komering (Sumatra meridionale, Indonesia).* (IT ISSN 0391-9838, 1993).

Osservazioni di campagna ed analisi degli scivolamenti superficiali nell'area tufacea del bacino del Fiume Komering hanno mostrato che il meccanismo che innesca lo scivolamento del suolo nei tufi molto alterati è la variazione di profondità di una zona più o meno umida fino al raggiungimento di una soglia critica. Un modello combinato di stabilità ed infiltrazione dà la possibilità di calcolare la probabilità di collasso per area e, quindi, la quantità di suolo rimobilizzato, utilizzando un approccio di tipo stocastico. Una stima dell'erosione per scivolamento superficiale è stata eseguita per tre differenti situazioni di utilizzo del suolo: *ladang* (recentemente preparata), campi di caffè e foresta secondaria. Una prima simulazione tentata con il modello dà già un'indicazione dei fattori principali che contribuiscono ad incrementare il pericolo di scivolamenti superficiali nel caso di deforestazione e di passaggio a *ladang*. I parametri più sensibili del sistema stabilità sembrano essere il contenuto iniziale di acqua nel suolo e la profondità della zona delle radici.

TERMINI CHIAVE: Frane, Scivolamenti superficiali, Cambiamenti di uso del suolo, Sumatra (Indonesia).

INTRODUCTION

In the last 15 years, nearly the entire Komering river is affected by an increased river bedload and deposition of sands. These changes in the water and sediment regimes have caused increased flooding and waterlogging, which have become so severe that cultivation in some areas has to be abandoned several years ago. Especially in the Komering floodplain the rice cultivation which is closely related to the flooding system is seriously threatened. The bedload increase is attributed to those part of the upper catchment that were already instable and had a high rate of sediment delivery to the river system. (MEIJERINK & *alii*, 1988). One of these unstable areas was studied in more detail, to model the effect of deforestation on the increase of soil slip frequency and sediment yield.

The study area forms the N.W. flank of the Gunung Seminung volcano-complex with andesitic covers on the steeper slopes of the volcano mantle and ignimbritic tuff covers («Ranau tuff» and «Semutt tuffs») at the foot of the complex. The ignimbritic tuff area between Muaradua and Lake Ranau forms a volcanic plain with elevations from 125 m to 550 m and a general slope of 10 to 20%. The plateau is highly dissected by U-shape canyons and V-shaped gullies with an internal relief from 15 to 120 m. These canyons in the tuff area are characterised by wide flat valley floors and steep slopes with cliffs up to 70-80 degrees. Dominant slope angles vary between 30 and 45 degrees. The smaller V- shape gullies show the same distribution of slope classes as the main canyons (SUKMANTALYA, 1989).

According to KOOIMAN (1987) six dominant land cover types could be distinguished in the study area: secondary forest, abandoned ladang invaded by grasses and shrubs, ladang and coffee gardens, paddy fields. Ladangs are small

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agricultural fields, which are made by clearing and burning of the forest vegetation. They are temporary used for cultivation (shifting cultivation) and are abandoned after some years. In the study area they are then invaded by grasses (*Imperata cylindrica*) and shrubs (*Schima-bancana*).

The mean annual rainfall in the Upper Komering catchment area is about 3 000-3 500 mm in the western part and 2 000-2 500 in the eastern and central part of the area. According to OLDEMAN & LAS (1979), the agroclimatic zone of the study area can be classified as B1: that is an area having 7 to 9 months rainfall of more than 200 mm per month and less than 2 dry months with rainfall less than 100 mm.

They monthly average temperature ranges from 23 to 28 degrees in most of the months.

OBSERVATIONS ON LANDSLIDES AND RELATED FACTORS

In the study area between Lake Ranau and Muaradua, which is dominated by Ranau tuffs, different types of landslides were observed during the field campaign. Deep seated slumps 50 to 150 m in length and probably 20 to 30 m in depth were found. They occur in all types of vegetation and the observed ones were not active. On many of these slides fully secondary forest or remnants were found. On the steepest slopes (70°) some medium to large (more than 20 m in length) rock slides were observed, which developed in the unweathered tuff. These rock slides were rather recent and they developed also on slopes with a dense secondary forest vegetation cover.

Relative deep seated slumps occurred at the head of the smaller dense vegetated gullies with concentration of groundwater or at places where surface water concentrates along the impermeable roads down to the gully heads. The slip surfaces of these slides reach a depth of 4 to 6 m up to the unweathered tuff.

However, the most active and most frequently occurring mass movements are the surficial soil slips. They were investigated in the field in more detail. Their size is rather limited (10-20 m) and the depth is no more than 1.50 m. The frequency of occurrence of these slips led to the conclusion that they form an important contribution to the actual sediment yield in this area. Field observations revealed that 10 to 30% of the material of these soil slips is directly transported from the source area to the primary gullies.

Terrain observations showed that a number of factors influences the frequency of occurrence of these slips. The different cross sections which were made in the field, gave an impression of soil slip frequency in relation to the vegetation cover. The soil slips could not be detected on the airial photographs (scale 1; 50.000 and 100.000) and therefore a systematic frequency analysis of these slips could not be made. However, the field observations made it reasonable to assume that there exists an increase in frequency of soil slips with a decrease in density of vegetation cover in the range from fully secondary forest, herbs and shrub vegetation (abandoned ladangs) to recent ladang with crop vegetation.

One of the causes of these obviously stabilizing effect of the vegetation cover on these surficial soil slips can be the root mantle which increases the cohesion of the top soil. The «buttress» effect of the tree stems and especially the network of the thick root branches can hold also the top soil on its place (GRAY & MEGAHAN, 1981). At many places it was observed that the bigger vertical tree roots of the forest vegetation anchored themselves 1-2 m in the unweathered tuff layers.

The soil slips develop on the steeper slopes between 35° and 45° which are the dominant slope classes along the canyons and gullies. Apart from the slope angle which can be considered as a main factor in the development of these soil slips, slope form and the position on the slope are additional factors. It was observed that soil slips occurred in the flat lateral concavities of the slope which form the onset towards a gully. Slips can also be initiated along road cuts.

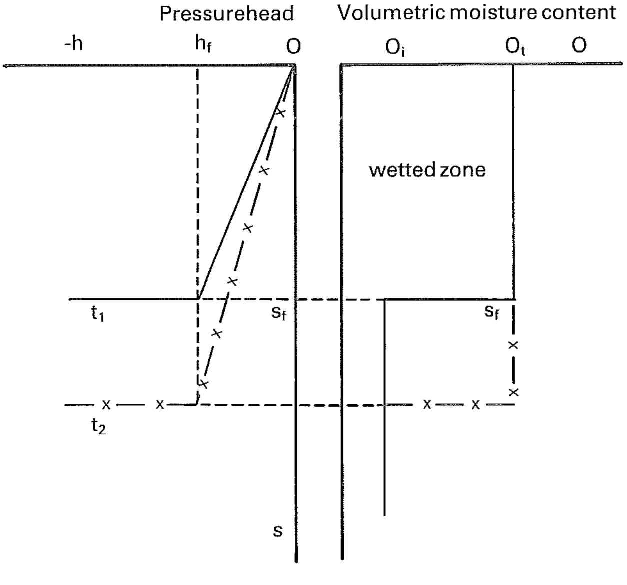

FIGURE 1 - Green and Ampt model of infiltration. Wetted profile at two different times. (After KOOREVAAR & *alii*, 1983).

The strength characteristics of the regolith is another important stability factor. Obviously the weathered tuff soil, which has a loamy sand texture, becomes unstable on slopes varying from 35° to 45°. This is an indication for high strength characteristics of the soil material. A complete regolith profile in the tuff area consists of an organic top soil 50 cm to 1 m thick followed by a completely weathered tuff layer with some cohesion and a thickness of 1 to 3 m and below this layer a gradual change to more or less unweathered cemented tuff.

No direct observations could be made about the hydrological influence of the vegetation i.c. evapotranspiration and the effect on the soil water balance. These effects must be rather important since a number of farmers have reported that soil slips occurred within a year after clearing of the land for a ladang field. This may indicate that the mechanical effect of the forest vegetation on slope stability is less important than the hydrological effect because the clearing of the land does not influence the strength of the root system after one year but must change immediately the soil water balance (see below). The slipsurfaces were found at a certain depth (80 cm to 120 cm) below the soil surface within the weathered layer. Terrain observations revealed that the slip surfaces did not develop on a hydrological and lithological boundary between two different layers giving rise to positive pore pressures as may be expected. The only explanation for the development of surficial soil slips in these deep weathered tuff layers is the triggering of these slips by a downward moving wetting front to a certain critical depth. This causes a differentiation in strength between the more or less wetted top soil and the stronger unsaturated subsoil (see below).

In the next section the stability conditions of the slopes with respect to these surficial slips will be analysed in a quantitative way. The main purpose is to determine in a more or less quantitative way the frequency of soil slips and the amount of soil displacement under different landcover types.

MODELLING OF SOIL SLIP FREQUENCY

The basic principle of the model is the assumption, inspired by field observations, that the soil slips are triggered by a downgoing wetting front until a critical depth below the rootzone in a deep cohesive soil. In the model it is assumed that after ponding time a wetted saturated zone is going downward and that the critical depth of this zone is the triggering factor. Fig. 1 gives schematically the pressure head distribution of this wetted saturated zone at time t_1 and t_2. In the wetted zone the volume fraction of water (θ_t) is uniform and constant with time. At the wetting front there is a very sharp change of θ_t to θ_i (the initial moisture content which is constant through the profile). The pressure head at the wetting front h_f, has also a constant value independent of the position of the wetting front (s_f). These assumptions, which are quite realistic for water infiltrating into coarse-texture soils, are used in the infiltration model of Green and Ampt (KOOREVAAR & *alii*, 1983).

The wetted top layer has a lower strength than the secondary layer because the first layer has a less negative pore pressure than the dryer secondary layer (see fig. 1). The influence of negative pore water pressure on soil strength can be written in a general equation (FREDLUND, 1987):

$$s = c + \sigma_n \tan\phi_s - u_w \tan\phi_u \qquad (1)$$

where s = soil strength (kPa),
c = soil cohesion (kPa),
σ_n = normal stress (kPa),
ϕ_s = angle of internal friction saturated soil,
u_w = pore water function (kPa),
ϕ_u = angle of internal friction unsaturated soil.

According to FREDLUND (1987) the ϕ value related to negative pore pressures are different from ϕ values related to neutral or positive porewater pressures. This is true if the saturated soil is compared with the unsaturated condition of the soil. In our case the wetted zone has a negative pressure head (see fig. 1); however, it is considered as completely saturated. Therefore it is assumed that there is no difference between the ϕ values at the right hand of equation 1. In this case equation 1 can be simplified to:

$$s = c + (\sigma_n - u_w) \tan\phi_s \qquad (2)$$

where ϕ_s is valid for a saturated soil and u_w is negative!

Fig. 1 shows that the pore water pressure u_w at a potential slipsurface, which must lie at a depth H_c inside the wetted zone, is given by:

$$u = h_f/s_f \cdot H_c\gamma_w \qquad (3)$$

where u_w = pore water suction (kPa),
h_f = pressure head at wetting front (m) (fig. 1),
s_f = depth of wetting front (m) (fig. 1),
H_c = depth of slip surface (m) (fig. 1),
γ_w = bulk density water (kNm^{-3}).

If fig. 1 is considered as a slice of an infinite slope equilibrium model, the following equation is obtained for a cohesive soil with a percolating wetting front:

$$F = \frac{c + (\gamma_s \cos^2\alpha - h_f/s\gamma_w)\, H_c \tan\phi_s}{\gamma_s\, H_c \sin\alpha \cos\alpha} \qquad (4)$$

where γ_s = wet bulk density (kNm^{-3}),
α = angle of slip surface.

The depth H_c ($O< H_c < s_f$) of the slip surface is found for a minimum F-value for a given depth of the wetting front (h_f/H_c = constant). It can be proved mathematically that F in equation (4) has no minimum value and therefore the slipsurface will develop at the wetting front ($H_c = s_f$). Therefore equation 4 can be rewritten:

$$F = \frac{c + (\gamma_s \cos^2\alpha\, s_f - \gamma_w h_f) \tan\phi_s}{\gamma_s \sin\alpha \cos\alpha\, s_f} \qquad (5)$$

The equation shows that the stability F of the slope depends on the infiltration depth (s_f) of the wetting front and the pressure head h_f. The pressure head h_f cannot be measured directly in the field but can be derived from sorpetivity values which are determined experimentally by infiltration tests (KOOREVAAR & *alii*, 1983).

Given a rainstorm with a given intensity n the time of ponding (t_p) can be calculated from:

$$t_p = \frac{k_t\, h_f\, (\theta_t - \theta_i)}{n\, (n - k_t)} \qquad (6)$$

where t_p = ponding time (s),
k_t = saturated hydrologic conductivity ($m\ s^{-1}$),
θ_t = volumetric moisture constant saturated soil (–),
θ_i = initial volumetric moisture constant (–),
n = rainfall intensity ($m\ s^{-1}$).

From that time t_p the depth s_f of the «complete» saturated wetted zone can be determined by the model of Green and Ampt from:

$$t - t_p = \frac{\theta_t - \theta_i}{k_t}\left[s_f + h_f \ln\left(\frac{s_f - h_f}{- h_f}\right)\right] \qquad (7)$$

where t = duration of rainstorm (s).

Given the variation of the different parametric values, required in the stability equation, a probability of failure can be calculated for different slope classes and durations and intensities of rainstorms. If information is available about the distribution of intensities and durations of these storms an estimate of the frequency of land slips and amount of soil displacement per slope class can be made. This will be done in the next section for the steep slope classes in tuffs in the Upper Komering area.

AN ESTIMATE OF THE AMOUNT OF SOIL SLIP DISPLACEMENT ON THE TUFF SLOPES OF THE UPPER KOMERING AREA

An estimate of the amount of soil slip displacement was done for three different situations of landuse:

- Ladang recently prepared without vegetation but still with a root «armament».
- Coffee field.
- Secondary dense forest.

Table I gives a survey of all the parameters which are needed for the simulation with the infiltration-stability model.

The initial moisture contents are assumed to be different for the three landuse situations. This is caused by differences in interception and evapotranspiration. MEIJERINK & *alii* (1988) showed that under forest in the Komerering area soil moisture is lower than under crop vegetation.

The mean initial soil moisture content is highest under recent ladang where the vegetation is completely destroyed. The initial soil moisture content and hence the storage capacity for the infiltrating water is a very sensitive parameter in the infiltration-stability simulation.

The pressure head at the wetting front was obtained from literature: A variation of pressure head between – 0.2 and – 0.4 was taken for these loamy sand soils. It is not a sensitive parameter in the model: after longer infiltration times it can be neglected.

The saturated hydrologic conductivity was determined by the inversal auger hole method (I.L.R.I., 1974) carried out on ladang and coffee fields.

The c and ϕ values were derived from back analyses of soilslips using the method given by VAN ASCH (1984). This is a rather quick field method to determine the strength parameter of the regolith material. The principal is based on back analyses of a number of soil slips of different size in the same type of regolith material. For this purpose the topographical profile across landslips must be measured in the field. It is essential that a part of the slipsurface is exposed in order to reconstruct the slipsurface. If it is assumed that the slipsurface has a circular form, only three points of this circle are sufficient to reconstruct the slipsurface. The many slips on these steep slopes show a large displacement out of the source area and therefore it was easy to detect the form of the slipsurface.

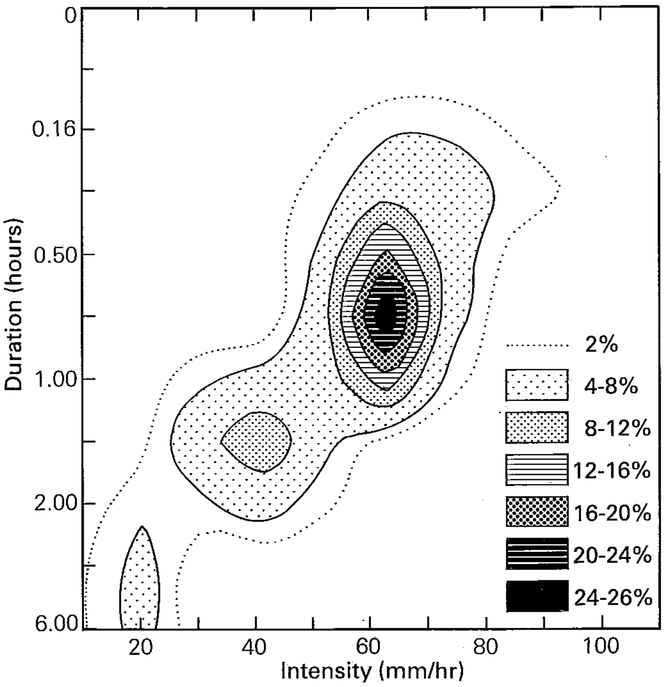

FIGURE 2 - The percentage distribution of rain, incidents with different duration and intensity classes; Station: Muara Dua - South Sumatra Province.

For each slip an equilibrium equation can be set up with the unknown parameter c and ϕ. An assumption has to be made of the height of the phreatic surface during failure. Mathematically two independent equilibrium equations set up for two slumps of different sizes in the same material are sufficient to solve c and ϕ. However, a more reliable mean estimate of the c and ϕ value is obtained if more than two slumps of different size, developed in the same material, are analysed. In this way c and ϕ can be derived by a linear fit of a number of equilibrium equations in which c and ϕ are the unknown parameters.

TABLE 1 - A survey of the variation of parametric values needed for the simulation with the infiltration-stability model.

	Ladang	Coffee	Forest
Saturated minus initial soilmoisture content (V%)	2 - 5	5 - 15	10 - 20
Pressure head at wetting front (m)	−0.2 - −0.4	−0.2 - −0.4	−0.2 - −0.4
Saturated hydrologic conductivity (m/day)	0.4 - 0.8	0.4 - 0.8	0.4 - 0.8
C-values of the soil (kPa)	0.3 - 0.7	0.3 - 0.7	0.3 - 0.7
C-value of the roots (kPa)	1 - 3	0.2 - 0.5	1 - 3
Ø value (degrees)	34 - 37	34 - 37	34 - 37
Wet bulkdensity (kN/m^3)	17 - 18	17 - 18	17 - 18
Root depth (m)	0.7 - 1.0	0.2 - 0.4	0.7 - 1.0
Overburden vegetation (kPa)	0	0.3 - 0.5	2 - 3

TABLE 2 - Probability of soil slip failure and mean estimate of soil displacement per year.

Slope (degrees)	Landuse	Storm intensity (mm/hr)	Storm duration (hour)	Probability of failure (%F<1)	No. of rain incidents (per year)	Mean displacement (tons/ha/year)
40 - 45	Ladang	70 - 80	0.5 - 1	0.33	15.37	913
		60 - 70	1 - 2	0.66	2.5	297
					Total	1210
40 - 45	Coffee	70 - 80	0.5 - 1	0.05	15.37	138
		60 - 70	1 - 2	2.6	2.5	1170
					Total	1308

The back analyses for eight soil slips show that the best fit for the c and ϕ value is obtained if no pore pressures neither positive or negative are assumed to be present during failure. This means that it seems reasonable to accept the concept of the triggering mechanism of a downgoing wetting zone, reaching a critical depth. The back analyses show also that the effect of a negative pore water pressure in the wetted zone can be neglected. This means that the term h_f in equation (5) can be neglected and that only the depth of the wetting front (s_f) is the most important output parameter from the infiltration model to the stability model.

For the variation values of the parameters given in Table 1, a probability of failure can be calculated with the computer programme SAFETY. It is assumed that all the parameters are normally distributed. A rain storm with a given duration and intensity class forms the input of the model. Using a Monte Carlo simulation a depth of the wetting front is calculated each time by the infiltration model. The calculated depth is introduced next in the slope stability model. The iteration is done 300 times. For each iteration the depth of the calculated wetting front is compared with the depth of the rootzone and the decision is made whether an extra cohesion of the roots must be taken into account. The output of the model gives a distribution of the Safety Factor (F). The percentage frequency of the Safety Factor below 1 is considered as the probability of failure. This percentage is considered as the percentage of area which might be affected by soil slips due to a given rain storm.

In the study area information about the distribution of intensity and duration of rain storms was limited. Fig. 2 gives the percentage distribution of rain incident with different duration and intensity classes.

The simulations for different rain intensity and duration classes show that only storms with a duration of 0.5 to 1 hour and 1 to 2 hours with the highest intensities give unstable conditions on slopes between 40° and 45° in ladang and coffee fields.

Table 2 gives the results for these effective rainstorms in terms of a probability of failure and the estimated soil displacement. The latter was calculated by multiplying the amount of rainfall incidents of a given duration and intensity with the probability of failure per incident. This gives a yearly mean percentage area affected by landslips. Given the mean depth of the soil slips, an amount of soil displacement per ha per year is obtained.

DISCUSSION AND CONCLUSIONS

Field observations and back analyses of soil slips in the tuff area of the Komering river basin showed that the triggering mechanism of soil slips in deep weathered tuffs is the downward percolation of a more or less saturated wetted zone until a critical depth. The depth of the wetted zone in a deep regolith is a threshold for failure if the soil has a certain cohesion. In this case the weathered tuff itself seems to have a cohesion and it is assumed that the roots which reach to a certain depth form also a cohesive element in the soil.

A combined infiltration and stability model gives the possibility to calculate the probability of failure per area using a stochastic approach. A first tentative simulation with the model gives already an insight in the main factors which contribute to the increase in danger for soil slipping in case of deforestation and a transverse into ladang fields. The most sensible parameters in the stability system appeared to be the initial moisture content of water in the soil and the depth of the rootzone. Sensitivity analyses with the infiltration model of Green and Ampt shows that the initial moisture content has a great effect on the storage capacity of the soil for infiltrating water and therefore influences stronghly the downward rate of the wetting front. The downward rate of the wetting front in combination with the root depth seem to be the key for explaining the differences in stability of the slopes under different vegetation and landuse systems: under recently logged forest the rate of downward movement of the wetting front will drastically increase because of the increase in mean initial soil moisture in the soil due to the absence of interception and evapotranspiration. One might expect a higher runoff on the scarcely vegetated fields compared with the densely vegetated fields. But the differences are probably not so large on these relatively permeable loamy sand soils which are not sensible for soil crusting.

The deep root systems may still be intact but the probability that the wetting front will pass below this root depth is increased. A rapid transition into a densely vegetated mixed garden system with coffee causes a lowering of the mean initial soil moisture storage and therefore a decrease of the downward rate of the wetting front. However, the mean root depth of these crop vegetations is much lesser than of the forest as was observed in the field. Therefore, the degree of (in)stability remains nearly the same as under a freshly cut forest. The tropical forest system seems to be very stable in this model because of the relatively low mean initial moisture contents, which were also observed in the field, and the relatively deep intact rootzone.

The simulation explain already the observations made in the field which show a rapid decrease of the frequency of soil slips in the range from freshly cut forest, mixed garden with coffee, abandoned ladangs with invasion of dense shrubs to secondary forests.

Due to the lack of information on landslip densities in relation to slope angle and landuse the model could not be calibrated in more detail.

A rough estimate of soil slip displacement by the model shows that for the ladang fields (just after the logging of the forest) and the coffee fields a mean amount of soil displacement of 1000-1500 tons per ha per year can be expected on the steepest slopes.

An estimate of direct sediment delivery to the river system is difficult and can only be given if more information is available from the field about the distribution of distances of the soil slips to the rivers.

For a good estimate of the spatial and temporal probability of failure and hence the areal amount of soil displacement it is necessary to know the spatial variation and kind of distribution of the most sensitive soil parameters in the model and also the areal distribution of the precipitation. Since the initial soil moisture distribution seems to be very important it is necessary to model more precisely the water balance of the top soil and especially the effect of evapotranspiration. Estimates of the sediment yield by soil slips therefore become more realistic if more data are available about distributions of the duration and intensity of rain storms and the duration of dry periods.

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