Modelling Runoff and Soil Loss from Bench Terraced Hillslopes in the Volcanic Uplands of West Java, Indonesia

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Abstract: Soil erosion remains a major problem in the volcanic uplands of Java, despite the widespread construction of backsloping bench terraces. As part of a larger project to elucidate the causes for this lack of impact, runoff and erosion processes were studied at different spatial scales in a small (1 km^2) volcanic catchment in West Java. The results demonstrate that soil loss from the terraces takes place in two stages: (i) transport of rainfall-detached sediment by splash and shallow overland flow (wash) from the terrace riser and bed into the toe drain; and (ii) entrainment and transport of sediment through the toe drain by concentrated runoff. A process model of runoff and soil loss has been developed, which first calculates rainfall erosivity and runoff depth for each terrace component (i.e. riser, bed and toe drain) on a storm basis. Next, depending on the dominant mode of transport, detachment and transport by rain splash, transport by wash and entrainment and transport by surface runoff are calculated, each as a function of vegetation and soil surface cover and the presence of a layer of deposited sediment. The model uses as few parameters as possible while retaining its physical character. The model was calibrated and tested using, inter alia, measurements of rainfall intensity and daily runoff and sediment yield from small sections of terrace risers or beds, as well as from six bench terrace units. Model performance was generally satisfactory and the results indicate where and how soil loss could easily be decimated. Implications for runoff and erosion modelling on terraced hillsides are briefly discussed and areas where further research is needed are indicated.

Keywords: Runoff; Erosion and sediment transport; Process-based model; Soil conservation; Bench terraces

1. INTRODUCTION

Soil erosion constitutes a major problem in the volcanic uplands of Java that affects the livelihood of millions of farmers, whereas the associated sedimentation causes additional problems downstream. In response, past development projects have advocated the construction of backsloping bench terraces, but despite widespread adoption the problems remain. Some have suggested that other sources than the now bench-terraced agricultural hillsides continue to provide the rivers with sediment, pointing at landslides, bank erosion, expansion of paddy rice fields and contributions from roads and village areas as potential culprits. However, recent research in the volcanic upland Cikumutuk catchment in West Java demonstrated that about two-thirds of the annual sediment yield of c. 60 t·ha^{-1} was generated on the terraced rainfed hillsides [Purwanto, 1999]. This raises the question as to why well-constructed bench-terraces still produce so much sediment and how erosion may be reduced most efficiently. Since late 1998, the processes leading to runoff and sediment production on bench terraces in the Cikumutuk catchment have been studied in detail. To provide a tool for evaluating the hydrological impacts of various ways of managing the terraces, a physical, process-based model has been developed. This paper gives an overview of the model and briefly discusses its implementation. Details of the experiments on which the model is based and of the development and validation of its components are given elsewhere [van Dijk and Bruijnzeel, 2001; van Dijk et al., in press].

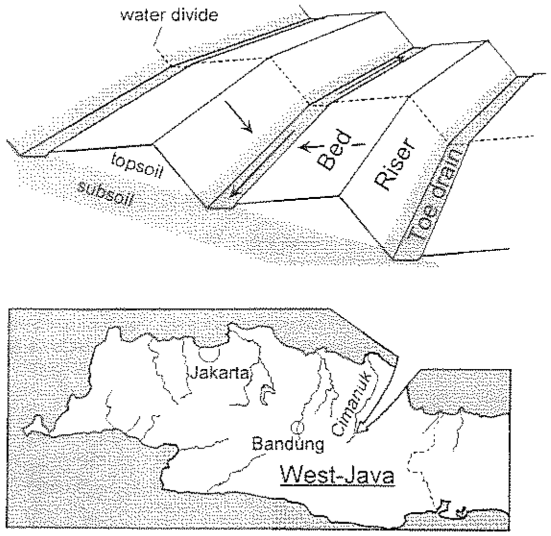

Figure 1. Location of the study area and general design of the back-sloping bench terraces.

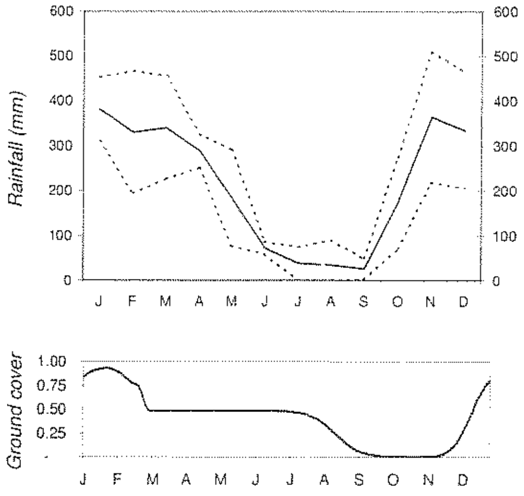

Figure 2. (a) Average monthly rainfall distribution in the study area (dotted lines indicate one standard deviation from the mean) and (b) generalised annual course of ground cover associated with the cropping system under study.

2. PHYSICAL SETTING

2.1 Study Area

The 1 km^2 upper catchment of the Cikumutuk river is situated about 40 km East of Bandung, West Java, in the middle reaches of the Cimanuk basin at an altitude of 560 to 740 m a.s.l. (7°03'S, 108°04'W; Figure 1). Slopes are generally about 15°. The Quaternary volcanic tuffs have weathered to kaolinitic Oxisols that consist of several decimetres of highly permeable well-aggregated soil on top of a less permeable, massive subsoil (Figure 1). About two-thirds of the catchment are occupied by mixed crops planted on rainfed back-sloping bench-terraces, constructed during a past soil conservation project. The remainder consists of fallow land, paddy rice fields, settlements, home gardens and plantation forest. The area experiences a humid tropical climate with a drier season (average monthly rainfall less than 60 mm) generally extending from June until September and a mean annual rainfall of about 2600 mm (Figure 2a).

2.2. Terrace Design and Cropping Practice

The 'typical' terrace consists of a riser, a compacted toe drain that also acts as an access path and a bed that slopes back towards the toe drain (Figure 1). The terrace risers have slopes of 35-50° and a projected width of 0.5-1.3 m, whereas the terrace beds are constructed at an angle of 0-12° and have a width of 0.8 m or more, depending on the original slope. The toe drain has a width of 0.3-0.4 m and a slight gradient (up to 3°) towards the end of the terrace (Figure 1), where the runoff and sediment drain into a gully or onto a path. Typical terrace lengths along the contour measure 15-40 m. Crops planted on these rainfed terraces usually include cassava and maize, often intercropped with upland rice, groundnut or other legumes. The crops are sown or planted a few weeks after the first frequent rains, normally at the end of October or beginning of November. The crops are harvested in February or March, except for cassava which is usually left growing until the dry season. The seasonal development of ground cover is illustrated in Figure 2b [see Van Dijk and Bruijnzeel, 2001 for details].

2. PROCESS IDENTIFICATION AND MODEL DESCRIPTION

3.1. Experimental Approach

From October 1994 onwards various methods were used to elucidate the processes dominating erosion on the different components of the terrace, including:

- a combination of Gerlach-type trough and modified splash boards to study detachment and transport by rain splash and shallow overland flow (wash) on the terrace risers;
- differently-sized splash cups to study rain splash on the terrace beds; and
- 0.3x0.6 m soil trays exposed to natural rainfall to study the relationship between rainfall erosivity, slope, soil surface cover and splash and wash processes [Wan et al., 1996].

In addition, runoff and sediment yields were measured daily (as well as instantaneously for a number of events) at the scale of:

- Artificial Boundary Erosion Plots (ABEPs), encompassing terrace riser or bed sections with artificial boundaries on two sides; and
- Non-imposed Boundary Erosion Plots (NBEPs), encompassing entire, hydrologically defined bench terrace units (Figure 1).

The most important findings and their implications for modelling as listed below were used to formulate model equations, designed in such as way as to require as few parameters as possible, yet preserving a clear physical formulation.

3.2. Runoff Generation

The relationship between rainfall and runoff rates appeared to be described very well by the spatially variable infiltration model (SVIM) of Yu et al. [1997]. Assuming an exponential rainfall depth-intensity distribution, the SVIM theory can be used to derive an analytical expression (Eq. 2, Table 1) relating event runoff depth to depth-averaged storm intensity $\bar{R}$ (cf. Eq. 1) and average maximum infiltration rate, I_m. The parameter S_I was introduced to Eq. 2 to simulate the combined effect of canopy and surface depression storage and initial additional infiltration related to soil matric suction effects [cf. Yu et al., 1997]. The overall runoff response of the contributing areas (terrace riser, bed and toe drain) is approximated well by a similar function (Eq. 3), for which the spatially-averaged parameter $\tilde{I}_m$ may be derived from the I_m values of the respective areas. To allow for the fact that the storage capacity in the toe drain may intercept some runoff originating from the terrace riser and bed as well, the value of $\hat{S}_I$ was calibrated using terrace runoff measurements, instead of using a spatial-average value.

2.3 Erosion and Sediment Transport Processes

Soil loss from the bench terraces proved to occur in two steps: (i) transport of rainfall-detached sediment by splash and shallow overland flow (wash) from the terrace riser and bed to the toe drain; and (ii) transport of suspended sediment and active entrainment of accumulated sediment by runoff in the toe drain. Mass-wasting on the often bare risers, active entrainment of soil on the risers and beds by runoff, and splash in the toe drain appeared to play only a minor role. On an event basis, the combined result of the three main modes of sediment transport is expressed by Eq. 4. Furthermore, the process research suggested that:

- detachment and transport by splash during a storm is best predicted by the kinetic energy of rain falling at intensities higher than a threshold intensity [Hudson, 1965].
- soil detachability is high and appears to be unrelated to slope gradient;
- the average distance and relative importance of splash in the downslope and upslope directions increase and decrease, respectively, with increasing slope;
- the erosive power of runoff on the terrace beds and risers is too small to actively entrain soil particles. However, part of the fine particles detached by rainfall are transported into the toe drain by shallow overland flow (wash);
- the effect of vegetation and soil surface cover on soil detachment can be described by an exponential decay function [Laflen and Colvin, 1981].

The above findings were incorporated in a series of equations describing the various processes as a function of the amount of kinetic energy of rain (Eq. 5-7). Using a threshold rainfall intensity of 20 $\mathrm{mm \cdot h^{-1}}$ gave the best result. Storm kinetic energy was estimated accurately on an event basis using Eq. 5, which combines the exponential rainfall depth-intensity distribution theory with a generalised exponential equation relationship between rainfall intensity and kinetic energy contents [van Dijk et al., in press; van Dijk et al., in press]. Using the calculated amount of storm kinetic energy, splash transport can now be predicted using Eq. 6 [van Dijk et al., in press]. Naturally, whether splash transport leads to a net soil loss from a given surface area also depends on the degree of compensation afforded by sediment

Table 1. Model equations.

Depth-averaged storm rainfall intensity:

$$\breve{R} = \frac{\sum_{i=1}^{n} \left(R^2 \Delta t\right)_i}{P} \tag{1}$$

Component area runoff:

$$Q_{tot} = P\left[1 - \frac{I_m}{\breve{R}} \ln\left(1 + \frac{\breve{R}}{I_m}\right)\right] - S_I \tag{2}$$

Terrace runoff:

$$\tilde{Q}_{tot} = P\left[1 - \frac{\tilde{I}_m}{\breve{R}} \ln\left(1 + \frac{\breve{R}}{\tilde{I}_m}\right)\right] - \tilde{S}_I \tag{3}$$

Sediment yield:

$$\begin{aligned} \sum M &= M_{sp} + M_{wa} + M_{en} = \\ &\frac{T_{sp}}{L} + c_{wa} Q_{tot} + c_{en} Q_{tot} \end{aligned} \tag{4}$$

Storm kinetic energy for $R > R_K$:

$$\begin{aligned} E_{R_K} &= P e_{\max}\left[\exp\left(-\frac{R_K}{\breve{R}}\right)\right. \\ &\left. - \frac{a}{b\breve{R} + 1} \exp\left(-bR_K - \frac{R_K}{\breve{R}}\right)\right] \end{aligned} \tag{5}$$

Potential splash transport:

$$M_{sp} = \frac{T_{sp}}{L} = \frac{1}{\pi L} \Lambda_0 \left(1 + \lambda S^p\right)\left[DE\right]_{20} \tag{6}$$

Potential wash transport:

$$M_{wa} = c_{wa} Q_{tot} = j \frac{\left[DE\right]_{20}}{P} Q_{tot} \tag{7}$$

Potential runoff transport:

$$M_{en} = c_{en} Q_{tot} = \bar{c}_t^{\,\beta} Q_{tot} = \left(k Q_e^{\,0.4}\right)^{\beta} Q_{tot} \tag{8a}$$

with

$$k = F \frac{\sigma}{\phi_e \left(\sigma/\rho - 1\right)} \frac{S^{1.3}}{n^{0.6}} \left(\frac{\sum A}{W_{td}}\right)^{0.4} \tag{8b}$$

and

$$\tilde{Q}_e = \left(\frac{\Sigma \tilde{Q}^{1.4}}{\tilde{Q}_{tot}}\right)^{2.5} = \left(\frac{F\left(\tilde{I}_m, \breve{R}\right)}{\tilde{Q}_{tot}}\right)^{2.5} \tag{8c}$$

Actual sediment yield:

$$\begin{aligned} \sum M^* &= H f_v f_s \sum M \\ &= e^{-\gamma_m m} e^{-\gamma_v C_v} e^{-\gamma_s C_s} \sum M \end{aligned} \tag{9}$$

Table 2. List of symbols.

ΣA	total terrace area (m^2)
a	constant in rainfall intensity-kinetic energy relationship
b	coefficient of the rainfall intensity-kinetic energy relationship ($h \cdot mm^{-1}$)
C_v, C_s,	fractional vegetation and soil surface cover, resp.
c_{en} , c_{wa}	depth-averaged concentration of entrained and washed sediment, resp. ($g \cdot dm^{-3}$)
c_t	depth-averaged concentration of entrained sediment at transport limit ($g \cdot dm^{-3}$)
D	soil detachability for rainfall (in $g \cdot J^{-1}$)
E_{Rk}	storm kinetic energy of rain falling at $R > R_K$ (e.g., E_{20} in this study, in $J \cdot m^2$)
e_{max}	max. kinetic energy of rainfall ($J \cdot m^{-2} \cdot mm^{-1}$)
F	fraction of stream power effective in erosion
f_v, f_s	erosion reduction factor of vegetation and soil surface cover, resp.
H	fractional cover of deposited sediment
I_m	average maximum infiltration rate ($mm \cdot h^{-1}$)
$\tilde{I}_m$	spatially-averaged max. infiltration rate ($mm \cdot h^{-1}$)
j	fraction of detached soil remaining in suspension
k	factor defined by Eq. 8b
L	slope length (m)
ΣM	potential total erosion rate ($g \cdot m^{-2}$)
ΣM^*	actual erosion rate ($g \cdot m^{-2}$)
M_{sp}	potential splash erosion ($g \cdot m^{-2}$)
M_{wa}	potential wash erosion ($g \cdot m^{-2}$)
M_{en}	potential runoff entrainment erosion ($g \cdot m^{-2}$)
m	mass of deposition layer ($g \cdot m^{-2}$)
n	Manning's roughness coefficient ($m^{-1/3} \cdot s$)
P	storm rainfall depth (mm)
p	exponent of the slope - splash length relationship
Q_{tot}	contributing area runoff depth (mm)
$\tilde{Q}$	instantaneous rate of runoff from terrace ($mm \cdot h^{-1}$)
$\tilde{Q}_{tot}$	average runoff depth for the entire terrace (mm)
$\tilde{Q}_e$	effective runoff rate, defined by Eq. 8c ($mm \cdot h^{-1}$)
R	rainfall intensity ($mm \cdot h^{-1}$)
R_K	threshold rainfall intensity (20 $mm \cdot h^{-1}$ in this study)
$\breve{R}$	depth-averaged rainfall intensity (Eq. 1; $mm \cdot h^{-1}$)
S	slope gradient
S_I	additional water storage/infiltration (mm)
$\tilde{S}_I$	spatially averaged value of S_I (mm)
Δt	duration of time interval (h)
T_{sp}	potential splash transport rate (in $g \cdot m^{-1}$)
W_{td}	width of the toe drain (in m)
β	relative erodibility (<1)
γ_v, γ_s	coefficient of actual erosion -vegetation/soil surface cover relationship (Eq. 9)
γ_m	coefficient of the deposition layer mass-cover relationship.
Λ_0	splash length on a horizontal plane (m)
λ	coefficient of the slope - splash length relationship
ϕ_e	effective sediment settling velocity ($m \cdot s^{-1}$)
ρ	density of water ($g \cdot dm^{-3}$)
σ	density of sediment ($g \cdot dm^{-3}$)

splashed onto it from adjacent areas. The interactions between processes leading to wash transport are less understood, but a good approximation was obtained after assuming that a constant (but slope-dependent) fraction of the total concentration of soil particles in the fallen raindrops immediately after detachment remains suspended and may be carried off (Eq. 7).

In addition to sediment transport by splash and wash, sediment in the toe drain may also be entrained by runoff itself. This process is described according to Rose-Hairsine theory [Rose, 1993; Yu et al., 1997; Eq. 8a-c]. Using the exponential rainfall intensity distribution theory referred to earlier, the effective runoff rate Q_e (Eq. 8a) is calculated using Eq. 8c.

The effect of vegetation cover and/or soil surface cover on sediment production is described in the model by an exponential decay function [Laflen and Colvin, 1981; Eq. 9]. Furthermore, the actual amount of sediment transported through the toe drain was assumed to be linearly dependent on the area of soil covered by previously detached sediment. This was estimated in turn as a function of the amount of sediment accumulated in the toe drain (Eq. 9).

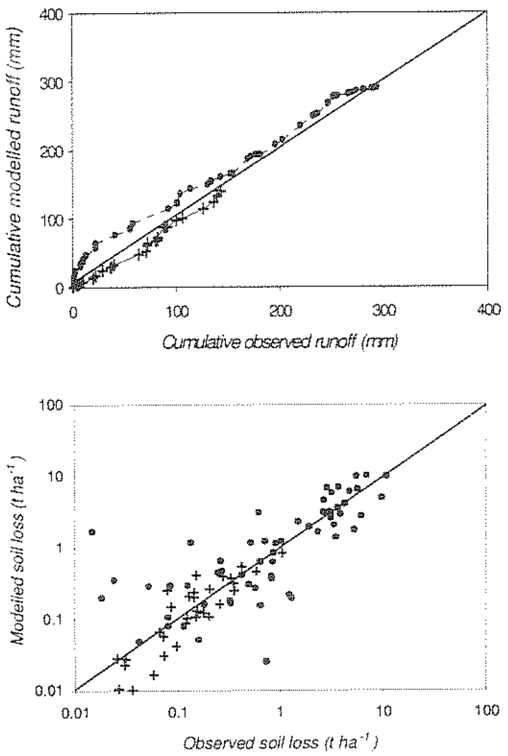

Figure 3. Observed and modelled amounts of (a) cumulative runoff and (b) event soil loss on a terrace bed (pluses) and riser (dots) section plot, respectively.

4. MODEL APPLICATION

4.1. Model Validation, Calibration and Testing

The model was evaluated in various ways. Where possible, the theory was validated using small-scale process measurements, such as those listed in Section 3.1 as well as runoff transport studies using a flume [Rose, 1993]. Using initial parameter values derived from these experiments, the model was calibrated with measurements of runoff and sediment yield from two bare plots encompassing a section of terrace riser or bed, respectively. In addition, two sections of terrace riser having a partial grass and shrub cover respectively, and two terrace bed sections planted with a mixed crop of maize, rice and cassava, with and without surface mulch, respectively, were used to derive parameter values for use in Eq. 9.

The model was tested using a data-set covering two seasons of daily rainfall intensity data plus runoff and sediment yield measurements made on 14 to 18 small (c. 1-6 m^2) erosion plots on terrace risers or beds with variable vegetation and soil surface covers. In addition, runoff and sediment yield data for six entire terrace units of contrasting size (53-231 m^2), design and management were used as well. Storm depth and depth-averaged rainfall intensity, terrace size, slope and width of terrace components, degree of vegetation and soil surface cover and their variation in time are inputs required by the model, whereas calibrated values were used for all other parameters. To be able to assess the prediction errors related to the runoff and erosion sub-models separately, the erosion model was also tested with optimised values for the two hydrological parameters I_m and S_I.

It appears that both the runoff and the erosion submodels generally performed well. However, simulated runoff amounts were affected by relatively small differences in I_m and S_I. Using values that were fitted to runoff measured on the plot under consideration rather than the calibration plots greatly enhanced predictions of event runoff, resulting in an average Nash-Sutcliffe model efficiency of 0.75 and 0.82, for bed and riser sections and terrace units, respectively. Soil loss was also predicted with fair accuracy, resulting in average model efficiencies of about 0.47 and 0.64, for the terrace bed and riser sections and entire terrace units, respectively.

The differences could be considerable for individual storms, but there did not appear to be a systematic under- or overestimation for either small or large events in most cases and the difference between cumulative observed and modelled soil losses was usually within 20%. Furthermore, it was observed that the performance of the model increased as erosion rate itself increased.

The presence of low vegetation and mulch cover (such as harvest residues) increased the infiltration capacity of the soil considerably [Yu et al., 1997] and had an even more pronounced effect on soil losses. Other important factors that determined the magnitude of erosion on the terraces were the dimensions and gradients of the bed and riser and, in particular, the gradient of the toe drain.

5. CONCLUSIONS

Despite some remaining limitations to the knowledge and mathematical description of runoff and sediment processes in the studied environment, the present model results indicate with sufficient certainty that soil loss can easily be decimated from a technical point of view, by reducing either the supply of sediment from the terrace riser and bed to the toe drain or the transport capacity of flow through the toe drain. The former is achieved most easily by greater vegetation or soil surface cover on the terrace bed and riser, which not only reduces rainfall detachment but also the volume of runoff. This also reduces transport capacity in the toe drain. The latter can also be achieved by increasing the hydraulic roughness or decreasing the gradient of the toe drain. However, the apparent technical simplicity of such measures indirectly stresses the fact that, in practice, improved soil management on Java's hillsides is also constrained by socio-economic issues [Purwanto, 1999]. Nonetheless, without a thorough understanding of the processes involved, debates on the effectiveness of proposed soil and water conservation measures will continue to prevent the necessary action being taken. The current research should prove useful in this respect, in that it clearly identifies patterns, processes and remedies.

6. ACKNOWLEDGEMENTS

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