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Runoff and soil loss from bench terraces in upland West Java, Indonesia and implications for process modelling

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Abstract The impact of bench terracing of steep tropical hillsides on runoff and sediment production is generally studied with bounded plots or the Universal Soil Loss Equation. As a preliminary to the modelling of runoff and erosion in this kind of artificially modified terrain this paper discusses an alternative approach which treats each backsloping terrace as a separate unit or "natural boundary erosion plot" (NBEP). The water and sediment outputs from two pairs of NBEPs were determined on a daily basis and compared with the corresponding amounts generated on the steep risers of the terraces. The terraces produced large amounts of runoff (up to 28% of rainfall) and sediment (up to 176 t ha^{-1} per rainy season), mainly from the riser and adjacent gutter sections. The implications of the present findings for the modelling of soil loss from bench terraces are briefly discussed.

INTRODUCTION

In response to the generally perceived, but as yet inadequately quantified problems of accelerated erosion, siltation and flooding on the densely populated island of Java a major reforestation and "regreening" programme was launched in the mid seventies (Pickering, 1979). As the programme developed, an increasingly large proportion of the budget was spent on the construction, rehabilitation and maintenance of check dams and bench terraces (Anonymous, 1989). The usefulness of the programme in reducing downstream floods and sediment loads has been questioned by some who considered that the relative contribution of geological erosion (e.g. landsliding in steep headwater areas, bank erosion) to overall stream sediment loads remained undervalued (Diemont *et al.*, 1991). Similarly, attention has been drawn to the allegedly large volumes of runoff and sediment generated on rural roads, trails and settlements (Rijsdijk & Bruijnzeel, 1990). Partly as a result of such observations, watershed management in Java is currently undergoing considerable revision in terms of assumptions and approaches. However, regardless of what the chief sources of the abundant sediment are in Java's rivers, without sound quantitative information the debate is bound to continue. More importantly, it will also be impossible to evaluate the effectiveness of costly soil conservation programmes. With these questions in mind the Cikumutuk Hydrology and Erosion Research Project (CHERP) was initiated in late 1994 in the volcanic steeplands around Malangbong, West Java. The project is a joint effort of the Indonesian Ministry of Forestry and the Vrije Universiteit Amsterdam (VUA). The main objective of the first phase of the project (1994–1997) is to collect baseline data on catchment sediment yield and runoff response, on-site erosion and sediment delivery at different levels of scale for the prevailing land use and soil conservation setting. A second phase (1998–2001) will deal with the impacts on runoff and sediment yield of various conservation methods at the plot- to sub-basin scale (Bruijnzeel & Purwanto, 1997). This paper discusses the application of a new technique for the measurement of runoff and sediment yield from backsloping bench terraces (Bruijnzeel & Critchley, 1996) in the heavily eroding Cikumutuk catchment as a preliminary to the modelling of erosion processes under artificially modified topographic conditions. The implications of the present findings for soil conservation and watershed management are discussed by Purwanto & Bruijnzeel (1998), respectively.

QUANTIFYING RUNOFF AND EROSION ON BACKSLOPING TERRACES

The most widely used procedure for measuring runoff and surface erosion on fields with low, uniform gradients and homogenous vegetation cover is to use some version of the conventional bounded plot (Wischmeier & Smith, 1978). However, narrow reverse sloping rainfed bench terraces in steep tropical terrain present a very different situation and there is as yet no standard method of quantifying hydrological and erosion processes under such conditions (Hudson, 1995). Bruijnzeel & Critchley (1996) discussed the problems associated with the use of small bounded plots and zero-order basins in bench terraced steeplands. They proposed an alternative approach, the "natural boundary erosion plot" (NBEP), which comprises a single backsloping terrace unit with its actual hydrological boundaries. Whilst these may not be "natural" in the literal sense of the word, the boundary is constructed by the farmer and not artificially imposed by the researcher. An NBEP unit consists of a

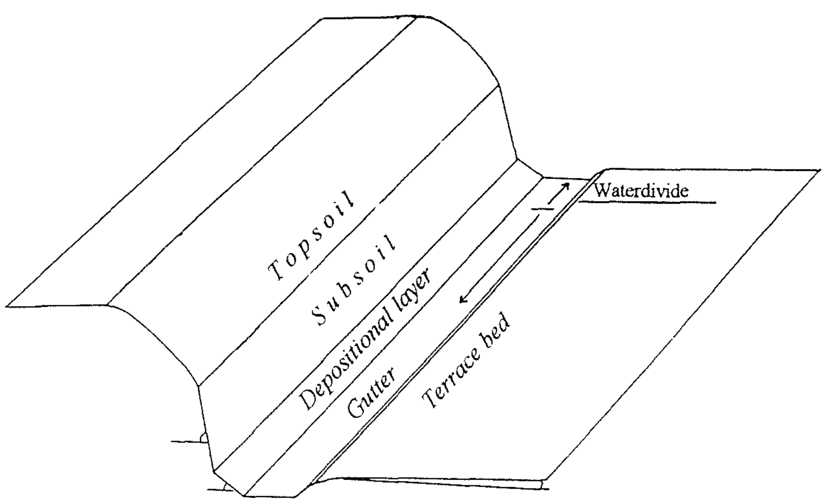

Fig. 1 Schematic representation of a reverse sloping bench terrace.

terrace bed and its adjacent upslope terrace riser, with the drain located at the foot of the riser. Runoff and eroded material can be monitored conveniently at the outlet of the drain (Fig. 1). The chief drawback of the NBEP approach is that there is no "standard" sized NBEP. Each terrace has its own dimensions, depending on slope gradient and morphology, and therefore its own sediment delivery factor (Bruijnzeel & Critchley, 1996). In addition, the dimensions of an NBEP may vary between consecutive rainy seasons because of changes in the gradient of the toe-drain related to the redistribution of soil material. This may be brought about by farming operations (e.g. hoeing of the beds or cleaning the risers) or by peak rainfall events causing the risers to slump. As a result, comparisons between NBEPs will always need to be made with care. On the other hand, there is no disturbance to the land or crop, and there are no edge effects caused by the placing of artificial plot boundaries.

If knowledge of the source of the runoff and eroded material within the plot is required, the NBEP can be equipped with additional instrumentation. However, the separate, yet synchronous measurement of runoff and sediment produced by the terrace riser and the terrace bed poses logistical problems if the measurements are made on one and the same NBEP whose integrated output is being monitored as well. Such problems relate mainly to interference with the runoff process through compaction of access trails to installations within the plot, or runoff collectors installed to catch the runoff from a specific part of the NBEP blocking the flow from another part. Therefore, an intermediate approach was followed by the present study. Runoff and sediment produced by the risers were measured on an event basis on nearby terrace units having similar dimensions to the NBEPs under study, using collecting troughs inserted into the riser face (Critchley & Bruijnzeel, 1995). A more extensive approach was followed at the NBEPs themselves where riser dimensions were determined repeatedly in combination with the reading of a large number of erosion pins. In this way, disturbance of the NBEPs was kept to a minimum while retaining the possibility of drawing up a sediment budget.

STUDY AREA

The 105 ha study basin is located about 55 km ESE of Bandung at an elevation of 575–750 m a.m.s.l. on the northwestern footslopes of Mount Cakrabuana (1721 m) in the headwaters of the Cimanuk River basin (Fig. 2). The area receives an average annual rainfall of *c.* 2370 mm (Malangbong, 1971–1987) distributed over about 125 rain days. Rainfall is generally less than 100 mm per month in June, July and August. The soils are "reddish brown latosols" which have developed in Holocene andesitic volcanic ashes and Pliocene/Pleistocene andesitic breccias. The soil profile consists of a fine sandy loam (30–70 cm thick depending on slope steepness) overlying a clay loam which grades into a massive silty clay at *c.* 120 cm depth. Almost 80% of the basin is covered by rainfed bench terraced fields (*tegal*) that are mostly used for the mixed cultivation of hill rice, maize and cassava (rainiest months: November–Februry), followed by groundnuts, maize and the remaining cassava (using residual moisture: March–June). Irrigated rice fields (*sawah*) occupy about 15%, mostly in the valley along the main stream while the remaining 6% are made up by residential areas (including homegardens). Most of the homegardens and *sawah* are privately owned but for historical reasons the ownership status of the majority of the rainfed fields is unclear. The ensuing insecurity of land tenure constitutes one of the main obstacles to investments in soil conservation measures. The 1.1–1.7 m long riser faces of the terraces are kept bare to prevent the development of pests whereas the only conservation measures practised currently is to leave some of the harvested material on the site or, occasionally, to dig silt traps at the outlet of the toe drain (Purwanto & Bruijnzeel, 1998).

METHODS

As part of a "nested" set-up for the study of runoff and sediment yield at

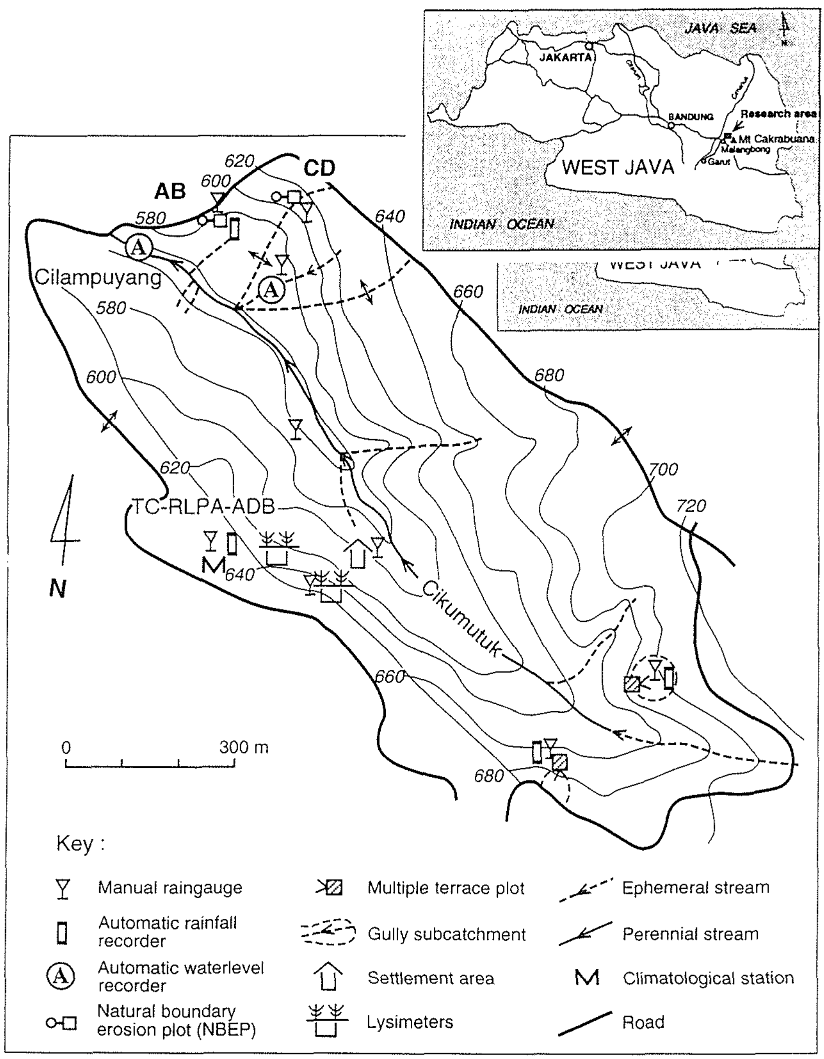

Fig. 2 Location and instrumentation of the study catchment.

Table 1 Basic characteristics of four "natural boundary erosion plots" in the Cikumutuk basin, West Java.

Terrace	Bed area* (m^2)	Riser area (m^2)†	Total plot area (m^2)	Fraction occupied by riser‡
A	133	50/40	187	0.27/0.21
B	98	34/25	136	0.25/0.18
C	19	34/26	54	0.63/0.48
D	27	43/31	70	0.62/0.45

* Excluding toe-drain.

† Expressed as riser face area and projectional area, respectively.

‡ Expressed as the ratio of actual and projected riser surface area, respectively, to total projected plot area.

progressively larger levels of scale (Bruijnzeel & Purwanto, 1997), two complexes of backsloping bench terraces were selected for the construction of NBEPs (Fig. 2). Two NBEPs (A and B) were built on a relatively gentle slope (original gradient 8–10°) and an additional two (C and D) on a steeper slope (original gradient 20–22°). The basic characteristics of the four NBEPs are listed in Table 1. Terrace risers make up *c.* 20–45% of the total plot area (depending on original slope gradient) on a projectional basis. Expressed as riser face area, these figures may increase to more than 60% on the steeper slopes (Table 1). Adding the (projected) areas of the toe-drains would raise the respective fractions by another 8 and 16%, respectively.

Rainfall was measured daily at each terrace pair using a standard raingauge placed at 1.5 m to avoid rain-shadow and surface splash effects. The four terrace units were drained via a concrete 90° V-shaped inlet into a 210-l capacity stilling basin in which coarse material could settle. The stilling basins had a divider system allowing one-fifth of the excess runoff to be drained into a first collecting drum of 180-l capacity. The latter, in turn, was equipped with a divider system discharging one-seventh of the excess runoff into a second collecting drum of 200-l capacity. All collecting devices were covered against rainfall. Measurements of runoff volumes were made the morning after each event using a graduated yardstick and converting water levels to volumes by pre-determined conversion equations. Depth-integrated 0.5–1.5-l samples were taken from the stilling basin and, where necessary, from the collection drum(s) for the determination of the concentration of sediment in suspension. The water in the drums (but not in the stilling basin) was stirred thoroughly before sampling. The volume of any coarse material that had settled in the stilling basin was determined separately after gradually draining off the supernatant water after which a 100 cm^3 core sample was taken for the volume to weight conversion. All collectors were cleaned after sampling was completed. Concentrations of sediment in suspension were measured by filtration through pre-weighed "Melita" coffee filters, oven-drying the residues at 105°C for 24 h and weighing to the nearest 0.0001 g. A comparison of sediment concentrations in streamflow obtained with the paper filter method and 0.45 μm Millipore filters suggested an underestimation of 3–6%. The present data were adjusted accordingly. It is possible, however, that this represents an underestimate because of the presence of finer particles in the collected runoff compared to the streamwater.

During the 1995/96 rainy season, riser erosion was estimated using 370 erosion pins (5 mm diameter, length 50 cm) inserted horizontally into the riser. Four pins were used per metre of riser length which were read five times between

10 November 1995 and 24 April 1996. On three occasions, the dimensions of the risers were measured as well to allow the computation of the volume of soil eroded between these two dates. A number of benchmark pins installed vertically at the top of the risers and connected by horizontal wiring facilitated the measurement of terrace dimensions. The lowermost pins stuck out 100 mm to allow the quantification of deposition of loose material at the foot of the riser. Finally, the rate of gutter fill-up by eroded material was monitored separately. Because the precision with which the pins could be read was *c.* 1 mm at best, an uncertainty of 0.8–0.9 kg m^{-2} was implied per reading given the prevailing bulk density of 0.8–0.9 g cm^{-3}. Separate observations of terrace bed erosion were not begun until the 1996/97 rainy season and will not be considered further.

RESULTS

Rainfall, runoff and sediment yield totals for the four NBEPs during the main part (November–April) of the 1995/96 rainy season are listed in Table 2. Overall runoff response was very similar for the two plots on the steeper slope (terraces C and D), with an average runoff coefficient of 0.28 for both. The runoff response was more variable for the two NBEPs on the gentler slope (A and B), with average runoff coefficients of 0.16 and 0.26, respectively (Table 2). One possible reason for this discrepancy could be related to the fact that the riser of terrace B was both shorter (less high) and narrower (on a projectional basis). Exfiltrating throughflow from the riser face, as has been reported for terraces in central Java by Bruijnzeel & Critchley (1996), was not observed. Despite the difference in overall response, daily runoff totals for the two terraces were fairly well-correlated (R-squared 0.78). To examine to what extent such differences in runoff response between adjacent plots might be related to potential differences in runoff contributions by the riser and gutter areas of the respective terraces, runoff totals were also expressed as a fraction of the latter areas (on a projectional basis; cf. Table 1). If the resulting "riser cum gutter runoff coefficient" (RGRC) would be less than unity, then this could be taken as evidence that all the runoff could be provided (at least in theory) by the riser cum gutter area. If, on the other hand, the value of the RGRC would exceed unity, then contributions

Table 2 Rainfall, runoff and sediment yield totals for four "natural boundary erosion plots" during the 1995/96 rainy season (1 November–30 April) in the Cikumutuk basin, West Java.*

Terrace	Rainfall (mm)	Runoff (mm)	Runoff (%)	Sediment yield: NBEP (kg m^{-2})†	Riser (kg m^{-2})†	Riser (%)‡
A	2318	381	16	9.6	28.8	70
B	2318	591	26	10.9	35.8	67
C	2218	621	28	16.0	28.7	88
D	2218	613	28	17.6	32.1	83

* Quoted figures differ somewhat from the ones given by Purwanto & Bruijnzeel (1998) due to the use of a different measuring period and slight differences in plot size. The present values should be regarded as final.

† Expressed per m^2 of projected total plot and riser areas, respectively.

‡ Sediment input from riser (kg) expressed as a percentage of total soil loss (kg) for the period 11 November 1995 until 30 April 1996.

from other parts (notably the terrace bed) would be required. On a seasonal basis, the RGRC for terraces D and C was about 0.45 *vs* 0.57 and 0.93 for terraces A and B, respectively. This finding lends some support to the contention that the majority of the runoff is generated on the riser cum gutter area. These values were raised to *c.* 0.53 (terraces C and D), 0.63 (terrace A) and 1.02 (terrace B) when including only the rainfall of runoff generating events (2114 and 1868 mm for the lower and upper group of terraces, respectively). In about 20 and 10% of the events, runoff contributions from outside the riser cum gutter area were inferred for storms larger than 40 and 60 mm on the lower and upper group of terraces, respectively. Further support for the above contention comes from the fact that the relationships between daily rainfall and runoff did not show major changes as the wet season progressed. If the terrace beds were a major supplier of runoff, then the marked changes in plant cover occurring on the beds throughout the harvesting cycle would have certainly shown up.

The sediment yield data in Table 2 illustrate the fact that surface erosion on back-sloping bench terraces in humid tropical volcanic steeplands can still be unacceptably high. The cumulative pattern of soil loss from terraces A and C (Fig. 3) exhibited a relatively steep beginning, followed by a gradually less steep intermediate section and a much flatter final part. This pattern recurred on all four plots and is thought to reflect, respectively, the presence of readily available material for transport at the beginning of the rainy season, the gradual protection of the surface by residual coarse particles (on the risers) and the growing crops (on the beds), and the mulching effect of leaving coarse harvesting residue (such as corn stalks) behind in the drainage gutter (cf. Purwanto & Bruijnzeel, 1998). The volcanic soil of the study area tends to form small aggregates (size distribution peaking at 0.8–2 mm) upon drying which were seen to accumulate at the foot of the risers during rainless spells. A comparison of aggregate size distributions of *in situ* topsoil and subsoil riser material, material deposited at the foot of the riser, and sediment retrieved from the stilling basins of the NBEPs suggested that (a) the bulk of the eroded aggregates derived from the topsoil part of the riser and (b) the coarse material leaving the terrace unit closely resembles that found at the foot of the riser.

To examine the idea of the terrace riser being the chief source of eroded soil more quantitatively, the overall seasonal sediment losses from the NBEPs were compared with the corresponding amounts generated on the risers as evaluated from the erosion pin and riser dimension measurements (Table 2). The erosion intensity on the unprotected terrace risers was very high (28.8–35.8 kg m^{-2} projected). As a result, the amounts of sediment produced by the risers of the two NBEPs on the steeper slope (C and D), where the risers made up almost half of the total terrace area (Table 1), equalled 83–88% of the seasonal soil loss. Even on terraces A and B (where the risers constituted a smaller fraction of the total plot; Table 1), riser erosion potentially contributed 67–70% of the total soil loss (Table 2). The quoted percentages become even more impressive if the volumes of freshly eroded riser material that went into storage in the drainage gutter (8–13% at A, B; 2–6% at C, D) are added. Although pin-based estimates of riser erosion are admittedly crude, they are nevertheless of the same order of magnitude between terraces (Table 2). Work is currently in progress to refine the above estimates using more sophisticated techniques to determine the volumes of runoff and sediment produced by the risers on an event basis (Critchley & Bruijnzeel, 1995).

IMPLICATIONS FOR PROCESS MODELLING

The artificial character of backsloping terraces presents problems to the modelling of runoff and soil loss from terraced hillsides. In simple empirical models like the Universal Soil Loss Equation (USLE) an attempt has been made to account for the effect of terracing by assuming a slope length factor (*LS*) based on the terrace

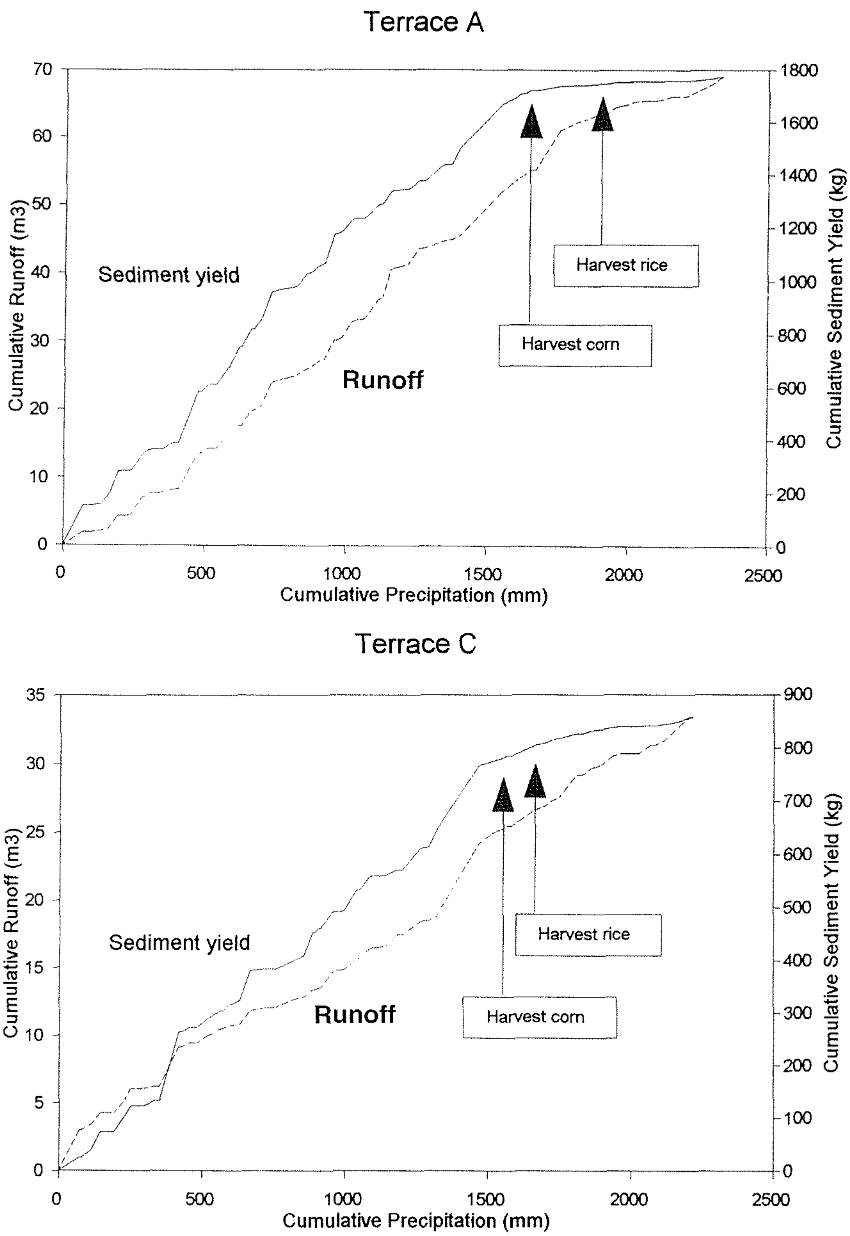

Fig. 3 Cumulative runoff and soil loss patterns *vs* rainfall between 1 November 1995 and 30 April 1996 at two terraces (A and C) in the Cikumutuk basin, West Java.

interval and the gradient of the terrace bed, in combination with the use of the "contour cultivation" value for the "support practice" factor (*P*). However, this method is only suitable for slopes up to 25% (Wischmeier & Smith, 1978). As shown by the data in Table 2, the erosion control measure (terracing) may also become an erosion hazard in itself. This, of course, is not reflected in the USLE approach. Within the more recently developed "Revised USLE" (RUSLE, Renard *et al.*, 1995), the effect of terracing is taken into account via a specific subfactor whose value depends on the gradients of the terrace bed and toe-drain. However, height, slope angle and condition of the terrace riser are not included as controlling variables.

More physically-based erosion models combining the unit stream power concept with a digital elevation model (DEM) of the hillside (e.g. Vertessy *et al.*, 1990) also run into problems when applied to backsloping terraces where runoff is flowing in the reverse direction of that indicated by the DEM. Arguably, a solution would be to treat each individual backsloping terrace as a micro-catchment consisting of a very steep slope (the riser face) and a much flatter slope (the terrace bed) which both contribute water and sediment to a central drainage (the gutter; Fig. 1). Modelling soil erosion and deposition on the terrace bed and gutter sections would then present no specific problems compared to "ordinary" hillslopes. However, the steep nature of the riser, where soil removal is likely to be dominated by rainfall detachment without subsequent deposition on the riser face itself (only later in the gutter), will require adaptation of currently used models describing soil loss from much flatter slopes (e.g. Rose, 1993). Also, the contrast in width of the three main terrace elements poses problems with the application of distributed models using a fixed grid cell size. If the width of the toe-drain (typically 30–40 cm) is taken to define the size of the grid cell, then a very large number of cells will be required to cover the much wider (up to 4 m) beds in the case of the 20–30 m long terraces of the study area. This, in turn, leads to excessive computer-user time requirements and it may be advisable to use contour-based (e.g. TOPOG; Vertessy *et al.*, 1990) rather than grid-based distributed models (e.g. ANSWERS or LISEM; De Roo *et al.*, 1996) to describe the water and sediment outputs from individual terraces. Upscaling the latter to the entire drainage basin using distributed models is still a long way off, considering also such complicating factors as the presence of sediment trapping irrigated rice terraces in the central valley bottom, the role of residential areas and other compacted surfaces like trails in generating and routing runoff, etc. Therefore, more empirical approaches linking seasonal sediment loss per terrace to terrace size or width (which may be themselves derived from a DEM) or to the fraction occupied by the riser cum gutter section may be used for the time being.

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