42 A New Approach towards the Quantification of Runoff and Eroded Sediment from Bench Terraces in Humid Tropical Steeplands and its Application in South-Central Java, Indonesia

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42.1 INTRODUCTION

Rainfed smallholder cultivation on the densely populated island of Java (Indonesia) started to expand onto steep forested slopes as early as the 19th century (Palte 1989). More than a century later, Pickering (1979) summarized the overall environmental situation on Java as follows:

> Thus, soil fertility is reduced; hydrological balances are disturbed; springs dry up or have diminished discharges; less water is available for irrigating the plains and lower slopes; and there is a steady increase in both the frequency and size of floods and in the silting up of rivers, irrigation channels and reservoirs.

In response to these generally perceived, but often inadequately quantified problems, a major reforestation and "regreening" programme was launched by the Indonesian Government in the mid-1970s in 22 large "critical watersheds" mostly situated in Java and Sumatra. Reforestation is mainly carried out on state-owned land managed by the Forest Department whereas the "regreening" part of the programme concerns private land, especially on slopes above 50%. 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 regreening programme in reducing downstream stream sediment loads has been questioned by some who consider that the role of geological erosion has been seriously underestimated (Diemont *et al.* 1991). Clearly, without identifying and quantifying the sources of stream sediment in specific catchment areas it is impossible to evaluate the need for (or the effectiveness of) expensive soil conservation programmes.

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A start was made to address some of these questions under the umbrella of the 1992–1995 collaborative "Tropical Steeplands Project" between the Vrije Universiteit Amsterdam, The Netherlands, and Gadjah Mada University, Yogyakarta, Indonesia. Research under the project embraced several aspects of erosion and sediment delivery within the 12.5 km^2 Kedungkeris catchment, Gunung Kidul district, Yogyakarta Province, South-Central Java. Part of the research was focused on developing suitable techniques to quantify amounts of runoff and sediment from steep bench-terraced hillsides. A basic description of the methodology used by the project and some preliminary results obtained for the 1993/1994 rainy season were given by Critchley and Bruijnzeel (1995a). The present chapter describes the experimental plots and techniques in more detail and gives the final results. In addition, the pros and cons of the methodology and the implications of the present findings for tropical watershed management programmes are discussed.

42.2 MEASURING EROSION FROM TERRACES: PRACTICE AND PROBLEMS

The most widely used procedure for measuring runoff and surface erosion on fields with low gradients is to use some version of the conventional "Wischmeier" plot, originally developed in the USA for large fields with a uniform slope and a homogeneous vegetation cover (Wischmeier and Smith 1978). However, narrow rainfed bench terraces on a steep slope present a very different situation and there is as yet no standard reliable method of quantifying runoff and erosion processes in this kind of terrain (Hudson 1995). If a standard bounded 22.1 m plot is aligned downslope it will usually transect two or more terraces (depending on slope steepness and therefore terrace width). In doing so the plot will cross several terrace banks (or "risers") and drainage ways as well. Where terraces have lateral drainage paths – as is the case with the backsloping bench terraces typical of large parts of southeast Asia – a conventional plot with artificial side boundaries only serves to interrupt the drainage way, thereby interfering with the normal processes. The result is that such a plot may only collect runoff and sediment from the lowest terrace bed, and so give artificially low values (Rijsdijk and Bruijnzeel 1990). An additional problem is that an artificially bounded plot tends to get in the way of farming operations and this may influence the results as well, even when the boundaries are removed temporarily during the operation.

An alternative to the conventionally sized erosion plot is to reduce its dimensions drastically so that it can be accommodated on the flat of a single terrace bed. Such tiny plots (say, 1 × 3 m or 2 × 4 m; Coster 1938) may be useful when comparing the *relative* effect on runoff and erosion of agronomic treatments (e.g. mulching versus none) but they are clearly unsuitable for predicting runoff or erosion from the terraced unit as a whole. Not only is it difficult to align these plots in the direction of the overland flow, but more importantly they exclude contributions from the terrace riser which may be a significant source of sediment (Critchley and Bruijnzeel 1995b). Alternatively, one could monitor the runoff and sediment yield for a zero- to first-order bench-terraced catchment and so derive the net sediment production from a group of terraces. Because such areas would often be at least several hectares in size, the associated volumes of runoff and sediment that need to be handled require a streamflow gauging structure plus automated equipment for measuring water levels in the channel as well as samples for the collection of sediment carried in suspension. In addition, a device may be needed to measure bedload transport. Whilst this technique has been used successfully to compare conservation treatments (including terracing) on small tropical agricultural catchments (Amphlett 1989), the approach may require the quantification of within-channel contributions to overall sediment transport. In addition, the larger the size of the gauged catchment, the more numerous the opportunities for eroded sediment to move into (temporary) storage (Walling 1983).

In view of these difficulties, many tropical researchers have resorted to a simple theoretical calculation of erosion rates using the Universal Soil Loss Equation (USLE) (El-Swaify *et al.* 1982). Whilst attempts have been made to adjust the USLE for use under humid tropical conditions (Roose 1977; Bols 1978; Wood and Dent 1983; Harper 1988) there is no specific basis in the model to account for the effect of backsloping bench terraces in steep landscapes (Hudson 1995). The conventional method of calculating soil loss through the USLE for terraced land involves the assumption of a slope length factor (*LS*) based on the terrace interval and 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 of up to 25% (Wischmeier and Smith 1978). In steep to very steep terrain, where terrrace risers may reach several metres in height, the erosion control measure may take up a significant portion of the landscape and so becomes itself an erosion hazard (Critchley and Bruijnzeel 1995b). This, of course, is not reflected in the traditional 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 is dependent on the gradients of the terrace bed and toe-drain. Height, slope and condition of the riser section are not included as controlling variables. According to Renard (1995), of all the RUSLE factors, values for the *P* factor are the least reliable. The RUSLE is currently being tested for use in steep terraced terrain in Taiwan (Foster 1995) where terrace risers usually consist of stone walls and are therefore well protected (C. S. Ting, pers. comm.). However, the data on sediment production from unprotected terrace risers that would be required to calibrate the model for the conditions prevailing in so many tropical steepland areas, are largely lacking. It is in this context that the concept of the "natural boundary erosion plot" (NBEP) may prove useful.

42.3 THE "NATURAL BOUNDARY EROSION PLOT"

The concept behind the NBEP has its origins in methodology developed for measuring runoff and sediment yield from residential areas and footpaths in the Konto area, East Java (Rijsdijk and Bruijnzeel 1990). In contrast to the standard bounded runoff plot, the NBEP approach uses a single terrace unit with its actual boundaries. Whilst these may not be "natural" in the literal sense of the word, the boundary is constructed by the farmer and not artificially determined by the researcher. As shown in Figure 42.1, the NBEP unit comprises a terrace bed and its associated upslope terrace riser. The total area of a "typical" terrace unit in this part of Java varies between locations as a result of differences in slope but usually ranges between 50 and 500 m^2 (Critchley and Bruijnzeel 1995b). The drain of such a backsloping bench terrace is located at the foot of the riser. Runoff, and eroded material, is channelled out of the individual terrace unit along the drain and can be monitored conveniently at the outlet (Figure 42.1). Depending on resources, amounts of runoff and sediment carried in suspension can be measured at various levels of sophistication. These range from employing volumetric techniques for measuring discharge (facilitated by the installation of a small V-notch at the outlet of the drain) and manual sampling using locally recruited assistants, to the automated set-up mentioned earlier for zero- to first-order catchments. As described in more detail in the next section, an intermediate level of sophistication was chosen by the Tropical Steeplands Project which involved the installation of a stilling basin equipped with a V-notch, pipe divisor systems and collection drums.

Naturally, measuring the bulk outputs of water and sediment from an NBEP does not provide information on the source of the eroded material within the plot. Knowledge of the latter is important because of the large contrast in agricultural production potential between terrace bed and riser. This has led to the development by the project of another specific methodology to measure the amounts of runoff and sediment generated by the terrace riser. Basically, a set of removable metal troughs are attached to the foot of a terrace riser via a metal plate fixed into the riser. These "terrace riser troughs" collect both runoff (as well as direct rainfall) and sediment washed down or splashed from the riser face above it (Figure 42.1). As such, they are similar to the "subsoil fall traps" used on streambanks by Duijsings (1985). A basic description of the terrace riser trough technique and a discussion of some preliminary results on riser erosion as obtained for part of the 1993/94 rainy season have been presented by Critchley and Bruijnzeel (1995b).

42.4 MATERIALS AND METHODS

42.4.1 Study Area

The Kedungkeris catchment (7° 50′ SL; 110° 36′ EL) is located about 40 km southeast of the provincial capital of Yogyakarta in the South-Central part of Java (Figure 42.2). The steep (most slopes are 15°–25°) northern half of the catchment is largely underlain by the Nglanggran Formation which consists of the erosion-resistant andesitic breccias and lavas of Lower Miocene age forming the Baturagung Range (200–775 m a.s.l.). The gentler (5°–10°) southern slopes of the catchment constitute the domain of the Oyo Formation of Middle Miocene age, with its more erodible tuffaceous sandstones and marls (130–200 m a.s.l.; Rahardjo *et al.* 1977). Due to its somewhat sheltered position with respect to the rain bringing northwesterlies, the study area is relatively dry compared to the rest of Central Java. Annual rainfall in the central part of the study area is about 2050 mm, more than 75% of which falls during the period November–April (Sutrisman 1992). Both inter-annual and spatial variability of rainfall are high (MacDonald and Partners

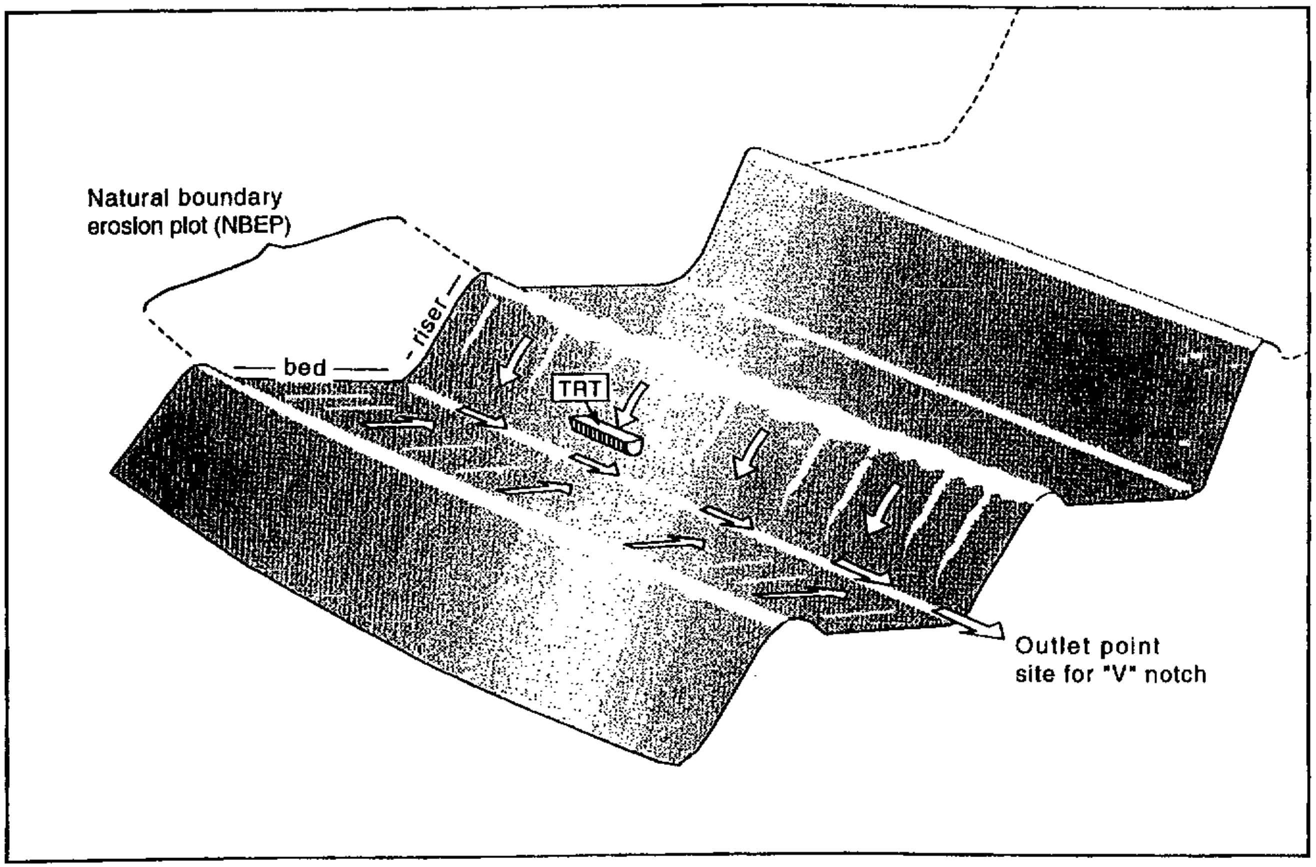

Figure 42.1 Schematic drawing of a Natural Boundary Erosion Plot with one terrace riser trough in place

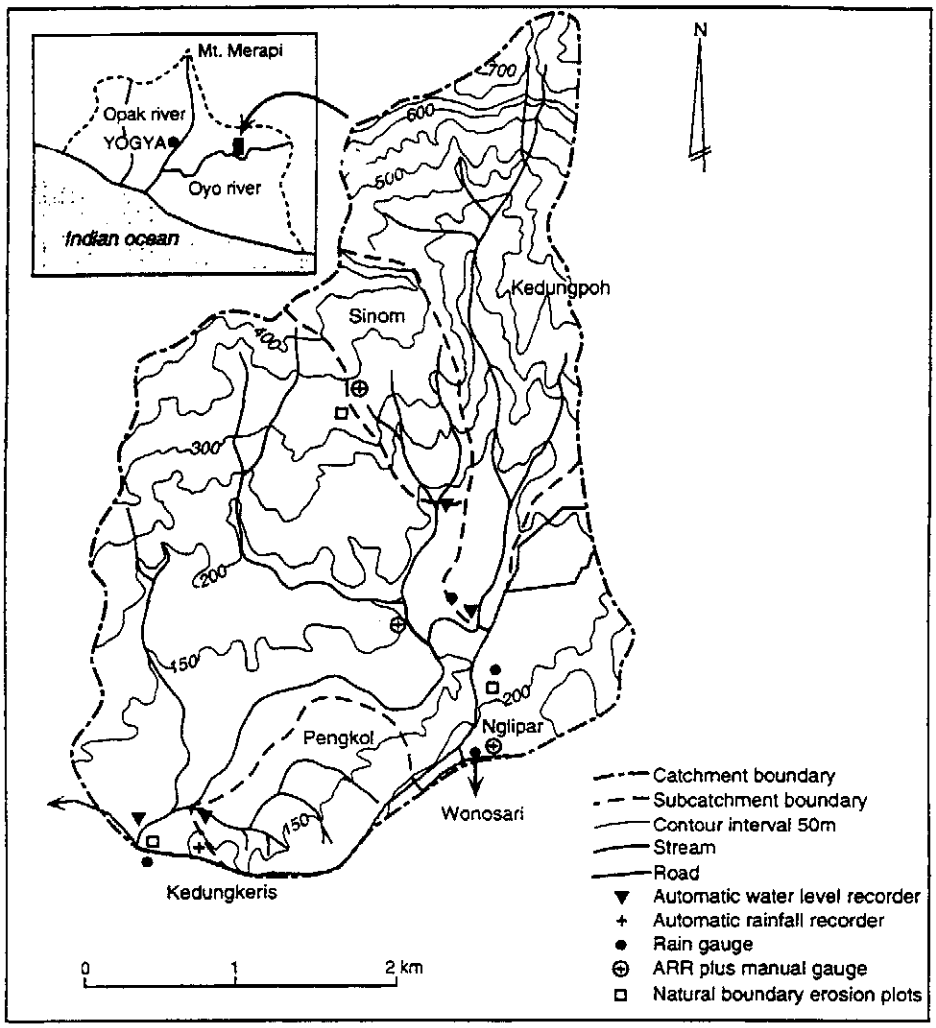

Figure 42.2 Location of study area

1984), with the upper reaches of the catchment being somewhat wetter than the lower parts due to orographic effects. The wettest months are January, February and March, when rainfall usually reaches 300 mm/month or more, whereas the period between June and October is distinctly dry, with most months receiving less than 60 mm each (MacDonald and Partners 1984).

Maximum 30-min rainfall intensities recorded at the height of the rainy season of 1993/94 (mid-January until mid-March) were generally less than 40 mm/h at Sinom (elevation 385 m a.s.l.) in the central upper part of the catchment. Only six out of 36 storms attained maximum intensities between 40 and 80 mm/h, and only during two of these was a value of 60 mm/h exceeded. Rainfall at Nglipar in the lower part of the catchment (elevation 180 m a.s.l.) was more intense, with 14 storms out of 41 having maximum 30-min intensities above 40 mm/h, half of which reached values of 60 mm/h or more.

The majority of the study area consists of rainfed farmland which has been terraced by the farmers themselves, and is planted typically with the annual crops of upland rice, maize, cassava and various legumes. As a result of the long dry season most arable land lies bare at the start of the rainy season. In combination with the fact that planting usually takes place about two to four weeks after the initial return of the rains (to minimize the risk of crop failure in case of a temporary withdrawal of the monsoon; Nibbering 1991), this makes for a potentially high erosion hazard during the early part of the rainy season.

The viability of the NBEP approach was explored during the 1992/93 rainy season at three locations within the study catchment, namely at Sinom, Nglipar and Kedungkeris. The Sinom site (original slope gradient 20°–25°) was considered representative of conditions prevailing in the central part of the catchment underlain by the breccias of the Nglanggran Formation. The Nglipar site (original slope gradient *c.* 10°) represented conditions associated with the tuffaceous marls and claystones of the Oyo Formation. On the basis of the soil textural and chemical information presented in Sutrisman (1992), the soils of the two plots were tentatively classified as Hapludalfs according to the US Soil Taxonomy System. Both soil profiles were truncated by erosion, the one at Nglipar even to the extent that it is classified as a Lithic Hapludalf. A third site (Kedungkeris), situated on the gentle footslopes near the outlet of the catchment and underlain by clayey Eutropepts of very low infiltrability, turned out to be less suitable for the new methodology because the occasionally forward-sloping terraces frequently overtopped, even during moderate rainfall intensities. As such the results obtained for the Kedungkeris site are not considered further. Two sets of three adjacent terraces were selected near the hamlets of Sinom and Nglipar for observations of runoff and sediment production, either at the scale of an entire plot (at Sinom High, Sinom Low and Nglipar Low) or the riser section alone (at Sinom Middle, Nglipar High and Nglipar Middle). Some basic characteristics of the respective plots are listed in Table 42.1. Terrace risers are seen to generally make up at least 10% of the total plot area, even on a projected area basis, and often much more (Table 42.1).

42.4.2 Plot Instrumentation

Rainfall at the two sites was measured daily using a standard rain-gauge with an orifice of 100 cm^2, placed at 1.5 m above the ground to avoid rainshadow effects of the surrounding crops (mostly cassava and maize, interspersed with low rice and legumes) or surface splash. In addition, SIAP 8100 UM rainfall recorders were installed next to the manual gauges at the Sinom site and at the Nglipar basecamp (about 300 m from the plot). The pluviograph at the rather remote Sinom site was equipped with a weekly chart having a time resolution of one hour whilst that at Nglipar had a daily clock and a time resolution of 10 min. A third manual guage was installed next to the recording gauge at the basecamp.

The three plots for which overall runoff and sediment production were to be determined (Table 42.1) were each equipped with a 100-litre capacity concrete stilling

Table 42.1 Basic characteristics of six "natural boundary erosion plots", Gunung Kidul, Java. All measured values have been rounded off to the nearest five, except for the slope of the toe drains

Plot	Bed area (m^2)	Riser area (m^2) (actual/ projected)	Riser height (m) and slope (degrees)	Fraction occupied by riser[a]	Slope of toe drain (degrees)
Sinom High[b]	110	60/20	1.65/70	0.15/0.35	2
Sinom Middle[c]	175	80/35	2.20/65	0.17/0.31	—
Sinom Low[b]	325	165/35	3.40/75	0.10/0.34	3
Nglipar High[c]	180	65/35	1.05/55	0.16/0.26	—
Nglipar Middle[c]	—	90/55	1.50/50	—	—
Nglipar Low[b]	450	65/50	1.50/40	0.10/0.13	1

[a] Expressed as the ratio of projectional and actual riser surface area, respectively, to total projectional and actual plot surface area.

[b] Used for measurements of runoff and sediment yield at the plot scale.

[c] Used for measurements of terrace riser erosion only.

basin to trap coarse eroded sediment. At the "upstream" end of the stilling basin a metal 90° V-notch blade was installed to facilitate entry of the runoff and to enable instantaneous measurements of discharge to be made if desired. At the "downstream" end of the stilling basin a 1:5 divider system was constructed using 7.5 cm diameter metal pipes. One-fifth of the runoff was thereby led to a 150-litre capacity collecting drum which also had a 1:5 divider system (made of 2.5 cm diameter metal pipes), one of which was connected to a second drum with a capacity of 200 litres. This basic set-up proved adequate for the Sinom High and Nglipar Low plots but not for the Sinom Low terrace where runoff volumes were much larger due to contributions by subsurface flow emanating from the riser during and after storms. Here the drum assemblage was replaced by a 2000-litre capacity concrete basin. To gain insight in the timing and duration of the (subsurface) flow at the Sinom Low plot, a Leopold & Stevens "Type F" water-level recorder (daily clock) was installed in the basin which was used to obtain a trace of the water level during a number of storms. Measurements of rainfall and runoff volumes were made in the morning after the event. Half-litre samples for the determination of the concentration of sediment in suspension were taken from the stilling basin and, where necessary, from the collection drum(s). 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 by syphoning. All collectors were cleaned after sampling was completed. The associated amounts were usually negligible. Concentrations of sediment in suspension were measured by filtering the samples through pre-weighed "Melita" coffee filters, oven-drying the residues at 105°C for 24 h and weighing them to the nearest 0.01 g. A comparison of concentrations obtained with this paper filter method and 0.45 μm Millipore filters for similar soils elsewhere in Java suggested an underestimation of up to 6% by the former (L. A. Bruijnzeel, unpublished data). No correction factor has been applied to the present data.

42.5 RESULTS AND DISCUSSION

42.5.1 Runoff

The three NBEPs under study (Sinom High, Sinom Low and Nglipar Low) were in operation between 21 November 1993 and 15 March 1994. Table 42.2 summarizes the rainfall and runoff totals as recorded for the respective plots. The total rainfall at the Nglipar site was close to the corresponding seasonal average value for the period 1979–1990 (1314 mm; Sutrisman 1992). Runoff response varied considerably between plots, even within one and the same group of terraces, as at Sinom. Here the average runoff coefficient for the lower terrace was twice that found for the uppermost terrace. Values for the Sinom sites were two to four times that of the Nglipar site, despite the fact that field and laboratory measurements of topsoil infiltration capacity (using the double-ring technique) and saturated hydraulic conductivity (constant head method), respectively, gave consistently higher values for the soils at Sinom compared to those at Nglipar. The overall runoff coefficient obtained for the Nglipar plot (0.12) was remarkably similar to values normally associated with rainfed broad-based terraces on volcanic soils elsewhere in Java (Coster 1938; Rijsdijk and Bruijnzeel 1990). The low runoff total at Nglipar is likely to be caused by the irregular surface of its terrace bed, which provided ample detention storage opportunities. Another factor may have been the presence of rice plants in the toe drain which tended to trap runoff (and sediment). The relatively high runoff coefficient obtained for the Sinom High terrace (0.24) is probably related to its comparatively small surface area (Table 42.1), in combination with a slightly steeper gradient of the terrace bed towards the toe drain than was determined for the other terraces (3° versus 1°–2°). The vegetation on the Sinom High terrace was similar to that for the nearby Sinom Low plot.

As shown in Figure 42.3, runoff volumes were reasonably well correlated with rainfall on an event basis for the Sinom High and Nglipar Low terraces (R^2 values of 0.55 and 0.59, respectively) but not at all for the Sinom Low site. Correlations improved markedly, particularly for the Sinom Low terrace, when events occurring in the first six weeks of the rainy season were excluded from the analysis. During the latter period the soils were hoed in preparation for planting. This, together with the much lower moisture contents of the topsoil, effectively increased the rainfall absorbing capacity of the surface, leading to the generally low response observed during this time of the year (Figure 42.3(c)).

Table 42.2 Rainfall and runoff totals, average runoff coefficients and net erosion rates for three Natural Boundary Erosion Plots, Gunung Kidul, Java, between 20 November 1993 and 14 March 1994

Plot	Rainfall (mm)	Runoff (mm)	Runoff coefficient	Net erosion (kg/m^2)
Sinom High	1585	375	0.24	0.87
Sinom Low	1585	772	0.49	2.40
Nglipar Low	1308	162	0.12	0.28

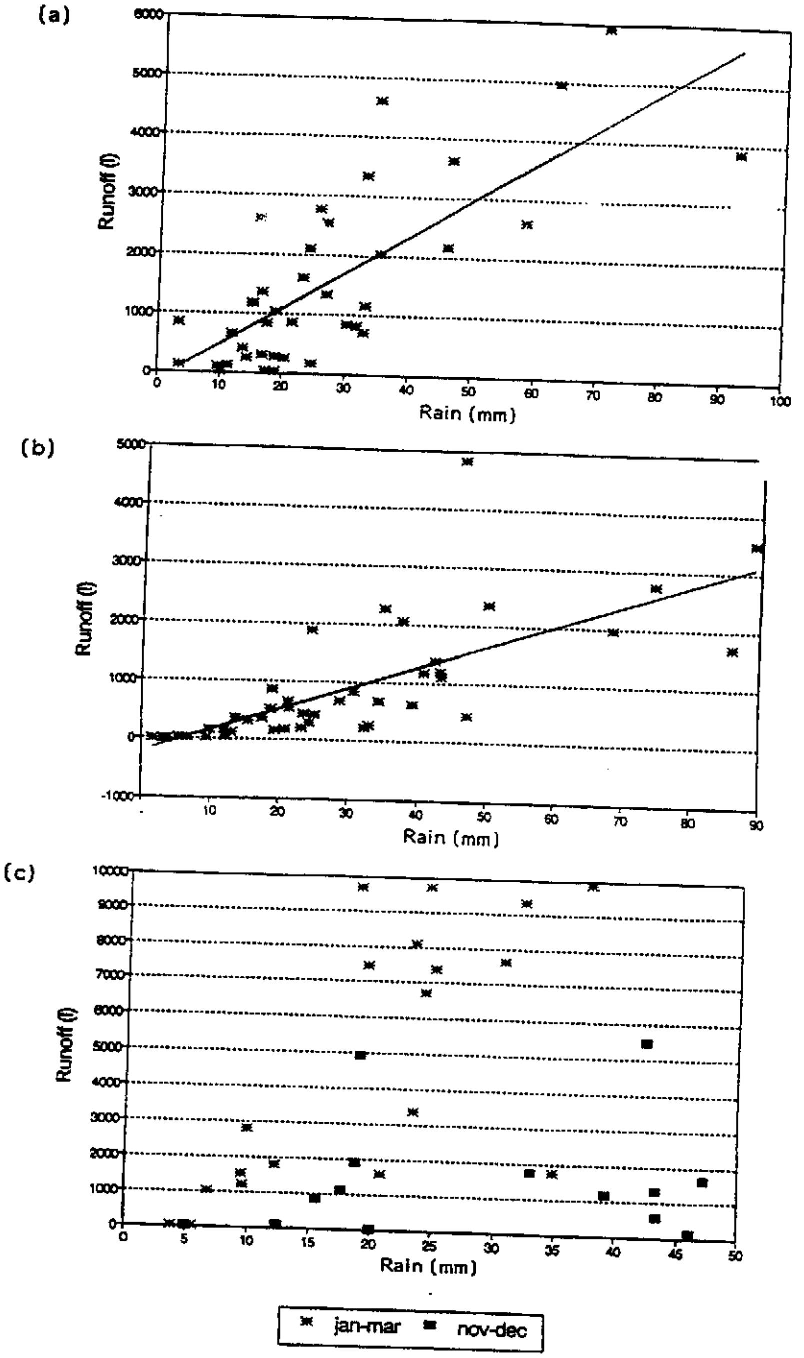

Figure 42.3 Relationships between rainfall (in millimetres) and runoff (in litres) at the three Natural Boundary Erosion Plots (21 November 1993–15 March 1994): (a) Nglipar Low; (b) Sinom High; (c) Sinom Low (■, events occurring in November–December; ✱, events occurring in January–March)

However, from late January onwards, the runoff response of the Sinom Low plot started to change, with high runoff coefficients occurring increasingly frequently (cf. Figure 42.3(c)), despite the almost complete crop canopy. Between 23 January and 13 March 1994, runoff volumes for 13 out of 37 storms even exceeded the corresponding inputs via rainfall. Throughflow was observed to discharge out of macropores in the riser face (especially towards the base of the riser) into the NBEP's toe drain at this location on many occasions and was undoubtedly responsible for the markedly high overall runoff coefficient obtained for the Sinom Low site (Table 42.2). The importance of throughflow (or "return flow"; Dunne 1978) to total runoff production at the site was confirmed by continuous measurements of the water level in the large collection basin of the Sinom Low terrace at the height of the rainy season. An example is given in Figure 42.4 for a composite storm event occurring on 29 January 1994 which delivered 68 mm of rain. During the event the electrical conductivity (EC) of the total runoff was measured on several occasions. By combining this information with previously established average values (which were assumed constant for the purpose of the exercise) for the EC of overland flow (*c.* 20 μS/cm) and return flow (*c.* μS/cm) at this site in a two-component mixing model (Pinder and Jones 1969), the relative contributions of subsurface flow to total runoff were estimated. As shown in Figure 42.4, runoff consisted entirely of overland flow during the first part of the storm but contributions by return flow became increasingly important during the second half and continued to produce runoff for several hours after the rain had stopped. The procedure was repeated for 22 events recorded between mid-January and mid-March for which a return flow component could be established. Subsurface contributions ranged from 23% to 89% of the total runoff, with values between 40% and 70% occurring most frequently. The maximum observed duration of subsurface flow was 28 h after the last rainfall.

Because the phenomenon did not manifest itself until about two months after the onset of the rainy season, one would have expected a dependency of subsurface flow contributions on antecedent moisture conditions in the soil. However, the regression equation linking the two variables had a very low coefficient of determination ($R^2 = 0.13$) although its (positive) slope differed significantly from zero at the 95% level.

No subsurface contributions were observed at the almost adjacent Sinom High terrace, although the phenomenon was observed on several other terraces at the same elevation as (or slightly below) the Sinom Low terrace. This finding highlights the problem of selecting truly "representative" sites. Subsurface flow occurred occasionally at the Nglipar Low plot as well, mostly in small quantities and only after the three-day antecedent precipitation index (API, using a k value of 0.88; Shaw 1988) had exceeded a value of 50 mm.

Nevertheless, the results obtained for the Sinom Low plot point to an important aspect which seems to have been largely overlooked in soil conservation circles: the construction of bench terraces in shallow soils (as often found in degraded tropical steeplands) can interfere with subsurface drainage pathways. As will be shown below, the "return flow" that is produced in this way adds to the overall erosion hazard by increasing the efficiency with which the sediment is removed from the terraces. This stands in contrast to the more general finding that subsurface drainage

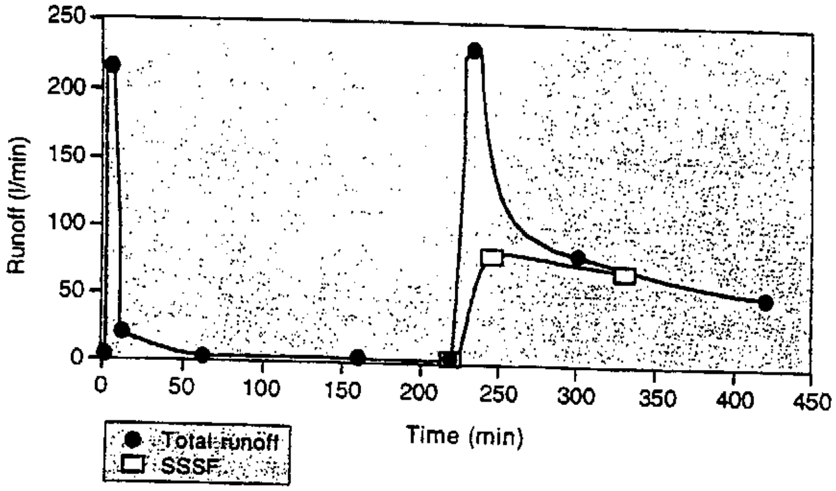

Figure 42.4 Total runoff and the contribution by subsurface stormflow (SSSF) versus time at the Sinom Low terrace on 29 January 1994. Discharge values are in litres per minute

of agricultural fields seems to be effective in reducing overland flow and erosion (Renard 1995).

42.5.2 Sediment Production

Whilst the runoff coefficients for the Sinom High and Sinom Low terraces were two and four times that obtained for the Nglipar plot, corresponding amounts of sediment per unit area were three and almost nine times as high, respectively (Table 42.2). Per unit amount of runoff, the Sinom Low terrace lost on average about 35% more sediment than its upslope counterpart, and about 75% more than the Nglipar Low plot. There can be little doubt that the presence of subsurface return flow (cf. Figure 42.3) and a slightly steeper toe drain (Table 42.1) at Sinom Low are responsible for this. At 0.28 and 0.87 kg/m^2, the seasonal net erosion rates for the Sinom High and Nglipar Low plots are low by Javanese standards (Carson 1989), whereas the 2.40 kg/m^2 obtained for the Sinom Low terrace is similar to values that have been reported for (single) broad-based forward-sloping terraces on volcanic ash soils elsewhere in Java (Rijsdijk and Bruijnzeel 1990), which tend to be more erodible than the soils of the study area (Ambar and Wiersum 1980; El-Swaify *et al.* 1982). Interestingly, seasonal soil losses as calculated with the USLE were within 10% of the measured values for the Sinom High and Nglipar Low terraces (if an arbitrary value of 0.3 was used for the *P*-factor) but net erosion at Sinom Low was underestimated by about two-thirds.

However, this apparent agreement between measured and USLE-predicted soil loss assumes a different perspective once the erosion that actually occurs within the plots is taken into account. Although seasonal totals of riser erosion are not yet available, detailed observations for the period mid-January until mid-March 1994 suggested average riser erosion rates of 8.49 ± 0.88 (SE) kg/m^2 (riser face area) at Nglipar and 5.37 ± 1.57 kg/m^2 at Sinom Middle (W. R. S. Critchley and L. A. Bruijnzeel, unpublished). The difference between the two sites mainly reflects the contrast in material exposed in the respective plots. Although the height and slope of the risers at Sinom were greater than those at Nglipar (Table 42.1), the effect is apparently compensated by the fact that about half the riser face at Sinom consisted of relatively resistant rotten rock, whereas at Nglipar the material was soft throughout. Terrace riser erosion intensities were measured simultaneously at both Sinom Middle and Sinom Low during two weeks in January–February 1994. Values obtained for the riser at the Sinom Low terrace were on average 70% of those determined for the riser of the Sinom Middle terrace (Critchley and Bruijnzeel, unpublished). Multiplying the average values for riser erosion intensity by the respective riser face areas (Table 42.1) enables a first estimate to be made of overall sediment production by the risers of the three NBEPs (Table 42.3). A comparison of the resulting volumes of sediment generated by the risers with the amounts that actually left the plots during the same period shows that the former exceeded the latter at two out of three plots (Table 42.3).

The low value of the sediment delivery factor at the Nglipar Low plot (11%) probably reflects the dense cover of rice plants in the shallow toe drain that has been referred to already. Together with the low gradient of the latter (Table 42.1) this proved effective in trapping most of the sediment gathered by the risers. Smaller riser failures were occasionally observed elsewhere in the erodible deposits of the Oyo Formation but did not occur on the risers studied by the project. However, the Nglipar Low terrace lost about 750 kg of riser material to its adjacent downslope terrace in a single failure during a heavy storm in February 1994. The damage was repaired by the farmer on the following day and as such did not constitute a loss to the plot. Nevertheless, such events illustrate the importance of spatial and temporal variability in riser erosion and can easily dwarf the amounts of sediment generated by surface erosion processes as monitored by the terrace riser troughs. The fact that the net output of sediment from the Sinom Low terrace exceeded the overall contributions by the riser by about 10% (Table 42.3) must be ascribed largely to the higher transporting capacity of the runoff here. The latter, no doubt, mainly reflects the extra contributions of runoff by subsurface flow, possibly with a minor effect of the slightly steeper toe drain (Table 42.1). Although some erosion from the terrace bed is theoretically possible, it is more likely that the discrepancy between sediment

Table 42.3 Riser erosion, net sediment yield and sediment delivery fraction for three Natural Boundary Erosion Plots, Gunung Kidul, Java, between 20 January and 12 March 1994. Inputs and outputs rounded off to the nearest five

Plot	Input from riser (kg)	Net soil loss (kg)	SDR
Sinom High	320	90	0.28
Sinom Low	620[a]	685	1.11
Nglipar Low	550	60	0.11

[a] Assuming riser erosion intensity at Sinom Low is 70% of that at Sinom Middle.

input from the riser and net output from the plot reflects contributions by unrecorded small riser failures (see also below).

Whilst the inputs of sediment from riser erosion could be refined (e.g. by using a stratified sampling approach supplemented by regular detailed measurements of riser dimensions), the figures presented in Table 42.3 strongly suggest that the majority of the material leaving the NBEPs is derived from the terrace risers. This is supported by the observation that sediment losses for a given amount of rainfall at the two terraces at Sinom were similar or higher during the second half of the rainy season compared with values obtained at the start of the rains. If the terrace bed had been a major contributor of sediment then the values associated with the beginning of the rainy season – when most of the terraces lay bare – would have been much higher than later on in the season when a good cover was established. However, soil loss for a given rainfall amount at Nglipar tended to be higher in November and December than in January until March, suggesting that the terrace bed did indeed contribute. Additional observations are needed to evaluate the relative magnitude of such contributions.

42.5.3 NBEPs: A Method Worth Developing

Although the usefulness of the NBEP approach for the determination of runoff and sediment yield from backsloping bench-terraced hillsides has been demonstrated in the preceding section, they have certain limitations. The first is the precondition that there must be a "natural" drainage point from each plot which can be used for monitoring. Not all terraces are constructed in this way (Hudson 1995). Secondly, it must be emphasized that there is no "standard" NBEP. Each terrace has its own dimensions and therefore sediment delivery factor. Also, each terrace has its characteristics, as illustrated by the example of the Sinom Low NBEP where the occurrence of subsurface return flow greatly influenced the results. Obviously, comparisons between NBEPs need to be made with care. Several terrace units will usually be needed to assess their representativeness. In order to extrapolate the results to a hillside or a whole catchment, a nested set-up, in which progressively larger units are being monitored for their runoff and sediment yield, would seem to be the most promising way forward in this respect (Dickinson *et al.* 1990; Rijsdijk and Bruijnzeel 1990). The contrast in results obtained at Nglipar for different parts of the rainy season also indicates that at the small end of the scale, separate observations of riser and bed erosion are required if the source of the sediment emanating from the terrace unit is to be known.

Despite its limitations, the NBEP method has merit also for the monitoring of runoff and erosion from built-up areas, settlements, footpaths and dirt roads, where standard runoff plots are impractical (Rijsdijk and Bruijnzeel 1990). In its basic form the NBEP is quick and cheap to set up, there is no disturbance to the farmer's land or crop, and there are no "edge effects" caused by the placing of artificial plot boundaries. Whilst experience to date may be limited, it certainly appears from the data presented in this chapter that the NBEP can be a valuable tool for monitoring runoff and erosion from bench-terraced land.

5.4 Implications for Watershed Management in Steepland Areas

Leaving the rather special situation encountered at Sinom Low aside for the moment, the data in Table 42.3 suggest that a considerable proportion of the material eroded from the terrace risers is contained within the plots, where it is redistributed by the farmer (mostly during the dry season). This does not mean, however, that soil losses from bench-terraced land cannot be substantial. Ongoing research using similar methodologies in steep bench-terraced terrain underlain by highly erodible volcanic ash deposits in the Garut District of West Java has shown that both overall seasonal erosion rates for the terrace units as a whole (8.0–17.9 kg/m^2) and riser erosion alone (23–41 kg/m^2) can be much higher than observed by the present study (E. Purwanto and L. A. Bruijnzeel, unpublished).

If the hypotheses proffered above were substantiated in other areas then the major impact of terrace riser erosion will be felt downstream rather than on-site (Critchley and Bruijnzeel 1995b). As such, the frequently quoted statement of Doolette and Magrath (1990) that the costs of soil erosion in Java mainly manifest themselves as on-site losses of plant productivity (estimated by them at about 300 million US dollars per year) rather than as off-site losses (such as reduced efficiency of irrigation systems and reservoirs due to siltation, estimated at 25–90 million US dollars per year), may well be in need of revision. Programmes which promote terracing – or terrace rehabilitation – as blanket remedies for improving poor soil water and management practices in degraded upland areas need to reconsider their strategies in view of the limitations of these structures. The "terrace riser problem" has largely been overlooked, or at least underestimated.

One way of increasing the effectiveness of watershed development programmes is to monitor more carefully the on-site and downstream consequences of their interventions. Such monitoring needs to be accompanied by adaptive research and must accommodate the land users' perspective. The proposed "natural boundary erosion plot" approach fulfils these criteria.

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