Terrace Riser Erosion: Quantifying a 'Hidden' Source of Sediment in Bench Terraced Landscapes

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Abstract: The bench terraces that cover many steep agricultural hillsides in the humid tropics are generally considered to constitute an excellent method of conserving soil. However one component of that system, the terrace riser, can be a significant source of sediment, especially when risers are tall and not protected by stone or vegetation. Hitherto, there has been inadequate recognition of this problem. Neither has there been any reliable means to quantify the sediment yielded by risers. The 'terrace riser trough' was therefore developed specifically for this purpose. Prototype terrace riser troughs were installed in bench terraced land in a rainfed catchment close to Yogyakarta, south-Central Java, Indonesia. Erosion rates from bare terrace risers in two locations over a five month period during the 1993/1994 rainy season were estimated to be 12.0 ±2.6 (S.E.) kg/m² and 12.4 ±1.2 kg/m² (on a surface area basis) respectively. In a comparative trial the following year, vegetated risers were found to produce only 12% of the sediment yielded by adjacent bare terrace risers of similar dimensions. Clearly, protection of terrace risers is of vital importance where bench terraces are constructed or rehabilitated.

1 Introduction

Over recent decades, bench terraces have been the technical focus for watershed management programmes in many steep agricultural uplands of the humid tropics. Construction of new, and rehabilitation of existing, bench terraces has been, for example, prominent in Indonesia's massive 'regreening programme' launched in the 1970s (Pickering, 1979). In their ideal form, bench terraces can reduce erosion, make farm operations easier, manage surface water, and lead to increases in productivity of land (Sheng, 1989; Doolette and Magrath, 1990; Hudson, 1992). However, it is self evident that the beneficial impacts of bench terraces are contingent on their being initially constructed and subsequently kept up to a high standard (Haigh, 1989; Thomas, 1993). Where bench terraces fail to achieve their objectives it is often the terrace riser which can be identified as the weak link within the system. While the technical ideal may be a riser protected with a stone face, close to the vertical, or alternatively a 45° structure densely covered with productive fodder grass, in reality many risers are simply bare, and trimmed back to unstable angles by impoverished hill farmers anxious to maximise their cultivable area. If the riser is tall, steep and poorly protected it effectively becomes an erosion hazard in itself (Critchley and Bruijnzeel, 1995). This problem is compounded if the parent material is highly erodible (e.g. volcanic tuffs), or if the riser cuts through subsurface drainage channels in shallow soils, or where the subsoil has a high content of silt or sand (Bruijnzeel and Critchley, 1996). Discrete terrace riser failures (slumps) may also occur after heavy storms (Euphrat, 1987). While much of the material eroded from terrace risers in this way may be redistributed on the terrace bed below by the farmer, it may account for the majority of sediment which is transported out of a bench terrace unit (Bruijnzeel and Critchley, 1996). The erosion risk posed by risers has not yet been adequately addressed or acknowledged by those involved in watershed management. The research reported in this paper has made a start through pioneering a simple but versatile method of quantifying the sediment generated by terrace risers within the context of a sediment delivery study in south-Central Java, Indonesia.

2 Study area

The 12.5 km² Kedungkeris catchment is situated some 40 km south east of Yogyakarta in the Gunung Kidul District of Yogyakarta Special Province. Annual average rainfall is slightly over 2,000 mm, more than 75% of which falls during the November to April rainy season. The majority of the study area comprises rainfed farmland which has been settled and terraced by the farmers themselves during the course of this century.

Within the Kedungkeris catchment, two locations were selected for the study of erosion processes. The Nglipar site, with an original gradient of approximately 10° represented conditions associated with the tuffaceous sandstones and marls of the lower catchment. Original slopes at the second site, Sinom, were steeper than at Nglipar, and generally ranged from 15°—30°. Land use within the Sinom subcatchment was mapped and classified as rainfed land (52.5%), scrub (27.5%), house compounds/ home gardens (12%), irrigated fields (4.5%), roads (2.0%), and watercourses (1.5%). Nearly half of the terrace risers were classed as poorly vegetated or bare (Critchley and Bruijnzeel, 1995).

3 Estimating terrace riser erosion

Sediment produced by risers is best studied in relation to the overall production of sediment from terraces. In the present study this was achieved by the use of an experimental innovation, namely the ‘natural boundary erosion plot’ (NBEP). The NBEP comprises a typical, single back-sloping terrace unit - i.e. a terrace bed and its associated upslope riser - with instrumentation for monitoring at the outlet of the toe-drain (Bruijnzeel and Critchley, 1996). NBEP boundaries are not literally natural, but are those predetermined in the field by the farmer rather than artificially established by the researcher. While the NBEP provides data regarding the net quantities of runoff and sediment emanating from the terrace unit, it effectively constitutes a ‘black box’ at the micro-level, in that it does not give information about where the sediment originates. Initial observations, however, suggested that the terrace riser itself was the main source. Although there was some evidence of riser slumping, it was splash, sheet and rill erosion that appeared more important.

Where trees were planted on the terrace lip, they contributed to rilling through stemflow, and enhanced splash erosion through the increased erosivity of the crown drip compared to that of the incident rain (Wiersum, 1985). Loose deposits of sediment were seen to build up at the base of the risers, and during rainfall, particles could be observed to move down the riser face in a form of sheet or ‘slurry’ flow. In especially intense rainstorms, particles were seen to be splashed away from the riser face by up to several centimetres. The conventional approach towards measuring the overall effect of such processes would be to use erosion pins (Zachar, 1982). While cheap, and theoretically allowing a mapping of the terrace riser over time, these have certain specific disadvantages. Erosion pins are vulnerable to human interference (either driven deeper in, or removed). More importantly, they cannot record runoff or collect samples of sediment for individual rainfall events: measurements only have meaning when taken over a lengthy period (a growing season, for example) covering a number of events. Even then they can only be accurate to ±1 mm at best, equivalent to 0.5—1.5 kg/m² (depending on soil bulk density) per reading. The terrace riser trough (TRT), developed by the project, was intended by contrast to collect the full product of runoff and sediment from a specific portion of terrace riser for each rainfall event. Given this objective, metal troughs were designed which could be fitted to the base of terrace risers, and removed to measure the runoff and sediment collected (Critchley and Bruijnzeel, 1995). Troughs were limited to a 50 cm length to avoid problems with curves in the riser. The volumetric capacity of

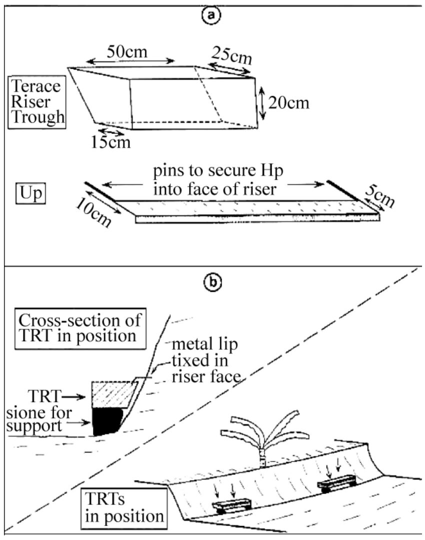

Fig. 1 The Terrace riser trough (a) design (b) positioning in-field

the prototype was determined by assuming a runoff coefficient (0.6) for a typical projectional catchment area above the trough (0.5 m²) for a given maximum design rainstorm (65 mm). The resultant capacity was ±20 litres. This however proved to be an under-design for certain risers during rainfall events above 50 mm. TRTs were positioned underneath metal lips fixed into the riser face, and were supported underneath with stones (Fig.1).

4 Plot instrumentation

During the 1993/1994 rainy season, three terrace units were chosen for study at both Sinom and Nglipar, making six in total. In each case these were adjacent units, labelled (taking Sinom for an example) 'Sinom High' (SH), 'Sinom Middle' (SM), and 'Sinom Low' (SL). Three of these terrace units were selected to be NBEPs, and three others were used to site the terrace riser troughs (see Table 1 for details). Troughs were not sited on risers within NBEPs as there would have been extra compaction of the toe-drain by repeated passage for monitoring purposes, and, to some extent, 'competition' for the same sediment. However, for a period of three weeks, the Sinom Low plot was instrumented with three TRTs for cross-calibration with Sinom Middle (Bruijnzeel and Critchley, 1996).

During early 1995, data collection was restricted to TRTs, and the location limited to Sinom. Sinom Middle was again used, and this time Sinom Low was instrumented with TRTs for the duration of two months. In addition, an extra nearby terrace unit was selected on the basis of its riser being vegetated, enabling a strategic comparison to be made with the other bare risers. The new terrace unit was named 'Sinom Rumput' (SR; *Rumput* meaning grass in *Bahasa Indonesia*; Table 1).

Table 1 Characteristics of 'Natural Boundary Erosion Plots' and terrace risers monitored by 'Terrace Riser Troughs' during the rainy seasons of 1993/1994 and 1994/1995

Plot	*Riser area* (m²) *actual/projected*	*Riser height* (m) *and slope (degrees)*	*Number of troughs* 1993/1994	1994/1995
Sinom Middle (SM)	80/35	2.20/65	5	3
Sinom Low (SL)	165/45	3.40/75	-	3
Sinom Rumput (SR)	130/65	2.65/60	-	4
Nglipar High (NH)	65/40	1.05/50	2	-
Nglipar Middle (NM)	90/55	1.50/50	3	-

The troughs were placed at variable intervals along the chosen terrace risers, in sites selected for their representativeness in terms of erosion features, degree of exposure of rotten rock, plant cover, riser slope and height, etc.. At Sinom, where conditions were more varied (Critchley and Bruijnzeel, 1995), troughs were spaced at approximately 10 m. At Nglipar, where riser material was more uniform, the spacing was increased to 20 m. The monitoring procedure established during the first season involved measuring the sediment captured after rainfall events, on a daily basis. Rainfall was measured using a freely exposed standard rain-gauge with an orifice of 100 cm² near each group of plots. The morning after significant rainfall, when the coarser fractions of sediment had settled, each TRT was removed from under its fixed lip. The content of individual TRTs was measured. First the supernatant fluid was poured off. Following this, the remaining sediment was scooped out and placed in a polythene bag and then transferred to filter paper to be sun dried to constant weight. A sediment total was then calculated for each TRT per rainfall event from the sum of the coarse and suspended fractions (Critchley and Bruijnzeel, 1995).

To enable the calculation of the sediment yield per unit area of riser face for each storm, the 0.5 m length of trough was multiplied by the face height (*not* the vertical height) of the riser commanding the trough in each case. This gave the contributing area for each TRT (typically 0.4 m^2— 0.6 m^2). The amount of sediment emanating from the terrace riser as a whole was estimated by averaging the results from the TRTs and extrapolating to the whole riser.

5 Results and discussion

Sediment yields were monitored for the full duration of the experiment. During the 1993/1994 rainy season (mid-November 1993 to mid-March 1994), 39 rainfall events produced sediment captured by TRTs at Sinom compared with 30 at Nglipar. During early 1995 (mid-January to mid-March only), there were 29 such events at Sinom. Average sediment yields per part season (taking early and late seasons separately to facilitate comparisons) per terrace riser are presented in Table 2 together with the respective amounts of rainfall.

Table 2 Average sediment yields (and SEs) for terrace risers, during the rainy seasons of 1993/1994 and 1994/1995

Plot	*Period**	I	II	III	IV
Sinom Middle		6.65 ±1.35	5.35 ±1.55	12.00 ±2.65	6.05 ±1.90
Sinom Low		-	-	-	2.80 ±0.55
Sinom Rumput		-	-	-	0.75 ±0.10
Nglipar		3.95 ±0.35	8.50 ±0.75	12.45 ±1.20	-

* Period I: mid-Nov 1993 to mid-Jan 1994; rainfall 422 mm (Sinom) and 251 mm (Nglipar)
Period II: mid-Jan to mid-Mar 1994; rainfall 998 mm (Sinom) and 928 mm (Nglipar)
Period III: mid-Nov 1993 to mid-Mar 1994; rainfall 1420 mm (Sinom) and 1179 mm (Nglipar)
Period IV: mid-Jan to mid-March 1995; rainfall 837 mm (Sinom only)

Over a five month period during the 1993/1994 rainy season, the erosion rate (per m^2 surface area of riser) was calculated to be 12.0 ±2.6 (S.E.) kg/m^2 at Sinom and 12.4 ±1.2 kg/m^2 at Nglipar, respectively. The period recorded for 1993/1994 covers approximately 90% of the average seasonal rainfall (1,600 mm) at Sinom and 75% of that amount at Nglipar. Approximate seasonal sediment yields for 1993/1994 can therefore be estimated to be about 13.5 kg/m^2 at Sinom and about 16.5 kg/m^2 at Nglipar. Taking these estimated seasonal totals, risers at Sinom (represented by Sinom Middle) produced about 20% less sediment than at Nglipar. While the riser was higher and steeper at Sinom (Table 1), nearly half of the exposed surface consisted of relatively erosion-resistant, though rotten volcanic breccia. At Nglipar, the whole riser face was composed of more erodible subsoil material derived from marly deposits (Bruijnzeel and Critchley, 1996). These results agree again broadly with the preliminary estimates for TRT-derived rates of riser erosion in the West Java study previously referred to, viz. 11 kg/m^2 — 22 kg/m^2 over 5½ months (Van Eijk, 1997).

The results for Sinom Middle were consistent between the two directly comparable periods of early 1994 and early 1995 (Table 2). Somewhat surprisingly however, there was little difference in sediment yield for Sinom Middle between the first part of the rainy season (late 1993) and the second part (early 1994) despite the fact that the rainfall recorded in the second part of the season was just over twice as great. On the other hand, the Nglipar sites showed a two-fold increase in erosion in the latter part of that season, accompanying a 370% increase in rainfall (Table 2). One explanation could be that riser erosion at Sinom is essentially supply limited (risers being relatively hard and resistant to erosion), whilst this was not the case at Nglipar (risers formed from more erodible materials).

The quantities of sediment produced by the bare terrace risers (Sinom Middle, Sinom Low, Nglipar Middle and Nglipar High) are considerable. For the three terrace units (NBEPs) monitored during early 1994, the input of sediment from the risers (approximated by extrapolation from average rates on TRT-monitored adjacent risers) exceeded the net soil loss from the plot by nearly ten times at Nglipar Low, and nearly four times at Sinom High. The exception was Sinom Low, where the net soil loss from the plot was marginally higher than the gross input from the riser, due to the greater transport efficiency out of the plot associated with the phenomenon of subsurface flow emerging from the riser (Bruijnzeel and Critchley, 1996). However, the contrast between the bare and vegetated risers at Sinom is equally remarkable. Here, the sediment produced by Sinom Rumput was only 12% of that yielded in the comparative period by Sinom Middle, the nearby bare terrace riser of similar height and gradient (Table 1). This confirms the logic, and the visual evidence, that vegetation may provide an effective protection of the riser against erosion.

The data from Sinom can be used to illustrate the relationships between daily rainfall amounts and sediment yield. As previously noted, the riser of the Sinom Middle terrace was monitored for a comparable period (mid-January to mid-March) in both 1994 and 1995. During the same period in 1995, the riser of the adjacent grass covered Sinom Rumput terrace was also monitored, allowing a potentially interesting indicative comparison to be made between risers of similar height and inclination, but with contrasting cover. In each of the three situations, erosion data were averaged per event and subjected to best-fit regression analysis. The best-fit relationships between daily rainfall and sediment yield were of the double logarithmic type, with coefficients of determination of 0.49 (SM 1994), 0.77 (SM 1995) and 0.95 (SR).

While the more or less gradual processes of riser erosion which are related to individual rainfall events can be recorded by TRTs, there are two other processes which need to be recognised. Firstly there is the human element: farmers cut away at the base of risers, primarily to increase cultivable area by clearing debris which has been washed down, but this may also trigger some extra erosion through destabilisation of the riser. Secondly, and significantly in certain situations, there are riser failures, where slumping occurs usually when an unstable riser becomes saturated (Euphrat, 1987). Where these discrete events happen, the amount of material eroded can, locally, dwarf the more gradual processes. Slumping was not observed at Sinom during the 1993/1994 season, though one riser failure at Nglipar that season resulted in approximately 750 kg of riser material falling onto the bed below. However this was repaired by the farmer the following day. During the 1995 season at Sinom, slumping was relatively frequent. Measurements were made of these occurrences on the risers monitored. At Sinom Middle, seven slumps were recorded, representing 0.95 m^3 of material. The corresponding figures for the Sinom Low riser were 12 slumps involving 1.35 m^3.

Therefore, the amount eroded from the riser of Sinom Middle through slumping in 1995 (equivalent to about 950 kg) was approximately twice that lost by the TRT monitored processes (i.e. 5.37 kg/m^2 times 80 m^2, or 430 kg; Table 1 and Table 2). It is pertinent that the vegetated riser (Sinom Rumput) suffered no slumps during the same time period. Two further comments need to be made regarding slumping. First, farmers may repair such riser damage (as was noted at Nglipar in 1993/1994) thereby effectively reversing the process. Second, the slumped material is less vulnerable to transport out of the terrace system, as it tends to fall in a mass into the toe-drain which is then circumnavigated by runoff flowing out of the terrace. This contrasts with the splash, sheet and rill processes that provide small particles of sediment which fall directly into the toe-drain, often while it is flowing, and can thus be readily transported away. Nevertheless if the slumped material is not rapidly replaced or spread by the farmer, it will present a vulnerable target itself for splash and rill erosion.

6 Conclusions and considerations

This study set out to estimate erosion from terrace risers, and in order to facilitate this developed a new tool in this context, the terrace riser trough, to measure sediment generated as a result of various erosion processes. The TRT proved effective in capturing both sediment and runoff from the riser face. Furthermore it is not an expensive item to make, nor difficult to install or operate. It does not need an artificially bounded catchment, nor does it interfere with farmer activities. Although the current study made little use of the potential for farmer participation in research, the TRT does indeed offer those possibilities. The utility of the TRT has already led to the adoption of a modified and enlarged version in an erosion study elsewhere on Java (Purwanto and Bruijnzeel, 1997; van Eijk, 1997). Terrace riser troughs are but tool in this research. These should be used, ideally, in association with complementary techniques at different levels of scale within the catchment, constituting a ‘nested’ approach (Rijsdijk and Bruijnzeel, 1990).

However, even a set-up involving numerous TRTs cannot tell the whole riser erosion story. They must be supplemented with mapping of riser failures where these occur. Furthermore, farmer activities need to be monitored where these have an impact on the riser. Finally, despite some of the limitations of erosion pins in the riser face cited earlier (lack of sensitivity; possibility of human interference, etc.), they can provide useful additional information, allowing mapping of the riser face over time. van Eijk (1997) suggests that erosion pins can be used successfully to give seasonal rates of riser erosion, as they can facilitate measurement of loss of slumped materials, and they avoid potential cumulative errors in sampling which may be associated with TRTs. Further work is necessary to establish the complementarity of TRTs and erosion pins in terrace riser research.

Terrace risers constitute a very important component of terraced hillsides, and their significance increases with steepness of the landscape. Where risers are not protected, they present a distinct erosion hazard. Terracing a hillside may make one section of the new landscape, namely terrace beds, less prone to erosion than the original slopes, but this is only achieved at the cost of increasing the erosion potential in another element, namely the risers (Critchley and Bruijnzeel, 1995). Depending on hillside topography and geological substrate, significant amounts of the sediment eroded from the risers may or may not actually leave the terrace unit in the case of back-sloping terraces. Where it does not, most of it is incorporated into the adjacent downslope terrace bed: in other words, the terrace level sediment delivery ratio is low. Where overall sediment losses from terrace units are high, the majority of this sediment almost certainly originates from the risers (Bruijnzeel and Critchley, 1996; Purwanto and Bruijnzeel, 1997). As suggested by Bruijnzeel and Critchley (1996) this may throw a new light on the on-site costs of erosion. The cost in terms of production loss through on-site erosion may not be as high as previously estimated - e.g. for Java, by Doolette and Magrath (1990) – because the eroded material recorded downstream originates largely from an unproductive component of the terraces. This simultaneously highlights the importance of riser protection as a means to reduce downstream impacts.

If the foregoing hypotheses regarding the central, and hitherto overlooked role of terrace risers prove to be true then watershed management programme designers need to review certain activities, especially indiscriminate construction of new terraces. They may be better advised to concentrate on improvement and rehabilitation of existing structures, with an emphasis on protection of risers with productive vegetation or stone where available. Simultaneously, further applied research is essential to investigate further the problem, and both the technical impacts and land user acceptability of potential remedies (cf. Purwanto and Bruijnzeel, 1997).

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End Note

Please contact the authors for further data/ a full draft of this paper which has been abridged for publication here.

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