

## Soil erosion, suspended sediment sources and deposition in the Maw-Ki-Syiem drainage basin, Cherrapunji, northeastern India

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**Abstract**  $^{210}\text{Pb}_{\text{ex}}$  and  $^{137}\text{Cs}$  activities in soil and sediments were used to investigate soil erosion, suspended sediment source and deposition in the Maw-Ki-Syiem drainage basin on the southern slopes of the Meghalaya plateau in northeastern India. This area is known for its high rainfall ranging from 8000 to 24 000 mm year<sup>-1</sup>. It is shown that in the grassland areas hillslope erosion rates are low (0.21 kg m<sup>2</sup> year<sup>-1</sup>) with most of the mobilized sediment being trapped on the foot-slopes. Stream and recent flood plain sediments are derived primarily from gully and channel bank erosion. The estimated rates of sedimentation on the flood plain are 0.83 g cm<sup>-2</sup> year<sup>-1</sup> using  $^{137}\text{Cs}$  and 1.72 g cm<sup>-2</sup> year<sup>-1</sup> using  $^{210}\text{Pb}_{\text{ex}}$ .

**Key words** caesium-137; Cherrapunji; flood plain sedimentation; lead-210; overbank deposits; sediment tracing; sediment transfer; soil erosion; suspended sediment source

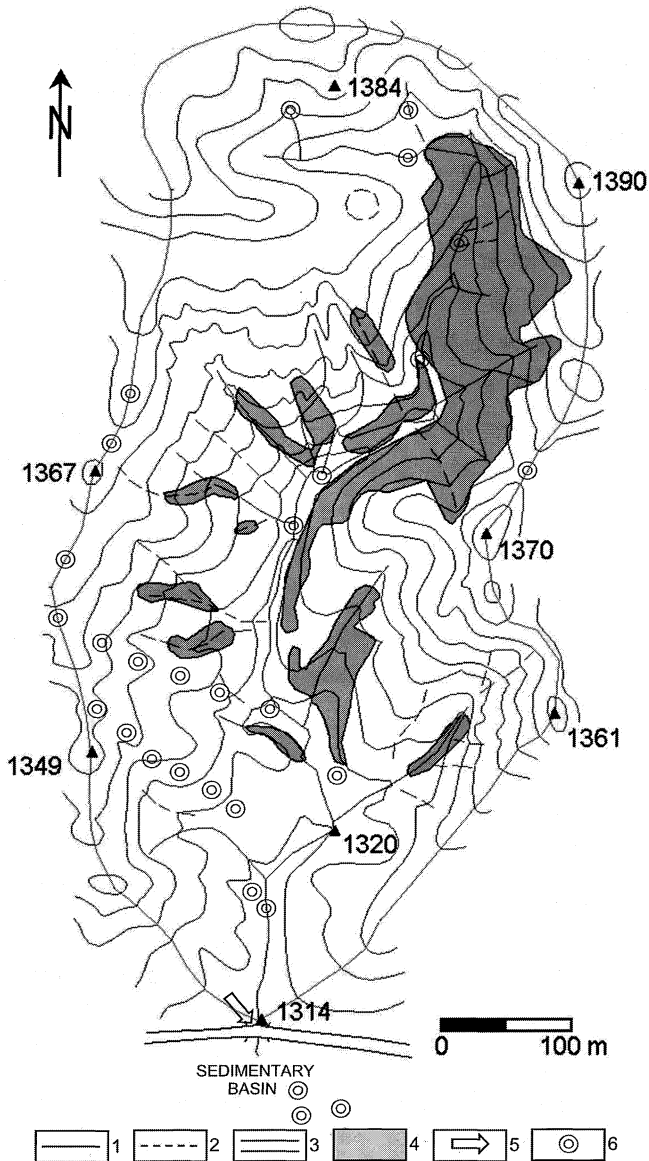
### INTRODUCTION

The Cherrapunji area in northeastern India is known for its high rainfall (8000 to 24 000 mm year<sup>-1</sup>); with daily falls exceeding 500 mm (Singh & Syiemlieh, 2001). The extreme rainfalls have the potential to cause extreme soil erosion and sediment transfer, and provide an unusual opportunity to study the influence of high magnitude short recurrence interval rainfall events on sediment production and transfer (Froehlich, 2004c).

Much of the Cherrapunji region has been degraded through forest clearing for shifting cultivation, and many previously forested slopes are now grasslands. The cultivation practices, overgrazing, and high rates of sheet flow, produced by heavy rainfalls, accelerate soil erosion, which has caused a substantial degradation of the upper soil profile. If ecologically sustainable land management is to be achieved we need to ensure that the downstream impacts of land uses are minimized. An essential part of this is to reduce the delivery of pollutants to streams. Rectification actions aimed at reducing pollutant delivery need to target the major sources of sediment. In this paper  $^{210}\text{Pb}_{\text{ex}}$  and  $^{137}\text{Cs}$  activities in soil and sediments are used to identify the major sources, transport pathways and storage areas in the drainage basin.

### THE STUDY DRAINAGE BASIN

The Maw-Ki-Syiem drainage basin is located in the Cherrapunji area on the southern slopes of Meghalaya plateau in Northeastern India. It is 0.21 km<sup>2</sup> in area and ranges in altitude from 1308 to 1390 m a.s.l. (Fig. 1). The underlying rock-type is thick-horizontally-bedded



**Fig. 1** The Maw-Ki-Syiem study drainage basin (source Starkel *et al.*, 2002). 1, perennial streams; 2, seasonal streams; 3, main road; 4, woodland and scrub; 5, gauging board; 6, sampling sites (contours every 5 m).

limestone and sandstone. The soils range from Alfisols, Inceptisols to Ultisols (cf. Starkel & Singh, 2004). The slope soils are largely degraded. Long-term erosion has removed much of the fine sediment and produced skeletal debris and a very resistant, compact and impermeable layer on the soil surface, which can be up to 30 cm in depth. Sands and gravels constitute approx. 85% of the upper soil profile, and in some areas exposed bedrock bears testament to intensive soil erosion in the past (Froehlich, 2004a,b,c).

The soil and waste cover is shallowest in the headwater areas and deepest (up to 95 cm) in the eastern part, which was cultivated recently. The variable thickness of soil and waste cover depends on the rate of soil erosion and slope gradients. The foot slopes have a very narrow zone of thin sandy-silty deluvial deposits with a depth of up to 90 cm deep. The dense grass covered foot slope and swampy valley bottom act as a trap retaining eroded sediments from upslope. The valley floors have moist shallow sandy-silty alluvial soils, which cover impermeable bedrock.

The Maw-Ki-Syiem drainage basin can be divided into four geomorphological units: (a) the gullies in headwater areas; (b) steep grassland slopes in middle; (c) swampy valley bottom with step-pool sequence; and (d) bedrock waterfall stream channel and sedimentary basin in the lower reach. Natural grassland is the predominant land use. Small areas of forest and scrub occupy approximately 16% of the drainage basin (Fig. 1).

## FIELD AND LABORATORY METHODS

The extreme rainfall events in the study area make it difficult to monitor sediment processes using traditional methods. The use of the fallout radionuclides as a sediment tracer offers a potential tool to investigate soil erosion, sediment source, sediment transfer and sedimentation in areas with limited sediment monitoring programmes (e.g. Walling & Collins, 2000; Froehlich & Walling, 2002; He *et al.*, 2002; Walling, 2002). It is generally assumed that total  $^{137}\text{Cs}$  fallout can be treated as homogeneous at the scale of the field or small basin (e.g. Walling & Quine, 1993; Walling & Collins, 2000; Loughran *et al.*, 2002).

To assess the hillslope erosion sampling strategies in the study, drainage basins were based on a transect approach. Samples were collected from two downslope transects with 12 sampling points each. Reference sites for  $^{210}\text{Pb}_{\text{ex}}$  and  $^{137}\text{Cs}$  were sampled on top of grassed hillcrests. The grass cover was similar at each of the sites. In addition cores of footslope waste cover and overbank deposits were collected in the lower reach of the drainage basin (Fig. 1). Soil cores were obtained by hammering a 75-mm diameter steel corer into the ground. The samples were collected at sufficient depth in order to include all  $^{210}\text{Pb}_{\text{ex}}$  and  $^{137}\text{Cs}$  present in the soil and colluvial/alluvial deposits profile.

Information on suspended sediment sources was assembled using the “fingerprinting” approach (Peart & Walling, 1988; Walling & Woodward, 1992; Collins *et al.*, 1997). Samples of surface material from potential sources (grassland slopes, forest slopes, paths, gullies and channel bank) were collected from an area of 1 m<sup>2</sup>. It is not possible to directly compare the  $^{137}\text{Cs}$  content of these source materials with that of the suspended sediment transported by the stream, because of contrasts in the grain size composition of source materials and suspended sediment and the known enrichment of the finer fractions in  $^{137}\text{Cs}$ . The <0.063 mm fraction of the source materials was therefore separated for gamma spectrometry analysis and the resultant values of  $^{137}\text{Cs}$  content were used for comparisons with those associated with the fine fresh bottom channel deposits as suspended sediment.

The use of  $^{210}\text{Pb}_{\text{ex}}$  and  $^{137}\text{Cs}$  to estimate soil erosion and deposition rates is based on a comparison of  $^{210}\text{Pb}_{\text{ex}}$  and  $^{137}\text{Cs}$  activity at a sample site with concentration of  $^{210}\text{Pb}_{\text{ex}}$  and  $^{137}\text{Cs}$  measured at the reference site (input site). Sample sites with  $^{210}\text{Pb}_{\text{ex}}$  and  $^{137}\text{Cs}$  concentrations less than the reference sites are eroding, while sample sites with concentrations greater than the reference sites are sites of soil deposition. Measurements of

$^{210}\text{Pb}_{\text{ex}}$ ,  $^{226}\text{Ra}$  and  $^{137}\text{Cs}$  activities in soil and sediment cores collected from the drainage basin were used to estimate soil redistribution rates at representative locations within the study drainage basin. These data were extrapolated to the entire drainage basin, in order to estimate rates of soil loss from the grassland slopes. A comparison of the  $^{137}\text{Cs}$  content of the fine fresh deposits of the suspended sediment and material from the potential suspended sediment sources has been used to establish major potential sources. Cores collected from the flood plain areas bordering the stream in the lower reach of the drainage basin and  $^{210}\text{Pb}_{\text{ex}}$ ,  $^{226}\text{Ra}$  and  $^{137}\text{Cs}$  measurements on these cores were used to estimate rates of overbank deposition on the flood plains.

Soil and sediment samples were dried at 90°C for 48 h, weighed and passed through a 2-mm screen. Particles >2 mm were discarded. The 100 g of <2 mm fraction was packed into 500 dm<sup>3</sup> Marinelli beakers for gamma-ray analyses. The analyses are made at the Homerka Laboratory of Fluvial Processes Institute of Geography and Spatial Organization Polish Academy of Sciences at Frycowa using the Perkin Elmer (EG & G ORTEC) Digital Gamma Ray Spectrometer (DSP<sup>EC</sup>) working in 16.384 regime channel spectra with a High-Purity Germanium coaxial detector (45% efficiency and 1.4 keV resolution). The system was calibrated with standard reference materials and the International Atomic Energy Agency Standard IAEA-6 Soil and IAEA-327 Soil. Estimates of  $^{210}\text{Pb}_{\text{ex}}$ ,  $^{226}\text{Ra}$  and  $^{137}\text{Cs}$  activity of the soil samples are made using the GammaVision A66-B32, version 5.13 software (1999). The  $^{210}\text{Pb}_{\text{ex}}$ ,  $^{226}\text{Ra}$  and  $^{137}\text{Cs}$ , was detected at the 46.52, 185.99 and 661.62 keV photopeak, respectively, and count time for each sample was 86 400 s, providing a measurement precision of ±4 to 6%. Sub-samples of each of the cores collected at each sampling point were combined and analysed for particle size characteristics using a Malvern Instruments MasterSizer S, after pre-treatment with H<sub>2</sub>O<sub>2</sub> and disaggregation, and for organic matter content by loss-on-ignition at 600° for 3 h.

## SOIL EROSION AND SEDIMENT TRANSFER

Precise estimation of the reference value is fundamental for calculating losses and gains of  $^{210}\text{Pb}_{\text{ex}}$  and  $^{137}\text{Cs}$  to determine erosion and deposition rates. The depth distributions of the  $^{210}\text{Pb}_{\text{ex}}$  and  $^{137}\text{Cs}$  activities in five reference sites were examined to estimate the reference inventories (Fig. 1). The reference sites were located in areas considered to have similar history of precipitation and fallout to those of the transect sites.

The profiles collected from undisturbed grassland locations show that the majority of  $^{210}\text{Pb}_{\text{ex}}$  and  $^{137}\text{Cs}$  fallout had been retained near the soil surface. The profiles exhibit an exponential decline in radioisotopes concentration with depth. Figures 2 and 3 show typical depth distributions of  $^{210}\text{Pb}_{\text{ex}}$  and  $^{137}\text{Cs}$  in reference soil profiles, which is typical of an undisturbed soil profile, with highest concentration in the surface soil layer (cf. Walling & Quine, 1993; Walling & Collins, 2000). Below a peak in activity concentration at about 2–3 cm, the profile shows an exponential decline in  $^{210}\text{Pb}_{\text{ex}}$  and  $^{137}\text{Cs}$  activity with depth. In each case >75% of the total inventory occurs in the top 15–18 cm, indicating that downward transfer is minimal. Much of the vertical translocation of  $^{137}\text{Cs}$  in these profiles can be related to organic matter production at the grassland surface and chemical diffusion connected with heavy rainfalls and also downward transport by macropores in skeletal topsoil profile.

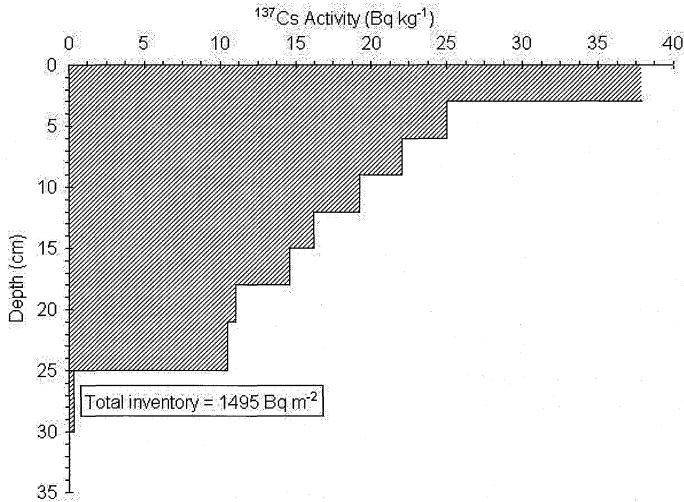


Fig. 2 Distribution of  $^{137}\text{Cs}$  in the soil profile collected on watershed (reference site) of the Maw-Ki-Syiem drainage basin.

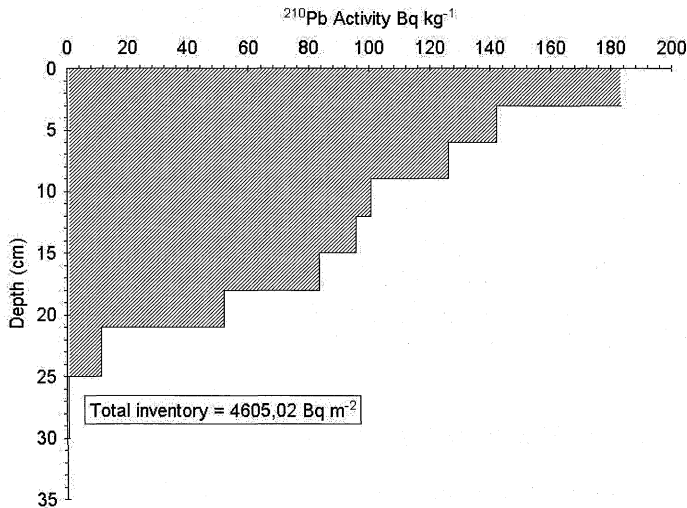


Fig. 3 Distribution of  $^{210}\text{Pb}$  in the soil profile collected on watershed (reference site) of the Maw-Ki-Syiem drainage basin.

The reference inventories were estimated from the five sites to be  $1425 \pm 38.7 \text{ Bq m}^{-2}$  for  $^{137}\text{Cs}$  and  $4605 \pm 55.4 \text{ Bq m}^{-2}$  for  $^{210}\text{Pb}$ . Amounts of fallout generally increase with increasing rainfall (e.g. Longmore, 1982). Further sampling is required to investigate both the local and regional variability of fallout input in the Meghalaya plateau and to assess its influence on the erosion rate estimates.

Comparison of the transect site inventories with those of the reference sites shows that both erosion and deposition are evident along each of the transect (Fig. 4). Based on the  $^{137}\text{Cs}$  data, soil redistribution rates were calculated using the Proportional Model (Walling &

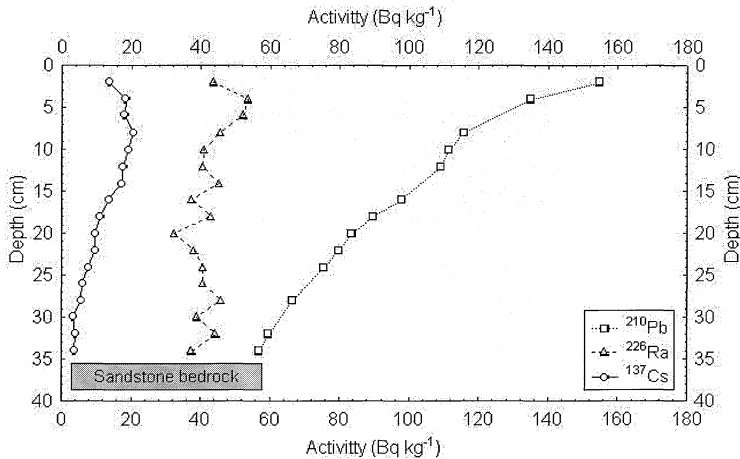


Fig. 4 The  $^{210}\text{Pb}_{\text{ex}}$ ,  $^{226}\text{Ra}$  and  $^{137}\text{Cs}$  depth distributions associated with a soil core collected from the grassland footslope in the Maw-Ki-Syiem drainage basin.

He, 1999). Most part (<96%) of the transects represents eroding sites, with a average erosion rate of  $0.21 \text{ kg m}^{-2} \text{ year}^{-1}$ . The deposition area is limited to only 4% of the total length with a mean deposition rate  $3.5 \text{ kg m}^{-2} \text{ year}^{-1}$ . The distribution of  $^{137}\text{Cs}$  inventories on the grass covered steep slopes evidences rather minimal soil redistribution. However, the absence of consistent relationships between erosion rates and topographic parameters for the Cherrapunji region, which are commonly used in calibration erosion estimation procedures, raises important questions concerning accuracy of soil erosion rate estimate.

The magnitude of  $^{137}\text{Cs}$  transfer from the slopes to valley bottom and its vertical distribution in footslope profiles suggest an accumulation rate of about  $0.85 \text{ mm year}^{-1}$ . Dense grass covering the footslope and valley bottom is acting as a filter to retain most of the eroding soil particles in the upslope. This indicates that the present day sediment delivery ratio for the study drainage basin is relatively low.

## SEDIMENT TRANSFER AND SEDIMENTATION

Sediment source fingerprinting techniques were used to provide information on the main sources of the suspended sediment exported from the drainage basin. The potential sources identified were the surface soil of grassland areas and woodlands drained by dispersed overland flow and sheet flow and linear erosion of paths, channel banks and gullies (Fig. 5).

Low concentration of  $^{137}\text{Cs}$  in fine fresh sediment in bottom channel and overbank deposits indicates that main sediment sources of suspended sediment are active gullies, channel bank and path surface material. This indicates that linear erosion plays an important role in sediment delivery.

Cores collected from the flood plain area were used to quantify sedimentation rate on the flood plain in the lower reaches of the study drainage basin (Figs 6 and 7). The cumulative mass depth of the 1963  $^{137}\text{Cs}$  peak was used to estimate the rate of sedimentation and the CFCS model for  $^{210}\text{Pb}_{\text{ex}}$ . The  $^{210}\text{Pb}_{\text{ex}}$  provide estimates of sedimentation rate extending back over 100 years (He & Walling, 1996).

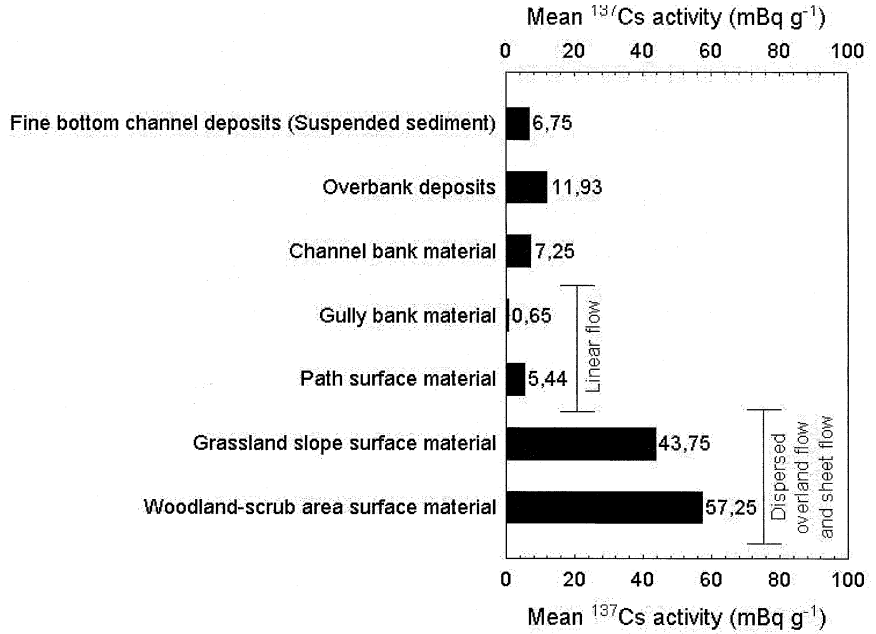


Fig. 5 The <sup>137</sup>Cs concentrations associated with suspended sediment and potential source materials within the Maw-Ki-Syiem drainage basin.

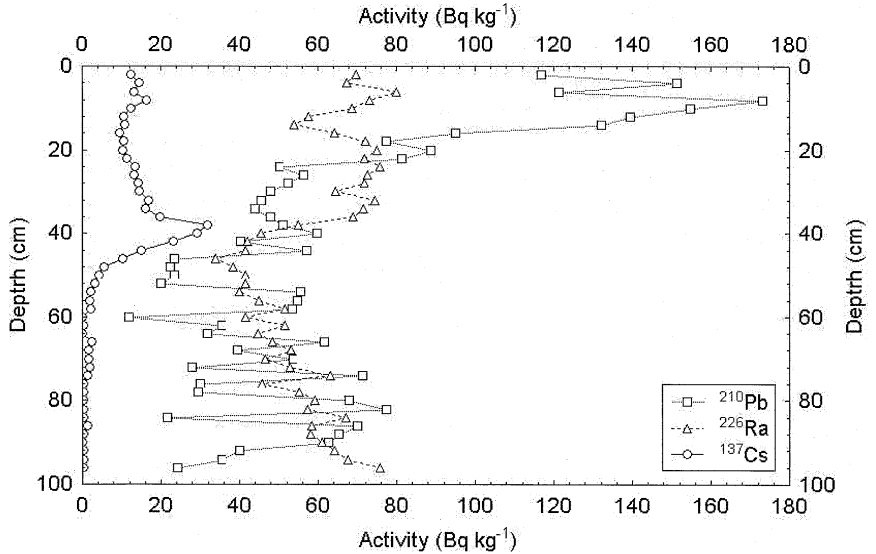


Fig. 6 The <sup>210</sup>Pb<sub>exs</sub>, <sup>226</sup>Ra and <sup>137</sup>Cs depth distributions for a sediment core collected from the flood plain of the Maw-Ki-Syiem stream.

The <sup>137</sup>Cs sedimentation rates estimated for the individual cores ranged from 0.74 g cm<sup>-2</sup> year<sup>-1</sup> to 1.80 g cm<sup>-2</sup> year<sup>-1</sup> and 0.91 to 1.65 g cm<sup>-2</sup> year<sup>-1</sup> for <sup>210</sup>Pb, respectively.

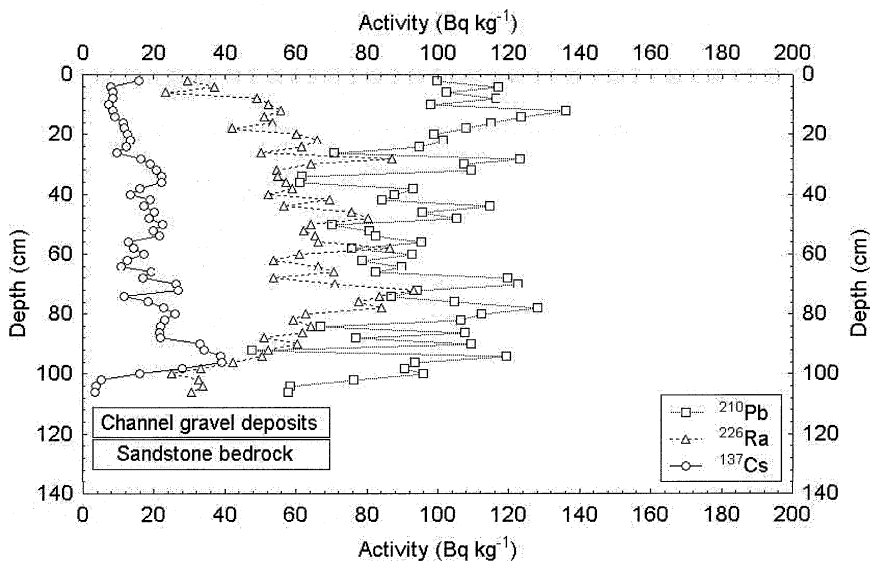


Fig. 7 The  $^{210}\text{Pb}_{\text{ex}}$ ,  $^{226}\text{Ra}$  and  $^{137}\text{Cs}$  depth distributions for a sediment core collected from the flood plain of the Maw-Ki-Syiem stream.

## CONCLUSIONS

The results show that a very small amount of soil is eroded from the grassland slopes of the Maw-Ki-Syiem drainage basin, and that the eroded soil is deposited at the foot of the slopes. The hillslope erosion rate is estimated to be  $0.21 \text{ kg m}^2 \text{ year}^{-1}$  but little hillslope sediment is delivered to the streams. Gullies, channel banks and path surface material were identified as the primary sources of stream sediments. The flood plain sedimentation rates were estimated to be between  $0.74$  and  $1.65 \text{ g cm}^{-2} \text{ year}^{-1}$ . Any strategy aimed at reducing soil erosion and sediment yields from this area should clearly focus on reducing erosion and sediment delivery from the gullies, channel banks and path surfaces. The approach applied in the Maw-Ki-Syiem drainage basin should provide a viable means of investigating soil erosion, sediment transfer and sedimentation in other study areas of extreme rainfalls with limited sediment monitoring programmes.

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