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# The use of $^{137}Cs$ and $^{210}Pb_{ex}$ to investigate sediment sources and overbank sedimentation rates in the Teesta River basin, Sikkim Himalaya, India

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**Abstract** This paper presents results from an investigation of suspended sediment sources and overbank sedimentation rates within the Teesta River basin, India. Sediment source fingerprinting techniques were used to provide information on the primary sources of the suspended sediment exported from the mountain part of the basin. Erosion of areas disturbed by mass movement provided the major source of the suspended sediment load of the river and channel and gully erosion were also important sources. The $^{210}Pb_{ex}$, $^{226}Ra$ and $^{137}Cs$ depth distributions in sediment cores collected from flood plains within the Teesta River basin have been used to derive estimates of overbank sedimentation rates. The estimated sedimentation rates at these flood plain sites vary from 0.21 cm year$^{-1}$ for the upper flood plain level at the site near Boogadong to 3.56 cm year$^{-1}$ at the site near the confluence of the Teesta River with the Great Rangit River.

**Key words** $^{137}Cs$; $^{210}Pb_{ex}$; $^{226}Ra$; flood plain; overbank sedimentation; sedimentation rate; sediment transfer; suspended sediment source; Teesta River

## INTRODUCTION

The high energy and active morphodynamic environments associated with mountain areas introduce important constraints in the application of traditional or classical monitoring techniques aimed at elucidating the sediment budgets of such areas. Furthermore, such techniques possess many limitations in terms of operational problems, the substantial resources required and their limited spatial and temporal coverage. The use of $^{210}Pb_{ex}$, $^{226}Ra$ and $^{137}Cs$ as sediment tracers affords a valuable means of overcoming many of the limitations of classical monitoring techniques and investigating the mobilization of sediment and its transfer through the fluvial system over time scales of several decades and over a range of spatial scales (cf. Froehlich & Walling, 1992; Walling, 2003). This paper presents results from part of a wider investigation of sediment sources and of patterns and rates of overbank sedimentation within the Teesta River basin, India, based on sediment tracing techniques (cf. Froehlich, 2000; Froehlich & Walling, 2002).

## THE STUDY AREA

The Teesta River comprises the main fluvial system of the Sikkim Himalaya and the adjacent foreland of the Ganga-Brahmaputra Plain (Fig. 1). The uplifted Sikkim

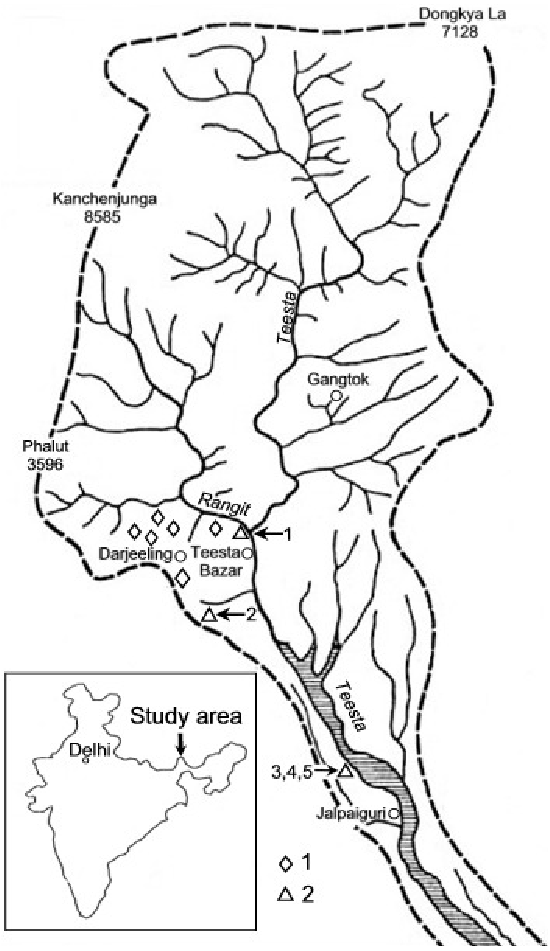


**Fig. 1** A sketch map of the Teesta drainage basin showing the location of the sampling sites: 1, surface material from potential suspended sediment sources; 2, sediment cores from overbank flood plain deposits.

Himalaya, which rises to above 6000–8500 m a.s.l., is characterized by highly active erosion, sediment transport and fluvial sedimentation processes, which in turn reflect the high monsoon precipitation (4000–6000 mm), the high relief energy and the effects of deforestation and poor land management (cf. Froehlich & Starkel, 1987, 1993; Hamilton, 1987). The headwater areas are occupied by tea gardens, cultivated fields, forests and glaciers. Mass movements play an important role in sediment mobilization and sediment transfer to the river channel systems. The adjacent subsiding foreland plains are characterized by sedimentation, lateral shifting of the river channels and avulsion (cf. Froehlich, 2000). Viewed in a global context, this area is characterized by high denudation rates, with sediment yields exceeding 500–1000 t km$^{-2}$ year$^{-1}$ in many areas (cf. Walling & Webb 1983; Goswami, 1985).

## METHODOLOGY

Use of the environmental radionuclides $^{137}$Cs, $^{210}$Pb$_{ex}$, and $^{226}$Ra as sediment tracers has been shown to offer considerable potential for assembling information on sediment sources, sediment transfer and sedimentation rates within drainage basins (cf. Walling, 2003). Caesium-137 is an artificial radionuclide with a half-life of 30.17 years produced by the atmospheric testing of thermonuclear weapons and releases from nuclear reactors. The atmospheric testing of high-yield atomic weapons in the mid and late 1950s and the early 1960s caused the widespread introduction of $^{137}$Cs into the global environment and additional inputs were received in certain areas in the Northern Hemisphere in 1986 as a result of the Chernobyl accident. The $^{137}$Cs derived from bomb tests was released into the stratosphere and circulated globally before being deposited as fallout. Subsequent to its deposition as fallout, $^{137}$Cs was rapidly and strongly adsorbed by fine-grained particulate matter at the soil surface (Frissel & Pennders, 1983) and its redistribution is primarily associated with the mobilization, transport and deposition of soil and sediment particles.

Unlike $^{137}$Cs, $^{210}$Pb is of natural origin and is a product of the $^{238}$U decay series, with a half-life of 22.26 years. It is derived from the decay of gaseous $^{222}$Rn the daughter of $^{226}$Ra. Radium-226 occurs naturally in soils and rocks and will generate $^{210}$Pb that will be in equilibrium with its parent. Diffusion of a small quantity of the $^{222}$Rn from the soils introduces $^{210}$Pb into the atmosphere and its subsequent fallout provides an input of this radionuclide to the soil surface. This fallout component is commonly referred to as "unsupported" or "excess" $^{210}$Pb, i.e. $^{210}Pb_{ex,}$ to distinguish it from the *in situ* $^{210}$Pb which is in equilibrium with its parent $^{226}$Ra. The $^{210}Pb_{ex}$ fallout input is essentially constant through time and the supply to the soil surface is therefore continuously replenished. As with $^{137}$Cs, the $^{210}Pb_{ex}$ fallout is rapidly and strongly adsorbed by the surface soil and its subsequent redistribution occurs in association with soil and sediment particles. The naturally occurring $^{226}$Ra within the soil can also be used as a sediment tracer.

Sediment source fingerprinting techniques were used to provide information on the main sources of the sediment exported from the mountain part of the study basin. Fallout radionuclides (i.e.$^{137}$Cs and $^{210}Pb_{ex}$) are particularly useful as fingerprint properties, since they are effectively independent of soil type and substrate properties and are able to provide information as to whether the fine sediment transported by a river originated from surface or subsurface sources (Walling & Woodward, 1992; Loughran & Campbell, 1995).

Fallout radionuclides have also been widely used for dating recent horizons in lake sediments in work carried out over the past 40–150 years, and essentially the same approach has been successfully applied to flood plain sediments (e.g. Ritchie *et al.*, 1975; Walling & He, 1997). In the case of $^{137}$Cs, the period of maximum fallout in 1963 is commonly marked by a peak of $^{137}$Cs activity in an accreting sediment profile (Fig. 2). For $^{210}Pb_{ex}$, fallout inputs can be treated as essentially constant through time and the rate of decrease of $^{210}Pb_{ex}$ activity downcore will be a direct reflection of the sedimentation rate.

Age–depth curves can be derived from $^{210}Pb_{ex}$ measurements on lake sediment cores through application of the CFCS (constant flux and constant sedimentation rate), CIC (constant initial concentration) and CRS (constant rate of supply) $^{210}$Pb dating models (see Oldfield & Appleby, 1984; He & Walling, 1996). The concepts involved in $^{210}$Pb dating models for lake sediments can also be applied to overbank sediment deposits on river flood plains, although the models employed may require some modification (cf. He & Walling, 1996). In this investigation, the CFCS model used for

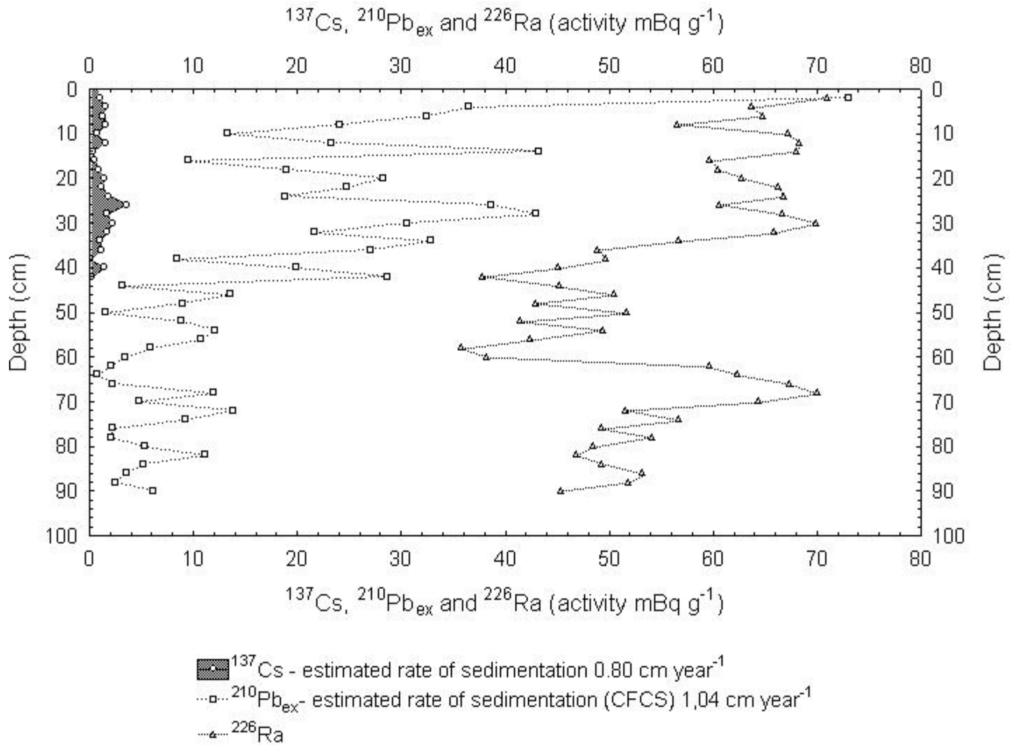


**Fig. 2** The $^{210}$Pb$_{ex}$, $^{226}$Ra and $^{137}$Cs depth distributions for a sediment core collected from the flood plain of the Sukna River near Siliguri in the foothills of the Sikkim Himalaya.

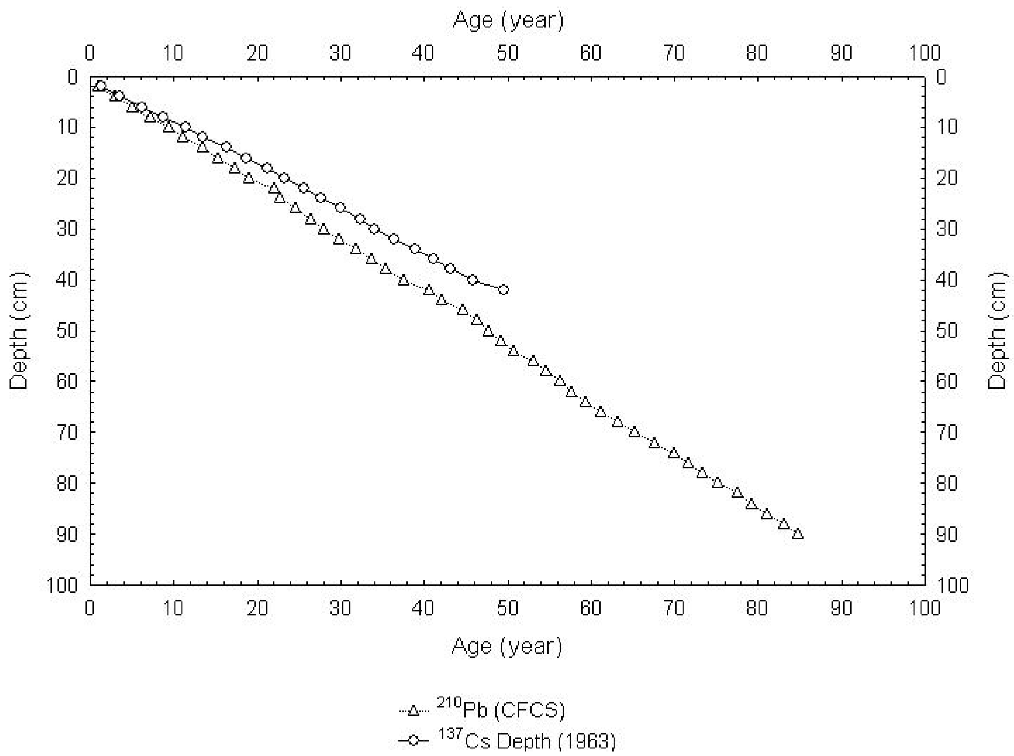


**Fig. 3** Comparison of the age-depth relationships derived from the CFCS flood plain $^{210}$Pb model and from the $^{137}$Cs depth distribution for the sediment core collected from the flood plain of the Sukna River (see Fig. 2).

$^{210}Pb$ dating of lake sediments was applied to the flood plain sediment cores collected from the Teesta River. The age–depth curve established for the core presented in Fig. 2 is shown in Fig. 3.

Overbank deposition on flood plains has been shown to represent an important transmission loss in many fluvial systems and an attempt has been made to use $^{210}Pb_{ex}$ and $^{137}Cs$ measurements on flood plain cores to document rates and patterns of recent deposition on the flood plain of the Teesta River. At each study site, representative sediment cores were collected from the flood plain. The cores were collected using a 75-mm diameter steel core tube inserted using a hammer. The cores were approx. 100–230 cm long and were sectioned into 2-cm increments, in order to determine the depth distribution of $^{210}Pb_{ex}$ and $^{137}Cs$. All samples were dried at 105°C, disaggregated and sieved to pass a 2-mm mesh prior to analysis of their $^{210}Pb$, $^{226}Ra$ and $^{137}Cs$ activity by gamma spectrometry. Gamma assay was undertaken in the Department of Geography of the University of Exeter, UK and in Poland at the Homerka Laboratory of Fluvial Processes of the Institute of Geography and Spatial Organization of the Polish Academy of Sciences, using a low energy, low background, n-type Ortec HPGe detector calibrated with Standard Reference Materials and radionuclide standards.

## FINGERPRINTING SEDIMENT SOURCE

A characteristic feature of the mountainous headwaters of the Teesta River basin is the direct contact of the steep slopes with the river channels. This close linkage between the slopes and the channels plays an important role in sediment delivery. Most of the fine sediment mobilized from landslides, earth flows, and the networks of gullies and roads, which are primarily subsurface sources, is delivered directly to the stream channels and the downstream increase in suspended sediment concentration reflects the increasing input of sediment by linear erosion. In contrast, most of the sediment mobilized within the tea gardens and from cultivated plots bordered by agricultural terraces on the slopes of the catchment, which are largely surface sources, is transferred through a cascading system and a substantial proportion will be redeposited at the foot of the slopes as well as on the valley floors and does not reach the stream channels. Comparison of the $^{137}Cs$ activity of suspended sediment collected from the headwater areas of the Teesta River with that of potential sources (Fig. 4) clearly demonstrates that subsurface sources associated with landslides, earth flows and gullies are the dominant suspended sediment sources in the Sikkim Himalaya.

The grain size composition of the soils within the Teesta basin is characterized by the dominance of the sand-sized fraction and a relatively low clay content (below 10%). Such coarse sediment is conducive to deposition and therefore limits the delivery of suspended matter from the catchment surface to the channel system by overland flow (Froehlich *et al.*, 2000). The importance of landslides, earthflows and gullies as suspended sediment sources was further confirmed by the low concentrations of $^{137}Cs$ found in recent overbank deposits collected from the flood plain of the upper Teesta River (see Fig. 4). These concentrations were very similar to those associated with sediments collected from the eroded colluvial tongues of landslides and earthflows. Much higher $^{137}Cs$ concentrations were associated with surface soils in

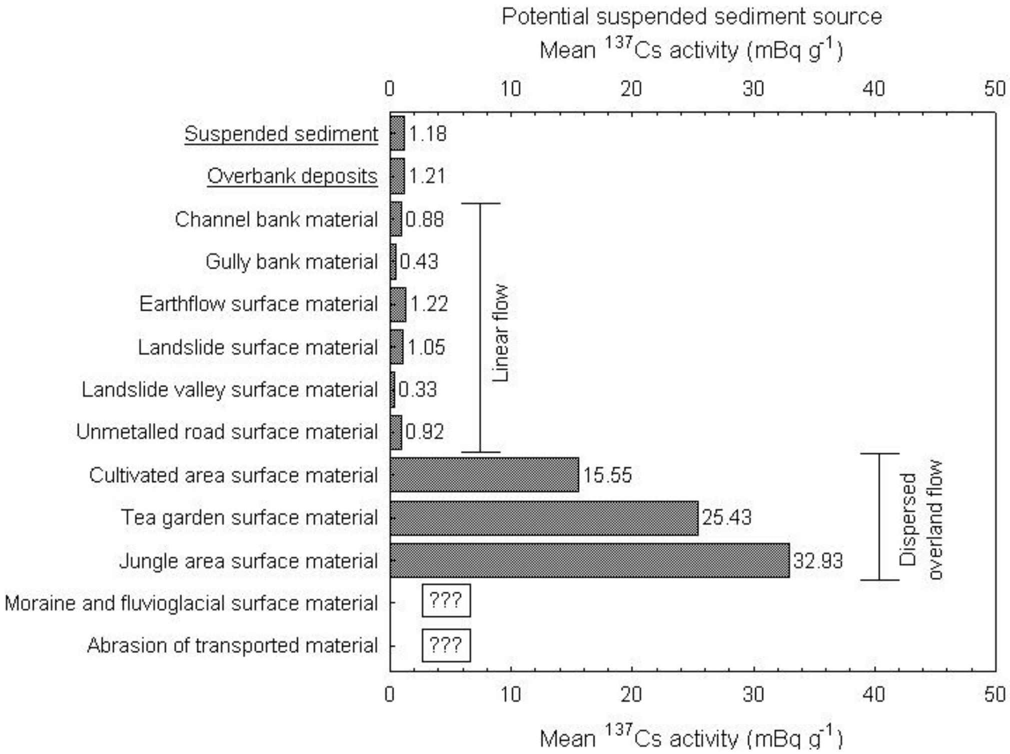


**Fig. 4** A comparison of the $^{137}$Cs concentrations associated with suspended sediment and recent overbank deposits with those of potential source materials, for the headwaters of the Teesta River.

the tea gardens and forests, where suspended sediment mobilization and transport occur in association with dispersed overland flow. The evidence provided by the $^{137}$Cs concentrations associated with the overbank flood plain deposits indicates that, during the annual floods, the main sources of suspended load are landslides and earthflows (Fig. 4). Furthermore, the low concentrations of $^{137}$Cs found in overbank deposits confirm previous conclusions regarding the limited importance of dispersed slope wash as well as overland flow in runoff and sediment generation within the Darjeeling Himalaya (cf. Froehlich *et al.*, 1990).

## RATES AND PATTERNS OF FLOOD PLAIN SEDIMENTATION

The Teesta River attains bankfull discharge almost every year during the floods generated by the monsoon rainfall. Extreme floods resulting from several days of continuous rainfall, which inundate the whole flood plain of the Teesta River, occur with a frequency of 20–30 years (cf. Froehlich & Starkel, 1987). Suspended sediment concentrations seldom exceed 1500 mg $L^{-1}$. These conditions exert an important influence on the potential for overbank flood plain sedimentation, which will be further influenced by the local microtopography and vegetation cover of the flood plain surface.

Traditionally, rates of overbank deposition of fine sediment on the flood plains of mountain rivers have been assumed to be low, due to the high channel slopes and associated high flow velocities. Channel incision could also be expected to further reduce rates of overbank deposition. Information on contemporary rates of overbank sedimentation on the flood plains of the Teesta River basin is needed to resolve these uncertainties and to provide an improved understanding of the contemporary development of the channel and flood plain systems.

Figure 2 provides a typical example of the depth distribution of $^{210}Pb_{ex}$, $^{226}Ra$ and $^{137}Cs$ in the flood plain sediments from the foothill zone of the study basin. This clearly demonstrates the potential for using such measurements for estimating recent rates of overbank flood plain sedimentation. The estimated annual accretion rate for this core collected from the flood plain of the Sukna River near Siliguri was approx. 1 cm year$^{-1}$. A higher annual accretion rate of ~3.5 cm year$^{-1}$ was documented for a core collected further upstream from the flood plain of the Teesta River at its confluence with the Great Rangit River near Teesta Bazar in the Sikkim Himalaya (see Table 1).

Downstream in the alluvial plain, several distinct levels of the flood plain may be distinguished. The lower one, which is up to 1.5 m above the level of the river bed, is composed of silts and clays with intercalations of sands. It is inundated every year and at the sampling site near Boogadong it is restricted mainly to fragments lying between embankments. This sedimentary unit is 80–120 cm thick and underlain by the coarse sands of the channel facies. The accretion rates estimated for the core collected from this area of flood plain range from 1.91 to 2.60 cm year$^{-1}$ (see Table 1). Cores were also collected from two higher flood plain levels at the site near Boogadong (see Table 1). Here, the accretion rates are generally lower and show a decline with increasing distance from the river channel and increasing height above the river. This pattern is likely to reflect a reduction of both the frequency and duration of inundation, as well as reduced inundation depths, with increasing distance from the channel.

The relatively high deposition rates reported for the Ganga-Brahmaputra Plain in Table 1 reflect the efficiency of the erosional systems and sediment production of the Sikkim Himalaya. With the high frequency of lateral channel migration and avulsion, the sedimentation on the flood plain is dispersed across a very wide zone. Most of the point bars and central bars are of a similar elevation to the lower flood plain, but they

**Table 1** The study sites and the rates of recent overbank flood plain sedimentation estimated from $^{210}Pb_{ex}$ (the CFCS method of calculations) and $^{137}Cs$ (depth to 1963 surface) measurements.

| Site no. (Fig. 1) | Location* | Part of Teesta basin | $^{210}Pb_{ex}$ rate of sedimentation (cm year$^{-1}$) | $^{137}Cs$ rate of sedimentation (cm year$^{-1}$) |
|---|---|---|---|---|
| 1 | The flood plain (4–5 m) of the Teesta River near its junction with the Great Rangit River | The Sikkim Himalaya | 3.46 | 3.56 |
| 2 | The flood plain (1.2–1.5 m) of the Sukna River near Siliguri | The foothills of the Sikkim Himalaya | 1.04 | 0.80 |
| 3 | The flood plain (1.2–1.5 m) of the Teesta River near Boogadong | The lowland of the Ganga-Brahmaputra | 2.60 | 1.91 |
| 4 | The flood plain (2–3 m) of the Teesta River near Boogadong | The Lowland of the Ganga-Brahmaputra | 2.32 | 2.03 |
| 5 | The flood plain (4–6 m) of the Teesta River near Boogadong | The Lowland of the Ganga-Brahmaputra | 0.33 | 0.21 |

*The height values listed relate to the height of the flood plain above the river.

are composed only of the sand fraction. A cover of fine overbank deposits is absent, because the absence of vegetation cover limits the deposition of the finer fractions. These bars are amongst the most dynamic forms in the wide flood channels. As in the mountain reaches, the overbank deposits are characterized by very low concentrations of $^{137}$Cs, which again point to the delivery of material from the slopes by the widespread mass movements (Fig. 4). Some of the fine material also originates from the abrasion of coarser sediment, which does not contain this radioisotope.

## CONCLUSIONS

The $^{137}$Cs and $^{210}$Pb$_{ex}$ content of suspended sediment samples collected from headwater areas of the Teesta River indicate that most of the sediment is derived from the slopes by mass movement and linear erosion, whereas tea plantations and the cultivated slopes are much less important as sediment sources. The $^{137}$Cs and $^{210}$Pb$_{ex}$ content of the recently deposited flood plain sediments within the upper Teesta River basin also reflect the land use and prevailing mechanisms of erosion processes within the study catchment and provide similar evidence of the importance of mass movements and linear erosion as the dominant mechanisms of sediment mobilization.

The $^{210}$Pb$_{ex}$, $^{226}$Ra and $^{137}$Cs depth distributions in the sediment cores collected from the flood plains within the Teesta River basin have been used to derive estimates of overbank sedimentation rates for these sites, assuming a constant annual sediment deposition rate. The estimated sedimentation rates at these flood plain sites vary from 0.21 cm year$^{-1}$ for the site near Boogadong on the River Teesta to 3.56 cm year$^{-1}$ for the site on the Great Rangit River near Teesta Bazar. In general, highest accumulation rates occur closest to the channel and values decrease with increasing distance from the channel. Overall deposition rates are high in the context of long-term flood plain accretion.

Similar rates of deposition have been estimated for other flood plain locations within the Teesta River system, indicating that flood plain accretion is widespread and that even in these high energy mountain environments, significant transmission losses may occur in association with flood plain deposition. The results obtained have important implications for the interpretation of downstream suspended sediment fluxes in the study river in terms of sediment mobilization and transfer within the upstream basin. Further work is, however, required to quantify the magnitude of the transmission losses involved.

The results obtained for the study area clearly demonstrate that measurements of $^{210}$Pb$_{ex}$, $^{226}$Ra and $^{137}$Cs in flood plain cores can provide an effective means of quantifying contemporary rates of overbank flood plain deposition. However, a more intensive sampling programme is required to provide a more rigorous assessment of recent rates of overbank sedimentation and the spatial patterns involved and of contrasts between tributaries.

Further integrated studies are also required, in order to obtain a clear appreciation and understanding of the erosion, sediment delivery and sedimentation processes operating in this region and of the role of land use and human activity in perturbing the natural system. Improved understanding of the spatial variability of soil erosion on slopes, of sediment sources and of sedimentation is essential for protecting soils against erosion and reducing rates of sedimentation. The approach successfully applied in the Teesta River basin should afford a feasible basis for establishing the link between the main source of suspended sediment and overbank deposition further downstream in other study areas, in order to inform the design and implementation of catchment management and sediment control strategies.

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