The use of environmental radionuclides in investigations of sediment sources and overbank sedimentation rates in the Himalaya Foreland, India

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Abstract This paper presents some preliminary results from an investigation of overbank sedimentation rates on the flood plains of the Teesta and Brahmaputra Rivers in the Himalaya Foreland, India. The $^{210}Pb_{ex}$, ^{226}Ra and ^{137}Cs depth distributions in sediment cores have been used to derive estimates of overbank sedimentation rates. The estimated sedimentation rates for the flood plains of the Teesta River 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. Mass movements and channel and gully erosion are the dominant suspended sediment sources in the Teesta River basin. A similar accretion rate of 2.24 cm year^{-1} was documented for a site on the flood plain of the Brahmaputra River near Guwahati, where the river enters the Ganga-Brahmaputra Plain.

Key words ^{137}Cs; $^{210}Pb_{ex}$; Brahmaputra River; Ganga-Brahmaputra Plain, India; overbank sedimentation; sedimentation rate; sediment sources; flood plain; Sikkim Himalaya; Teesta River

INTRODUCTION

The high energy and active morphodynamic environments associated with mountain areas introduce important technical constraints in the application of traditional classical techniques for investigating erosion and sediment transfer. These techniques also possess many limitations in terms of operational problems, the substantial resources required and their limited spatial and temporal coverage. In addition, it is difficult to use short-term, site-specific measurements in the interpretation of the medium-term dynamics of contemporary processes, such as flood plain evolution. As a result, relatively little is currently known about the residence times of sediment particles moving through the fluvial system of drainage basins of different scales. The use of environmental radionuclides, including caesium-137 (^{137}Cs) and lead-210 (^{210}Pb), as sediment tracers (see Walling, 2006) offers a valuable alternative and complement to traditional classical techniques and affords a valuable means of investigating the mobilization of sediment and its transfer through the fluvial system over timescales of several decades and over a range of spatial scales (e.g. Walling & Bradley, 1990; Froehlich & Walling, 1992; Walling & Woodward, 1992; Allison *et al.*, 1998). This paper presents some preliminary results from an investigation of overbank flood plain sedimentation rates and suspended sediment sources within the Teesta and

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Brahmaputra river basins in the Himalaya Foreland, India, that has attempted to exploit the potential for using environmental radionuclides (see also Froehlich, 2000; Froehlich & Walling, 2006).

THE STUDY AREA

The Teesta River forms the main fluvial system of the Sikkim Himalaya and its foreland within the Ganga-Brahmaputra Plain (cf. Froehlich *et al.*, 2000). The uplifting Sikkim Himalaya, rising 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, 1993). Fluvial processes are dominant, and the channel network is being actively changed (Coleman, 1960). Mass movements play an important role in sediment mobilization and transfer to the river system. The subsiding plains are characterized by sedimentation, and lateral shifting and avulsion of the river channels (Froehlich, 2000). At the global scale, this area must be seen as being characterized by high denudation rates, reaching 500–1000 t km^{-2} $year^{-1}$ (see Walling & Webb, 1983; Goswami, 1985).

METHODOLOGY

As indicated above, the use of environmental radionuclides (^{210}Pb, ^{226}Ra and ^{137}Cs) as sediment tracers offers considerable potential for assembling information on the main sediment source and on patterns and rates of overbank flood plain sedimentation with-in a drainage basin. Caesium-137 is an artificial radionuclide with a half-life of 30.17 years produced by nuclear fission and releases from nuclear reactors. Widespread global release of ^{137}Cs into the environment was associated with the atmospheric testing of high-yield atomic weapons in the 1950s and the early 1960s. As a result of these tests, radiocaesium was released into the stratosphere and circulated globally. Following the Chernobyl Nuclear Power Plant accident in 1986, certain areas in the Northern Hemisphere received an additional input of ^{137}Cs. On reaching the land surface as fallout, ^{137}Cs is rapidly and strongly adsorbed by fine-grained particulate matter in the surface soil (see Frissel & Penders, 1983) and its subsequent redistribution is primarily associated with erosion and deposition.

In contrast to ^{137}Cs, ^{210}Pb is a naturally occurring radionuclide. It is a natural 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 soil introduces ^{210}Pb into the atmosphere and its subsequent fallout provides an input of this radionuclide to the soil surface that is not in equilibrium with its parent ^{226}Ra. This fallout component is commonly referred to as "unsupported" or "excess" ^{210}Pb ($^{210}Pb_{ex}$). Its fallout input can be viewed as being essentially constant through time and the supply to the soil surface is therefore continuously replenished. After fallout, the radionuclide is, like ^{137}Cs, rapidly and strongly adsorbed by the surface soil.

Sediment source fingerprinting techniques were used to provide information on the main sources of the sediment exported from the mountain part of the study catchment. Environmental radionuclides are particularly useful as sediment source tracers or fingerprints, because they are effectively independent of soil type and substratum properties (Peart & Walling, 1986; Burch *et al*., 1988; Walling & Woodward, 1992; Loughran & Campbell, 1995). Most studies using radionuclides as sediment finger-prints have used ^{137}Cs.

Overbank deposition on flood plains will frequently represent a major conveyance loss in the transfer of sediment through the fluvial system and an attempt has been made to use environmental radionuclides to document the pattern and recent rate of overbank deposition on the flood plains of the Teesta and Brahmaputra rivers. This approach has been successfully used in a number of previous studies (e.g. Ritchie *et al*., 1975; Walling & Bradley, 1989; He & Walling, 1996a,b; Walling & He, 1997). The flood plain surface will receive inputs of radionuclides, both directly from atmospheric fallout and in association with deposited sediment eroded from the upstream drainage basin, and the vertical distribution of the radionuclide activity in a sediment core can provide information on the sedimentation rate. Use of ^{137}Cs measurements to estimate the sedimentation rate is based on either the assumption that there is a relationship between the temporal pattern of atmospheric fallout and the vertical distribution of ^{137}Cs in the sediment profile or that the level associated with the 1963 fallout peak can be identified (Fig. 1). Lead-210 has been used widely for

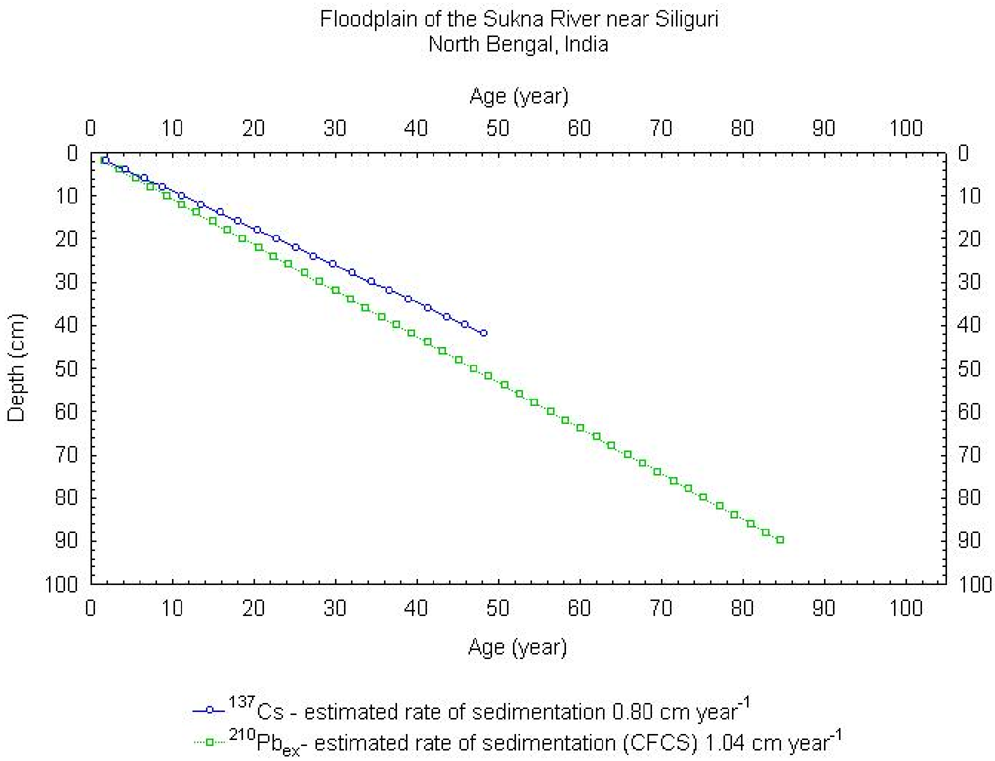

Fig. 1 Comparison of the age-depth relationships derived using the CFCS flood plain model for $^{210}Pb_{ex}$ and from the ^{137}Cs depth distribution, for a sediment core collected from the Sukna River flood plain near Siliguri in the foothills of the Sikkim Himalaya.

dating recent horizons in lake sediment cores over the past 100–150 years, through the application of the CFCS (constant flux and constant sedimentation rate), CIC (constant initial concentration) and CRS (constant rate of supply) ^{210}Pb dating models (Appleby & Oldfield, 1978; Robbins, 1978; Oldfield & Appleby, 1984). The concepts involved in ^{210}Pb dating models for lake sediments can also be applied to flood plains (He & Walling, 1996b) and the CFCS model was employed in this investigation.

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, ^{226}Ra, $^{210}Pb_{ex}$ and ^{137}Cs. All samples were dried at 105ºC, 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 at the Department of Geography of the University of Exeter using an Ortec HPGe N-type detector calibrated with Standard Reference Materials and radionuclide standards. The $^{210}Pb_{ex}$ activity was calculated by subtracting the ^{226}Ra-supported ^{210}Pb activity from the total ^{210}Pb activity.

FINGERPRINTING SEDIMENT SOURCES

A characteristic feature of the Upper Teesta basin is the direct contact of steep slopes with the river channels. This plays an important role in sediment delivery. The grain size composition of soils is characterized by the dominance of sandy fractions and a relatively low content of clay of below 10%. Such composition limits the potential delivery of suspended matter by overland flow. Much of the sediment mobilized from the network of gullies, earth flows, landslides and roads is, however, delivered directly to the stream channels and the downstream increase in suspended sediment concentra–tion reflects the increasing input of sediment by linear erosion. Most of the sediment mobilized by surface wash and related processes from the tea gardens and cultivated plots bordered by agricultural terraces on the slopes of the catchment is, in contrast, transferred by a cascade system and is redeposited at the foot of the slopes, as well as on the valley floors, and does not reach the stream channels.

The importance of landslides and gullies as a suspended sediment source in the Sikkim Himalaya was confirmed by using ^{137}Cs to fingerprint the potential sediment sources. Caesium-137 concentrations found in recently deposited overbank sediments on the flood plain of the Teesta River (e.g. Figs 2, 3 and 4) were very much lower than those associated with surface soil in the tea gardens, cultivated plots and forests where sediment mobilization is predominantly by dispersed overland flow and the mobilized sediment will be characterized by ^{137}Cs activities similar to those in the surface soil. The fine overbank sediment deposits are seen as representative of the suspended sediment transported by the river during overbank floods and the low ^{137}Cs activity associated with these deposits indicates that during overbank flood events the dominant sources of suspended sediment are the eroding colluvial tongues of landslides and earthflows as well as active gullies and channel erosion. The low concentration of ^{137}Cs in the deposited sediment confirms the limited importance of dispersed slope wash and overland flow in both runoff generation and sediment mobilization in the Sikkim Himalaya.

PATTERNS AND RATES OF FLOOD PLAIN SEDIMENTATION

The Teesta River attains bankfull discharge almost every year during floods caused by the monsoon rainfall. Extreme floods resulting from several days of continuous rainfall, which will inundate the whole flood plain of the Teesta River, occur with a frequency of 20–30 years (Froehlich & Starkel, 1987; Starkel & Sarkar, 2002). Suspended sediment concentrations during floods are relatively low and seldom exceed 1500 mg L^{-1} (cf. Abbas & Subramanian, 1984). This situation, coupled with the frequency of flood plain inundation noted above, exerts an important influence on the potential for overbank flood plain sedimentation, which will be further influenced by the microtopography and vegetation cover of the flood plain surface.

Traditionally, rates of overbank deposition of fine sediment in mountain rivers have been assumed to be low, due to the high channel slopes and associated high flow velocities. Channel incision could 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 explore these assumptions further and to provide an improved understanding of the contemporary development of the channel and flood plain systems. Figures 2 and 3 provide typical examples of the depth distributions of ^{210}Pb, ^{226}Ra and ^{137}Cs in the flood plain sediments of the mountain part of the drainage basin, which clearly demonstrate their potential for estimating recent rates of overbank flood plain sedimentation. The estimated accretion rate for the Teesta flood plain in the Sikkim Himalaya is relatively high, and it amounts to approx. 3.5 cm $year^{-1}$ (Fig. 2).

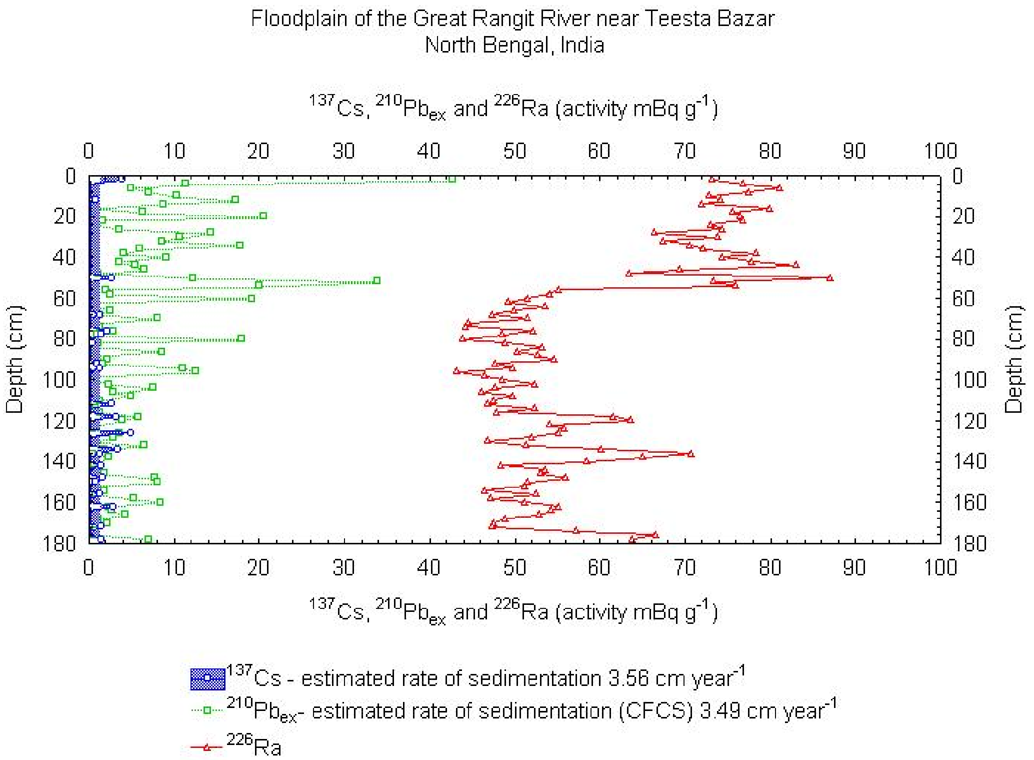

Fig. 2 The $^{210}Pb_{ex}$, ^{226}Ra and ^{137}Cs depth distributions in a sediment core collected from the flood plain of the Great Rangit River near its junction with the Teesta River in the Sikkim Himalaya.

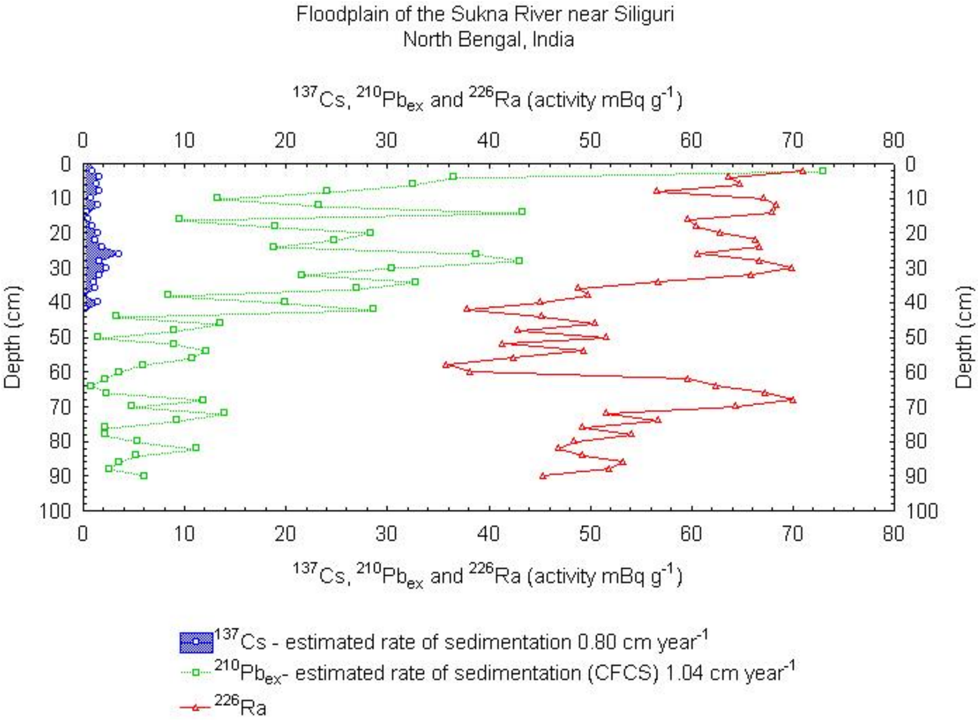

Fig. 3 The $^{210}Pb_{ex}$, ^{226}Ra and ^{137}Cs depth distributions in a sediment core collected from the Sukna River flood plain near Siliguri in the foothills of the Sikkim Himalaya.

However, for the flood plain of the smaller Sukna River, which is located in the foothills nearby, the accretion rate is estimated to be only approx. 1 cm year^{-1} (Fig. 3).

Downstream in the alluvial plain two distinct levels of the flood plain may be distinguished. The lower one, which is approx. 1.2 m high, is composed of silts and clays, with intercalations of sands. It is inundated every year and near Jalpaiguri it is mainly restricted to fragments between the embankments. This 80–120 cm thick unit is underlain by gravels of the channel facies. The estimated accretion rate of this flood plain unit ranges from 1.91 to 2.6 cm year^{-1} (Figs 4 and 5). This relatively high deposition rate reflects the efficiency of the erosional system and of sediment mobilization within the Sikkim Himalaya. Due to the high frequency of lateral channel migration and avulsion, sedimentation on the flood plain is dispersed across a very wide zone. A similar elevation is reached by most of the point bars and central bars built only of sandy fractions. They do not have a cover of overbank deposits, because the lack of vegetation cover limits the deposition of fine fractions. These bars are the most dynamic forms in the wide flood channels. As with the mountain reaches, these overbank deposits are characterized by very low concentrations of ^{137}Cs, which reflect the delivery of material from slopes affected by intensive mass movements (Fig. 4). Some of the fine particles also originate from abrasion of boulders and gravel, which do not contain this radioisotope. This is a further cause of the low ^{137}Cs concentration.

The accumulation rates estimated for the coring points closest to the channel on each river bank (Figs 4 and 5) exceed the corresponding values for the more distant cores along the same transect (see results for Fig. 6). A similar pattern of decreasing sedimentation with increasing distance from the river channel has been observed in other transects. It is likely to reflect a reduction in the frequency and duration of

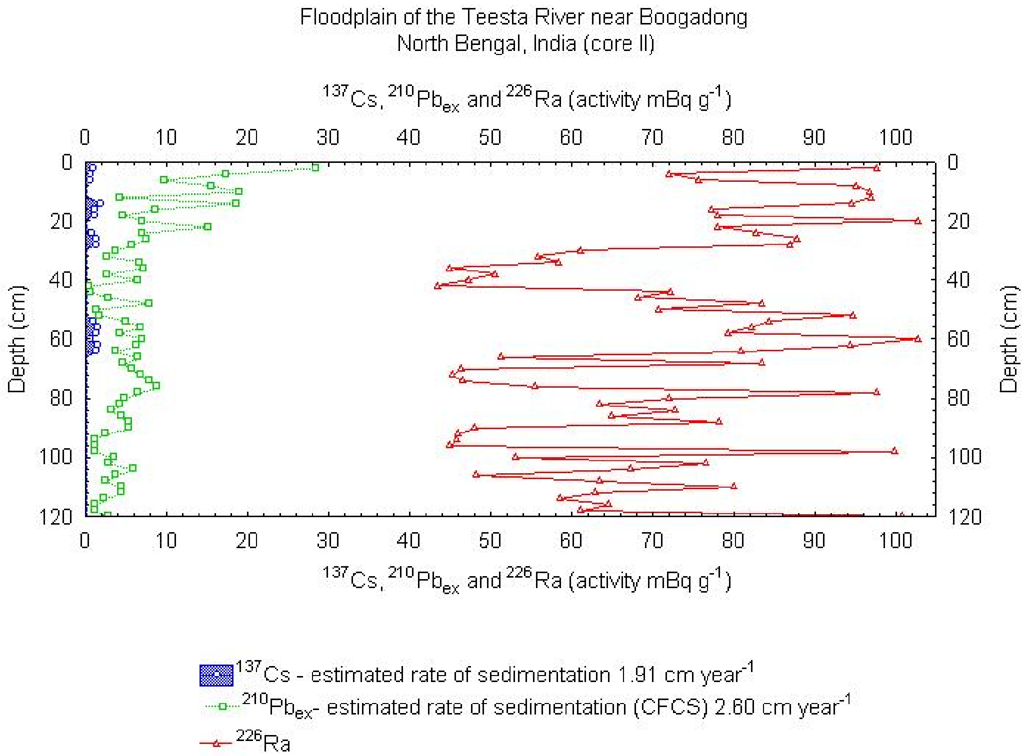

Fig. 4 The $^{210}Pb_{ex}$, ^{226}Ra and ^{137}Cs depth distributions in a sediment core (II) collected from the Teesta River flood plain near Boogadong in the Ganga-Brahmaputra plain.

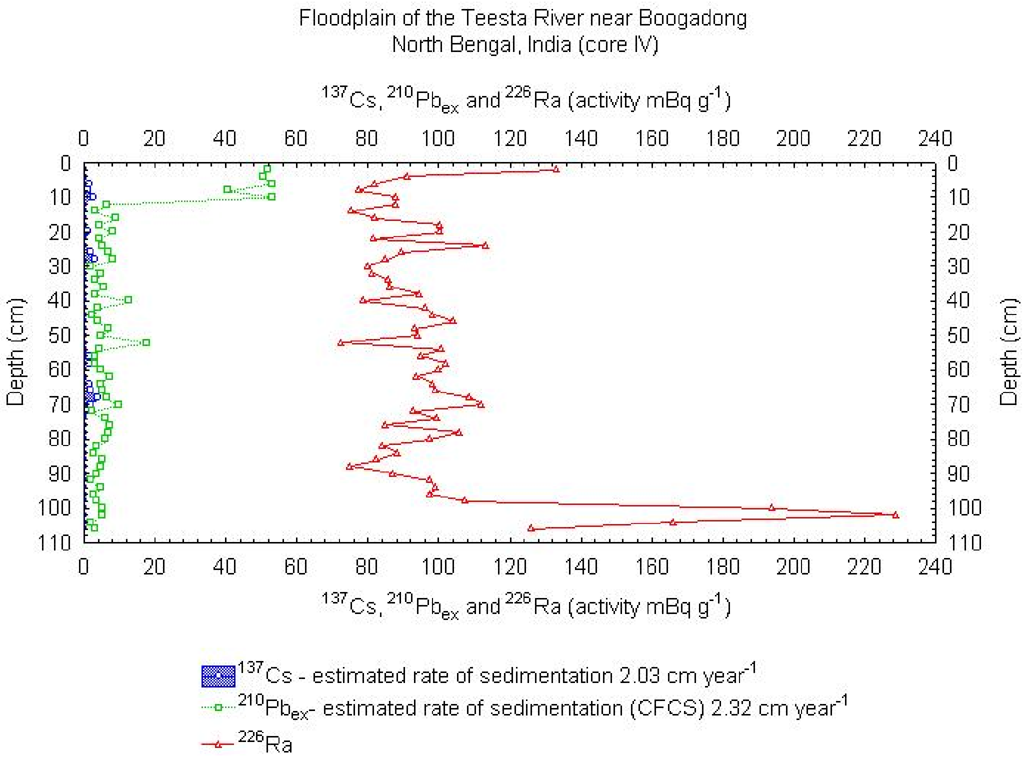

Fig. 5 The $^{210}Pb_{ex}$, ^{226}Ra and ^{137}Cs depth distributions in a sediment core (IV) collected from the Teesta River flood plain near Boogadong in the Ganga-Brahmaputra plain.

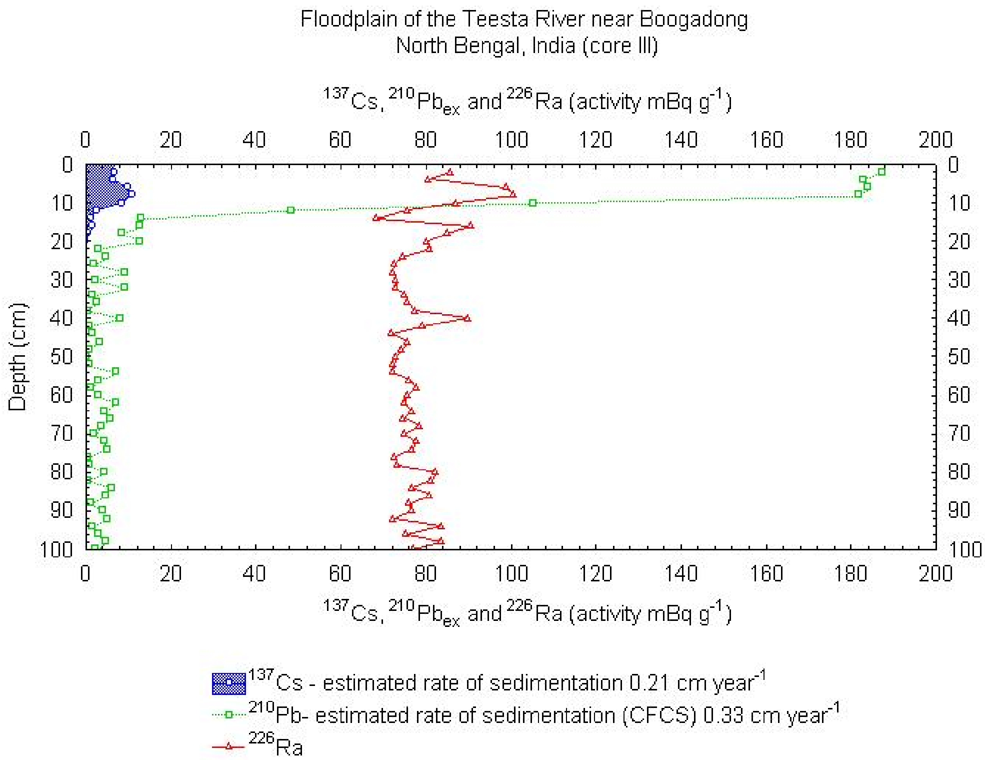

Fig. 6 The $^{210}Pb_{ex}$, ^{226}Ra and ^{137}Cs depth distributions in a sediment core (III) collected from the Teesta River flood plain near Boogadong in the Ganga-Brahmaputra plain.

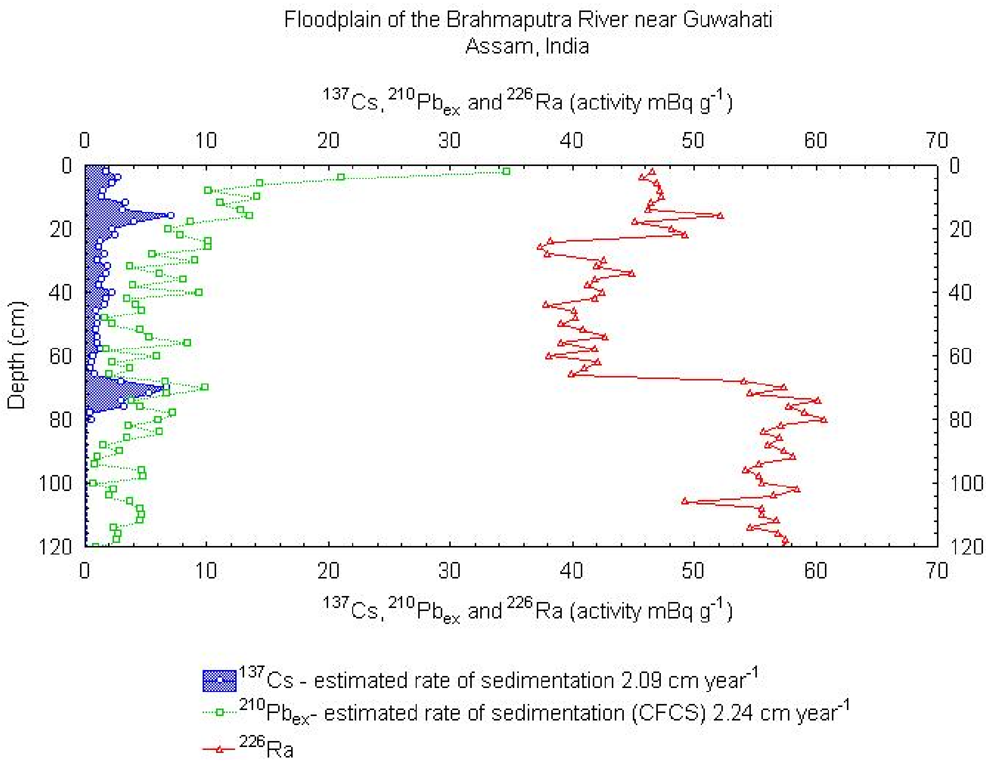

Fig. 7 The $^{210}Pb_{ex}$, ^{226}Ra and ^{137}Cs depth distributions in a sediment core collected from the Brahmaputra River flood plain near Guwahati in the Ganga-Brahmaputra plain.

inundation, with increasing distance from the river channel. The sedimentation rates for the transects within the alluvial plain range from 0.21 cm year^{-1} to 2.03 cm year^{-1}, estimated by ^{137}Cs, and from 0.33 cm year^{-1} to 2.60 cm year^{-1}, estimated using ^{210}Pb$_{ex}$, respectively. Similar rates of deposition have been estimated for the Brahmaputra flood plain near Guwahati (Fig. 7).

CONCLUSIONS

The ^{137}Cs content of recently deposited flood plain sediments reflects land use and the main mechanisms of sediment mobilization. A substantial proportion of the sediment transported was mobilized from the slopes by mass movement and linear erosion, whereas cultivated slopes and tea plantations are not important as sediment sources. The ^{210}Pb$_{ex}$ and ^{137}Cs depth distributions in 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 uniform sediment deposition rate. The estimated sedimentation rates at these flood plain sites vary from 0.21 cm year^{-1} at the site near Boogadong on the River Teesta to 3.56 cm year^{-1} at the site on the Great Rangit River near Teesta Bazar. In general, the 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 deposition rates 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 sediment delivery 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 basin. However, further work is required to quantify the magnitude of the transmission losses involved.

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

Further integrated studies are required in order to obtain a clearer appreciation and understanding of sediment mobilization, delivery and deposition processes in this region, and of the role of land use and human activity in disturbing the natural conditions. 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 sedimentation problems.

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