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Estimating erosion rates on sloping agricultural land in the Yangtze Three Gorges, China, from caesium-137 measurements

X.X. Lu [1], D.L. Higgitt *

Department of Geography, University of Durham, Science Laboratories, South Road, Durham DH1 3LE, UK

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Abstract

The paper describes the application of caesium-137 measurements for estimating soil erosion rates in a small catchment in the Three Gorges region of the Yangtze River, China. The construction of the Three Gorges Dam has drawn attention to the impact of erosion and sedimentation, but there are relatively few quantitative estimates of sediment transfer for this area. The suitability of the fallout radionuclide, caesium-137, for the rapid appraisal of soil redistribution in the steep and dissected terraced landscape of the Three Gorges is investigated here. Previous applications of the technique in Chinese agricultural environments have indicated the difficulty of obtaining reliable baseline fallout estimation. The integration of monthly rainfall data with a model of global strontium-90 fallout is developed to provide an independent estimate of baseline fallout, which is consistent with field measurements. The method also enables a mass balance model of caesium-137 mobility to be calibrated. Mean annual soil loss during the last four decades is estimated at 4500 t km^{-2} yr^{-1}. Erosion rates are strongly related to field slope angles but highly variable spatially. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Soil erosion; Caesium-137; Strontium-90; Three Gorges; Yangtze; China

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1. Introduction

The Three Gorges Project (TGP) on the Yangtze River in China, will create the largest dam hydro-electric power scheme in the world. The scheme is controversial for

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* Corresponding author. Fax: +44-191-3742456; e-mail: d.l.higgitt@durham.ac.uk

[1] Present address: Department of Geography, University of Western Ontario London, Ontario, NGA 5C2, Canada

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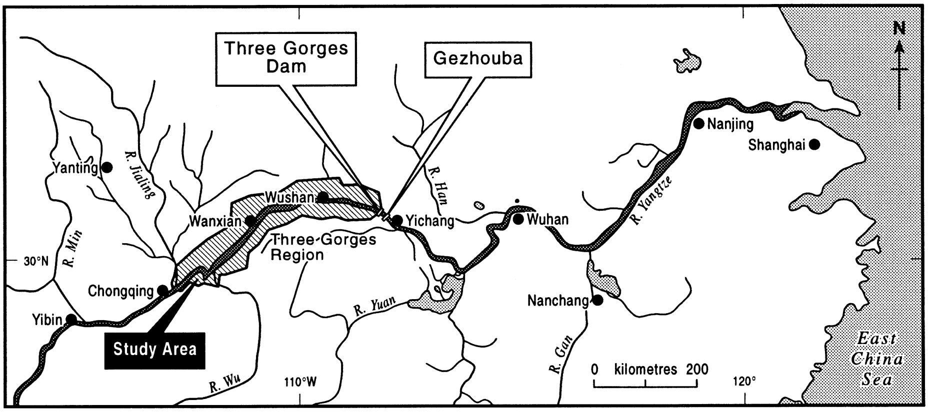

Fig. 1. The Yangtze Three Gorges.

several reasons including the likely impact of sedimentation on the operation and useful life of the reservoir. The riparian counties along the Yangtze between Chongqing and Yichang are generally referred to as the Three Gorges region (Fig. 1) and contain a substantial amount of arable land on steep slopes known to be susceptible to soil erosion. Reliable estimates of the current rates of soil erosion and sediment delivery in the area are useful in assessing the potential sedimentation of the Three Gorges Reservoir. Given that the flooding of the main Yangtze valley will result in the forced relocation of 1.2 million people, many of whom may migrate upslope in the same vicinity, the erosion hazard in the Three Gorges is likely to be enhanced. Evaluation of erosion status has been conducted as part of the TGP feasibility study (CAS, 1988). It is estimated that annual soil loss amounts to 157 million t of which 40 million t are delivered to the Yangtze (Shi et al., 1992). The latter represents a specific sediment yield of about 700 t km^{-2} yr^{-1}. However, the limited amount of monitoring of erosion dynamics through plot experimentation raises questions about the reliability of estimates derived from the extrapolation of plot results. Alternative methods for estimating erosion rates from field measurements, such as the application of caesium-137 (^{137}Cs), offer the prospect of additional information on erosion rates. This paper is concerned with the applicability of caesium-derived erosion estimates in a small catchment, Yiwanshui, Changshou County, conducted as part of a broader study of sediment budgets in the Three Gorges region. The dual aims are to evaluate and adapt the ^{137}Cs methodology and to provide estimates of soil erosion rates in a typical Three Gorges agricultural landscape.

2. Plot- and site-based erosion estimates

The most widely used erosion model for estimating soil loss in China is the Universal Soil Loss Equation (USLE) originally developed in the eastern USA for large fields with relatively gentle slopes (Wischmeier and Smith, 1978). Although many researchers are prepared to defend its simplicity and elegance as a means of identifying erosion hazard (e.g., Newson, 1997) there are concerns that erosion estimates are unreliable beyond the geographical and parameter limits of the original model. Problems in applying the USLE, specific to the Three Gorges region, involve the nature of terrain. The nomographs for factors in the USLE are derived from a standard bounded plot length of 22.1 m. In the Three Gorges region, where arable land occurs on steep and dissected terrain, such a plot length would transect two or three terraced fields. Instigating plot experiments to derive parameter values for the USLE applicable in the study area require one of two approaches. First, plots may be replicated at the standard length by eliminating terrace boundaries to create a uniform slope. Such plots would not be representative of the surfaces upon which agricultural practices and erosion processes take place. The alternative is to reduce the dimensions of the plots to fit the scale of an individual terrace. Small plots will be useful for conducting experiments on the effectiveness of different management practices or crop selections, but may be unsuitable for providing parameter values for the USLE. Additionally plots enclosing field terrace surfaces may neglect soil redistribution from terrace edges (Bruijneel and Critichley, 1996).

Some objections to a plot-based erosion estimate may be overcome by the use of methods which attempt to estimate erosion at a point. The ^{137}Cs technique has become a popular method for the rapid appraisal of net soil redistribution over the period since the onset of bomb-test fallout (ca. 40 years). The advantages and limitations of ^{137}Cs measurements for obtaining erosion estimates have been discussed in more detail elsewhere (Ritchie and McHenry, 1990). The basic premise is that ^{137}Cs, distributed throughout the stratosphere by nuclear weapons testing, has accumulated in soils as a result of atmospheric fallout. Globally significant levels of fallout commenced around 1954 and reached a maximum in 1963 when the Nuclear Test Ban Treaty was signed. In most soils strong adsorption of ^{137}Cs occurs close to the surface such that its subsequent redistribution will be predominantly sediment-associated. The half-life of 30.2 years makes ^{137}Cs suitable for tracing sediment redistribution since the onset of fallout accumulation. Assuming that the baseline inventory of fallout to a particular region can be estimated, the depletion or enhancement of ^{137}Cs at a sample site can be used to estimate net soil loss or gain, respectively, averaged over a period of ca. 40 years. The ^{137}Cs-derived estimate is therefore different in nature to the plot-based estimate. The former provides a net redistribution (including deposition from upslope) at the point of sampling whereas the latter represents the amount of soil transported from the plot area to the collection trough. Direct plot experiments will yield soil losses for the finite length of the experiment which is normally a relatively short period. USLE parameters derived from plot experiments generate annual soil loss estimates. In comparison, the ^{137}Cs estimate refers to and average over a period of about 40 years.

The assumptions of the ^{137}Cs technique are not without difficulties. In particular, the estimation of baseline fallout to a region is problematic in regions where there is no archived information on atmospheric fallout rates and where undisturbed sites are unusual. Similarly, the methods for translating ^{137}Cs measurements into soil redistribution require careful consideration. Consequently, the extension of the ^{137}Cs technique into new field locations, as a means of quantifying erosion rates, must pay particular attention to the validity of the inherent assumptions.

3. Study area

The Three Gorges is the term applied to the 20 counties along the Yangtze valley between Chongqing and Yichang (Fig. 1). The combined land area is 55,800 km^2 and the population is approximately 16 million. The TGP dam site, a short distance upstream of Yichang (Hubei Province), commenced construction in 1993 and is expected to be completed in 2010. As the Yangtze has one of the highest sediment loads amongst the world's great rivers (Summerfield and Hulton, 1994), there has been much concern about the impact of sedimentation on the operation and life span of the reservoir. Studies examining sediment yields within the Upper Yangtze (Gu and Douglas, 1989; Qian et al., 1993) have noted the lack of evidence for increasing sediment load transport at Yichang, in spite of apparent increases in soil erosion within the basin. By examining sediment yield time series in sub-catchments of the Upper Yangtze, Lu and Higgitt (1998) identified parts of the basin that have increased or decreased in importance as suppliers of sediment during the last 40 years. Although sedimentation will be dependent on loads supplied from throughout the entire 1 million km^2 catchment of the Upper Yangtze, it can be argued that the erosion in the Three Gorges is particularly important for at least two reasons. First, the proximity of sub-catchments to the reservoir means that there is less opportunity for the storage of eroded sediment between source and sink, a factor which is significant in large basins. Second, the erosional impact of the displaced population, including the likelihood of agricultural extensification onto steeper slopes, is significant.

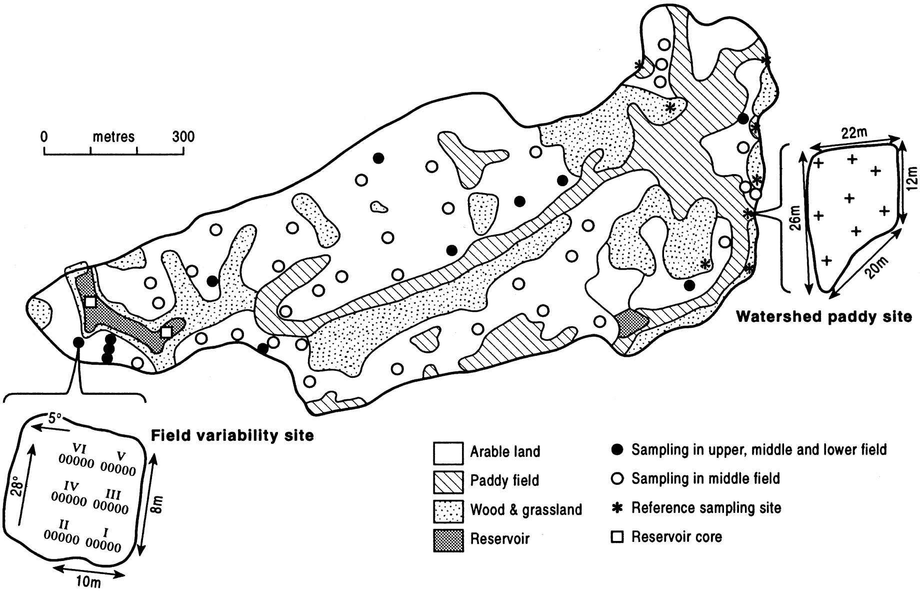

Fig. 2. Land use and sampling distribution in Yiwanshui catchment, Changshou County.

Yiwanshui catchment (29.9°N, 107.0°E) is located in Changshou County about 80 km downstream of Chongqing city. It lies 5 km from the south bank of the Yangtze River. A small reservoir constructed in 1958, drains a catchment area of 0.7 km^2. The catchment is dominated by Triassic purple shales and sandstones, with smaller outcrops of yellow sandstone on the watershed. The soils generally reflect the underlying geology. Purple shales weather rapidly in the subtropical climatic conditions yielding soils with high mineral contents that are suitable for agriculture. These soils (purple soils in Chinese classification) are noted to be particularly susceptible to erosion and coarsening through the loss of fines (Gong and Shi, 1992). The yellow sandstones, by contrast, weather less rapidly and are predominantly occupied by secondary woodland. Woodland also extends to the steepest slopes. Arable cultivation on terraced fields is the dominant land use of the catchment. Based on the dimensions of fields sampled during the study the mean field length in the catchment is only 8 m and slopes range from 16° to 36°. The lowland and valleys within the catchment are developed as paddy fields. The terrain of the Three Gorges is dissected by streams and gullies such that the distribution of the arable land may be highly fragmented and difficult to access. It is estimated that

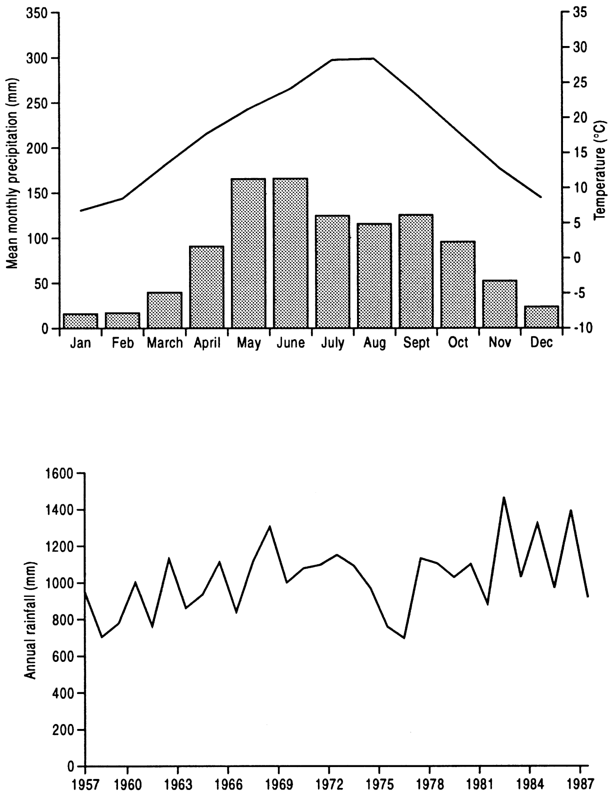

Fig. 3. Summary climate data for Changshou County. (a) mean monthly temperature and precipitation (1957–1987); (b) annual precipitation totals (1957–1987).

about 10% of the land surface in the Three Gorges comprises gullies, ditches and terrace edges (SWCOSP, 1983). Using field mapping combined with a 1:10,000 scale land use map prepared by the Changshou County Soil and Water Conservation Office, the proportion of land cover types in the catchments is as follows: Arable 57%; Paddy 20%; Woodland 10%; Gully, ditch and terrace edge 10%; Reservoir 3%. The distribution of land-use is shown in Fig. 2.

The Three Gorges experiences a subtropical monsoon climate. Changshou County meteorological station, 5 km from the catchment, records a mean annual temperature of 17.6°C and mean annual precipitation of 1031 mm (Fig. 3). The monsoon generally penetrates in May and June sometimes causing flooding problems and high erosion potential, whereas the high temperatures and lower rainfall of July and August may result in drought-related problems. The climate provides the potential for 2 or 2.5 crops per year. During winter and spring the main crops are rape on the valley floors and footslopes and wheat of the sloping or upland terraces. During summer and autumn, the main crops are rice in the valley and irrigated footslopes and maize and sweet potatoes on the slopes. Rotation on the sloping arable land may typically involve wheat–maize–sweet potato or wheat–maize–beans. Traditional cultivation practices have been sympathetic to soil conservation. Slope length and angle are controlled by dividing slopes into sequences of terraced fields, with associated ditching to divert runoff. Most farmers practice downslope tillage procedures. Although local experimentation has shown that contour cultivation can retain moisture levels as well as reduce erosion hazard (SWCOSCC, 1988), downslope tillage is easier to undertake and can assist the drainage of excess water in the earlier part of the monsoon season.

4. Methods

The ^{137}Cs technique is based on the comparison of inventories at eroding or accumulating locations with estimates of the cumulative, or ‘‘baseline’’, fallout. Accordingly, sampling was divided between attempts to derive the baseline inventory and a distributed network of samples from arable land across the catchment. Samples for the estimation of baseline inventory should ideally be collected from level grassland or woodland which has not been disturbed during the period of fallout accession, nor subject to additions such as dust fall. Such locations are impossible to find in China where level ground is a valuable commodity and an alternative means must be adopted. Studies of the variability of ^{137}Cs fallout in non-eroding locations have also indicated the need to collect a number of samples so that the estimate of the baseline inventory can be constrained within given confidence limits (Sutherland, 1991, 1994). The lack of suitable sites and the logistic difficulties of transporting samples back to the laboratory means that many previous applications of the ^{137}Cs technique in China have relied on very few reference samples. Two approaches to estimating baseline fallout were undertaken. Conventional soil sampling from sites in woodland around the watershed was combined with sampling from a paddy field also located at the watershed. An alternative procedure is to examine the relationship between ^{137}Cs fallout and precipitation. The semi-empirical model of Sarmiento and Gwinn (1986) for predicting ^{90}Sr fallout was adapted using monthly precipitation data from Changshou. This procedure for estimating fallout is also useful for constraining the relationship between ^{137}Cs flux and soil redistribution.

Soil sampling throughout the remainder of the catchment was originally planned on a grid system but the discontinuous nature of the dissected arable land made this difficult to implement. Sampling was largely confined to arable land (rather than paddy fields or woodland areas) with soil cores collected from the mid-point of 44 terraced fields 100–200 m apart (locations on Fig. 2). Bulk samples were collected to a depth of 20 cm using a 4 cm diameter coring tube. The sampling depth was considered sufficient to remove the plough layer which is typically 15–20 cm on arable land. Coarse, weathered parent material is frequently encountered below this depth. At 11 of the fields, 3 bulk samples were collected at the upper, mid and lower parts of the field surface to examine within-field distribution. More detailed sampling was undertaken on one field, 8 m long and 10 m wide (labelled ‘‘Field Variability Site’’ in Fig. 2). The field slopes at 28° downslope and 5° across the slope. A 2×3 m grid of samples were collected at 5 cm increments by combining 5 cores from each site. Recent studies using ^{137}Cs to examine erosion on Chinese agricultural fields (Zhang et al., 1993; Quine et al., 1997; Quine et al., 1999a,b) have tended to concentrate on detailed patterns of soil redistribution within individual terrace fields. In this study, sampling has been distributed throughout the catchment to examine potential relationships between field and terrace characteristics and estimated erosion rates.

The appropriateness of single cores collected from field centres requires some justification as the studies above indicate that intra-field variation in soil redistribution is marked. On fields of relatively constant slope angle, typical of small terraces, the net redistribution of soil by tillage processes, which is a function of the rate of downslope change in tillage translocation flux, is close to zero away from the upper and lower field boundaries. Examples of soil redistribution (e.g., Quine et al., 1999a) indicate that soil redistribution at mid-slope locations lies close to the estimate of gross erosion for the field.

Soils were air dried, disaggregated, lightly ground and sieved through a 2 mm mesh. The two size fractions were weighed and a sub-sample of 500 g of the < 2 mm fraction packed into a Marinelli beaker for gamma ray spectrometry. Caesium-137 activity was determined from the photopeak at 662 keV, measured on an EG and G Ortec Loax coaxial detector at the University of Durham. Typical count times are 40,000 s and analytical errors ± 5 to 10% (1 s.d.), dependent on activity. All measurements have been decay-corrected to 1994.

5. Results

5.1. Estimating baseline inventory from soil sampling

The lack of level undisturbed sites presents difficulties for the estimation of the baseline fallout. A paddy field located in a col on the eastern watershed of the catchment was selected for study. The paddy, used for wheat in winter and rice in summer, was

Table 1
Summary statistics of ^{137}Cs inventories at baseline sampling sites

	n	Range	Mean	STD	CV (%)
(a) Cores from watershed paddy field					
All samples	8	1807–2862	2250	306	13.6
Outlier excluded	7	1807–2373	2163	201	9.3
(b) Other baseline sampling sites					
Land use	Cs-137 activity (Bq m^{-2})				
Paddy	1824 ± 224				
Paddy	2155 ± 298				
Paddy	2158 ± 285				
Woodland	2127 ± 149				
Woodland	2200 ± 198				
Woodland	2662 ± 159				
Woodland	5092 ± 243				

isolated from run-on from upper slopes and had been in existence before the onset of atmospheric fallout. Eight cores were collected from the paddy. Three of these cores were sampled at 10 cm increments to a depth of 40 cm. No ^{137}Cs was detectable below 30 cm except in one sample. This sample also had a higher inventory than the other cores and represented an outlier. The coefficient of variation of 13.6% was similar to variability of baseline fallout experienced in Europe (Higgitt, 1995) and somewhat lower than variability reported from some environments with more intense rainfall regimes (Fredericks et al., 1988). When the outlier was removed the coefficient of variation reduced to $< 10\%$ and the mean (and standard error) ^{137}Cs inventory is 2163 ± 76 Bq m^{-2}. An additional 6 cores were collected from other sites along the watershed (Table 1). One sample, collected from woodland had substantially higher ^{137}Cs inventory, but tree ages here of around 20 years mean that ground disturbance may have been considerable. The remaining samples were relatively close to the mean value from the paddy, which was therefore used for the study as an estimate of baseline fallout. The value was also similar to a baseline reported from Yanting, near Chengdu (Quine et al., 1992). Using the criteria outlined by Sutherland (1991), the observed variability from the paddy field site suggests that the number of cores collected is sufficient to estimate mean baseline fallout within a 10% error margin at the 95% level of confidence, though the choice of site is unorthodox.

5.2. Estimating baseline inventory from atmospheric records

In the absence of reliable baseline sampling sites, an alternative way of estimating the atmospheric fallout to a particular location is to establish a relationship between fallout deposition and precipitation. In general terms, there is an observed linear relationship between ^{137}Cs fallout and annual precipitation for a given latitudinal zone (Davis, 1963). Such a relationship has been used to check the reliability of baseline samples in a variety of locations (Lance et al., 1986; Loughran et al., 1988; Kiss et al., 1988; Basher and Matthews, 1993). In many applications of the ^{137}Cs technique it is useful to have information on the variability of atmospheric radionuclide concentrations during the period of fallout accumulation. Mass balance procedures for translating soil ^{137}Cs inventories into net erosion estimates require such data. However, no systematic record of atmospheric fallout of ^{137}Cs has been reported in China. In this study a semi-empirical model developed for predicting ^{90}Sr fallout (Sarmiento and Gwinn, 1986) is adapted and extended in order to provide both a means of estimating total fallout and its temporal variability.

The Sarmiento and Gwinn model estimates monthly variations in ^{90}Sr concentration as a function of latitude. Sr-90 concentration (in femtocuries per cubic meter, fCi m^{-3}) in surface air is given by,

$$C(t,\phi) = R(\phi)\,\mathrm{Cref}(t)\left[1 + g(m,\phi)\right] \tag{1}$$

Where m is the month, ϕ is latitude, and t is time in months running from 1 to 252 for January 1954 to December 1974. Values of the function Cref(t) were tabulated by Sarmiento and Gwinn (1986). $R(\phi)$ and $g(m, \phi)$ can be calculated for the latitude of Changshou (29.9°N) based on the related tables provided by Sarmiento and Gwinn (1986). The ^{90}Sr deposition rate (FA) was then calculated as

$$\mathrm{FA} = C(t,\phi)\left[V_\mathrm{d}(\phi) + V_\mathrm{w}(\phi,t)\right]/100 \tag{2}$$

where V_d and V_w are the dry and wet deposition rates (cm s^{-1}) and V_w is expressed in terms of the monthly precipitation P (cm) as

$$V_\mathrm{w} = aP^{b} \tag{3}$$

Using tables provided by Sarmiento and Gwinn (1986), the dry deposition rate V_d, and the constants a and b for wet deposition can be obtained. Values of monthly precipitation (P) were obtained from a local county meteorological station based on daily rainfall records. The ^{90}Sr fallout (FA) is calculated for months between January 1954 and December 1974. A ratio of 1.65:1 is characteristic of production rates of isotopes of ^{137}Cs relative to ^{90}Sr and is essentially independent of location (Callender and Robbins, 1993), though it may be slightly varied throughout the year (Sarmiento and Gwinn, 1986; Hirose et al., 1987). The total flux of ^{137}Cs for the period 1954–1974 (based on the precipitation model and corrected for decay to 1994) is 1683 Bq m^{-2}. This is equivalent to 78% of the total fallout estimated by the baseline samples. Although the atmospheric fallout world-wide was limited after the mid-1970s, the total accumulated fallout during the 20 years between 1974 and 1994 cannot be ignored due to frequent bomb tests in the late 1970s in China and the Chernobyl accident in 1986.

Japanese fallout records (Hirose et al., 1987) indicate that fallout between 1974 and 1985 was mainly from Chinese nuclear tests. An estimated 200 Bq m^{-2} (decay corrected to 1994) accumulated during this period. Evidence for a modest enrichment of Chernobyl derived radiocaesium in Chinese lakes (Wan et al., 1990) suggests that Yiwanshui catchment is likely to have received some additional fallout around 1986. Consequently, the estimates of fallout derived from precipitation records and from sampling baseline sites are close. The use of the ^{90}Sr fallout model has the advantage of providing an indication of the temporal variability in fallout accumulation which can be used as input for time-step mass balance models of ^{137}Cs redistribution by erosion processes (Fig. 4).

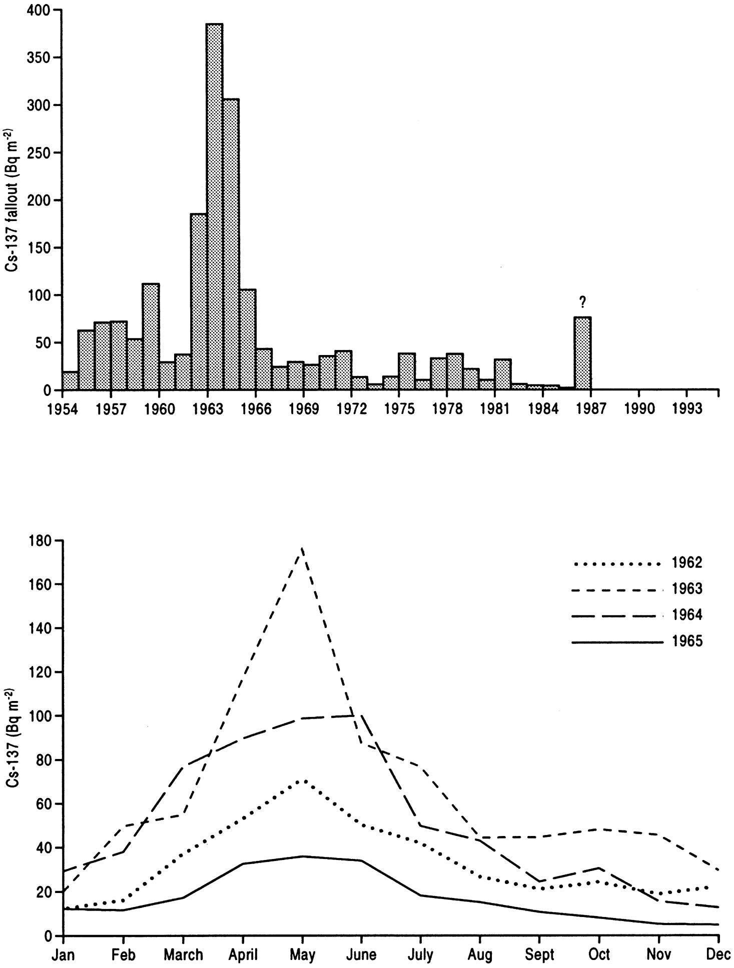

Fig. 4. Baseline ^{137}Cs inventory estimation from precipitation data. (a) Annual ^{137}Cs fallout to catchment estimated from Sarmiento and Gwinn (1986) model; (b) Seasonal variation in ^{137}Cs fallout at the time of maximum atmospheric concentrations (1962–1965).

5.3. Patterns of ^{137}Cs inventories

Spatial variations in the ^{137}Cs inventories measured in soil samples can be used to identify the most significant source areas of sediment and to examine relationships between erosion rates, topographic and land use factors. Previous studies have demonstrated that topographic attributes are capable of explaining some of the variation in soil flux (Martz and De Jong, 1987; Chappell et al., 1996), albeit that the relationship can be complex. There is a significant correlation ($\alpha = 0.05$) between the ^{137}Cs inventory and the slope angle, but not with slope length (Table 2). Whereas the USLE incorporates slope length into erosion estimation, this study, and others using ^{137}Cs (Kiss et al.,

Table 2
Correlation matrix for slope angle, length, ^{137}Cs inventory and gravel content of core samples ($n = 66$)

	Slope angle (°)	Slope length (m)	Cs-137 (Bq m^{-2})	% > 2 mm
Slope angle (°)	1.00			
Slope length (m)	0.07	1.00		
Cs-137 (Bq m^{-2})	−0.34**	−0.02	1.00	
% > 2 mm	0.46**	−0.03	−0.62**	1.00

** Significant at $\alpha = 0.05$.

1986), find no relation between erosion rate and slope length. There is however, an observed relationship between ^{137}Cs inventory and gravel content. Increased stoniness is a detrimental consequence of soil erosion in the purple soils of the Three Gorges. The strong correlation between gravel content and slope angle and the lack of correlation with slope length affirms the distribution of ^{137}Cs and also suggests that simple texture measurements might be used as qualitative indicators of erosion.

On 11 terraced fields bulk samples were collected at upper, mid and lower positions to investigate whether there is any consistent variation in ^{137}Cs inventory (Fig. 5). When the mean inventories for each slope position is summarised (Table 3) a minor depletion at the upper slope position and accumulation at the lower edge of the terrace is observed. Similar patterns of ^{137}Cs redistribution in Yanting have been associated with tillage erosion (Quine et al., 1992, 1999a). A pattern of downslope fining is also observed, with gravel contents being higher at the upper slope locations. Accumulation on the lower terrace is not consistent in every case and appears to be related to terrace design. Four basic forms of dry terrace were observed within the catchment (inset in Fig. 5). Design varies according to the provision of boundary ditches and constructional barriers. Type IV terraces with minimal ditching are the most common in the catchment and also the most susceptible to erosion. Rill networks have been observed cutting across sequences of terrace fields and risers. Upslope ditches (Types I and II) limit run-on at the upper edge of the terrace while lower edge barriers (Types I and III) limit transfer to the next terrace. The sediment delivery ratio as well as net soil loss is likely to be related, in part, to terrace design. A more detailed analysis of small-scale variation is available from the individual field where six sectioned cores were obtained. Each core is a composite of five replicates. The depth distributions of the cores are displayed in Fig. 6. The values show high variability within a short distance, but is consistent with the pattern of lower edge accumulation observed on most field terraces. Depletion in surface ^{137}Cs concentrations near the upper boundary reflects the recent addition of terrace riser material to the field surface.

A central assumption is that the ^{137}Cs redistribution is almost exclusively sediment-associated. While the actions of soil management practices such as ploughing may result in a net downslope transport of soil (tillage erosion), the role of deliberate removal and redistribution of soil materials by farmers has not been considered in any detail. Tillage processes mix ^{137}Cs vertically within the soil profile but also lead to the horizontal displacement of soil. There is increasing evidence that tillage displacement may be as

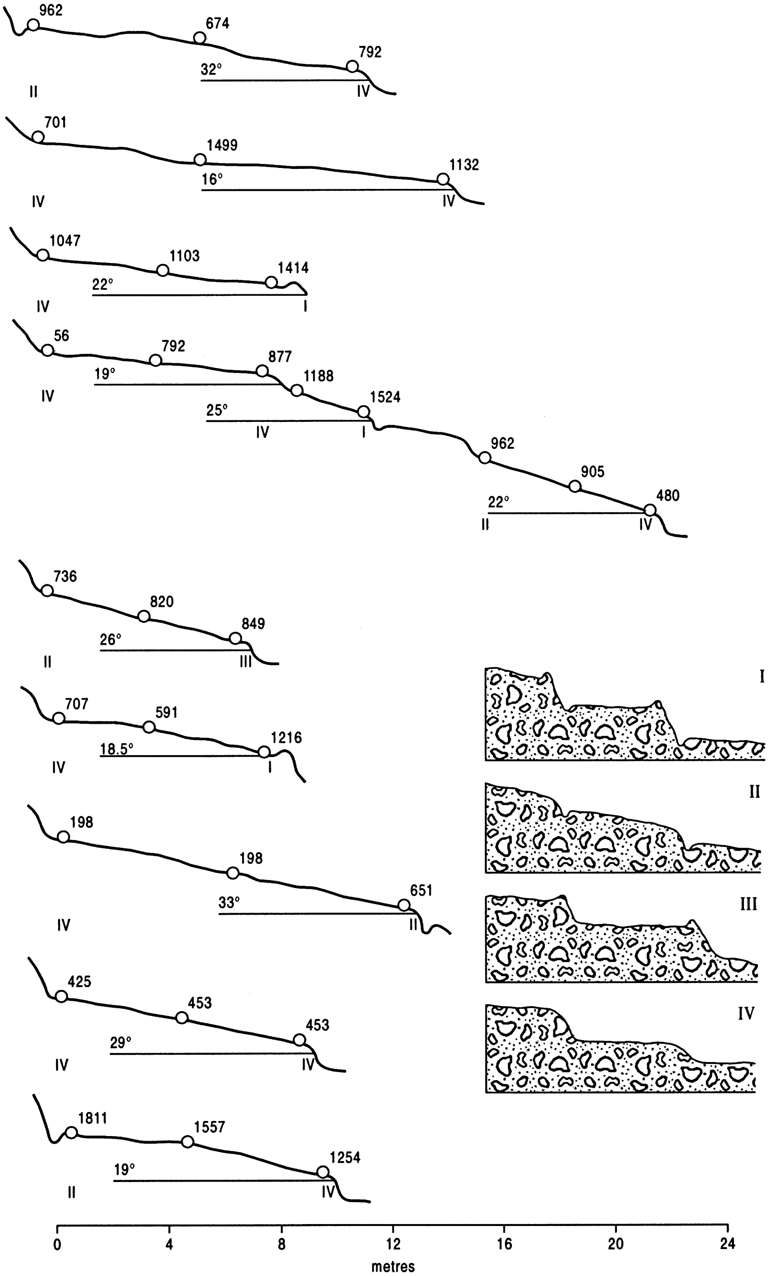

Fig. 5. Variation in ^{137}Cs inventories across sampled terrace field profiles (inset: typology of dry terrace designs observed in the catchment).

Table 3
Caesium-137 inventory and gravel content by slope position within field terraces

137Cs inventory (Bq m^{-2})					> 2 mm fraction (%)			
Slope position	Mean	S.D.	Min	Max	Mean	S.D.	Min.	Max.
Upper	802	484	59	1803	21.5	20.9	0.0	63.3
Middle	860	426	212	1542	13.2	16.0	3.4	53.1
Lower	971	364	461	1535	10.3	10.6	0.0	27.7

important as water erosion in determining long term patterns of soil redistribution on agricultural land (Quine, 1995, Quine et al., 1997, 1999b). Tillage redistribution at each point within a cultivated field is the result the balance between upslope and downslope translocation flux while the magnitude of the fluxes is a function of slope angle (Lindstrom et al., 1992; Govers et al., 1994). Predominantly, tillage erosion is a feature of mechanised agriculture on moderately sloping land, although Zhang et al. (1993) report estimates of tillage erosion as high as 2380–6270 t km^{-2} yr^{-1} for gently sloping land (5.2–7.4°) at Yanting, Sichuan Province. On the steeper slopes of the Yiwanshui catchment, tillage is non-mechanised and undertaken by buffalo draught or manually and

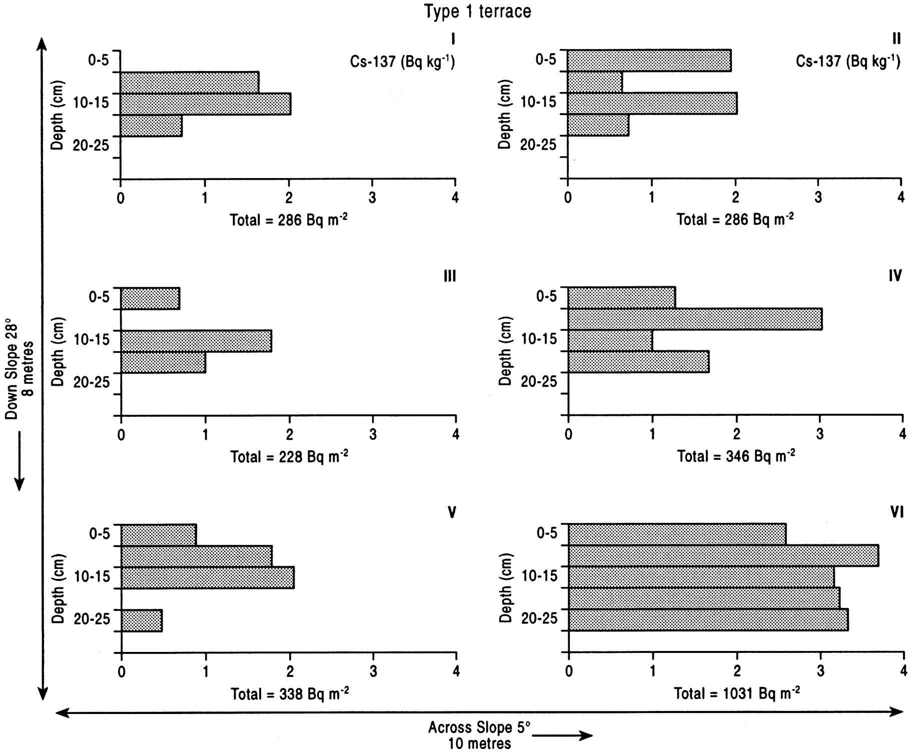

Fig. 6. Depth distribution of six cores collected within one terrace field.

plough depths are shallow (15–20 cm). Whereas Quine et al. (1999a) have attempted to simulate tillage erosion within individual terrace strips, no attempt has been made here to segregate the effects of tillage from water erosion, or to examine the detailed pattern of soil redistribution within fields. Rather, the mid-slope locations are selected as sites where the impact of tillage translocation is likely to have a limited effect on the net redistribution of ^{137}Cs. Further redistribution of ^{137}Cs may be associated with the harvest of root crops like sweet potato and peanut, but this is likely to be limited. Deliberate soil redistribution is a traditional method for maintaining soil fertility and has been observed throughout the catchment. Freshly weathered material from terrace risers is often added to field surfaces and fine material trapped in lower edge ditches are often returned to the field surface. Some levelling of field surfaces by redistributing material from the upper to the lower part of the field is common when terrace sequences are constructed and may be practised periodically. Such activities disrupt the tracing attributes of ^{137}Cs. To some extent, the net downslope impact of levelling practices might be regarded as an additional aspect of tillage erosion. It is difficult to evaluate its impact quantitatively in terms of biasing the spatial pattern of ^{137}Cs inventories, but it is generally assumed that its impact is relatively minor compared to redistribution of soil by erosion processes.

In summary, the pattern of ^{137}Cs inventories within the Yiwanshui catchment are significantly correlated with slope angle across the field surfaces, but are independent of slope length. It is apparent that soil management practices and the design of the terraces have an impact on the net transfer of ^{137}Cs within and between fields.

5.4. Estimates of soil loss

A number of approaches have been developed to estimate soil loss/gain from ^{137}Cs inventories. The conditions of model use and the relative advantages and disadvantages of design have been reviewed by Walling and Quine (1990). Mass balance procedures appear to offer the best prospect for obtaining erosion estimates as a number of refinements regarding the environmental mobility of the radionuclide can be incorporated into the procedure (Quine, 1995). The ^{137}Cs inventory at a sampling point can be simulated over time in relation to time-dependent input of fallout, radioactive decay, losses to leaching, cropping and soil erosion. The vertical distribution of ^{137}Cs within the soil, the effect of mixing by tillage and the enrichment associated with size selective transport of eroded material can also be incorporated into the mass balance procedure.

Given the coarse particle size properties of soils within the catchment and the observations of downslope fining within individual terraced fields, preferential enrichment of ^{137}Cs is likely to occur. Based on a comparison of ^{137}Cs concentrations in arable land, woodland, terrace edges and reservoir sediment, Lu (1998) derives a factor of 1.50 for the enrichment of ^{137}Cs concentration due to the preferential transport of fines. This value is higher than ^{137}Cs enrichment reported elsewhere (De Jong et al., 1983) but similar to total phosphorous and potassium enrichment ratios for similar coarse soils in the Yangtze valley (Lu and Shi, 1994). A problem in applying mass balance models in China is the absence of information on the rate of fallout accumulation over the period of weapons testing. The first attempt to apply the ^{137}Cs technique in China used a simplifying assumption to circumvent this problem (Zhang et al., 1990). Incorporating the enrichment ratio above, all fallout is assumed to have occurred in 1963 and the net soil loss (depth) can be expressed as

$$\Delta H = HK_2^{-1}\left[1-(A_t/Y_t)^{1/(t-1963)}\right] \tag{4}$$

where A_t = total ^{137}Cs in plough layer, at time t (Bq m^{-2}), Y_t = cumulative baseline fallout at year t (Bq m^{-2}), H = depth of plough layer (cm), ΔH = depth of annual soil loss (cm), K_2 = enrichment ratio.

Using a plough layer depth of 20 cm, the simple mass balance procedure yields estimates of soil loss ranging from 1400 to 20,920 t km^{-2} yr^{-1}, with a mean of 6532 t km^{-2} yr^{-1} for sloping arable land. Comparing different calibration procedures, the simple mass balance model tends to give relatively high estimates of soil loss, especially for samples with a high percentage loss of ^{137}Cs. The proxy atmospheric fallout data derived from the Sarmiento and Gwinn model, supplemented by Japanese fallout records provides the input for running a time step mass balance model. In this case, the original Kachanoski and De Jong (1984) model was used:

$$\mathrm{d}A_t/\mathrm{d}t = D_t - (E_t\mathrm{K}_2/M + K_1)A_t \tag{5}$$

where D_t = atmospheric deposition rate of ^{137}Cs (Bq m^{-2} yr^{-1}) in year t, E_t = average annual erosion rate (kg m^{-2} yr^{-1}), K_1 = annual radioactive decay constant for ^{137}Cs (0.023 yr^{-1}), M = mass of soil in plough layer (kg m^{-2}).

The data yields net erosion estimates ranging from 907 to 12,527 t km^{-2} yr^{-1} with a mean rate of 4559 t km^{-2} yr^{-1}. Erosion estimates based on the Kachanoski and De Jong (1984) model are, as expected, lower than those derived from the Zhang et al. (1990) model (Fig. 7). Nevertheless, the former retains many simplifications including an immediate mixing of ^{137}Cs throughout the plough layer, whereas ^{137}Cs will be concentrated near the soil surface during the period between fallout and tillage. The estimates are also sensitive to the plough depth parameter. Erosion estimates produced from ^{137}Cs redistribution are also average rates for the period since fallout began to accumulate (i.e., 40 years). While this is an advantage for placing short term monitoring

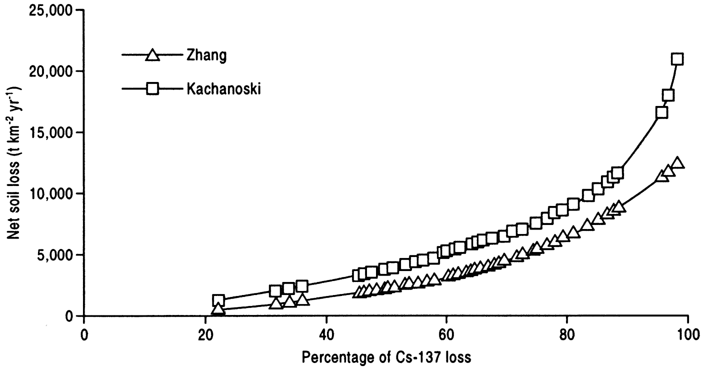

Fig. 7. Comparison of net soil loss estimates derived from two mass balance procedures.

Table 4
Proportion of Yiwanshui samples in different erosion classes

Erosion class	Equivalent erosion rate ($t\ km^{-2}\ yr^{-1}$)	Percent of samples in Yiwanshui catchment
Not Obvious	< 500	0
Slight	500–2500	26
Moderate	2500–5000	41
Severe	5000–8000	23
Very Severe	8000–13,000	10
Extremely Severe	$> 13,000$	0

results into a broader context there are limitations if the intensity of erosion and land-use history has varied.

The estimated rates of soil loss from a single location within a field represent average net erosion at the specific sampling location. However, it is argued that these midslope location be regarded as indicative of the gross erosion rate on the field. The mean gross erosion rate gives some indication of the relative status of erosion within the catchment as a whole. At around 4500 $t\ km^{-2}\ yr^{-1}$, the rate of soil loss is high by international standards but equivalent to other sites in southern China. However, the mean value masks considerable variability and the distribution of land with respect to erosion intensity is of more interest. Semi-quantitative erosion audits classify land into six categories with notional soil loss rates. All sites in the Yiwanshui catchment display net soil loss. Almost half the catchment has moderate erosion rates (Table 4), a quarter suffers severe loss and 10% are extremely severe. The largest rates of soil loss are associated with the steeper slopes within the catchment, but the spatial distribution of these sites is scattered. The influence of terrace design in establishing the slope gradient across the terrace riser and the relative amount of run-on from above has an important influence of ^{137}Cs redistribution and precludes any attempt to derive an interpolated map of field intensity. Rather, a stratified sampling strategy based on different terrace configurations is called for.

6. Summary and conclusion

The study has attempted to use the ^{137}Cs technique to estimate net rates of soil loss in a typical headwater catchment of the Three Gorges area, China. The use of ^{137}Cs measurements has a number of logistic advantages over more conventional monitoring methods but a number of uncertainties regarding the assumptions of the technique require attention. The main concerns are the difficulty of estimating the baseline fallout, the extent to which ^{137}Cs redistribution is directly related to soil erosion processes, the procedures to derive quantitative erosion rates from ^{137}Cs measurements, and the errors associated with such estimates.

The use of a hydrologically isolated paddy field as a baseline sampling site yielded a number of replicate cores with limited variability. In a subtropical zone experiencing intense monsoon rainfall, spatial variability in the wet deposition of fallout might be anticipated. In fact, the coefficient of variation calculated is lower than most previously reported studies, though this may in part reflect mixing within the paddy field. The use of the Sarmiento and Gwinn model to estimate atmospheric fallout over time, calibrated to local precipitation records yields similar baseline estimates to field samples and provides the time-series of fallout accumulation required for a more sophisticated mass balance model. Estimation of baseline fallout from precipitation records is useful for applying the ^{137}Cs technique in other parts of China where potential baseline sampling sites are difficult to find or are suspected to have been heavily disturbed. The use of a time-step model (Kachanoski and De Jong, 1984) yields lower estimates of net soil loss than the simpler lumped model (Zhang et al., 1990). The mass balance could be refined further to account for monthly variations in fallout accumulations and the timing of tillage events. The errors associated with soil loss estimation at individual sites remain high. The measured ^{137}Cs inventory incorporates both analytical error and uncertainty associated with the estimate of fallout.

The mean gross soil loss for the Yiwanshui catchment has been calculated as 4500 t km^{-2} yr^{-1}. This value indicates that soil movement in the dissected arable land surrounding the emerging Three Gorges Reservoir is severe, but masks considerable variability in soil loss which is partly explained by the slope gradient across terraced fields. The gross soil loss does not indicate the volume of sediment delivered to the Yangtze as there are numerous opportunities for storage within or off terraces. Improved estimation of soil erosion rates on the arable land surrounding the Three Gorges Reservoir must be coupled with analysis of sediment delivery pathways in order to provide information about sedimentation impacts downstream. A sediment budget of the Yiwanshui is currently under investigation using reservoir cores. The estimates of soil loss from this study suggest that the ^{137}Cs technique is suitable in the subtropical terraced environment. The major remaining uncertainty facing its application is the extent to which deliberate removal of soil material in the process of terrace maintenance compromises the tracing capability of ^{137}Cs. Observations of agricultural activity suggest that deliberate soil redistribution occurs frequently but that their impact is relatively minor compared to the movement of material by erosion processes. The pattern of ^{137}Cs redistribution in the catchment suggests that terrace configuration is an important control on soil loss.

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