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### Use of radionuclide, field based and erosion modeling methods for quantifying rates and amounts of soil erosion processes

Consultancy Report submitted to International Atomic Energy Agency (IAEA) as fulfillment of Contract I1406/RO

By P.J. Wallbrink, V. Belyaev, V. Golosov, A.S. Murray, and A.Yu Sidorchuk



Consultancy Report  
CSIRO Land and Water, December 2002



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## **Executive summary:**

This report is divided into two sections. The first section describes a comparison and integration of methods for deriving quantitative erosion rates on a severely eroded arable landscape. The second section is devoted to a study of the development and causes of gully erosion incorporating radionuclide and physically based methods.

## **Section I**

In this study we use a number of different methods to assess soil redistribution and sediment delivery occurring in a study area containing grassed slopes, a large arable field of 1.3 km<sup>2</sup> with incised gullies and downslope depositional fans and grassed bank/Balka system. The methods include: two variations of the soil survey approach; a proportional <sup>137</sup>Cs conversion model; a mass balance <sup>137</sup>Cs conversion model; a <sup>137</sup>Cs based tracer budget; direct measurement of gully volume by theodolite; examination of <sup>137</sup>Cs depth profiles; and finally a modified version of the USLE. Our results highlighted the importance of i) comparing such techniques, ii) validating the results from them, and iii) the value from combining or integrating them. In particular, the soil survey approach (using depletions in A<sub>plough</sub>, A, A<sub>b</sub> horizons) was able to separate the influence of sheet and ephemeral gully erosion by analyzing pit data from interill and gully hollow locations separately. The estimated soil redistribution rates using the proportional <sup>137</sup>Cs and Mass-Balance <sup>137</sup>Cs models were similar to one another 5.5 ± 0.8 and 5.3 ± 0.8 kg m<sup>-2</sup> yr<sup>-1</sup> respectively and gave better estimates of soil redistribution when combined with direct measurements of gully volumes. Rates and locations of sediment redeposition within sinks such as lower field boundaries and grassed valley banks were best evaluated by combining <sup>137</sup>Cs depth profile analysis and conversion models with careful soil descriptions. There was a good agreement between the soil survey and the <sup>137</sup>Cs tracing (combined with gully volume measurement) approaches. The Russian version of the USLE underestimated total surface erosion by a factor of 6 compared to the physically based approaches. The model may have been better used to assess soil redistribution occurring within interill areas, in which case the discrepancy could provide some insight into the contribution of tillage erosion. We conclude that it should be used with caution in arable regions where ephemeral gullying occurs.

## **Section II**

The Stavropol region of southern Russia is seriously affected by human-induced gully erosion. A lack of detailed information on the different stages of gully formation resulting from major agricultural expansion ~100 years ago, is an obstacle for management and containment of these systems. In this study we combine measurements of particle-bound radionuclides (<sup>137</sup>Cs, <sup>210</sup>Pb, <sup>226</sup>Ra, <sup>232</sup>Th and <sup>40</sup>K) and classical geomorphology to investigate and reconstruct the different phases of development of a gully during the last ~50 years. We believe the first phase (1) involved an initial incision into the bottom of a small valley (catchment area ~1 km<sup>2</sup>) about 100 years ago. A short period of rapid growth was followed by a longer stage of gully stabilization. Subsequent phases were; (2) the period 1954-1960 – in which re-incision in the lower gully reach was initiated by a high-magnitude event, and a substantial amount of sediment was delivered to the gully fan; (3) ~1960-1986 – the nickpoint retreated slowly, sediment was re-deposited nearby, and the fan surface

became stable; (4) 1986-1987 – a dam was built in the gully mouth and breached shortly after construction following 2 days of high rainfall, and substantial sediment accumulated in the gully above the dam and below the spillway channel on the fan surface; (5) 1987-1993 – the nickpoint retreat continued and the lower fan surface was stable until 1993 when the last significant runoff event overlaid it by ~10 cm of fresh sediment. These detailed reconstructions of gully development stages allow the contribution of high-magnitude events to gully growth and regional sediment delivery to be assessed. They further guide management actions to prevent such dam failures in the future.

**Key words:** sheet erosion, ephemeral gullies, Cs-137, USLE, gully erosion, gully development, radionuclides, sediment accumulation, landscape reconstruction

**“Use of radionuclide, field based and erosion modeling methods for quantifying rates and amounts of soil erosion processes”**

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## **Background**

In 1994 an international Russian-Australian research team undertook an extensive field study of water erosion processes on arable slopes at three key sites in the Stavropol region of South-West European Russia. The Australian team was led by CSIRO Land and Water scientists, the Russian team was represented by academics and students from Moscow State University Laboratory of Soil erosion and channel processes. The main aim of this study was to use different fallout radionuclides (such as  $^{137}\text{Cs}$  and  $^{210}\text{Pb}$ ) as tracers to assess the magnitude of slope wash, rill and gully erosion and subsequent deposition. The tracer methods were also to be assessed against traditional soil erosion monitoring approaches and the results combined and integrated together where appropriate. The study sites were chosen in the northern hemisphere because the  $^{137}\text{Cs}$  content is much higher in European soils than Australia, and hence more readily detectable with smaller uncertainties. In addition the research data would build upon the considerable knowledge base of erosion activity developed by Moscow State University in this region using traditional methods over a period of years.

Three study sites were chosen, with different erosion processes predominating in each. Slope wash and rill erosion processes dominated at the first site (Gefitskoe), gully erosion was the principle process at the second site (Gully site), and all three processes operated at the third site (Valley site). A total of about 500 soil samples were taken from these research areas. A small portion of these (about 50) were analysed in Russia for their  $^{137}\text{Cs}$  content alone, these gave quite promising results. The rest of the samples were sent to Australia in order to analyse them using the more sophisticated gamma spectrometers available at the CSIRO laboratories. The CSIRO equipment also analysed materials for their  $^{210}\text{Pb}$  and  $^{226}\text{Ra}$ ,  $^{40}\text{K}$  content, which are powerful tracers of surface eroded sediment, and a methodology previously unavailable in Russia.

Additional information has also been collected from the three study sites in the intervening period, including meteorological data, digital elevation models, and a history of land use and land use changes. All the soil samples originally taken have now been analyzed at CSIRO, and the final data set is unique as it allows one of the first opportunities to correlate estimates of soil loss and gain using fallout tracers, with estimates made by other independent techniques, such as the USLE and direct measurement of soil redistribution by theodolite, soil pits, and Digital Elevation Models. Most importantly, these objectives are co-incident with those outlined in the IAEA CRP on assessment of soil erosion through the use of Cs-137 and related techniques as a basis for soil conservation, sustainable agricultural production and environmental protection (D1-RC-629.2) in which it is deemed necessary to provide independent validation of Cs-137 derived erosion estimates.

This report provides an analysis of the results and interpretations of the first two study areas, Gefitskoe, and the gully site. The results from each area are written up and presented separately. They form the basis of research papers, that have or will soon be, submitted to international journals.

## **Acknowledgments**

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## **Section I: A comparison of direct measurement, USLE and Cs-137 based methods for evaluating severe sheet, rill and gully erosion**

Note: This section will be submitted to the journal 'Geomorphology' as manuscript titled: V.R. Belyaev, P.J. Wallbrink, V.N. Golosov, A.S. Murray, A.Yu. Sidorchuk., "A comparison of direct measurement, USLE and Cs-137 based methods for evaluating severe sheet, rill and gully erosion"

## Introduction

Human-accelerated soil erosion is estimated to affect  $\sim 1094 \times 10^6$  ha of continental landmasses (Lal, 1994). However in many areas reliable measurements of erosion are limited and assessing the extent and seriousness of erosion remains a difficult task (Higgitt, 1991). Catchment managers and landuse agencies are increasingly required to make decisions regarding the impact of landuse, or land management changes on sediment delivery downstream. The advent of GIS based tools combined with erosion models such as USLE (and its derivatives) appears to promise much in terms of documenting slope erosion at catchment scales, especially where labour and funding is limited or where data is absent or of poor quality (Prosser et al., 2001). However care must be taken to assess the appropriateness of such erosion models, and the circumstances under which they can be applied. One way to achieve this is to compare model based estimates of erosion losses to that predicted by independent methods.

The methods for measuring erosion and redistribution at the hillslope scale include theodolite surveys, rill volume measurements (Poesen et al., 1996; Govers and Poesen, 1988), suspended sediment runoff monitoring (Kronvang et al., 1997), soil surveys (Larionov et al., 1973) and various tracing techniques of which  $^{137}\text{Cs}$  is the most widely adopted (Ritchie et al; 1974; Kachanoski, 1987; Walling and Quine, 1991; Walling and He, 1999). The outcomes of these measurements may then be incorporated into a sediment budget (Dietrich and Dunne, 1978; Loughran et al., 1992; Golosov et al., 1992; Walling, 1999). Any comparison of methods needs to be undertaken at the same spatial and temporal scales, and the suitability of a method to a particular spatial and temporal resolution must be accounted for. The upscaling of results from single techniques can also result in a poor understanding of erosion. An example of this would be extrapolation of soil loss rates from erosion plots to whole slope or catchment scales without allowing for deposition and storage and how this may result in reduced sediment delivery to streamlines (Walling, 1983).

The opportunities for comparison and integration of results from different methods are limited and examples in the literature are rare (Montgomery et al., 1997; Turnage et al., 1997). The scarcity of such comparisons is unfortunate as important information on the role of different erosion processes and their influence at different scales is not captured (Boardman et al., 1990). Furthermore as some methods are

suitable to quantifying particular processes (say plots for sheet or rill erosion) while others to quantifying overall net losses (say inventories of  $^{137}\text{Cs}$ ), it is believed that a combination of approaches will probably yield the most informative estimates of soil redistribution and losses occurring from large fields and small catchments. These are the scales that management is most frequently undertaken and for which information is required.

Our study aims to apply a suite of methods to evaluate soil redistribution in a study area comprising grassed slopes, a large arable field and downslope depositional areas (Total area  $\sim 2.0 \text{ km}^2$ ). Erosion in the arable field ( $1.3 \text{ km}^2$ ) arises from concentrated and unconcentrated flow as well as tillage translocation. This is an ideal environment for comparing methods because it allows for detachment, entrainment, transport, deposition and storage at a scale that is realistic for assessment of whole slope losses and their integration into any catchment scale model. Where appropriate we combine approaches to quantify the importance of particular processes and their contribution to soil redistribution within, and sediment losses from, the field. Data from these methods are incorporated into a provisional sediment budget which we use to estimate sediment delivery into the adjoining drainage network. We believe this is the first time that such a comparison, and combination, of approaches has been applied at this scale.

There are 3 different methodological approaches used in this study i) physically based methods ii) soil redistribution tracing use of caesium-137 ( $^{137}\text{Cs}$ ) methods and iii) application of a modified for Russia version of the USLE model. The advantages and disadvantages of the different methods and approaches are also discussed.

## **Study area**

### *General region*

The general study region is located on the eastern edge of the Stavropol upland (Fig. 1). It is characterized by contrasting topography (relative height range of about 100 to exceeding 150 m) mainly resulting from tectonic uplift associated with the development of the Caucasian folding zone during the Neogen-Quaternary period. The geology is complex - sandstones, clays and marls predominate, in some areas bedrock is covered with Late Quaternary loess loams up to a few meters thick

(Belousov and Enman, 1999). Chestnut soils (alfisols, according to the USDA soil classification) prevail in the region and chernozem soils generally occupy arable areas. Cultivated land occupies about 45-50% of the territory, mainly on flat interfluvial and gentle slope areas. Pastures prevail on steeper slopes of rivers or within ephemeral stream (balka) valleys. Climate of the region is characterized by a relatively cold winter with temperatures below zero for 3-4 months and a hot summer with temperatures up to 40°C. Mean annual precipitation is 400 mm, most of it associated with heavy summer rainstorms in excess of 30-60 mm for one event (Climatological., 1990).



Figure 1. The study area location (the Upper Kalaus river basin is shown in grey and marked by an arrow).

The region is seriously affected by soil degradation usually associated with the spring snowmelt (February-March) and summer rainstorms (May-July). Average erosion rates of 0.5-1 t ha<sup>-1</sup>y<sup>-1</sup> (0.05-0.1 kg m<sup>-2</sup> y<sup>-1</sup>) for the snowmelt period and 20-30 t ha<sup>-1</sup>y<sup>-1</sup> (2-3 kg m<sup>-2</sup>y<sup>-1</sup>) for summer have been reported (Ryabov, 1974; Zaslavski, 1979; Sidorchuk and Golosov, 1995). These rates are not sustainable for local soil types and large volumes of sediment have been delivered into valleys of low order ephemeral streams and small rivers. This has resulted in partial infilling and loss of permanent watercourses in the region (Golosov et al, 1997).

### *The study site*

Our study area was located on the northern slope of the Dolgaya balka (where the Russian term 'balka' stands for a small valley without permanent watercourse) 3.5 km north of the Gofitskoe village (Figure 1). The height range between the balka bottom and the ridgetop is about 150 m. The length of the slope is about 2.5 km and has a complex form (fig. 2). The upper part is a relatively steep uncultivated convex escarpment 600-700 m long (unit 1, fig. 2) with average gradient of 0.1-0.2 (5-11°). It is predominantly covered with grasses, only a few trees are present. It then changes downwards into the midslope concavity (unit 2, about 300-400 m long), which connects the upper steep section to the lower gentle straight slope. This slope is about 1500 m long, (comprising units 4-7) with an average gradient of 0.04-0.05 (2.7-3°) and undulating cross profile. The cultivated part of the study area (comprising units 2, 4-7) is ~1800 m long, with average width of ~700 m and area of ~1.3 km<sup>2</sup>. The forest shelter belt (width ~35 m, unit 3) designed to protect the field from wind erosion runs along the entire length of the western side of the paddock. It has been a permanent feature since the beginning of cultivation. The total area of units 1-7 is ~2.0 km<sup>2</sup>.

The study field has a Chernozem soil (described below). Visual observation suggests that the soil surface in the cultivated area is about 10-20 cm lower than the adjacent undisturbed surface of the forest shelter belt (Unit 3). The field was cultivated around 1930 (Yasunskii, 1978). Summer wheat was the main crop before the 1950s. After this winter wheat, corn, sunflower and sugar beetroot were introduced along with a three year crop rotation.

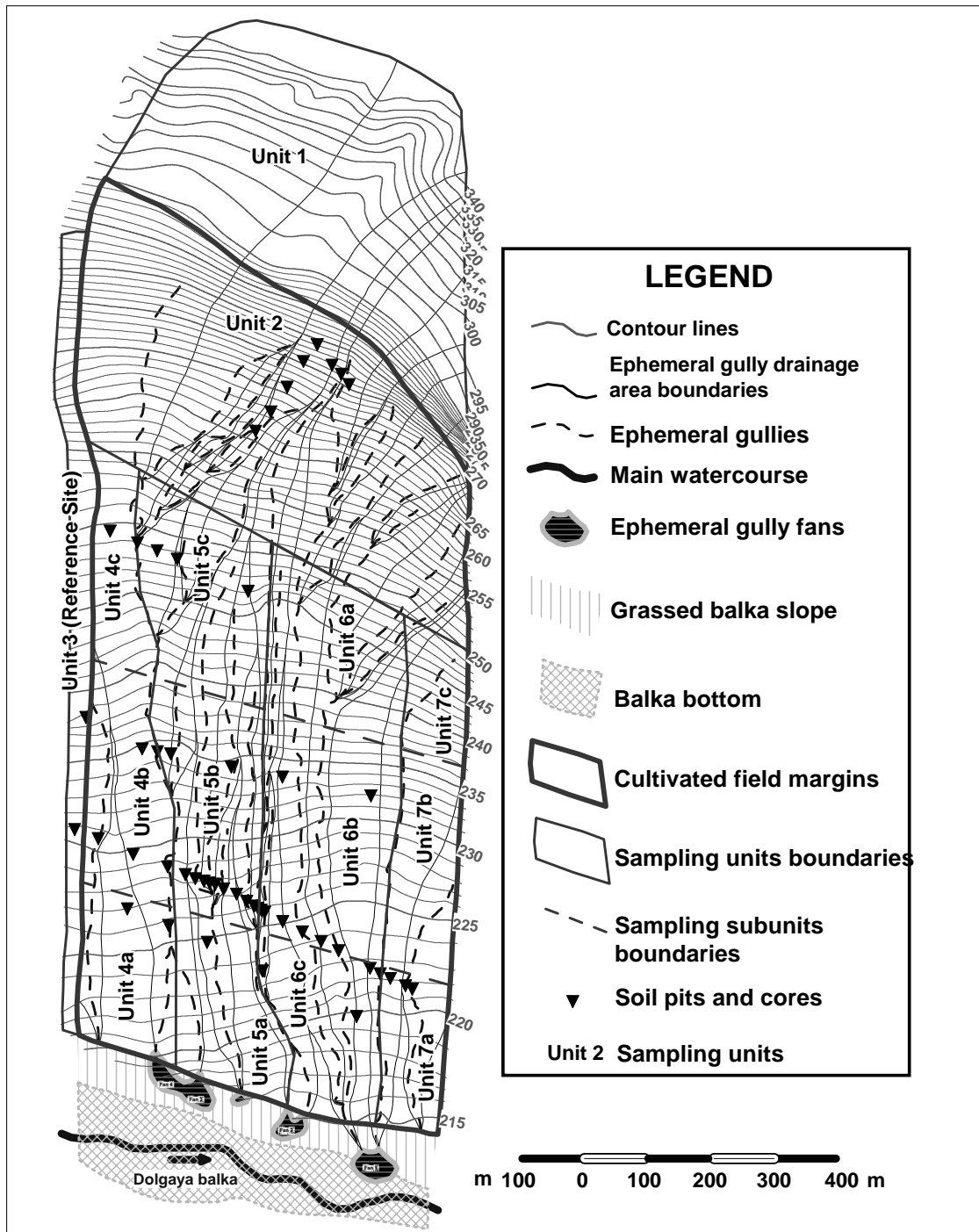


Figure 2. Landscape units of the study area (for sampling strategy see description in text).

### *Erosion forms of the study site*

The major features of the study area are a series of parallel hollows running downhill almost the entire length of the arable slope (fig. 2). Large rills/ephemeral gullies, with depths varying from 0.1 to ~1.0 m, and widths of 0.5 to ~5.0 m occupy the bottom of the hollows; the length of the main branches can exceed ~1 km. Their

heads are usually located in the upper concave part of the arable slope (unit 2). Runoff concentrates in these gully systems and numerous secondary gully branches occur on the field, forming a dense network. The location of the most prominent gullies are given on figure 2 which also shows that most of the field is potentially linked to downslope areas by concentrated runoff through this network. Sediments from the gullies are deposited as a series of fans on the grassed balka slope below the lower field boundary (fig 2).

Observations over successive years have shown that the ephemeral gullies are semi-permanent features and reappear almost at the same place, even after their removal by ploughing. In general, the largest branches of the gullies are completely infilled by ploughing during the cereals treatment only, although the general shape remains as a mould. Effectively the cycle of their infill and reincision is repeated not more than once per 3 years. The material filling the gullies after ploughing is very loose, the bulk density is less than  $1.0 \text{ g cm}^{-3}$ . This low density combined with the concentration of water flow in these depressions makes it easier for erosion to occur at the same locations again.

Soil translocation by tillage (Quine, 1999) appears to be an important mechanism for redistributing soil within the field. Sheet erosion by overland flow also delivers sediment into the rill network as well as delivering it directly out of the field onto the lower parts of the cultivated slope. The cultivated field is separated from the Dolgaya balka bottom by a grassed buffer strip less than 100 m wide. A few depositional fans occur at the outlets of the largest ephemeral gullies. Most of the grassed slope, however, does not show any visible evidence of substantial sedimentation, although some studies (Panin et al., 2001) have shown that these areas may be important sediment sinks.

## **Methods**

The cultivated field in the study area is subject to a combination of rill (ephemeral gully), sheet and tillage erosion. We aim to evaluate the total soil loss that occurs from the study area, as well as the contributions from all the different erosion processes in the arable field. The methods used to achieve this are described below.

The first approach involves comparing the thickness of upper organic soil horizons in disturbed cultivated areas (such as our study field) to those in undisturbed

soils. The decrease of thickness in the  $A_{\text{plough}}$ ,  $A_1$  and AB horizons in the cultivated areas can be used to estimate the total soil loss for the entire period of cultivation, although it is unable to determine the particular erosion process responsible for that depletion (Larionov et al., 1973). Some refinement of this approach is possible by choosing different geomorphic locations for the survey pits (Kiriyukhina and Serkova, 2000) for example rill versus interill zones. Limitations to this approach are often associated with variations in natural soil horizon thickness. However, it has been shown that in cases of severe soil losses (to which the study site is believed to belong) this variation is less than that due to erosion (Larionov et al., 1973). In addition, if multiple observations from undisturbed locations are made then natural soil variability can be described and accounted for.

Directly measuring the volume of rills and ephemeral gullies, approach can also be used to estimate the amount of material removed from the field by concentrated water runoff (Boardman and Evans, 1994). This requires the date and timing of incision to be known which can be determined via farm records and aerial photography (Poessen et al., 1996), the volumes themselves are measured by theodolite and cross sectional area survey.

The use of  $^{137}\text{Cs}$  in soil erosion studies is now widespread and there are many examples of its use in quantifying rates of soil redistribution (Ritchie et al., 1974; Kachanoski, 1987; Walling and Quine, 1990; Higgitt 1991; Wallbrink and Murray, 1996; Walling and He, 1998, 1999; Panin et al., 2001). The basis of the technique involves comparing the  $^{137}\text{Cs}$  inventory ( $\text{Bq m}^{-2}$ ) within a disturbed soil to that in a nearby 'reference' location (Walling and Quine, 1990). The reference inventory is usually measured directly or can be obtained from relationships between  $^{137}\text{Cs}$  activities and annual rainfall, (Basher et al., 1995). A relative  $^{137}\text{Cs}$  loss in the soil with respect to the 'reference' value indicates erosion, a relative gain represents deposition. A number of different models have been proposed for converting radionuclide inventories to soil redistribution rates. These generally fall into two categories – empirical relationships and theoretical models, reviews of these can be found in Walling and Quine, (1990) and Walling and He, (1999).

The  $^{137}\text{Cs}$  method can be used to derive an average soil redistribution rate for the period since commencing of fallout (1953 for the Northern hemisphere) however it also cannot distinguish between the effects of different erosion processes during this time. It has also been argued that the technique is limited to sites where sheet and

shallow rill erosion predominate, as deep rilling and gulying involve redistribution of subsoil material having no  $^{137}\text{Cs}$  content. However, in this paper we aim to demonstrate how total soil losses, and the relative contributions to it from different erosion processes can be obtained when  $^{137}\text{Cs}$  data and physical measurements are combined. Furthermore, measurements of  $^{137}\text{Cs}$  can also be combined with measurements of landscape attributes to derive  $^{137}\text{Cs}$  based tracer budgets (Quine et al., 1994; Wallbrink et al., 2002). These can be used to quantify soil redistribution between different units of the study area as well as any export from it to off-site locations.

Finally we compare the results of these field methods to those made using a USLE-based erosion model. We use an evolution of the original equations from Wischmeier and Smith, (1965;) and its later RUSLE developments (Renard et al., 1994). Specifically the model gives estimates of sheet erosion rates basing on detailed topographic data and local soil properties as well as rainfall records and land use information. The version we used was developed for use in Russia using a large spatially distributed dataset of coefficients. Modifications include an improved set of equations for determining topographic factors (Larionov et al., 1998), calculating and mapping a rainfall erosivity index for European Russia (Krasnov et al., 2001), as well as adaptation of land use factors and soil protection techniques specific to the Russian agricultural system. The output is generated as a series of geocoded points with values of soil loss which can then be exported to various GIS tools for visual presentation and manipulation with other spatial data.

### *Experimental design and sample analysis*

Fieldwork was undertaken in the summers of August 1993 and August-September 1994. The initial work in 1993 involved physical descriptions of the study area, in particular the erosion and deposition zones. A series of soil samples were collected from the cultivated field (ie. the soil surface, soil pit walls, gully walls and gully floor) as well as one of the ephemeral gully fans on the grassed balka slope below the lower field boundary. Initial results showed that soils from the cultivated field plough layer contained substantial  $^{137}\text{Cs}$  activities, suggesting that  $^{137}\text{Cs}$  could be used to assess the rates of surface soil redistribution in the study area, and that further sampling was justified. At the same time, no detectable  $^{137}\text{Cs}$  was found in the walls

and floor of the ephemeral gully system. We concluded from this that other methods (ie. physical measurements) were required to quantify the contribution of the ephemeral gullies to soil loss from the field.

Consequently, the major part of the fieldwork was carried out during August-September 1994. The experimental program was designed to fulfill the data requirements of the methods discussed above, and was divided into five main areas:

i) The organic layer thickness of the soil surface was measured in 35 soil pits and 19 soil cores (locations given in fig 2.). Four of the pits were outside the cultivated area at undisturbed locations. The locations of the pits and cores in the cultivated field were chosen to represent i) the hollows in which the ephemeral gullies were located and ii) the flat or slightly undulating interfluves between them. In total, 5 pits and 11 cores were taken from the hollows and 24 pits and 8 cores were taken from the interfluves between them. Soil profile attributes from these locations were also analyzed to qualitatively determine differences in linear erosion and slope wash rates. Samples from different soil layers were taken from pits in both the cultivated and undisturbed locations to determine changes in soil bulk density.

ii) The cross-sections and thalweg profiles of the ephemeral gullies were measured by tape in 50 representative locations. The cross-sectional areas were combined with measurements of their average size and length (as well as known temporal and spatial patterns) to estimate the soil volumes lost from these systems.

iii) A topographic survey of the study field was undertaken using an optical theodolite. The survey mainly covered the lower cultivated part of the study area with an emphasis on the ephemeral gully network. This formed the basis of a digital elevation model which was also used in the USLE modeling work.

iv) The soil sampling for  $^{137}\text{Cs}$  inventories involved taking i) depth increment samples from pits, and ii) a series of bulked cores from the different landscape units (Fig 2). One pit was excavated within the reference area (unit 3), three at different parts of the cultivated field (units 4, 5, and 6) and two from depositional surfaces (one in a sheet deposition zone and another in an ephemeral gully fan). The pits were sampled to 0.4 m depth with known cross-sectional area and depth intervals of 5 cm. The gully fan however was sampled to 1.0 m depth, the bottom layer representing the original soil surface. The bulked cores were obtained by driving a 24.5 x 7.5 cm cylindrical steel corer into the soil. Cores were taken from the seven sampling units (given in Fig. 2), as well as the sheet deposition zones and ephemeral gully fans. Each

unit was divided into three roughly equal areas, and then ten cores were taken randomly from each area, weighed and then mixed together as a group. One subsample was then extracted (about 250 g) for subsequent gamma analysis from each group. This procedure provided  $n = 30$  individual cores to describe the  $^{137}\text{Cs}$  activity in each unit, of which 3 (mixed samples) were actually analysed. The mixing method does not allow a point-based analysis of  $^{137}\text{Cs}$  distribution; however it provides a cost-effective method to quantify differences in mean  $^{137}\text{Cs}$  inventories between landscape units (Wallbrink et al., 2002).

v) A series of bulked soil samples were taken from units 1-6 (fig 2.) to determine the particle size characteristics in erosion, deposition and transport zones, as well as investigate the relationship between particle size and radionuclide content. The bulked samples were comprised of individual samples randomly obtained from the soil surface (normally 10) within each unit and then mixed thoroughly together. About 1.0 kg was then weighed, wet sieved and settled into <2, 2-10, 10-20, 20-40, 40-63, 63-125, 125-250, 250-500 and >500  $\mu\text{m}$  size fractions. The separated fractions were then oven dried, weighed again and then analysed for their  $^{137}\text{Cs}$  content. All  $^{137}\text{Cs}$  and grain size analyses were undertaken in the CSIRO L&W radionuclide facility in ACT, Australia. The soil and sediment samples were oven dried, ashed at 400°C, ground in a ring mill, and then analysed by gamma spectrometry according to methods outlined in Murray et al. (1987). Detectors used were two 'Ortec' and one 'Canberra' HPGe Closed Ended 'n' type Coaxials. Samples were counted for a minimum of 85 ks.

vi) Finally, a USLE-based model was employed to independently calculate surface sheet erosion from the study field. The coefficients required to run this model include topography, geology, climate, soil, vegetation properties and land use and these were defined from a combination of field observations, laboratory analysis, as well as published and unpublished sources. The model runs on a PC platform and was developed in the Laboratory of Soil Erosion and Channel Processes, Faculty of Geography, Moscow State University. Land use data (for the USLE modeling and determination of rill/gully volumes), was collected from the literature, as well as topographic maps and discussions with local authorities. The rainfall record was obtained from the nearby cities of Svetlograd and Stavropol.

## Results and Discussions

### *Estimates of soil loss based on soil survey and pit data*

As above, the change in thickness of the  $A_{\text{plough}}$ ,  $A_1$  and AB horizons between observed and ‘reference’ soil pits can be used to estimate total soil loss. We use two variations of this method. The first involves a simple spatial interpolation of the values from all the pits disregarding their geomorphic position. This provides a value of total average soil loss, but makes no allowance for the specific influence of the ephemeral gullies. The second approach assumes that gully erosion occurs as separate processes and that it is limited to the relatively small areas within the bottoms of the slope depressions. The surface sheet and ephemeral gully erosion rates are then calculated separately according to their surface areas and then combined to give a total.

The results are given in Table 1. The highest erosion rates ( $8890 \text{ t yr}^{-1}$ ) arise from the simpler spatial averaging used in the first approach, presumably because the values from the pits located in the hollows are interpolated to a larger surface area than they actually cover. The estimates based on the second approach are ~20% lower ( $7080 \text{ t yr}^{-1}$ ), and as we believe they are based on a more realistic concept of erosion processes, they are our preferred values. The difference between the two approaches also highlights the need to consider the different types of soil erosion that is occurring before interpreting data from this method. This is especially important in our study area where a spatial analysis based on regular grids poorly represents the active rill /gully erosion forms.

Table 1. Soil erosion rates and volumes estimated from soil survey pit data for the cultivated part of the study area ( $\sim 1.3 \text{ km}^2$ ).

	Approach I	Approach II		
	Spatial interpolation method (all points)	Sheet erosion zones	Linear erosion zones	Total erosion (sheet and linear erosion)
Average soil loss ( $\text{mm yr}^{-1}$ )	5.0	3.5	0.5	4.0
Average soil loss ( $\text{kg m}^{-2} \text{ yr}^{-1}$ )	7.0	4.9	0.7	5.6
Average annual soil loss ( $\text{t yr}^{-1}$ )	8890	6230	850	7080
Total soil loss since 1930 (t)	570000	399000	54300	453000
Total eroded layer since 1930 (mm)	320	225	30	255

In our field, the area directly affected by linear erosion forms (defined as the bottoms of slope depressions occupied by rills and ephemeral gullies) was 9.3 ha, or ~7% of the total field area (~127.0 ha). The calculated contribution of sediment from these features 850 t y<sup>-1</sup> represents about 12% of the total erosion amount (7080 t y<sup>-1</sup>; Table 1). This is about twice the relative yield expected from their area if it was affected by sheet erosion only. About 6230 t y<sup>-1</sup> (or 88%) of the total erosion from the field is estimated to be from sheet erosion on an annual basis using this method. The estimated sediment contribution from the gullies (12%) is consistent with the range, 10-46%, given in Poessen et al., (1996) for arable fields in Europe (derived from loess soils) and 19-81% for fields in North America.

The pit from the gully fan at the base of the field showed that the original soil surface was buried by ~1 m of deposited sediment. The surveyed area of the gully fans (fig. 2) was ~1.4 ha. Using this information we roughly estimate the total amount of sediment deposited on the fans to be ~9540 t or ~2% of the total soil eroded from the field since the beginning of cultivation (assumed to ~1930). No precise data is available on the amount of deposition on the grassed balka slope between the fans (area ~5.2 ha), but is believed to be about 10% of that on the fans (see discussion below). In combination these data suggest that no more than 4% of material eroded from the field is stored in these off-field sinks and the remainder, ~96%, has been delivered offsite to the valley bottom. This implies a very high sediment delivery ratio which is probably due to the narrowness of the grassed buffer zone although nonetheless agrees well with data from other methods presented below.

#### *Depth distributions and inventories of <sup>137</sup>Cs*

The depth incremental profiles of <sup>137</sup>Cs from different units of the study area are given in figure 3. The profile for the undisturbed site (fig. 3a) has an exponential shape, with the majority of the <sup>137</sup>Cs inventory being retained within the upper 10 cm of soil- this is generally consistent with those observed in undisturbed soils elsewhere (Owens et al., 1996; Wallbrink et al., 1999) although with the Chernobyl fallout overlaid onto the surface layer. The total inventory agrees well with the integral samples taken from the same unit (3) nearby. The reference <sup>137</sup>Cs inventory was calculated to 5440±380 Bq m<sup>-2</sup>, representing the mean of the inventories from the unit

3 integral samples (n=30 cores, 3 mixed samples counted) and the reference pit. The coefficient of variation in the undisturbed sampling site was 7.1%. The reference inventory value is also relatively close to that of another detailed sampling site ( $4910 \pm 1360 \text{ Bq m}^{-2}$ ) located in the Kalaus river basin nearby (Belyaev et al., submit). The Chernobyl contribution at that site was established to be  $\sim 30\%$  of the total  $^{137}\text{Cs}$  inventory. Based on the geographical closeness of the two sites, we make the assumption that a similar contribution from chernobyl fallout has occurred here. This has important implications for conversion of our  $^{137}\text{Cs}$  data to soil redistribution rates described further below.

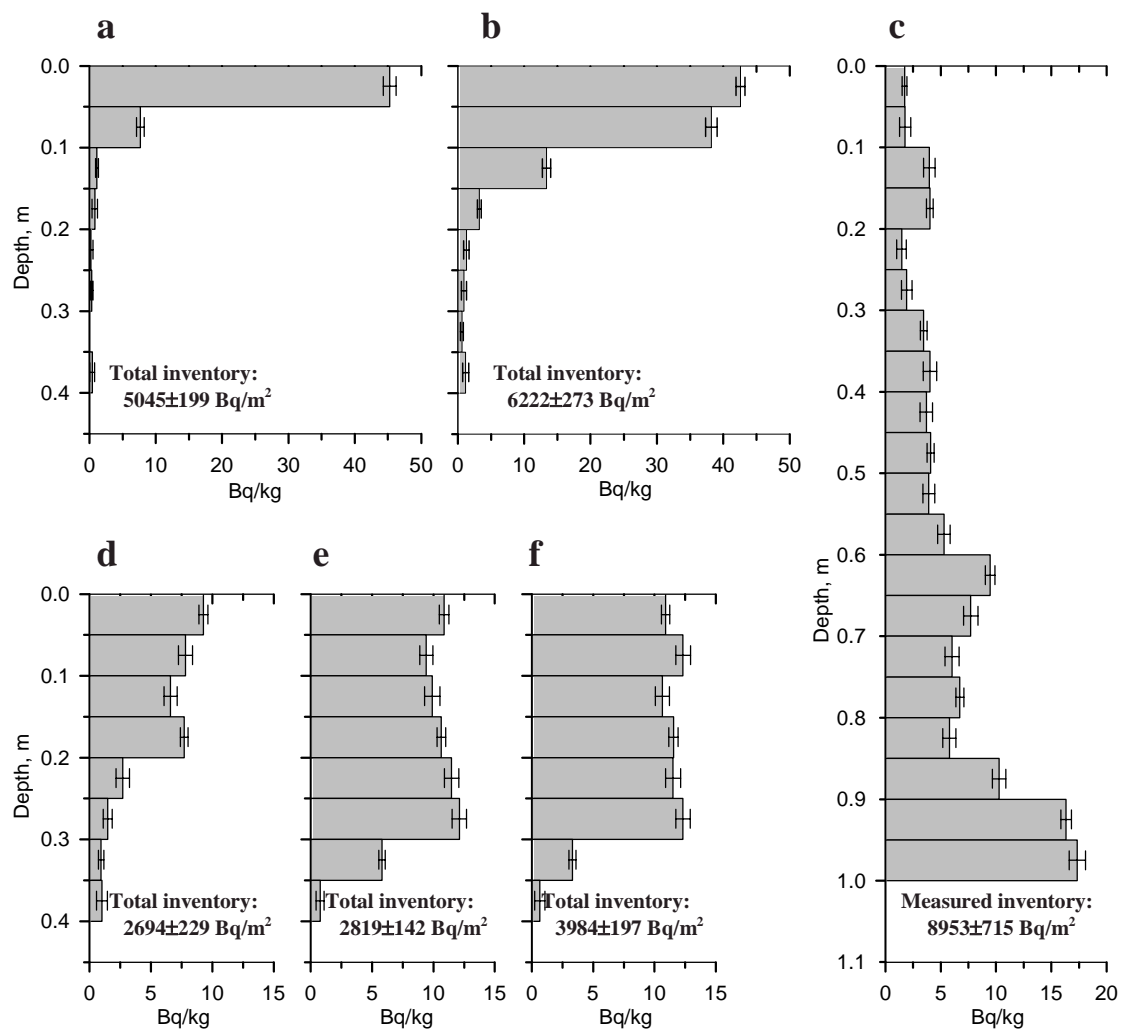


Figure 3  $^{137}\text{Cs}$  depth profiles and inventories in different landscape positions: a) undisturbed forest shelter belt soil; b) grassed balka slope below the cultivated field; c) ephemeral gully fan; d), e) and f) different parts of the cultivated field.

Depth profiles from the depositional locations (fig. 3b,c) in the study area show evidence of continuing sedimentation. In the sheet deposition zone (fig 3b) the

increase in total  $^{137}\text{Cs}$  inventory (~20%) and depth penetration (~10 cm) - relative to the reference site- suggest that soil with a high radionuclide content has gradually accumulated here during the fallout period. This supports the conclusion that sheet erosion is the predominant sediment source of recently deposited material for that part of the grassed balka slope. There are no additional  $^{137}\text{Cs}$  peaks in the depth profile to that at the surface. This implies that the rates of sedimentation here are low and that peaks from the recent sediment deposits overlay one another in the top 10 cm of the profile.

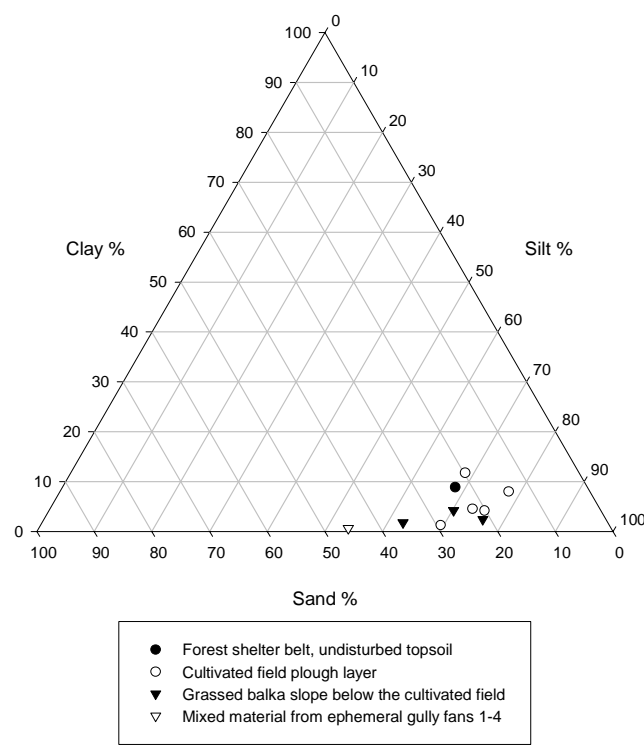
The  $^{137}\text{Cs}$  distribution in the fan of the ephemeral gully (fig. 3c) however shows that substantial sediment accumulation has occurred. We did not sample below 1.0 m depth so we conservatively place the 1963 peak at this layer. This depth also has the highest  $^{137}\text{Cs}$  activities  $17.5 \text{ Bq kg}^{-1}$ , and coincides with the location of the original soil layer observed at the base of the pit. The overlaying sediment layers generally have low  $^{137}\text{Cs}$  concentrations implying that deep linear erosion of subsoil is the main source of these deposits and that the contribution of  $^{137}\text{Cs}$ -rich material from sheet and tillage erosion has been minimal.

The depth distributions of  $^{137}\text{Cs}$  in the cultivated parts of the field (fig. 3d,e,f) are relatively uniform and constant with depth, and similar to those reported in the literature (Walling and Quine, 1990; Owens et al., 1996). The small differences between the pits are best explained by variability of the bulk density in the plough layer which presumably arises from compaction by agricultural machinery as well as variations in plough depth (which is 20-30 cm). It can also be seen that depth penetration of  $^{137}\text{Cs}$  exceeds 25 cm in these areas, implying that our integral sampling approach (using the 25 cm metal corer) may have underestimated the  $^{137}\text{Cs}$  inventories in these locations. The average quantity of  $^{137}\text{Cs}$  below 25 cm was estimated to be ~13% (from the data in Figure 3d,e,f) and so we use this to correct the other inventory values (see below) obtained by the metal corer.

#### *Particle size analysis*

Enhancement of  $^{137}\text{Cs}$  due to sediment fining during transport has been identified as an important factor when applying conversion models to  $^{137}\text{Cs}$  data (Walling and Quine, 1990; Walling and He, 1998; 1999). The particle size composition of topsoil from different parts of the study area is given in Figure 4,

however the data show no significant differences in grain size between undisturbed, eroded and deposited soils. The exception is the bulk sample from the gully fans with high sand and low silt and clay content, presumably reflecting loss of fines to the valley bottom. One of the samples from the grassed balka slope is also enriched in sand and depleted in fines, although the others lie within the range of samples from the plough layer.



Undisturbed	22.95	68.19	8.86
Cultivated	14.13	77.89	7.98
Cultivated	29.27	69.46	1.27
Cultivated	19.79	68.44	11.77
Cultivated	22.14	73.35	4.51
Cultivated	20.23	75.59	4.18
Grassed	35.55	62.67	1.78
Grassed	25.58	70.21	4.21
Grassed	21.41	76.20	2.39
Fans 1-4	45.63	53.75	0.62

Sample site	Sand, %	Silt, %	Clay, %
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Figure 4: Particle size composition of topsoil at different landscape positions.

Observations of sediment texture in the down-slope gully deposition pits, also suggest that aggregate saltation is an important sediment transport mode in addition to fluvial transport. For example, large aggregates of up to 2-3 cm, were frequently observed in sediment layers. These were rounded and sometimes coated in sand. We conclude that particle size variability and especially selective erosion and accumulation will probably not significantly bias the relationship between soil redistribution and  $^{137}\text{Cs}$  inventories in our study area. Therefore we do not incorporate particle size correction factors in our subsequent manipulations as the texture variation between samples and locations is generally within the range of 10-15%. The exception here is the ephemeral gully fans (as above), where depletion of  $^{137}\text{Cs}$  has occurred due to loss of fines. However, we resolve this problem by using direct measurements of the deposition layer thickness from the pits as well as supporting data from  $^{137}\text{Cs}$  depth distributions.

#### *Assessing soil redistribution using a $^{137}\text{Cs}$ budget*

In this section we construct a  $^{137}\text{Cs}$  budget to quantify soil redistribution rates for the study area. The method is described more fully in Wallbrink et al., (2002) however briefly, involves determining the surface areas and mean  $^{137}\text{Cs}$  inventories within each landscape unit (fig. 2). The product of these data enable total storages and losses of  $^{137}\text{Cs}$  to be calculated for each landscape unit in relative and absolute terms. The data from the individual units can then be incorporated into a catchment budget enabling the overall  $^{137}\text{Cs}$  fluxes and sinks to be calculated for the entire study area. In creating this budget we assume that  $^{137}\text{Cs}$  is redistributed with transported sediment, that no external sources of  $^{137}\text{Cs}$  are present, and that the mean inventories of  $^{137}\text{Cs}$  in the landscape units have been properly characterized by our sampling methodology. The budget (fig. 5) shows that most of the  $^{137}\text{Cs}$  loss occurs from the cultivated slopes ( $3980\pm 550$  MBq) from where it is directly (or at least quickly) delivered to the main valley bottom and out of the study area system. Only ~1% of the total  $^{137}\text{Cs}$  loss ( $88\pm 37$  MBq) is redeposited within intermediate sink areas, ie. the sheet deposition zones or the ephemeral gully fans. A further loss of  $480\pm 120$  MBq has occurred from the grassed upper slope area, although this represents only some 5% of the total loss amounts over the 40 year period.

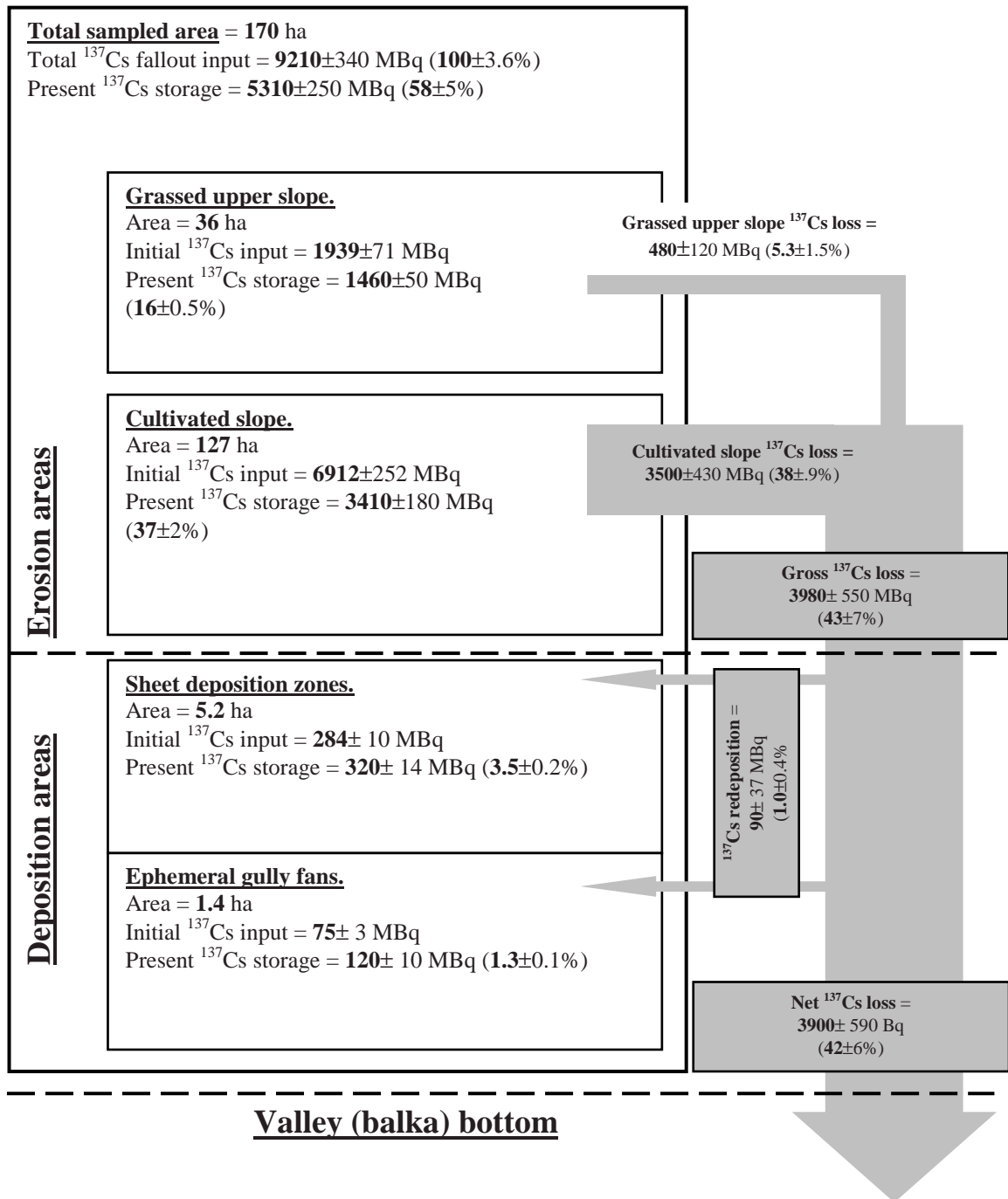


Figure 5. <sup>137</sup>Cs redistribution budget for the study area.

Estimates of sediment loss and gains can also be made using this data, and is undertaken by multiplying the <sup>137</sup>Cs losses or gains from each landscape unit by their average measured <sup>137</sup>Cs activity in the surface soil (neglecting fallout history, landuse changes and assuming erosion is uniform). Values for <sup>137</sup>Cs concentrations (Bq kg<sup>-1</sup>), losses and gains (MBq), as well as calculated erosion and deposition amounts (t) for

the main landscape units, are given in Table 2. These show that some 399,200±68,000 (t) soil has been eroded from the arable field in the study area since beginning of fallout in 1953. It also shows that further losses of 34,800±12,000 (t) have occurred from the grassed upper escarpment in this time, as noted from the <sup>137</sup>Cs budget above, (unit 1, fig. 2). This suggests that erosion in the region occurs even under natural vegetation, especially where steep converging slopes favor runoff concentration.

Table 2. <sup>137</sup>Cs based sediment budget show losses and gains as well as soil redistribution for different landscape units of the study area.

Landscape units	Area (ha)	<sup>137</sup> Cs loss/gain (MBq)	Mean <sup>137</sup> Cs concentration (Bq kg <sup>-1</sup> )	Soil loss/gain (t)
Grassed upper escarpment	35.6	-480±120	13.9±0.5	-34780±12000
Arable field	127.0	-3500±430	9.2±0.5	-399200±68000
Sheet deposition zone	5.2	320±14	19.7±0.6	2060±4710
Ephemeral gully fans	1.4	120±10	6.0±0.5	8040±1500
Gross loss	162.6	-3980±550	-	-433980±80300
Net loss	162.6	-3900±590	-	-423890±86500

The total amount of soil and soil depth eroded since 1930 can also be estimated if it is assumed that erosion rates established from the <sup>137</sup>Cs data (for the period 1953 – 1994) remain constant back to 1930. Using this approach the soil loss from surface runoff erosion is calculated to be 7.9±1.3 kg m<sup>-2</sup> y<sup>-1</sup>. This is higher than that obtained from the soil survey data (4.9 kg m<sup>-2</sup> y<sup>-1</sup>, Table 1) reflecting either errors in converting the <sup>137</sup>Cs budget into a sediment budget or a real increase in erosion rates after 1953.

#### *Assessing soil redistribution using <sup>137</sup>Cs conversion models*

Soil redistribution rates can also be derived from <sup>137</sup>Cs data using conversion models. These relate <sup>137</sup>Cs inventories (Bq m<sup>-2</sup>) to rates of soil loss (t ha<sup>-1</sup>). A number

of different factors are accounted for in the models depending on their degree of complexity. Two different conversion models were applied to the data in this study: i) the proportional model and ii) the mass balance model. Full details of i) are given in de Jong et al., (1983) and Kachanoski, (1987) and ii) in Walling and He, (1998; 1999).

The strength of the proportional model is its simplicity. It assumes that the  $^{137}\text{Cs}$  inventory change in a plough layer is directly related to the average soil redistribution rate. Alternatively the mass balance model is more sophisticated taking into account the  $^{137}\text{Cs}$  fallout history, dilution of  $^{137}\text{Cs}$  in the plough layer by incorporation of subsoil, erosion events prior to tillage, and characteristics of the initial depth distribution of  $^{137}\text{Cs}$ . As the study area has experienced a contribution (~30%) of Chernobyl fallout the ability to account for changes in the temporal fallout pattern seemed an important advantage of the latter model.

The results of these models are presented in Table 3 (which also contains a summary of the  $^{137}\text{Cs}$  budget for comparison). Erosion values estimated by both models are surprisingly similar, and within uncertainties of one another. This was unexpected as discrepancies between these models have been recently reported mainly associated with overestimation of erosion rates by the proportional model (Walling and He, 1999). The good agreement in our study area is best explained by the fact that soil erosion rates are high, as seen by the >50% depletion of  $^{137}\text{Cs}$  from the cultivated part of the study area. Under such circumstances the uncertainties associated with the  $^{137}\text{Cs}$  technique are substantially decreased.

The soil redistribution rates from both conversion models ( $5.5\pm 0.8$  and  $5.3\pm 0.8$   $\text{kg m}^{-2} \text{y}^{-1}$ ) are lower than from the  $^{137}\text{Cs}$  budget ( $7.9\pm 1.3$   $\text{kg m}^{-2} \text{y}^{-1}$ ; Table 3). However, they are comparable to the soil survey data for unconcentrated surface runoff erosion ( $4.9$   $\text{kg m}^{-2} \text{y}^{-1}$ ; Table 1). There are two important implications from this. Firstly, the reason for the discrepancy between the budget values and the other methods is most likely due to the transition from the radionuclide to sediment flux data. It may be necessary to allow for a temporal variation of  $^{137}\text{Cs}$  concentration in the plough layer (which was neglected in the process of constructing the  $^{137}\text{Cs}$  budget). However, in practical terms this requires incorporating an additional modeling procedure and so it seems more prudent to use conversion models, especially when spatially distributed data are available. Secondly, the data imply that

no significant increase in soil redistribution rates occurred in the interrill areas between 1930-1953 and 1953-1994. This suggests that the total eroded soil depth, and volume, calculated from the  $^{137}\text{Cs}$  conversion models is probably valid for the entire period of cultivation.

Table 3. Soil redistribution rates and volumes estimated from  $^{137}\text{Cs}$  budget and conversion models.

		Method I. Estimated from $^{137}\text{Cs}$ budget	Method II. $^{137}\text{Cs}$ conversion models	
			Proportional model	Mass-balance model
Arable field (area ~127.0 ha)	Average soil loss ( $\text{mm y}^{-1}$ )	5.6±1.0	3.9±0.6	3.7±0.6
	Average soil loss ( $\text{kg m}^{-2} \text{y}^{-1}$ )	7.9±1.3	5.5±0.8	5.3±0.8
	Average annual soil loss ( $\text{t y}^{-1}$ )	9980±1700	6950±1040	6680±1000
	Total soil loss since 1930 (t)	638700±109000	437700±65700	421000±63000
	Total eroded layer since 1930 (mm)	360±60	250±40	240±40
Ephemeral gully fans (area ~1.4 ha)	Average deposition ( $\text{mm y}^{-1}$ )	10.5±2.0	4.9±0.7	4.5±0.7
	Average deposition ( $\text{kg m}^{-2} \text{y}^{-1}$ )	14.7±2.8	7.0±1.0	6.3±0.9
	Average annual sedimentation ( $\text{t y}^{-1}$ )	202±38	95±14	86±13
	Total sedimentation since 1930 (t)	12870±2400	5970±900	5440±820
	Total deposited layer since 1930 (mm)	670±130	310±50	280±40
Sheet deposition zone (area ~5.2 ha)	Average deposition ( $\text{mm y}^{-1}$ )	0.7±1.6	1.1±0.2	1.1±0.2
	Average deposition ( $\text{kg m}^{-2} \text{y}^{-1}$ )	0.9±2.3	1.5±0.2	1.5±0.2
	Average annual sedimentation ( $\text{t y}^{-1}$ )	50±120	80±12	80±12
	Total sedimentation since 1930 (t)	3290±7540	5070±760	5080±760
	Total deposited layer since 1930 (mm)	45±100	69±10	70±11

The calculated deposition rates for the balka bank grassed buffer zone from the conversion models are lower than that from the soil pit and  $^{137}\text{Cs}$  depth distribution profiles (Table 3). However, deposition rates for gully fans are difficult to derive using conversion models, especially where a high contribution of subsoil occurs. It should also be noted that these conversion models were designed for application to

arable fields. It is unlikely that their application to uncultivated areas such as our grassed slope will yield reliable results. We believe that the best approach to quantify sediment accumulation in such uncultivated areas can be obtained by comparing  $^{137}\text{Cs}$  depth distributions in these areas to those from undisturbed reference areas.

#### *Combining $^{137}\text{Cs}$ conversion modes data with gully volume measurements*

The estimated volumes of gully erosion were based on the assumption that their observed pattern of temporal development was constant for the period of cultivation since 1930. Complete infill of the gullies takes place only when the fields are cultivated for wheat – which is normally once every three years. However, major re-incision is likely to be associated with extreme summer rainstorms, which have a recurrence period of 8-10 years in this region (Belyaev et al., submit). On this basis, we suggest a conservative estimate of the complete cycle of ephemeral gully formation here, of ~10 years, although we acknowledge the cycle may alter due to changes in land management practices, extreme runoff events and the introduction of heavy agricultural machinery. Consequently, our loss estimates from the gullies here should be treated as a tentative conservative estimate. Nonetheless using the above information (including the low bulk density of the gully infill material) the volumes of material eroded from the ephemeral gully network have been calculated (Table 4). This has been further combined with the estimated erosion rates from the interrill surfaces (from the  $^{137}\text{Cs}$  conversion models) to derive total soil erosion rates for the arable field (table 4).

Tables 4 and 1 show that the soil survey method (Approach II) and the  $^{137}\text{Cs}$  conversion models (combined with gully volume measurements) provide similar estimates of soil loss from our arable field. The predictions of average soil loss ( $\text{mm y}^{-1}$ ), average annual soil loss ( $\text{t y}^{-1}$ ) and total soil loss since 1930 (t) are also all within uncertainties of one another. These similarities increase our confidence in the results and support the co-application of both methods in the future. We note that this does not increase the cost or effort of field investigations as soil survey and  $^{137}\text{Cs}$  sampling can be simultaneously undertaken.

Table 4. Estimates of total soil erosion by combining gully volume measurements with <sup>137</sup>Cs conversion model data.

Method	Ephemeral gully volumes*	Proportional model with ephemeral gully volumes added	Mass-balance model with ephemeral gully volumes added
	linear erosion zones	Total erosion	Total erosion
Average soil loss (mm y <sup>-1</sup> )	0.4	4.3	4.1
Average soil loss (kg m <sup>-2</sup> y <sup>-1</sup> )	0.6	6.1	5.9
Total eroded layer since 1930 (mm)	27	272	262
Average amount of soil eroded (t y <sup>-1</sup> )	742	7690	7424
Total soil loss since 1930 (t)	47516	485209	468472
Note: * assuming bulk density of 1.0 Mg m <sup>-3</sup> , and re-incision cycle of 10 years			

*Estimates of soil loss using modified for Russia RUSLE*

Estimates of sheet erosion rates for the arable field from our RUSLE method are given in Table 5. The model was run with a DEM of the study field, digital representation of the network of major flow lines, land use characteristics, soil mechanical properties (obtained from our study site) and erodibility coefficients (from the dataset within the model). The major constraint was the requirement for rainfall erosivity index (R) which is generally calculated using long-term information on individual rainfall events. However, such data for the study area was only available for the period 1960-1980. Our calculations are initially based on data from this period and then later extrapolated to 1930-1994, although in doing so we make the assumption that rates of sheet erosion are constant which is partially supported by the Cs-137 data from above.

Table 5. Estimates of soil loss by sheet erosion from the study field obtained using modified for Russia version of the USLE model.

	Average (1960-1980)	Maximum (1968)	Minimum (1978)
Rainfall erosivity index	13.9	34.4	0.7
Average soil loss (kg m <sup>-2</sup> y <sup>-1</sup> )	0.9	2.7	0.1
Annual eroded layer (mm)	0.7	2.0	0.1
Average amount of soil eroded (t y <sup>-1</sup> )	1175	3490	81
Extrapolated for 1930-1994 period assuming constant erosion rates:			
Total eroded layer since 1930 (mm)	42	125	3.0
Total soil loss since 1930 (t)	75200	223360	5184

Calculations were initially undertaken on an annual basis with inputs of R estimated separately for each year. Spatially distributed estimates of annual soil losses from each grid cell were averaged to obtain a single representative value over the 21 year period (first column in Table 5, Figure 6a). However, it is also possible to analyse each year individually. Differences in predicted erosion rates arising from variations in the annual rainfall erosivity index are given in Table 5 and Figure 6b, c. For example, the highest number of heavy rainstorms (and thus highest R value) occurred in 1968; the year with lowest R value was 1978 (a drought year). There is nearly a factor of 30 difference in predicted soil losses between these years. Clearly the model is sensitive to R and applying the model without detailed information on this could lead to serious errors.

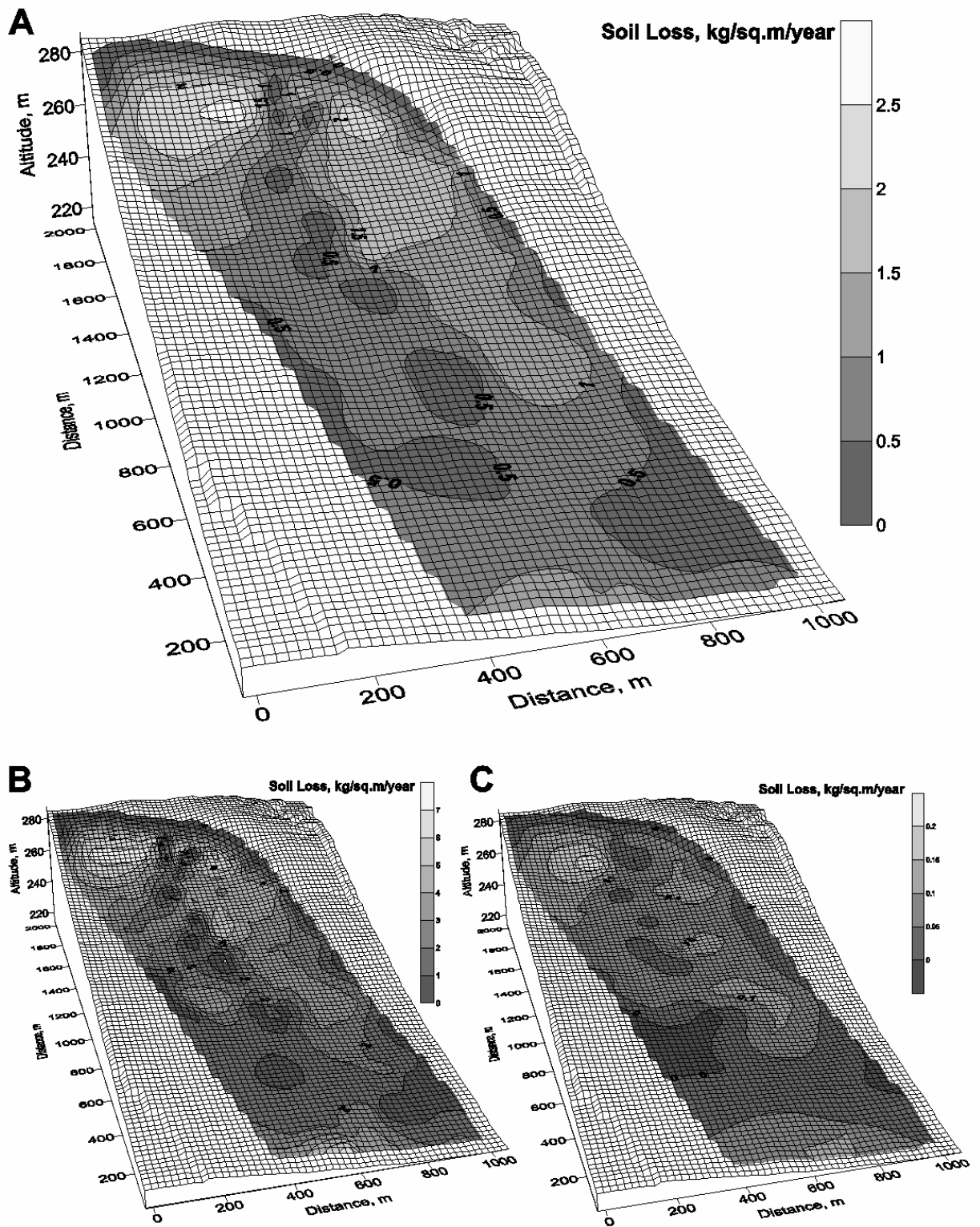


Figure 6. Maps of average sheet erosion rates calculated using modified for Russia USLE model: a) averaged for period 1960-1980; b) maximum (1968); c) minimum (1978).

The soil loss estimates from the modified USLE are lower than those from the field based methods (Tables 1-4). Even the maximum possible erosion rate value from 1968, ( $2.7 \text{ kg m}^{-2} \text{ yr}^{-1}$ ) is a factor of 2 below the mean of the soil survey and Cs137 based approaches ( $5.6$  and  $6.0 \text{ kg m}^{-2} \text{ yr}^{-1}$ ; respectively). The mean value  $0.9 \text{ kg m}^{-2} \text{ yr}^{-1}$  is a factor of 6 below the mean soil survey and Cs-137 based approaches. We believe the model has underestimated soil losses; the principal reason being the models foundation on empirical data derived from erosion plots with relatively uniform soil surface characteristics. The consequence is a failure to account for larger scale redistribution processes such as ephemeral gully formation and tillage translocation. A similar phenomenon was observed by Turnage et al., (1997) who report RUSLE derived erosion rates a factor of 10 lower than those from  $^{137}\text{Cs}$  in cultivated fields which they also attribute to RUSLE failing to account for rill and gully erosion. In this respect our USLE model also does not account for the gully network although Figure 6 shows that the main slope depression in the central part of the field is treated as a zone of decreased erosion.

However these shortcomings do not mean USLE is inappropriate for our study area. A strength of the model may be its ability to assess sheet erosion rates between the gully systems, especially where redistribution occurs by sheet and rainsplash erosion. We aim to test this idea in future developments of our work. The discrepancy between erosion rates calculated using the model and those from the field techniques may also be attributable to tillage translocation. If this is correct then tillage may be responsible for more than 80% ( $5.6 - 0.9 = \sim 4.7 \text{ kg m}^{-2} \text{ yr}^{-1}$ ) of the sediment redistributed into the ephemeral gully network. Although this figure appears high, it is consistent with values of  $5.5 \text{ kg m}^{-2} \text{ yr}^{-1}$  for tillage translocation in cultivated terraces of the loess plateau reported by Quine et al., (1999). Further evidence is also given in Quine, (1999) that tillage erosion may generally dominate over water erosion in terms of soil redistribution in cultivated fields.

To fully exploit the potential of erosion modeling on large arable fields such as ours with complex topography and multiple erosion processes, it is probably necessary to combine three separate models – i) for interrill erosion, ii) for rill and ephemeral gully erosion and iii) for tillage translocation. Such work is beyond the scope of the present analysis, however will be explored in the future.

### *Comparing and combining results from different methods*

We have employed a number of different methods to quantify the redistribution of soil from the different parts of our study area. In some cases the methods overlap in their ability to predict redistribution rates and so there is the opportunity to compare and/or combine results from them. With the exception of the USLE-based modeling, all the methods suggest severe soil losses from the arable part of the study field (units 4-7). The average overall soil erosion rate varies between  $0.9 \text{ kg m}^{-2} \text{ y}^{-1}$  (USLE; Table 5) and  $7.9 \text{ kg m}^{-2} \text{ y}^{-1}$  ( $^{137}\text{Cs}$  budget; Table 3). The estimates from the physically based methods were very similar (between  $5.6$  and  $7.9 \text{ kg m}^{-2} \text{ y}^{-1}$ ; Tables 1-4), the best agreement was between the soil survey method approach ii) ( $5.6 \text{ kg m}^{-2} \text{ y}^{-1}$ ) and the combined  $^{137}\text{Cs}$  conversion model with gully volume measurements ( $6.1 \text{ kg m}^{-2} \text{ y}^{-1}$  – proportional model,  $5.9 \text{ kg m}^{-2} \text{ y}^{-1}$  – mass-balance model). The physically based methods also estimated the total eroded layer for the entire cultivation period to be 255, 272 and 262 mm (soil survey, proportional model with gully volumes, and mass-balance model with gully volumes, respectively; Tables 1-4). These are consistent with one another given their uncertainties and our visual observations of the relative height difference between the undisturbed soil in the adjacent forest shelter belt (unit 3) and the arable field.

The erosion rate values ( $\text{t yr}^{-1}$ ) for each part of the study area, from each of the different methods, are also summarized in Table 6 (which lists the methods 1-8). By calculating our preferred redistribution rates for each of the landscape units the data can be used as the basis of a provisional sediment budget. In terms of erosion from the grassed upper escarpment area (unit 1) there is only one estimate ( $870 \text{ t yr}^{-1}$ ) derived using method (3). If processes are separated into sheet and ephemeral gully erosion in the arable field then there are four estimates of sheet loss, methods (2,4,5,8). We take the average of the three field based approaches (2,4,5) deriving a value of  $6620 \text{ t yr}^{-1}$ . We exclude the USLE based value however because it has not accounted for the gully erosion (as above). There are four estimates of deposition in the grassed areas (methods 3,4,5,6) and although we favor method (6) because it is the most direct, we have no reason to discount the  $^{137}\text{Cs}$  budget method, and so we take the average of them,  $\sim 115 \text{ t yr}^{-1}$ . The values from the two  $^{137}\text{Cs}$  conversion models (4,5) are neglected as the models are designed to be used in arable fields, not for offsite sedimentation. A similar argument applies to the deposition on the gully fans. Again,

we favor the most direct estimate from method (6) - the  $^{137}\text{Cs}$  depth profiles – although we cannot discount the predictions of methods (2) and (3), and so we include them to derive an average value of  $\sim 250 \text{ t yr}^{-1}$ . Total losses from the system have been estimated by five different methods and there is reasonably good agreement between them. However we choose to take the average of methods (2,3,4,5) and exclude that of method (1) as it has not provided a realistic conceptualization of erosion on the arable field. Nonetheless from these data we calculate the sediment delivery from the field to be  $\sim 7680 \text{ t yr}^{-1}$ .

Table 6. Summary of average annual soil losses and gains ( $\text{t yr}^{-1}$ ) from the different study area landscape units

Methods	Landscape units					
	Grass area - erosion	Main arable slope (erosion)		Grassed lower slope and balka bank (deposition)		Sediment delivery to the balka (output)
		Sheet erosion areas	Ephemeral gullies	Sheet deposition areas	Ephemeral gully fans	
1) Soil pit survey (i)		8890			150	8740
2) Soil pit survey (ii)		6230	850		150	6930
3) $^{137}\text{Cs}$ budget	870	9980		50	200	10500
4) $^{137}\text{Cs}$ proportional model		6950		80	95	6780
5) $^{137}\text{Cs}$ mass balance model		6680		80	86	6510
6) $^{137}\text{Cs}$ depth profiles				180	490	
7) Direct gully volume measurement			740			
8) USLE		1175				
Preferred values – (methods used)	870 (3)	6620 (2,4,5)	795 (2,7)	115 (3,6)	250 (1,2,3,6)	7680 (2,3,4,5)
Note: a) Rounding errors occur in this table b) Reasons for selection of methods described in text						

A sediment budget for the study area showing the long term annual redistribution of soil within and from the field (averaged over 1930-1993) can now be constructed using these data (Figure 7). It shows that most erosion occurs from the arable field and that no significant redeposition occurs even along the field's lower margin. Negligible sedimentation occurs in fans on the lower grassed buffer strip which does not exceed 5% of the total soil loss from the field. This implies that about 95% of eroded sediment is delivered to the downslope balka system. This in turn supports the findings of Golosov et al., (1997) that many first order rivers and channels have aggraded following intensive agriculture and cultivation. This

underlines an urgent need for developing a system of watercourse protecting measures in the Stavrapol region.

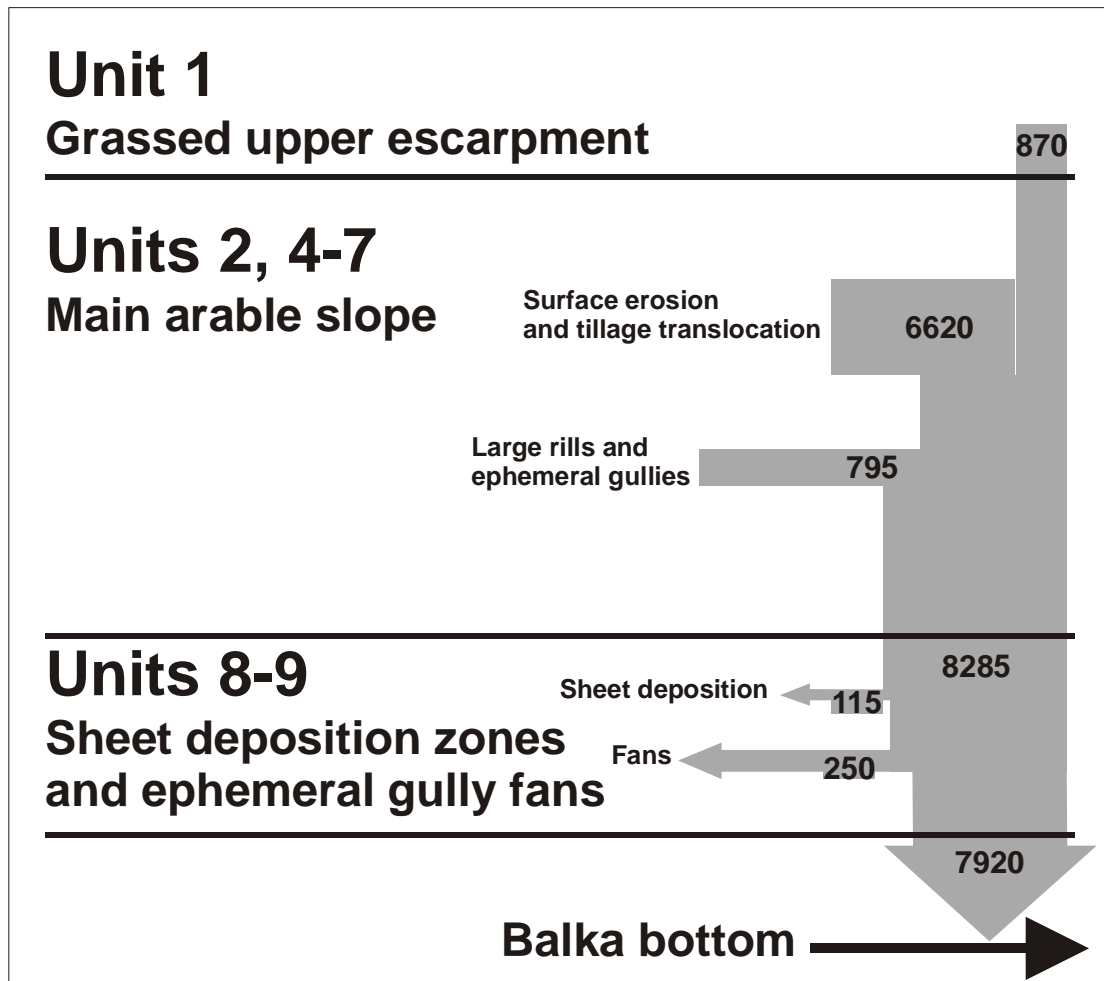


Figure 7. Sediment budget for study area based on data in Table 6.

The USLE-based modeling does not allow sediment budgets to be constructed directly as they can not estimate sediment storages. Nevertheless, our provisional budget (from above) suggests that USLE predictions of sediment delivery to the drainage system would be significantly underestimated as tillage and gully erosion are not accounted for.

## Summary and Conclusions

We have compared a number of independent methods to assess soil redistribution and sediment delivery from a study area containing grassed upper slopes, a large arable field of 1.3 km<sup>2</sup> with semi-permanent rill and ephemeral gully network, downslope buffer zone of grassed dry valley (balka) bank with depositional fans. In the arable field surface erosion was found to be important and responsible for redistributing surface soil and delivering it to the gully network at an annual rate of ~5 kg m<sup>-2</sup> yr<sup>-1</sup>. The tillage translocation was not directly measured but by implication could be as high as 80%, this is consistent with observations elsewhere (Quine et al., 1999). The ephemeral gully network is a transport pathway for eroded material as well as a source of fresh material in itself (at ~1 kg m<sup>-2</sup> yr<sup>-1</sup>), this is consistent with studies cited in Poessen et al. (1996) that such gully systems in cultivated fields contribute at least 10% of the total sediment flux. The process of removing the gullies by ploughing does not remove the features in the longer term, nor the processes which create them. Sediment deposition in storages at the outlet of the field were measured and shown to be low (representing only 5% of total eroded material). The data from the different processes and methods were combined in a sediment budget showing that inputs from erosion far exceed the capacity for storage. Sediment losses from this system are high and the potential for downstream impacts are large.

Our attempts to use multiple independent methods to evaluate soil redistribution rates has highlighted the importance of i) comparing such techniques, ii) validating the results from them, and iii) the value from combining or integrating them. Each method has strengths and weaknesses and in some cases we have suggested improvements to them. The soil survey approach (using depletions in A<sub>plough</sub> A, AB horizons) conceptually cannot separate the contributions from specific erosion processes. However, we were able to separate the influence of unconcentrated and concentrated flow erosion by analysing data from soil survey pits located within and outside hollow network separately. The precision of the method is difficult to assess, but could probably be improved by analysing more reference pits to evaluate variability in natural soil morphometry.

We have shown that the <sup>137</sup>Cs technique can be combined with direct measurements of rill/gully volume to better estimate soil redistribution in locations where ephemeral gullying occurs. In this situation the recurrence intervals for the

formation and destruction of these features must be known in order to extrapolate results to longer periods. Rates and locations of sediment redeposition within sinks such as lower field boundaries, plough terraces and grassed valley banks can also be evaluated by combining  $^{137}\text{Cs}$  depth profile analysis, conversion models, and careful soil description.

To best describe soil redistribution using  $^{137}\text{Cs}$  conversion models in large areas (such as our study field  $1.3 \text{ km}^2$ ) a large number of individual soil samples ideally should be taken (Walling and He, 1999). However in some cases this would be unaffordable or impractical, so we support the mixing method used here, where large groups of samples taken from defined landscape units are mixed together into one representative sample for that unit (Wallbrink et al., 2002). A drawback is that this does not allow detailed point-based spatial analysis of isotope (and thus soil) redistribution to be undertaken, although it does provide the means to cost effectively quantify mean  $^{137}\text{Cs}$  and soil redistribution rates at the landscape unit and entire field scale. It is this scale of data which is often required for regional GIS models and land management authorities.

There was a good agreement between the soil survey and the  $^{137}\text{Cs}$  tracing (combined with gully volume measurement) approaches. We believe that significant advantages in both precision and process understanding are gained when these techniques are used together. This does not increase either field efforts or costs as soil survey and  $^{137}\text{Cs}$  sampling can be conducted simultaneously.

Finally, the Russian version of the USLE significantly underestimated erosion at the whole field scale compared to the direct approaches. However, our study field was large and contained complex topography and erosion forms. The model may have been better used to assess sediment delivery occurring from smaller segments of the field to the main rills and gullies. In this case the model could be used together with the field-based techniques. The discrepancy between the modified USLE and field techniques-based estimates of soil loss from inter-rill areas could provide some insight into the contribution of tillage erosion. However the model should be used with caution for catchment scale predictions of sediment delivery to streams in the Stavropol region, or in any other arable regions where deep rilling and ephemeral gullying are important soil degradation processes.

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## **Section II: Reconstructing the development stages of a gully in Russia**

Note: This section has been submitted to Earth Surface Processes and Landforms as manuscript titled:  
V.R. Belyaev, P.J. Wallbrink, V.N. Golosov, A.S. Murray, A.Yu. Sidorchuk., “Reconstructing the  
development stages of a gully in the upper Kalaus basin - Stavropol region (southern Russia)”

## **Introduction**

### *The Problem*

Gully erosion is an active and widespread geomorphic process in the upper Kalaus river basin on the Stavropol upland of Southern European Russia. This steppe landscape has some of the highest soil erosion and gully rates within European Russia, with mean rainfall erosion rates of up to 20-30 t ha<sup>-1</sup>y<sup>-1</sup> (Ryabov, 1974; Zaslavski, 1979). These have been mainly associated with phases of high intensity summer rainfall, which have an average return period of 8-10 years and last for 2-4 years (Ledneva and Mescherskaya, 1977, Climatological., 1990).

Dense gully networks now occupy many catchments in the region and new flow lines have occurred in response to anthropogenic activity (Kosov, 1978; Sidorchuk and Golosov, 1995). There has been a substantial loss of productivity from these lands due to the effects of erosion and sedimentation (Sobolev, 1961) as well as significant loss and damage to infrastructure such as roads and bridges. Significant off-site impacts such as eutrophication and increased turbidity of rivers have also been observed, in addition to substantial aggradation of ephemeral streams, sediment infilling of the upper reaches of drainage networks and loss of permanent watercourses (Golosov et al, 1997).

The primary cause of the severe soil and gully erosion is believed to be a combination of intensive grazing on upland areas (Shul'zhenko et al, 1977) and active cultivation. Both of these became more widespread within the last 100 years (Tcvetkov, 1957; Golosov, 1996). In particular, because slopes in the region are quite steep, serious cultivation in the Upper Kalaus basin only began in 1925–1935 with introduction of more advanced agricultural machinery. This took place during the transition period from individual to collective farming in Russian agriculture (Yasunskii, 1978). Maximum rates of gully erosion were observed in the first half of the 20<sup>th</sup> century when the area under cultivation increased to around 40-55% (Tcvetkov, 1957; Kosov, 1978)

In response to the growth of these gullies systems a program of small dam construction was initiated in the region, most of them built in the upper reaches of small rivers, creeks (balkas) or gullies. The purpose of some was to buffer runoff, trap sediment and prevent gully growth while others were built to protect roads and

infrastructure (Prytkova, 1972). The sediment accumulated above these dams provides an additional record of erosion and sediment delivery within the catchments.

### *Processes and knowledge gaps*

The process by which gully growth occurs in the region can be summarised by the following stages of development. i) a few years of very rapid incision - characterised by nickpoint growth and gully deepening with active deposition on a downslope fan, ii) this is followed by a decrease in linear growth but an increase in volume growth rate due to active bank retreat and iii) beginning of deposition in lower parts of a gully bottom. The process continues until iv) the gully reaches a critical size where the catchment area above the nickpoint provides insufficient runoff to maintain its active retreat; following this v) gully length and nickpoint activity stabilize, although the gully volume continues to increase due to sidewall retreat, the gully sides become more gentle and vegetated. During this final stage, redeposition of eroded material from a gully walls (as well as sediment from the upper catchment) within the gully bottom is the main process. It finally leads to channel infilling and a change from V-shaped to U- or box-shaped cross-section. Further cycles of re-incision and filling can then occur in the gully floor (Sobolev, 1961; Rozhkov, 1981; Gully erosion, 1989).

Managing these active gully systems requires a quantification of the processes outlined above. The role of climate (in particular rainfall) in gully formation and development must also be assessed. Although some knowledge of the landuse and climate conditions during the last active phase of gulying in this region exists, only average rates of longitudinal growth (or main nickpoint retreat) are reported in the literature for Stavropol region and some other parts of European Russia (Kosov, 1978; Gully erosion, 1989; Nazarov, 1992; Rysin, 1998). There is a lack of detailed quantitative information about the stages and processes of gully development during this critical period of rapid regional growth.

### **Objectives of this study**

To address this gap we aim to reconstruct the phases of development in a gully, typical for the Upper Kalas river basin. To achieve this we combine two

different approaches. The first is a conventional geomorphological description of soil pits, theodolite survey, temporal analysis of maps, geological surveys, rainfall and land use records. The second involves more novel radionuclide-based tracing techniques, including measurements of fallout Cesium-137 ( $^{137}\text{Cs}$ ) and unsupported (or 'excess') lead-210 ( $^{210}\text{Pb}_{\text{ex}}$ ) as well as lithogenic radium-226 ( $^{226}\text{Ra}$ ), thorium-232 ( $^{232}\text{Th}$ ) and potassium-40 ( $^{40}\text{K}$ ). The tracer measurements are undertaken on material from detailed depth-incremental and integral sampling of the gully bottom, banks, fan and erosion source and deposition areas in the gully and surrounding catchment. The combined data allow us to accurately reconstruct the temporal stages of incision and infill of this gully over the last ~50 years and link them to their likely anthropogenic and natural causes. Further, we assess the inputs of different sediment sources to and from the gully network and derive sediment accumulation rates on the fan associated with the gully system. This detailed temporal and process understanding of the gully system is necessary to improve land management, design and construction of erosion and sedimentation counter-measures for the region.

#### **The study area and known history**

##### *The Kalaus river basin and Stavropol region*

The Kalaus river basin is located in Southern European Russia on the eastern edge of the Stavropol upland (Fig. 1).



Figure 1. The upper Kalaus basin and the Stavropol region location.

The upper part of the Kalaus basin is characterised by contrasting relief, with a relative height range of ~ 100 - 150m. The slopes are steep, with dominantly convex or convex-concave profiles. The geology of the Stavropol upland is very complex as it lies adjacent to the northern edge of the Caucasian mountains. Sandstones, clays, limestones and marls are the predominant bedrock types. Soils are classified as chestnut, according to the Russian soil classification (alfisols by the USDA soil classification). Cultivation occupies about 45-50% of the territory, mainly on flat interfluves and gentle slopes. Pastures prevail on steep slopes of river or ephemeral stream (balka) valleys. The climate of the region is characterised by relatively cold winters with temperatures around zero from November to February and a hot summer with temperatures up to 40°C. Mean annual precipitation is about 400 mm (Fig. 2). Observable high variability from year to year is mostly associated with heavy rainstorms in May-August, which sometimes exceed 30-60 mm for one event (Climatological..., 1990).

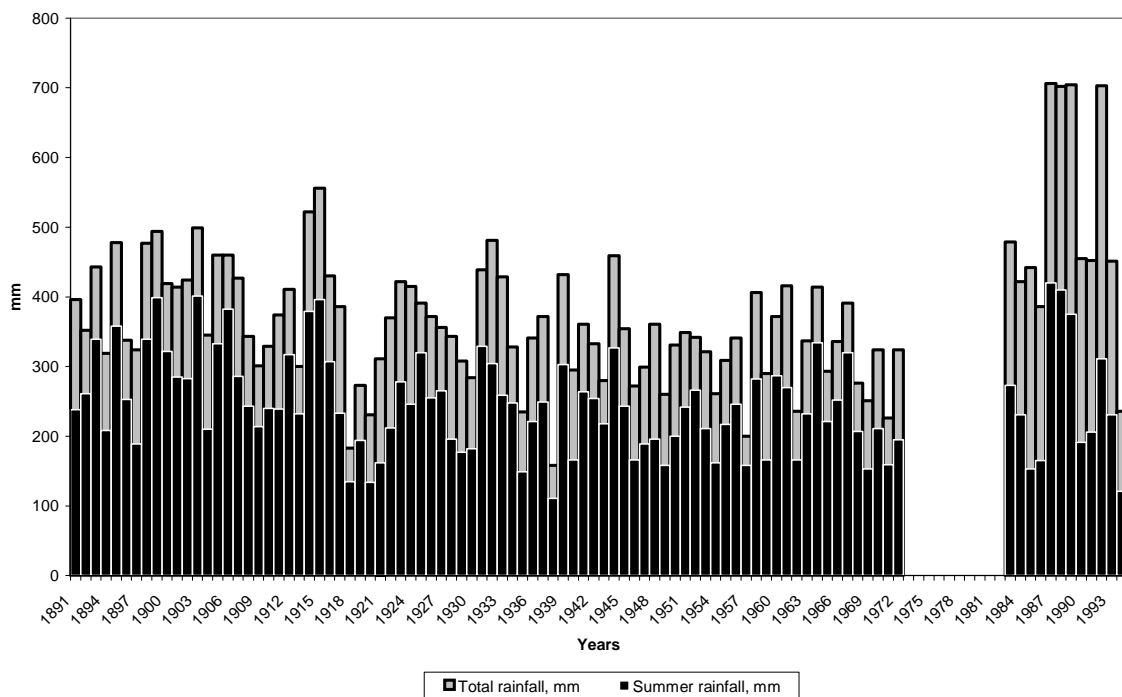


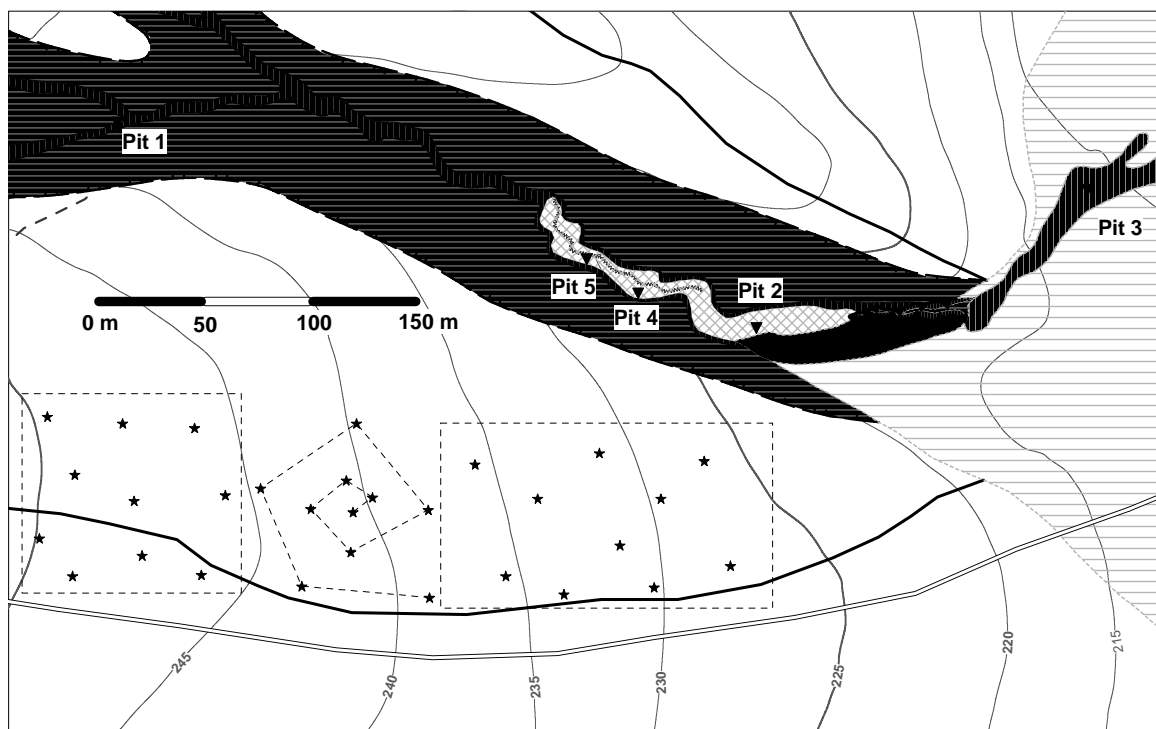
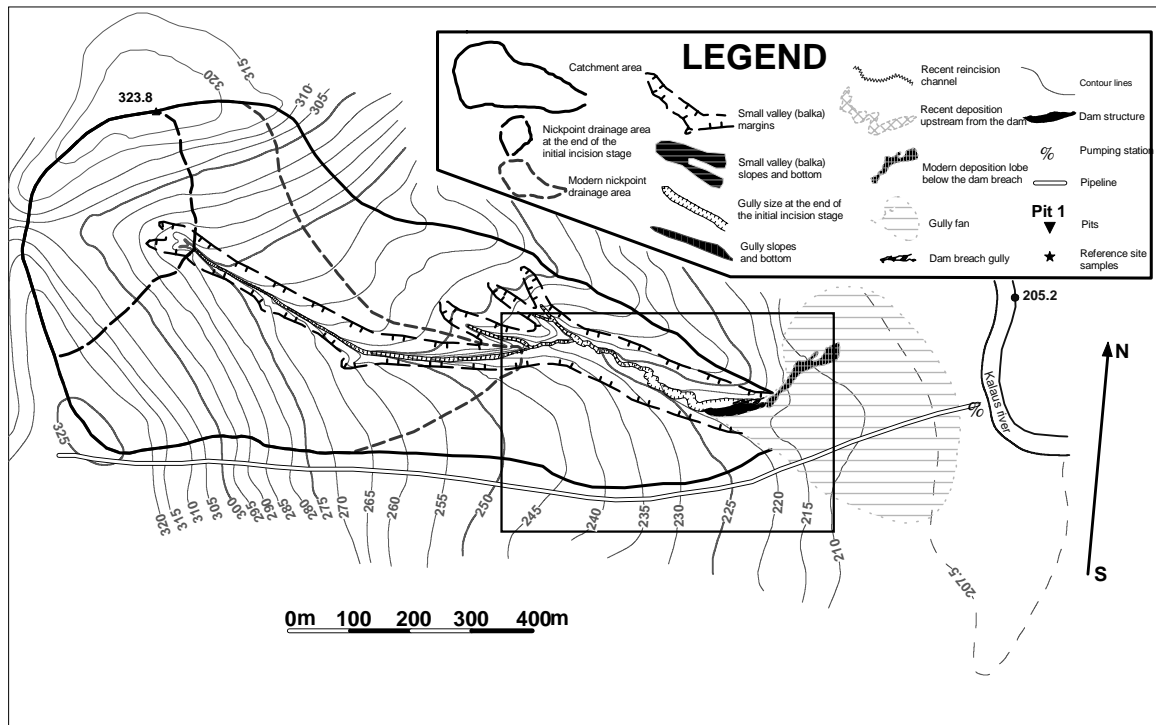
Figure 2: Annual and summer (May-August) rainfall record for the Stavropol region (data from 1973 to 1982 have been unavailable). Based on averaged information from 5-10 monitoring stations. Average annual rainfall for the observation period is represented by a dashed line.

### *The study area gully system*

The study area gully system is located on the western slope of the Kalaus river valley, ~1.5 km to the south of the village of Sergeevskoe. Valley slope here is characterised by a convex-concave-convex profile, presumably reflecting the complicated bedrock geology and presence of the Kalaus river terraces. The topographic range between the interfluvium and the main river is about 120 m, slope gradients decrease from 5-11° in the upper sections to 0.5-3° in the lower (Fig. 3a). The gully catchment area is ~0.63 km<sup>2</sup>, with length ~1.5 km and width varying between 250 to ~700 m. The gully occupies about 80% of the catchment length. It is a typical bottom gully (Kosov, 1978) developed within a larger Pleistocene fluvial landform - hollow (Rozhkov, 1981). It has a few small tributaries in the middle section. The bottom of the gully itself is filled with recent sedimentation and partly (in the middle and lower reaches) cut by the modern incision channel which has a length of about 400 m and cross-section from ~0.5x0.5 m to ~1x1 m. Permanent pasture is the predominant landuse in the catchment area, including the gully banks.

### *Known phases of development*

During its initial stages it is believed that the study area gully followed the general scheme of development reported in the introduction as characteristic for the region. It is well known that large-scale agricultural development of the area began not earlier than 100 years ago (Tsvetkov, 1957). It is suggested that the initial incision in the balka floor began when overgrazing caused rapid vegetation loss, increased runoff and vulnerability of the Pleistocene hollow infill sediments and bedrock to erosion. After a few years of very high erosion the gully reached its present length, by which stage the nickpoint apparently had insufficient catchment area to sustain further growth (Belyaev, 2002). Currently the catchment of the main gully head has an area of ~0.1 km<sup>2</sup> (Fig. 3a).



**Figure 3. Study site general scheme (a) and enlarged geomorphological map of the studied gully middle and lower parts and sampling points locations (b).**

The following period of stabilization resulted in gully infill and changes to the long profile and cross-sectional form. A gradual increase in thalweg gradient associated with aggradation is believed to have finally caused re-incision in the gully

floor to begin. An increased frequency of heavy summer rainstorms after the 1950s (Climatological., 1990) combined with irrigation water dumping through the gully (which began in early 1980s - local farming authorities, personal communication) might also have led to more active erosion. The nickpoint then started to retreat upstream, most likely at one of the long profile convexities. The incision channel that developed is much smaller than the gully itself, its modern dimensions (as above) are ~400m in length (of which ~260m is an active erosion reach, while the lower ~140m represents a transport and deposition zone). Such channel incisions are reported to be very common for gullies in this region, and throughout European Russia (Gully erosion, 1989).

#### *Construction and failure of the earthen dam*

As a part of a regional infrastructure program an earthen dam was built across the gully mouth in early 1986 (local sources, personal communication). This was aimed to protect a pumping station located on the Kalaus river nearby and a pipeline delivering water from the station (Fig. 3a,b). Substantial deposition upslope of the dam then occurred. It was breached shortly after construction although no precise information on the timing of this breach is available. A short (~50 m), narrow (1-3 m) and deep (up to ~3.5 m) incision channel with nearly vertical walls formed in the breached dam wall along the toe of adjacent northern slope. Material from this channel, as well as that from the main gully, was then deposited downstream of the breach incision forming a prominent deposition lobe on the northern side of the main gully fan (length ~150 m, width 10-40 m, area approximately 2900 m<sup>2</sup>).

#### **Methods**

##### *Methods for gully analysis*

Gullies are a familiar feature of many landscapes and the literature records numerous examples of methods for their analysis. For example, Ireland et al., (1939); Veretennikova and Belyaev, (2000) measured the growth rate of gully dimensions by re-survey at frequent intervals over time. Alternative information can be obtained from air-photos which can be converted into GIS layers (Beavis et al., 1999). Topographic map analysis and field surveys of key areas have also been carried out in

European Russia (Kosov and Konstantinova, 1973; Nazarov, 1992; Rysin, 1998). The main outcome has been maps of gully specific length ( $\text{km km}^{-2}$ ) and density (gullies  $\text{km}^{-2}$ ) estimated for each of first order river basins within study areas.

More sophisticated landscape reconstructions now include measurements of radionuclides to quantifying key processes and rates. Wallbrink and Murray (1993) quantify the relative contributions of sediment from gully walls and overlaying sheet flow using  $^{137}\text{Cs}$ ,  $^{210}\text{Pb}_{\text{ex}}$  and  $^7\text{Be}$ . Olley et al. (1993) use measurements of lithogenic  $^{226}\text{Ra}$  and  $^{232}\text{Th}$  to demonstrate that the major source of deposited sediment in a gully was erosion from within the gully itself. Trzcinka et al, (1993) used  $^{137}\text{Cs}$  inventories and erosion pins to test a geomorphological model of a field tunnel system. Murray et al., (1993) combined  $^{137}\text{Cs}$ ,  $^{226}\text{Ra}$  and  $^{232}\text{Th}$  with stratigraphic descriptions to determine the origin of sediment in an underground cave system.

As some other areas of the European Russia, the Stavropol region has received both global and Chernobyl  $^{137}\text{Cs}$  fallout. According to the former Soviet Union radiation situation map (Map., 1998), Chernobyl contributed an additional 50-100% to the bomb-derived  $^{137}\text{Cs}$  in this region. For the purposes of this study Chernobyl deposition represents an unambiguous time line at 1986, and as so provides information on recent erosion rates, transport and deposition. To our knowledge this is the first such attempt to use Chernobyl  $^{137}\text{Cs}$  fallout for recent gully development reconstructions.

#### *Sampling design and analysis for this project*

A detailed sampling program was carried out within the study area gully and its catchment during two successive years (1993 and 1994). The sampling design involved a combination of the approaches outlined above, and can be divided into five different areas.

i) *Landuse and climate records.* A database of background knowledge for the general region and the study area was derived by gathering topographic information from maps, as well as the long term rainfall record for the Stavropol region (Fig. 2). Records of landuse changes were obtained from the local authorities and landholders as well as through discussions with the engineer responsible for the construction of the dam.

ii) *Theodolite survey*. A full topography survey was undertaken of the original gully dimensions, the location of the re-incised nick-point, the location of the dam, the dimensions of the dam breach channel and the recent deposition lobe overlaying the original gully fan at the base of the system.

iii) *Sediment stratigraphy investigation*. Three geological pits were excavated with depth incremental sampling in 1993, a further two pits were excavated in 1994. The locations of the 5 pits are shown on Figures 2 and 3. Depth incremental samples were taken from a known cross-sectional area for different depth intervals (from 5 to 15 cm), usually increasing downwards. A detailed morphological description of grain size, colour and texture was undertaken for each sampling increment in each pit. *Pit 1* was taken from a terrace within the gully approximately 1.5 m above its thalweg, and ~10m downstream from the modern nickpoint location. Its purpose was to determine the ages and stages of deposition onto the terrace; *Pit 2* was taken from an accumulation area immediately above the dam. This was to establish accumulation rates and the timeframe for pre-dam and post-dam aggradation in the lower part of the gully system; *Pit 3* was excavated from the recent deposition lobe below the dam breach incision. The purpose of this pit was to determine the timing, extent, and origin of the overlaying material on the gully fan; finally *Pits 4 and 5* were excavated within the sediment transit and deposition zone in the lower gully reach just upstream from pit 2. These were to establish the extent of post-dam sedimentation.

iv) *Reference samples for radionuclide inventories*. A series of samples were taken from a relatively gentle grassed slope on the southern side of gully catchment (Fig. 3b) to determine the reference inventories of  $^{137}\text{Cs}$  and  $^{210}\text{Pb}$ . Two different strategies were used. Firstly ten individual depth-integrated cores were taken from points along a spiral of increasing diameter. The total area covered by this method was about 100x100 m. Secondly, 20 depth-integrated cores were obtained from two plots located upslope and downslope of the spiral (10 from each). The upper plot had an area of about 100x100 m and the lower plot – about 100x150 m. The cores from the spiral were measured individually while those from each plot were mixed together, providing two additional bulk samples for analysis. The dimensions of the corer were 24.5 cm depth and 7.5 cm diameter.

v) *Erosion source sampling*. In addition to reference site samples, a series of ‘surface scrape’ samples was taken to characterise various sediment sources within and around the gully system. These were obtained by removing the surface material

over a ~10x10 cm area to a depth of ~2 cm. The material was then analysed for its tracer properties in order to match them with the material in the gully deposition zones. The sampling locations were: (a) the surface (top 2 cm) of the catchment topsoil (1 sample); (b) the catchment topsoils averaged to ~25 cm (reference site samples); (c) material eroding from active channel banks in gully re-incision channel (5 samples), (d) actively eroding floor of the re-incision channel (10 samples amalgamated into one); (e) active re-incision channel banks formed in parental material, supposedly Pleistocene hollow infill (8 samples); and (f) the actively eroding walls of the dam breach channel (10 samples amalgamated into one).

### *Radionuclide preparation and analysis*

Representative material from the different depth increments of the different pits (as well as that of the surface scrapes) were transported to the CSIRO Land and Water, radionuclide laboratory in Australia, where they were oven dried, ashed at 400<sup>0</sup> C, ground in a ring mill, and then analysed by gamma spectrometry for <sup>137</sup>Cs, <sup>226</sup>Ra, <sup>228</sup>Ra, <sup>228</sup>Th, <sup>40</sup>K and <sup>210</sup>Pb according to methods outlined in Murray et al., (1987). The activity of <sup>232</sup>Th was calculated from the mean of the activities of its two daughters <sup>228</sup>Ra and <sup>228</sup>Th, assuming secular equilibrium between <sup>228</sup>Ra and <sup>232</sup>Th. Detectors used were two 'Ortec' and one 'Canberra' HPGe Closed Ended 'n' type Coaxials. Samples were counted for a minimum of 85 ks.

## **Results and discussion**

### *Rainfall records and theodolite survey*

The rainfall data obtained from a few meteorological stations of the Stavropol region is given in Figure 2. The data cover the period from 1891 to 1994 (1973 - 1982 is unavailable), and show that high annual amount of precipitation is generally associated with high summer rainfall. This is characterized by high intensity rainstorms which have extreme erosivity and with a return interval of ~10-15 years, although no precise periodicity can be observed. The location and dimensions of the gully, incision-channel, dam, dam wall, incision breach and catchment study area are given in Figures 3a and b. They have been overlaid onto contours obtained from the published topographic map of this area.

*Reference inventories of fallout  $^{210}\text{Pb}$  and  $^{137}\text{Cs}$*

The  $^{137}\text{Cs}$  and  $^{210}\text{Pb}_{\text{ex}}$  inventories ( $\text{Bq m}^{-2}$ ) of the reference site samples are given in Table 1. There is a high coefficient of variation associated with both radionuclides, 28 % and 41 % respectively, although both are within the range reported in the literature (Wallbrink et al., 1994; Owens and Walling, 1996). They can also be used to determine a range of inventories characterizing the atmospheric influx of both  $^{137}\text{Cs}$  and  $^{210}\text{Pb}_{\text{ex}}$ , represented here by confidence intervals calculated at 90% significance level (Table 1).

**Table 1. Reference site radionuclide inventories.**

	Average reference inventory, $\text{Bq m}^{-2}$	Standard deviation, $\text{Bq m}^{-2}$	Coefficient of variation, %	Confidence interval (for 90% significance), $\text{Bq m}^{-2}$
$^{137}\text{Cs}$	4910	1360	28	$\pm 410$
$^{210}\text{Pb}_{\text{ex}}$	3340	1360	41	$\pm 410$

The average annual fallout of  $^{210}\text{Pb}_{\text{ex}}$  can be used to date sediment sequences in deposition sites. It can be estimated from the reference site inventory (of  $^{210}\text{Pb}_{\text{ex}}$ ) if i) the inventory is assumed to represent the long-term equilibrium between atmospheric influx and radioactive decay and ii) that fallout has been constant over time. In this case, annual fallout of  $^{210}\text{Pb}_{\text{ex}}$   $I_{\text{Pb}}$  can be estimated as:

$$I_{\text{Pb}} = A_{\text{refPb}} \cdot \lambda_{\text{Pb}} \quad (1)$$

where

$A_{\text{refPb}}$  is the average  $^{210}\text{Pb}_{\text{ex}}$  reference site inventory,  $\text{Bq m}^{-2}$ ; and

$\lambda_{\text{Pb}}$  is the  $^{210}\text{Pb}_{\text{ex}}$  radioactive decay constant,  $0.031 \text{ y}^{-1}$ .

This yields a value of  $104 \text{ Bq m}^{-2}$  ( $\pm 13 \text{ Bq m}^{-2}$  for 90% significance), which is also within the range of fallout  $^{210}\text{Pb}_{\text{ex}}$  values reported in the literature (Moore and Poet, 1976; Walling and He, 1999).

### Radionuclide signatures of different sediment sources

The radionuclide signatures of the different sediment sources within the study catchment are given in Table 2. There are differences between one, or all of these variables for most of the sources considered. The highest fallout nuclide values are found in the top 2 cm layer of the catchment surface soils, above and outside the gully system (source a). The lowest values of both  $^{137}\text{Cs}$  and  $^{210}\text{Pb}_{\text{ex}}$  have been found on material derived from the banks of the dam breach (source f). This is not surprising as the banks are vertical and there is no opportunity for exposure to either fallout radionuclide. The highest  $^{226}\text{Ra}/^{232}\text{Th}$  ratio ( $1.17\pm 0.02$ ) was on material from the dam breach gully walls (source f). The lowest value  $0.51\pm 0.01$  was on material from the bottom of the re-incision channel (source d). There were also differences in the  $^{40}\text{K}/^{232}\text{Th}$  signature between the sources. The lowest was from the dam breach gully walls ( $7.0\pm 0.1$ ) (source f), the highest from the channel walls of the re-incision - channel ( $13.5\pm 0.3$ ) (source c). Other sources considered have intermediate values of the parameters measured.

Table 2. Radionuclide signatures for different sediment sources within the catchment.

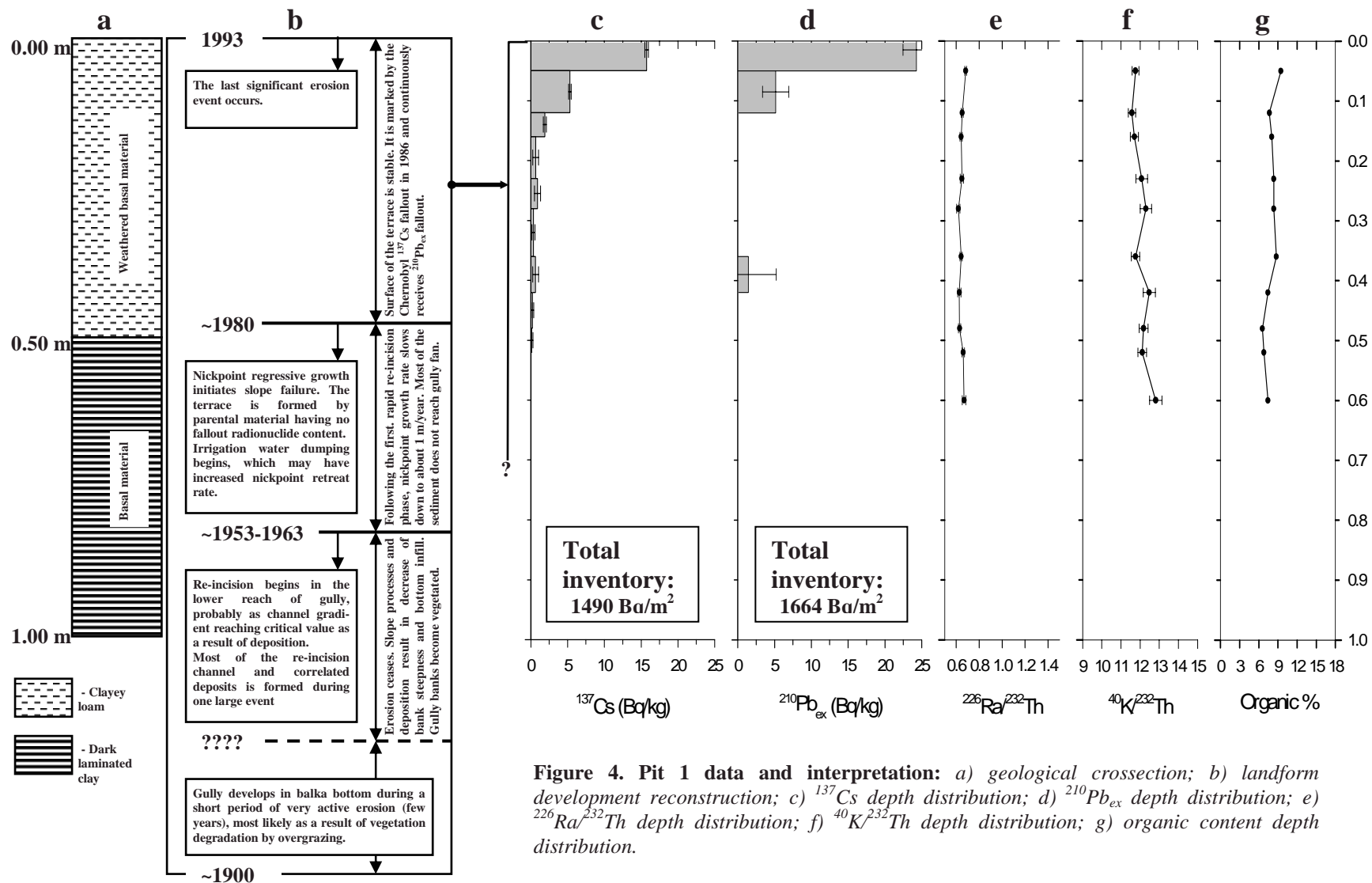
	Catchment topsoil (surface layer ~2 cm)	Catchment topsoil (averaged for layer ~25 cm)	Re-incision channel (banks)	Re-incision channel (bottom)	Re-incision channel banks (parental material)	Dam breach gully banks
	(a)	(b)	(c)	(d)	(e)	(f)
$^{137}\text{Cs}$ , Bq kg <sup>-1</sup>	56.1±1.0	13.2±0.3	1.0±0.2	1.5±0.2	2.6±0.3	0.01±0.1
$^{210}\text{Pb}_{\text{ex}}$ , Bq kg <sup>-1</sup>	56.2±4.3	8.9±2.6	1.2±2.5	0.00±3.9	3.1±2.8	0.00±2.9
$^{226}\text{Ra}/^{232}\text{Th}$	0.63±0.02	0.56±0.01	0.59±0.01	0.51±0.01	0.65±0.01	1.17±0.02
$^{40}\text{K}/^{232}\text{Th}$	12.5±0.3	9.6±0.2	13.5±0.3	7.2±0.1	12.1±0.3	7.0±0.1

### Analyses of Pit 1 data and determination of Chernobyl $^{137}\text{Cs}$ fallout inventory

Pit 1 was excavated to provide information on soil structure, radionuclide content of the gully infill sediment, and the contribution of Chernobyl  $^{137}\text{Cs}$ . Low inventories of both  $^{137}\text{Cs}$  and  $^{210}\text{Pb}_{\text{ex}}$  were found in the pit compared to the reference site,  $^{137}\text{Cs}$ :  $\sim 1490$  Bq m<sup>-2</sup> and  $^{210}\text{Pb}_{\text{ex}}$ :  $\sim 1660$  Bq m<sup>-2</sup>. Their depth distributions were

also similar (Fig. 4), and virtually all of the inventory was contained within the top 15 cm. Both showed an exponential decline with depth. Their profile shape is consistent with those evolving from recent fallout on a stable surface (Wallbrink et al., 1994; Owens et al., 1996), and further infers that no significant erosion has occurred since the initial deposition. The annual fallout amount of  $^{210}\text{Pb}_{\text{ex}}$  (calculated from above) can be used to date the numbers of years the terrace surface has been exposed prior to 1993, and calculates to ~1975-1980 supporting the theory that its origin is fairly recent. Importantly, fallout of bomb derived  $^{137}\text{Cs}$  had effectively ceased prior to the new terrace surface forming. Thus, the entire  $^{137}\text{Cs}$  inventory in this core can be attributed to post-1986 Chernobyl fallout. Furthermore, the detailed local rainfall record (Svetlograd meteorological station, personal communication) shows that no runoff-generating rains occurred during April and May of 1986 (when peak Chernobyl fallout occurred), and it can be assumed that no significant redistribution of Chernobyl  $^{137}\text{Cs}$  occurred prior to its adsorption to soil particles in Pit 1. The  $^{137}\text{Cs}$  inventory here is equivalent to ~30% of the total reference amount and is consistent with estimates presented in the former USSR distribution map (Map., 1998)

The material observed in the *Pit 1* was a dark laminated parental clay with an upper weathered layer (~0.5 m), into which the main gully was cut. This probably represents older sediment infilling the hollow bottom during Late Pleistocene. Sediment from modern gully infill is usually characterised by a lighter texture of silty and clayey loam with sandy and gravelly lenses. Therefore it is likely that the local terrace in the gully bottom sectioned by *Pit 1* is a result of recent slope failure. This is also supported by the terrace morphology - local extent, uneven surface, gradient from the terrace brow to the main gully bank, well-seen curved sheer wall at the back of the terrace. The slope failure here was probably initiated when nickpoint retreat caused an instability of the adjacent slope and its eventual collapse. The nickpoint position observed in 1993 was about 10 m upstream from the *Pit 1* site. Assuming an average rate of nickpoint propagation of  $\sim 1 \text{ m y}^{-1}$  (Kosov, 1978; Gully erosion, 1989; Nazarov, 1992; Rysin, 1998), this slope failure can be dated to 1983, which is close to the date obtained from  $^{210}\text{Pb}_{\text{ex}}$  data. Further supporting evidence comes from the relatively low organic content within the top layer of core (Fig. 4), showing that no significant soil development has occurred. More or less constant values of lithogenic radionuclide ratios also point to a uniformity of sediment origin (Murray et al., 1993), i.e. by soil slumping.



**Figure 4. Pit 1 data and interpretation:** a) geological cross-section; b) landform development reconstruction; c)  $^{137}\text{Cs}$  depth distribution; d)  $^{210}\text{Pb}_{\text{ex}}$  depth distribution; e)  $^{226}\text{Ra}/^{232}\text{Th}$  depth distribution; f)  $^{40}\text{K}/^{232}\text{Th}$  depth distribution; g) organic content depth distribution.

## *Description and analyses of Pit 2*

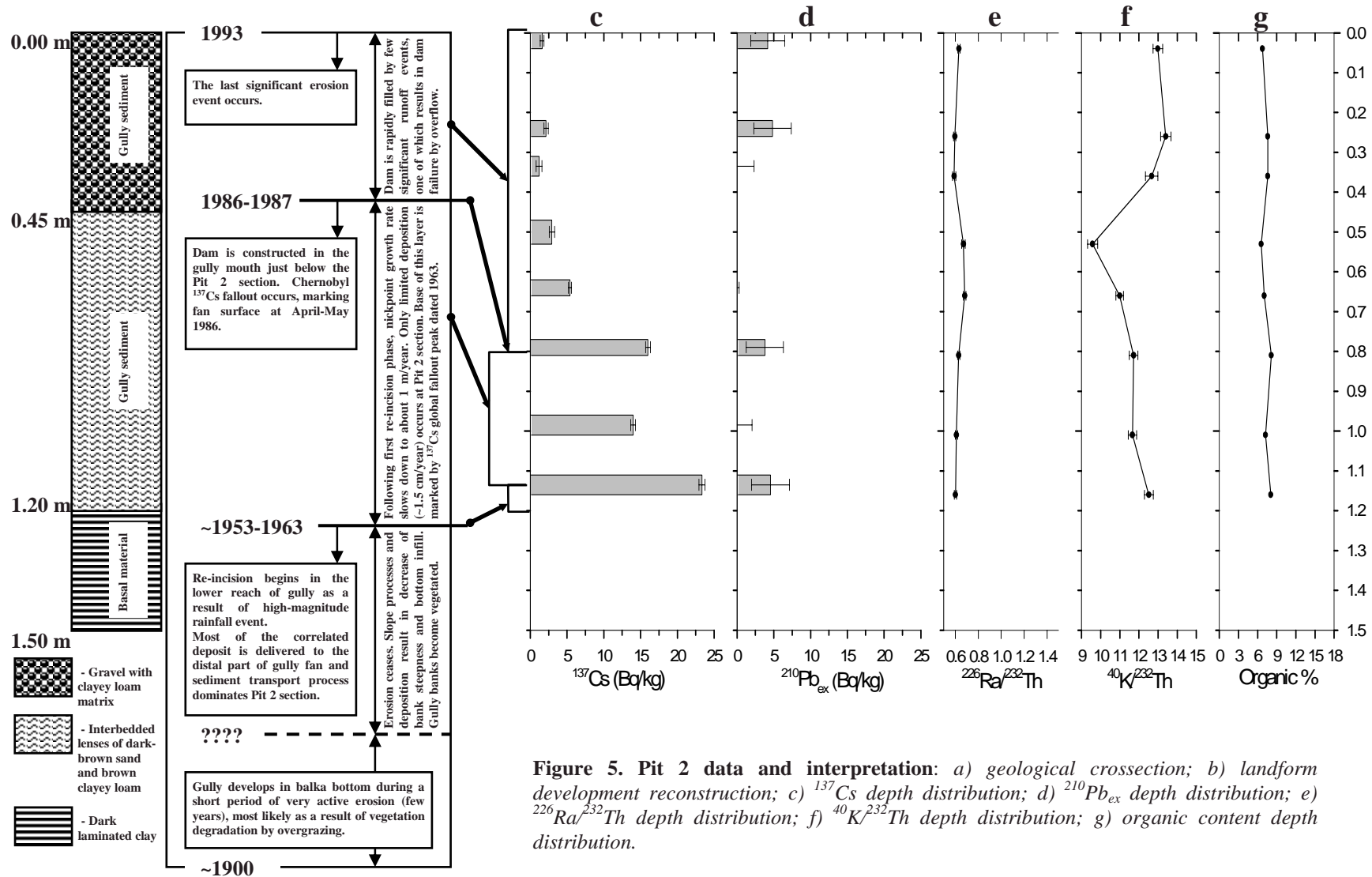
*Pit 2* was excavated just upstream of the dam wall and analyses from it are shown in Figure 5. Unfortunately, only samples from certain depth intervals were measured for their radionuclide content, and thus the total inventory and overall depth distribution of radionuclides can only be inferred. Nevertheless, some important observations can be drawn from the available data.

Firstly, the total depth of recent gully sediment at this point is 1.2 m. Below this depth, the parental material exposed at the pit base, is similar to that forming the terrace at *Pit 1* (dark laminated clay). The gully long profile (described later as fig. 10) shows that the initial gully thalweg had a convexity at this point. Therefore, no substantial accumulation could have occurred here naturally, without the influence of the dam constructed in the gully mouth in 1986. This point also has some support from the depth distribution of  $^{137}\text{Cs}$ . Two peaks are observed at depths of  $\sim 1.15$  m and  $\sim 0.8$  m. The first one can be partially attributed to the global fallout peak that occurred in 1963 (Walling and He, 1992). The second is likely to represent the Chernobyl fallout of April-May 1986, as the concentration is similar to that from the surface layer of *Pit 1* ( $\sim 15 \text{ Bq kg}^{-1}$ ). The sediment accumulated between the parental material layer and the 1963  $^{137}\text{Cs}$  peak is most likely to have been deposited at the beginning of the re-incision phase that followed the relatively long period of gully infill, supposedly beginning in the 1950s-1960s. However, the low  $^{210}\text{Pb}_{\text{ex}}$  concentration suggests that there was no prominent period of stable surface associated with this sediment layer, as one would expect from the period between the end of infilling and the beginning of re-incision. Hence, it is proposed that during the gully infill period this location in the gully system probably underwent sediment transport or even minor erosion and the surface coincided with the top of the parental material layer. This is supported by the gully long profile shape not promoting deposition here.

Deposition between the hypothesised 1963 and 1986  $^{137}\text{Cs}$  peaks (total layer  $\sim 35$  cm) possibly coincides with a period of channel re-incision during this time. The nickpoint retreat rate and aggradation at *Pit 2* during that period of time are believed to be relatively constant, the latter calculated to be  $\sim 1.5 \text{ cm y}^{-1}$ . The absence of a discernable peak in  $^{210}\text{Pb}_{\text{ex}}$  inventories between 1.15 and 0.8 m in the core also supports this theory, however it is acknowledged that the resolution of sample analysis is insufficient to be absolutely certain.

The dam was built in 1986 blocking the gully mouth just below *Pit 2*. Rapid deposition then occurred upstream of it. There is no direct evidence of sedimentation rate, but we suggest that most of the sediment above 0.8 m depth was accumulated during a few high-magnitude events following dam construction. The lithogenic radionuclide ratios (in particular  $^{40}\text{K}/^{232}\text{Th}$ , Fig. 5e,f), show evidence of a boundary at ~0.5 m depth, coinciding with an exponential upward decline of  $^{137}\text{Cs}$ . It is probable that the first ~35 cm of this (~0.8 – 0.45m) deposit was associated with the first significant runoff event in the gully after dam construction. In 1987 extreme rainstorms occurred during the May-July period (Fig. 2), likely to produce significant sediment runoff rapidly filling the dam and decreasing its capacity. The dam wall was eventually breached, most likely during a period of especially high rainfall (~90 mm) around the 7-8<sup>th</sup> of July 1987. Its capacity by that time had already been decreased by about half (Fig. 5).

After failure of the dam, a substantial portion of sediment delivered from upstream began to bypass the *Pit 2*, and was transported through the dam breach to a fresh deposition lobe that formed below, where *Pit 3* was located (Fig. 3b). Some deposition would have continued to occur at *Pit 2*, however, as significant widening of the gully and a decrease in the gradient of the thalweg would have promoted it here. It is assumed that this deposition continued gradually, although still at a considerable rate, as no peak in  $^{210}\text{Pb}_{\text{ex}}$  concentration is observed at the core up to the surface, until the sampling in 1993. The low  $^{137}\text{Cs}$  concentrations (~3 Bq kg<sup>-1</sup>) on deposited sediment in this zone are consistent with that measured on the recent incision channel banks. This is supported by the lithogenic signatures. For example the  $^{40}\text{K}/^{232}\text{Th}$  incision-channel bank signature of 12.1±0.3 Bq kg<sup>-1</sup> (Table 2) is consistent with the range on sediments of 12.0-13.0 Bq kg<sup>-1</sup>; similarly for  $^{226}\text{Ra}/^{232}\text{Th}$ , with values of 0.65±0.01 Bq kg<sup>-1</sup> (Table 2) and range of 0.58-0.62 Bq kg<sup>-1</sup> respectively.



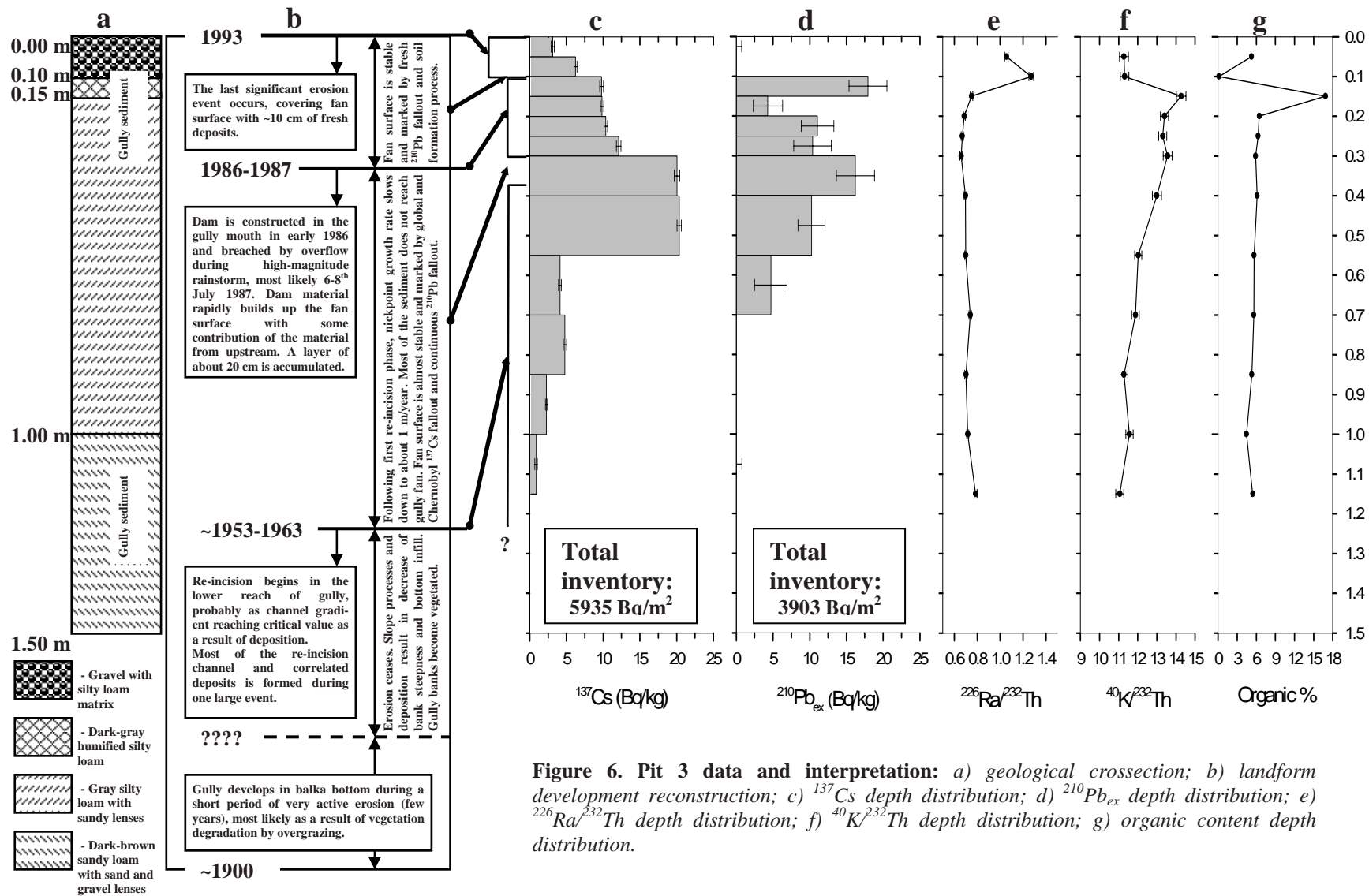
**Figure 5. Pit 2 data and interpretation:** a) geological cross-section; b) landform development reconstruction; c)  $^{137}\text{Cs}$  depth distribution; d)  $^{210}\text{Pb}_{\text{ex}}$  depth distribution; e)  $^{226}\text{Ra}/^{232}\text{Th}$  depth distribution; f)  $^{40}\text{K}/^{232}\text{Th}$  depth distribution; g) organic content depth distribution.

### *Description and analyses of Pit 3*

*Pit 3* provides the most detailed information on development of this gully, the analyses from it are given in Figure 6. Three sedimentation episodes and two major phases of relative stability can be reconstructed from this core.

Firstly, only one significant peak in  $^{137}\text{Cs}$  depth distribution can be observed at between 0.3-0.5 m depth. It is surmised from this that the 1986 Chernobyl fallout has overlaid almost directly the earlier peak associated with bomb derived  $^{137}\text{Cs}$ . This places the surface of the fan in 1963 at about 0.4 m, with approx 0.1 m of sedimentation on top of this in the intervening years, thus defining the 1986 Chernobyl horizon at ~0.3 m. The  $^{210}\text{Pb}_{\text{ex}}$  data support this conclusion showing a peak at 0.3 m depth, its overall down core distribution is attenuated by relatively constant sediment dilution, more than that usually observed at undisturbed locations (Wallbrink et al., 1999).

The layer below ~0.4 m is attributed to an episode of relatively intense deposition associated with the beginning of the recent incision development. Concentrations of  $^{137}\text{Cs}$  here form a tail reaching ~1.15 m depth. This depth of penetration is significant and cannot be due to vertical migration alone (Walling and He, 1992) and so we believe that this entire layer formed after 1953 i.e. the beginning of  $^{137}\text{Cs}$  global fallout. No  $^{210}\text{Pb}_{\text{ex}}$  is found below 0.7 m inferring that at least the lower 45 cm of this layer has been formed during a single major event. The total inventory of  $^{210}\text{Pb}_{\text{ex}}$  within the 0.3-0.7 m layer ( $1550 \text{ Bq m}^{-2}$ ) is consistent with a date of 1955-1960 as the timing of that event. The lithogenic radionuclide signatures are similar to those from recent incision-channel banks i.e.  $^{226}\text{Ra}/^{232}\text{Th}$   $0.70 \pm 0.05$ , and  $^{40}\text{K}/^{232}\text{Th}$   $12.0 \pm 1.0$ . It is concluded that initial incision into the gully bottom infill sediments began after 1953, but before 1963, probably as one single major event. The most likely years from the precipitation record are 1958-1961 (Fig. 2). The base of the sediment layer attributed to that event and the position of the older fan surface is uncertain, as sampling appeared not to be deep enough to reach it.



**Figure 6. Pit 3 data and interpretation:** a) geological cross-section; b) landform development reconstruction; c)  $^{137}\text{Cs}$  depth distribution; d)  $^{210}\text{Pb}_{\text{ex}}$  depth distribution; e)  $^{226}\text{Ra}/^{232}\text{Th}$  depth distribution; f)  $^{40}\text{K}/^{232}\text{Th}$  depth distribution; g) organic content depth distribution.

After that major erosion event, later deposition rate was much slower ( $\sim 3.3 \text{ cm y}^{-1}$  prior to 1963 and  $\sim 0.3 \text{ cm y}^{-1}$  from 1958-1961 to 1986) as nickpoint growth slowed down to its average reported linear retreat rate of about  $1 \text{ m y}^{-1}$ . More active deposition took place upstream at pit 2 during this latter period, as discussed above.

After the dam was constructed (and then breached) in 1986-87,  $\sim 30 \text{ cm}$  of sediment was deposited at *Pit 3* by 1993. However, this layer itself can be separated into two parts, representing two episodes of sedimentation and one of surface stabilization. The boundary between the two sedimentation episodes coincides with the thin organic-rich layer between 0.1 and 0.15 m depth, and the high  $^{210}\text{Pb}_{\text{ex}}$  peak suggesting a period of surface stability and ephemeral soil formation. The  $^{210}\text{Pb}_{\text{ex}}$  dating gives 1986-1987 as the beginning of this stable period, however it must be treated as maximum estimate as some nuclide influx with sediment may have occurred. In any case, this coincides with the hypothesized date of the dam failure and suggests that  $\sim 20 \text{ cm}$  layer was deposited quickly, possibly during the overspill and gully breach formation itself. Independent evidence to support this comes from the age of a tamarisk shrub found growing in the lower end of the gully breach thalweg. An analysis of its growth rings suggested it was  $\sim 4$  years old, giving 1989 as the upper date for the beginning of the stable period. This date agrees well with the two other lines of evidence discussed above.

The most obvious source of the material in the 0.1-0.3m zone is the breach walls, however the lithogenic radionuclide signatures indicate that significant contribution of eroded material from upstream also took place, most likely from the banks and floor of the incision channel. Some material may also have come directly from surface erosion of the adjacent northern slopes of the catchment evidenced by the relatively high  $^{137}\text{Cs}$  ( $\sim 10 \text{ Bq kg}^{-1}$ ) and  $^{210}\text{Pb}_{\text{ex}}$  ( $\sim 4\text{--}11 \text{ Bq kg}^{-1}$ ) concentrations in this layer. This is approximately the concentration expected if pure topsoil eroded material was mixed with that from the incision-channel and the dam breach walls (Fig. 6, Table 2).

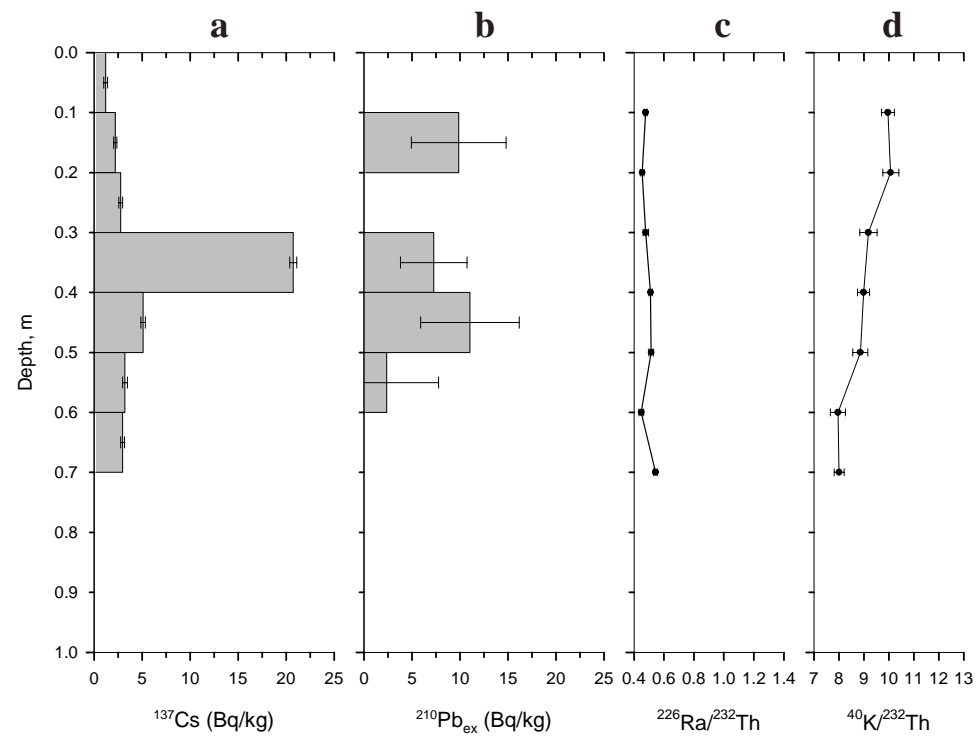
Finally, the top layer of about 10 cm has no detectable  $^{210}\text{Pb}_{\text{ex}}$  suggesting that the modern surface is very young and had not yet been labelled by atmospheric fallout prior to sampling (i.e. August 24, 1993). This layer is therefore attributed to one rainfall event, presumably occurring immediately prior to fieldwork. According to Figure 2 the most likely dates are on August 6 1993 (22.5 mm) and August 13 1993

(21.2 mm). The important contribution of the dam breach material to this layer is seen from the  $^{226}\text{Ra}/^{232}\text{Th}$  data. This also presumably reflects its active volumetric growth during these two events. Delivery from this source is also supported by the decrease in  $^{40}\text{K}/^{232}\text{Th}$  ratios (Fig. 6e, f).

#### *Description and analysis of Pit 5*

In order to assess the upstream extent of sedimentation resulting from construction of the dam, two smaller pits (*Pit 4* and *Pit 5*) were excavated within the lower reach of the gully, ~70 and 110 m from the dam respectively (Fig. 3b). It is believed that neither pit was excavated deep enough to capture the entire  $^{137}\text{Cs}$  inventory. Nonetheless, the significant  $^{137}\text{Cs}$  peak at 0.3-0.4 depth in *Pit 5* (Fig. 7) may be used to distinguish between pre- and post-dam sediments. The  $^{137}\text{Cs}$  concentration in this layer is consistent with that from Chernobyl fallout (~20 Bq kg<sup>-1</sup>), supporting a 1986 sediment date and representing ~30 cm of sedimentation since dam construction. This is corroborated by the  $^{210}\text{Pb}_{\text{ex}}$  data, implying that ~20 cm was deposited soon after the dam construction. This was followed by period of relative stability in which the gully bottom was labelled with  $^{210}\text{Pb}_{\text{ex}}$ , forming the peak at 0.1-0.2 m. The inventory of  $^{210}\text{Pb}_{\text{ex}}$  within this layer (852 Bq m<sup>-2</sup>) is very similar to that of pit 3 (814 Bq m<sup>-2</sup>) and points to a similar date for the beginning of the stable period – 1986-1987. However, as for *Pit 3*, some influx of sediment bound  $^{210}\text{Pb}_{\text{ex}}$  could have occurred. The absence of any  $^{210}\text{Pb}_{\text{ex}}$  in the upper 10 cm of *Pit 5* indicates sediment that has been deposited recently, supporting the information from *Pit 3*.

There were no further  $^{137}\text{Cs}$  peaks below the 0.3-0.4 m peak, and one may have been expected coinciding with the 1963 fallout peak. The total inventory in this pit is also lower than the reference inventory (2490 vs 4910 Bq m<sup>-2</sup>, respectively) suggesting that the 1963 peak lies beneath the lowest sampling increment. This infers that the sediment measured in *Pit 5* at 0.7 m to the 1986 peak, at 0.3-0.4 m, was accumulated between these two dates, and gives a lower estimate of average deposition rates here of ~1.5 cm y<sup>-1</sup>. (Although it should be noted that the  $^{210}\text{Pb}_{\text{ex}}$  distribution below 0.3 m infers that deposition during this period was not constant, and that the estimated rate provides an approximation of accumulation only).



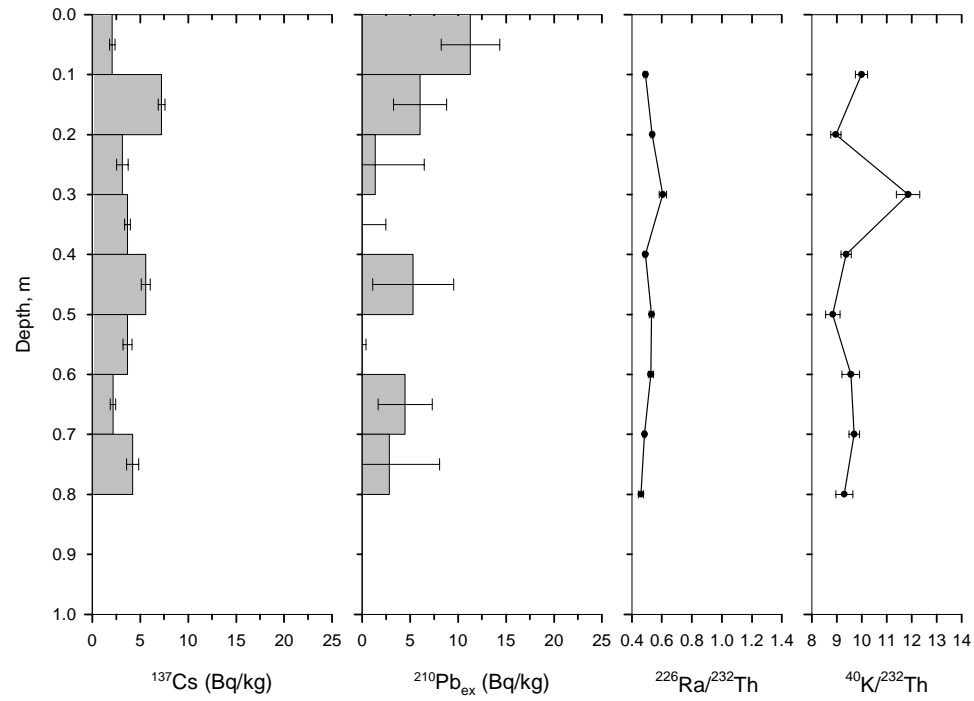
**Figure 7. Pit 5 radionuclide data:** a)  $^{137}\text{Cs}$  depth distribution; b)  $^{210}\text{Pb}_{\text{ex}}$  depth distribution; c)  $^{226}\text{Ra}/^{232}\text{Th}$  depth distribution; d)  $^{40}\text{K}/^{232}\text{Th}$  depth distribution.

Nevertheless, the data show that deposition associated with construction of the dam was significant, and extended as far as 110 m upstream from the dam (Fig. 9 – long profile). This points out a high contemporary sediment yield from the gully catchment. Lithogenic radionuclide signatures suggest that catchment topsoil had contributed significantly to sediment deposited before 1986, but post-dam sediment largely originated from within the gully sources with very limited portion of catchment-derived particles.

#### *Description and analyses of Pit 4*

The data from *Pit 4* core (Fig. 8) are more difficult to interpret as its location is likely to experience deposition of mixed sediments from two sources – the main gully and a tributary gully branch dissecting the southern slope of the main gully. This branch, in turn, delivers sediment from its eroding bottom and disturbed surface areas upslope (i.e. associated with pipeline construction). As a result, *Pit 4* has experienced short spells of rapid deposition divided by periods of relative stability, as indicated by both  $^{137}\text{Cs}$  and  $^{210}\text{Pb}_{\text{ex}}$  concentrations with depth.

Firstly, the upper peak in  $^{137}\text{Cs}$  concentrations (0.1-0.2 m) is relatively weak compared to those of the other pits. However it is believed that this still represents the Chernobyl fallout (and 1986 date) although it has probably been partly eroded by the July 1987 event. This infers that only about 10 cm has accumulated after construction of the dam. This seems reasonable as *Pit 4* is located within the concave bend of the main gully southern slope, and is relatively far from the modern gully channel where most of the recent accumulation has occurred. The inventory of  $^{210}\text{Pb}_{\text{ex}}$  within the upper layer of the core also supports this conclusion, although the influx of eroded sediment from catchment topsoil makes interpretation of  $^{210}\text{Pb}_{\text{ex}}$  in this location problematic.



**Figure 8. Pit 4 radionuclide data:** a)  $^{137}\text{Cs}$  depth distribution; b)  $^{210}\text{Pb}_{\text{ex}}$  depth distribution; c)  $^{226}\text{Ra}/^{232}\text{Th}$  depth distribution; d)  $^{40}\text{K}/^{232}\text{Th}$  depth distribution.

Two other small peaks in  $^{137}\text{Cs}$  concentration 0.4-0.5m and 0.7-0.8 m can also be observed. With the  $^{210}\text{Pb}_{\text{ex}}$  and lithogenic radionuclide data they imply that deposition at the site probably occurred as few distinctive events rather than as a continuous process. This again shows that estimates of average erosion and deposition rates provide only a limited insight on geomorphic processes. The variation of erosion, deposition and sediment delivery that occurs within individual events must also be evaluated. It is also probable that during each event the relative contribution of the within-gully and catchment surface sediment sources significantly changed. This is particularly evident for the 0.2-0.4 m layer, which has decreased  $^{210}\text{Pb}_{\text{ex}}$  and  $^{137}\text{Cs}$  values, as well as substantial variations in the  $^{226}\text{Ra}/^{232}\text{Th}$  and  $^{40}\text{K}/^{232}\text{Th}$  ratios.

#### *Synthesis of pit, long profile, rainfall, geomorphic and radionuclide data*

The pit-based analyses of erosion and deposition (covering a time scale of the last ~50 years) can be combined with the known history of general gully network development for the region to reconstruct the different phases of evolution of this gully over the last 100 years. It is believed that the first phase involved the initial incision into the bottom the study area valley (~1 km<sup>2</sup>) about 100 years ago. This was most likely due to vegetation degradation resulting from serious overgrazing, which may have made the initial hollow bottom more vulnerable to erosion. A short period of rapid growth was then followed by a longer period of gully stabilization. This was characterized by gradual infill of the gully floor. Erosion then recommenced at some point in the gully thalweg, resulting in a relatively small incision channel being formed. The most likely cause of the new erosion cycle has been an increase of the thalweg gradient resulting from continuous aggradation of the bed, although a change in annual precipitation patterns may also have had an effect. The *Pit 3* data, where no less than 0.75 m of sediment was deposited in a layer below 0.4 m (Fig. 6), infers that a significant portion of this incision channel probably formed during one event. The most likely timing of this was between 1958 and 1961. This is derived from a combination of the  $^{137}\text{Cs}$  data (inferring a period between 1953 – 1963); the  $^{210}\text{Pb}_{\text{ex}}$  data (inferring a period between 1955 – 1960); and the rainfall record (Fig. 2).

Following that event, growth of the incision-channel probably slowed and its nickpoint retreat rate was approximately equal to that reported elsewhere (~1 m y<sup>-1</sup>)

(Kosov, 1978; Gully erosion, 1989; Nazarov, 1992; Rysin, 1998). Most of the material eroded from the incision-channel did not reach the main part of gully fan during this time (~ 0.1 m deposited between 1963 and 1986 at *Pit 3*), instead accumulating in its apex and the lower reaches of the gully. For example between 1963 and 1986, about 0.35 m was deposited at *Pit 2*; at least 0.7 m at *Pit 4*; and a minimum of 0.4 m at *Pit 5*. The fallout and lithogenic radionuclide data from *Pit 4* and *Pit 5* also suggest that sediment deposited within the lower gully reach originated not only from the incision-channel, but also from surface erosion of the adjacent catchment slopes. Modern dimensions of the incision-channel are ~400 m length (comprising ~260 m eroding zone and ~140 m of transport and deposition zone) with average depth and width both about 1 m. Active retreat of the nickpoint continued up to the fieldwork period (1993-94). The amounts, depths and timing of these deposition events as well as the theodolite data, have been used to calculate the changes in long profile dimensions over the life of the gully, shown in Figure 9.

After the dam was constructed in 1986, sediment was quickly deposited as a wedge upstream, as seen by the ~0.8 m thick layer of sediment at *Pit 2*. Sedimentation resulting from the dam was also observed at *Pit 5* (~0.3 m) and at *Pit 4* (~0.1 m), 110 and 70 m upstream respectively. Soon after its construction the dam was breached by an overspill, most likely during the extreme event of 6-8 July 1987. As a result of this, a narrow and deep incision gully formed across the northern end of the dam, with length and depth of ~50 and ~ 2.5 m respectively. An increase in length of ~1.5 m was observed between the two successive field visits in 1993 and 1994, caused by headward growth. A fresh deposition lobe has been formed below the breach channel onto the original fan, its surface and boundary easily distinguishable by texture, colour and vegetation from the underlying older fan surface. Accumulation here has not been constant. At *Pit 3* (Fig. 6) a sediment layer of ~0.3 m was deposited after 1986. The lower 0.2 m accumulated soon after dam failure, followed by a few years of stable surface marked by fallout of  $^{210}\text{Pb}_{\text{ex}}$  and high organic content. The last significant erosion event deposited a further 0.1 m onto that surface, most likely in August 1993. A similar event sequence after the dam construction is suggested by the *Pit 5*  $^{210}\text{Pb}_{\text{ex}}$  data (Fig. 7).

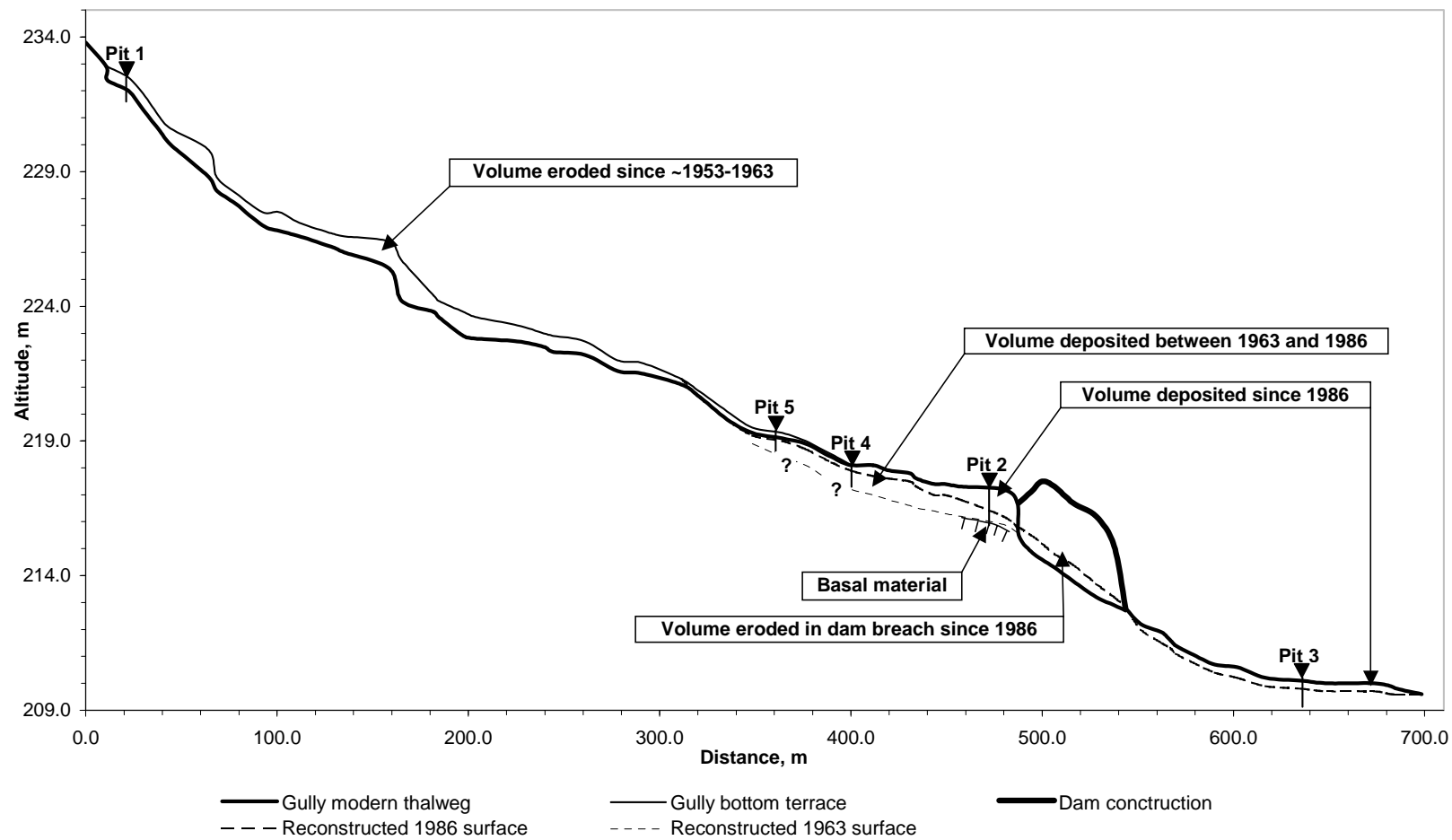


Figure 9. Long profile of the middle and lower parts of the studied gully and reconstructed volumes of recent erosion and deposition.

*Estimating volumes of eroded and deposited material and contribution from different sediment sources*

An attempt has also been made to calculate approximate volumes of eroded and deposited material at various locations in the gully network. A detailed survey enabled the incision-channel and gully breach volumes to be precisely estimated, however, deposited volumes were less accurate as their calculations were based on point observations from the pit exposures as well as the survey data. The total volume of the incision-channel was estimated to be  $\sim 400 \text{ m}^3$  (erosion from 1955-1960 to today) and the dam breach gully –  $\sim 350 \text{ m}^3$  (erosion from 1986 to today). Material deposited in the gully floor upstream of the dam was calculated to be  $\sim 450 \text{ m}^3$  upstream from the dam and  $\sim 600 \text{ m}^3$  on the lower fan below it, since 1986 (Fig. 9). Clearly, the deposition volumes are significantly higher than that of the erosion features. The tracer data indicates that the difference is due to additional material derived from gully bank failures. For example, the modern incision channel undercut the main gully banks (up to 3-4 m high) as it retreated upstream and sediment from this was found in *Pit 1*. Other investigations have also shown that the contribution of gully bank failures to total gully sediment yield can outweigh that of nickpoint retreat and bottom erosion (Blong et al., 1982; Crouch, 1990).

The radionuclide data also show that surface erosion has been a significant contributor to the gully sediment yields at recent stages in the evolution of this gully. This underlines the important role that gullies can play in total sediment delivery from catchments, as they increase the probability that sediment eroded from slopes will reach the catchment outlet.

There was not enough information to obtain reliable estimates of pre-1986 deposition, either above or below, the dam. However, it is important to note that sedimentation generally occurred in the lower gully reach for low-magnitude high-frequency events and on the gully fan for relatively rare extreme events. As a result, in the later stages of gully evolution only extreme events seemed to play a role in sediment delivery to catchment outlet. The minor events mainly seemed to prepare material, destabilize gully walls and redeposit sediment within the thalweg. Although this conclusion is obvious from a common sense point of view, the radionuclide

technique used here provided direct evidence to support it, which otherwise would be available only through continuous monitoring over many years. It is also possible to move from qualitative to quantitative assessment using the technique presented here.

## Conclusions

This section has attempted to reconstruct the recent development phases of a large gully (typical of many in the Upper Kalaus river basin). Although the process has been by deduction, we have attempted to corroborate our inferences by evidence from different approaches and methods. It is believed that the first phase (1) involved an initial incision and creation of a gully in the floor of a small valley (catchment area  $\sim 1 \text{ km}^2$ ) about 100 years ago. Triggers were probably overgrazing and associated vegetation degradation. A short period of rapid growth was followed by a longer period of gully stabilization. Subsequent phases were (2) the period  $\sim 1954\text{--}\sim 1960$  – in which a small channel was formed by re-incision of the gully infill sediments, probably initiated by a high-magnitude event, a substantial amount of sediment was delivered to the gully fan; (3)  $\sim 1960\text{--}1986$  – the nickpoint of the incision channel then slowly retreated, sediment was re-deposited nearby, and the lower fan surface became stable; (4)  $1986\text{--}1987$  – a dam was built in the gully mouth and breached shortly after construction (following a short period of high rainfall) – substantial sediment accumulated in the gully above the dam and below the spillway channel onto the fan surface; (5)  $1987\text{--}1993$  – the slow nickpoint retreat continued, and the fan surface was stable until  $\sim 1993$  when the last significant runoff event overlaid it by  $\sim 10 \text{ cm}$  of fresh sediment.

The results of this section show that radionuclide tracers can be a powerful addition to conventional methods for reconstructing periods of erosion and deposition, as well as for sediment sourcing and routing. An important overall outcome of these results is the causal link between high-magnitude rainfall events and gully growth and offsite sediment delivery. Furthermore, they highlight the fact that sediment delivery within and from these gullies can change abruptly and occur over very short (i.e. event scale) timeframes. Construction and placement of impoundment structures, such as dams, need to be considered carefully with respect to particular catchment characteristics. The information can then be used to avoid such failures as the dam breach reported here. This will have important downstream benefits in terms of

reducing the aggradation of ephemeral streams and loss of watercourses as outlined by Golosov et al. (1997) in this region.

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