Human-accelerated soil redistribution within an intensively cultivated dry valley catchment in southern European Russia

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Abstract The Stavropol Uplands is an area with some of the most severe soil erosion in European Russia. This poses serious problems in the region and requires quantitative assessment. The study reported used a combination of methods (geomorphological mapping, soil profile comparison, ^{137}Cs tracing and USLE-based modelling) to investigate soil and sediment redistribution during the period of serious human impact within the Maly Kazgulak dry valley catchment (area ~14 km^2, main valley length ~10 km). Soil redistribution dynamics were assessed for two different timespans, corresponding to the periods before and after the beginning of ^{137}Cs fallout. By studying three typical slope segments in the upper part of the catchment, the main characteristics of sediment delivery from arable slopes have been established. By combining this information with stratigraphic descriptions and ^{137}Cs data from sediment sections in the valley bottom, a provisional sediment budget has been constructed for the upper part of the study catchment. The general similarity of valley slope morphology within the study catchment provides a basis for extrapolating the data obtained to the entire catchment area.

Key words caesium-137; dry valley catchment; human impact; sedimentation; sediment budget; sediment redistribution; soil erosion; southern European Russia; USLE-modelling

INTRODUCTION

In this paper we present an attempt to quantify rates and patterns of soil and sediment redistribution within a small dry valley catchment affected by about 150 years of intensive cultivation. The study area is located in the Stavropol Uplands, one of the regions of European Russia most seriously affected by soil erosion. The study involved choosing a representative sub-catchment, based on geomorphic and land-use characteristics, and applying a range of different methods for reconstructing the sub-catchment sediment budget. The multi-technique approach allowed a sediment budget to be produced for two different time intervals, namely, the entire period of intensive cultivation and the post radiocaesium fallout period (since 1954). The results obtained for the representative sub-catchment were extrapolated to the entire dry valley catchment area, based on a detailed analysis of its geomorphic structure and land use.

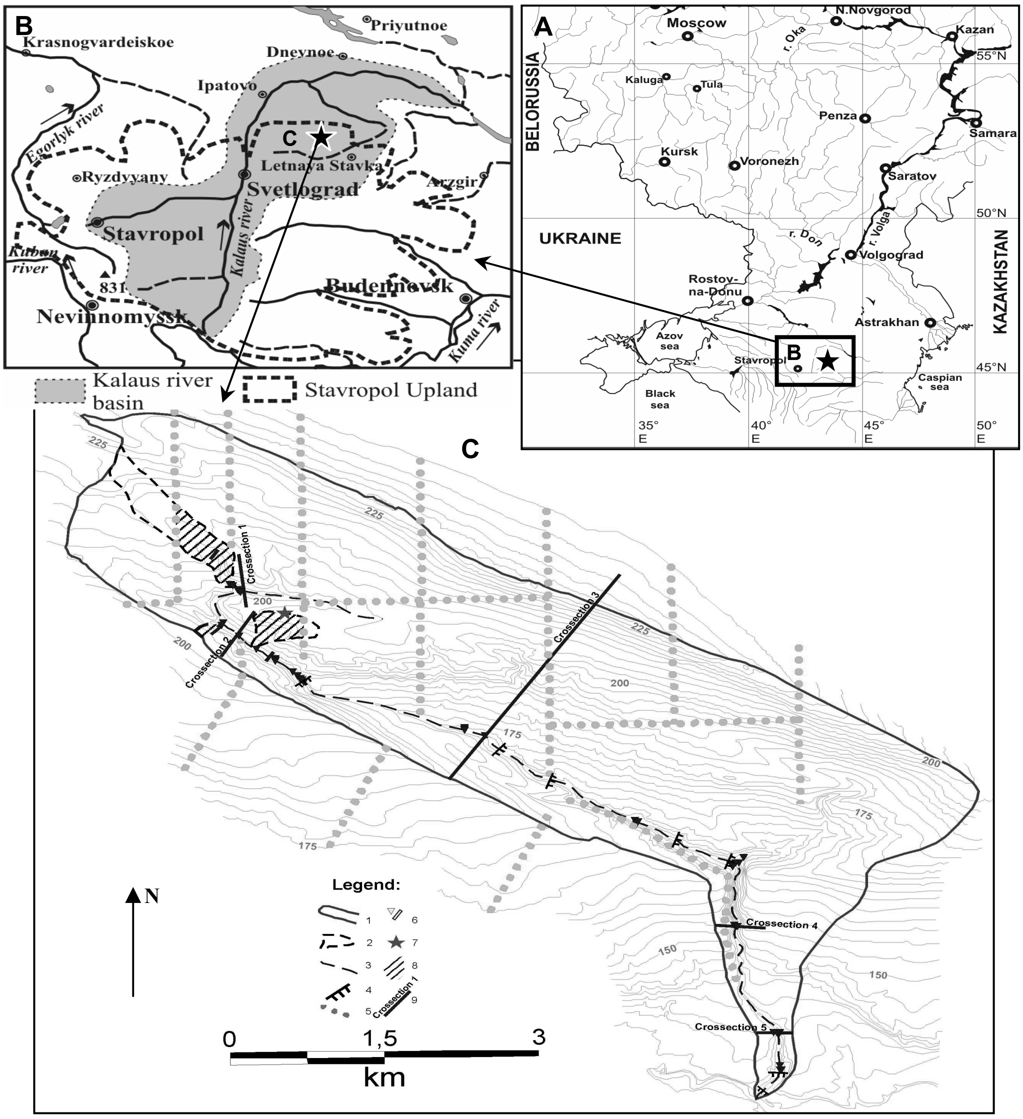

Fig. 1 The location of the case study area within European Russia (A) and within the Stavropol Uplands (B). The general features of the case study catchment are depicted in (C). Legend: 1: catchment boundary; 2: key slope catchment boundaries; 3: main valley thalweg; 4: earth dams; 5: forest shelter belts; 6: pits, cores and trenches; 7: ^{137}Cs reference sampling site; 8: areas of detailed investigations; 9: locations of the cross-sections.

CHARACTERISTICS OF THE STUDY SITE

The Maly Kazgulak dry valley catchment selected for this case study is located in the northeastern part of the Stavropol Uplands, within the Aigurka River basin, about 4 km north of Kazgulak village (Fig. 1). It has a drainage area of about 14.5 km^2. The main valley has a length of about 9.5 km and its long profile is generally straight, with local convexities and concavities. The altitudinal range between the valley source and the catchment outlet is about 80 m, and the average thalweg gradient is 0.009. The width of the valley bottom varies from 30–40 to 50–60 m in the upper part and decreases to 20–50 m in the middle and lower parts. The catchment is characterized by short (<500 m) convex slopes and long (up to >2000 m) concave–convex slopes. The latter are dissected by numerous hollows (Fig. 1(C)). Slope gradients are moderate, varying from 0.02 to 0.07, and only locally exceed 0.1 on convex dry valley banks. The natural landscape of the study area prior to the onset of intensive agriculture in the late 19th and early 20th centuries was represented by steppes. Soil cover is dominated by chestnut soils developed on Quaternary loessial loams.

The climate of the study area is semiarid, with relatively cold winters (temperatures <0°C for 3–4 months) and hot summers (temperatures up to 40°C). The mean annual precipitation is 400 mm, most of which is associated with heavy summer storms producing 30–60 mm or more during a single event. The inter-annual variability of precipitation is also high, with annual totals ranging from 150 to 700 mm over about 100 years of direct meteorological observations. Usually 4–8 drier years are followed by 2–4 wetter years.

The catchment has been intensively cultivated for about 150 years. Before 1917, wheat, barley, oats, maize and sunflower were cultivated in a three-field crop rotation. During Soviet times, winter cereals with row crops remained dominant, but more varied crop rotations were introduced. Agricultural development after 1917 was directed towards collectivization, resulting in increased field size and the use of heavier machinery. In 1950 a number of smaller collective farms were amalgamated into one large unit, which is still in operation today. At the same time, changes in the boundaries of the arable fields, creation of forest shelter belts and construction of earthen dams in the main valley bottom occurred (Fig. 1(C)). Today, more than 90% of the total catchment area is cultivated.

FIELD AND LABORATORY METHODS

The methods employed for estimating soil redistribution rates included the soil-morphological method (Larionov *et al.*, 1973), the use of ^{137}Cs measurements (Walling & He, 1999), and USLE-based modelling (Larionov *et al.*, 1998; Krasnov *et al.*, 2001). In addition, the total thickness of the layer of valley bottom sediment associated with the period of intensive agriculture was determined by direct stratigraphic observations.

The first stage of the investigations included a reconnaissance survey of the geomorphology of the catchment and direct observations of the stratigraphy of the main valley bottom using pits and cores located along morphologically representative cross-sections (Fig. 1(C)). In total, 33 pits and 10 cores were examined. As a result, detailed information on valley bottom sedimentation has been obtained. Three main slope types in terms of morphology and land use have been distinguished, viz.: (a) relatively long (up to >2000 m) concave–convex cultivated slopes dissected by hollows; (b) short (<500 m) convex cultivated slopes; (c) relatively short (<500 m) convex pasture slopes. In the second stage, a sub-catchment (242.6 ha) within the upper part of the main valley, separated from its lower reaches by a closed earth dam, was studied in detail (Fig. 2). In total, 54 pits were excavated on slopes of different morphologies, and all of these were sampled for ^{137}Cs activity. Of the 43 pits and cores associated with the main valley bottom, 19 were located within the upper sub-catchment selected for detailed study. Four of those were sampled depth-incrementally to document the ^{137}Cs depth distribution (Fig. 2(A)). Samples destined for radiocaesium analysis were processed in the laboratory and counted for not less than 12 hours. Soil redistribution rates were estimated from the ^{137}Cs measurements using the proportional model and the simple mass-balance model (see Walling & He, 1999).

RESULTS AND DISCUSSION

The ^{137}Cs reference inventories

The ^{137}Cs depth distribution in the soil at the reference site (pit Ref-1, Fig. 2(A)), coupled with detailed observation of the soil structure, indicated that the site had been cultivated after 1954. Nevertheless, the location of the reference sampling site pit at the top of a relatively flat interfluve confirms that no radionuclide loss or gain could have occurred here, either by water erosion or tillage translocation of topsoil. In addition, a further 12 bulk cores collected adjacent to the main reference pit were characterized by a relatively low scatter of ^{137}Cs inventories with a coefficient of variation of 23%. The ^{137}Cs inventory for the reference site selected for the study has therefore been used to represent the baseline fallout input for use with the calibration models.

Soil redistribution on the slopes of the sub-catchment selected for detailed investigation

Initial analysis of soil redistribution rates on the three types of slope distinguished within the sub-catchment (Fig. 2(C)) demonstrated that only the arable slopes with hollows generated sediment which reached the bottom of the main valley or its tributaries. The other two slope types were characterized by very low rates of soil redistribution and, consequently, there were appreciable uncertainties associated with the results obtained from the three techniques employed. It seems most likely that all sediment mobilized on those slopes is retained within their lower parts and that no sediment export into the main valley bottom occurs, although the available data are insufficiently precise to fully support this conclusion. Nevertheless, the total area of short convex slopes (both cultivated and grazed) within the study sub-catchment is 55.9 ha or 23%, whereas the area occupied by slopes with hollows is 178.5 ha or 73.6%. A decision was therefore taken to concentrate effort on assessing soil redistribution within, and sediment delivery from, the latter, as representing the main sediment source within the study area.

The estimates of soil redistribution and sediment delivery for the sampled slope hollow (Fig. 2) are presented in Fig. 3 and Table 1. As can be seen, all the techniques employed document significant rates of soil redistribution, although the precise values vary substantially (8.7 to 24.1 t ha^{-1} year^{-1} for gross erosion; 6.4 to 63.8 t ha^{-1} year^{-1} for within-slope redeposition; and 2.2 to 12.2 t ha^{-1} year^{-1} for net erosion). The spatial patterns of soil redistribution provided by the ^{137}Cs and soil-morphological methods are also generally similar (Fig. 3(a)–(c)). The USLE-based model provides good estimates of sediment mobilization from the slopes (Table 1), but fails to provide an adequate representation of the spatial pattern of soil redistribution, because it takes no account of within-slope redeposition (Fig. 3(d)).

The most notable difference between the results is that for the estimates of sediment redeposition on the slopes and the lower parts of the hollow provided by ^{137}Cs measurements and the soil-morphological method. The latter produced much higher rates of redeposition (63.8 t ha^{-1} year^{-1}), whereas both ^{137}Cs calibration models yielded moderate values (6.4 t ha^{-1} year^{-1} from the proportional model and 11.8 t ha^{-1} year^{-1} from the mass-

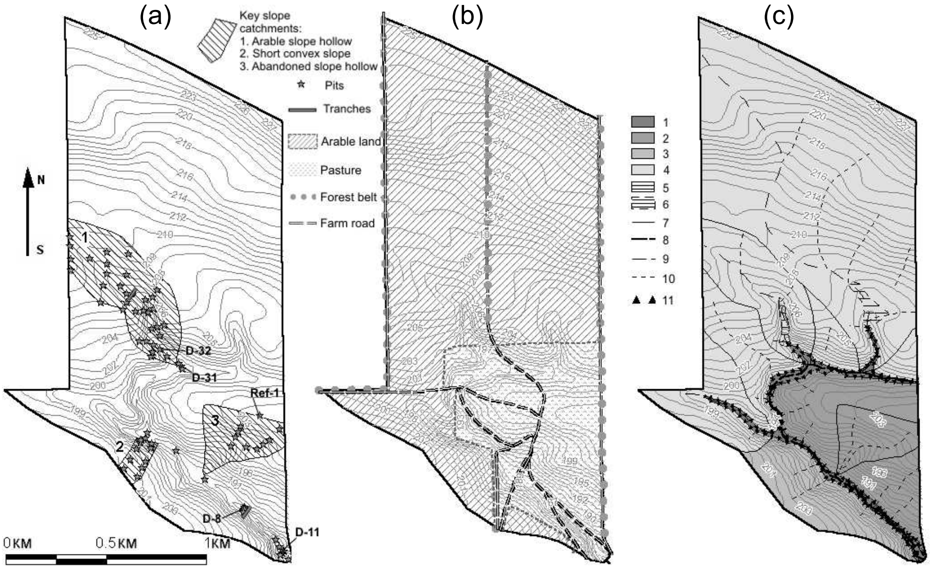

Fig. 2 The upper subcatchment of the Maly Kazgulak dry valley selected for detailed investigations: (a) detailed study areas and observation points; (b) land use; (c) geomorphological map. Legend: 1: main valley bottom; 2: abandoned arable slopes, currently permanent pasture; 3: short convex arable slopes; 4: long arable slopes dissected by hollows; 5: directly observed depositional zone in the lower part of slope hollow; 6: supposed depositional zone in the lower part of slope hollow; 7: slope catchment boundaries; 8: main valley thalweg; 9: thalwegs of large slope hollows; 10: thalwegs of smaller slope hollows; 11: main valley bottom boundary.

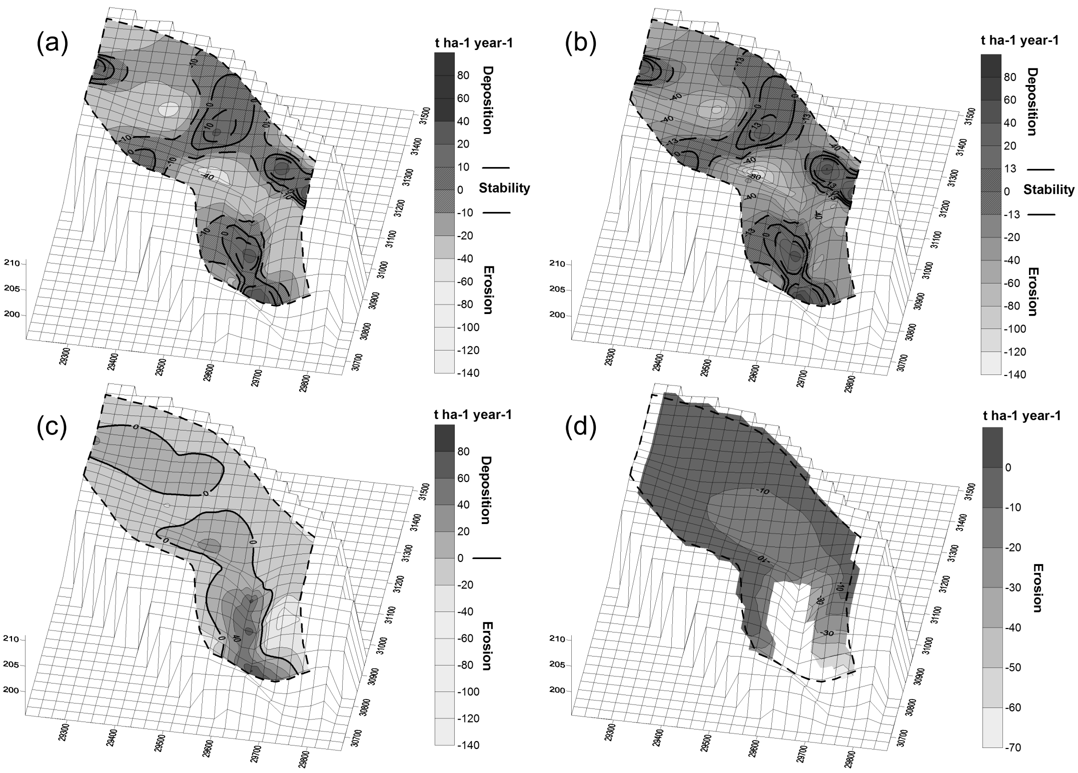

Fig. 3 The estimates of soil redistribution rate obtained for the slope hollow catchment using: (a) ^{137}Cs measurements and the proportional model; (b) ^{137}Cs measurements and the mass-balance model; (c) the soil-morphological method; and (d) a USLE-based model.

Table 1 Average soil redistribution rates for the case study arable slope hollow catchment estimated by different methods.

Method	^{137}Cs proportional model	mass-balance model	Soil-morphological	USLE
Period	1954–2002	1954–2002	1864–2002	1864–2002
Eroded area (ha)	9.0	9.7	10.5	16.9
Average erosion rate (t ha^{-1} year^{-1})	13.7	24.1	8.7	11.6
Volume eroded (t year^{-1})	123	233	91	196
Volume eroded over the period (t)	5918	11222	12613	27048
Total eroded layer (mm)	44	77	80	106
Depositional area (ha)	0.9	1.0	7.7	–
Average deposition rate (t ha^{-1} year^{-1})	6.4	11.8	12.6	–
Volume deposited (t year^{-1})	6	11	97	–
Volume deposited over the period (t)	278	566	13386	–
Total deposited layer (mm)	20	38	115	–
Total slope catchment area (ha)	18.7			
Average net erosion rate (t ha^{-1} year^{-1})	6.5	12.2	2.2	–
Average annual sediment export (t year^{-1})	117	222	40	–
Sediment export over the period (t)	5640	10655	5615	–
Total denudation layer (mm)	21	39	20	–

balance model). The main reasons for this apparent discrepancy are probably: (a) a change in the spatial-temporal pattern of soil redistribution towards decreased deposition and increased erosion after the change in land use in the early 1950s; (b) selective deposition of coarser particles in the hollow bottom, with the finer particles carrying the highest ^{137}Cs activities being transported further to the main valley bottom; (c) the possible influence of deep linear erosion features, such as ephemeral gullies, mobilizing subsoil material bearing no atmospheric fallout radionuclide content; (d) the insufficient depth of the bulk ^{137}Cs sampling within depositional locations.

Deposition in the main valley bottom and the bottoms of the tributary valleys

Detailed stratigraphic surveys of the main valley bottom and those of its main tributaries have shown that the thickness of the sediment layer associated with the period of intensive agricultural activity within the catchment is essentially uniform (Table 3). Within it at some locations we have observed secondary erosional boundaries and depositional bodies, associated with alternating episodes of local incision and aggradation. The total thickness of this anthropogenic sediment varies between 0.1–0.2 m (terraces) and 4.5 m (extreme aggradation in a former reservoir in the lower part of the valley), with mean values of 1.12 m for the upper sub-catchment and 1.16 m for the entire valley bottom. The associated deposition volumes are 140 510 t and 839 820 t respectively (Table 3). Assuming a period of cultivation of approximately 150 years, the average aggradation rate is about 7.5–7.7 mm year^{-1}.

Additional time marks within the anthropogenic sediment layer were obtained by analysing the ^{137}Cs depth distribution in three pits located in the main valley bottom and one in the lower part of its tributary hollow (Figs 2(a) and 4). Values of the ^{137}Cs

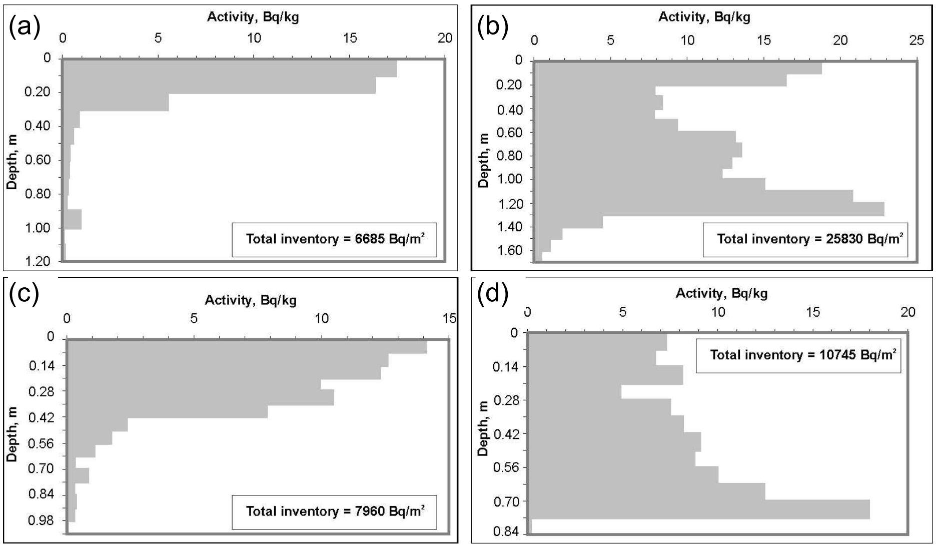

Fig. 4 Depth distributions of ^{137}Cs in the sediment within the main valley bottom; (a) pit D-8; (b) pit D-11; (c) pit D-31; (d) pit D-32. For pit locations see Fig. 2(a).

Table 2 A simplified sediment budget for the upper part of the Maly Kazgulak catchment (total area 242.6 ha), representing sediment export from slope hollows (total area 178.5 ha), within-slope redeposition and main valley bottom aggradation (total area 8.2 ha).

Method	Sediment export from slopes (t) / redeposition within slopes (t) / sediment delivery ratio (%)			Valley bottom aggradation (t)
	^{137}Cs proportional model	^{137}Cs mass-balance model	Soil-morphological	
1954–2002	55 315 / 2730 / 95	104 510 / 5555 / 95	–	82 280*
1864–2002	–	–	55 060 / 68 645 / 45	140 510**

*^{137}Cs vertical profiles
**geological survey

inventory in depositional locations are 3 to 7 times higher than for the reference site. However, the shape of the radiocaesium vertical profile differs from place to place. In pits D-8 and D-31 (Fig. 4(a) and (c)) aggradation was lower and probably occurred at the same time as the ^{137}Cs fallout, whereas in pits D-11 and D-32 (Fig. 4(b) and (d)), sedimentation was much greater and has continued to the present. On average, about 0.7 m of the total 1.12 m (or 82 280 t of 14 0510 t, Table 2) of anthropogenic sediment within the main valley bottom of the upper sub-catchment was deposited during the last ~50 years, reflecting an increase in the aggradation rate to about 14 mm year^{-1}.

A provisional sediment budget for the upper part of the dry valley catchment

Combining the results presented above, it has been possible to establish the general patterns of soil and sediment redistribution within the upper part of the study catchment over the timespans considered above (Table 2). Modern rates of soil and sediment re-distribution on the slopes, and export to the main valley bottom, within the case study sub-catchment are well documented by the ^{137}Cs technique, except for the possible need for more detailed sampling of depositional zones in the lower parts of hollows. Total sediment export from the slopes since 1954, calculated as the average of the results provided by the two ^{137}Cs conversion models (Table 2), equals ~79000 t, which is very close to the estimate of sedimentation in the main valley bottom (82280 t, Table 2).

The differences between the results provided by the ^{137}Cs and the soil-morphological methods (Tables 1 and 2), probably reflect significant changes in rates and spatial patterns of soil and sediment redistribution associated with changes in land use (new field boundaries, creation of forest belts, and dam construction) in the early 1950s, almost coincident with the beginning of the radiocaesium fallout period. The relatively low sediment delivery ratio calculated by the soil-morphological method does not adequately represent the contemporary situation, because the depositional areas and volumes are likely to reflect the pre-1950s land use pattern, when the area of the key slope hollow catchment sampled was about 30% larger. The estimates of sediment export for the entire cultivation period provided by the soil-morphological method are also lower than the volume of valley bottom sedimentation, since significant sediment-producing areas above the present forest belt are not taken into account (Fig. 1(C)).

Another possible reason for the underestimation of sediment export from the slopes by the soil-morphological method is the failure to take account of linear erosion. This may be active in the bottoms of large hollows during extreme runoff events and can partially rework sediment in depositional zones. Such events associated with ephemeral gully formation in hollows most likely occurred prior to the planting of the forest belts, when flows in the lower parts of hollows could have been much higher than modern ones, due to the larger drainage areas involved. It has been shown for another catchment in the Stavropol region that episodic formation of linear erosion features, such as ephemeral gullies on arable slopes, can result in dramatically increased soil erosion rates (up to 50 t ha^{-1} year^{-1}) and sediment delivery ratios (up to 100%) (Belyaev *et al.*, 2005). More research is necessary within the case study catchment to confirm this assumption.

The general characteristics of soil and sediment redistribution within the study catchment

As demonstrated by analysis of the topography of the Maly Kazgulak catchment, the morphology of the cultivated slopes is relatively uniform (Fig. 1(C)). The three main morphological slope types distinguished within the upper part of the catchment (Fig. 2) also occur throughout the catchment. Of these, cultivated slopes with hollows are the most widespread, occupying >90% of the total catchment area (Table 3). Thus, slopes with hollows can be considered to be the main source of sediment delivered to the main valley bottom.

This assumption is, of course, a simplification, because there are steep (>10–15°) erosional valley slopes in its lower deeply incised section (Fig. 1(C)). This slope morphology is not represented in the upper and middle parts of the catchment. Despite the absence of cultivation on these slopes, visual examination showed that some sheet and rill erosion can occur there in periods when the vegetation cover is sparse or reduced by grazing. Such slopes can be episodically active as a result of downcutting by the stream

Table 3 Amount of sediment export from slope hollow catchments, redeposition within hollow bottoms and aggradation of the main valley over the entire 150-year period of intensive cultivation, based on the results of the soil-morphological method and the valley bottom stratigraphy.

	Detailed study area—the upper part of the catchment	Entire catchment
Area (ha)	242.6	1450.0
Area of slope hollow catchments (ha, %)	178.5 / 73.6	1325.0 / 91.4
Redeposition in slope hollow bottoms (t)	68 645	501 850
Sediment export from slope hollow catchments to the valley bottom (t)	80 000*	584 875
The valley bottom area (ha)	8.2	43.5
Average depth of the anthropogenic sediment layer (m)	1.12	1.16
Aggradation over the entire period of intensive cultivation (t)	140 510	839 820

*Taking account of the change in the spatial pattern of cultivated land.

channel during high-magnitude runoff events, and can therefore deliver some material into the valley bottom as a result of landsliding, rock falls and scree activity. However, the spatial extent of these erosional slopes is very low compared to that of the cultivated slopes with hollows. Hence, sediment production from the former can indeed be treated as negligible for this preliminary analysis.

Using these assumptions, the results obtained for the entire period of intensive cultivation by applying the soil-morphological method within the upper sub-catchment, were extrapolated to the entire Maly Kazgulak catchment area (Table 3). In contrast to sediment delivery from cultivated catchment slopes, valley bottom aggradation was studied in detail over its entire length (Fig. 1(C)). As valley bottom sediment volumes were found to be very similar along the whole valley length (Table 3), comparison of the volume of material associated with this storage, with the volume of sediment delivered from cultivated slopes and with hollows estimated by extrapolation, provides a means of validating the approach used. The volume of sediment exported from the slopes has been adjusted to account for change in drainage area, resulting from the creation of artificial runoff boundaries (forest shelter belts) in the early 1950s, by simply multiplying the volume of sediment exported by the percentage change in drainage area, and thereby assuming a constant average erosion rate over the catchment.

It can be seen that the results of the extrapolation are generally satisfactory, although the discrepancy between the sediment export from the slopes and the deposition in the main valley bottom remains rather high (Table 3). This highlights the need to improve assessment of the variations in the spatial and temporal pattern of within-slope soil redistribution and sediment delivery to the valley bottom indicated above. The most important needs are for investigations of one or two more slope hollow catchments, in the middle and lower parts of the valley, and additional depth-incremental and deeper bulk ^{137}Cs sampling, to permit more detailed characterization of the depositional zones.

CONCLUSIONS

1. Despite the relatively short (~150 years) period of intensive cultivation of the studied catchment, intense soil degradation (8.7 to 24.1 t ha^{-1} year^{-1}) and valley

bottom aggradation (>1 m, with ~0.7 m in the last ~50 years) have occurred. These rates of soil loss and aggradation are significantly higher than those observed in the more northern areas of European Russia with a longer land use history. During the last ~50 years soil erosion rates on the slopes slightly increased, whereas redeposition within the lower parts of the hollows declined. As a result, sediment export from slopes increased, leading to increased aggradation in the main valley bottom (Table 3).

2. Arable slopes dissected by hollows, which occupy >90% of the catchment area are the major sediment source. This conclusion confirms the findings of another investigation in a similar catchment in the Stavropol region (Belyaev *et al.*, 2005).
3. The area occupied by degraded soils within the slopes with hollows is an order of magnitude larger than that of the depositional zones (Table 1, Fig. 3). This highlights the need for the design and implementation of soil protection measures in the region, in order to maintain sustainable agricultural development.

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