Valentin N. Golosov[1,2,*], Xinbao Zhang[2], Tang Qiang [2, 3], Ping Zhou[2], Xiubin He[2]

[1] Faculty of Geography, Moscow State University, Moscow 119991, Russia; Tel.: +7-495-9395044; e-mail: gollossov@gmail.com

* **Corresponding author**

[2] Key Laboratory of Mountain Surface Processes and Ecological Regulation, Institute of Mountain Hazards and Environment, Chinese Academy of Sciences, Chengdu 610041, China

[3] University of Chinese Academy of Sciences, Beijing 10049, China

QUANTITATIVE ASSESSMENT OF SEDIMENT REDISTRIBUTION IN THE SICHUAN HILLY BASIN AND THE CENTRAL RUSSIAN UPLAND DURING THE PAST 60 YEARS

ABSTRACT. Agricultural lands around the globe have been seriously affected by soil erosion and resultant on- and off-site eco-environmental problems. Quantitative assessment of sediment redistribution allows for explicit understanding the effects of natural and anthropogenic agents on catchment soil erosion and sediment delivery. To this end, sediment redistribution at field and catchment scales in two agricultural regions of the Sichuan Hilly Basin in southwestern China and the Central Russian Upland was comprehensively assessed using multiple approaches including 137Cs tracing, soil morphology comparison, empirical-mathematic modeling, sediment budgeting, discharge and sediment monitoring, and sediment dating. Field measurements were undertaken in the zero-order small catchments (with drainage area less than 0,25 km2), and soil erosion rates were found to be 6–7 t ha–1-yr–1. Long-term repeated measurements indicated that both precipitation changes and conservation practices had contributed to the alleviation of soil erosion on hillslopes. However, eroded sediment was transferred from hillslopes to streams through different pathways for both regions. High slope-channel connectivity and substantial proportions of sediment delivery were observed in the Sichuan Hilly Basin. Changes of riverine suspended sediment yield were indicative of soil erosion and sediment delivery on upland catchments. Large quantity of sediment was redeposited on first-order dry-valley bottoms and only 4–12% of the gross sediment load was delivered into adjacent river channels in the Central Russian Upland.

KEY WORDS: sediment redistribution, Cesium-137 tracing, sediment budget, sediment delivery ratio, slope-channel connectivity

INTRODUCTION

Agricultural lands around the globe have been seriously affected by soil erosion and resultant on- and off-site eco-environmental problems (land degradation, productivity loss, channel siltation, freshwater contamination) [Syvitski et al., 2005; Van Oost et al., 2007]. However, soil erosion and sediment redistribution differ spatially and temporally according to regional physical settings and the existence of anthropogenic disturbances. Quantitative assessment of sediment redistribution within a catchment would allow for an explicit understanding of the effects of both natural and anthropogenic agents (precipitation change, land use change, channel closure, soil conservation practices, etc.) on catchment soil erosion and sediment delivery.

However, it is difficult to evaluate the specific ways in which different influencing factors contribute to the observed changes. It is particularly a problem in areas with high population density and a high proportion of cultivated lands, due to the complex interactions between diverse controlling factors. The sediment budget approach provides a valuable integration framework for studying the various processes of sediment mobilization, transport, and deposition occurring within a catchment [Trimble, 1983; Walling, 1983; Walling et al., 2011]. It is also useful for understanding the ways in which sediment within a catchment responds to environmental and anthropogenic changes [Walling et al., 2001; Rommens et al., 2005], which must be considered when implementing soil conservation and sediment management strategies. Based on environmental features and scales of investigation, more attention can be given to quantifying the sediment delivery ratio [Golosov et al., 1992; Owens et al., 1999; Walling et al., 2002], evaluating sediment storage in ponds and reservoirs [Trimble, 1976; Walling et al., 2006], and de-coupling slope and linear elements of fluvial systems [Vandaele and Poesen, 1995; Belyaev et al., 2005b]. As Trimble [1983] described in relation to the Coon Creek Basin in the United States of America, the sediment budget can be considerably transformed by climatic and anthropogenic changes over relatively short time interval. Although a large bulk of studies have been conducted at various scales, a comprehensive overview of this situation for a specific hotspot region was rarely reported. To this end, changes in sediment redistribution patterns within small catchments in two contrasting physical settings of the Sichuan Hilly Basin in Southwestern China and the Central Russian Upland were comprehensively assessed, in an attempt to compare sediment redistribution in small catchments and evaluate the different factors influencing changes in slope-channel sediment delivery coupling in two contrasting regions during the past 60 years.

STUDY AREA

The study was conducted at two contrasting regions: the Sichuan Hilly Basin in Southwestern China (Fig. l) and the Central Russian (Srednerusskaya) Upland (Fig. 2), both of which are characterized by a high proportion of cultivated lands and have been subjected to severe soil erosion (Table 1).

The Sichuan Hilly Basin

The Sichuan Hilly Basin is located within the upper Yangtze River Basin in southwestern China. Regional topography is characterized by numerous small catchments with drainage areas less than 0,25 km^2 and steep concave slopes with gradient ranges from 20°–25° near the top to 5°–10° at the catchment outlets that form the larger catchments with flat valley permanently widening downstream. Surface land is covered by purple soil, classified as Entisol by the soil taxonomy of the US Department of Agriculture [He et al., 2007, 2009]. The area of agricultural land (upland terraces and orchards) changes in a range of 20–60% of the total area of the small slope catchments. Crop rotation for the slope area since 1980s includes corn, sweet potato, rape, and wheat. Before the 1980s, government regulations generated very different crop rotations for various counties. The rest of the small catchment lands are under forest or very steep wastelands. Valley bottoms are mostly used as paddy fields.

Three typical small catchments (Wujia, Jiliu, and Tianmawan) were selected to evaluate the mean annual specific sediment yield (SSY) (see Fig. 1). The Wujia and Jiliu catchments in the Yanting County, central Sichuan Hilly Basin, have drainage areas of 0,22 and 0,09 km^2, respectively. They have similar physical geographic and land-

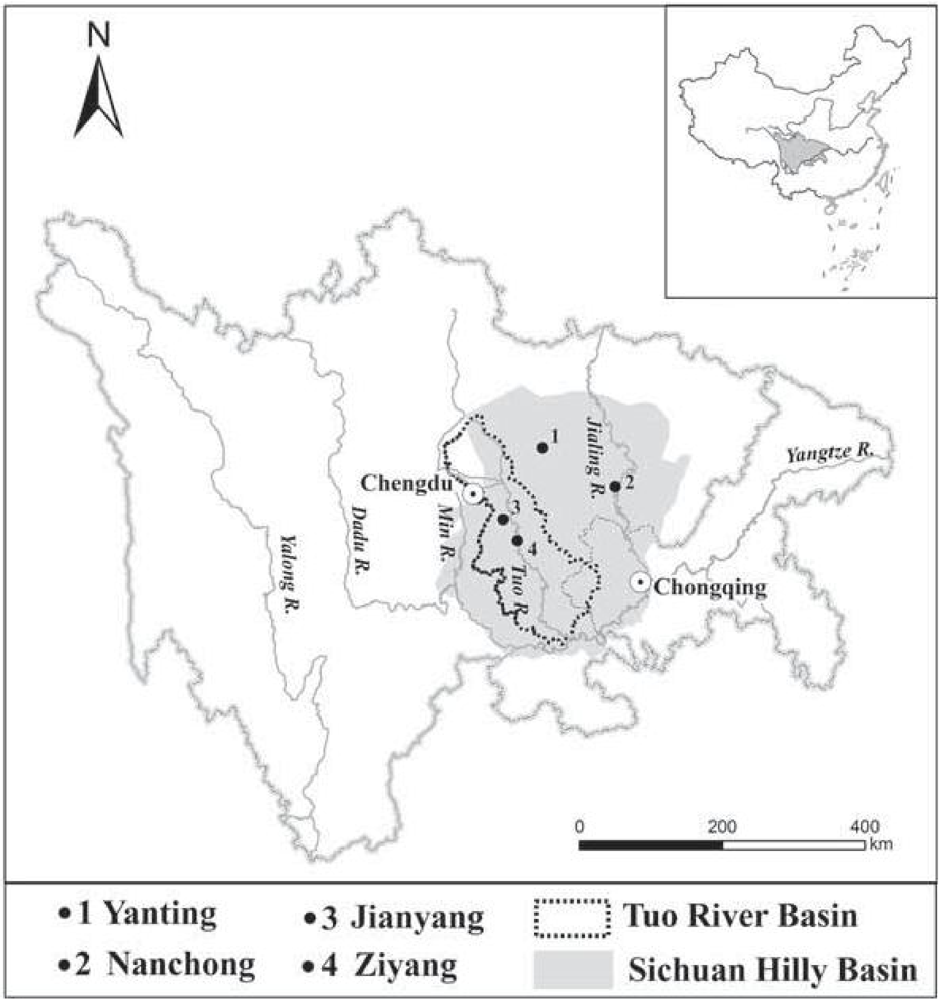

Fig. 1. A sketch map of the Sichuan Hilly Basin in Southwestern China, with the study sites and the Tuo River basin also indicated.

use conditions, with elevations that vary between 420 and 560 m and a relative relief of 140 m. The catchments are underlain by horizontally bedded mudstones, siltstones, and sandstones from the Jurassic Penglaizhen Group. The landform typically comprises steep sandstone cliffs with slopes of 25–30° separated by gentle mudstone and siltstone terraces of < 10°. The gentle terraces and steep slopes account for one- and two-thirds of the catchment area, respectively. The gentle terraces have been cultivated for centuries, whereas the steep slopes were originally covered by wild grasses, but have gradually been afforested with cypress trees since the 1970s. The Tianmawan watershed

Table 1. Geographic characteristics for the study regions of the Sichuan Hilly Basin in Southwestern China and the Central Russian Upland

Region	Area (km^2)	Percentage of agricultural land (%)	Topo-graphy (m)	Population density (persons km^{-2})	Geology	Soil
The Sichuan Hilly Basin	105 000	40–60	250–650	540	Horizontally bedded Mesozoic mudstones, siltstones and sandstones	Purple soil of fast weathering rocks
The Central Russia Upland	105000	60–70	130–300	40	Horizontally bedded Mesozoic limestone, chalk overlaid by loess	Typical and leached chernozem, grey forest soil

Fig. 2. Schematic map of the Central Russian Upland in the European part of Russia and the locations of the study sites.

in Nanchong has a drainage area of 0,19 km^2 and elevations ranging between 310–420 m. The catchment is underlain by horizontally bedded mudstones and siltstones from the Jurassic Suining Group [Li et al., 1991]. The landform typically comprises dozens of small steep cliffs separated by short gentle terraces. The steep cliffs have typical heights of a few meters and are covered by wild grasses and scattered young cypress trees. The gentle terraces with slopes of < 10° and lengths of 10–30 m are mostly rain-fed areas. Purple soils dominate in the three study catchments, but important differences in erosion resistance depend on parent lithology. Due to different proportions of sandstone, the purple soils of the Penglaizhen and Suining Group have relatively high and low erosion resistances,

Table 2. Regional climatic conditions for the study areas of the Sichuan Hilly Basin and the Central Russian Upland

Region	Climate	Annual average precipitation (mm)	Maximum precipitation (mm-day^{-1})	Mean temperature in January (°C)	Mean temperature in July (°C)	Frost-free period (days)
The Sichuan Hilly Basin	Wet subtropical monsoon	900–1100	100–120 (May)	+6,5	+27,5	280–330
The Central Russian Upland	Temperate continental	500–700	80–90 (July)	–8	+18	220–230

respectively [He, 2003]. The cropland ratio in the Tianmawan catchment is 0,45, while that for the other two catchments is 0,25. Annual precipitation is 1010 mm in Nanchong and 826 mm in Yanting, 70% of which occurs in the wet season from June to September. From 1949 to 1956, each of the study catchments was impounded by an earth dam, 4,5 m high and storage volumes ranging between $1{,}5–5{,}1 \cdot 10^4$ m^3. The dams were made of soil dug from the valley bottoms within the ponds. The ponds have simple water delivery facilities comprising weirs or bottom culverts with intakes. The storage water in the ponds is used for irrigation in spring and summer. The pond in the Jiliu catchment has no flood spill ditches and the pond in the Wujia catchment has a ditch that is seldom used. The pond in the Tianmawan catchment has a flood spill ditch that was seldom used until 1981, but after reorganization of the land management system that year, it has been used to divert floods with high sediment concentrations away from the pond.

The Central Russian Upland

The topography of the Central Russian Upland is characterized by a relatively high drainage density (1,5 km km^{-2}), largely represented by dry valley systems. The elevation between hilltops and valleys ranges from 50 to 110 m. Inter-fluvial convex slopes have gradients increasing from 1°–2° to 3°–5° and lengths increasing from 300–500 m to 800–1200 m, depending on the order of interfluves. Most of the inter-fluvial slopes are cultivated with areas of shallow soils under forest or meadows. These are connected to short and relatively steep (10–15° and more) valley slopes by sharp convex slope breaks, which are not used as cultivated fields. Crop rotations have changed several times during the last 60 years with varying proportions of wheat, barley, buckwheat, corn, sunflower, annual and perennial grasses, fallow, sugar beets, and potato, depending on field location relative to the road network, government decisions during Soviet times, and market prices over the last 20 years. The main climatic characteristics of both regions are presented in Table 2. Soil losses from the catchment area mainly occurred during heavy storm events in May–September for both areas, but additional erosion during snowmelt was observed in the Central Russian Upland in March–April.

Assessments of soil redistribution rates for two periods in the Central Russian Upland were conducted at the Gracheva Loschina catchment (1,98 km^2) and the Lebedin catchment (15,2 km^2), which are typical firsts and third Hortonian order catchments within the River Vorobzha basin, left-hand tributary of the Seim River, drainage centre part of the Kursk Region (Fig. 3).

Both catchments have eart·hen dams at their outlets, which were constructed in 1986 and 1956, respectively. These enabled the calculation of detailed sediment budgets for both catchments. In addition, soil conservation measures have been employed on 70% of the Gracheva Loschina catchment

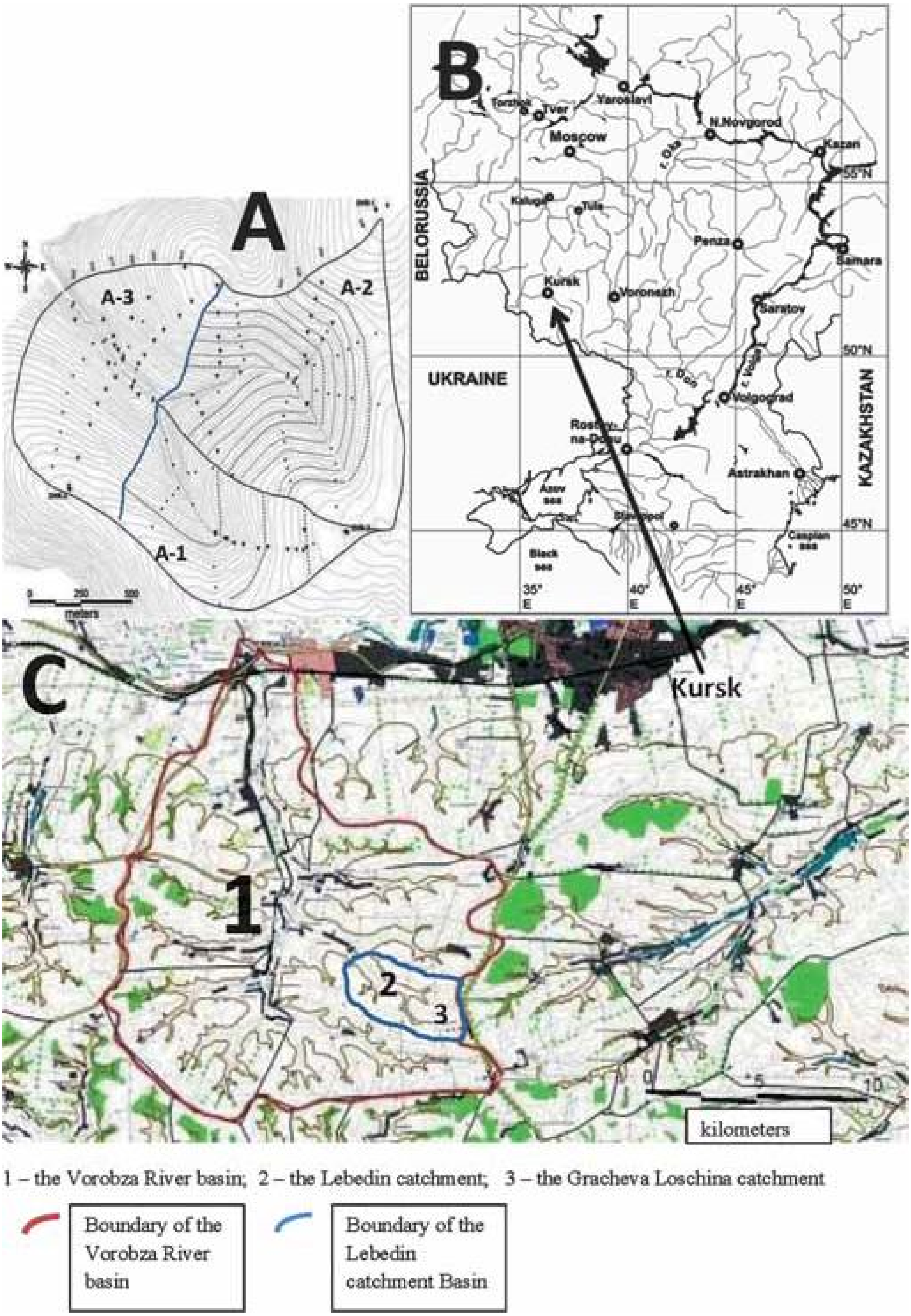

Fig. 3. Location of the Vorobza River basin within the European part of Russia:

A – topographical map of the Gracheva Loschina catchment and location of sampling points;
A-1, A-2 and A-3 – sub-catchment numbers;
B – schematic map of the European part of Russia;
C – topographical map of the Vorobza River basin and location of the Lebedin catchment and the Gracheva Loschina catchment within the Vorobza River basin.

since 1986. Different sets of soil conservation measures were applied within the two sub-catchments (Fig. 3-A). Two-rowed forest shelter-belts planted in parallel with the slope topography contour lines and grassed waterways along hollow bottoms were introduced within both sub-catchments. A water retention ditch, about 1 m deep, was dug within each forest shelter-belt between the two rows of trees. The bottoms of the hollows were sown with perennial grasses and used as erosion-protected and sediment-intercepting pathways for surface runoff. In addition, contour terraces parallel to the contour lines with relative heights of about 1 m were constructed between forest shelter-belts in the Lebedin catchment (Fig. 3, A-2). Runoff along those terraces is diverted under very low gradient towards the grass-covered waterways in hollow bottoms. The rest of the catchment slopes remained cultivated in the traditional manner (Fig. 3, A-3). Thus, it is possible to evaluate the effects of soil conservation on soil erosion and sediment redistribution.

METHODS

^{137}Cs tracing

^{137}Cs tracing has been widely used to quantitatively evaluate soil erosion [Owens et al., 1997; Walling and He, 1998; Zhang et al., 1998; Mabit et al., 2008; Porto et al., 2011;] and sediment deposition rates [Walling and He, 1997; Hughes et al., 2010;]. Core samples for local ^{137}Cs references were collected depending on local landscape conditions from flat grassland, non-irrigated flat cultivated fields, and old terraces [Zhang et al., 2003; Belyaev et al., 2009; Golosov et al., 2011; Golosov et al., 2013]. Bulk samples from soil cores were collected at each of the reference sites from 4 to 28 points, using steel tubes with an inner diameter of 80 or 70 mm, up to a constant depth of 30 cm. Additional samples were collected from a few sampling points from a depth of 30–60 cm, to assess the possibility of deeper penetration of ^{137}Cs along the soil profile. The vertical distribution of ^{137}Cs in the soil profile at each reference location was examined by collecting depth-incremental samples with a fixed surface area and depth-increments of 3-5 cm down to a depth of 30–40 cm from one of the sampling points. The transect approach was used to assess the redistribution of ^{137}Cs along the cultivated slope. From 3 to 18 sampling points were selected along each transect, according to the slope profile complexity. Three to four bulk samples (0–30 cm) were collected at each sampling point using steel tubes with an inner diameter of 70–80 mm and these were thoroughly mixed into a single sample to account for the local variability of the ^{137}Cs inventory associated with cultivated surface micro-topography, variable plough layer thickness, and initial fallout variability. In addition, some sampling points were located within potential depositional areas along the lower field boundary and on ploughed terraces and slope toes (both cultivated and under grass). Sectioned cores were collected in these location to evaluate the total ^{137}Cs inventory in the soil profiles. Depth-incremental sampling was used to follow the determination of ^{137}Cs vertical distribution curves for the different sediment sinks (dry valley bottoms, dry ponds, and floodplains). Samples from ponds with water were taken by drilling a core with a diameter of 98 mm at the centre of the ponds. A PVC pipe with a diameter of 100 mm was used to protect the core during the drilling [Zhang et al., 2006a]. The resulting ^{137}Cs vertical distribution curves for each sampled section were used to calculate the sediment volumes deposited within given sediment sinks over different time intervals. Subsequently, a detailed geodetic survey was conducted for each sampling site using a differential positioning system (DGPS) or a digital tacheometer, to document their detailed longitudinal profiles or sediment sink area.

Samples were weighed, air- or oven-dried, re-weighed after drying, disaggregated by grinding, sieved to 2 mm, and homogenized. Representative sub-samples of sufficient weight were then placed into plastic containers of specific geometry for analysis by gamma spectroscopy. The ^{137}Cs activity in the sub-samples was measured at 661,66 keV using a high-resolution, low-background, low-energy, hyperpure N-type germanium coaxial gamma-ray detector coupled to an amplifier and multichannel analyser. The counting time for each sample was sufficient to determine the isotope activity with a maximum relative error of ±5–10% at the 95% level of confidence (0,5–24 hours depending on the ^{137}Cs activity in each individual sample). Conversion models used to convert ^{137}Cs concentration in soil to sediment redistribution rates for cultivated slopes were described elsewhere [Zhang et al., 2003; Zhang et al., 2006b; Golosov et al., 2011].

Soil morphology comparison

The soil profile morphology comparison method is based on comparing the thickness and horizon composition of soil in areas affected by various soil redistribution processes to those in locations where soil profile is regarded as undisturbed. It allows us to estimate the total soil loss or gain for the entire period of cultivation, although disregarding the processes responsible for soil redistribution [Belyaev et al., 2004, 2005a, b; Rommens et al., 2005; Golosov et al., 2011].

Empirical-mathematical model

The empirical-mathematical model (EMM) utilizes a combination of the Universal Soil Loss Equation (USLE)-based approach for estimating rainfall-induced sheet erosion and the model developed in the Russian State Hydrological Institute for estimating sheet erosion from snowmelt runoff. The model was designed for application under conditions in Russia and supplied with a large spatially distributed dataset of coefficients [Larionov et al., 1998; Krasnov et al., 2001]. The input data required for the model calculation include detailed topographical parameters of slope transects oriented along the surface runoff flow lines, local soil properties, precipitation records, and land use and crop rotation information.

Sediment budget

Sediment budget calculation within a drainage catchment includes the application of all the above-mentioned methods and techniques. Large-scale geomorphological mapping was used for the area evaluation of different morphological units within the studied catchments. Mean soil loss/gain within each morphological unit was determined using ^{137}Cs techniques, the soil profile morphology comparison method, and erosion model calculation. As a result, it was possible to check the correctness of each technique applied, which enabled the calculation of catchment sediment budgets based on the evaluation of soil losses from arable hillslopes, sediment redeposition within cultivated slopes, and the aggradation of uncultivated valley banks and dry valley bottoms, along with the deposition in the small reservoir upstream from the earthen dam at the catchment outlet. Values for soil redistribution rates and sediment delivery ratios were determined for different geomorphological units within a smaller catchment, and were then used to determine sediment budgets for larger catchments based on distinguishing similar types of morphological units and estimating erosion rates using the erosion model. The resulting values for sediment delivery into the main valley of the Lebedin catchment were comparatively tested against the sedimentation rates and volumes obtained from an analysis of the ^{137}Cs-based valley bottom sediment microstratigraphy, including the dry reservoir infill. Only the ^{137}Cs technique, together with information about land use, was applied to calculate the sediment budget for the Tianmawan catchment in the Sichuan Hilly Basin.

Sediment dating

The sediment volumes in ponds and reservoirs were determined based on detail depth measurements taken along cross-sections. The number of cross-sections depended on water body size. Total sedimentation was determined based on the differences between the initial bottom area and bottom area surface at the moment of field survey. The majority of reservoirs in the Sichuan Hilly Basin were constructed during the 1950s, whereas the Central Russian Upland reservoirs were constructed during the 1960s–1970s. Detailed measurements of sediment depths were taken for each small field pond in the case of the Central Russian Upland.

RESULTS

Soil erosion from individual fields

Cultivated fields in the Sichuan Hilly Basin are located on steep concave slopes with gradients ranging from 5–35° within slope close to circle from zero-order catchments with a total area < 0,25 km^2 and within valley bottoms. Paddy fields in valley bottoms have a gradient close to 0° and there is no erosion except in extremely high flooding with rare recurrence. The cultivated fields typically occupy 30–40% of the total area of the zero-order sub-catchments. The other land uses are woodland and wastelands. The typical lengths of sloping fields are 5–35 m, parts of which are terraces that mainly occupy the steep slopes. According to the observation data, erosion from a short field with a length of < 10 m and a gradient < 5° is low, amount to a mean annual soil loss of 500–700 t ha^{-1}yr^{-1}. However, soil loss increases considerably on steep slopes with length ranging from 10–35 m up to 7000 t ha^{-1}yr^{-1}. The proportion of such fields does not usually exceed 10% of the total zero-order catchment area.

There is a completely different type of cultivation in the Central Russian Upland, in which the majority of the slopes are cultivated, with the exception of steep valley banks and valley bottoms. Typical slope lengths and gradients change in a range of 250–900 m and 1–6°, respectively. Individual fields have areas of 10–50 ha, depending on the dry valley system configuration and unpaved road network. Long-term annual soil losses range from 200 to 2000 t ha^{-1}yr^{-1}, depending on the relief features and crop rotations for the fields (Table 3), with

Table 3. Mean annual net soil losses from cultivated fields in the Central Russian Upland based on 137Cs technique (CS) and soil profile morphology comparison (SPM)

Site location	Annual precipitation (mm)	Mean slope length (m)	Average slope gradient (°)	Method	Number of transects	Time interval	Mean net soil erosion rates (t · km^{-2} · yr^{-1})	Net soil erosion rates (t · km^{-2} · yr^{-1})	Reference
Plavsk district, Tula region	650	700	2	Cs	4	1986–2009	875	210–1490	[Golosov et al., 2013]
Kromy district, Orel region	570	550	3,5	Cs	2	1986–2010	1085	580–1510	[Golosov et al., 2013]
Kursk district, Kursk region	570	470	3,3	CS	2	1986–2007	1165	360–1970	[Golosov et al., 2013]
Novosil distrct, Orel region	536	660	2,2	SPM	3	1700–2000	1070	850–1470	[Golosov et al., 2011]
Zheleznogorsk district, Kursk region	570	300	1,5	SPM	5	1780–2010	955	410–1780	[Golosov et al., 2012]
Mean value	300–700	1,5–3,5					1030		

mean values on regional scale of around 600–700 t ha^{-1}yr^{-1} (Table 4).

Table 4. Mean annual soil erosion rates for cultivated slopes during 1970–1980s calculated using modified version of the USLE-based empirical model (rain-fall erosion) and State Hydrological Institute model (erosion during snow-melting) for regions of European Russia, located within the Central Russian Upland [Sidorchuk et al., 2006]

Region	Mean annual soil erosion rate (t·km^{-2}yr^{-1})
Tula	750
Orel	530
Kursk	600
Belgorod	780
Mean for Central Russian Upland	670

The difference between the mean annual soil losses obtained from field methods for individual transects (Table 3) and those calculated using erosion models (Table 4) is associated with inclusion in the regional model calculation of both upland and lowland areas. Field-based results can overestimate actual soil losses, because both applied techniques are characterized by the combined effect of soil redistribution by water and tillage erosion and soil losses due to the harvesting of sugar beet and potato. The latter cannot be separately evaluated by the net erosion rates calculation. According to existing data, soil losses accompanying the harvest of root crops can reach 400–500 t·ha^{-1}yr^{-1} [Belotserkovsky and Larionov, 1988; Poesen et al., 2001]. Hence, it is more likely that mean annual soil losses for the Central Russian Plain are 800–900 t·ha^{-1}yr^{-1}, due to the proportion of root crops in the crop-rotation, whose share increased to 15–25% during the second half of the twentieth century.

Sediment redistribution within catchments

The Sichuan Hilly Basin. It is of great significance for understanding the slope-valley connectivity that the sediment budget for the small sub-catchments in both studied regions be evaluated. The Tianmawan catchment in Nanchong was selected for such evaluation. There are two groups of terraces in the catchment: gentle terraces with mean slopes of 5° and slope lengths of less than 10 m, and relatively steep terraces with slopes of 10–11° and slopes lengths of 15–20 m. The soil losses on terraces were determined using ^{137}Cs tracing. The total sediment volume for the 1963–1981 period was determined based on ^{137}Cs chronology in pond deposits (Fig. 4) and pond surface area. The pond is located in the catchment outlet. Additionally, possible sediment deposition was checked for the paddy fields located upstream from the ponds. The new land created by silting at the upstream delta of the pond has been brought under cultivation as paddy fields in the Tianmawan catchment. However, local farmers were unable to distinguish the new paddy fields from the old fields because the pond was created so long ago. It was found to have a very limited deposition based on 137Cs depth distribution curve for the paddy field, which is located near the pond (Fig. 5).

Based on the available data, it is possible to roughly estimate the total sediment budget for the catchment (Table 5). It is more likely that it traps the pond's efficiency about 90%. Likewise, it should be considered part of the sediment redeposited within the paddy field beyond the pond. Different time intervals were used to calculate soil losses and sedimentation rate, which are additional source of uncertainty. Therefore, based on the sediment budget estimation and the evaluation of possible sediment deposition within paddy fields, the sediment delivery ratio (SDR) coefficient for the studied sub-catchment in 1963–2004 is very close to 1. The SSY was also determined using 137Cs technique for the two other catchments (Wujia and Jiliu), located in the Yanting County (Table 6). The SSYs for deposition in the ponds were estimated from the deposition volumes, the elapse time since construction, trap efficiency, sediment bulk density (1,4 t-m 3), and catchment areas.

TIn 1956, a small reservoir was made at the outlet of the Wujia catchment for irrigation purpose by constructing an earth dam with a height of 4,75 m. The Wujia catchment is very small and characterised by steep terrain. The eroding purple soil is very fine, with 99% of the particles less than 0,5 mm in diameter. Field investigation indicated that no significant deposition occurred in the gully bottom upstream from the reservoir. The reservoir has a current storage capacity of 25 000 m^3 with a maximum water depth of 3.0 m and a surface area of 9200 m^2. This dam has a spillway and bottom culvert with several

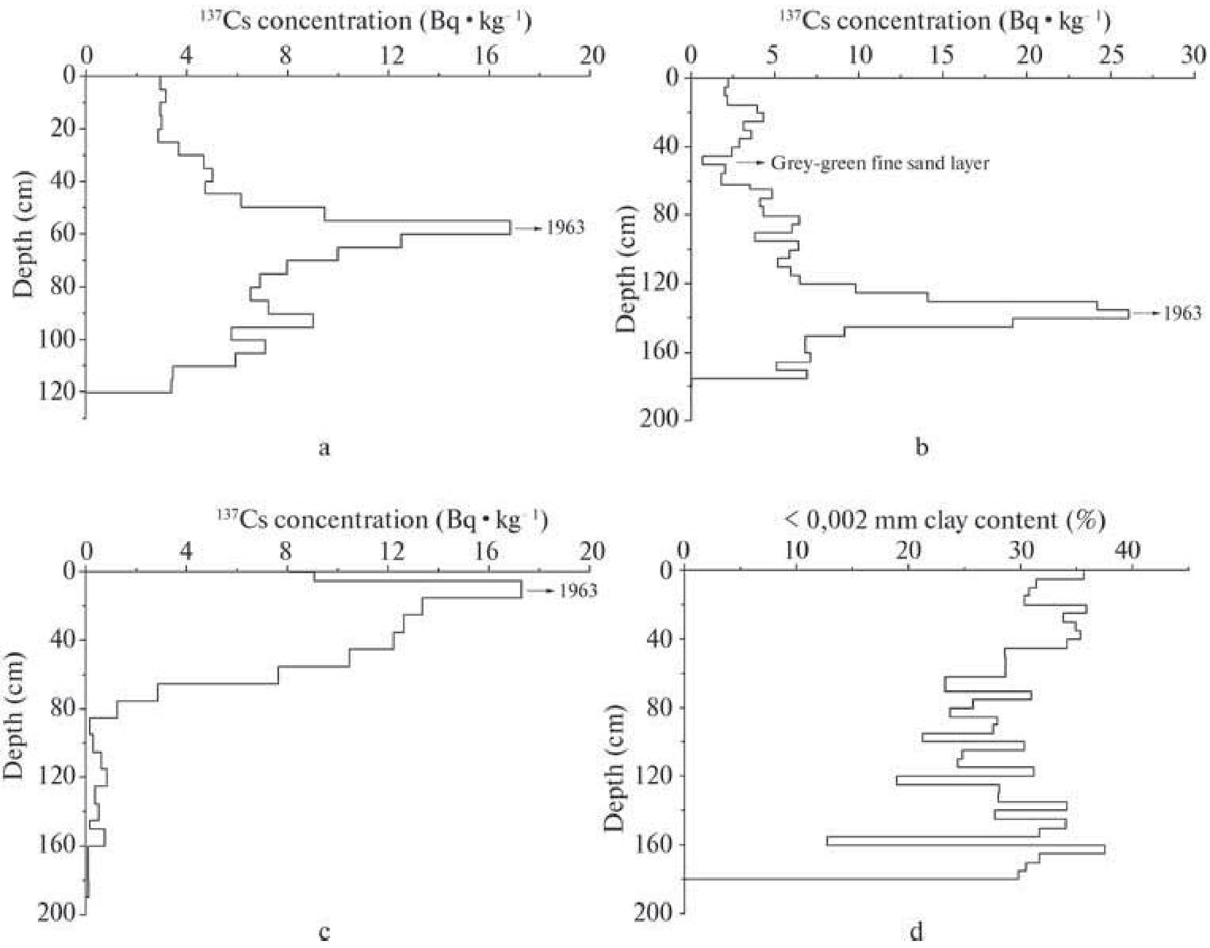

Fig. 4. 137Cs depth distribution along the deposited sediment profiles in the ponds at:

(a) Wujia catchment, (b) Jiliu catchment, (c) Tianmawan catchment;
(d) Clay content in the ponds at Tianmawan catchment.

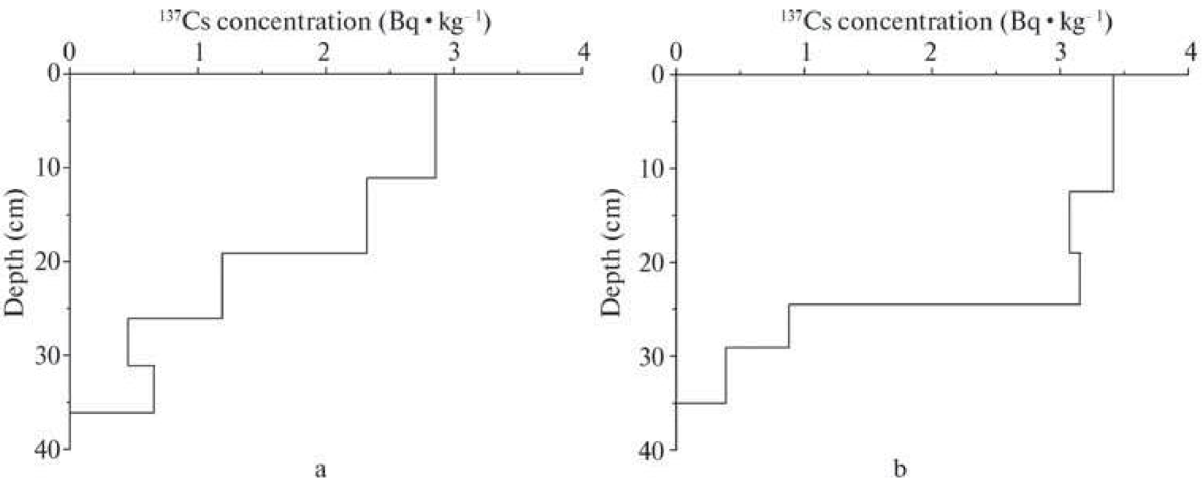

Fig. 5. ^{137}Cs depth distribution along two sediment profiles on the paddy field in the Tianmawan catchment of the Sichuan Hilly Basin.

Table 5. Sediment budget estimated for the Tianmawan catchment in the Sichuan Hilly Basin

	Mean annual soil losses ($t \cdot km^{-2} \cdot yr^{-1}$)*	Area (ha)	Annual Soil Loss (1963–2004)	Annual Sediment Storage (1963–1981)
Cultivated terrace with mean slope 5°	7,6	7,03	53	
Cultivated terrace with mean slope 10–11°	47	1,52	71	
Annual soil losses			124	
Sediment deposition in the pond				107

* Based on ^{137}Cs technique (see Table 3).

Table 6. Specific sediment yield for the three selected zero-order small catchment in the Sichuan Hilly basin observed using ^{137}Cs dating

Catchment	Catchment area (km^2)	Sampling time	Deposit area (nr)	Depth of the 1963 137Cs peak	Sediment volume (1963–2003) (m^3)	Specific sediment yield* ($t \cdot km^{-2} \cdot yr^{-1}$)
Tianmawan	0,19	2004	5534	25	1384*	566
Wujia	0,22	2003	7349	60	4409	701
Jiliu	0,09	2003	1259	145	1826	713

*For the period of 1963–1981.

intakes on the left side. The maximum sediment deposition depth since 1956 has between 1,3 m and 5000 m^3 of sediment deposited in the reservoir, which was estimated from the changes in its water storage volume. Parts of the fringe areas in the reservoir were dredged in 1985. Based on the deposited sediment volume in the reservoir (since 1956), the SSY of the studied catchment is estimated to be 642 $t \cdot km^{-2} \cdot yr^{-1}$.

In the Jiliu catchment, a grey-green fine sand layer was found in the sediment profile. It is likely associated with sediment delivered to the pond in 1984, when a road was constructed in the catchment area. The estimated annual average SSY is 584 $t \cdot km^{-2} \cdot yr^{-1}$ for the 1984–2003, which is less than that during the 1963–1983. The decrease in SSY may be attributed to a reduced sediment delivery ratio caused by road construction that may have disrupted the connectivity of upland sediment transport pathways.

The SSY data for the 79 catchments, calculated from the reservoir sediment survey, are presented in Table 7. The SSY varies spatially between the catchments in each group. However, the mean SSY increases from small ponds to small reservoirs with a subsequent reduction for medium reservoirs. The mean values for the different groups change within a range of 641–849 $t \cdot km^{-2} \cdot yr^{-1}$ and is relatively similar for all groups. Furthermore, there

Table 7. Specific sediment yields calculated from pond deposits in the Sichuan Hilly Basin

Sediment sink	Catchment area (km^2)	Number of ponds	Mean catchment area (km^2)	Specific sediment yield ($t \cdot km^{-2} \cdot yr^{-1}$)			Standard deviation	Cv (%)
				Mean	Max	Min		
Small field ponds	< 0,25	60	0,11	641	1568	79	686	60
Large field ponds	0,25–2	4	1,02	762	958	632	142	19
Small reservoir	2–15	9	9,6	849	2238	71	676	80
Medium reservoir	15–60	6	39,3	733	1780	306	474	65

is some increase in SSY from small ponds to small reservoirs in a catchment area of <15 km^2. Gully and bank erosion may be responsible for some of this increase in SSY, particularly given the relatively high channel gradients and high intensity of weathering of up to 1,2 cm · yr^{-1} [Li, 1991]. However, there may be a range of uncertainty associated with different proportions of land use for catchment in different areas.

The very high variability of SSY for each group of ponds and reservoirs has two causes. The first is high variability of soil erodibility due to differences in parent rocks. For example, even heavy rain-storms with a mean rainfall intensity around 80 mm per hour produce very low runoff (runoff coefficient <0,01) in zero-order catchments with sandstone parent rocks and sandy loam soil [Yang et al., 2009]. The second cause is the spatial and temporal variability of land use over the last 50–60 years for individual catchments. The proportion of arable lands, forests, and wastelands is not uniform for the Sichuan Hilly Basin. The area proportion of individual cultivated fields have a high slope gradient, high erosion rate and crop rotation, all of which are factors influencing the variability of SSY for individual small catchments. However, very high connectivity between cultivated slopes and river channels are typical in the Sichuan Hilly Basin.

Central Russian Upland. A detail study of soil loss and sediment redistribution rates was conducted in the Gracheva Loschina catchment (see Fig. 3-A) through the application of multiple methods and approaches. Analysis of bomb-derived ^{137}Cs inventories at different geomorphic landscape units can be effectively applied to evaluate sediment budgets in small catchments over the last 45–50 years [Loughran et al., 1992; Owens et al., 1997; Walling et al., 2002]. The Gracheva Lochina catchment, thus provided a unique opportunity to establish a closed system sediment budget based on the redistribution of the Chernobyl-derived ^{137}Cs. To design a representative sampling programme, a detailed large-scale geomorphological map was created based on a combination of already available topographical data (1:10 000 scale map with 1 m contour intervals) and additional DGPS and digital tacheometer surveys were conducted in select parts of the catchment. The sampling programme was used to characterize all of the important geomorphic units in terms of ^{137}Cs inventory and, subsequently, the sediment redistribution between them (see Fig. 4-A). The area of each geomorphological unit was determined based on the geomorphological map constructed and a ^{137}Cs budget was compiled for each of the three sub-catchments, distinguished on the basis of different post-1986 land use patterns. The application of soil morphological method allows sediment redistribution to be defined for the entire period of cultivation. According to the vertical distribution of magnetic spherules [Olson et al., 2008], sedimentation length in the deposition zone of the main valley bottom is about 150 years. The mean values of soil losses for the entire period of cultivation obtained from the soil survey data are in good agreement with those provided by the erosion model (Table 8).

Table 8. Evaluation of gross (bold characters) and net erosion rates for different time intervals based on different independent methods in the Gracheva Loschina catchment

Method	1857–2006	1964–1986	1986–2006
Soil Morphological Comparison	**15.7**		
Erosion Model Calculation		**15,3**	**6,0**
^{137}Cs budget			2,4
Sediment deposition in the valley bottom (vertical distribution of 137Cs)		3,7*	1,5

*Does not consider possible sediment export through the catchment outlet.

Table 9. Sediment redistribution in the Gracheva Loschina catchment obtained by different methods

Method	Time interval (year)	Gross Erosion (t/%)	Deposition within cultivated field (t/%)	Deposition within hollows and valley bottom (t/%)	Output from the catchment (t/%)
Soil Morphological Method	1857–2006	400375/100%	33650/8,4%	39220/9,8%	327505/81,2%
Erosion model calculation and sediment deposition in the valley bottom (vertical distribution of ^{137}Cs)	1964–1986	66148/100%	6615/10%	15757/2,8%	43776/66,2%
^{137}Cs budget*	1986–2006	50989/100%	33778/82,8%	8766/17,2%	0
Erosion model calculation and sediment deposition in the valley bottom (vertical distribution of ^{137}Cs)	1986–2006	22606/100%	17050/75,4%	5556/24,6%	0

*With bomb-derived ^{137}Cs.

Sediment deposition along the cultivated slope toes is about 8% (Table 8), which is in good agreement with the value for the same morphological unit defined on the basis of the ^{137}Cs budget for the area without soil conservation measures. Hence, it is possible to use this value to determine sediment deposition along the lower parts of cultivated slopes for the 1964–1986 (Table 9).

The sediment budget for the Gracheva Loschina catchment was calculated from the 137Cs total inventory data using the following equation based on the simple proportional conversion model:

$$R = \frac{\int_S AdS - \int_S A_{ref}dS}{C_p \Delta t S},$$

where R = the mean annual soil loss/gain, kg · m^{-2} · yr^{-1} (negative values indicate erosion and positive values indicate accumulation); Δt = time elapsed since fallout of Chernobyl-derived ^{137}Cs, year; Cp = the ^{137}Cs concentration in the plough layer, Bq · kg^{-1}; A = the ^{137}Cs inventory at the sampling point, Bq · m^{-2}; $\int_S A_{ref} dS$ = the total 137Cs fallout inventory within a geomorphic unit, Bq; $\int_S AdS$ = the total 137Cs inventory within the geomorphical unit, Bq; S = the area of the geomorphical unit, m^2.

Data for the individual geomorphological units were integrated to provide the sediment budget for the entire catchment over the post-1986 period [Golosov et al., 2008]. Table 10 shows that according to the sediment budget derived from the 137Cs budget, more than 80% of the sediment that eroded from arable hillslopes was redeposited within the slopes after the introduction of SCMs, while only < 20% was delivered into the valley bottoms.

The higher volumes of gross erosion and within-slope redeposition provided by the 137Cs budget approach can be explained, like the case study with individual soil transects, by the fact that the ^{137}Cs technique provides an integral evaluation of soil redistribution, including both water erosion and tillage translocation. The latter is especially important in the sub-catchment with contour terraces.

Table 10. Mean annual erosion rates and total soil losses from cultivated slopes of the Lebedin catchment for three time intervals covering the entire period after dam construction in the catchment outlet

Period	Mean annual erosion rate (t · ha^{-1} · year^{-1})	Total soil losses (t)
1956–1964	8,5	83 912
1964–1986	10,6	287 769
1986–2008	6,8	191 848
Mean for 1956–2008	8,6	563 529

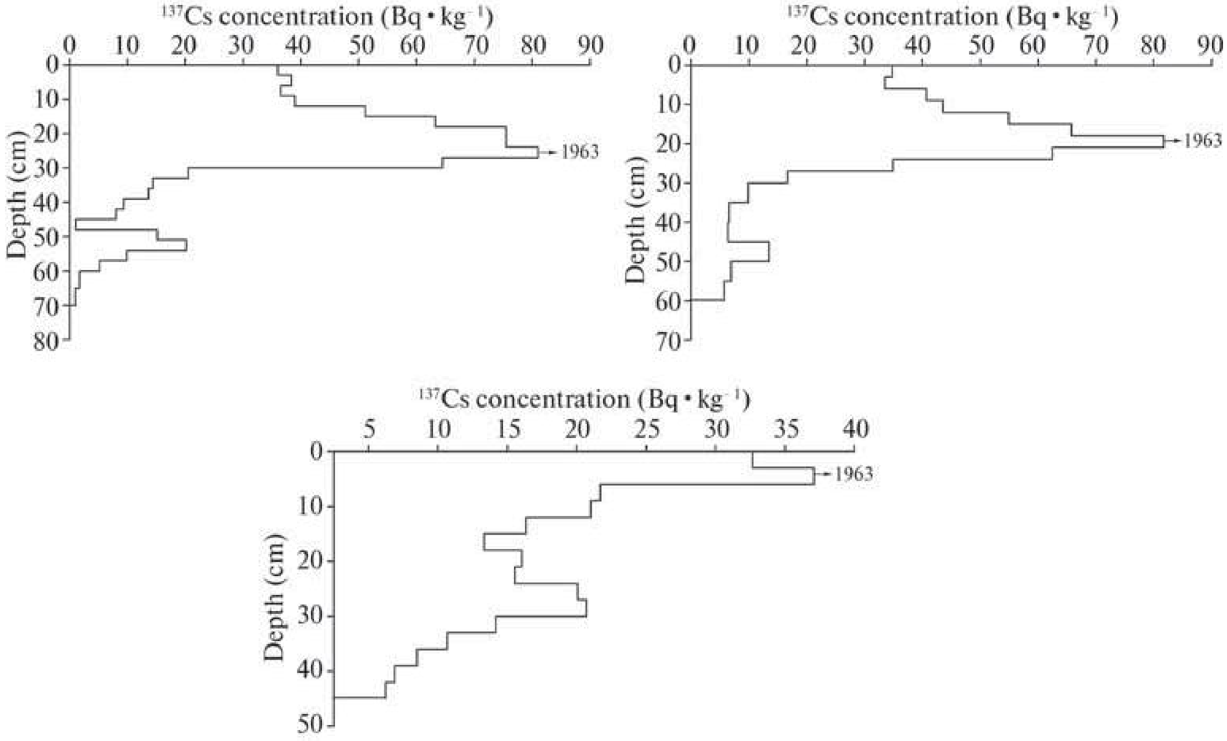

Fig. 6. ^{137}Cs depth distribution in dry valley bottom of the Lebedin catchment in the Central Russian Upland.

The application of the Chernobyl-derived ^{137}Cs to establish the sediment budget of a small cultivated catchment provided results comparable with data produced by independent techniques. In addition, it allows the effectiveness of various SCMs to be evaluated through comparisons with the sediment budgets constructed for earlier periods using methods with different temporal resolutions [Golosov et al., 2008]. The application of SCMs in the Gracheva Loschina catchment since 1986 has reduced average soil loss rates by at least a factor of 2,5, calculated based on the 137Cs budget method.

The gross erosion rates for the arable hillslopes of the Lebedin catchment during 1956–1964, 1964–1986, and 1986–2008 were calculated for known cultivated areas and crop rotations using the USLE-based model (Table 10). Analysis of the vertical distribution of 137Cs at several incremental depths and depositional locations enabled us to evaluate deposition rates over different time intervals. The deposition rates for the different parts of dry valley bottoms were within a range of 0,8–1,0 cm-yr–1, whereas for the 1964–1986 period, the rates ranged between 1,0 and 1,2 cm-yr–1 (Fig. 6).

A detailed determination of areas consisting of different morphological units (including main bottom level, 1–2 terrace levels, and discontinuous valley bottom gullies) within the main valley bottom (third-Hortonian order) of the Lebedin catchment and its tributaries of first and second-Hortonian orders, was conducted using tacheometric and GPS surveys. The total volume of sediment deposition was calculated based on morphological unit areas and 137Cs-based aggradation rates for the main bottom of the Lebedin catchment valley (a third-order valley) and Gracheva Loschina catchment valley (first and second- order valleys) (Table 11).

In addition to sediment deposition in the valley bottoms, other sediment sink zones were observed including redeposition within cultivated fields, redeposition along the toes of cultivated fields (at ploughed terraces), steep grassed dry valley sides, and the uncultivated parts of slope hollows (infilled valley side gullies). It is difficult to accurately

Table 11. Total sediment deposition in valley bottoms of different orders (Lebedin catchment) for different periods

Valley	Hortonian order of the valley	Sediment deposition (t)		
		1956–1964	1964–1986	1986–2008
Gracheva Loschina	1	1 260	5 044	250
	2	2 814	11 256	10 553
Other valleys	1	5 591	22 365	16 773
	2	12 665	50 661	39 579
	3	7 156	28 625	28 625
Total volume in valley bottoms upstream from reservoir reservoir		29 486	117 951	95 555
Reservoir		46 769		
Total volume		289 761		

calculate the sedimentation volume for each of these zones, but it is possible to estimate the percentage of sedimentation in each zone based on observation data during extreme erosion events, which occurred in the Kursk region [Belyaev et al., 2008] and detailed measurements undertaken within the Gracheva Loschina catchment. Redeposition within the cultivated fields, according to direct measurements, after snowmelt and rainstorm runoff events usually varies within a range of 2–25% of gross soil values for the respective fields. A detailed evaluation of the gross and net erosion rates at slope catchments was also supported with the ^{137}Cs technique [Golosov et al., 2011]. The average within-field sediment redeposition was around 10% of the total eroded volume [Golosov et al., 2008]. The deposition along the cultivated field toes is usually more significant and varies between 5% and 30% of gross soil losses, according to different measurements and observations [Kuznetsova et al., 2007; Belyaev et al., 2008]. We determined that 8% of hillslope-mobilized material remains stored on cultivated field toes in the Gracheva Loschina catchment. The most difficult task is to estimate sediment deposition on the grassed valley sides, due to the extremely random nature of this process. Data obtained after extreme erosion events [Belyaev et al., 2008] and during snowmelt periods [Litvin, 2002] show that about 2–7% of the sediment mobilized from cultivated land is redeposited within these morphological units. Sediment deposition in the uncultivated parts of slope hollows (most of which actually represent infilled formerly active valley side gullies) was calculated based on direct measurements of the total sediment volumes stored in the hollows of the Gracheva Loschina catchment and the total number of uncultivated hollows in the valley sides of the Lebedin catchment. By combining all of the above data and comparing the results with the USLE-based soil loss calculations, we concluded that the empirical erosion model overestimated the total soil loss from the cultivated slopes of the Lebedin catchment by about 11%.

A comparison of the total soil losses from cultivated hillslopes with sediment deposition in the valley bottoms also demonstrated that the proportion of sediment deposition in valley bottoms from total soil losses did not differ significantly between the different time intervals considered. Thus, 57% of the material that erodes from cultivated slopes remains redeposited in the valley bottoms, 33% along the pathways from the cultivated slopes to the valley bottoms, and only about 10% of sediment is transported further downstream and reaches the catchment outlet reservoir.

The volume of sediment redeposited within the main reservoir at the catchment outlet is thus proportional to the volume of sediment potentially exported from the Lebedin catchment. In this respect, it is notable that before 1986 about 12% of total soil losses reached the catchment outlet. After 1986 the percentage of sediment reaching the

Table 12. Evaluation of proportion of sediment exported from the Lebedin catchment into the River Vorobzha valley for two time intervals (if the catchment outlet reservoir did not exist)

Period	Gross soil losses (t)[a]	Deposited volume in bottoms (t)[b]	Sediment valley	Pond-deposited sediment (t)	Percentage of sediment potentially exported from the Lebedin catchment
1956–1986	330796	189296		39754	12%
1986–2008	170745	100465		7015	4%

[a] Based on corrected empirical model calculations.
[b]Based on ^{137}Cs dating and area of bottoms.

Lebedin catchment outlet decreased at least threefold (Table 12), mainly as a result of lower surface runoff and erosion during the spring snowmelt period [Petelko et al., 2007]. Consequently, it can be tentatively suggested that during the last two decades, the volume of sediment delivered into the River Vorobzha valley from its main tributary catchments fell by about one-third. So the majority of the sediment that erodes from cultivated fields is redeposited within the dry valley catchments.

The SSY data for the 66 catchments, calculated from the reservoir sediment survey data [Shumakov, 2007] and the evaluation of sediment deposition in the small field ponds [Litvin, 2002], are presented in Table 13. Interestingly, the mean annual soil losses from slope cultivated catchments (ponds with an area of < 0,25 km^2) are in the same ranges as soil losses from small catchments of the same size in the Sichuan Hilly Basin (see Table 7). There is 100% arable land in the given slope catchment of the Central Russian Upland, so the values of the sediment deposition in field ponds are characterized as the mean net soil losses, which are usually equal, but more often less than the gross soil losses. However, the SSYs sharply decrease for the small catchments with an area of < 10 km^2 (Table 13) due to sediment deposition on the uncultivated slope toes, dry valley banks, and, particularly, on the dry valley bottoms. This was demonstrated in more detail in the results of the sediment redistribution study for the Lebedin catchment. The subsequent decrease in SSY and increase in catchment area is also associated with sediment deposition on the dry valley bottoms and small river floodplains. The high variability of SSY for individual catchment groups can be explained by morphological differences and spatial variations in crop-rotation and extreme rain-storm events. In particular, high soil losses are observed on the slope catchments with a high concentration of runoff along the ephemeral gullies [Desmet et al., 1999; Vandaele et al., 1996]. In addition, a proportion of the "warm" slopes (Western and Southern) within catchments also considerably influence erosion rates during snow-melt [Litvin, 2002] and variability decreases with an increasing catchment area (see Table 13).

Table 13. Specific sediment yield within ponds and reservoirs of different sizes in the Central Russian Upland

Sediment sink	Catchment area (km^2)	Number of ponds	Mean catchment area (km^2)	Specific sediment yield (t · km^{-2} ·yr^{-1})			Standard deviation	Cv
				Mean	Max	Min		
Small in-field ponds	< 0,25	10	0,12	686	2230	320	590	86%
Small reservoir	0,25–10	11	4.5	133	309	37	96	73%
Medium reservoir	10–50	28	32	102	194	5	53	52%
Large reservoir	50–100	17	73	87	144	24	37	44%

DISCUSSION

It is typical in the Sichuan Hilly Basin for SSY to increase with catchment area growth of up to 10 km^2, due to the increased contribution of gully/bank erosion with the greater catchment area. The relative contribution of erosion under forest and in the gullys of the Sichuan Hilly Basin, according to the results of the application of the fingerprinting technique, can reach 40–45% of the total sediment production [Zhang et al., 2011]. However, it is necessary to organise the direct measurement of gully wall and river bank retreat for its quantitative assessment, along with sediment losses from wastelands under the forest and without canopy cover for a more detailed understanding of the natural processes in sediment budgeting.

The rates of bed and bank erosion decrease, along with SSY, due to the increasing proportion of flat paddy fields (valley bottoms) that are not producing additional sediment yield. Thus, it is possible to expect some decrease in SSY with a basin area increase in river catchments with an area of less than 100 km^2, even given the extremely low floodplain sedimentation rates, likely river basin in the Sichuan Hilly Basin. This suggestion should be confirmed by direct measurements, but the intensive use of all floodplains as cultivated lands (mostly paddy land) and the deep incision of local river channels into parent rocks provide partial confirmation. However, if we compare the mean annual SSY of the Tuo River (basin area 23 283 km^2) (see Fig. l) for period 1957–1966 with the mean annual SSY for medium size reservoirs (a catchment area of < 60 km^2) from 1950–2000 (see Table 7), we do not find any differences. Thus, it is more likely that soil losses from zero-order catchments were high in the 1957–1966. This is also confirmed by the ^{137}Cs depth distribution profile in the studied ponds, where the ^{137}Cs peak was found to be 40–60 cm deeper. The initial ^{137}Cs fallout occurred in 1954, so it is likely that soil loss was the highest in 1957–1966. A sharp increase in the number of ponds and, particularly, reservoirs during the late 1950s–1960s led to a considerable decrease in both water discharge and sediment yield during 1967–1984, compared with previous time intervals. However, it is more likely that soil losses from cultivated fields do not decrease considerably. This is partially confirmed by the sharp increase in SSY in 1982, which was more likely associated with few extreme rain-fall events. It is more likely that the gradual increase in the area under forest in the Sichuan Hilly Basin and crop rotation changes since the 1980s considerably contributed to decreasing SSY during 1985–2000, compared with 1967–1984. Simultaneously, we observed a clear decreasing trend in the maximum rain-fall intensity during the summer months in the Sichuan Hilly Basin since 1990, according to meteorological data [Zhai et al., 2005]. There has also been some decrease (about 100 mm) in summer precipitation, based on analysis of data from meteorological stations [Xu et al., 2008]. Thus, both natural factors and soil conservation measures are responsible for the decreasing SSY during l985-2000.

The Sichuan Hilly Basin is characterized by a very high connectivity between slopes and river channels to transport the majority of eroded sediment from zero-order catchments to river streams (Fig. 7). A completely different situation is observed within the Central Russian Upland, where only a small proportion of the sediment eroded from cultivated lands enters the river channel, due to sediment accumulation in various sediment sinks along pathways from cultivated slopes to river channels, and subsequent sediment deposition on small river floodplains. The later can be used as an indicator of the sediment quantities passed through the river valley bottoms in different time intervals. As a detailed investigation of overbank deposition rates undertaken for the Central Russian Upland small rivers shows, using both bomb-derived and Chernobyl-derived ^{137}Cs as time markers, floodplain deposition has decreased noticeably, in most cases by 3–4 times during 1986–2008, compared with 1964–1986 [Golosov et al., 2010].

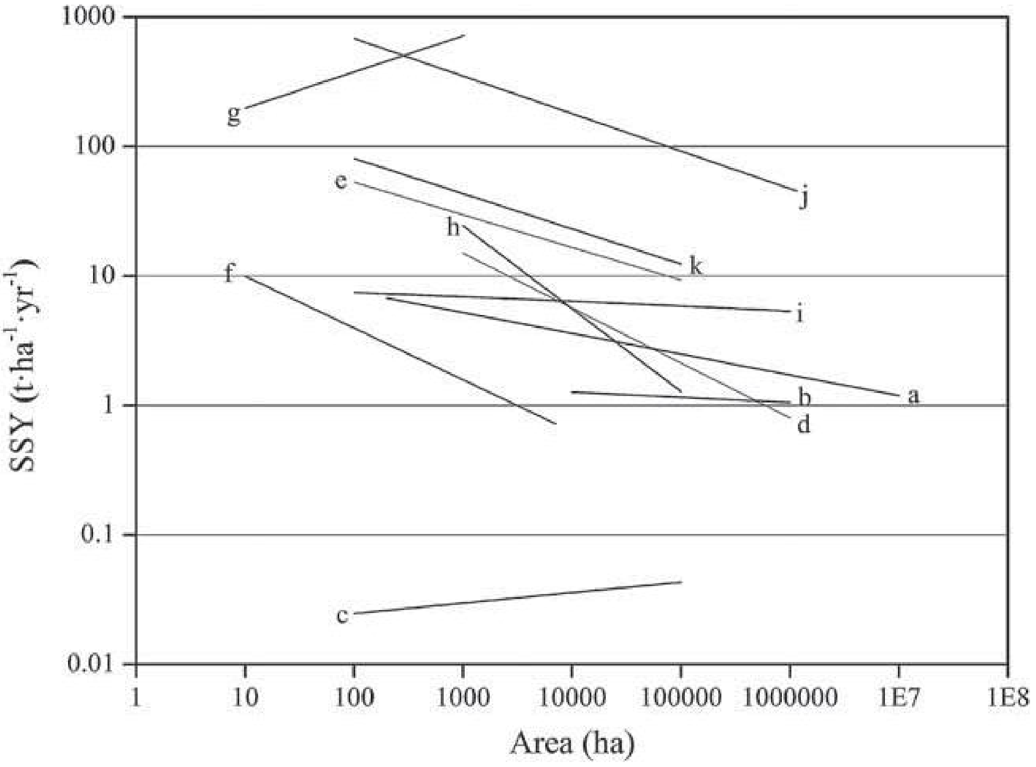

Fig. 7. The documented relationships between specific sediment yield and catchment area for studies around the world:

a – USA [Dendy and Bolton, 1976], b – World [Fleming, 1969], c – Zambia [Sichingabula, 1997], d – Spain [Verstraeten and Poesen, 2001], e – Morocco [Lahlou, 1988], f – Central Belgium [Verstraeten and Poesen, 2001], g – Italy [de Vente and Poesen, 2005], h – Tunisia [Albergel et al., 2000], i – Ethiopian Highlands [Nyssen et al., 2004], j – Northern Ethiopian [Haregeweyn et al, 2008], k – Sichuan Hilly Basin (this study), l – Central Russian Upland (this study).

Comparing the total soil losses from zero-order catchments, the Sichuan Hilly Basin is characterized by relatively mean rates (see Fig. 7), which are observed in the USA, part of Europe, including the Central Russian Upland, and the other parts of the world, particularly given the relatively high proportion of naturally-induced erosion (gully and wastelands). However, the subsequent sediment transport along the fluvial drainage system is completely different. Even for river basins with an area of > 20 000 km^2, SSY exceeds 400 $t \cdot km^{-2} \cdot yr^{-1}$. This can be explained by the very low sedimentation on floodplains and the very high proportion of sediment delivered to the large river channel. Sediment redistribution within the Central Russian Upland is very similar to that in some regions of Europe, such as Belgium. It is characterized by the deposition of a high proportion of eroded sediment from cultivated land sediment before they were delivered to the river channels. The results show that SSY decreases by one order for the river basin with an area of > 100 km^2 compared to the SSY from a zero-order slope catchment.

CONCLUSION

Although with contrasting landscape and climate condition, annual soil losses from zero-order slope catchments in the Sichuan Hilly Basin and Central Russian Upland during the last 60 years have been of the same magnitude (6–7 $t \cdot ha^{-1} \cdot yr^{-1}$). A clear decreasing trend in soil erosion rates has been observed in the last 20–25 years in both regions due to climate fluctuations (a decrease in the intensity of heavy rains in the case of the Sichuan Hilly Basin, and decreasing soil losses during snow-melt in the case of the Central Russian Upland). The implementation of soil conservation practices also contributed to the decreased soil losses, particularly in the Sichuan Hilly Basin. Slope-channel connectivity is the main difference between the two regions. The majority of the sediment that eroded from slope catchments was transported directly to the river channels in the Sichuan Hilly Basin. Thus, riverine SSY serves as a direct indicator of soil losses from the basin area. The majority of the soil that erodes from the cultivated field of the Central Russian Upland was redeposited in different sediment sinks (mostly in dry valley bottoms), with less than 10% delivered to the river channels. This is the main reason for the significant differences in riverine SSY between the Sichuan Hilly Basin and Central Russian Upland. It is that the re-activation of secondary incisions in dry valley bottoms spurred by climate change, as observed during the Pleistocene on the Russian Plain [Panin et al., 2009], has caused high amount of sediment to be transported to the river channels.

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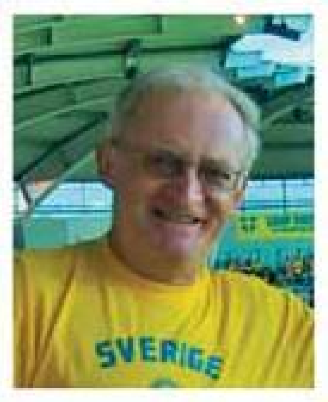

Valentin N. Golosov, D.Sc. in Geography, is Principal Research Scientist of the Laboratory for Soil Erosion and Fluvial Processes, Faculty of Geography, Lomonosov Moscow Strate University. His research interests are concerned with fluvial geomorphology, soil and sediment and sediment-associated pollutants redistribution in the river basins, radioecology. He is former president of International Commission of Continental Erosion of the International Association of Hydrological Sciences, member of Steering Committees of International Sediment Initiative (UNESCO) and World Association Soil and Water Conservation, expert of IAEA. He published more 150 papers in national and international per-reviewed journals and Proceedings of symposia and conferences.

Xinbao Zhang is Professor of physical geography at the Institute of Mountain Hazards and Environment, Chinese Academy of Sciences (CAS). He is vice-president of International Commission of Continental Erosion of the International Association of Hydrological Sciences, expert IAEA. His main research interests are: soil erosion and mountain environment evolution. His research specialty is using the radioactive tracer of Cs-137 in evaluating soil erosion. He published more than 100 papers with 20 indexed by SCI.

Tang Qiang is a Research Fellow at the Research Center of Eco-environmental Sciences, Chinese Academy of Sciences (CAS). He received Ph.D. degree in Soil Science from the Institute of Mountain Hazards and Environment, CAS. His research specialties are sediment tracing and fingerprinting at catchment scale.

Ping Zhou is Associated Professor of soil and water conservation at the Institute of Mountain Hazards and Environment, Chinese Academy of Sciences (CAS). She received PhD. Degree in ecology from the Institute of Soil and Water Conservation, CAS. Her main research interests are: restoration ecology, soil erosion of the slope land, soil and water conservation of the watershed.

Xiubin He is Professor in soil science at the the Institute of Mountain Hazards and Environment, Chinese Academy of Sciences (CAS). He received PhD. degree in soil science from the Institute of Soil and Water Conservation, CAS. His main research interests are: soil erosion process: soil conservation and catchment sedimentation.He has published more than 120 papers in peer-reviewed journals.