Influence of agricultural development and climate changes on the drainage valley density of the southern half of the Russian Plain

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Abstract

The southern half of the Russian Plain is characterized by a relatively short history of intensively ploughed lands. The duration varies from approximately three centuries in the southern part of the forest zone to less than one century in some parts of the steppe zone. It was found that after cultivation, on more than 40% of lands in river basins the drainage valley density (D_{dv}) decreased by 15% to 58% in all landscape zones. In the first stage, the D_{dv} decrease was mostly associated with increasing surface runoff coefficient after cultivation of virgin lands with proportional decreases in groundwater runoff. In the second stage, usually after reaching areas of arable lands in river basins >60%, the volume of eroded sediments entering small river channels exceeded the transport capacities of the permanent watercourses. As a result, the river channels completely silted. In later stages, the sediment redistribution cascade within the small river basins of the Russian Plain stabilized because of the increasing proportion of sediment eroded from the basin areas and re-deposited before entering the river channels because of the increasing area of sediment sinks due to the increase in dry valley lengths and total areas. The morphological parameters of small valleys and groundwater discharges are the key parameters that affect the intensity of small river aggradation on the regional scale.

Key words soil erosion, sediment redistribution, climate change, land use change, European Russia

1. Introduction

The historical intensification of anthropogenic influences on river basins in plains and lowland areas has usually been associated with an increase in the area of cultivated lands. The most evident examples are the consequences of the intensive ploughing of the Great American and Russian Plains during the last two to three centuries. Tremendous volumes of soil material were removed from the cultivated slopes because of accelerated sheet, rill and gully erosion.

Erosion occurred in conjunction with intensive sediment deposition at the base of cultivated slopes and within first-order valleys adjacent to cultivated fields and land traditionally used as pastures (Trimble, 1974; Golosov et al., 1997, Walling & Collins, 2008, Walling et al., 2011), but some sediments were transported to river streams. These land use changes resulted in the 5 to 7-fold increase in sediment discharge in some disturbed river channels (Dedkov & Moszherin, 1984; Wilkinson & McElroy, 2007). A number of sediment redistribution models can describe soil losses and sediment deposition at the hillslope or slope catchment scale (Tucker et al., 2001; Verstraeten, 2006), but upscaling sediment transport models to the landscape scale is difficult (Fryirs & Core, 2014). The main problems are associated with the verification of the models for new landscape conditions. The assessment of small river aggradation dynamics in association with intensifying anthropogenic influence on their catchment areas provides a good opportunity for understanding the sediment fluxes in river basins of diverse landscape zonges with varied durations of intensive agriculture activities.

Trimble and Lund (1982) showed for the Coon Creek basin that the intensification of erosion from initially cultivated fields produced huge amounts of sediments that were partly delivered to valley bottoms with an extremely high intensity of sediment deposition because of the limited transport capacity of river channels. A similar intensification of sediment redistribution was observed in other parts of the Great Plains immediately after the initial tillage of virgin lands (Phillips, 1991, 1993). It is also possible to find some clear indicators of intensive erosion and deposition in areas with a longer history of intensive agriculture around the globe (Hoffmann et al., 2007, 2009; Notebaert & Verstraeten, 2010; Houben, 2012; Dotterweich, 2013). In addition, changes in river water discharge are usually associated with the expansion of cultivated lands within catchments, which leads to the sharp increase of both surface runoff and maximum water discharges in river channels as well as sediment transfer from interfluve areas to valley bottoms (Harvey, 2001; Walling et al., 2002). Further downstream through fluvial systems, an increase in maximum water discharges may result in the incision of medium size river channels (Downs et al., 2013). This happens because of the redeposition of eroded sediments within first-order valley bottoms, including river channels, and the growing transport capacity of flow downstream, and can finally lead to the transformation of stream patterns (Grenfell et al., 2014).

The Russian Plain, which has an area of 460×10^6 ha, is one of the largest plains with a known history of intensive agricultural development that started at the end of the 17th century in the central part of the plain and later expanded to the south until the beginning of the 20th century. The expansion of arable lands was accompanied by increasing rates of sediment redistribution. One of the consequences of this process was the change in drainage valley densities in various landscapes of the Russian Plain. Since the end of the 20th century, there have been considerable climate and land use changes in this region, and they have led to changes in the rates of erosion and accumulation and, as a result, have affected permanent and temporary streams.

The objective of this paper is to evaluate the influence of land-use and climate changes during the last centuries on the sediment redistribution and drainage valley density in some landscape zones of the southern half of the Russian Plain (European Russia).

Study area

1.1. General description of the study area

The Russian Plain occupies a vast area from the coast of the Arctic seas in the north to the foothills of the Caucasus Mountains and Caspian Sea in the south. There are few landscape zones within the Russian Plain; however, the northern half of this region is not suitable for intensive agriculture due to its climate conditions and poor soil quality. The southern half of the Russian Plain comprises the southern part of the forest, forest–steppe and steppe landscape zones, and it is one of the major agricultural regions in the Russian Federation (Fig. 1). It is characterized by a temperate continental climate with a mean annual precipitation of 400–600 mm, one third of which falls during the 5 to 6 months long cold season from the end of November until the end of March - beginning of April. The precipitation and moisture availability gradually decrease in the south–south–eastern direction. In the central part of the Russian Plain, around the city of Moscow, the annual precipitation is in the range of 600–700 mm, and the mean temperature in July is 18–20° C. The annual precipitation near the northern coast of the Caspian Sea is less than 200 mm, and the mean temperature in July increases to 23–24° C.

The relief of the southern half of the Russian Plain comprises a combination of uplands and lowlands that are strongly dissected by a fluvial network down to bedrock and overlain by Pleistocene loess of varying thicknesses. Moraines provide the parent materials for local soils in the northwestern part of the area. Soils types change from north to south from podzol and grey forest soils to some types of chernozem in the middle part and chestnut soils in the southern part of the steppe zone. The major bedrock types include limestone, dolomite, clay and sand of different ages.

The major rivers of the region belong to the Don and Volga River basins. The river regime is characterized by a high spring flood in April and May and low water conditions during the rest of the year, with some rising of the water levels after localised heavy rainstorms or long periods of moderate intensity autumn rainfall. Systematic monitoring of water discharges over a network of hydrological stations shows that more than 60% of the river runoff is accounted for by spring floods. The contribution of the spring runoff to the annual river runoff increases from the forest to semi-desert zones, and the proportion of subsurface and underground runoff decreases in the same direction. The density of the perennial network decreases from the north to the southeast. A detailed description of the climate's influence on drainage density has been reported elsewhere (Gregory, 1976; Gregory & Gardiner, 1975).

The area to the south of the Bryansk - Moscow – Kazan – Ufa line is the region of intensive agriculture activity (Litvin, 2002). Soil erosion during snow melting and rainstorms occurs mostly on the arable lands of the Russian Plain. The relative contribution of different types of soil erosion changes from the central part of the Russian Plain to the south. Sheet and rill soil erosion in the forest zone during snow melting and rainfall occur to a practically equal extent, but rainfall erosion prevails in the forest-steppe zone and northern part of the steppe zone, and in the southern part of the steppe zone, only rainfall erosion is observed (Litvin, 2002; Sidorchuk et al., 2006). The mean annual soil losses from cultivated land changes range from 1 to 3 t ha^{-1} within the lowlands to 6 to 8 t ha^{-1}in the uplands, with the maximum (10 t ha^{-1}) observed near the Caucasus Mountains in the Stavropolskiy Krai (Sidorchuk et al., 2006).The intensity of gully erosion has been relatively low during the last two decades; however, there were a few stages during the period of intensification of land cultivation when it was high, in particular in the uplands (Butakov et al., 2000).

2.2. Land use changes during the last three centuries

The population density on the Russian Plain was relatively low until the beginning of the 18th century. The cultivated fields were mostly located in the southern half of the forest zone, but their proportion was less than 30-35% of the total area of the small river basins (Tsvetkov, 1957). A considerable increase in the area of arable lands in all landscape zones of the southern half of the Russian Plain was observed during the 18th and 19th centuries (Fig.2). However, the area of arable lands had almost reached a maximum in the southern part of the forest zone and north of the forest-steppe zone by the beginning of the 19thcentury.A slight growth in arable lands was recorded at the end of the 19th century. Despite the increase in the area of arable lands in the central and southern parts of the forest-steppe and steppe zones, their share of the total area rose above 50% only in the second half of the 19th century and by its end (Fig.2). During the 20th century, the area of arable lands was relatively stable. However, there were two intervals associated with World War I and the Civil War (1914-1921) and World War II (1941-1945) when the area of agricultural lands decreased by 10-15%, in particular in the Don and the Oka River basins. In addition, a slight trend of decreasing area of arable lands was observed until the 1990s because of urbanization.

The collapse of the Soviet Union in 1991 caused a serious crisis in agriculture because of financial problems and structural reorganization. As a result, from 1991 to 2003, the area of arable lands in the southern half of the Russian Plain decreased. In the southern part of the forest zone, it was observed to a greater extent because of that area's soils, which were relatively poor when compared with chernozem. In the dry steppe – semi-desert zones, more than one third of the arable lands were abandoned because those lands had been irrigated during the Soviet period (Table 1). In addition, the reduction in arable land in the forest-steppe and steppe zones mostly occurred because of funding limitations during the 1990s. Recently, however, the area of arable lands in the steppe zone has been practically restored to its pre-1991 size.

2.3.Climate fluctuations during the last three centuries

It should be emphasized that during the period of direct meteorological observations (since the mid-19th century), the climate conditions have not been uniform; this was also the case in previous centuries judging by the nonuniform data reconstructed from various sources (Lyakhov, 1992). The greatest fluctuations were observed under winter conditions when colder winters alternated with milder winter periods. Cold winters mostly occurred during the first half of the 19th century. However, those temperature fluctuations did not substantially affect the annual surface runoff, which varied from 0.3 to 0.4 in the Moscow Region (forest zone) and 0.2 to 0.25 for the Kiev Region (south of the forest zone) (Fig.1) (Klige et al., 1993). On the other hand, the available monitoring data suggest that the coefficient of snow melting runoff was close to 1.0 during cold winters because of the greater depth of soil freezing. Thus, it is likely that high erosion rates from cultivated fields were characteristic of the first half of the 19th century. At the same time, some deficit in the ground water supply was probably typical for small river streams in summer low water periods.

According to meteorological observations in the southern part of the Russian Plain for the period from 1936 to 1997, a positive linear trend in the time series of heavy precipitation during the warm season was statistically significant at the 0.01 level (Groisman et al., 2005). In addition, trends in very heavy (upper 1% of rain events) and even extreme precipitation were statistically significant at the 0.05 level or above. As can be seen in the results, precipitation during storm events had increased.

The last 20-25 years have been characterized by unusually warm winters, - in particular in the southern half of the Russian Plain because of global warming. As a result, the coefficient of surface snow melting runoff considerably decreased for both cultivated fields and compacted fields after harvesting (Fig.4). Accordingly, spring flood levels decreased considerably, in particular in small rivers. This is confirmed by the serious decrease in floodplain sedimentation rates since 1986 compared with the period from 1964 to 1986 (Table 2).

As a result of both the positive trend in extreme rainfall (Groisman et al., 2005) and the negative trend in surface snow melt runoff (Petelko et al., 2007), the proportion of sediments eroded from cultivated slopes and delivered by surface runoff to river channels in the southern part of the Russian Plain has decreased considerably during the last few decades (Golosov et al., 2013).

3. Methods

To evaluate the changes in drainage valley density between the 1820-30s and 1940-50s, a few typical river basins in each landscape zone were selected (Table 3). This period was focused on because of the significant changes in the area of arable lands observed in the forest-steppe and steppe zones of the Russian Plain that occurred at that time. Two sets of maps were used for the comparison: 1:126 000 scale maps made by the Military Topographic Corps in the middle of the 19th century and 1:300 000 scale (photographically reduced to 1:100 000) National maps produced by the Soviet Army in the 1940–50s.To avoid possible technical errors sometimes found on old maps, the thalwegs of all the valleys (including both dry valleys and valleys with watercourses) were digitized from the 1:300 000 scale maps using MapInfo GIS. All the valley thalwegs were drawn through the middle of the valley bottoms so that river meandering could not influence the results of the comparison. A code indicating the presence or absence of a stream on the historical maps was allocated to each valley stretch. The stream courses on the old maps were identified based on some key elements of the hydrological network pattern, including tributary confluences, river bends and the locations of populated areas. The basin boundaries were also digitized and stored in separate tables as polygons. Overlaying the thalweg network over individual catchment areas allowed a determination of the total lengths of streams in individual catchments and their changes between different dates. The drainage valley density (D_{dv}) for each catchment was defined as:

$$D_{dv} = L_t/S_{w.}$$

Where: L_t- total valley length with permanent streams, km; S_w – catchment area, km^2.

According to a mapping manual, watercourses should be mapped based on their status during a low water phase of the warm period of the year, which in the Russian Plain usually occurs in August–September (Kovalevskiy, 1973). The positions of headwater stream sources at that time were the most stable one from year to year and, therefore, were representative for a period of time. This mapping principle has been used since the ‘‘Governmental Instruction on Land Survey, 1797’’, which served as a guidebook for field surveys and the subsequent compilation of maps (Vereschaka, 2002).

It is necessary to emphasize that the assessment of D_{dv}, which has changed during the last centuries, was used only as an indicator of the influence of climate and land-use changes on the proportions of surface and underground water runoff and sediment delivery ratios from the cultivated slopes to the valley bottoms of small rivers.

Administrative units were used to compile statistical information on land use at the State level. The land use information (arable land area and crop rotation) was selected for each province in those economic regions that were characterized by relatively uniform types of industrial and agricultural development. The compiled information was used to identify possible stages of increases/decreases in anthropogenic influence on the sediment redistribution at the regional scale and to estimate soil losses for the selected time intervals for each economic region.

A modified version of the Universal Soil Loss Equation (USLE) was used for the calculation of soil losses due to rainfall-induced sheet erosion, and a model developed by the Russian State Hydrological Institute was used for estimating sheet erosion from snowmelt runoff. These two models were combined and improved by G.A. Larionov and colleagues into a single PC-based model designed for application in Russia and are accompanied by a large spatially distributed dataset of different parameters (e.g., erosion index of precipitation and soil erodibility factor)(Larionov, 1993; Larionov et al., 1998; Krasnov et al., 2001). The model can be used to create various scale maps of soil erosion rates. This model was used for the evaluation of soil losses for the entire period of intensive cultivation for various administrative regions of the European part of Russia and for the assessment of sediments eroded from cultivated fields in some key catchments.

A sediment budget approach was used for the evaluation of sediment redistribution in several key catchments in some landscape zones of the Russian Plain to identify changes in their sediment delivery ratios over the years. Several methods and techniques have been used for the evaluation of the different individual components of the sediment budget. Soil redistribution on cultivated lands was determined using a soil-morphological method, erosion model calculations and the ^{137}Cs technique (Golosov et al., 1992, 2013; Golosov, 2002a,b; Golosov & Ivanova, 2002; Belyaev et al., 2009). Direct measurements of the sediment redistribution after heavy rainstorms were also used for the evaluation of the proportion of sediments redeposited within catchments (Belyaev et al., 2008). The volume of sediments produced by gully erosion was estimated using direct surveys of gully parameters (width, length and depth) coupled with the old maps used to evaluate the ages of the gullies. Sediment depositions on the uncultivated valley sides and bottoms, including the river floodplains, were determined using a buried soil method together with sediment dating based on the bomb-derived and Chernobyl-derived ^{137}Cs and ^{14}C chronometers (Kurbanova & Butakov,1996; Belyaev et al., 2005a,b; Golosov, 1998a,b; Golosov et al., 2008, 2010). In addition, some river basins under various degrees of anthropogenic pressure were directly monitored with regard to sediment deposition on the floodplains (Kurbanova, 1996). Detailed descriptions of the methods and techniques used for the sediment budget calculations and the evaluation of the erosion and depositional rates for individual slopes, slope catchments and small river basins have been published elsewhere (Golosov, 1988; Kurbanova, 1996; Ivanova et al., 1998; Golosov, 2006; Belyaev et al., 2009; Golosov et al., 2013). Similar approaches for the calculation of the sediment budgets for small river basins have been applied for the Loess Belt area in Belgium (Rommens et al., 2005, 2006, 2007; Notebaert et al, 2009, 2010; Verstraeten et al., 2009) and for small catchments in Italy (Porto et al., 2011).

In addition, some data were collected from the State monitoring system, including water and sediment discharge measurements at hydrological gauging stations located in various parts of river basins, from slope catchments to rivers of diverse sizes. Published results of the long-term monitoring of surface water runoff were used for snow melting in natural and cultivated slope catchments to evaluate the influence of anthropogenic and climate changes on the proportion of surface and underground runoff and on some recent trends in spring floods on the Southern Russian Plain (Koronkevich, 1990; Koronkevich et al., 1994; Petelko et al., 2007).

4. Results and discussion

Based on the research on the drainage density of the landscape zones of the southern half of the Russian Plain (Table 3), the maximum reduction in D_{dv} was identified in the southern part of the forest-steppe and steppe zones. The drainage valley density in the studied river basins decreased by more than 50% in one century. There were no significant differences between the river basins draining the uplands and lowlands. A similar reduction in the drainage density has been described in the southern part of the steppe zone in Ukraine, where the lengths of the river streams declined by 63.8% from 1863 to 1968 (Pogrebnoy, 2010).

Detailed studies of the D_{dv} changes were conducted for the Savala River basin (Fig.5). The length of the river's watercourse was assessed for six periods, which revealed two stages of a considerable reduction in the watercourse length (Fig.6) (Panin & Golosov, 2001). The first stage occurred in the first third of the 19^{th} century, when arable lands reached almost 60% of the total basin area. The second stage occurred during the last decades of the 19th century, when the area of arable lands peaked after the 1861 land reform. During the 20th century, there was a trend of some reduction in the length of the river network in the Savala River basin.

More recent data have demonstrated that the same trend occurred in the Voronezh Region, which is located in the forest-steppe and the northern part of the steppe zones, during the second half of the 20th century and until the beginning of the 21st century. D_{dv} for the small river basins decreased by 10-42% from 1964 to 2008, and the maximum changes were observed in the southern part of this region in the Kalachskaya Upland (Zhigulina, 2013).

The significant reduction in D_{dv} in the forest-steppe and steppe zones of the Russian Plain during the last centuries was undoubtedly associated with two main factors: climate and land use changes (Golosov & Panin, 2006). However, to predict the effects of these changes, it is necessary to determine which of these factors played the most decisive role in the changing landscapes and the implications of those changes in the various agro-climatic zones of the Russian Plain.

A temporal-spatial assessment of soil losses from arable lands was undertaken based on the application of the modified USLE version and State Hydrological Institute's models (Larionov, 1993). The availability of information regarding the area of cultivated lands, the type of crop rotation and LS factor is not uniform for the last three centuries for large territorial units within the Russian Plain. Some temporal variations in the erosion index of precipitation and spring surface runoff were not taken into consideration because of the lack of meteorological observations. During the 18th century, the highest soil losses occurred in the Non-chernozem Region of Russia around the city of Moscow because of the higher population density. This entire region is located in the forest zone. During the 18th century, the area of arable lands was relatively small in the southern part of the forest and forest-steppe zones. The 19th century was characterized by the greatest soil losses in all the landscape zones, with the exception of the central and southern parts of the steppe zone (Fig.7). The main reason for this was a sharp expansion of arable lands and, in particular, the 1861 land reform. Even some very steep valley banks were cultivated, especially in the forest-steppe zone, which is dominated by the most fertile chernozem soils. At the same time, the formation of anthropogenic gullies in the forest-zone peaked (Fig.8). The maximum soil losses in the steppe zone were observed from 1887 to 1980 (Fig.7), which was simultaneous with a sharp increase in the area of arable lands (Fig.2). It should be emphasized that the average density of gullies reached its maximum in the forest-steppe zone, but it was significantly lower in the steppe and forest zones (Litvin et al., 2003).

It is clear that gross soil losses from the arable lands were not directly transported to the river valley bottoms. The relationship between on-site rates of soil losses and the sediment yield at a catchment outlet is expressed in terms of the sediment delivery ratio (SDR), i.e., the sediment output from a catchment divided by the gross erosion within the catchment, and SDR allows the identification of the proportion of sediments transported to river channels (Walling, 1983). For the Russian Plain landscapes, the SDR is influenced by the slope-channel connectivity as well as by the deposition and storage of sediments within the dry valley bottoms and river floodplains. A combination of field methods and erosion model estimates was used to evaluate the sediment redistribution dynamics for time intervals during the last centuries for a few second to third-order catchments located in the forest-steppe zone.

The Chasovenkov Verkh catchment, which is located in the middle of the Plava River basin, was selected for a detailed study of the sediment redistribution for the entire period of intensive ploughing in the northern part of the Srednerusskaya Upland in the forest steppe zone (Fig.1). The total area of this third-order catchment is 42 km^2. The period of intensive ploughing for this catchment is 300-400 years. Soil losses from the arable slopes were estimated using a soil-morphological method and erosion model calculations. The annual erosion rates based on the soil morphological method varied in the range from 4.1to 3.0 t ha^{-1} for the 300-400 year period of intensive ploughing. The erosion model calculation resulted in an annual erosion rate of 4.2 t ha^{-1}. It should be taken into consideration that the soil morphological method evaluates the total soil degradation, including water and tillage erosion, soil loss during harvesting and bioturbation. The mean annual deposition rates on the uncultivated valley sides were determined using the ^{137}Cs technique only for the period since 1986 (Fridman et al., 1997). Buried soil methods and the ^{137}Cs technique (both Chernobyl-derived and bomb-derived ^{137}Cs were used for dating) were applied to identify the sedimentation rates in the main valley and a typical tributary for a few cross-sections located along the valley bottoms for three time intervals: 1690 to 1954, 1954 to 1986 and 1986 to 1996. A geodesic survey was used to determine the areas of the valley bottoms. There have been no active gullies in the Chasovenkov Verkh catchment since 1954. Several slope gullies appeared mostly at the end of the 19th century in this catchment. An assumption was made that the volume of sediments entering the valley bottom due to gully growth was proportional to the volume of the alluvial fans, which were not included in the sediment budget. However, it is more likely that part of the gully sediments were transported downstream from the gully mouths. Therefore, the calculation of the sediment redistribution for the period from the beginning of intensive ploughing until 1954 is not accurate, and it is likely that the proportion of sediments transported from the catchment was probably higher. The volume of sediments eroded from the arable slopes and re-deposited within the catchment was compared for the periods of agricultural development in the catchment, which clearly showed an SDR trend of an increasing proportion of sediments re-deposited within the catchment (Fig. 9). A permanent watercourse existed in two-thirds of the main valley according to the 1830 topographical maps. Some steep valley banks were partly cultivated after the 1861 land reform, and this facilitated the delivery of eroded sediments to the valley bottom. At the same time, gullies were formed on the valley sides. Their alluvial fans blocked the channel flowing in the creek bottom, creating conditions for damming the flow. This accelerated the accumulation of slope runoff sediments. Because the cross-section of the stream channel was small and because of the low transport capacity, the channel was completely silted during a few large erosive events. The 1909 map already showed that the main valley of the Chasovenkov Verkh was a dry valley without a permanent watercourse.

The Popov Ovrag catchment is another example of the detailed study of the dynamics of sediment redistribution. Similar to the Chasovenkov Verkh catchment, field methods and erosion models were usedto evaluate the sediment budget components. This catchment is located within the Oksko-Donskaya Lowland, and it is a left tributary of the Vyazovka River, which is located in the upper Savala River basin (Fig.1) (Ivanova et al., 1998). The catchment area of the Popov Ovrag (41.2 km^2) includes relatively flat interfluve surfaces that are complicated by closed shallow depressions. The shapes and lengths of the catchment slopes to a large extent determine the specifics of transport and accumulation of material within the catchment area.

According to the Atlas of the Tambov Province, arable lands occupied 2.5% of the catchment area by the 1880s. Some ploughed fields were located near the mouth of the catchment. There was a permanent stream in the middle and lower reaches of the main valley. A very slow expansion of arable lands was observed until the mid-19th century, when the arable lands occupied 13.5% of the catchment area, according to the military topographical map of the Tambov Province. Gullies did not yet appear at that time, and the permanent watercourse still existed in the bottom of the main valley. The turning point in the agricultural use of the catchment took place after the 1861 land reform, during the first post-reform decade, when the area of cultivated lands increased dramatically largely due to the ploughing of relatively steep-sloped areas, with a high risk of gully erosion. By 1899, the area of arable lands reached 58%. In addition to the extension of the area of arable lands, the risk of erosion was elevated because almost two-thirds of the valley sides were ploughed, which eliminated a natural buffer zone that prevented the mass flow of sediments into the valley bottom. Maps produced by the “Expedition to explore the sources of the most important rivers of European Russia” in 1899 showed the "Popov Ovrag" valley as a dry partly swamped valley. In 1995, when a detailed field survey was undertaken, the situation was the same. The rates of annual sheet and rill erosion changed in the range of 1.0 to 2.2 t ha^{-1} during the entire period of land cultivation. As a result, the input of gully erosion in the total sediment budget was higher than that of sheet and rill erosion (Fig.10). Most sediments, eroded from slopes and valley banks were re-deposited in the main valley bottom.

Similar methods were used for the evaluation of the sediment redistribution at several small catchments located in the forest-steppe and steppe zones of the Russian Plain (Golosov, 1998a, 2002a). The sediment fluxes estimated for the studied catchments exceeded the transport capacities of the permanent watercourses, which would flow under natural conditions in catchments with the appropriate catchment area (Fig.11). If the volume of sediments delivered to small river channels exceeds the transport capacity of the permanent watercourses, intensive channel aggradation begins.

Floodplain sedimentation rates are an indirect indicator of the influence of basin erosion on the sediment flux in small rivers and small river aggradation. The monitoring of water and sediment discharges in small rivers of Srednee Povolzie (southern part of the forest zone - northern part of the forest-steppe zone) (Fig.1) allowed an evaluation of the threshold proportion of cultivated lands that will dramatically increase the contribution of basin erosion to the river sediment discharge (Table 4). Similar results were obtained by the evaluation of floodplain sedimentation in small river basins with varied proportions of cultivated lands for the entire period of intensive agriculture (Table 5) and for several years at the turn of the 20^{th} and 21^{st} centuries in Srednee Povolzie (Table 6). A very significant decrease in floodplain sedimentation rates during the last 3 decades was recently identified in the small rivers of Central Russia (Golosov et al., 2010) (Table 2). This also demonstrates the difference between the input of river bank erosion and the combined contribution of basin erosion and river bank erosion, because the slope-channel connectivity decreased considerably in the forest-steppe and steppe zones of the Russian Plain during the last two and half decades (Golosov et al., 2013).

Minor river aggradation observed in the southern part of the forest zone (Table 3) may be largely explained by the low slope-channel connectivity during the last three centuries. This was confirmed by a complex analysis of sediment redistribution undertaken for the Protva River basin located in the southern part of the forest zone (Fig.1) (Golosov, 1988). The area of the Protva River basin is 1450 km^2, the mean annual water discharge is 9.92 $m^3 s^{-1}$, the mean maximum water discharge of snowmelt flood is 150 $m^3 s^{-1}$, and the mean maximum discharge of rainfall floods in the summer and autumn is 36.8 $m^3 s^{-1}$ (Akimenko & Yevstigneev, 2002). The contemporary landscapes of the Protva River area can be classified as glacial and glaciofluvial landscapes, which are presented at watersheds and in fluvial systems, respectively. Most elements of glacial/glaciofluvial morphology such as moraine hilltops, glaciofluvial hollows and sandurs constitute sub-horizontal surfaces with slopes less than 2° (Panin et al., 2009), which are partially used as cultivated lands. More than 95% of the interfluve areas have slopes <5°, and the gradients increase in the vicinities of the river valleys. According to monitoring over 15 years in a few small slope catchments, the annual rates of sheet erosion on arable fields varied from 1–2 to 5–8 t ha^{-1}, depending on the catchment morphology, meteorological conditions during snow melting, intensity of heavy rain-falls and crop-rotation (Golosov, 1996, 2006). According to the long-term gully monitoring, the rate of gully head retreat was approximately 1-1.5 m per year (Bolysov & Tarzaeva, 1996) and, therefore, the input of the gully erosion to the sediment budget was relatively small (Table 7). A quantitative assessment of the intensity of the main denudation processes and a morphometric analysis of various elements of relief for the entire basin allowed an estimation of the sediment budget for the Protva River basin (Table 7).

Sediments trapped at the bottom of cultivated fields and adjoining uncultivated parts of slopes are more typical for this landscape. It is necessary to emphasize, that sub-catchments of cultivated glaciofluvial hollows are the only part of the croplands that in fact belong to an "effective catchment area". Most sediments, that originate within such sub-catchments during erosion events, are usually transported to river channels. Most of the eroded sediments are delivered to river channels during snow-melting because of the low sediment concentrations and high volumes of water surface runoff, in particular in years with deeply frozen soils (Litvin, 2002; Golosov, 2006). The area of cultivated land in the Protva River basin during the last three centuries never exceeded 30% of the total area, which is very typical for most river basins in this landscape zone.

The most active transformations of watercourse length in the southern part of the forest zone were observed in the Zhizdra River and upper Oka River basins (Table 3). The Zhizdra River basin drains the area of the so-called "opolie" – a large ploughing area where almost all the forests were cleared. The highest proportion of arable lands within the "opolie" was observed at the end of the 19^{th} century (Tsvetkov, 1957). Some fields were abandoned during the 20^{th} century. It is likely that increasing surface runoff after the cultivation of previously forested areas led to a proportional decrease in underground runoff. Because of that, some small streams could have dried up during summer low water periods. However, the volume of sediments transported to river channels from cultivated lands did not considerably increase because of the weak slope-channel connectivity typical for this landscape. Therefore, the partly dry river channels were not silted. When some arable fields were abandoned, the permanent flows in the streams recovered.

A similar phenomenon was observed in small rivers of Srednee Povolzie (Dedkov et al., 1995), which are also located in the southern part of the forest zone of the Russian Plain. In south-west England, the length of small streams may change by 500% to 1000%, even seasonally, depending on meteorological conditions (Gregory & Walling, 1968).

The southern part of the steppe zone is characterized by a high erosion rate during heavy rainstorms. In particular, this is typical for the Stavropol Krai, where the erosion index of precipitation is the highest within the Russian Plain (Larionov, 1993). A study of sediment redistribution undertaken at a few small first to second-order catchments in the Kalaus River basin offered an estimate that the mean annual sheet and rill erosion rates in this region range from 6 to 15 t^{-1} ha^{-1} (Golosov, 2002, 2006; Belyaev et al., 2004, 2005). However, a substantial volume of sediments is transported from arable slopes to valley bottoms along some ephemeral gullies channels, which are very typical for this landscape. As a result, based on the ^{137}Cs technique, the mean annual deposition rates in the bottoms of the first-order valleys of those regions reached 50 mm $year^{-1}$, which is an approximately 3-fold excess of the mean annual deposition rates in other areas of the steppe zone (Golosov, 2006).

The coefficient of surface runoff during snow melting has considerably decreased in the forest-steppe and steppe zones of the Russian Plain during the last 2 to 3 decades (Fig.4), with a proportional increase in underground runoff. However, this has not led to the recovery of small rivers. The reason for this is the quite substantial thickness of sediments (1-3 m) that completely covering the valley floors of the first to third-order rivers (Golosov & Ivanova, 2000; Belyaev et al., 2005).

The analysis of the data presented above suggests that 40% of the arable lands in the total basin area is the threshold above which the contribution of basin origin sediments significantly increases in the overall sediment load of the small rivers on the southern half of the Russian Plain. However, the basin erosion had the most substantial effect on small rivers during the first 2 to 3 decades, when the area of arable lands exceeded 60% of the total basin area. A sharp reduction in the lengths of the permanent streams and a simultaneous increase in the lengths of the dry valleys occurred. Overland flow was concentrated in dry valley bottoms during snow melting or rainstorm events, but it did not produce distinctive channels. At later stages, some stabilization of the sediment redistribution pattern occurred within the river basins because of the increasing area of the sediment sinks associated with the growing dry valleys.

6. Conclusions

The intensive ploughing of basin areas was the primary reason of the aggradation of small rivers in the southern half of the Russian Plain during the last 1-2 centuries. It was found that the process of small river aggradation was initiated if the area of arable lands exceeded 40% of the total basin area, but the most intensive reduction of D_{dv} was observed in river basins where the proportion of arable lands exceeded 60%. However, increases in groundwater flow due to local hydrogeological conditions and the morphological characteristics of the river valleys may have been factors that hindered the silting of the riverbeds. A considerable decrease in D_{dv} was detected for the river basins in the southern part of the forest, forest-steppe and steppe zones, based on a comparison of similar-scale historical topographic maps. Depending on local conditions, D_{dv} may have decreased by 15% to 58% for various river basins. Both the increase in surface runoff, in particular during spring snow melting, and the considerable change in sediment redistribution within small river basins were responsible for riverbed siltation. Diminishing groundwater discharges during low water periods led to the migration of river sources downstream. Simultaneously, an increase in sediment volumes transported from arable slopes into riverbeds led to their gradual silting. Finally, the excessive volume of sediments has resulted in the complete disappearance of river channels. The increase in the lengths of the dry valleys coupled with the diminishing lengths of the permanent streams increased the area of accumulation zones and, therefore, caused a gradual stabilization of the length of the preserved river network by reducing the volume of sediments transported into the riverbeds. These conclusions are supported by the results of the detailed investigations of the dynamics of sediment redistribution for various time intervals for some key catchments and the evaluation of the floodplain sedimentation rates for river basins with varying proportions of forested areas.

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Table 1. Reduction in agricultural lands in some regions of the southern part of the Russian Plain after the collapse of the USSR

Region[1] (Oblast')	Landscape zone	Reduction in agricultural lands*, %	Region (Oblast' or krai)	Landscape zone	Reduction in agricultural lands, %
Kaluzhskaya	South of the forest zone	38,7	Rostovskaya	Centre of steppe zone	14
Tul'skaya	South of the forest and north of the forest-steppe zone	41	Stavropolskiy Krai	South of steppe zone	12,9
Tambovskaya	South forest-steppe – north steppe	23,2	Krasnodarskiy Krai	South of steppe zone	5,8
Voronezhskaya	South forest-steppe – north steppe	15,5	Volgogradskaya	South steppe and semi-desert zone	33,9

*- the area of agricultural lands in 1990 was 100%

[1] See Fig. 3 for the locations of the each region's (oblast') capital in the southern part of the Russian Plain

Table 2

Mean overbank sedimentation rates (mm year^{-1}) for the two time intervals based on ^{137}Cs vertical distribution curves (after Golosov et al., 2010) (for the river locations, see Fig. 1).

River	Turdei		Zhusha		Chern		Vorobzha		Konopelka	
Time interval	1986–2008	1964–1986	1986–2008	1964–1986	1986–2008	1964–1986	1986–2008	1964–1986	1986–2008	1964–1986
Upper cross-section	1.6–2.0	Not available	4.3–4.7	17.9–18.3	2.1–2.5	7.5–7.9	1.2–1.6	Not available	2.0–2.4	7.0–7.4
Extent of decrease	–		4.0		3.3		–		3.3	
Lower cross-section	6.8–7.2	7.9–8.3	4.3–4.7	13.4–13.8	2.2–2.6	7.9–8.3	1.2–1.6	10.7–11.1	1.6–2.0	8.9–9.3
Extent of decrease	1.15		3.0		3.4		7.8		5.0	

Table 3

Changes in the drainage valley densities (D_{dv}) for the some typical river basins in the southern half of the Russian Plain for one century

River basin	Latitude[d]	Longitude	Area, km^2	D_{dv} [a] (km/km^2)		Change of D_{dv}, %		
				In 1820-1830 years	In 1940-1950 years	Total changes	Extension	Reduction
				South of forest landscape zone				
Moskva[b] (upstream from Moscow)	55,8[d]	36,3[e]	8 000	0,266	0,256	- 3,8	2,8	-6,6
Protva	55,1	36,3	4 520	0,259	0,244	-5,8	3,8	-9,5
Ugra[c]	54,9	35	15 600	0,238	0,220	- 4,1	9,4	-13,5
Oka (upstream from the confluence with the Zusha river)	52,9	35,9	7 280	0,273	0,271	- 0,7	17,2	-17,9
				North of forest-steppe landscape zone				
Pronya	53,9	39,5	10 300	0,293	0,195	- 33,4	4,7	-38,1
Zusha	53	37,1	7 000	0,227	0,161	- 29,3	4,7	-34,0
Don (upstream from the confluence with the Sosna)	53,5	38,5	13 100	0,236	0,132	- 44,0	5,4	-49,4
Sosna	52,4	37,6	17 000	0,291	0,211	- 27,3	6,0	-33,5
				South of forest-steppe and north of steppe landscape zones				
Oskol	50,4	37,9	14842	0.148	0.064	-56.6	4,0	-52,6
Tikhaya Sosna	50,7	38,7	4180	0.120	0.062	-48	3,7	-44,3
Osered'	50,8	40,5	2480	0.124	0.056	- 55,1	3,4	-51,3

Ikorets	51.4	40	1850	0.184	0.184	- 59,2	4,2	-55
			Centre and southern parts of steppe landscape zone					
Chernaya Kalitva	50,4	39,3	5560	0.098	0.037	-62.3	3,8	-58,5
Sredny Egorlyk	46,4	41,3	2190	0,106	0,06	-43,4	1,4	-44,8
Kalitva	48,9	41	10 454	0,103	0,053	- 48,1	2,7	-50,8
Chir	49	42	10 500	0,086	0,043	- 50,0	2,2	-52,2
Kalaus	48,4	42,5	9 200	0,113	0,061	- 46,2	6,2	-52,3
Tsimla	45,4	42,8	1540	0,088	0,034	-46,9	2,6	-49,5

[a]D_{dv} measured along the valley axis, i.e., reflects the length of the valley stretches that are occupied by permanent streams, without respect to river sinuosity.

[b]River basin mainly drains lowlands;

[c]River basin mainly drains uplands

[d]Latitude and longitude refer to the geographical centre of each basin

Table 4

Some characteristics of the water and sediment discharges for the Srednee Povolzie river basins, which have various proportions of arable lands

Area of arable lands, %	Number of river basins	Share of water discharge during spring flooding in total discharge, %	Water level mean amplitude for individual years, cm	Duration of spring flooding, days	Specific suspended sediment yield, $t \cdot km^{-2} \cdot yr^{-1}$
0-19	2	48	166	31	-
20-39	3	55	252	29	28
40-59	8	51	294	30	96
60-79	11	67	417	28	193
80-100	4	64	304	29	234

Table 5

Mean depths of floodplain deposition since the beginning of intensive cultivation for river basins with varied areas of arable lands (for the river basins in Srednee Povolzie) (after Kurbanova & Butakov, 1996)

Area of arable lands in the river basin, %	Number of river basins	Mean depth of floodplain deposition since the beginning of intensive cultivation, cm	Mean volume of floodplain deposits since the beginning of intensive cultivation, m^3
0-20	13	14	32
20-40	19	32	52
40-60	28	81	310
60-80	52	112	314
80-100	12	126	434

Table 6

Contemporary mean annual floodplain deposition rates in the small rivers of Srednego Povolziya

River and location of observation	Period of observation, year	Forested area in the basin, %	Floodplain deposition rate, mm per year
River Kiya (right tributary of the Vyatka River, bridge on the Shemordan – Kukmor road)	1983-2001	6	19
River Nurminka (right tributary of the Vyatka River, Manzanares village)	1983-2003	2	21
River Vala (left tributary of Kilmen River, near the bridge on the Mogza – Izhevsk road)	1981-1993	49	4,5
Creek Malininsky (left tributary of the Ulema River, Fedorovka village)	1983-1998	63	0,29

Table 7

Total volume of material redistributed by various processes and the sediment budget of the Protva River basin (after Golosov, 1988)

Process	Total volume of material mobilized, T	Volume of deposition on the slope t %	Volume of deposition in the dry valleys, t %	Volume transported to the river channels t %	Sediment budget, %	
					Input to the river channel	Output from the river channels
Rainfall erosion (cultivated fields)	261530	252760 96.6	2800 1.1	5970 2.3	11.2	-
Erosion during snow melting (cultivated fields)	88730	59580 67	8130 9.2	21020 23.8	39.3	-
Creep[1]	6580	5920 90		660 10	1.2	-
Total:	356840	315300 88.3	13890 4.0	27650 7.7	51,7	-
Gully erosion	5500	-	2350 43	3150 57	5,.9	-
Channel erosion	?	-	?			-
Sediments from urban area				} 22720[2]	42,4	
Road erosion	?	-	?			
Volume of sediments passed through the Spas-Zagorie gauging station (the lower Protva River)	41800	-	-	-	-	78,1
Floodplain sedimentation	11720	-	-	-	-	21,9

[1] – based on creep measurements using the Young method (for details, see Azhigirov and Golosov, 1990)

[2] – preliminary assessment based on irregular measurements

Figure headings

Fig. 1. Landscape zones of the southern half of the Russian Plain and the locations of the key field study sites.

Legend: - sediment redistribution and river aggradation study, **1** – the Protva River basin; **2** – Chasovenkov Verkh catchment); **3** – the Savala River basin (Popov Ovrag catchment); **4** – the Kalaus River basin with few catchments; - overbank sedimentation rates study; **5** – Srednee Povolzie, floodplain sedimentation rates for the period of intensive agriculture; **6** – Srednee Povolzie, monitoring of sedimentation rates; **7-11** – evaluation of sedimentation rates for two time intervals for the Konopelka, Vorobza, Chern', Zhusha and Turdei Rivers respectively; **12** – location of the Novosil experimental station; - location of the study area on the globe

Fig. 2. Percentage of arable lands (as % from total area) for different regions of the southern half of the Russian Plain since the end of the 17th century (based on archival and statistical data) (Tsvetkov, 1957; Lyuri et al., 2010).

1- South forest-steppe – north steppe landscape zone, lowland area (Tambov Region)
2- Centre and southern part of the steppe zone (Rostov Region, Volgograd Region, Stavropolskiy Krai and Krasnodarskiy Krai)
3- Southern part of the forest and northern part of the forest-steppe zone (Tula Region)
4- South forest-steppe – north steppe landscape zone, upland area (Voronezh Region)

Fig. 3. Locations of the province capitals (oblast' or krai) of the southern half of the Russian Plain with different dynamics of arable lands during the last decades (see Table 2).

Legend: - capital of province

Fig. 4. Surface runoff coefficient during spring snow melting for the1959-2005 period - from: A-ploughing; B - compacted ploughed field after harvesting (data of long-term monitoring on Novosil Experimental station, after Petelko et al., 2007). See Fig. 1 for location Novosil Experimental station.

Fig. 5. Changes of permanent watercourse pattern for periods from 1830th (A) to 1940th (B), the Savala River basin. See Fig. 1 for the location of the Savala River basin

Fig. 6. Relationship between percentage of arable land area (2) and percentage of total watercourse length (1) for the Savala River basin for period 1780 -1990 (total watercourse length in 1780 is 100%). See Fig. 1 for the location of the Savala River basin

Fig. 7. Soil losses (Er, million cubic meters) from arable lands for various landscape zones of Southern part of the Russian Plain in the 17th – 20th centuries (based on data from Sidorchuk, 1995)

Legend: 1 – forest zone (Central Non-chernozem region); 2 – south of forest and north of forest-steppe zone (Sregnee Povolzie region); 3 –forest-steppe and north of steppe zone (Central Chernozem region); 4 – steppe zone (south of Russian Plain)

Fig. 8. Dynamics of the formation of anthropogenic gullies in the forest steppe zone in the central part of the Russian Plain (based on Moryakova, 1988)

Fig. 9. Sediment redistribution (% and t) in the Chasovenkov Verkh catchment (the Plava River basin) for the following time intervals: A – 1700- 1954; B – 1954-1986; C – 1986-1997. See Fig. 1 for the location of the Chasovenkov Verkh catchment.

Legend: E – slope erosion; A_{sl} – sediment deposition on the uncultivated parts of slopes; A_{tr} – sediment deposition in the tributary bottoms; A_{mv} – sediment deposition in the main valley; W_r – sediment transport to the Lokna River valley bottom.

Fig. 10. Sediment redistribution (% and t) in the Popov Ovrag catchment for two time intervals: A -1790-1954; B – 1954-1995. See Fig. 1 for the location of the Popov Ovrag catchment.

Legend: E_{sl}– soil losses, sheet and rill erosion; E_g – soil losses, gully erosion; A_{sl}– sediment deposition on the uncultivated parts of slopes; A_{vb} – sediment deposition in the valley bottom; W_r – sediment transport to the Vyazovka River

Fig. 11. Correlation between sediment flux and catchment area for the Russian Plain

1 – curve of maximum sediment flux for the permanent streams with appropriate catchment areas (after Rzhanitsin,1985) 2 – Sediment yield of the catchment studied in detail - with a completely silted riverbed and lack of permanent flow