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DEGRADATION, REHABILITATION, AND CONSERVATION OF SOILS

Contemporary Trend in Erosion of Arable Southern Chernozems (*Haplic Chernozems Pachic*) in the West of Orenburg Oblast (Russia)

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Abstract—The contemporary trend in the degradation of arable southern chernozems (Haplic Chernozems Pachic) in the steppe zone of south-eastern European Russia under the impact of water erosion has been evaluated based on a field study of changes in the deposition rate of eroded products on the bottoms of the currently stable negative landforms within a small catchment (1.92 km^2 in area) with almost completely tilled slopes in the west of Orenburg oblast, in the basin of the Samara River (a left tributary of the Volga River). The dating of deposited sediments and the analysis of their temporal dynamics have been performed using the radioactive isotope ^{137}Cs as a chronomarker. The results of a thorough analysis of catchment topography, grain size distribution data on soils and sediments, hydrometeorological observations, and satellite data have been used. It is found that the mean accumulation rate of chernozem erosion products on the bottom of a small catchment valley was 1.9–2.0 cm/year (16.5–28.4 kg/m^2 annually) during the period of 1959–1986 (4.2–4.8 cm/year, or 30.4–83.5 kg/m^2 annually in 1959–1963) compared to only 0.52–0.68 cm/year, or 6.6–11.9 kg/m^2 annually, during the period of 1986–2016; i.e., the thickness of deposited sediments decreased at least by 3.0–3.6 times, and their mass decreased by 2.0–4.3 times (2.9 times on the average). It is shown that the main reason for the presumed significant decrease in the erosion rate of southern chernozems in the region during the last decades was the reduction in surface water runoff from slopes during the spring snowmelt period, as well as the probable change in the structure of crop rotation toward some increase in the share of perennial grasses, and erosion control measures.

Keywords: southern chernozem (Haplic Chernozem Pachic), erosion, sediment, sedimentation, stratozem (Fluvisol), caesium-137, dry valley, catchment, climate change, surface water runoff, steppe, Russian Plain

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INTRODUCTION

The water erosion (hereafter, erosion) of soils, which is the most common type of soil degradation, is one of the most important environmental problems of humanity, which causes deterioration in quality and frequently loss of soil resources on the Earth. The tillage of catchment slopes activates erosion by 3–4 orders of magnitude on the average compared to the natural landscapes [8]. On the other hand, the rate of soil loss from arable lands is significantly variable in time, which is primarily due to varying hydrometeorological conditions (changes in the amount of precipitation, heterogeneous distribution of their fallout layer and intensity among the seasons, different soil freezing depths in winter, types of spring snowmelt, etc.) and economic activities (changes in the areas of cultivated lands and their crop rotations, tillage practices, erosion control measures, etc.).

The last decades in European Russia were characterized by notable climatic and hydrological changes [25, 26, 32], which should affect the rates of erosion and accumulation of its products in all links of the regional fluvial network. Frolova et al. [25] note a significant degradation of spring flood as a water regime phase on rivers in the most part of Russian Plain, which was due to the rise in winter air temperatures and the increase in the number and duration of thaws reducing the reserve of water in the snow during the snowmelt period and the maximum water discharge during the spring flood. On the other hand, the changes in land use (reduction in the cropland area, especially during the period of 1991–2005; alternation of crop rotations; etc.) most significantly affected the southern regions of the forest zone [28]. In the steppe zone, the area of cropland decreased less significantly, although noticeably, by 27.5%. According to the erosion models calculations [28], the total soil loss in the steppe zone decreased by 14% on the average during the period from 1980 to 2012. Unfortunately, no results of field studies are available to confirm the presence and intensity of the reduction trend in the mean annual erosion rate of chernozemic soils in the south-eastern steppe region of European Russia during the last decades. Soil erosion surveys were not performed there in this time. It should be noted that the development of erosion in the steppes of Southern Cis-Urals has specific features. These are sheet, rill and gully erosion due to snowmelt and rainfall runoff; however, in contrast to the forest-steppe zone, deflation is also manifested in all forms (dust storms, snow drift, etc.), which also increases the area of eroded soils [6]. It was shown [18] that the wind pattern in the Russia area significantly changed in the second half of the 20th century primarily due to the decrease in extreme wind velocities during all seasons, except summer [4]. This fact leads to the absence of possibility for increase in chernozem deflation in the considered region of European Russia.

The aim of this work is to estimate the current (since the 1950s) trend in the erosion degradation of southern chernozems (Haplic Chernozems Pachic (WRB, 2006) [16]) in the western part of Orenburg oblast on the basis of field studies in a typical plowed small catchment of the Samara River basin. Along with the scientific value, the results of this work can be considered in applied terms for the development of efficient erosion control measures and recommendations on the optimization of land use pattern in steppe small catchments.

CHARACTERIZATION OF THE CATCHMENT AND THE PHYSICOGEOGRAPHICAL CONDITIONS OF THE STUDY AREA

The studied small catchment of 1.92 km^2 in area (Fig. 1) is located on the central part of the left bank of the Bol'shaya Pogromka River (a left tributary of the Samara River, in the Samara–Buzuluk interfluve) at 3.5 km to the northwest from the center of the settlement of Suvorovskii (Totskoe district, Orenburg oblast). In the middle part of the northern catchment area, a grader road (up to 1–1.5 m in height) passes from the west to the east (it was laid even before 1972 [24]); the road is regularly maintained in good condition. The road separates an area of 0.37 km^2 (19.3%) to the north of the main catchment area.

Relief and geological structure. The catchment is located within the Buzuluk Depression of the Volga–Ural anteclise on a Pliocene denudation plain (northern megaslope of the Obshchy Syrt Upland) composed from the surface by Triassic deposits, including clay shales, aleurites, sandstones, and conglomerates [7]. The highest interfluve areas in the region are covered by Jurassic deposits (sandstones, clays, marls, bituminous shales, etc.). Most slopes in the interfluves are covered by soil-forming Late Quaternary deluvial loams.

The mean height of the catchment area is 176.4 m; its maximum height is 202.9 m (in the southern extremity of the catchment), and its minimum height is 157.8 m (dry valley bottom); the height amplitude of the catchment is about 45 m. The general slope of the catchment area is about 2° (to the north of the grader road, 1.7°). Two large hollows of 1890 m (western hollow that continues the main small valley) and 1310 m (eastern, hollow-tributary) spread from the south to the north, to direction of the main small valley. Apart from these two relatively large erosion landforms, a network of smaller forms (rills, gullies, etc.) is developed within the catchment area.

The climate in the region is temperate continental, with a hot summer accompanied by dry winds and a cold winter with a steady snow cover. According to the data of the closest meteorological (weather) station in the city of Sorochinsk, Orenburg oblast (55 km to the east of the catchment area), the mean annual air temperature was 4.7 ± 0.3°C during the period of 1946–2015 and showed a tendency of increasing in time: 4.2 ± 0.3°C in 1946–1986 and 5.3 ± 0.4°C in 1987–2015. A rise in the mean monthly air temperature was also observed during April–March (the months of the most active snowmelt in the region), from 6.0 ± 0.9°C in 1946–1986 to 6.8 ± 0.9°C in 1987–2015. This was accompanied by the shift of the stable transition of mean daily air temperature over 0°C from April 5 (1960–1986) to April 2 (1987–2015).

The mean annual precipitation was 373 ± 19 mm in 1960–2015, including 251 ± 16 mm (~67%) during the warm season (April–October) and 122 ± 9 mm (~33%) during the cold season (November–March). The mean monthly precipitation values show a pronounced annual course with a minimum in February and a maximum in July. Beginning from the 1960s, a general increase in precipitation during the warm season was also noted (231 ± 17 mm/year in 1960–1986; 268 ± 24 mm/year in 1987–2015; Δ = +16%), when the number and role of rainfall events increased (Table 1). The cold season in the region under study was characterized by a similar increase in precipitation: 114 ± 14 mm/year in 1960–1986; 133 ± 12 mm/year in 1987–2015 (Δ = +17%). Over the last 55–60 years, this tendency was accompanied by both an increase in the water reserve in the snow cover (to the east of the catchment, according to the Sorochinsk meteorological station data) in late March–early April and a slight decrease (to the north of the catchment, according to the Buguruslan meteorological station, Orenburg oblast) (Fig. 2) on the background of a general rise in temperature (reduction in the freezing depth) of soil during this season (Table 2).

Landscapes. The catchment is located in the steppe zone (southern steppe subzone), within the Obshchy Syrt Upland district of the Obshchy Syrt–Cis-Ural landscape province [7]. The native plant cover mainly consists of sheep fescue–stipa steppe formations alternating with small oak–elm and oak–lime forest areas [7]. To the late 1990s, the total area of plowed virgin lands in the Totskoe district of Orenburg oblast made up 23.3% under the general tendency of

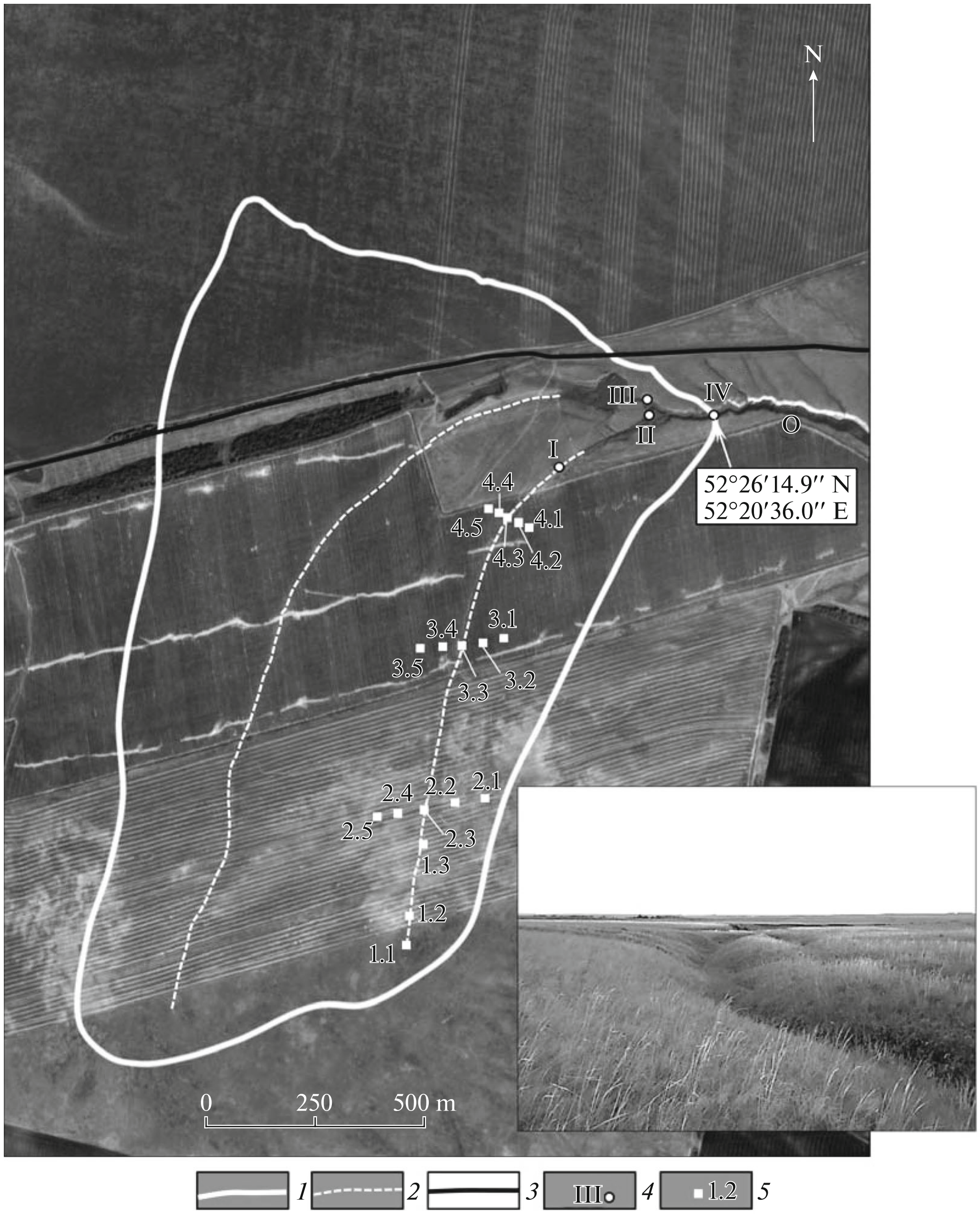

Fig. 1. GeoEye image of the catchment under study: (*1*) catchment watershed line with respect to the soil profile IV; (*2*) western and eastern hollow thalwegs; (*3*) grader road; (*4*) stratozem (Fluvisols) soil profiles in the bottom of the main valley (soil profiles III and IV) and its right (eastern) hollow-tributary (soil profiles I and II); (*5*) southern chernozem sampling sites for estimating the ^{137}Cs concentration and the thickness of the humus horizon within the tilled part of the eastern hollow catchment; (O) bottom gully. Photo: The main valley upstream of soil profile III (A.V. Gusarov, August 2016).

land abandonment since the 1990s. The soil cover of interfluves in the studied region consists of slightly eroded and slightly deflated medium-deep southern chernozems on Late Quaternary deluvial loams [7].

The land use pattern within the catchment area is as follows: cropland (in 2016, technical crops: sunflower etc.), 1.59 km^2 (82.7%); natural stepped meadows used for pasture and hay making, 0.3 km^2 (15.6%); antierosion and wind-break plantation of ash-leaf maple (*Acer negundo* L.) along the grader road in the north-western part of the catchment, 0.028 km^2 (1.5%); and a livestock pond located to the north of the lower reaches of the western hollow, 0.00362 km^2 (0.2%).

METHODS OF STUDY

Analysis of the thicknesses of sediments accumulated in different times, as well as stratozems devel-

Table 1. Changes in rainfall events with different rain layers during the warm season (April–October) at the meteorological station in the city of Sorochinsk in 1966–2015 for two time windows

Rain layer, mm	Periods		Changes, ±%
	1966–1986	1987–2015	
Total precipitation	1048*/2.3** (100)	772/3.4 (100)	–26.3/+47.8
<10	1005/1.8 (75.1)	709/2.5 (67.3)	–29.5/+38.9
10–20	40/13.3 (21.2)	54/11.2 (23.0)	+35.0/–15.8
20–30	2.9/23.5 (2.8)	6.9/23.4 (6.1)	+137.9/–0.4
30–40	0.0/0 (0)	1.4/34.5 (1.8)	
40–50	0.5/47.5 (0.9)	1.0/45.1 (1.8)	+100.0/–5.1
>50	Absent		–

* Number of rainfall events (events/10 years).
** Mean rain layer per one rainfall event (mm); the mean contribution (%) of rain layer to the formation of annual precipitation is given in parentheses.

Table 2. Changes in the spring soil temperature (°C) at different depths at the Orenburg and Buguruslan meteorological stations during the period 1963–2011/2013 for two time windows

Meteorological station, city	Month (ten-day period)	Period, years	Depth, cm		
			160	80	20
Orenburg	March (last)	1963–1986	1.01 (17)	–0.49 (57)	–0.54 (79)
		1987–2013	1.64 (7)	0.09 (37)	0.27 (59)
	April (first)	1963–1986	1.16 (13)	0.16 (30)	2.24 (24)
		1987–2013	1.89 (0)	1.20 (22)	3.63 (15)
Buguruslan	March (last)	1977–1986	1.94 (0)	0.04 (40)	– (–)
		1987–2011	2.98 (0)	1.10 (8)	0.19 (36)
	April (first)	1977–1986	1.95 (0)	0.35 (33)	– (–)
		1987–2011	2.92 (0)	1.35 (0)	1.20 (20)

The share (%) of the years with the negative mean ten-day soil temperature at the specific depth is given in parentheses.

oped on them (Fluvisols, according to WRB, 2014) and accumulated on the bottoms of small negative, relatively stable linear landforms (untilled parts of hollows and bottoms of small valleys), allows estimating the total intensity and temporal variability of erosion processes occurring within their catchment areas [8, 11]. These first-order valleys form a sort of buffer which traps a significant part of sediments washed from the tilled slopes and thus hamper their input to the river network [8, 9].

The use of the artificial radioactive isotope caesium-137 (^{137}Cs), which appeared in the environment with the beginning of open-air nuclear tests in 1954, as a chronomarker is one of the most common methodological approaches to the estimation of the contemporary accumulation rate of material eroded from croplands [11, 12, 27, 30, 31, 34, 36, 37]. One distinguishes primarily bomb-derived ^{137}Cs, which fell out onto the Earth (predominantly in the Northern hemisphere [33]) since the beginning of the period of nuclear explosions with a maximum in 1963 (peak period of 1962–1964). The second (smaller) peak of global fallouts was observed in 1959 (in European Russia, in 1958–1959 [23]). The two global (bomb) peaks are supplemented by a peak of Chernobyl-derived ^{137}Cs (accident at the Chernobyl NPP in April, 1986), the fallout area of which mainly includes Eastern, Central, and Northern Europe regions [2]. These peaks fix, with a good accuracy (±2–4 cm), the vertical location of soil surface on the bottoms of first-order valleys and in other undisturbed zones of steady accumulation in the moment of ^{137}Cs fallout in these years. When the above ^{137}Cs-marking layers remain within the stratozems, it is possible to date them and to determine the sedimentation rate during three time windows: 1958/1959–1963, 1963/1964–1986, and from 1986/1987 to the sampling moment. It was shown [37] that the ^{137}Cs concentration peak can occur at 2–4 cm from the soil surface depending on soil type and climatic conditions; only for very acid soils, which are not used in agriculture, it can occur at 5–6 cm from the surface due to ^{137}Cs vertical migration. For chernozems, its occurrence depth is generally 2–3 cm. The vertical migration of caesium is most

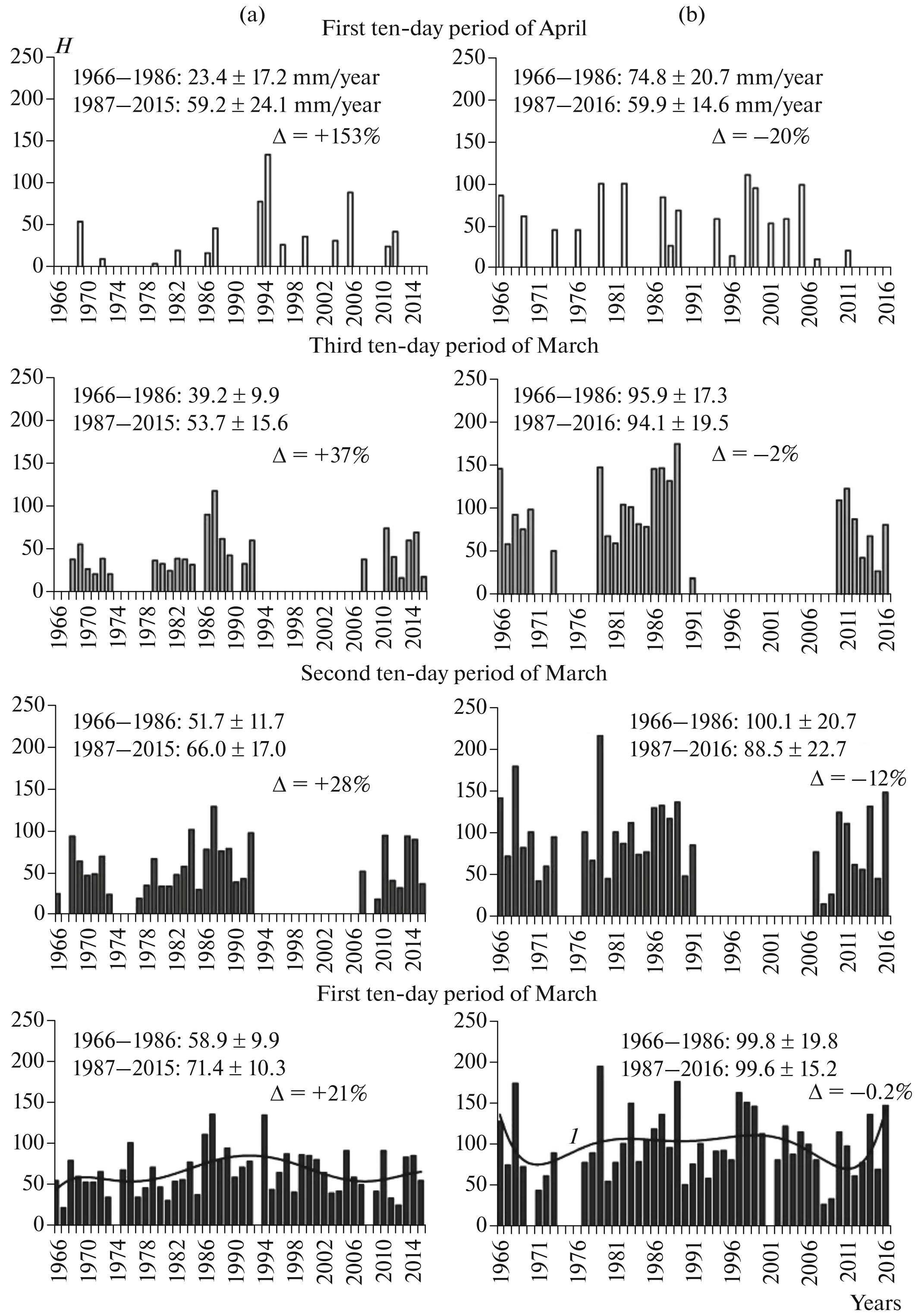

Fig. 2. Long-term variability of water reserves in the snow cover (*H*, mm) at the meteorological stations in the cities of (a) Sorochinsk and (b) Buguruslan in March and April 1966–2015/2016: (*1*) polynomial trend of degree 6; (Δ) relative change in the *H* value between the periods. The zero values in March of some years are generally related to the absence of data.

active in the first years after the fallout of the isotope from the atmosphere; it significantly decelerates with time and depth. Therefore, the concentrations of ^{137}Cs in the zones of regular accumulation of sediments mainly vary only due to its decay. The only methodological problem is the assignment of separate peaks to interlayers accumulated due to the redeposition by water flows of soil erosion products from the overlying zones more or less saturated with ^{137}Cs of bomb-derived or Chernobyl-derived origin. However, distinct peaks of ^{137}Cs fallen with atmospheric precipitation in 1959, 1963, and 1986 cannot be due to the redeposition of soil material, except the cases of well-fixed differences in grain size distribution between the sediment layers: an abrupt increase in the share of generally fine (clay) fraction compared to the higher and lower layers [8, 37].

The sedimentation rate of soil material removed from erosion-active catchment areas is closely related to the dynamics of erosion and soil loss on these areas. Nonetheless, the exact calculation of changes in erosion rate from the dynamics of the related sediment accumulation is still methodologically difficult, if the studied erosion–accumulation system is not enclosed (e.g., in the presence of any “sediment trap” (pond, lake, etc.) intercepting all the sediments removed from the catchment area).

During the fieldwork, a tachometric survey of the catchment valley with a digital tachometer was performed in August 2016, which was supplemented by a high-accuracy aerial survey of the entire catchment surface to develop its digital 3D model with a DJI Phantom 4 drone in May 2017. A part of valley bottom and some hollows located upstream of the head of the incised bottom gully were surveyed in detail. Based on the survey results, sites were selected to establish four soil (stratozem) profiles[1], which characterize the transport pathway segments of sediments removed from cropland differing in the features of transition. In the profiles, stratozem samples were taken layer by layer (with 2–3-cm intervals from the upper sediment layers and with 5-cm intervals from the lower layers) to determine the concentration of ^{137}Cs. In addition, samples of southern chernozems were taken from the arable part of the eastern hollow catchment to determine the ^{137}Cs concentration in integrated samples from the $A1_{ca} + A1B_{ca}$ humus horizon and estimate its thickness and grain size distribution in three transverse catenas and along the hollow thalweg (Fig. 1).

Under laboratory conditions, in the Research Laboratory of Soil Erosion and Fluvial Processes, Faculty of Geography, Moscow State University (executive in charge—M.M. Ivanov), soil samples were dried, ground, weighed (with density determination), and sieved through a 1-mm sieve. In the prepared samples, the specific concentration of ^{137}Cs was determined with a coaxial germanium γ-ray spectrometer within correctness 5–10%. For each soil profile, the vertical distribution of ^{137}Cs concentration was plotted. In the Research Laboratory of Ecological Innovations, Department of Applied Ecology, Institute of Environmental Sciences, Kazan Federal University (executive in charge—I.B. Vybornova), grain size analysis of the collected samples (less than 2 mm (2000 μm) in size) was performed by the laser diffraction method with a Microtrac Bluewave S3500 analyzer (three-laser technology) from 70 measurements within all grain-size fractions for a sample. The mineral composition of three samples from the soil profile I was determined by X-ray diffractometry on a Shimadzu XRD-700 diffractometer in the Lithological Laboratory, Department of Mineralogy and Lithology, Institute of Geology and Oil-Gas Technologies, Kazan Federal University (executive in charge—A.A. Eskin).

In addition, results of meteorological monitoring observations were collected and analyzed about the interannual distribution of rainfall events with rain layers (layers of liquid precipitation) of <10, 10–20, 20–30, 30–40, 40–50, and >50 mm during the period of 1966–2015; water reserves in the snow during the period of 1966–2015/2016 from the data of the Sorochinsk and Buguruslan (132 km to the north from the catchment) meteorological stations; changes in soil temperature at different depths before spring snowmelt during the period 1963–2013 from the data of meteorological stations in Orenburg (~200 km to the southeast of the catchment) and Buguruslan (open electronic data of the All-Russian Research Institute of Hydrometeorological Information—World Data Center); and long-term water discharges and suspended sediment yields in the Samara and Buzuluk Rivers (Orenburg oblast), the hydrological gauging stations of which, respectively, in the villages of Elshanka (53 km to the northwest) and Perevoznikovo (27 km to the northwest) are the closest to the small catchment area under study. To reveal possible radical changes in the cropland area and the crop rotation within the catchment under study, available satellite images of the USGS Landsat Global Archive were collected and analyzed.

RESULTS

Analysis of the vertical distributions of ^{137}Cs and grain sizes in stratozems, in combination with the field description of accumulated sediments, allows interpreting the general direction of changes in the rates of erosion–accumulation processes within the catchment area under study.

In the layer of erosion products of arable chernozemic soils penetrated by the soil profiles, the ^{137}Cs concentration peak (>15–30 Bq/kg), which we dated at 1986 (Chernobyl-derived ^{137}Cs), the closest to the present-day stratozem surface, can be identified with

[1] Soil profile maximum depth and maximum sampling depth, respectively (m): profile I, 1.00 and 0.73; profile II, 1.05 and 0.80; profile III, 0.72 and 0.58; profile IV, 0.96 and 0.81.

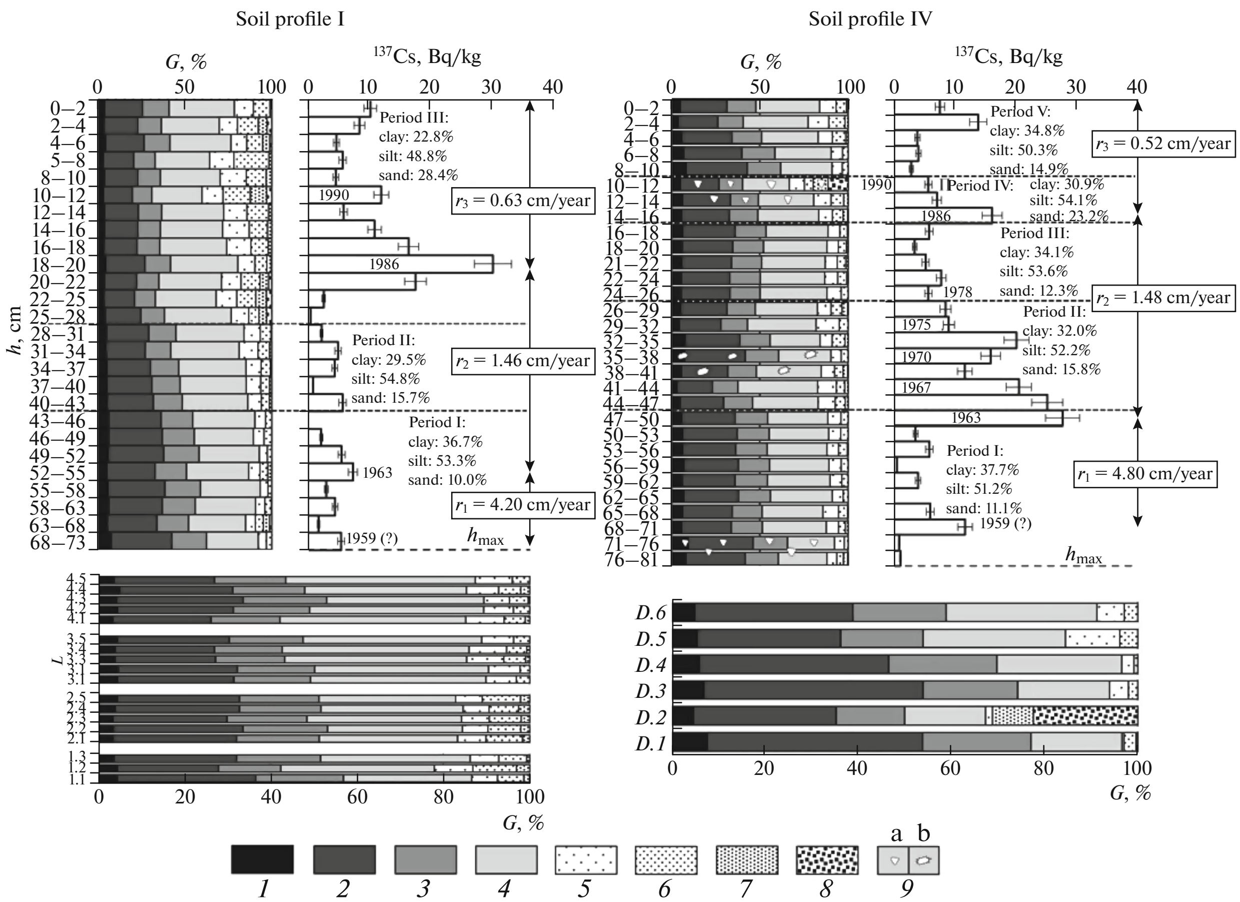

Fig. 3. Vertical distribution of ^{137}Cs concentration and the changes of grain size distribution (*G*) in soil profiles I and IV of stratozems (Fluvisols), (*L*) integrated samples from the $A1_{ca}$+ $A1B_{ca}$ humus horizon of southern chernozem from the eastern hollow (see Fig. 1), and (*D.1*, *D.2* ...) fresh landslide bodies deposited on the bottom at the foot of the left side of the valley. Key: (*h*) profile depth (h_{max} is the maximum sampling depth, cm); sedimentation rates during the periods: (r_1) 1959–1963; (r_2) 1963–1986; (r_3) 1986–2016; texture: (*1*) fine clay (0.2–1 μm); (*2*) coarse clay (1–5 μm); (*3*) fine silt (5–10 μm); (*4*) coarse silt (10–50 μm); (*5*) fine sand (50–100 μm); (*6*) small-grained sand (100–250 μm); (*7*) medium-grained sand (250–500 μm); (*8*) coarse- and large-grained sand (500–2000 μm); (*9*) carbonates ((a) differently-rounded breakstone; (b) soil neoformations).

some degree of reliability. It is poorly identified (<12 Bq/kg) only in soil profile III because of the subsequent partial erosion of sediments to which it is confined. In general, the peak of Chernobyl-derived ^{137}Cs in all soil profiles is buried by sediments deposited since 1986 at more or less similar depths: profile I, 0.18–0.20 m (the mean sedimentation rate is 0.65 cm/year); profile II, 0.18–0.21 m (0.68 cm/year); profile III, 0.14–0.17 m (0.55 cm/year); profile IV, 0.14–0.16 m (0.52 cm/year). The identification of this ^{137}Cs peak allows dividing the entire penetrated stratozem layer into two layers formed before and after 1986, respectively. In profile IV, the peak of 1963 is also reliable identified (at a depth of 0.47–0.50 m), which indicates the position of bottom sediment surface in the moment of maximum bomb-derived ^{137}Cs fallout. In the other soil profiles, the peak of bomb-derived ^{137}Cs is identified less reliably (10–15 Bq/kg), which can be due to its significant erosion by snowmelt and rainfall flows.

The most part of the stratozem layer penetrated by the profiles contains the radioactive isotope, except one interlayer[2] in soil profiles I (at a depth of 43–46 cm) and IV (at a depth of 62–65 cm) with the absence of caesium (Fig. 3). Consequently, even with consideration for the probable vertical migration of ^{137}Cs, the entire sediment layer containing the isotope below the 1986 peak can be dated to the period of 1954–1986, because the nuclear test in 1954 was the only source of artificial ^{137}Cs input to the soil during this period. However, the initial occurrence depth of ^{137}Cs from the 1954 fallout cannot be determined exactly for three reasons: first, its share was extremely low compared to the next fall-

[2] These interlayers free from ^{137}Cs are most probably related to the accumulation of sediments containing no isotope (undercut sides of the small valley, bottoms of deep rills, etc.).

Table 3. Mineralogy of samples of the sediment layers separated in profile I

Sediment layer depth	Sampling depth	Mineralogy, %
cm		
0–28	14–16	Montmorillonite, 57; quartz, 34; albite, 5; chlorite, 3; dolomite, 1
28–43	34–37	Montmorillonite, 60; quartz, 31; albite, 4; chlorite, 3; microcline, 2
43–73	58–63	Montmorillonite, 54; quartz, 28; calcite, 8; albite, 5; microcline, 2; muscovite, 2; chlorite, 1

outs; second, the present-day concentration of the isotope dated to this year in sediments is extremely low, because the ^{137}Cs half-life is 30.2 years and more than 60 years have elapsed since its fallout; and third, because of the bioturbation of soil material.

In all of the studied soil profiles, the depth of sediments accumulated during the period 1954(?)–1986 (lower layer) exceeds in thickness of the superimposing layer of sediments deposited in 1986–2016 (upper layer). The differences in the thicknesses of the considered sediment layers increase toward the small valley mouth.

The comparison of the positions of dated ^{137}Cs peaks with the vertical variation of grain size distribution of sediments in the most representative soil profiles I and IV allowed split, with some degree of probability, the stratozem layer into separate accumulation stages of the erosion products of southern chernozem on the arable part of the catchment area supplemented, in soil profile IV, by material produced due to ephemeral gully (rill) erosion and bank erosion of the small valley sides. For the specification of the dating of separate stratozem layers, along with the content of ^{137}Cs and differences in grain size distributions, we analyzed the correlation of the proportions of their clay and sand fractions with the changes in the suspended sediment yield of the Samara River (Fig. 4) on the basis of the following considerations. The suspended sediment yield of any river is formed from the products of both riverbed (vertical and horizontal deformation of riverbeds) and basin (sheet, rill and gully erosion) components [14, 15]. The changes in the proportions of these components caused by the variation of natural conditions on the catchment area (interannual climate changes, including the variation of surface runoff during the period of snowmelt and runoff-forming rainfalls, soil freezing depths, and land use pattern) always affect the suspended sediment yield of the river. Any significant increase in the volume of suspended sediments is due to the abrupt increase in the share of the products of basin erosion (soil loss from the catchment areas of active erosion, including croplands) in the river flow [13]. Sediments transported by slope runoff generally consist of clay and fine silt particles because of the redeposition of coarser particles during the transport from these areas to river channels. Consequently, the mobilization of fine fractions and their redeposition during their transportation increase abruptly in the years of large suspended sediment yield in basin geosystems. In the years of decreased suspended sediment yield, on the contrary, their concentration in river water and sedimentation products of soil material removed from the catchment area is lower.

The formation history of sediments (stratozems) on the valley site with soil profile I[3], which can be considered the most responsive to changes in the basin component of erosion (slope wash-out) because of its intermediate position on the pathways of sediments from arable slopes to the higher links of the fluvial network (Fig. 1), well agrees with the long-term dynamics of suspended sediment yield in the Samara River, in whose basin the analyzed small catchment is located. In the stratozem profile, three layers of sediments are distinguished, which were formed in different periods and have different proportions of the clay, silt, and sand fractions (Fig. 3). The topmost (latest) layer accumulated after the period of 1983–1984 contains the smallest amount of clay (including about 3% fine clays) and the largest amount of sand (including the maximum content of the coarse sand fraction in sediments presumably of 1990). The lowest (oldest) layer (presumably of 1959–1967), on the contrary, is characterized by the highest clay content (including about 6% fine clays) and the lowest sand content, which is lower than in the topmost layer by almost 3 times. Gabbasova et al. [6] noted a similar tendency of a significant decrease in the content of physical clay and silt in the eroded typical chernozems of the neighboring Republic of Bashkortostan (Russia) during the last 35 years. Changes in the mineralogy of sediments in the three layers of soil profile I are shown in Table 3: the share of quartz gradually decreases and the content of carbonate minerals increases from the upper to the lower layer. The revealed tendency of changes in the grain size of sediments with depth in profile I during

[3] The soil profile is located in the gently sloped and untilled (meadowed) lower part of the eastern hollow bottom, which is the closest to the cropland edge, where the runoff is widely spread. In this part of hollow, accumulation processes always prevailed significantly over potential erosion, which could occur only in the case of repeated annual runoff, when freshly deposited sediments had no time to be reliable fixed by herbaceous vegetation after previous runoff and erosion.

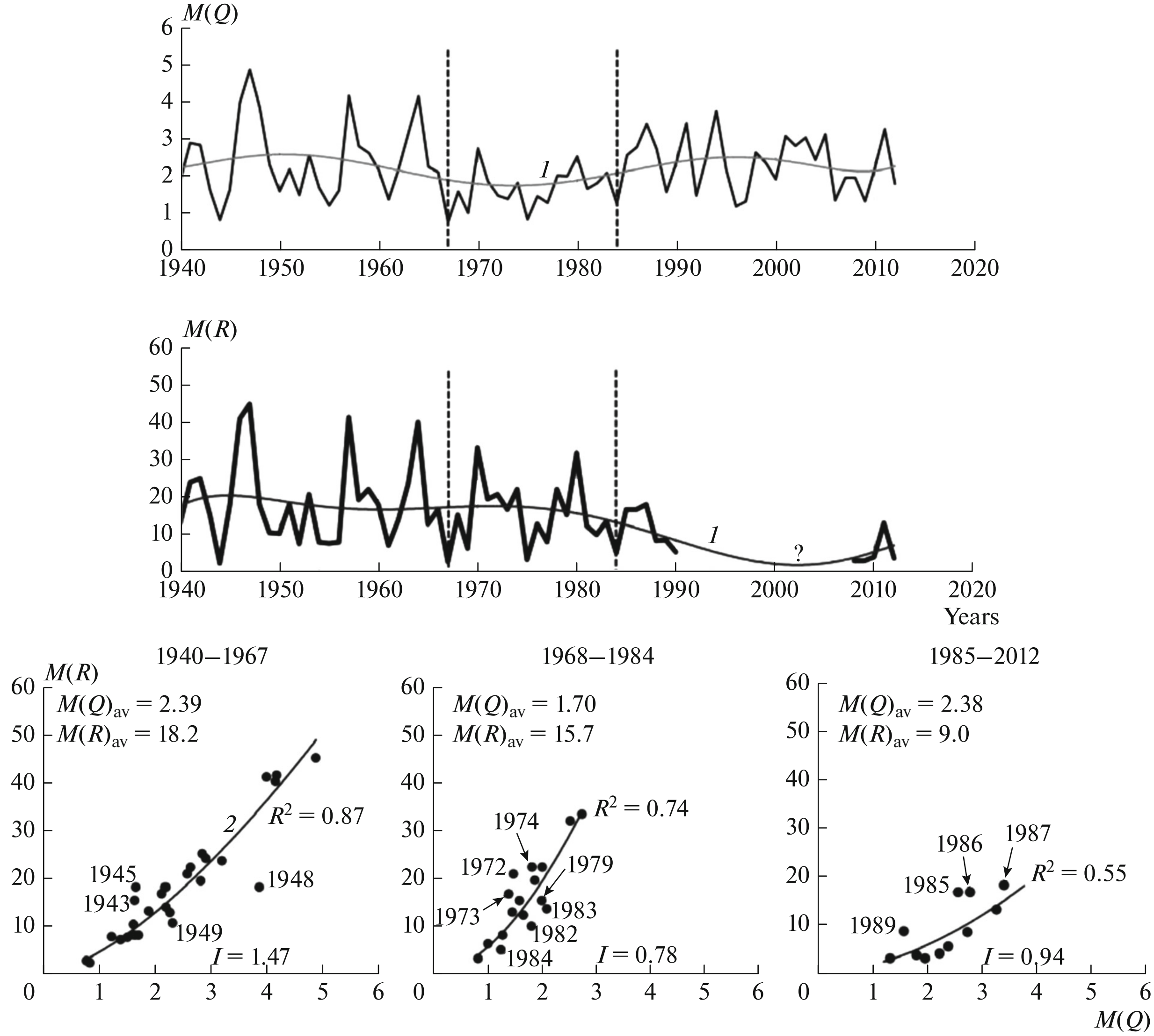

Fig. 4. Long-term variability of water discharges ($M(Q)$, L/(s km^2)) and suspended sediment yield ($M(R)$, t/(km^2 year)) of the Samara River at Elshanka (basin area is 22800 km^2) during the period 1940–2012: ($M(Q)_{av}$) averaged water discharges (L/(s km^2)); ($M(R)_{av}$) averaged suspended sediment yield (t/(km^2 year)); (1943, 1945 ...) years of observations; (*I*) mean spring-flood runoff in the river basin (mm/day); (*1*) polynomial trend of degree 6; (R^2) approximation coefficient of the exponential trend line (*2*). No data on $M(R)$ for the period 1991–2007 are available.

the accumulation period corresponds to the temporal dynamics of suspended sediment yield in the Samara River basin, where the same three periods are distinguished, with the general tendency of decrease in the contribution of the basin component to suspended sediment yield. Thus, the subdivision of the stratozem layer in profile I suggests a distinct reduction in erosion rate within the cropland of the catchment area under study by at least three times between the periods of 1959–1986 and 1986–2016.

The formation history of stratozem in soil profile IV, which can be conventionally considered as an intermediate element between the sheet-rill-gully and riverbed erosion systems [14, 15] in the river basin, was more complicated than in soil profile 1. This resulted in a more complex periodization of the accumulation of sediments with different proportions of fine and coarse grain-size fractions up to the formation of interlayers of differently-rounded breakstone (Fig. 3). The reason is the location of the soil profile on the bottom of a relatively deep small valley, on the sides of which pre-Quaternary deposits (including marl) are frequently exposed, as well as the larger area of the catchment located up the stream of soil profile IV, which implies the formation of more intensive surface runoff. None-

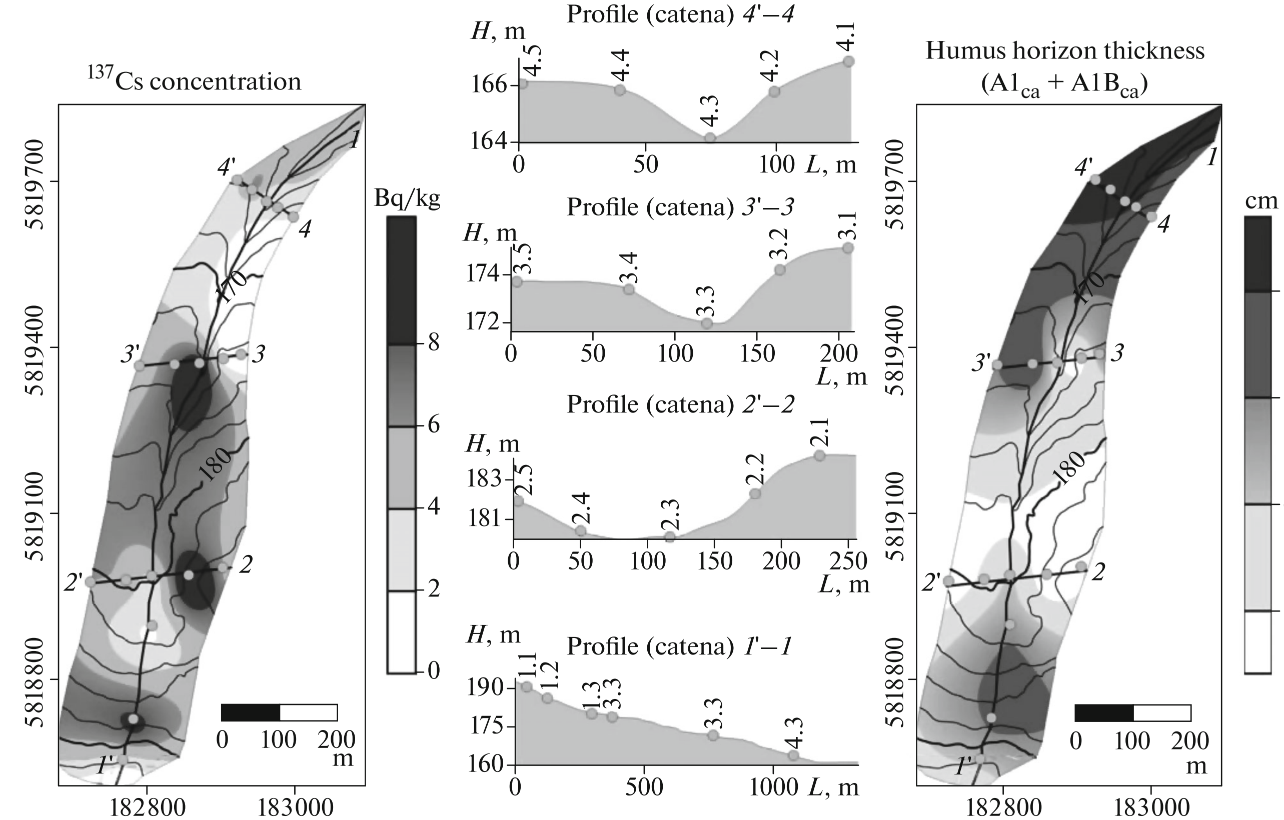

Fig. 5. Map-scheme of the $A1_{ca} + A1B_{ca}$ humus horizon thickness of southern chernozem and its integrated ^{137}Cs concentration within the eastern hollow catchment of the small valley catchment under study: (*H*) absolute height; (*1'–1...4'–4*) profiles (catenas) with (1.1, 1.2...4.5) sampling points (see Fig. 1); (*L*) horizontal traversing along the profiles.

theless, a reduction in sedimentation rate by app. 4 times between the periods of 1959–1986 and 1986–2016 is also revealed there[4], which characterizes the temporal dynamics of erosion–accumulation processes within the entire small catchment area. It is important to note that the proportions of the clay, silt, and sand fractions for the two first periods of sedimentation are almost similar to those revealed in soil profile I for the same periods, which suggests that soil erosion products from the arable catchment area were the dominant sources of sediments during these periods. No similar equivalence was observed over the last 35–40 years.

The distributions of the thickness of the $A1_{ca}$ + $A1B_{ca}$ horizon [16] and its content of ^{137}Cs in southern chernozem of the eastern hollow within the catchment area under study are shown in Fig. 5. The hollow catchment can be subdivided into three sublatitudinal sectors depending on the thickness of the $A1_{ca} + A1B_{ca}$ horizon: the lower sector of increased thickness below catena *3'–3*, the middle sector of decreased thickness between catenas *2'–2* and *3'–3*, and the upper sector of conventionally normal thickness above catena *2'–2*. The distribution of ^{137}Cs is slightly different. The lower sector is characterized by a reduced ^{137}Cs concentration (<5 Bq/kg). Areas with increased and decreased ^{137}Cs contents alternate along the hollow thalweg, which can be interpreted as the alternation of accumulation and erosion areas. The content of caesium in catenas *3'–3* and *2'–2*, each catena being located on one hollow side, largely corresponds to the degree of soil erosion: the reduced soil profile corresponds to a decreased ^{137}Cs concentration. No analogous tendency is traced on the opposite sides. Despite of schematism of these distribution plots, a general tendency is observed: the most active erosion of soils (and, hence, a decrease in the humus horizon thickness of southern chernozem) was observed in the middle sector of the hollow catchment, from which erosion products were removed down the slope and partially accumulated in the lower reach of the hollow (increased thickness of the humus horizon). The lowest slopes of the hollow bottom in its lower part favored the accumulation of fine sediment particles (clay and silt fractions) compared to any locations upstream (Fig. 3). The comparison of the map-scheme of humus horizon thickness distribution with the land use pattern on the catchment

[4] With consideration for the difference in the density of sediment layers, the following sedimentation rates were recorded: 28.4 kg/m^2 annually in 1959–1986 (mean density 1394 kg/m^3) and 6.6 kg/m^2 annually in 1986–2016 (1231 kg/m^3); i.e., their values decreased in 4.3 times.

Table 4. Changes in the summer mean-monthly water discharges in the Buzuluk River at the village of Perevoznikovo and the monthly atmospheric precipitation at the Sorochinsk meteorological station during the period 1951–2015 for two time windows

Period, years	Water discharges, m^3/s			Precipitation, mm		
	June	July	August	June	July	August
1951–1986	1.25 ± 0.25	1.08 ± 0.24	0.93 ± 0.19	49.3 ± 12.0*	44.4 ± 9.7*	25.8 ± 8.9*
1987–2015	2.96 ± 0.39**	2.62 ± 0.44**	2.16 ± 0.36**	50.8 ± 12.8	37.4 ± 10.2	39.7 ± 8.7
Change, ±%	+136.8	+140.5	+143.3	+3.0	–15.8	+53.9

* During the period 1966–1986.
** During the period 1987–2013.

area (Fig. 1) shows that tillage across the slopes, which is operated at least since 1984 (according to Landsat images), is the obvious reason for the enhanced erosion in the middle sector of the hollow, where the slopes are sufficiently high (between catenas *2'–2* and *3'–3*). Despite the increased thickness of humus horizon in the lower part of the hollow catchment (accumulation of erosion products and mechanical soil erosion under tillage on the upper part of slope), enhanced erosion also could occur there in the years when the lower catchment area was also tilled. The upper reach of the hollow is characterized by the humus horizon thicknesses of southern chernozem (0.3–0.5 m) close to those developed under natural steppe formations [22, 35]. The slightly lower content of ^{137}Cs in the near-mouth part of the arable hollow catchment area can be due to the enhanced removal of the major part of the Chernobyl-derived isotope from the catchment sector before the first tillage, when it occurred on the soil surface. This could also be due to the deeper sampling because of the thicker humus horizon (compared to the samples taken on the resting part of the catchment area), which resulted in a higher dilution of samples with soil material from deeper horizons containing no ^{137}Cs. Analogous distribution features of conventionally uneroded, differently eroded, and aggraded soils apparently occurred in the neighboring (western) hollow of the catchment under study.

DISCUSSION

The obtained results clearly show a decrease in the accumulation rate of sediments on the valley bottom of the small catchment under study during the last 30 years: from 1.9–2.0 cm/year, or 16.5–28.4 kg/m^2 annually, in 1959–1986 (4.2–4.8 cm/year, or 30.4–83.5 kg/m^2 annually, in 1959–1963) to 0.52–0.68 cm/year, or 6.6–11.9 kg/m^2 annually, in 1986–2016; i.e., the thickness of sediments decreased between the periods under study in at least 3.0–3.6 times, and their mass decreased in 2.0–4.3 times (in 2.9 times on the average). Consequently, a proportional decrease in the erosion rate of southern chernozem within the catchment area may be supposed, with some degree of conventionality; unfortunately, it cannot be quantified from the recorded accumulation dynamics alone. Both changes in the hydrological–climatic conditions in the region and the changes in crop rotations, as well as erosion control measures, could cause the recorded directional variation of soil loss.

Changes in hydrological–climatic conditions. The main natural reason for the noted differences in the rate of erosion–accumulation processes was changes in hydrological–climatic conditions in the region, including the earlier noted tendency of air temperature rise, especially in spring period. Despite the difficulties in the determination of directional changes in the reserve of water in the snow of the small catchment during the last half-century (Fig. 2), it is safe to say that the rise of air temperature in winter against the background of increased precipitation in the same season resulted in a decrease in the soil freezing depth, which is clearly reflected in the change in their temperatures at different depths before snowmelt (Table 2). This, in turn, affected the ratio between the surface and ground water runoffs. The decrease in the aeration zone depth resulted in the formation of cellular structures of the frozen zone thickness distribution with the dominance of slightly frozen areas, which increased the loss of snowmelt runoff by filtration and groundwater supply. The runoff coefficient from slopes during the snowmelt period and, hence, the erosion capacity of the flow decrease, which extends the hydrograph of river spring-flood flow in time. Changes in water discharges in the neighboring Buzuluk River basin, which does not include the considered small catchment but forms a part of the Samara River basin, confirm these tendencies (Fig. 6). These changes include the reduction in the share of spring-flood flow in the annual river flow and the increase in its duration, as well as the decrease in the maximum (most erosion-hazardous) water discharge, which clearly reflects the general decrease of snowmelt rate in the basin during the last decades. The increase in the Buzuluk River water discharges in summer cannot be attributed only to the earlier noted increase of precipitation in the region during the warm season. Apparently, this increase is mainly due to the redistribution of snowmelt runoff into the soil and ground water flows, which steadily feed the river during the warm season. Only beginning from August, the relative role of

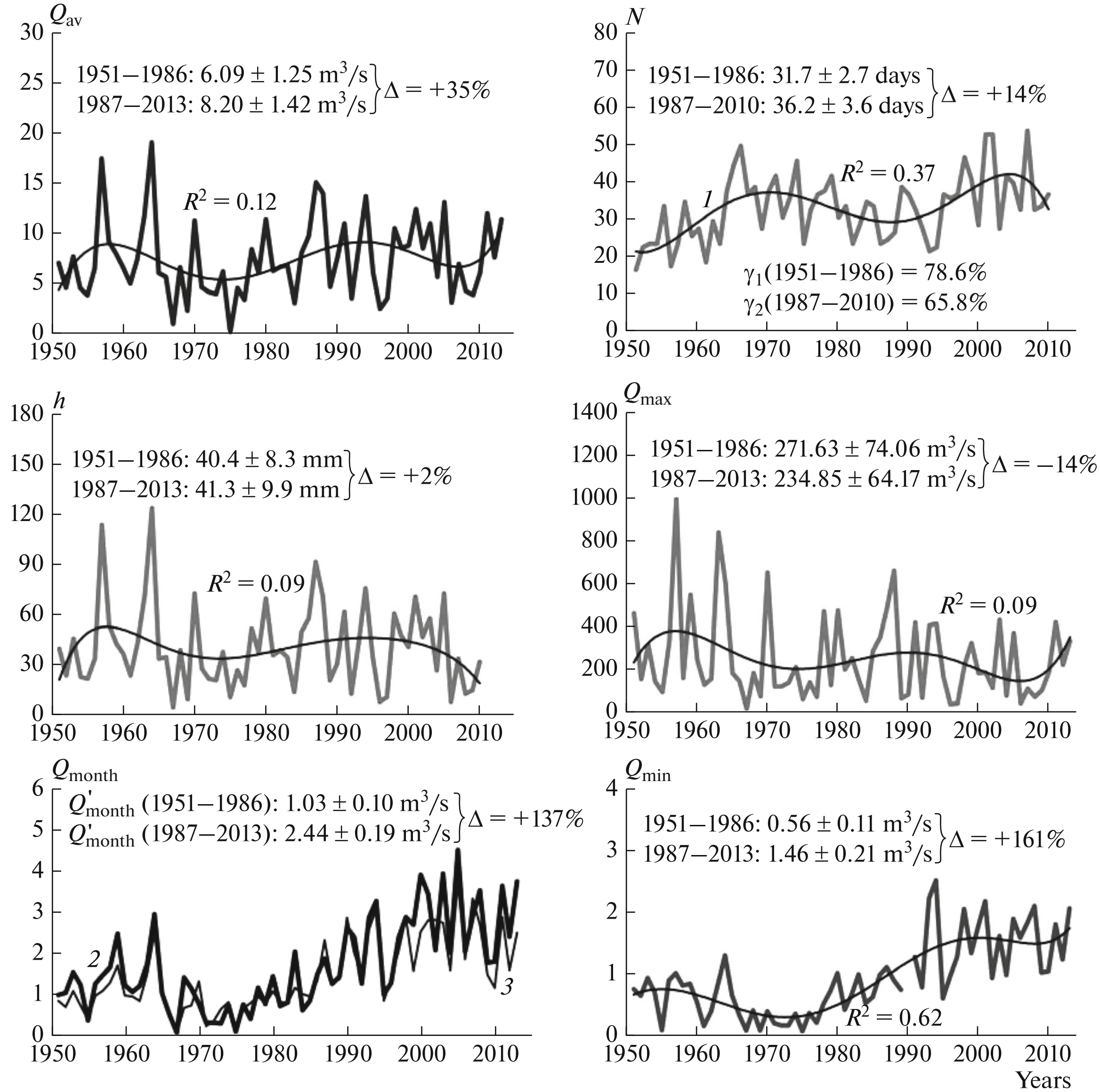

Fig. 6. Long-term variability of water discharges in the Buzuluk River at Perevoznikovo (basin area is 4280 km^2) in 1951–2011/2013. Water discharges (m^3/s): (Q_{av}) averaged annual, (Q_{max}) maximum annual, (Q_{month}) averaged monthly ((Q'_{month}) averaged monthly for the July–October period), and (Q_{min}) minimum during the ice-open river period; (*N*) spring-flood duration (days); (*h*) total spring-flood runoff layer (mm); (γ_1 and γ_2) shares of spring-flood runoffs in the total annual runoffs during the periods; (Δ) relative change in parameters between the periods; (R^2) approximation coefficient of the exponential trend line (*1*); (*2*) and (*3*) averaged Q_{month} for the June–August and September–October periods, respectively. No data on Q_{min} in 1991 are available.

rainfalls in the increase of river discharges appreciably increased during the last decades (Table 4).

The temperature conditions and freezing depth of soil significantly affect the development of erosion during the snowmelt period [3, 20]. This conclusion agrees with the rule of limiting factors of surface snowmelt runoff formulated by Barabanov [3], according to which runoff does not form under a certain (limiting) value of one of the factors (freezing depth, air temperature, and water reserve in the snow) regardless of the values of other factors. Komissarov and Gabbasova [19] showed that, in the years when the freezing depth of leached chernozem on the arable slopes of Southern Cis-Urals was within the range of 30–38 cm, surface runoff was absent regardless of snow reserve, soil water content, and soil protection by plants. The authors consider this freezing depth as a critical for the conversion of surface (snowmelt) runoff to underground runoff in the considered soil subtype. When the freezing depth exceeds the critical value, the volume of spring runoff on arable slopes is determined by specific hydrometeorological conditions during the snowmelt period.

The increase in the number of rainfall events (with the rain layer >20 mm) and their contribution to the formation of annual precipitation since the 1990s (Table 1) could enhance the erosion of soil and increase the suspended sediment yield in the Samara River basin. However, the soil-protection coefficients of agricultural crops in summer are higher than in spring in 1.5–2.3 times (and higher than in the snowmelt period in 2–3 times), and the soil is better protected from erosion. Therefore, it may be suggested that the effect of summer rainfalls with the rain layer more than 20–30 mm, which increased since 1990, was insignificant, for the reason that not every rainfall could result in soil loss because of different projective covers of soils. On the other hand, e.g., the strong rain (45.3 mm) fallen on April 23, 1992, in the city of Sorochinsk and its suburbs onto the thawed unprotected spring soil could result in a significant erosion and accumulation of a large mass of fine particles in sediments deposited on the bottom of the small valley after 1986 (the layer of 8–10 cm in soil profile IV (?)). Nonetheless, the rainfall runoff mainly enhanced linear erosion (including the periodical undercut of the small valley sides) and increased the grain size of sediments in the soil profiles since the mid-1980s (Fig. 3). The poorly seen peaks of ^{137}Cs concentration in 1986 in the stratozem profiles located on the valley bottom (soil profiles III and IV) are most probably result from soil erosion during the formation of such runoff.

The increase in the frequency of extreme rainfalls at the general increase of precipitation in the summer of 2017, which is universally observed in European Russia, including the Southern Cis-Urals, can be an anomalous phenomenon proceeding against the background of the manifested trend of increasing extreme precipitation in the warm season [29], as well as a new stage of consequences of climate changes in the last decades. This factor should be taken into consideration in the selection of agricultural crops for rotations in terms of their soil-protecting properties.

Changes in the land use pattern. The effect of the anthropogenic factor on the decrease in the rate of soil loss can be considered on the regional and local scales. Regional reasons are shown in Fig. 4, where three periods of erosion activity in the Samara River basin are clearly distinguished: 1940–1967, 1968–1984, and 1985–2012. The first period was characterized by the maximum water flow and suspended sediment yield, which indicated a relatively normal functioning of the erosion system in the river basin under the steady effect of economic activity on the catchment area at the largely high rate of soil erosion. The second, relatively low-water period (1968–1984), differed from the first period by the looser exponential correlation between the water discharges and suspended sediment yield, which was related to human activities rather than to hydrometeorological anomalies. On the plot of water discharge/sediment yield ratio in this period, the ratio points form two groups. The first group is characterized by anomalously high sediment yield (compared to the normal functioning described by an exponential correlation curve): +83.5% in 1972, +64.6% in 1973, and +35.4% in 1974. During this period, the anthropogenic factor played a significant role: capital investments to the agriculture of Orenburg oblast made up 1.4 billion rubles for the ninth five-year plan (1971–1975). Collective and state farms received 22000 tractors, about 11000 combines, and many other equipment types [5]. The increase in the amount of heavy machinery on the fields is one of the factors provoking a strong soil erosion through compaction, disturbance of its filtration properties, etc. Moreover, the total crop area in Orenburg oblast increased in the 1970s from 5.9 to 6.3 million hectares (by 7%), including from 4.5 to 4.8 million hectares (by 7%) on the area under cereal crops. Cereals occupied 72% in the structure of crops [17]. The second group of the points, with anomalously low values of suspended sediment yield, is confined to the late 1970s and the early half of the 1980s: 1979, –21.3%; 1982, –38.7%; 1983, –35.4%; 1984, –40.0%. In these years, erosion control measures (including antierosion bars, which occur in the near-mouth part of the western hollow of the catchment area) were undertaken on a cropland area of almost 2 million hectares in the oblast.

The third period (1985–2012) with the mean water flow equal to that in the first period (although the spring-flood flow during this period was lower than in 1940–1976 by 36%) was characterized by the lowest river sediment yield (Fig. 4). Along with the above noted climate changes, one of the reasons for the decrease in erosion rate in these years (since 1984/1985) is apparently related to the reorganization of the land use system after the collapse of the USSR: changes in the system of crop rotations (increase in the share of perennial grasses) in the entire river basin and the abandonment of croplands, although the rate of soil loss in the late 1980s was comparable to that in the preceding period. Another reason for the decrease in the amount of suspended sediments in the river is related to the construction of ponds on rivers and the establishment of earth dams and so-called rubber dams made of soft tissues, which were raised on small rivers in the oblast since 1984, as well as the Sorochinskoye reservoir, the largest in the Samara River basin (more than 0.134 km^3 in volume) and created in 1997.

The local effect of the anthropogenic factor within the small catchment area was related to the construction of a grader road (probably in the late 1960s) and the planting of a maple plantation (presumably in the late 1970s or the early 1980s), which could partially intercept eroded sediments from a relatively small area in the north-western corner of the catchment (Fig. 1).

No radical changes in the cropland area capable of reducing the soil loss rate were revealed after 1986 within the small catchment under study.

CONCLUSIONS

From the obtained results, an appreciable (at least threefold) decrease in the erosion degradation of southern chernozem in the studied small catchment area located in the western part of Orenburg oblast during the last decades is suggested on the basis of the unidirectional dynamics of the sedimentation rate of erosion products in the accumulative landscape positions and in the areas of sediment transport on the bottoms of small erosion landforms. The main reason for the noted dynamics was change in hydrometeorological conditions in the region: the reduction in snowmelt runoff due to the decrease in the soil freezing depth during the snowmelt period. The increase in the frequency of rainfalls with the rain layer more than 20 mm, which also occurred after 1986, had no effect on the general trend of decrease in the soil loss rate from the cropland within the catchment area under study, although it probably resulted in an increase in the contribution of rainfall erosion to the general degradation of soil cover in the Southern Cis-Urals. Secondary causes for the reduction in the contemporary erosion rate of southern chernozem can be changes in the structure of crop rotation toward some increase in the share of perennial grasses, as well as erosion control measures undertaken since at least the late 1970s.

Tendencies of decrease in snowmelt surface runoff and the mean annual rates of soil erosion and accumulation of erosion products are traced over almost the entire forest-steppe and steppe zones of the central part of Russian Plain [1, 10, 11, 21, 28]; in our opinion, they are also representative for chernozems in the southeastern steppe of the Plain.

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