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The impact of contemporary changes in climate and land use/cover on tendencies in water flow, suspended sediment yield and erosion intensity in the northeastern part of the Don River basin, SW European Russia

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ABSTRACT

The basin of the Don River (the fifth longest river in Europe), located mainly in the forest-steppe and steppe landscape zones, is one of the most populated and agriculturally developed regions of the East European (Russian) Plain. Sheet, rill and gully erosion occurring chiefly in snowmelt period (March-April) and also in moderate-to-heavy-rainfalls season (chiefly May-to-September) is the main factor of present-day soil degradation within cultivated lands of this basin. Using monitoring hydrological data, it is shown, by the examples of the Khopyor River and the Medveditsa River flowing in the northeastern part of the Don River basin (SW European Russia), that suspended sediment yield of the rivers, as an objective and sufficiently accurate indicator of total erosion intensity in river basins, was reduced by 3.6–3.8 times between the 1960s–1970s and 2008–2015. This conclusion is consistent with change in sedimentation rates (using ^{137}Cs as a chronomarker) within one of the small catchments located in the basin of the upper reaches of the Medveditsa River. The noted dynamics in erosion intensity and suspended sediment yields took place against the background of a well-marked tendency (since the 1940s–1960s) of reduction in intra-annual unevenness of river water flow caused by a decrease in spring (snowmelt-induced, March-April) flood water flow, and by a more significant increase in water discharges during low-water-flow periods of year (winter (December-to-February) and river-ice-free period (mid-April-to-November)). These changes were accompanied by an increase in duration of spring (snowmelt-induced) flood flow with a reduction in its intensity, year-to-year anomalousness and contribution to total annual water flow of the rivers. The main reasons for all the changes noted over the last decades were climate change (a decrease in depth of soil freezing during snowmelt period caused by an increase in air temperature mainly in winter and spring months; an increase in winter thaws frequency) and human activity changes (mainly a reduction in cultivated land area, especially in the 1990s and early 2000s). The similar tendencies were identified over the last decades in other regions of the forest (south part), forest-steppe and steppe landscape zones of the East European Plain.

1. Introduction

The East European (Russian) Plain is the largest plain of the Earth's dry land with a well-expressed natural (landscape) zonality. Its southern half is considered to be one of the most agriculturally productive areas in Europe owing to the high organic matter content and fertility of regional soils (Stolbovoi, 2002). For centuries, fertile soils (chernozems, gray forest soils, etc.) have been intensively cultivated there. In the south of the forest zone, the expansion of arable lands was accompanied by significant deforestation. So, only during two and a half centuries European Russia lost almost a third of its forests: the area of forest cover in the region, equal to 53% at the end of the seventeenth century, had been reduced to about 35% by 1914 (Catchment ..., 2017). As a result of these processes, in regional fluvial geosystems of different orders there were noticeable changes in the depth and intensity of soil freezing, the soil filtration properties, in the ratio between surface and underground water runoff from hillslopes during the snowmelt periods and rainfall seasons. All these changes led to degradation (siltation and warm-season drying) of the regional creeks/small-rivers network, to changes in the hydrological and hydrochemical regimes of the rivers, activization of erosion in interfluves (the maximum soil losses in the forest and forest-steppe landscape zones were occurred after the agrarian reform in the Russian Empire in 1861 (Sidorchuk and Golosov, 2003)), and to reduction in the natural soil

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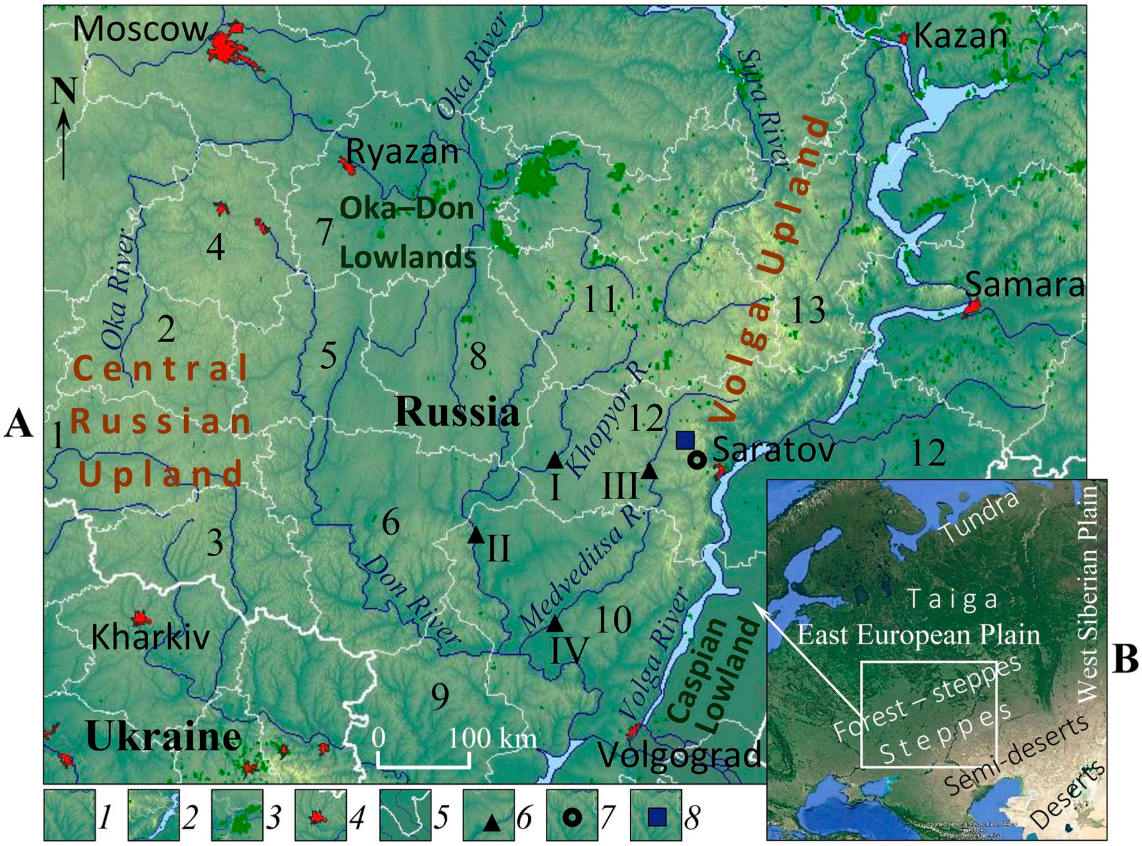

Fig. 1. Location of the investigated objects in the East European (Russian) Plain within European Russia (A – small scale DEM according to http://maps-for-free.com; B – landscape position according to Google Earth). *1* – river valleys; *2* – river valley reservoirs; *3* – forestlands; *4* – cities; *5* – domestic regional administrative borders in European Russia and Ukraine; *6* – hydrological gauging stations (the Khopyor River at: I – the city of Balashov, II – the village of Besplemyanovsky; the Medveditsa River at: III – the town of Lysyye Gory, IV – the village of Archedinskaya); *7* – the weather station in the town of Oktyabrsky Gorodok (51°38′09″N 45°27′19″E, the Saratov Oblast); *8* – the catchment of the studied dry valley “Srednyaya”. *The administrative regions (oblasts) of:* 1 – Kursk, 2 – Orel, 3 – Belgorod, 4 – Tula, 5 – Lipetsk, 6 – Voronezh, 7 – Ryazan, 8 – Tambov, 9 – Rostov, 10 – Volgograd, 11 – Penza, 12 – Saratov, 13 – Ulyanovsk.

fertility, to sharp increase in the volume of erosion products (especially suspended sediments) in rivers (Dedkov and Mozzherin, 1984; Dedkov and Mozzherin, 1996; Mozzherin and Kurbanova, 2004; Golosov, 2006; Dedkov et al., 2008; Gusarov, 2015; Golosov et al., 2017c; Litvin et al., 2017; and others), to active siltation and pollution (including pollutants supplied with mineral grains of washed-out soils) of natural and artificial water bodies (Prytkova, 1979, 1986; Okolelov et al., 2013) and river floodplains of the region (see Supplementary material ‘Examples for ‘Introduction”), and so on.

The last decades were characterized by noticeable hydrometeorological changes on most of the East European Plain (Maracchi et al., 2005; Shmakin and Popova, 2006; Dolgov, 2011; Popova and Polyakova, 2013; Madsen et al., 2014; Park et al., 2014; Barabanov et al., 2018b; and others). According to Frolova and co-authors (Frolova et al., 2015), there was a significant ‘degradation’ of river spring (snowmelt-induced) floods (i.e., a decrease in the proportion of snowmelt-induced flood water flow in the total annual water flow of rivers) caused by an increase in winter air temperatures, number and duration of thaws, that led to a decrease in maximum (per year) water discharges associated with the flooding caused by the melting of snow. The noted hydrometeorological changes could have a significant impact on the current erosion rates in the region, considering that sheet, rill and gully erosion occurring in the snowmelt period (March–April) and rainfall season (May to September/October) is the main factor of present-day soil degradation within cultivated lands of the East European Plain (Krasilnikov et al., 2016). The impact of these changes on erosion processes in the fluvial geosystems was supplemented by changes in land use/cover after the collapse of the Union of Soviet Socialist Republics (USSR) in 1991: reduction in area of cultivated lands, as well as changes in crop rotation (Lyuri et al., 2010).

The above-mentioned ‘degradation’ of spring (snowmelt-induced) floods of the regional rivers was most noticeable, for example, in the basin of the Don River (the basin area is about 422,000 km^2) that is one of the longest rivers in Europe. The basin of this river flowing chiefly within the steppe and forest-steppe landscape zones, mainly in the territory of European Russia, has a very high degree of ploughing. It is rightly considered to be one of the agricultural granaries of entire Russia. At the same time, there are almost no representative results of monitoring observations for overall tendencies of changes in the current rates of erosion and sediment yield in this basin (see Supplementary material ‘Examples for ‘Introduction”). Unfortunately, the national soil erosion surveys (mapping) that used to carry out in all administrative regions on a regular basis until 1991 are no longer undertaken since the USSR collapse. Nevertheless, an attempt was made to reconstruct changes in the erosion rates in several administrative regions of European Russia, based using some erosion models (Litvin et al., 2017).

Study purpose. The purpose of this study is, firstly, to identify general tendencies of changes in river water flow and soil (more precisely – soil (sheet), rill, and gully erosion in general) erosion intensity during the last 70–80 years within one of the most populated and agriculturally developed regions of the East European Plain – in the basin of the Don River, mainly by examples of its two northeastern river (sub)basins. Secondly, to assess the principal reasons for these tendencies.

Novelty of the study. For the first time for the basin of the fifth longest river of Europe, the Don River, by using the examples of its two largest tributaries (within European Russia), a typical complex scenario for the hydrological and erosion-intensity changes as a response to climate and land use/cover transformations over the last decades is presented. Despite the fact that the quantitative indicators of these changes are specific only for the (sub)basins of these tributaries and are theoretically partly expected (especially for water flow changes), they may be considered to be representative in general for the neighboring river basins within the forest-steppe and steppe landscape zones of the East European Plain as a vast and agriculturally productive region of Eurasia.

2. Materials and methods

2.1. Study area

The study area is the northeastern part of the Don River basin – the (sub)basins of the Khopyor River (upstream from the village of Besplemyanovsky) and the Medveditsa River (upstream from the village of Archedinskaya) (Fig. 1). The total area of the studied (sub)basins is 78,600 km^2, or 18.6% of the total area of the basin of the Don River, the fifth longest river in Europe. The studied (sub)basins are located within the territories of five administrative regions of European Russia – the Saratov Oblast, the Volgograd Oblast, the Penza Oblast, the Tambov Oblast, and the Voronezh Oblast (Fig. 1). The northern parts of these (sub)basins are situated in the forest-steppe landscape zone, the central and southern parts – in the steppe zone of the East European Plain.

2.2. Approach and methods

2.2.1. General approach to the study

The coupled analysis of long-term changes in water flow (by using river water flow according to hydrological observations at the gauging stations) and erosion intensity (by using suspended sediment yield according to hydrological observations at the gauging stations, and, additionally, accumulation rates of sediments on their migration pathways in the upper reaches of the studied river basins) was served as a general approach to the study. This approach is based on the river-basin principle of assessment.

2.2.2. Hydrological data analysis

Information sources. The data on the river water flow and suspended sediment yield were available from the All-Russia Research Institute of Hydrometeorological Information – World Data Centre, ARRIHI–WDC (http://meteo.ru), the Russian State Water Register (http://voda.mnr.gov.ru), and other sources. The long-term year-to-year variability in the river water flow (from 1940 to 2015) and suspended sediment yield (1935/1940–1975 and 2008–2015) in the studied (sub)basins was analyzed using the data from four hydrological gauging stations (Table 1).

River water flow. The data on the water flow were collected according to the following main characteristics: total annual depth of surface water runoff (H, mm); depth of spring (snowmelt-induced, March–April) flood water runoff (S, mm); spring (snowmelt-induced) flood duration (T, days); share of spring (snowmelt-induced) flood water runoff in the total annual water runoff in the river basins ($P = (S/H) \times 100$, %); maximum (per year) water discharge ($Q_{\max}$, m^3 s^{-1}) timed to the spring (snowmelt-induced) flood period; minimum water discharges ($Q_{\min}$, m^3 s^{-1}) for the winter period (December to February) and the river-ice-free period (open-water conditions, mainly mid-April to November). The separation of three hydrological periods in water flow time series was based on an analysis of year-to-year H-variability using the “Changepoint detection”, “Changepoints analysis” methods performed using the PELT algorithm (Killick et al., 2012). The search for the change points was made using the “Changepoint” package (Killick and Eckley, 2014) in the statistical analysis and programming environment R (R Core Team, 2017). These three periods identified in the H-variability time series were also extrapolated to time series of all the above-mentioned characteristics of the water flow (including the suspended sediment yield). In addition, the following characteristics of water runoff (flow) were calculated for each period: mean intensity of the spring (snowmelt-induced) flood water runoff ($Z = S/T$, mm per day); percentage of years with $P \geq 70\%$ – μ; dimensionless ratio between $Q_{\max}$ and $Q_{\min}$ (for the river-ice-free period) – η. The statistical analysis of the $Q_{\max}$ and $Q_{\min}$ time series included an estimation of monotonic (unidirectional) and periodic components, as well as an assessment of contribution of these components to overall variance of the time series. To evaluate monotonic trends, a linear regression model was chosen that relates the analyzed values to calendar years. The most significant wavelengths (rhythms) were calculated for the year-to-year (during 1940–2015) variability in maximum and minimum water discharges of the analyzed rivers using the Morlet (Gabor) wavelet transform procedure (Goupillaud et al., 1984) based on the WaveletComp package (Roesch and Schmidbauer, 2014, 2018).

River suspended sediment yield. The data on mean annual suspended sediment yield (W, kg s^{-1}, or Mg km^{-2} y^{-1}), as an objective and sufficiently accurate indicator of erosion intensity in river basins (Dedkov and Mozzherin, 1984), were available only for three hydrological gauging stations – the Khopyor River (at Balashov and Besplemyanovsky) and the Medveditsa River (at Lysyye Gory). The analyzed W time series, in contrast to the water time series, were intermittent. The longest break associated with absence of the data was timed to 1976–2007. To analyze the long-term variability in sediment yields, the ratio between mean specific suspended sediment yield and mean specific surface water flow (runoff), so-called modular specific W ((Mg km^{-2} y^{-1})/(L s^{-1} km^{-2})) – λ, was also calculated in order to minimize the role of water flow changes in the year-to-year W-variability.

Statistical significance. To identify statistically significant differences in average values of the analyzed hydrological characteristics between the separated periods, the Student's t-test was used to determine p-levels for these differences. All the average values were calculated with a 95% confidence interval for each period.

2.2.3. Field study

The small catchment studied. As a key field object of the study was one of the small catchments located on the left side of the Bolshoy Kolyshley River valley (the total river basin area is 651 km^2, a left tributary of the Medveditsa River) near the village of Varypayevka of the

Table 1

Analyzed rivers, their hydrological gauging stations (HGS) (see Fig. 1), and some river basin characteristics.

Rivers	HGS at:	HGS codes[a]	F, km^2	H, m	H, mm y^{-1}
Khopyor	The city of Balashov, 51°32′49″N 43°10′24″E[b]	78138	14,300	200	101.6
	The village of Besplemyanovsky, 50°44′33″N 41°51′58″E	78144	44,900	170	85.5
Medveditsa	The town of Lysyye Gory, 51°31′45″N 44°48′20″E	78196	7610	220	81.2
	The village of Archedinskaya, 49°53′35″N 43°06′45″E	78202	33,700	180	58.3

F – river basin area, H – mean absolute height in the corresponding river basin, H – average (for 1940–2015) annual depth of surface water runoff in the corresponding river basin.

[a] According to the Russian State Water Register (http://voda.mnr.gov.ru).

[b] Hereinafter, geographical coordinates of settlement centre.

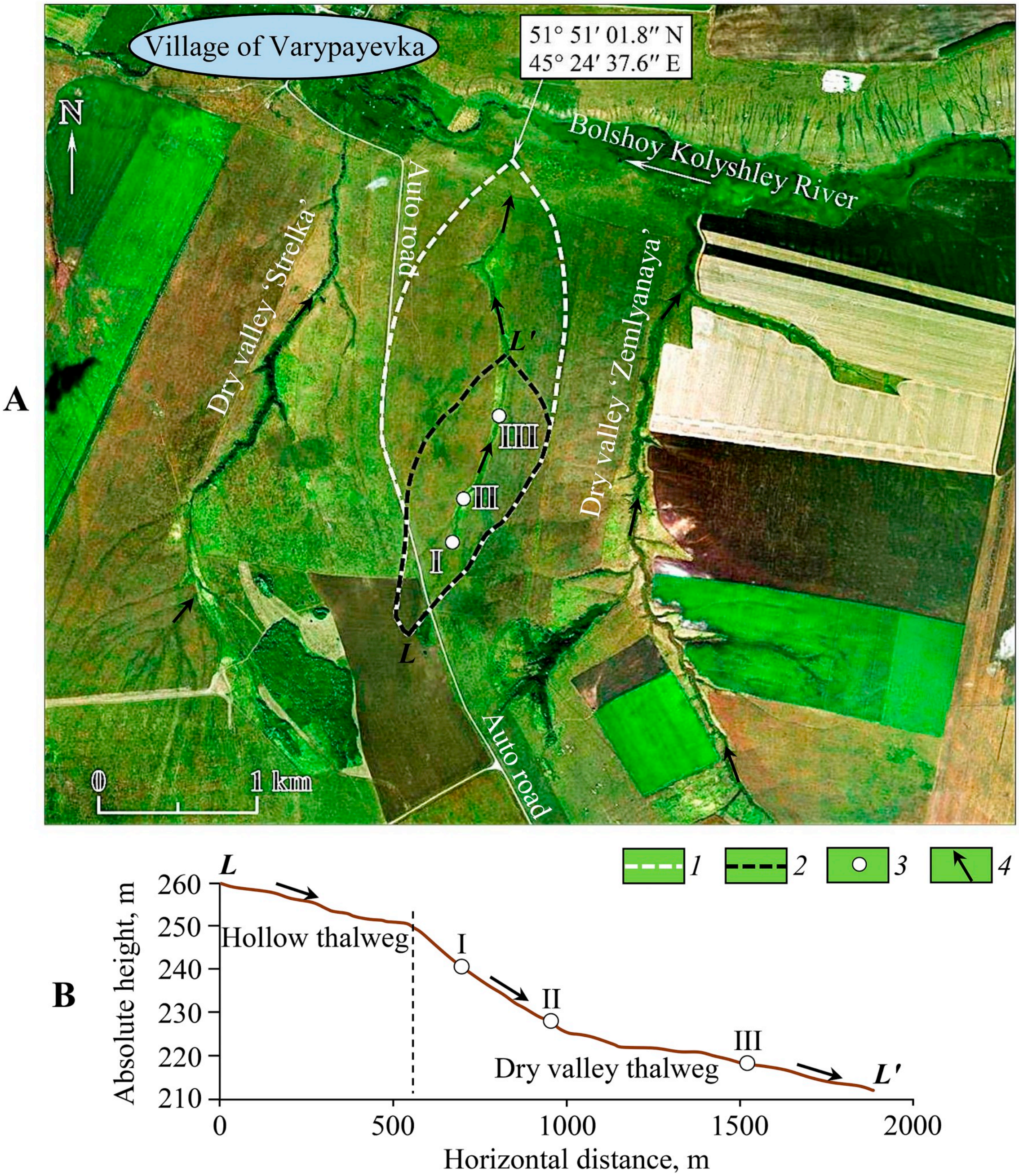

Fig. 2. The catchment of the studied dry valley "Srednyaya" (the Atkarsk administrative district of the Saratov Oblast, European Russia, see Fig. 1) in the satellite image taken on 28 th August 2014 (according to WorldView-2) (A). *1* – the boundary of the entire catchment; *2* – the boundary of the studied part of the catchment; *3* – location of the studied sediment sections within the dry valley bottom with their numbers (I, II, and III); *4* – direction of concentrated episodic surface water runoff within the local hollow/dry-valley network. B – the longitudinal profile along the thalweg of the studied dry valley (+hollow).

Saratov Oblast – the upper reaches of the dry valley "Srednyaya" ("Medium") (Fig. 1, see Supplementary material 'The catchment of the studied dry valley 'Srednyaya"). The catchment area is drop-shaped in a plan, typical for the region studied (Fig. 2). Water/sediment runoff from hillslopes goes to the meadow dry valley dividing the catchment area into two approximately equal parts. The dry valley bottom is a zone of transit and accumulation of soil materials washed down from the catchment hillslopes. The length of the investigated section of the dry valley together with a hollow in its upper reaches is 1850 m (the total length from the source to the outlet to the floodplain of the Bolshoy Kolyshley River is 3030 m). The area of the studied part of the catchment is 0.78 km^2, including the part of the catchment area (0.09 km^2) separated by the automobile road (presumably since the late 1960s) in the southwestern part of the catchment. The projection area of the dry valley is 0.069 km^2 (including the bottom – 0.01 km^2 with the average gradient of 0.027 (in the upper part of the studied section – 0.019, in the middle part – 0.048, in the lower part – 0.017)). The mean absolute height of the studied part of the catchment is 235 m (the height amplitude is 45 m); it is close to the mean absolute height of the Medveditsa River basin regarding the town of Lyssye Gory (Table 1). The mean slope surface gradient is about 2° (the maximum – 4.4°). Currently, the catchment area is ploughed up to almost 89%; the meadow areas (the dry valley sides, the dry valley bottom, the section adjacent to the auto road) do not exceed, in total, 11%. The soils on the catchment hillslopes are ordinary chernozems (Haplic Chernozems (Pachic)). At the time of fieldwork (the third 10-day period of June 2017) the cultivated ordinary chernozems within the catchment were sown with barley.

Sediment sampling. Three sediment sections (Fig. 2) were laid along the dry valley bottom: the upper section (I) with a depth of 64 cm, the middle section (II) – 30 cm, and the lower section (III) – 51 cm. The relatively shallow depths of sections II and III were owing to a high standing of groundwater level during the time of fieldwork. A description of the sediment (bottom soils – Fluvisols) horizons of each sediment sections was carried out. Sediment samples were taken layer-by-layer with increments of 2, 3, and 5 cm from the area of 10 × 10 cm and 15 × 15 cm using hand tools, and with increment of 10 cm at greater (under the groundwater level) depths using a metallic sampler (5 verticals in each sediment section up to a depth of 100 cm).

Sediment dating. The radioactive caesium-137 (^{137}Cs) with a half-life of 30.2 years is widely used to estimate current temporal dynamics of sedimentation rates in different-order fluvial geosystems (Owens et al., 1996; Walling et al., 2006; Mabit et al., 2008; Jweda and Baskaran, 2011; Du and Walling, 2012; Benmansour et al., 2013; Porto et al., 2014; and others). Within a large part of Europe several peaks of ^{137}Cs fallouts were recorded – the so-called global (bomb-derived) peaks, 1958–1959 and 1962–1964 with a maximum in 1963, associated with the years of the most active tests of nuclear weapons in an open atmosphere and widely distributed throughout the Northern hemisphere (Fig. 3), and the Chernobyl-derived ^{137}Cs caused by the accident at the Chernobyl Nuclear Power Plant (1986), the area of its fallouts is located predominantly in Eastern, Central, and Northern Europe (Atlas of Radioactive Pollution ..., 1998; De Cort et al., 1998). All the noted peaks with a high enough accuracy (± 1–3 cm) fix an altitude position of sediment surface in undisturbed zones of steady-over-time sedimentation (including first-order dry valley bottoms) at the years of ^{137}Cs fallouts (Appleby, 2008). The most active vertical ^{137}Cs-migration is occurred in the first years after the isotope deposition from the atmosphere, gradually slowing down in time by 1.5–2.0 times, depending on grain size composition of soils/sediments, their acidity, humus content, and water infiltration capacity, and so on (Kirchner et al., 2009; Buraeva et al., 2015; and others). If these marking ^{137}Cs-peaks (layers) are remained in accumulated sediment thickness, it becomes possible to determine sedimentation rates over the following periods – 1959–1963, 1963–1986, and from 1986 to the time of sampling. It is obvious that the sedimentation rates are in direct and close connection with dynamics of losses of soil materials washed out/down from erosion-active catchment areas (primarily hillslope cultivated lands) in the fluvial geosystems.

2.2.4. Laboratory analyzes

All the selected sediment samples were dried, disaggregated and passed through a sieve with a diameter of 2 mm at the Research Laboratory for Soil Erosion and Fluvial Processes (Faculty of Geography, Lomonosov Moscow State University, Russia). The ^{137}Cs concentration measurements were carried out using a γ-spectrometer SKS-07 (09) P-G-R with a high accuracy.

2.2.5. Other data collection

To assess the anthropogenic (mainly agricultural) impact on temporal dynamics of the water/sediment flow and erosion intensity in the studied river (sub)basins, information on the distribution of cultivated land areas for different time intervals (during the late USSR's period (1970, 1975, 1980, 1985, 1986, and 1987) and the post-USSR's period (every year from 1996 to 2017; no reliable data on cropland area changes during 1988–1995 were available)) was collected and analyzed. The changes in the cultivated land areas were detailed for different crops (cereals, perennial and annual crops, crops of sunflower, potato, and sugar beet, etc.). The statistical collections of the USSR (Agriculture of the USSR ..., 1988) and also the electronic statistical resources of the Russian Federation (https://fedstat.ru) were served as sources of the information. The data on long-term year-to-year precipitation variability in the studied region (from the the single weather station in the town of Oktyabrsky Gorodok) were available from the All-Russia Research Institute of Hydrometeorological Information – World Data Centre, ARRIHI–WDC (http://meteo.ru).

3. Results

3.1. River water flow changes

3.1.1. The changes in the Khopyor River basin

The analysis of the long-term year-to-year variability of the river water flow characteristics made it possible to identify the following principal regularities:

1. Three hydrological periods were singled out in the annual water flow (*H*, runoff) of the river – 1940–1966, 1967–1993, and 1994–2015, differing in their average characteristics (Figs. 4 and 5). The smallest

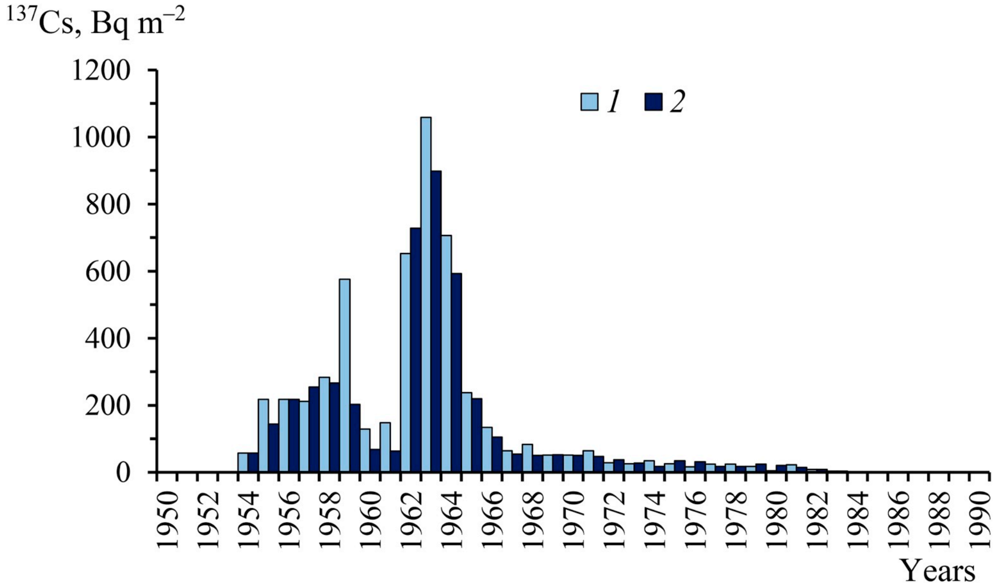

Fig. 3. The annual bomb-derived ^{137}Cs fallouts (*1*) in the Northern hemisphere (according to the generalized data of Zapata, 2002) and (*2*) in the Leningrad Oblast of the former Soviet Union (according to Silantyev and Shkuratova, 1983) during 1954–1983.

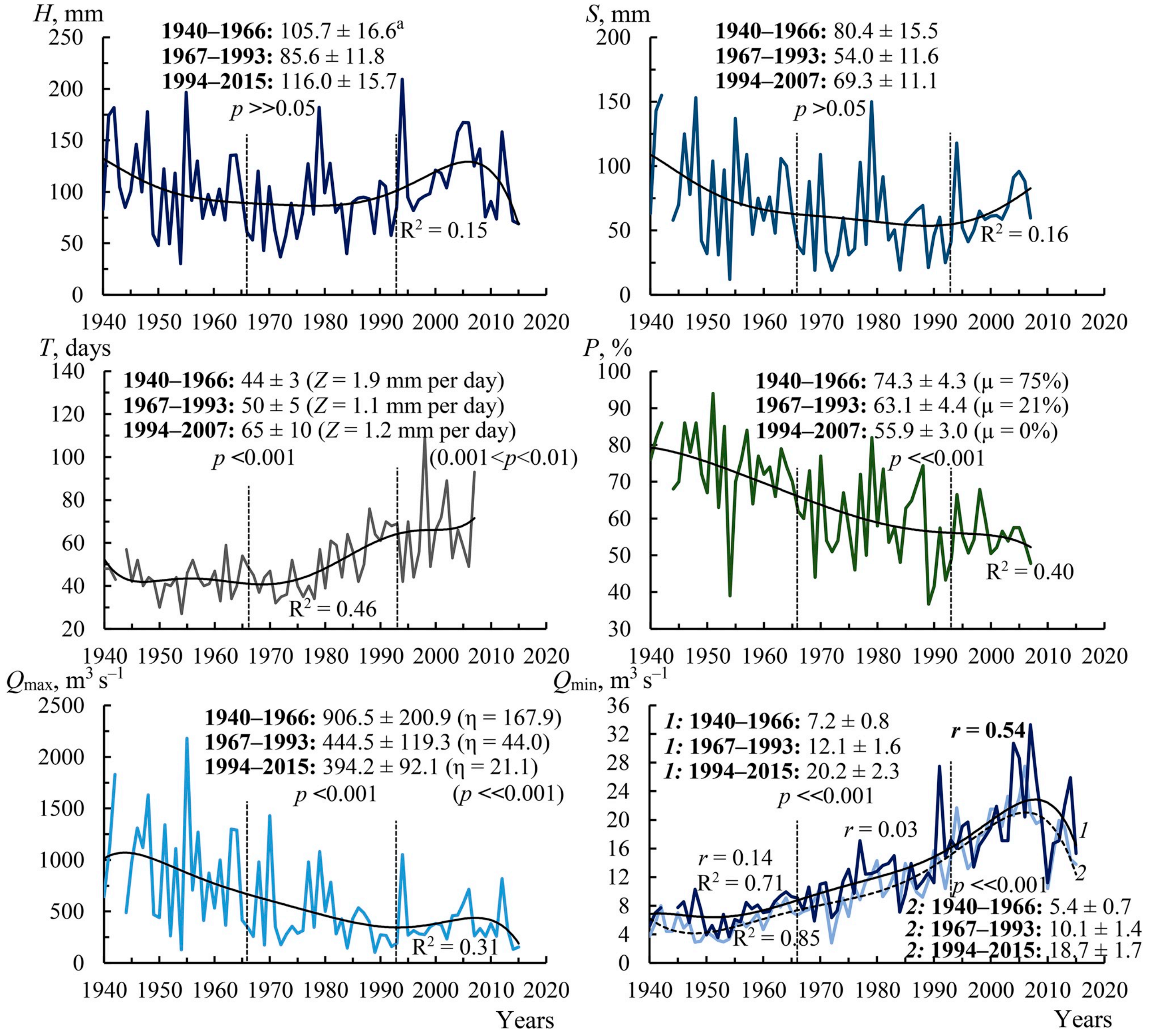

Fig. 4. The year-to-year changes in water flow of the Khopyor River at the city of Balashov (the Saratov Oblast, European Russia, see Fig. 1) during 1940–2015. H – total annual depth of surface water runoff in the river basin; S – total depth of surface water runoff for the spring (snowmelt-induced) flood period in the river basin; T – duration of the spring (snowmelt-induced) flood period; P – share of the spring (snowmelt-induced) flood surface water runoff in the total annual surface water runoff; $Q_{\max}$ – maximum (per year) water discharge timed to the spring (snowmelt-induced) flood period; $Q_{\min}$ – minimum water discharges for the winter period (*1*) and the river-ice-free period (*2*); Z – average intensity of the spring (snowmelt-induced) flood surface water runoff; μ – percentage of years with $P \geq 70\%$; η – average dimensionless ratio between $Q_{\max}$ and $Q_{\min}$ (*2*); R^2 – coefficient of sixth-degree polynomial trend approximation; r – coefficient of linear correlation between $Q_{\max}$ and $Q_{\min}$ (*2*) (statistically significant r ($p < 0.05$) is in bold); p – the probability of statistically significant differences in the corresponding average values between 1940–1966 and 1994–2007/2015 (the t-test). *Note.* No data on S, T, and P for 2008–2015 were available. [a] Hereinafter, a 95% confidence interval.

average values of the annual water flow (runoff) were observed in the medium period. Such dynamics reflects the features of the intra-annual redistribution in water flow between the periods: a reduction in the spring (snowmelt-induced) flood water flow with an increase in water flow during the low-water periods of the hydrological regime of the river. In this case, if water runoff depth for the spring (snowmelt-induced) flood in the river basin between 1940–1966 and 1994–2008 decreased only by 1.2 times at the city of Balashov (Fig. 4) and 1.4 times at the village of Besplemyanovsky, then the low-water-period runoff (reflected, in particular, in minimum water discharges, $Q_{\min}$) increased (a statistically significant increase) by 2.8 times (for the winter period) and 3.5 times (for the river-ice-free period) at Balashov (Fig. 4), and, respectively, 2.5 and 3.4 times at Besplemyanovsky (Fig. 5). Taking into account the fact that the most part of year falls to a low-water phase of the hydrological regime in these climatic conditions, the reason for the general increase in the annual water flow in the river basin in 1994–2015 compared to the previous periods becomes clear.

2. The greater reduction occurred in the maximum water flow ($Q_{\max}$) of the river. Between 1940–1966 and 1994–2015 it reduced by about 2.3 times (Figs. 4 and 5). This fact, against the background of the above-mentioned growth in the low-water-period water discharges, led to a general decrease (a statistically significant decrease) in the intra-annual unevenness of the flow (η) by about 8 times at the city of Balashov (Fig. 4), and by 4 times at the village of Besplemyanovsky (Fig. 5).

3. The duration of spring (snowmelt-induced) flood flow (T) increased by 3 weeks at the city of Balashov, and by 4 weeks at the village of Besplemyanovsky, that, against the background of the decrease in the total depth of runoff during the snowmelt-induced flood, had led to a

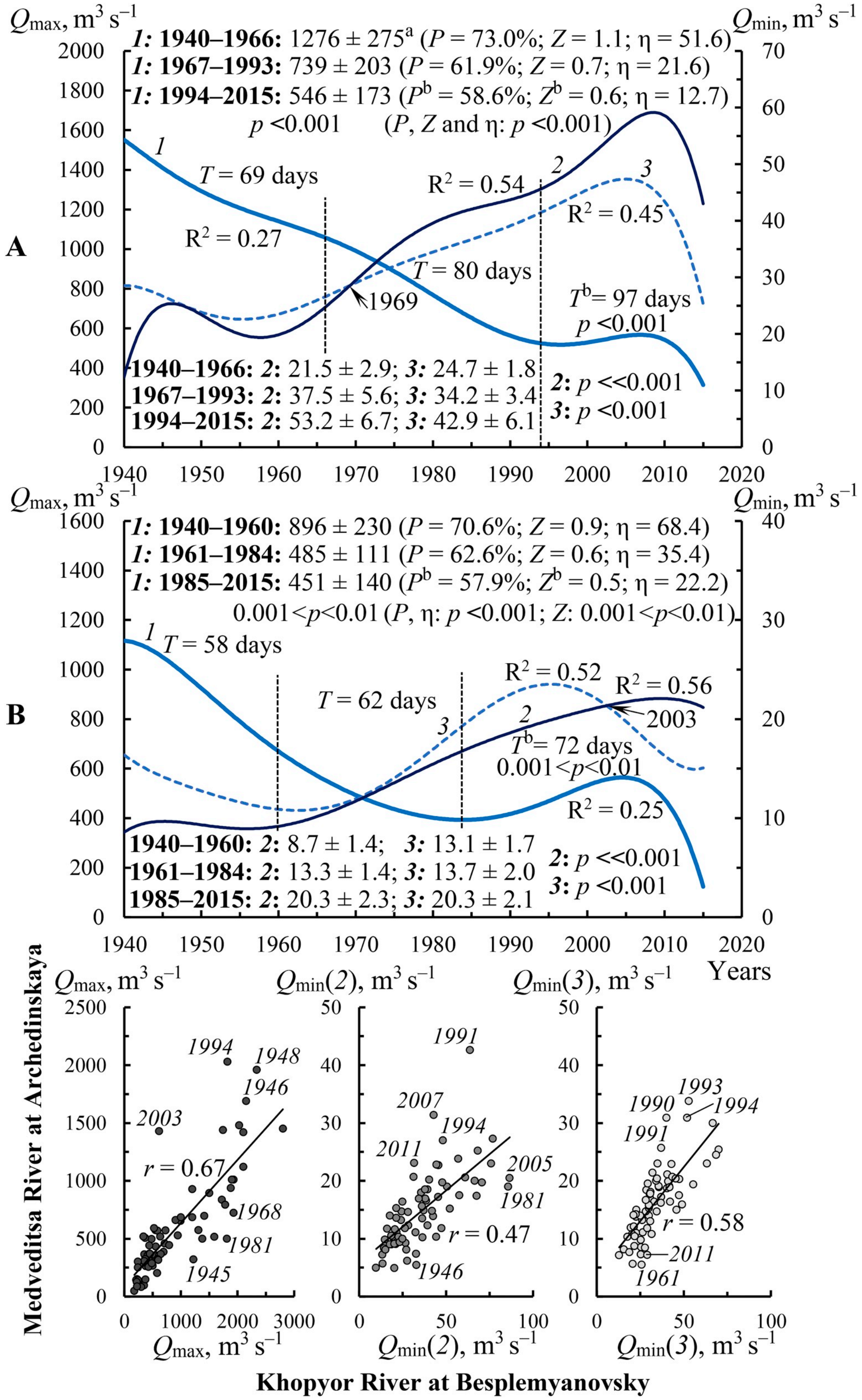

Fig. 5. The year-to-year changes in water flow of the Khopyor River at the village of Besplemyanovsky (the Volgograd Oblast, European Russia, see Fig. 1) (A) and the Medveditsa River at the village of Archedinskaya (the Volgograd Oblast, European Russia, see Fig. 1) (B) during 1940–2015.*1* – Q_{max}; *2* – Q_{min} for the winter period; *3* – Q_{min} for the river-ice-free period; η – average dimensionless ratio between Q_{max} and Q_{min} (*3*); p – the probability of statistically significant differences in the corresponding average values between the first and third monitoring periods (the *t*-test); r – linear correlation coefficient; *1945*, *1946* … – monitoring years. [a] Hereinafter, a 95% confidence interval. [b] Until 2008. Other symbols see Fig. 4.

statistically significant reduction in the intensity of the snowmelt-induced flood water flow (Z) by 37–45% between 1940–1966 and 1994–2015. If in 1940–1966 the average date of the beginning of spring (snowmelt-induced) flood was (at the city of Balashov) on 31 st March, whereas in 1994–2008 – on 19 th March. The share of spring (snowmelt-induced) flood water flow in the annual water flow of the river decreased (a statistically significant decrease) between these periods from 73–74% to 56–59%, respectively.

4. In the lower reaches of the river (at the village of Besplemyanovsky) the average volumes of the winter water flow have exceeded the average volumes of low-water-period water flow for the river-ice-free period approximately since 1969 (Fig. 5). In the middle

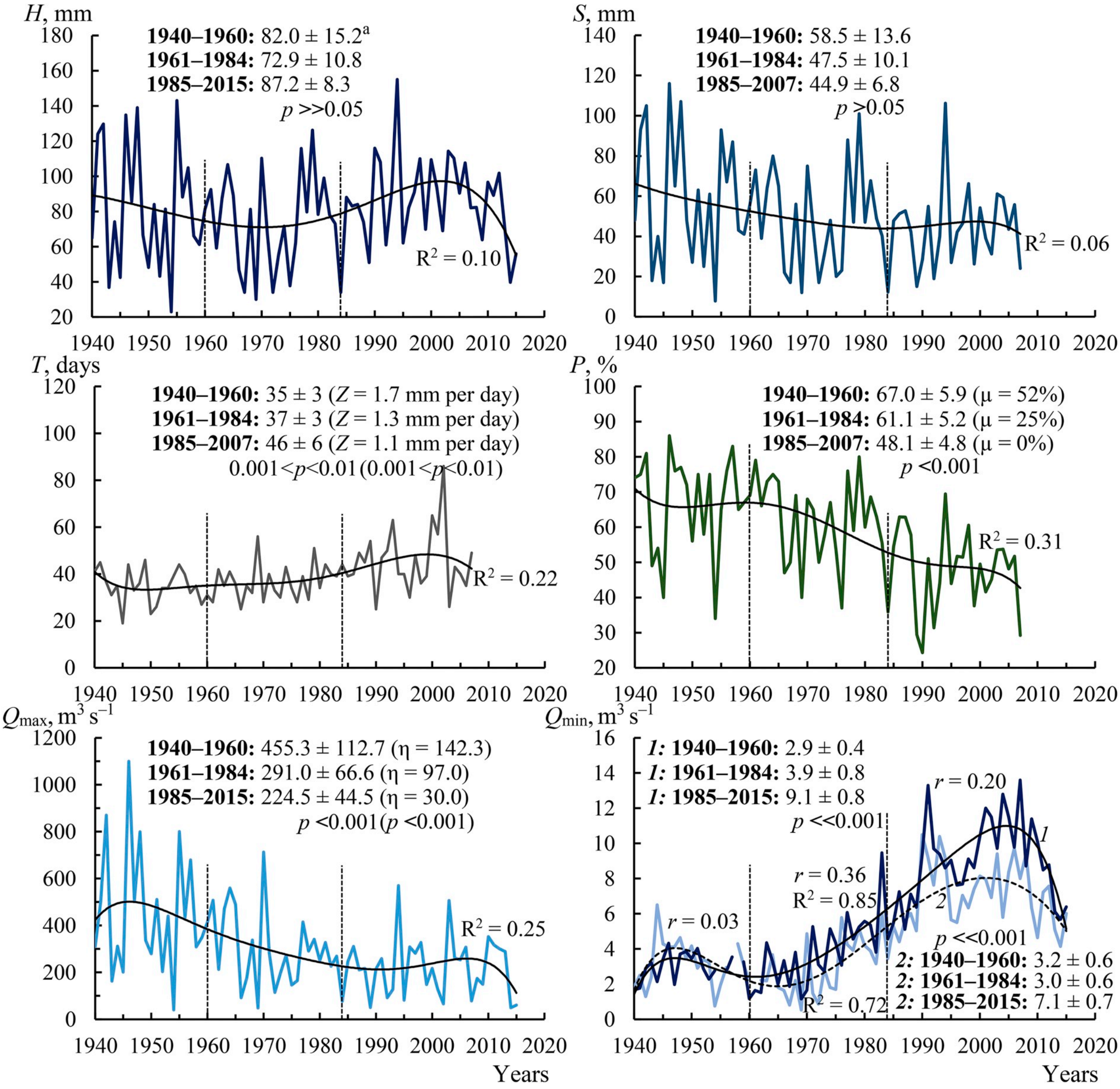

Fig. 6. The year-to-year changes in water flow of the Medveditsa River at the town of Lysyye Gory (the Saratov Oblast, European Russia, see Fig. 1) during 1940–2015. *r* – coefficient of linear correlation between Q_{max} and Q_{min} (*2*) (all the correlation coefficients are statistically insignificant, $p > 0.05$); *p* – the probability of statistically significant differences in the corresponding average values between 1940–1960 and 1985–2007/2015 (the *t*-test). *Note.* No data on *S*, *T*, and *P* for 2008–2015 were available. [a] Hereinafter, a 95% confidence interval. Other symbols see Fig. 4.

reaches of the river (at the city of Balashov) this tendency was established earlier, before 1940 (Fig. 4).

3.1.2. The changes in the Medveditsa River basin

1. In this river basin the similar tendencies were preserved, in general, over the three periods: 1940–1960, 1961–1984, and 1985–2015. There, water runoff depth for the spring (snowmelt-induced) flood decreased between 1940–1960 and 1985–2008 by 1.3 times at Lysyye Gory (Fig. 6), and by 1.4 times at Archedinskaya (Fig. 5). The low-water-period water flow (judging by minimum discharges) increased (a statistically significant increase) in the river at these gauging stations by 3.1 times (for the winter period) and 2.2 times (for the river-ice-free period), and by 2.3 and 1.5 times, respectively. Consequently, the rate of increment of the low-water-period water flow for the river-ice-free period in this basin was less than in the adjacent basin of the Khopyor River.

2. There was also a noticeable (statistically significant) reduction in the maximum (per year) water discharge: it decreased by about 2.0 times between 1940–1960 and 1985–2015. This, among other things, led to a decrease in the general intra-annual unevenness of the river water flow (η) by almost 4.7 times at Lysyye Gory (Fig. 6), and by 3.1 times at Archedinskaya (Fig. 5).

3. In contrast to the Khopyor River, an increase in duration of the spring (snowmelt-induced) flood water flow between 1940–1960 and 1985–2015 in the Medveditsa River was twice less: by 1.5 weeks at Lysyye Gory, and by 2 weeks at Archedinskaya. This fact, against the background of a decrease in water runoff depth for the spring (snowmelt-induced) flood, led to a reduction in the snowmelt-induced flood water flow intensity (*Z*) there by 41–44% between 1940–1960 and 1985–2008. If in 1940–1960 the average date of the beginning of the spring (snowmelt-induced) flood was (at Lysyye Gory) on 31 st March (as for the Khopyor River at Balashov), whereas in 1985–2008 – on 21 st March. The share of snowmelt-induced flood water runoff in the total annual water runoff of the river decreased (a statistically significant decrease) between these periods from 67–71% to 48–58%, respectively.

Table 2
Some quantitative characteristics of the year-to-year water flow variability of the studied rivers of European Russia during 1940–2015.

Rivers	Hydrological gauging stations at:	Characteristics of:				
		Linear trends		Spline trends		Rhythmicity[a]
		R^2	$\pm v$	R^2	N	
Q_{max}						
Khopyor	Balashov	0.27	−10.61	0.28	1.7	**2**, 4, 8, 12, 18
	Besplemyanovsky	0.25	−14.95	0.24	1.0	**2**, 3, 5, 12
Medveditsa	Lysyye Gory	0.21	−4.23	0.21	1.6	**2**, 3, 5, 8, 16
	Archedinskaya	0.15	−8.07	0.19	2.1	2, 4, 8, 16
Q_{min} (winter period)						
Khopyor	Balashov	0.64	+0.25	0.68	5.0	3, 4, 7, **13**
	Besplemyanovsky	0.49	+0.58	0.54	7.3	2, 4, **12**, 20
Medveditsa	Lysyye Gory	0.65	+0.12	0.83	7.5	3, 9, **14**
	Archedinskaya	0.53	+0.23	0.53	2.5	3, 4, 11
Q_{min} (river-ice-free period)						
Khopyor	Balashov	0.74	+0.24	0.85	7.4	3, 4, 13, **20**
	Besplemyanovsky	0.31	+0.32	0.44	6.1	3, 6, **12**, 21
Medveditsa	Lysyye Gory	0.45	+0.08	0.68	5.2	3, 7, **14**
	Archedinskaya	0.22	+0.13	0.49	4.7	3, **13**

R^2 – approximation coefficient for linear (spline) trends; $\pm v$ – rates of Q_{max} (Q_{min}) trend changes, ($m^3 s^{-1}$) per year; N – the number of degrees of freedom: the higher N, the greater the trend non-linearity. *Note.* All the linear trends of Q_{max} and Q_{min} for 1940–2015 have a great statistical significance ($p < 0.001$).

[a] The main rhythms, years (the rhythms with $p < 0.05$ are in bold).

4. In the upper reaches of the river (at Lysyye Gory), the average volumes of the winter water flow have exceeded the average volumes of low-water-period water flow for the river-ice-free-period approximately since 1958 (Fig. 6). This was especially evident in 2000–2010. In the lower reaches of the river this tendency manifested itself only after 2004 (Fig. 5).

3.1.3. *Other regularities*

Table 2 presents a number of characteristics of the long-term year-to-year variability in the maximum and minimum water discharges of the analyzed rivers. Its analysis allows identifying the following common regularities.

a The rate of trend changes in the maximum and minimum water discharges during 1940–2015 was the more significant, the lower the hydrological gauging stations are situated along the rivers. Especially large relative differences in these rates between the gauging stations were observed in dynamics of the minimum winter water discharges of both rivers, as well as in the rates of trend changes in the maximum water discharges of the Medveditsa River.

b The trend rates of the minimum water discharge changes in the rivers differed, in general, by the greatest non-linearity of growth, while in order to reduce the Q_{max} the trend rates had a character closer to linearity.

c The increase in the minimum water discharges occurred with a shift in their calendar dates: the minimum water discharges for the river-ice-free period had tended to shift towards earlier terms, whereas the minimum winter water discharges – towards later terms (Table 3).

d If the role of the short-period rhythms was more significant in the year-to-year variability of the Q_{max} time series, then the longer rhythms were stronger in the Q_{min} time series. For the time series of Q_{max} of the Khopyor River (at Besplemyanovsky and Balashov) and the Medveditsa River (at Lysyye Gory), short-wave oscillations were more characteristic up to 1980, of which a statistical significance had only the rhythm of 2 years. For the time series of Q_{min} (the winter period) of the Khopyor River and the Medveditsa River (at Lysyye Gory), and also Q_{min} (the river-ice-free period) of the Khopyor River (at Besplemyanovsky) and the Medveditsa River (at Lysyye Gory), only the rhythms of 12–14 years had a statistical significance, that began to manifest themselves after 1980.

e In the upper reaches of the rivers, the contribution of rhythmic components to the total year-to-year water flow variability was the smallest, less than 10%, whereas for the Q_{max} time series (with exception of the Khopyor River at Besplemyanovsky) the rhythmic components explained about 30% of their total year-to-year water flow variability.

f From the early period to the late one there were changes in abnormal intensity of the spring (snowmelt-induced) flood water flow (Z_{ab}): the number of positive (high) anomalies decreased, while the number of negative (small) anomalies, on the contrary, increased (Table 4). The reduction in the number of positive (high) Z_{ab} was more significant in the basin of the Khopyor River (1940–1966 – 5.2 anomalies for 10 years, 1994–2008 – 0.7 anomalies for 10 years) compared to the basin of the Medveditsa River (1940–1960 – 3.0 anomalies for 10 years, 1985–2008 – more than 0.8 anomalies for 10 years); the increase in the number of negative (small) anomalies was most noticeable, on the contrary, in the basin of the Medveditsa River. The highest Z_{ab}-values (≥ 2.0 mm per day) were timed to 1940–1966 in the basin of the Khopyor River, and the lowest Z_{ab}-values (≤ 0.2 mm per day) – to 1961–2008 in the basin of the Medveditsa River (Table 4).

3.2. *River suspended sediment yield changes*

The yield of suspended sediments that are primarily a product of soil (sheet), rill and gully erosion in interfluves, and also, to a much lesser extent, a product of lateral and vertical deformations of riverbeds (Gusarov, 2015; Gusarov and Maksyutova, 2019), had a steady downward tendency during the last decades in the basins of the Khopyor River and the Medveditsa River (Table 5). The suspended sediment yields of these rivers decreased by 3.6–3.8 times (a statistically significant reduction) between the 1960s–1970s and 2008–2015. In the basin of the Khopyor River this reduction was even more noticeable – by 4.8–5.4 times in 2008–2015 compared to 1930s–1960s. The yield in 1940–1950s was, on the average, even less than in the 1960s–1970s in the basin of the Medveditsa River at Lysyye Gory (Table 5). Over the last decades, there also was a decrease in the number of years with abnormally large yields of suspended sediments, and an increase – with abnormally small yields (especially in the basin of the Khopyor River) (Table 5). A visual representation of the suspended sediment yield changes is given by temporal changes in the index λ (Fig. 7). The higher

Table 3
The period-to-period changes in average calendar dates of the maximum (Q_{max}) and minimum (Q_{min}) water discharges of the Khopyor River and the Medveditsa River during 1940–2015.

Characteristics	Khopyor River at Balashov (monitoring periods)		
	1940–1966	1967–1993	1994–2015
Q_{max}	18 ± 3[a] April	16 ± 3 April	15 ± 3 April ($p > 0.05$)
Q_{min} (winter period)	31 ± 15 December	24 ± 14 January	20 ± 19 January ($p > 0.05$)
Q_{min} (river-ice-free period)	17 ± 8 September	19 ± 12 August	29 ± 12 August ($p \sim 0.01$)
	Medveditsa River at Lysyye Gory (monitoring periods)		
	1940–1960	1961–1984	1985–2015
Q_{max}	12 ± 3 April	6 ± 3 April	4 ± 3 April ($0.001 < p < 0.01$)
Q_{min} (winter period)	15 ± 12 December	22 ± 10 January	17 ± 11 January ($p < 0.001$)
Q_{min} (river-ice-free period)	17 ± 10 October	22 ± 16 September	10 ± 13 August ($p \ll 0.001$)

p – the probability of statistically significant differences in the corresponding average Q-values between the first and third monitoring periods (the t-test).
Note. In the presence of several minima in any analyzed year, the earliest minimum was taken into consideration.

[a] Hereinafter, a 95% confidence interval.

λ-values are noted, as a whole, for the Medveditsa River compared to the Khopyor River.

For a comparison, we present the data from the upper reaches of the Ilovlya River (a left tributary of the Don River) located between the basins of the Medveditsa River and the Volga River. There, at the village of Gvardeyskoye (50°39′00″N 45°24′00″E, the river basin area is 344 km^2), the following temporal dynamics in suspended sediment yield (W) was observed: until 1975 (according to 11-year monitoring) – $W = 18.0\,\mathrm{Mg\,km^{-2}\,y^{-1}}$, $\lambda = 9.5$ (Mg km^{-2} y^{-1})/(L s^{-1} km^{-2}), for 2008–2015 – $W = 1.4\,\mathrm{Mg\,km^{-2}\,y^{-1}}$, $\lambda = 1.2$ (Mg km^{-2} y^{-1})/(L s^{-1} km^{-2}).

A decrease in sedimentation rates on river floodplains of the region could be as a logical consequence of the mentioned reduction in sediment yields: for small rivers of the centre of the East European Plain these rates decreased by at least 5–7 times between 1963–1986 and 1986–2015 (Markelov et al., 2012).

3.3. *Estimation of erosion/sedimentation rate tendency within the small catchment studied*

In the sediment sections of the investigated dry valley bottom the Chernobyl-derived ^{137}Cs peaks, characterized the position of the sediment surface in 1986, are located either at the present-day sediment surface (section I) or at a relatively shallow depth (Fig. 8). The main bomb-derived ^{137}Cs peaks, characterized the position of the bottom sediment surface in 1963 and located at the depths of 21–24 cm, have remained only in the sediment sections I and III, although they probably were partly washed out there by concentrated episodic surface water runoff (Fig. 8). In the sediment section II the ^{137}Cs peak of 1963 could not be identified, since it was, apparently, washed out, being that the sediment section is located in the part of the dry valley bottom with a relatively large gradient. Based on the location of the ^{137}Cs peaks of 1963 and 1986 in the sediment sections I and III, we can suppose a significant decrease (at least 4–5 times in terms of sediment thickness) of the mean annual sedimentation rates in the dry valley bottom after 1986 compared to 1963–1986. In the sediment section I any deposits

Table 4
The period-to-period changes in the abnormal mean intensity of spring (snowmelt-induced) flood water runoff (Z_{ab}) in the basins of the Khopyor River and the Medveditsa River (European Russia, see Fig. 1) during 1940–2008.

River basin (basin area)	Monitoring periods	Years (Z_{ab}, mm per day)	
		≥1.00	≤0.30
Khopyor River at Besplemyanovsky (44,900 km^2)	1940–1966	**1941** (1.65), **1942** (2.49), 1945 (1.04), **1946** (1.52), 1947 (1.16), **1948** (2.05), **1951** (1.51), 1953 (1.42), 1955 (1.27), 1957 (1.64), 1959 (1.06), 1961 (1.00), **1963** (1.78), 1964 (1.77) $Z_{av} = 1.52 \pm 0.22$[b]; $f = 5.2$	1954 (0.23[a]) $f = 0.4$
	1967–1993	1968 (1.48), 1970 (1.17), 1977 (1.06), **1979** (1.80), 1981 (1.47) $Z_{av} = 1.40 \pm 0.26$; $f = 1.7$	**1972** (0.24), **1984** (0.22), **1989** (0.28) $Z_{av} = 0.25 \pm 0.03$; $f = 1.0$
	1994–2008[c]	2006 (1.68) $f = 0.7$	2004 (0.20) $f = 0.7$
Medveditsa River at Archedinskaya (33,700 km^2)	1940–1960	**1941** (1.57), **1942** (1.54), **1946** (1.37), **1948** (1.93), **1951** (1.02), 1956 (1.27) $Z_{av} = 1.45 \pm 0.25$; $f = 2.9$	Absent
	1961–1984	**1963** (1.35), **1964** (1.20), **1979** (1.15) $Z_{av} = 1.23 \pm 0.12$; $f = 1.3$	1967 (0.28), 1969 (0.10), **1972** (0.14), 1973 (0.26), 1983 (0.30), **1984** (0.13) $Z_{av} = 0.20 \pm 0.07$; $f = 2.5$
	1985–2008[c]	1994 (1.90), 2003 (1.85) $Z_{av} = 1.88 \pm 0.05$; $f = 0.7$	**1989** (0.18), 1992 (0.15), 1995 (0.20), 2001 (0.26), 2002 (0.30), 2007 (0.14) $Z_{av} = 0.21 \pm 0.05$; $f = 2.5$

Z_{av} – average Z_{ab} for the corresponding period, mm per day; f – Z_{ab}-frequency for the corresponding period, events per 10 years.
Note. Years coinciding in Z_{ab}-categories in the basins are in bold.

[a] The smallest spring (snowmelt-induced) flood surface water runoff over the entire monitoring period (1940–2008) was observed in this year.

[b] Hereinafter, a 95% confidence interval.

[c] No data for 2009–2015 are available.

Table 5
The period-to-period changes in the mean annual suspended sediment yield (*W*) of the Khopyor River and the Medveditsa River (European Russia, see Fig. 1) from the 1930s to 2015.

Khopyor River at Balashov			
Monitoring periods	1939–1966[a]	1967–1975	2008–2015
Average *W*, kg s^{-1}	4.3 ± 1.1[b]	2.7 ± 1.2	0.8 ± 0.5
p			$p_1 < 0.001$ $p_2 \sim 0.05$
Years with abnormally large *W* for this river ($\geq 6\ \text{kg s}^{-1}$)	1941, 1942, 1951, 1955, 1957, 1961, 1963, 1964	Absent	Absent
Years with abnormally small *W* for this river ($\leq 1\ \text{kg s}^{-1}$)	1954	1967, 1969	2008, 2009, 2011, 2014, 2015
Khopyor River at Besplemyanovsky			
Monitoring periods	1935–1966[c]	1967–1975	2008–2015[d]
Average *W*, kg s^{-1}	8.7 ± 2.1	6.8 ± 2.5	1.8 ± 0.6
p			$p_1 \ll 0.001$ $0.001 < p_2 < 0.01$
Years with abnormally large *W* for this river ($\geq 10\ \text{kg s}^{-1}$)	1941, 1951, 1953, 1955, 1957, 1963, 1964	1968, 1970	Absent
Years with abnormally small *W* for this river ($\leq 2.5\ \text{kg s}^{-1}$)	Absent	1972	2008, 2010, 2011
Medveditsa River at Lysyye Gory			
Monitoring periods	1940–1954[e]	1963–1975	2008–2015
Average *W*, kg s^{-1}	1.8 ± 0.6	3.6 ± 1.6	1.0 ± 0.5
p			$p_1 > 0.05$ $0.001 < p_2 < 0.01$
Years with abnormally large *W* for this river ($\geq 3\ \text{kg s}^{-1}$)	1946, 1953	1963, 1964, 1965, 1968, 1970, 1973	Absent
Years with abnormally small *W* for this river ($\leq 0.5\ \text{kg s}^{-1}$)	1943, 1945, 1954	1969	2008, 2014, 2015

The probability of statistically significant differences in the corresponding average *W*-values (the *t*-test): p_1 – between the first and third monitoring periods, p_2 – between the second and third monitoring periods.

Note. The relatively large average *W* of the Medveditsa River (12.6 $\text{Mg km}^{-2}\ \text{y}^{-1}$ in 1950–1975, 4.3 $\text{Mg km}^{-2}\ \text{y}^{-1}$ in 2008–2015) is partly because the interfluve surface of the left-bank part of its basin is composed by predominantly better eroded loess sediments of the Late Pliocene, whereas the surface of the right-bank part of the basin, as well as the entire basin of the Khopyor River (6–8 $\text{Mg km}^{-2}\ \text{y}^{-1}$ in 1950–1975, 1.3–1.8 $\text{Mg km}^{-2}\ \text{y}^{-1}$ in 2008–2015) are mainly represented by comparatively worse eroded loamy-sandy and loamy sediments of the Early Eopleistocene (Map of Quaternary Formations …, 2010).

[a] For 1939, 1941, 1942, 1944, 1947, 1950–1966.

[b] Hereinafter, a 95% confidence interval.

[c] For 1935–1941 and 1946–1966.

[d] Without 2009.

[e] For 1940–1941, 1943, 1945, 1946, and 1949–1954.

did not accumulate after 1986 at all (as a resultant of potential sedimentation/erosion ratio there). In the sediment section III, taking into account the difference in the mean densities of different thicknesses of the sediment, the sedimentation rates in terms of the specific gravity were 7.5 $\text{kg m}^{-2}\ \text{y}^{-1}$ in 1963–1986 (the average density is 962 kg m^{-3}) and 1.17 $\text{kg m}^{-2}\ \text{y}^{-1}$ in 1986–2017 (726 kg m^{-3}), that is, they have reduced by 6.4 times. The relatively deep position of the also expected ^{137}Cs peaks of 1959 in the sediment sections I and III with reference to the ^{137}Cs peaks of 1963 indicates a higher (almost 4-fold) rate of accumulation of sediment (erosion soil materials) washed down from the cultivated hillslopes in 1959–1963 compared to 1963–1986. In other words, at least since the late 1950s there has been a general steady tendency to decrease the sedimentation rates within the dry valley bottom (and, consequently, the hillslope erosion rates) of the studied small catchment in the basin of the upper reaches of the Medveditsa River.

3.4. Erosion modelling results

The erosion change modelling was carried out at Lomonosov Moscow State University (Litvin et al., 2017). The model block of rainfall-induced erosion was based on the worldwide-known Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978) that had previously been deeply modernized and adapted to the environmental conditions of the East European Plain. The snowmelt-induced erosion block of the modelling was used based on the re-worked erosion model of the Russian State Hydrological Institute (Guide for …, 1979). According to the results of this modelling, there was the following reduction in the total soil losses between 1980 and 2012–2014 in those administrative regions of European Russia, where the studied river (sub)basins are located (Fig. 1): the Penza Oblast – 55.3%, the Saratov Oblast – 41.7%, the Volgograd Oblast – 31.7%, the Tambov Oblast – 24.0%, and the Voronezh Oblast – 8.7%.

4. Discussion

The totality of the above-mentioned hydrological and erosion changes unambiguously indicates the temporal dynamics of factors controlling these changes. Considering the environmental conditions in the studied region, alteration in climate and human (primarily agricultural) activities could lead to such changes. The influence of changes in climate and land use/cover on water flow and soil erosion rates has been demonstrated in many parts of the globe (Ivanova et al., 1996; Fu et al., 2000; Kosmas et al., 2000; MacDonald et al., 2000; Lach and Wyżga, 2002; Van Rompaey et al., 2002; Asselman et al., 2003; Korytny et al., 2003; Poesen et al., 2003; Yang et al., 2003; Mozzherin and Kurbanova, 2004; Nearing et al., 2004; Owens, 2005; López-Moreno et al., 2006; Van Rompaey et al., 2007; Bakker et al., 2008; Cebecauer and Hofierka, 2008; Guo et al., 2008; Wyżga, 2008; Gonzalez-Hidalgo et al., 2009; Keesstra et al., 2009; Kozak, 2009; Zorn and Komac, 2009; García-Ruiz, 2010; García-Ruiz et al., 2010; Baumann et al., 2011; Dolgov, 2011; Du and Walling, 2012; Liu et al., 2012; Wyżga et al., 2012; Lu et al., 2013; Spalević et al., 2013; Zhao et al., 2013; Latocha et al., 2016; Wyżga et al., 2016; Borrelli et al., 2017; Catchment …, 2017; Golosov et al., 2017b; Panagos et al., 2017b; Gao et al., 2018; Nilawar and Waikar, 2018; Woldesenbet et al., 2018; Zhao et al., 2018;

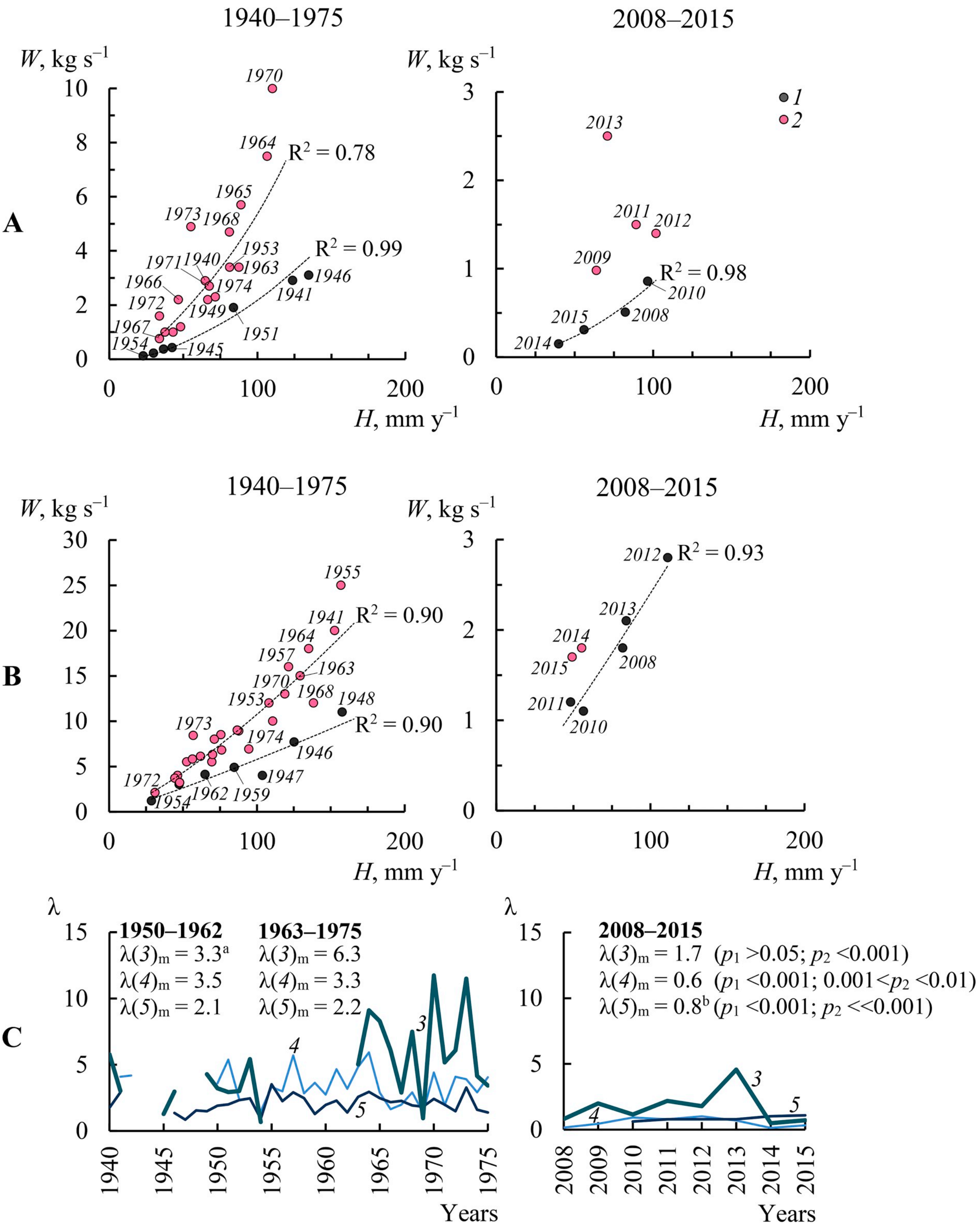

Fig. 7. The period-to-period variability of the relationship between the mean annual suspended sediment yield (*W*) and the total annual depth of the basin surface water runoff (*H*) in the Medveditsa River at the town of Lysyye Gory (the Saratov Oblast, European Russia) (A) and the Khopyor River at the village of Besplemyanovsky (the Volgograd Oblast, European Russia) (B) during 1940–2015.*1* (*2*) – years of relative weakening (activization) of the total soil-rill-gully + riverbed erosion in the river basins; R^2 – coefficient of power trend approximation; *1940*, *1941* … – monitoring years; λ – the ratio between average specific suspended sediment yield and average specific surface water runoff in the river basins – modular average specific suspended sediment yield (Mg km^{-2} y^{-1})/(L s^{-1} km^{-2}) (C); $\lambda(3)_m$, $\lambda(4)_m$, and $\lambda(5)_m$ – the λ-values averaged over the periods for the Medveditsa River (at Lysyye Gory), the Khopyor River (at Balashov), and the Khopyor River (at Besplemyanovsky), respectively. *Note-1.* The graphs (A) and (B) have no data for the following years: the Medveditsa River – 1942, 1944, 1947, 1948, 1955–1962; the Khopyor River – 1942–1945, 2009; *Note-2.* The average λ-values between the following periods differ with probability (the *t*-test): p_1 – 1950–1962 and 2008–2015, p_2 – 1963–1975 and 2008–2015. *Note-3.* The relatively small λ-values for the Khopyor River at Besplemyanovsky (see C) may also be owing to 3–6 times larger the area of its basin. [a] For 1949–1954. [b] No data for 2009 are available.

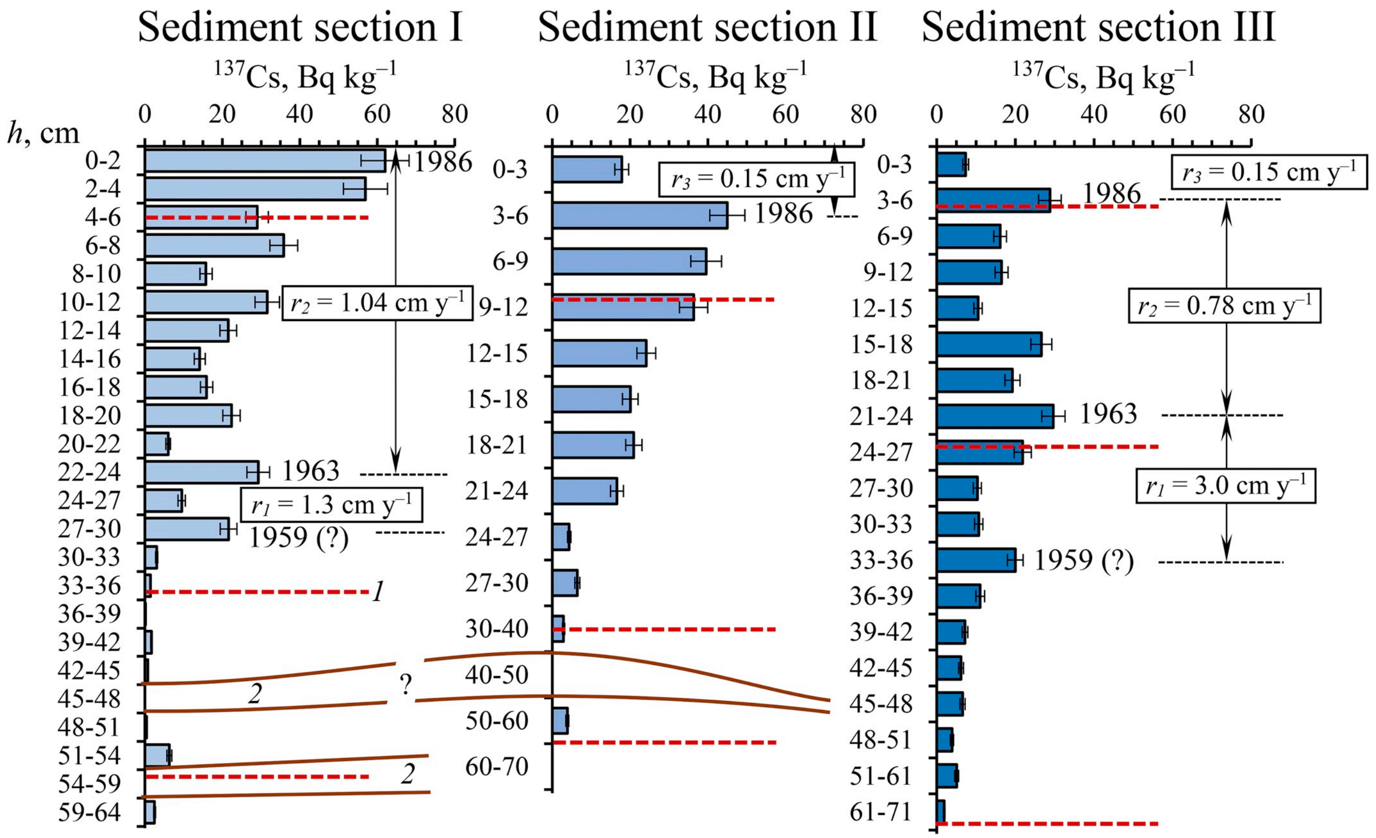

Fig. 8. The vertical ^{137}Cs distribution in the sediment sections (I, II, and III) within the bottom of the studied dry valley "Srednyaya" (the Atkarsk administrative district of the Saratov Oblast, European Russia, see Figs. 1 and 2) according to Gusarov et al. (2018c). *h* – depths of sampling; the average rates of sedimentation during the following periods: r_1 – 1959–1963, r_2 – 1963–1986, r_3 – 1986–2017; *1* – the boundaries of sediment layers distinguished by features of their grain size composition; *2* – the sediment strata with about zero ^{137}Cs concentration. *Note.* The ^{137}Cs concentrations in the studied sediment sections at the depths > 64–71 cm up to the maximum depths of sampling are close (or equal) to zero, and therefore they are not shown in the diagrams.

and others).

Due to a number of methodological difficulties (especially insufficient knowledge of the influence of the depth of soil freezing on water flow and erosion intensity, lack of data on the temporal dynamics of crops in the studied river (sub)basins, and so on) at this stage of the study, we cannot give an accurate estimate of the impact (contribution) of climate and land use/cover on these changes over time, as was done, for example, for the Huangfuchuan watershed on the northern Loess Plateau (China), where sediment load had been reduced by 70.5% during 1990–2012 compared to the baseline period of 1955–1989 (Zhao et al., 2018). According to these authors, human activities accounted for an average of about 94% of the total decline in sediment load there, whereas climate change contributed about 6%. Below we present only a qualitative assessment of the climate/land-use(cover) influence, that given separately for these two leading factors.

4.1. Climate and climate-induced changes

4.1.1. The changes in snowmelt water runoff

The modern climate change within the territory of European Russia was expressed over the last decades, first of all, in the stable positive temperature trend, especially in the winter and spring seasons (Maracchi et al., 2005). Hereinafter we give the data from the weather station in the town of Oktyabrsky Gorodok (see Supplementary Table 1), that is closest to the studied small catchment of the dry valley "Srednyaya" (Fig. 1). Simultaneously, the soil temperature in the region increased in the same period (Table 6), that contributed to a decrease in the depth of soil freezing at the end of the cold (winter) season of year before the snowmelt time. The temperature regime and the depth of freezing of soils have a significant effect on the snowmelt water runoff formation. This conclusion is consistent with the Barabanov's rule (Barabanov, 1993) of limiting factors of snowmelt surface water runoff: at a certain (limiting) value of one of the factors (depth of soil freezing, air temperature or water storage in snow) the surface water runoff is not formed, regardless of the importance of other factors. According to observations at the experimental drainage sites of the Scientific Research Institute of Agriculture of the South-East (the Saratov Oblast), the surface water runoff from cultivated lands and compacted autumn ploughs during the snowmelt time in 1973–1982 was, respectively, 10 and 34.5 mm, and decreased up to 1.3 and 9.1 mm in 2004–2014 (Medvedev et al., 2016). According to the data of field monitoring in 1959–2016 on some experimental stations located in the western and central parts of the forest-steppe and steppe landscape zones of the East European Plain (Barabanov et al., 2018a), there was also reduction in the surface water runoff coefficient during the spring snowmelt period from 0.3 to 0.5 in 1960–1970s up to 0.01–0.05 in 2000–2010s. The influence of the depth of freezing of soils on the surface water runoff formation is also confirmed by modelling and other field experiments (Gray et al., 1985; Ge et al., 2011; Li et al., 2012; Fouli et al., 2013; Koren et al., 2014; and others). This reduction in the snowmelt water runoff on interfluve hillslopes was naturally reflected in the the above-noted decrease of the river snowmelt flood water flow and its intensity, in the maximum annual water discharges in rivers of the region. Moreover, the increase in snowmelt-induced flood duration in the rivers studied (Figs. 4 and 6) also indicates the decrease in the surface water runoff intensity on interfluve hillslopes during the snowmelt time (see Supplementary material 'Flood flow intensity and erosion').

The similar tendency of decrease in the water discharges during the

Table 6

The period-to-period changes in average 10-day-period soil temperatures (°C) at different depths at the weather station in the town of Oktyabrsky Gorodok (51°38′09″N 45°27′19″E, the Tatishchevo administrative district, the Saratov Oblast, European Russia, see Fig. 1) during the spring months of 1963–2011.

Month (10-day period of the month)	Monitoring periods	Soil depths		
		20 cm	80 cm	160 cm
April (first)	1963–1986	1.11 (35)	0.12 (58)	0.83 (17)
	1987–2011	1.16 (32)	0.78 (32)	1.75 (0)
		p » 0.05	$p \sim 0.05$	$0.001 < p < 0.01$
March (third)	1963–1986	−1.03 (75)	−0.85 (75)	0.52 (33)
	1987–2011	−0.31 (60)	0.19 (36)	1.58 (4)
		$p > 0.05$	$0.001 < p < 0.01$	$p < 0.001$

p – the probability of statistically significant differences in the corresponding average values between the monitoring periods (the t-test).
Note. The proportion of years (in % of available data) with negative mean soil temperature is in parentheses.

spring (snowmelt-induced) floods over the last decades has also been found in the Baltic countries (Estonia, Latvia, and Lithuania) (Sarauskiene et al., 2015), as well as in eastern Scandinavia (Arheimer and Lindström, 2015), Poland, Belarus, and in the north of Ukraine (Kaczmarek, 2003).

On the other hand, the redistribution of snowmelt surface water runoff into underground water runoff is reflected in the increase in the low-water-period water discharges during the river-ice-free period (especially in May, June, and July). The increase in river water flow in the winter over the last decades was a consequence of thaws that have increased in frequency in the East European Plain (Frolova et al., 2015). The above-mentioned significant decrease in the intra-annual unevenness of river water flow in the studied (sub)basins, especially sharp since the 1990s, was one of the hydrological consequences of global warming in the region, began in the late 1970s. The same situation is observed practically throughout the entire basins of the Don River and the Volga River (Frolova et al., 2015).

The sharp reduction in the rates of erosion and its products (river suspended sediments, sediments accumulated in bottoms of dry valleys, etc.) over the last decades was closely associated with the decrease in surface snowmelt water runoff on hillslopes of the (sub)basins. Thus, according to observations at the experimental drainage sites of the Scientific Research Institute of Agriculture of the South-East (the Saratov Oblast), the earlier-mentioned decrease in the snowmelt water runoff led to reduction in the rate of soil erosion by 6.2 times (Medvedev et al., 2016). This fact, on the whole, was well consistent with the decrease in the rates of sediment accumulation in the dry valley bottom studied, according to our results. The rates of W-reduction noted earlier were somewhat less, that is, in our opinion, a consequence of a more complex structure and a larger area of river basins compared to the small catchments and, even more so, experimental sites. All this determines a more complex scheme for the delivery of sediments from hillslopes to the channels of small and, moreover, medium-size rivers in the forest-steppe and steppe environments of the East European Plain (Gusarov et al., 2019). A significant contribution to the decrease of the rates of erosion in the studied river basins has also been done by the reduction in the number of anomalies of snowmelt-induced water runoff since the early 1990s (Table 4).

4.1.2. *The changes in warm-season precipitation*

Estimating, even semi-quantitative, the contribution of heavy rainfalls to the above-mentioned dynamics of the erosion intensity for the entire studied region is currently difficult. This is owing to the high variability in directional changes in atmospheric precipitation in the forest-steppe and steppe zones of the region. So, in the Saratov Oblast over the warm season (April to October), the frequency of erosion-hazardous rainfalls (with the rainfall depth ≥ 30 mm) has grown in the last decades by 1.3 times compared to 1912–1980 (Levitskaya et al., 2015). Even if we take into consideration that such trend persists for the entire studied part of the basin of the Don River, as is observed, for example, in Central and Northern Europe (Mueller and Pfister, 2011; Fiener et al., 2013; Hanel et al., 2016), a hasty conclusion will be made about any significant increase in erosion activity in the warm season in the central part of the forest-steppe and steppe zones of the East European Plain caused by the following three assumptions. First, most erosion-hazardous rainfalls in the region happen in the summer months when the soil is more or less well covered with vegetation (including cultural one), and not each rainfall (sometimes even a heavy rainfall) can cause, in this connection, strong hillslope erosion and great sediment yield in the regional river network. Second, it is necessary to take into account that the rainfall erosivity in the most of Europe is higher compared to the East European Plain (Panagos et al., 2017a, 2017b). Third, as will be shown below, the area of cultivated lands in the studied (sub)basins has been decreased over the last decades; that fact means their conversion from potentially rainfall-erosion-dangerous lands to the category of almost safe ones. The abandoned lands with meadow or meadow-steppe vegetation strongly reduce a surface water runoff on interfluve hillslopes. The estimates of rainfall-induced soil erosion for May-to-September period, made using the modified Universal Soil Loss Equation (USLE), showed the following annual rates of soil losses: in the Saratov Oblast – 1.65 Mg ha^{-1} in 1980, and 1.55 Mg ha^{-1} in 2012; in the Voronezh Oblast – 2.96 Mg ha^{-1} in 1980, and 3.10 Mg ha^{-1} in 2012 (Sidorchuk et al., 2006; Golosov et al., 2018). In other words, the modelled erosion rates had changed little between 1980 and 2012.

As for the studied small catchment, there was the following situation with precipitation according to the weather station monitoring in the town of Oktyabrsky Gorodok (Fig. 1). Table 7 presents the distribution of April-to-October precipitation between two periods of 1966–2016: the average rainfall depth during one rainfall event for the most erosion-hazardous precipitation (≥ 30 mm) decreased over the last decades compared to 1966–1986. Moreover, the rainfalls giving the precipitation depth > 50 mm completely ceased: if in 1966–1986 there were only three of them (53.7 mm (20 th July 1966), 80.4 mm (1 st August 1976), 53.8 mm (27 th June 1985), repeating every 9–10 years, whereas during 1987–2016 these strong rainfalls were absent. In both monitoring periods, rainfalls with the precipitation depth of 40–50 mm were not recorded at all. In this regard, it is important to note that heavy precipitation (≥ 40 mm) is produced about 80% of total soil losses for the warm season according to year-to-year observations within slope catchments (Edwards and Owens, 1991; Gonzalez-Hidalgo et al., 2009; and others). Lu et al. (2013) indicated that every 1% change in precipitation has led to a 2%-change in sediment loads, and a 1.3%-change in water discharges. However, these quantitative calculations require the mandatory clarification for the steppe environment of the East European Plain. Some studies indicated that the impacts of rainfall intensity are even more important than rainfall amount (Shi and Wang, 2015; Tang et al., 2015; Wang et al., 2015; and others). Gully erosion, for example, is also adversely impacted by extreme rainfall (Dotterweich et al., 2003; Rodzik et al., 2009). Using the information

Table 7
The period-to-period distribution of precipitation (April to October) at the weather station in the town of Oktyabrsky Gorodok (51°38′09″N 45°27′19″E, the Tatishchevo administrative district, the Saratov Oblast, European Russia, see Fig. 1) during 1966–2016.

Rainfall depths, mm	Monitoring periods					
	1966–1986			1987–2016		
	Σ	*n*	Ω	Σ	*n*	Ω
In total	4426	2426.7	1.8	4354 (−1.6%)[a]	1858.3 (−23.4%)[a]	2.3 (+26.4%)[a], $p < 0.001$
< 10	3532	2374.8	1.5	3320 (−6.0%)	1792.7 (−24.5%)	1.9 (+26.7%), $p < 0.001$
10–20	555	41.4	13.4	718 (+29.4%)	53.3 (+28.7%)	13.5 (+0.1%), $p \gg 0.05$
20–30	148	6.2	23.9	237 (+60.1%)	10.0 (+61.3%)	23.7 (−0.8%), $p \gg 0.05$
30–40	100	2.9	34.5	78 (−22.0%)	2.3 (−20.7%)	33.9 (−1.7%), $p > 0.05$
40–50	No precipitation recorded					
> 50	89	1.4	62.6	0 (−100.0%)	0.0 (−100.0%)	0.0 (−100.0%), $p \ll 0.001$

Σ – the total April-to-October precipitation for 10 years in the corresponding period (mm per 10 years); *n* – the total amount of April-to-October rainfall events for 10 years in the corresponding period (units per 10 years); Ω – the average April-to-October rainfall depth for one rainfall event in the corresponding period (mm per one event); *p* – the probability of statistically significant differences in the average Ω-values between the monitoring periods (the *t*-test). *Note.* The contribution of precipitation with rainfall depths > 20 mm to its annual amount is 7.3–7.7% for both periods, or 0.4–0.7% in terms of the number of rainfall events.

[a] Relative change compared to 1966–1986.

from 1800 catchments in the USA and Canada, González-Hidalgo and co-authors (González-Hidalgo et al., 2013) concluded that the 25 largest daily precipitation events yielded 46–63% of the total sediment load.

In this region the overwhelming majority of precipitation, that form a surface water runoff, falls out during the summer months when soils, depending on structure of crops, are more or less protected by cultural vegetation. The results of analysis of satellite images of the studied territory, including the studied catchment, showed that before the beginning of the 1990s the harvest there had been removing from cultivated fields in the beginning and middle of August. It was in August (before 1986) that the mean monthly precipitation ≥30 mm was the highest in year, and had a statistically insignificant tendency to be reduced (Fig. 9). This circumstance could slightly contribute to (as an addition to the spring (snowmelt-induced) reduction) above-mentioned decrease in soil erosion. Since the early 1990s, the harvesting has been already carrying out in early September – the month when there was the statistically insignificant increase in this precipitation (with the depth of 30–40 mm). This circumstance, on the contrary, could slightly contribute to a certain increase in erosion of soils there in autumn, against the background of the general annual decrease in the rates of erosion. Consequently, the general long-term dynamics of precipitation with the depth of ≥30 mm, as a whole, could theoretically contribute to the general reduction in the intensity of erosion (including the soil losses) in the catchment area and, at least, adjacent areas. However, the statistical probability of this, according to the *t*-test, was small.

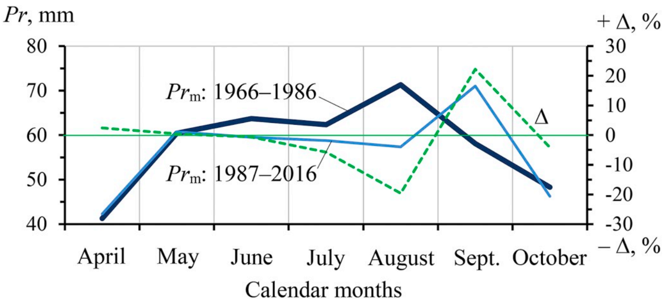

Fig. 9. The changes in April-to-October monthly precipitation (*Pr*, only years with monthly precipitation depth ≥30 mm) averaged over two periods (Pr_m) during 1966–2016, according to the data from the weather station in the town of Oktyabrsky Gorodok (51°38′09″N 45°27′19″E, the Tatishchevo administrative district, the Saratov Oblast, European Russia, see Fig. 1). ±Δ – relative changes in Pr_m between the periods. *Note.* The average Pr_m-values differ (the *t*-test) between both periods with $p \gg 0.05$ for all the months.

4.2. Human activity changes

4.2.1. The land cover changes

Since the late 1980s there were significant land cover changes in European Russia, that were intensified after the collapse of the USSR in 1991. These changes were manifested, above all, in a significant reduction in cultivated land area, especially in the Russia's administrative regions with inefficient agriculture (climate risk agriculture) in the forest zone (especially in the west of the zone), the dry steppe subzone, and the semideserts (the geographical region of the lower Volga River) (Fig. 10, Table 8). Within these administrative regions the cultivated lands occupied (less than 20–30% for 1970–1987) and currently occupy (less than 15–20% for 1996–2017) relatively small areas. In those administrative regions (oblasts) of European Russia, that include the basins of the Khopyor River and the Medveditsa River, the reduction in the total area of cultivated lands in 1996–2017 was 23–43% compared to the late Soviet Union's period (1970–1987): the greatest decrease in the cultivated land area was occurred in the Penza Oblast and the Volgograd Oblast (over 42%), the smallest decrease – in the Voronezh Oblast (Table 9, Fig. 10). Ivanov and co-authors (Ivanov et al., 2017), using the results of visual interpretation of multi-seasonal Landsat-5 and Landsat-8 images, found that in the basin of the upper reaches of the Medveditsa River upstream from the town of Atkarsk (the basin area is 3611 km^2), characterized by one of the most fertile soils in the region, the reduction of cultivated lands between 1985 and 2015 was 9.6% (from 68.5% to 61.9% of the basin area).

The reduction in the cultivated land areas was primarily owing to a significant decrease in croplands under cereals that occupied the dominant (53–68% in 1970–1987, 51–62% in 1996–2017) areas in the regional cultivated lands fund. The crops of annuals and perennials (except the Penza Oblast, the northernmost region located in the forest-steppe zone) were significantly reduced in area, but with a significant increase in the cultivated lands under sunflower crops in all these regions. The cultivated land area reduction was also primarily caused by the exclusion of erosion-hazardous areas from crop rotations, located on hillslopes with relatively large gradients. Taking into account the natural landscape conditions of the studied (sub)basins, the abandoned cultivated lands were converted to the category of meadows and meadow steppes with a well-developed sod with strong erosion resistance. On the abandoned lands snowmelt water runoff (as well as precipitation runoff) became almost completely redistributed into underground drainage water runoff (owing to the filtration). This fact, under the conditions of the above-mentioned decrease in the depth of soil freezing, provoked a significant decrease in maximum water discharges of rivers, total snowmelt-induced water runoff depth, and,

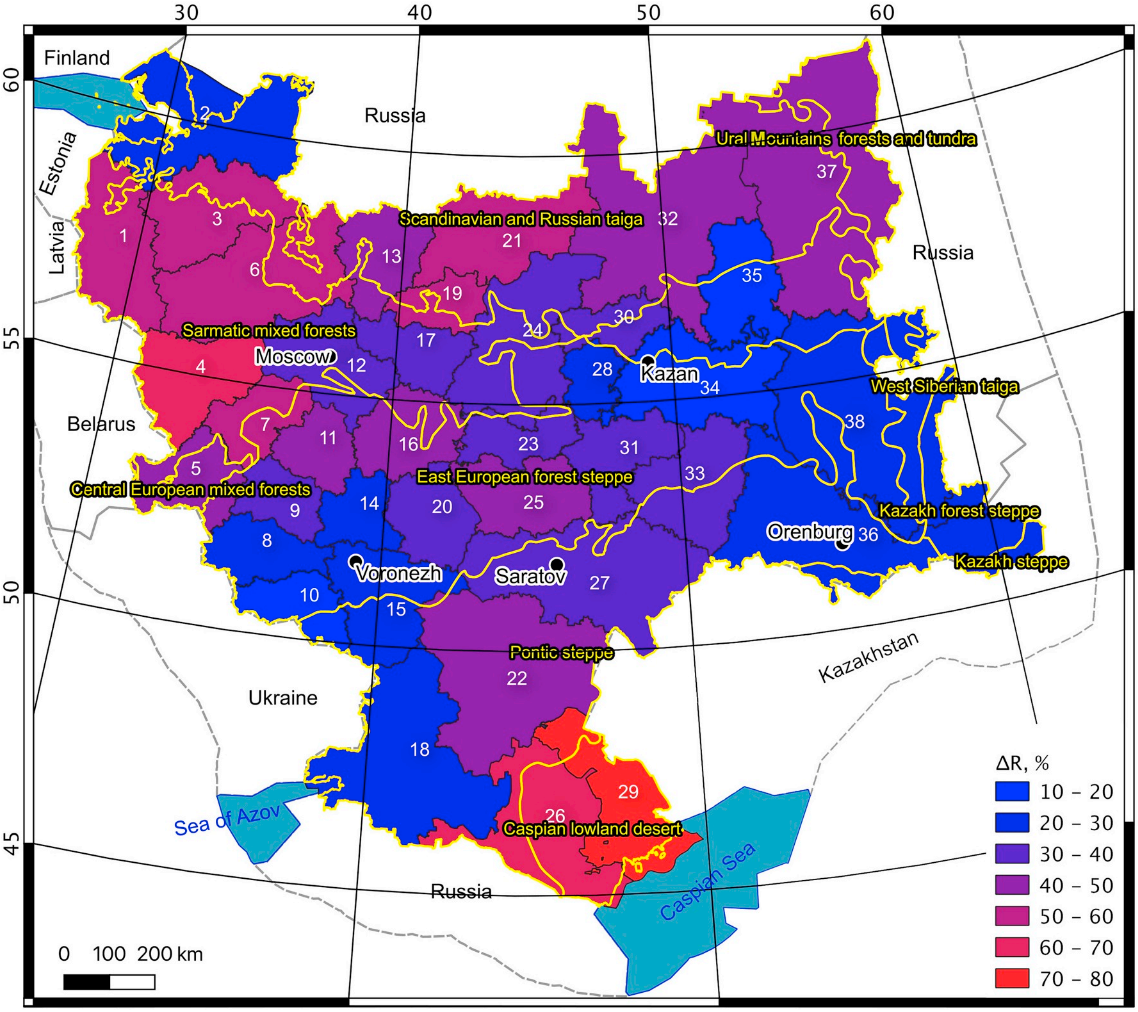

Fig. 10. The map of relative reduction (ΔR) in the total area of cultivated lands between the late USSR's period (averaged over 1970, 1975, 1980, 1985, 1986, and 1987) and the Russian Federation's period (1996–2017) within the most populated and agriculturally developed administrative regions of European Russia (without the Kaliningrad Oblast; according to the data from Agriculture of the USSR …,1988; and https://fedstat.ru). *The administrative regions of European Russia* (the names of the regions, where the studied river basins are located, are shown in bold): 1 – Pskov Oblast, 2 – Leningrad Oblast, 3 – Novgorod Oblast, 4 – Smolensk Oblast, 5 – Bryansk Oblast, 6 – Tver Oblast, 7 – Kaluga Oblast, 8 – Kursk Oblast, 9 – Orel Oblast, 10 – Belgorod Oblast, 11 – Tula Oblast, 12 – Moscow Oblast, 13 – Yaroslavl Oblast, 14 – Lipetsk Oblast, 15 – **Voronezh Oblast**, 16 – Ryazan Oblast, 17 – Vladimir Oblast, 18 – Rostov Oblast, 19 – Ivanovo Oblast, 20 – **Tambov Oblast**, 21 – Kostroma Oblast, 22 – **Volgograd Oblast**, 23 – Republic of Mordovia, 24 – Nizhny Novgorod Oblast, 25 – **Penza Oblast**, 26 – Republic of Kalmykia, 27 – **Saratov Oblast**, 28 – Chuvash Republic, 29 – Astrakhan Oblast, 30 – Mari El Republic, 31 – Ulyanovsk Oblast, 32 – Kirov Oblast, 33 – Samara Oblast, 34 – Republic of Tatarstan, 35 – Udmurt Republic, 36 – Orenburg Oblast, 37 – Perm Krai, 38 – Republic of Bashkortostan. *Note.* The boundaries of the landscape zones are given according to Olson et al. (2001).

Table 8
The changes in the total area of cultivated lands in different landscape zones of the East European Plain within European Russia between 1980 and 2012 (according to Golosov et al., 2017a).

Landscape zones	Area (× 10^3 ha) of cultivated lands in:		Changes in area, %
	1980	2012	
Forests (in total)	20,789.9	9222.1	−55.6
Forest-steppes	33,286.4	23,978.1	−28.0
Steppes	38,544.8	27,894.3	−27.6
In total	92,621.1	61,094.5	−34.0

therefore, a reduction in areas of active soil, rill and gully erosion, and erosion products (sediments) in river basins. It is known that the geomorphic response to land cover changes is non-linear: a small change in percentage of cultivated lands usually results in relatively large changes in erosion risk and sediment delivery. For example, a decrease in percentage of cultivated lands in a drainage basin by 5% may result in 8.5% lowering of mean annual soil erosion rate and as much as 13.5% lowering of sediment yield (Van Rompaey et al., 2003). However, this conclusion is valid for the plains of Western Europe, but needs to be seriously adjusted for the enviro-climatic conditions of the East European Plain, considering the winter freezing of soils and relatively long lengths of interfluve hillslopes in this region (especially in its southern half).

In addition, it should be noted that in the eastern part of the basin of the Don River (including the entire basin of the Medveditsa River), the reduction in the cultivated land areas was also continued over the last two decades. These areas decreased between 1996–2004 and 2005–2017 in: the Penza Oblast – by 16.9% (cereals – 22.4%), the Saratov Oblast – by 8.5% (20.4%), and the Volgograd Oblast – by 0.9% (12%). At the same time, in the western part of this river basin, on the contrary, there was a tendency (albeit weak) of restoring (increasing) the cultivated lands as a result of some improvement of the economic situation: the Tambov Oblast – by 3.9% (10.0%), the Lipetsk Oblast – by 2.5% (19.4%), and the Voronezh Oblast – by 0.5% (12.4%),

Table 9
The period-to-period changes in the area of cultivated lands in the European Russia's administrative regions where the studied river basins are situated

Characteristics (× 10^3 ha)	Administrative regions (oblasts) of:[a]				
	Saratov	Volgograd	Penza	Tambov	Voronezh
Region area	10,124	11,288	4335	3446	5222
Total area of cultivated lands	5830/3791	5192/2985	2388/1353	2211/1488	3142/2410
	−35.0%	−42.5%	−43.3%	−32.7%	−23.3%
Share of the total area of cultivated lands in the region area, %	57.6/37.4	46.0/26.4	55.1/31.2	64.2/43.2	60.2/46.2
Cereals	3938/2352	3225/1732	1495/729	1272/864	1655/1221
	−40.3%	−46.3%	−51.2%	−32.1%	−26.2%
Perennial crops[b]	267/227	218/93	186/232	160/86	159/152
	−15.0%	−57.4%	+24.9%	−46.5%	−4.6%
Annual crops[c]	495/145	641/101	188/76	197/49	233/119
	−70.7%	−84.2%	−59.6%	−75.1%	−48.8%
Crops of:					
Sunflower	287/706	183/574	32/101	100/255	224/400
	+146.3%	+213.6%	+217.1%	+155.0%	+78.7%
Potato	47/29	23/34	66/44	64/44	85/100
	−38.3%	+35.0%	−33.3%	−31.3%	+17.5%
Sugar beet	19/10	0/0.36	56/43	123/78	206/131
	−49.2%		−23.8%	−36.7%	−36.4%
Other crops	777/322	902/451	365/128	295/112	580/287
	−58.6%	−50.0%	−64.9%	−62.0%	−50.5%

Note. In numerator is the average area of cultivated lands during the late USSR's period (averaged over 1970, 1975, 1980, 1985, 1986, and 1987), in denominator is during the Russian Federation's period (averaged over 1996–2017); the percentage is relative change in the cultivated areas between these periods.

[a] See Figs. 1 and 10.

[b] Medicago sativa L., Onobrychis viciifolia, Agropýron, and others.

[c] Sorghum sudanense L., Setāria itālica, and others.

respectively.

As for changes in the land cover within the boundaries of the studied small catchment, our analysis of high-resolution Landsat images showed the following: in 1972–2001 the various crops (mainly spring ones) were sown in the catchment area, and in 2002–2014 there (as well as in adjacent small catchments) the role of perennials has increased (despite the general tendency of reduction in their areas in the Saratov Oblast, Table 9). The perennials, according to observations in some runoff experimental sites (Medvedev et al., 2016), well protect chernozem soils against erosion.

The above-mentioned changes in the structure of arable lands and their role in the regulation of hydrological and erosion processes are not unique to Europe at all (see Supplementary material ‘Examples from other regions of Europe’).

4.2.2. *The land use changes*

The sharp increase in suspended sediment yield in the basin of the Medveditsa River in 1963–1975 compared to 1940–1954 (Table 5) was not owing to an abnormal annual water runoff during this period. The annual water runoff was even the smallest in these years. In the second half of the 1960s and the first half of the 1970s there were planned processes of agricultural mechanization in the region, that became one of the significant factors of intensification of agrarian production in this period and subsequent years. From 1966 to 1974 the number of tractors in the Saratov Oblast increased by 24%, combine harvesters – by 33% (Necheporuk, 2013). The Saratov Oblast became a pioneer of introduction of new powerful tractors K-700 (“Kirovets”): 2456 units of K-700 were delivered only for 1965–1970. In the region, these heavy tractors were used on almost all types of fieldworks. More than 50% of agricultural transportation was accounted for just the K-700. As a result, by the early 1970s the grain production in state farms of the region was mechanized almost completely (Necheporuk, 2013). All these processes led, most likely, to activization of soil, rill and gully erosion in the croplands of the region through changes in a number of physical properties of regional soils. These changes were well demonstrated (Hammerová et al., 2013) by the example of loess chernozems of the Czech Republic. As a consequence, general washing-out of the soils was intensified and contributed to an increase in products of soil, rill and gully erosion in the rivers of the basin. The effects of these anthropogenic changes are clearly shown in Fig. 7. On the graph of the relationship between the mean annual suspended sediment yield and the annual water runoff depth of the Medveditsa River in the period before 1975 two scenarios (two curves) of erosion processes development in the river basin are identified: the years of relatively weakened erosion (mostly during the Second World War and the post-war years) – 1941, 1945, 1946, 1951, 1954 and others, and the years of relatively active erosion – predominantly the 1960s–1970s. Thus, the years that characterized by particularly high (with respect to the “normal” (for this scenario) functioning, described by a power-law curve of connection) sediment yield rates (rates of the total erosion), are distinguished in the last period: 1973 (+124.8%), 1972 (+67.7%), 1970 (+40.3%), 1965 (+15.4%), 1964 (+11.5%), and others. Indirectly, the human impact on the increase in river suspended sediment yield is indicated by the increase in the index λ in the 1960s and early 1970s (Fig. 7). The serious degradation in the agricultural mechanization, began in Russia since the years of political restructuring (1986–1991) and continued later, in the 1990s and early 2000s, led (together with the decrease in the areas of cultivated lands) to a significant decrease in anthropogenic stress on chernozem soils in the studied river basins. Moreover, the erosion intensity was also partially reduced by erosion control measures (including planted forests) carried out since the late 1970s and in the first half of the 1980s in the forest-steppe and steppe landscape zones of European Russia.

4.3. *Evidences from the neighboring river basins of the East European Plain*

a In the basin of the Sosna River at the city of Yelets (52°37′N 38°28′E, the basin area is 16,300 km^2), located in the northwestern part of the Don River basin (a right tributary of the Don River), generally the similar tendencies in water flow (runoff) and suspended sediment yield have been observed over the past 70 years (see Supplementary Table 2). In the basin of the Krasivaya Mecha River near the town of Yefremov (53°09′N 38°07′E, the basin area is 3240 km^2), located northward the basin of the Sosna River, in the extreme northwest of the Don River basin, the following temporal dynamics of suspended sediment yield (*W*) was recorded: in

1965–1975 – $W = 29.0\,\mathrm{Mg\,km^{-2}\,y^{-1}}$, $\lambda = 6.9$ $(\mathrm{Mg\,km^{-2}\,y^{-1}})/(\mathrm{L\,s^{-1}\,km^{-2}})$, in 2008–2015 – $W = 3.7\,\mathrm{Mg\,km^{-2}\,y^{-1}}$, $\lambda = 0.6$ $(\mathrm{Mg\,km^{-2}\,y^{-1}})/(\mathrm{L\,s^{-1}\,km^{-2}})$ ($p < 0.001$). Within the Lipetsk Oblast and the Orel Oblast (Figs. 1 and 10) where the Sosna River basin is located the cultivated land areas decreased from 1970–1987 to 1996–2017, on the average, by 24.6% and 30.1%, respectively. Within the Tula Oblast (Figs. 1 and 10) where the Krasivaya Mecha River flows this decrease was 44.0%. These facts again point to the common reasons for the erosion tendencies throughout the basin of the Don River.

b The reduction in erosion intensity and suspended sediment yields is also noted in the zone of mixed and broad-leaf forests of the western part of the plain. In the basin of the Desna River at the city of Chernigov, Ukraine (51°30′00″N 31°18′00″E, the basin area is 81,400 $\mathrm{km^2}$, or 91.6% of the total area of the river basin (the part of the Dnieper River basin, the southwest of European Russia, and the north of Ukraine) there was the following temporal dynamics in sediment yield in the second half of the twentieth century: 1949–1960 – $495.7 \pm 85.0 \times 10^3\,\mathrm{Mg\,y^{-1}}$, 1961–1970 – $432.9 \pm 73.6 \times 10^3\,\mathrm{Mg\,y^{-1}}$, 1971–1980 – $393.6 \pm 87.5 \times 10^3\,\mathrm{Mg\,y^{-1}}$, 1981–1990 – $481.5 \pm 134.0 \times 10^3\,\mathrm{Mg\,y^{-1}}$, and 1991–2000 – $250.0 \pm 50.7 \times 10^3\,\mathrm{Mg\,y^{-1}}$. The sharp decrease in the sediment yield after 1991 had the same reasons as those that have been discussed earlier. For example, in two administrative regions of European Russia, where the upper reaches of the Desna River basin are located, the cultivated land areas decreased even more significantly compared to the Don River basin: in the Bryansk Oblast the total cultivated land area had been reduced from 1970–1987 to 1996–2017 by 41%, including the cereals area – by 57%; in the Smolensk Oblast – by 60% and 75%, respectively (Fig. 10).

c The significant hydrological/erosion changes also occurred over the last decades in the basin of the Bolshoy Karaman River (a left tributary of the Volga River) at the village of Sovetskoye (51°27′N 46°44′E, the basin area is 3470 $\mathrm{km^2}$), flowing in the eastern (the Trans-Volga Region) part of the Saratov Oblast, within the steppe zone of the East European Plain (see Supplementary Table 3).

d In the basin of the Samara River (a left tributary of the Volga River) at the village of Yelshanka (the basin area is 22,800 $\mathrm{km^2}$, within the boundaries of the Orenburg Oblast (Fig. 10), the European Russia' east, the steppe Cis-Ural), we also note a reduction in suspended sediment yield over the last 30 years compared to 1940–1960 at least twice. This tendency is confirmed by the decrease in the rates of accumulation of washed-out soil material in the dry valley bottom of one of the small catchments of this basin: from 1959–1986 to 1986–2016 the rates decreased there at least by 3.0–3.6 times (Gusarov et al., 2018b; Gusarov and Sharifullin, 2019). There was also the decrease in the total cultivated land area from 1970–1987 to 1996–2017 by about 28% (including the cereals area – by 40.3%) in the Orenburg Oblast.

The tendencies of reduction in the snowmelt-induced water runoff and average annual rates of erosion and sedimentation have been traced over the last decades practically throughout the forest-steppe zone, as well as in the northern and eastern parts of the steppe landscape zone of the East European Plain (Golosov et al., 2011; Apukhtin and Kumani, 2012; Golosov et al., 2012; Markelov et al., 2012; Komissarov and Gabbasova, 2014; Golosov et al., 2017a, 2017b; Gusarov et al., 2018a, 2018c; Medvedeva, 2018; Platoncheva, 2018; Sharifullin et al., 2018; Gusarov and Sharifullin, 2019; and others). Most likely, these changes were representative for the entire chernozems zone of European Russia and Ukraine, and also have manifested themself in the south of the forest zone (the southern taiga) of the East European Plain's east (Rysin et al, 2017a, 2017b; Gusarov et al., 2018a). With the proceeding climate change and modern economic development trends in Russia, these tendencies can be continued there in the next decade at least.

In addition to the reduction in erosion/sedimentation intensity, some other environmentally-positive consequences of the above-mentioned hydrological changes in the studied region could potentially take place in the studied (sub)basins (see Supplementary material 'Other likely environmentally-positive consequences').

5. Conclusion

The above-foregoing allows us to make the following main inferences.

1. In the northeastern part of the Don River basin, the (sub)basins of the Khopyor River and the Medveditsa Rivers, located in the forest-steppe and steppe landscape zones of the centre of the East European Plain (within European Russia), there was the well-marked tendency to reduce the intra-annual unevenness of river water flow caused by the decrease in the spring (snowmelt-induced) flood water flow in 1940–2015 (by 1.2–1.4 times between 1940–1960 (1966) and 1985 (1994)–2015), and the more significant increase in water flow during the low-water-flow periods of year (the increase in minimum (the winter and river-ice-free-periods) water discharges by 2.5–3.5 times in the Khopyor River basin, and by 1.5–3.1 times – in the Medveditsa River basin). It was accompanied by the increase in the duration of snowmelt-induced flood flow with the decrease in its intensity, year-to-year anomalousness and contribution to the total annual water flow of the rivers. The reported changes well reflect the general tendency in the intra-annual redistribution of river water flow in the southern half of the East European Plain over the last decades (Frolova et al., 2015).

2. The suspended sediment yields of the rivers decreased by 3.6–3.8 times between the 1960s–1970s and 2008–2015; in the basin of the Khopyor River this decrease was even more noticeable compared to 1930s–1960s – by 4.8–5.4 times. These changes in the yield of suspended sediments, that are a product of mainly soil, rill and gully erosion in interfluves, clearly show the current downward tendency of the common erosion intensity in the studied river (sub)basins. This conclusion is well consistent with dynamics of sedimentation rates within the dry valley bottom of the studied catchment located in the basin of the upper reaches of the Medveditsa River. There, the rates were significantly (at least 4–5 times) decreased after 1986 compared to 1963–1986.

3. The main reasons for the above-mentioned hydrological and erosion/sedimentation changes over the recent decades were climate change (the decrease in the depth of soil freezing during the snowmelt period caused by the increase in temperature of the atmospheric air mainly in the winter and spring seasons (Park et al., 2014), the increase in the winter thaws frequency (Frolova et al., 2015), etc.) and human activity changes (the reduction in cultivated land area, especially noticeable in the 1990s and early 2000s, the reduction in agricultural machinery, and partly anti-erosion measures in the late 1970s and early 1980s, and so on).

4. The reduction in erosion/sedimentation intensity over the last decades is widely noted in many regions of the temperate climate zone of Eurasia – from Wales (Du and Walling, 2012) to the south of Eastern Siberia (Korytny et al., 2003).

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Conflicts of interest

The author declares no conflict of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2019.03.057.

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