Science of the Total Environment 719 (2020) 134770

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

The response of water flow, suspended sediment yield and erosion intensity to contemporary long-term changes in climate and land use/cover in river basins of the Middle Volga Region, European Russia

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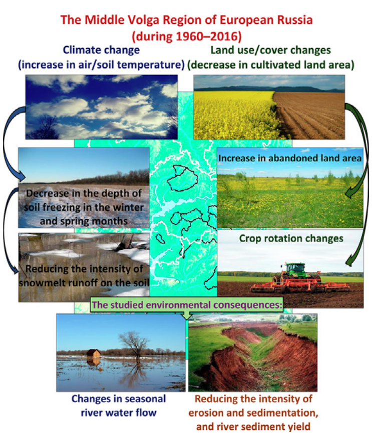
HIGHLIGHTS

- River water/sediment flow changes during 1960–2016 were investigated in the Middle Volga Region.
- The main objects of the study are 14 small and medium-size rivers with basin areas from 237 to 12,000 km^2.
- There was a trend of significant decrease in intra-annual irregularity of the water flow of the rivers.
- There also were downward trends in erosion intensity and river suspended sediment yield.
- The main reasons for these trends were changes in climate and cultivated land area.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 23 April 2019
Received in revised form 2 September 2019
Accepted 29 September 2019
Available online 14 November 2019

Editor: Ralf Ludwig

Keywords:
Snowmelt runoff
Flood
Soil freezing
Soil erosion
Cultivated land
East European Plain

ABSTRACT

The Middle Volga Region is one of the most populated and agriculturally developed geographic regions of the East European Plain within European Russia, where noticeable changes in climate and land use/cover were observed since the 1980s and the early 1990s respectively. The long-term year-to-year (trend) variability (during mainly 1960–2016) in water flow and suspended sediment yield of 14 small and medium-size rivers in the Middle Volga Region was analyzed in the paper. It is shown that in all the studied rivers there was a statistically significant decrease (on average, by 77.2 ± 4.5%) in the intra-annual irregularity of the water flow between 1960–1979 (as a baseline period) and 2002–2016 (the period of the greatest relative climate change in the region). This decrease was caused by a statistically significant reduction in the water flow during the snowmelt period (on average, by 37.4 ± 9.8%) and by an increase in the water flow during the low-water (baseflow) seasons – during the winter months (by 145.2 ± 57.6%) and the river-ice-free period (by 94.9 ± 39.7%). The intensity of snowmelt-induced flood flow has also statistically significantly decreased (by 40.4 ± 8.2%). At the same time, a reduction in the river suspended sediment yield was more significant – by 27.9 ± 26.9 times; it was the result of great changes in soil/rill/gully erosion intensity in the region. This reduction is confirmed by an analysis of sedimentation rates within one of the small (dry valley) catchments in the north of the studied region over the past 60 years. The changes in climate (chiefly a decrease in the depth of freezing of the soil during the snowmelt period, mainly April) and land use/cover, associated basically with reduction in cultivated land area (especially in the

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https://doi.org/10.1016/j.scitotenv.2019.134770

1990s, after the collapse of the Soviet Union), are considered to be as the main reasons for the aforementioned trends that were characteristic in general for almost the entire southern half of European Russia.

1. Introduction

In Eastern Europe, the last decades were characterized by noticeable climate change (Maracchi et al., 2005; The Fifth Assessment Report, 2014; Park et al., 2014; Shmakin and Popova, 2006; Popava and Polyakova, 2013; Shvidenko and Schepaschenko, 2013; Madsen et al., 2014; Park et al., 2014; The Fifth Assessment Report, 2014; Ashabokov et al., 2017; Perevedentsev et al., 2018; and others) that affected, *inter alia*, the inter- and intra-annual redistribution of water flow of rivers of the region. Since the early 1980s, in the greater part of the East European (Russian) Plain there is a general increase in the river water flow. Its intra-annual redistribution manifested itself in significant 'degradation' of snowmelt-induced flood (i.e., a decrease in the proportion of snowmelt-induced flood water flow in the total annual water flow of the rivers). This 'degradation' was caused by an increase in winter air temperatures, as well as in the number and duration of thaws, that resulted in a reduction in pre-spring water reserves in the snow, a decrease in maximum snowmelt-induced water discharges of the rivers (Dolgov, 2011; Blöschl et al., 2017; Frolova et al., 2017).

The snowmelt-induced flood 'degradation' in the plain was most marked in the basin of the Don River, and in the east of the Volga River basin (Frolova et al., 2015), where the share of snowmelt-induced water flow was reduced to 50% or less of the annual water flow, despite the fact that in the first half of the twentieth century this share was, on average, about 60–70% there. The 'degradation' of snowmelt-induced floods over the recent decades was also found in the western part of the forest landscape zone of the plain, in the Baltic countries (Sarauskiene et al., 2015). All these changes in the river water flow reflect significant changes in water runoff on interfluve slopes of the region. These hydrological and climate changes are likely to have affected current rates of soil-rill-gully erosion on the plain, since they reflect, first of all, the redistribution of surface and underground water runoff in terms of changing the depth of freezing of the soil due to global warming. It is important to note that the soil(sheet)-rill-gully erosion occurring in the snowmelt period (March–April) and rainfall season (May to October) is the main factor of present-day soil degradation within cultivated land of the East European Plain (Krasilnikov et al., 2016). Moreover, the impact of these changes on erosion processes in regional river basin geosystems was complemented by changes in land use/cover after the collapse of the Union of Soviet Socialist Republics (the USSR) in 1991: a reduction in the area of cultivated land (as the most erosion-dangerous area in river basins of the region), especially noticeable in the 1990s and the early 2000s, primarily in (sub)regions with inefficient (risky) agriculture in the forest landscape zone (Golosov et al., 2017a).

The research team from Lomonosov Moscow State University, Russia (Litvin et al., 2017), estimated probable erosion changes for administrative regions of European Russia using erosion models. According to this modelling, in the Middle Volga Region as one of the most populated and agriculturally developed geographic regions of European Russia, the overall relative decrease in soil losses in 2012–2014 had been estimated in the range of 34.7–58.5% compared to 1980. With these model assessments, there are almost no representative results of long-term field observations on the current rates of soil-rill-gully erosion in this region, that could have confirmed the model results. Some attempts to assess the overall direction of erosion intensity development over the past decades in the Middle Volga Region and adjacent regions were made earlier on river suspended sediment yield (Bobrovitskaya, 1996; Dedkov et al., 1997), as well as on the dynamics of the regional network of gullies (Stupishin et al., 1980; Butakov et al., 1987; Gully Erosion, 1990; and others). Despite all the scientific importance of these studies, the results obtained from them are outdated, because they characterize erosion-dynamic changes until the 1990s, before the period of the most active changes in both climate and land use/cover in the region (especially since 1991, after the collapse of the USSR). We also note that soil erosion surveys that used to carry out on a regular basis in the Soviet Union, have not been organized in the region over the last decades. Those not numerous modern works that based on field research were local (Medvedev et al., 2016; Sharifullin et al., 2018; Gusarov et al., 2018b,c; and others). In the recent years, the first attempts have been made to analyze the modern linear erosion network dynamics (rills and gullies) using remote (Medvedeva, 2018; Platoncheva, 2018; Sharifullin et al., 2019) and other instrumental (Gafurov et al., 2018; Sharifullin et al., 2019) methods in a number of test small catchments of the Middle Volga Region. Due to insufficiently representative either early or modern data, the results of these works are frequently contradictory regarding other field studies and the dynamics of factors controlling erosion processes. All of the above allows to suggest that the knowledge of the direction of the soil-rill-gully erosion development on modern cultivated lands in the Middle Volga Region in the changing climate and land use/cover is not complete and not systematized. The knowledge is also relevant because the Middle Volga Region had been earlier estimated (Dedkov and Mozzherin,1996) as the most erosion-prone region of the East European Plain (at least within European Russia).

Study purpose. The purpose of this study is, firstly, to identify general tendencies of changes in river water flow, soil erosion (more precisely – soil, rill, and gully erosion in general) and its products (river suspended sediment yield, and, as a complement, accumulated sediment) during the last 60 years within one of the most populated and agriculturally developed geographic regions of the East European Plain – in the Middle Volga Region, on the example of some river basins of this region, using the river-basin approach to research; secondly, to assess the principal reasons for these tendencies.

2. Study region

The study region is the territory in the middle reaches of the Volga River, the largest river in Europe in terms of water discharges and drainage basin area, within the boundaries of five administrative regions of European Russia – the Chuvash Republic, Republic of Tatarstan, Ulyanovsk Oblast, Samara Oblast, and Orenburg Oblast (its northwestern part) (Fig. 1). The northernmost part of the study region is located in the southernmost part of the southern subzone of mixed (coniferous-deciduous) forests of the taiga, the central and southern parts – in the forest-steppe and steppe landscape zones of the temperate climate zone within the East European Plain, characterized by the medium degree of ploughing up of land. The relief of the study region is the alternation of lowlands and uplands. The interfluve surfaces of the Volga Upland (the maximum height is about 380 m) and the Bugulma-

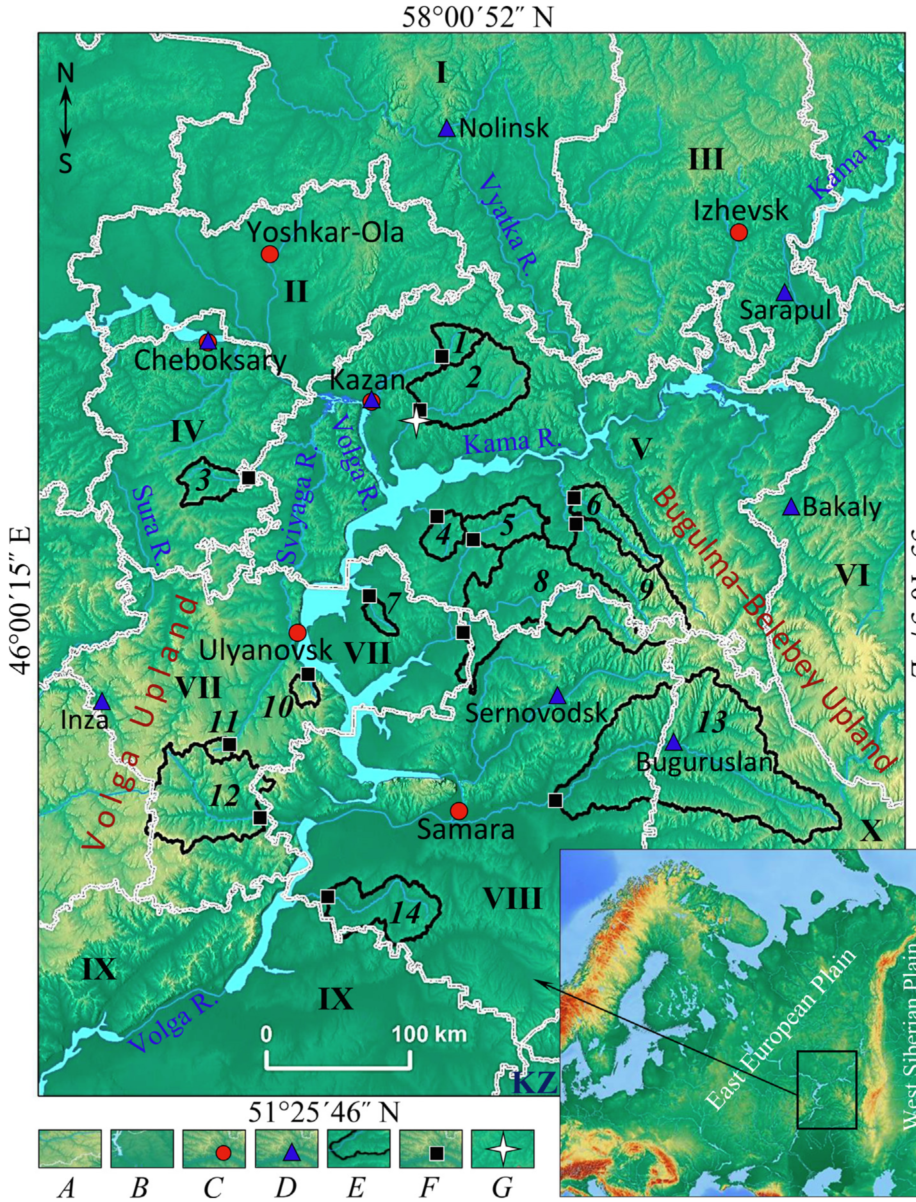

Fig. 1. Location of the study region in the East European (Russian) Plain within European Russia (DEM according to http://maps-for-free.com). *A* – uplands; *B* – lowlands and river valley reservoirs; *C* – regional capital cities; *D* – weather stations; *E* – borders of the investigated basins (see Table 1) of: *1* – Kazanka River at Arsk, *2* – Myosha River at Pestretsy, *3* – Kubnya River at Chuteyevo, *4* – Aktai River at Karavayevo, *5* – Maliy Cheremshan River at Abalduyevka, *6* – Kichuy River at Utyashkino, *7* – Krasnaya River at Krasnaya Reka, *8* – Bolshoy Cheremshan River at Novocheremshansk, *9* – Sheshma River at Sloboda Petropavlovskaya, *10* – Tushonka River at Sergeyevka, *11* – Sviyaga River at Koromyslovka, *12* – Syzranka River at Repyovka, *13* – Bolshoy Kinel' River at Timashevo, *14* – Chagra River at Novotulka; *F* – streamflow gauging stations; *G* – the catchment of the studied dry valley Temeva Rechka; KZ – the Republic of Kazakhstan. *The administrative regions of the Russian Federation:* I – Kirov Oblast, II – Mari El Republic, III – Udmurt Republic, IV – Chuvash Republic, V – Republic of Tatarstan, VI – Republic of Bashkortostan, VII – Ulyanovsk Oblast, VIII – Samara Oblast, IX – Saratov Oblast, X – Orenburg Oblast.

Belebey Upland (the maximum height is 479 m) (Fig. 1) are composed by rocks of marine origin of the Perm period in the north, and the Cretaceous and Paleogene periods in the south. In the prevailing territory, the surface of the aforementioned ancient marine deposits is overlapped mainly by relatively-small-thickness deluvium loams of the Quaternary (Map of Quaternary Formations, 2010). The Lower Trans-Volga Region (the area between the above-mentioned uplands) with dominant heights from 80 m to 150 m is predominantly the Volga River palaeo-valley (coinciding with one of the regional tectonic troughs of the Russian platform) composed mainly by clay-to-sandy estuary-lake and alluvial sediments of the Neogene and Quaternary. The zonal soils in the study region are predominantly *Greyic Phaeozems Albic* and *Chernozems*.

3. Materials and methods

3.1. 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 gauging stations) and erosion intensity (by using river suspended sediment yield according to hydrological observations at gauging stations, and, additionally, accumulation rates of sediment within one of the small (dry valley) catchments of the study region) was served as a general approach to the study. This approach is based on the river-basin principle of assessment.

3.2. Hydrological data analysis

3.2.1. Information sources

The data on river water flow and suspended sediment yield were available from the State water cadastres (collections) of the USSR (until 1978 – under the title "Surface Water Resources of the USSR"); Russian State Water Register (http://voda.mnr.gov.ru); the Automated information system of state monitoring for water bodies (Federal Agency for Water Resources of the Ministry of Natural Resources and Environment of the Russian Federation) – http://gmvo.skniivh.ru, and other sources. Despite the various sources of information, all the data analyzed are the result of long-term observations conducted by the Hydrometeorological Service of the former USSR and now the Russian Federation, according to a uniform state monitoring program.

3.2.2. Studied rivers

The main objects of the study are 14 small and medium-size rivers in the Middle Volga Region (Table 1, Fig. 1). The total (average) area of the basins of the studied rivers is 37,007 (2643 ± 1681) km^2; their average absolute height is 168 ± 22 m; the average (for 1960–2016) annual depth of surface water runoff in the basins – 129.8 ± 23.4 mm y^{-1}.

3.2.3. River water flow

The long-term year-to-year variability in river water flow (mainly from 1960 to 2016) and suspended sediment yield (1935/1940–1975 and 2002/2008–2016) in the studied basins was analyzed using the data from 14 streamflow gauging stations (Table 1, Fig. 1). The data on the water flow were collected according to the following main characteristics: total annual depth of the surface water runoff (*H*, mm); depth of spring (snowmelt-induced, March-April) flood water runoff (*Q(f)*, mm); spring (snowmelt-induced) flood duration (*D*, days); a share of the spring (snowmelt-induced) flood water runoff in the total annual water runoff in the river basins ($P = (Q(f)/H) \times 100$, %); maximum (once-only per year) water discharge (Q_{max}, m^3 s^{-1}) timed to the spring (snowmelt-induced) flood period; minimum (once-only per year) water discharges (Q_{min}, m^3 s^{-1}) during the baseflow seasons: for the winter months (from December to February) and the river-ice-free period (open-water conditions, mainly from mid-April to November).

Three hydrological monitoring periods in water flow series (1960–1979, 1980–2001, and 2002–2016) were identified 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) and the "Changepoint" package (Killick and Eckley, 2014) in the statistical analysis and programming environment R (R Core Team, 2017). The period of 1960–1979 was taken as a baseline period characterizing the dynamics of hydrological and erosion processes before the onset of the most noticeable current climate change in the region. The period of 1980–2001 is considered as a transition period to the period of 2002–2016, the period of the greatest climate change in both the Middle Volga Region and the Russian Plain as a whole. These three monitoring periods identified in the *H*-variability series were also extrapolated to series of all the above-mentioned characteristics of water flow, as well as suspended sediment yield.

In addition, the following characteristics of water runoff (flow) were calculated for each identified period: the mean intensity of the spring (snowmelt-induced) flood water runoff ($Z = Q(f)/D$, mm per day); the percentage of years with $P \geq 70\%$ – μ; the dimensionless ratio between Q_{max} and Q_{min} (for the river-ice-free period) – η.

3.2.4. River suspended sediment yield

The data on mean annual suspended sediment yield (*W*, kg s^{-1}, or Mg km^{-2} y^{-1}) were available only for 9 gauging stations. According to Stok Nanosov (1977), the average error in estimating the mean annual values of the yield in gauging stations in the former USSR was 8–10%. It is probable that it could have somewhat increased in the last decades. The analyzed *W* time series, in contrast to the water flow time series, were intermittent (Table 2). Additionally, for the Kazanka River and Myosha River (see Fig. 1) the suspended sediment yield was also analyzed for April (the spring (snowmelt-induced) flood period), the month with the highest water/sediment flow during a year in this region.

In any river basin, with very rare exceptions, there is no accumulation of all products of water erosion destruction of rocks and the soil composed its surface. Some part of the products moves with river water flow outside a basin, forming the so-called 'transit river erosion (more widely – mechanical) denudation', i.e. the total mass of erosion denudation products excluding their intra-basin accumulation (products of the so-called 'local denudation') (Dedkov and Mozzherin, 1984). The transit river (erosion) denudation

Table 1
The analyzed rivers, their streamflow gauging stations (SGS) (see Fig. 1), and river basin characteristics.

Rivers	SGS at:	SGS codes[a]	*F*, km^2	H, m	*H*, mm y^{-1}
Aktai	The village of Karavayevo, 55°05′43″N 49°50′21″E[b]	77201	690	132	99.1
Bolshoy Cheremshan	The village of Novocheremshansk, 54°22′19″N 50°09′06″E	77212	6050	143	112.1
Bolshoy Kinel'	The village of Timashevo, 53°19′33.6″N 51°10′45.4″E	77292	12,000	165	103.1[c]
Chagra	The village of Novotulka, 52°39′53.64″N 48°45′14.86″E	77336	2550	107	37.9[c]
Kazanka	The town of Arsk, 56°04′48″N 49°52′12″E	77166	650	159	166.3
Kichuy	The village of Utyashkino, 55°12′46″N 51°19′39″E	77189	1330	185	169.4
Krasnaya	The village of Krasnaya Reka, 54°33′59″N 49°07′41″E	77209	311	120	90.7
Kubnya	The village of Chuteyevo, 55°17′19″N 47°46′18″E	77164	930	153	121.3
Maliy Cheremshan	The village of Abalduyevka, 54°57′09″N 50°15′57″E	77217	1230	144	119.5
Myosha	The village of Pestretsy, 55°45′00″N 49°40′12″E	77197	3230	150	170.0
Sheshma	The village of Sloboda Petropavlovskaya, 55°03′35″N 51°21′43″E	77179	3110	205	156.7
Sviyaga	The village of Koromyslovka, 53°37′05″N 47°43′35″E	77138	237	246	220.0[d]
Syzranka	The village of Repyovka, 53°08′59″N 48°05′10″E	77329	4380	220	110.9[c]
Tushonka	The village of Sergeyevka, 54°03′34″N 48°30′55″E	77210	309	227	127.0

F – river basin area, H – the mean absolute height in the corresponding river basin, *H* – the annual (averaged for 1960–2016) 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 the SGS.
[c] For 1960–2015.
[d] For 1960–1995.

Table 2
The years of observation for suspended sediment yield (mean annual values) in the studied rivers of the Middle Volga Region (see Fig. 1).

Rivers	SGS at:	Years of observation
Bolshoy Kinel'	The village of Timashevo	1950–1961, 1965–1985, 1993–1995, 2000–2005, 2007–2015
Chagra	The village of Novotulka	1965–1976, 1978–1984, 2008–2015
Kazanka	The town of Arsk	1960–1985, 1989, 1992–2000, 2002–2016
Kichuy	The village of Utyashkino	1963–1982, 1984–1985, 1992–2012
Krasnaya	The village of Krasnaya Reka	1967–2013, 2015–2016
Myosha	The village of Pestretsy	1960–1985, 1988–1990, 1992–1994, 2001–2016
Sviyaga	The village of Koromyslovka	1963–1995
Syzranka	The village of Repyovka	1963–1975, 2008–2016
Tushonka	The village of Sergeyevka	1967–1995, 2008–2016

SGS – streamflow gauging stations (see Table 1).

influences (along with other mechanical denudation agents, as well as chemical denudation) on an average height of the basin and, along with tectonic movements, determines the general direction of development (ascending, descending or uniform) of its relief. The ratio between the products of the local and transit denudation varies depending on specific geological, geomorphological, climatic, and landscape conditions of river basins. Consequently, the sediment yield of rivers is one of the objective indicators of of erosion activity (more broadly, mechanical denudation) in their basins. The prevailing part of suspended sediment yield consists of soil-rill-gully erosion products delivering from interfluves, as observed, for example, in Eastern Europe (Dedkov and Mozzherin, 1984, 1996; Mozzherin and Kurbanova, 2004; Gusarov, 2015).

It should always be borne in mind that sediment yield cannot serve as an absolute measure of all erosion products due to the complicated (and not finally defined) mechanism of sediment delivery from erosion areas to riverbeds, which depends on a large set of factors (geological structure, morphometry and morphology of slopes, density of permanent and temporary streams, basin area, climatic characteristics, features of natural landscapes and the nature of their anthropogenic transformation, etc.) (Baartman et al., 2013; Belyaev et al., 2004; Catchment, 2017; De Rose et al., 2004; Dedkov, 2004; De Vente et al., 2007; Fryirs, 2013; Foerster et al., 2014; Golosov, 2006; Heckmann and Schwanghart, 2013; Heckmann et al., 2018; Koiter et al., 2013; Larsen et al., 2016; Sidorchuk, 2018; Preston and Dikau, 2004; Walling, 1983; Walling et al., 2001; and others). It was shown by some examples from the forest-steppe zone of the East European Plain (Gusarov et al., 2019a): not more than 1/3 of sediment mass mobilized on hillslopes reaches river floodplains. Thus, before reaching the channels of constant streams (creeks and rivers), a significant part of sediments (formed due to surface runoff on the hillslopes) first of all redistributes along the slopes themselves, in dry valleys (their sides and bottoms) and river valley sides within the upper links of fluvial networks with no permanent watercourses, and only then it goes directly to creeks/rivers (as a streamflow sediment yield). It is especially important to take into account when assessing the spatial heterogeneity of erosion intensity. However, when assessing the variability of the intensity of erosion within any one river basin for different time intervals (the temporal dynamics of sediment yield in relation to one gauging station), the importance of sediment yield as an indicator of the temporal dynamics of erosion (mechanical denudation) in this basin increases markedly. The sediment yield is widely used, despite a number of methodological flaws, in world practice to assess the temporal variability of erosion intensity (mechanical denudation) in fluvial systems of various scales (Bobrovitskaya, 1996; Dedkov et al., 1997; Walling et al., 2003; Bakker et al., 2008; Keesstra et al., 2009; Fuchs et al., 2011; De Girolamo et al., 2015; Gao et al., 2015; Shi and Wang, 2015; Sun et al., 2016; Vercruysse et al., 2017; and others). One of the main advantages of sediment yield for assessing the dynamics of erosion processes in fluvial geosystems is its integral character for rather large areas (river basins), that is important for studies at regional and global scales.

3.2.5. Statistical significance

To identify statistically significant differences in average values of the analyzed hydrological characteristics between the separated monitoring periods, the Student's *t*-test was used as fairly simple, but informative. All the average values were calculated with a 95% confidence interval for each monitoring period.

3.3. Field study

3.3.1. The small catchment studied

The results of field studies, previously carried out by us (Sharifullin et al., 2018; Gusarov et al., 2018a) outside of this research within one of the small catchments in the northern part of the study region, were used only to confirm the general current trends in erosion intensity, that are identified by river sediment yield dynamics.

The catchment of the dry valley Temeva Rechka is located in the basin of the Myosha River (F = 4180 km^2, a right tributary of the lower Kama River), 39 km south-eastward from the centre of the city of Kazan (Fig. 1), not far from the gauging station in Pestretsy. According to morphometric characteristics, the catchment is representative (an area, average height), almost representative (a height amplitude) or unrepresentative (an average slope) for the entire Myosha River basin. The length of the dry valley Temeva Rechka (within the analyzed site) is 1635 m (with a hollow in the upper reaches – 2087 m), the catchment area is about 1.13 km^2, the area of the dry valley is 0.19 km^2, the bottom area within the dry valley is 0.031 km^2, the average bottom gradient is 0.03. The average height of the catchment is 161 m, the height amplitude within the catchment is 74 m (Sharifullin et al., 2018). The relief of the catchment is a fragment of the denudation (middle-level) surface of levelling of the Eopleistocene age (the highest parts of local interfluves), passing lower into the deluvium-solifluction flat (up to 5°) surface of interfluve slopes of the Middle Pleistocene age (Butakov, 2003). The soil cover of the catchment surface in its upper parts is represented by *Greyic Phaeozems Albic* with clay/heavy-loamy texture, that has deluvium-solifluction sediments of the Late Quarter as soil-forming rocks. The average humus content in this soil is 3–4%. The current long-term level of soil erosion is evaluated to be moderate (Yermolaev et al., 2007). The catchment is located in the northern part of the forest-steppe landscape zone of the temperate climate zone. The indigenous plant formations of interfluve spaces are represented mainly by linden (mixed with oak, maple, and elm) forests (6% of the total catchment area), alternating with natural meadows, now significantly modified by man, that is expressed in a high modern tillage there (77% of the total catchment area) (Fig. 2).

3.3.2. Sediment sampling

Four sediment sections (Fig. 2) were dug up at the dry valley bottom during field work in the summer 2015. Their depths ranged from 57 to 70 cm. Sediment samples were taken layer-by-layer in

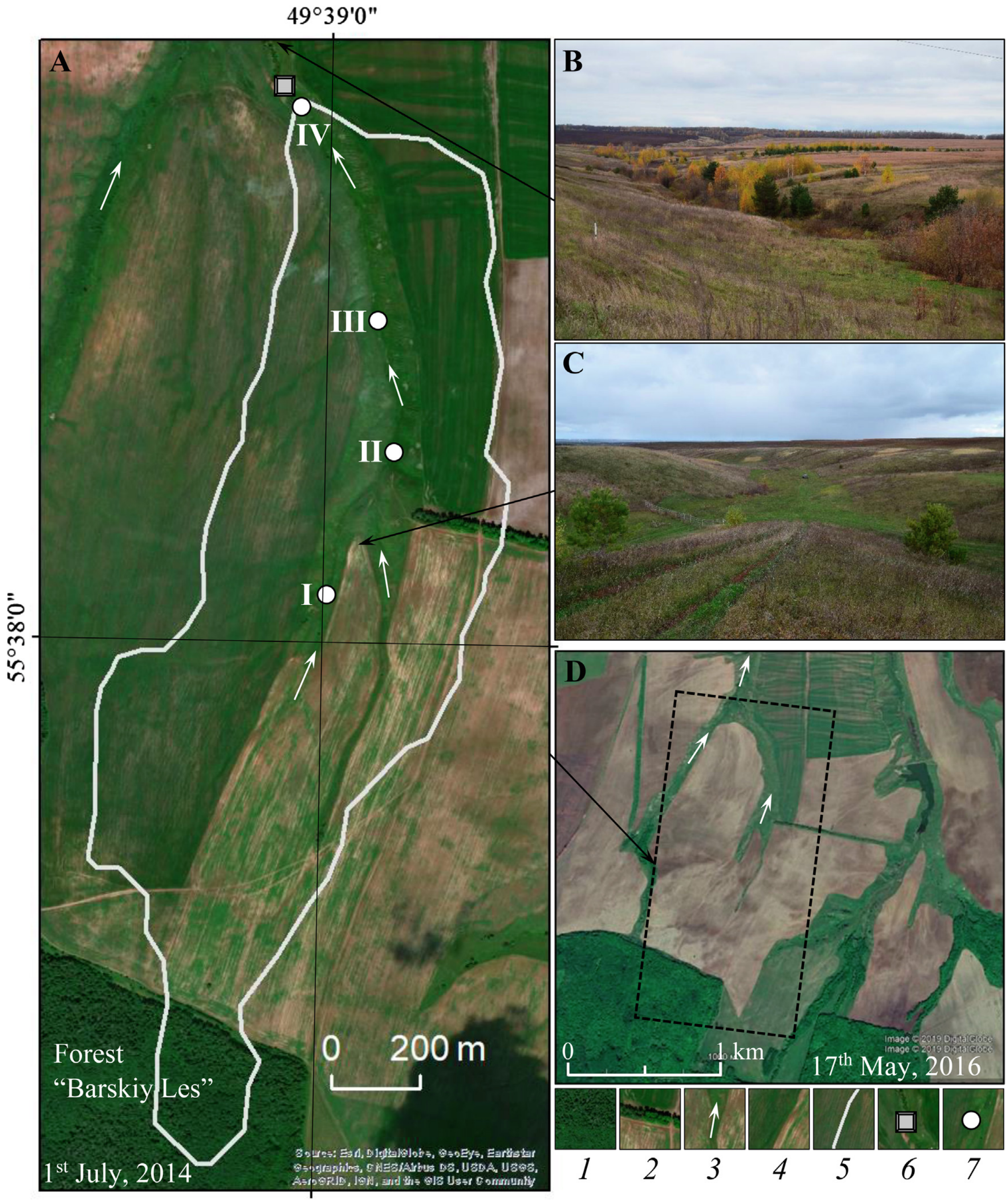

Fig. 2. The studied part of the Temeva Rechka catchment (A, D); B and C – various views of the main dry valley of the catchment (the photos were provided by A.G. Sharifullin). *1* – natural forests, *2* – plantation forests, *3* – episodic (snowmelt-induced and rainfall-induced) concentrated surface water runoff along dry valley bottoms, *4* – ploughland, *5* – the catchment boundary, *6* – the gully head cut within the bottom of the dry valley, *7* – location of the sediment sections I, II, III, and IV within the bottom of the dry valley.

increments of 2, 3, and 5 cm from an area of 10 × 10 cm and 15 × 15 cm using hand tools in each sediment section.

3.4. 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 caesium-137 concentration measurements were made using a γ-spectrometer SKS-07 (09) P-G-R with a high (5–10%) accuracy. All the laboratory tests were carried out as part of the Russian Science Foundation project (no. 15-17-20006).

The radioactive caesium-137 as a chronomarker. The radioactive caesium-137 (^{137}Cs) is widely used to estimate the 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; Benmansour et al., 2013; Porto et al., 2014; and others). Within a large part of Europe, several peaks of ^{137}Cs fallouts were found: firstly, 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

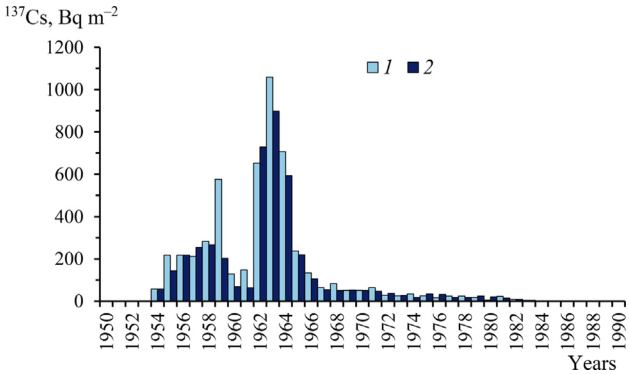

Fig. 3. The bomb-derived annual ^{137}Cs fallouts (*1*) in the Northern hemisphere (according to the generalized data of Zapata, 2002) and (*2*) in the Leningrad Oblast of the former Soviet Union (according to Silantyev and Shkuratova, 1983) during 1954–1984. The figure was stylized according to Gusarov, 2019.

of nuclear weapons in an open atmosphere and widely distributed throughout the Northern hemisphere (Fig. 3); secondly, the Chernobyl-derived ^{137}Cs caused by the accident at the Chernobyl Nuclear Power Plant (in 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 fix with a fairly high accuracy (±1–3 cm) 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 usually occurs in the first years after isotope deposition from the atmosphere, gradually slowing down in time by 1.5–2.0 times, depending on the grain size composition of soils/sediments, their acidity, humus content, infiltration capacity, and so on (Kirchner et al., 2009; Buraeva et al., 2015; and others). It follows logically from what has been said that if these marking ^{137}Cs-peaks (layers) are stored in any accumulated sediment thickness, it becomes possible to determine the sedimentation rates over the following periods – 1959–1963, 1963–1986, and since 1986 until sediment sampling date. It is obvious that the rates are in direct and close association with the dynamics of losses of soil materials washed out/down from erosion-active catchment areas (primarily cultivated lands) in the fluvial geosystems.

3.5. Other data collection

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 to assess the anthropogenic (mainly agricultural) impact on the temporal dynamics of the aforementioned water/sediment flow and erosion intensity in the studied river basins. 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 sources of the information were statistical collections of the USSR (Agriculture of the USSR, 1988) and electronic statistical resources of the Russian Federation (https://fedstat.ru). The data on long-term year-to-year precipitation variability in the study region were available from the All-Russia Research Institute of Hydro-Meteorological Information – World Data Center (http://meteo.ru).

4. Results

4.1. Hydrological changes

4.1.1. The changes in water flow

4.1.1.1. The annual water flow changes. No statistically significant directional changes in the mean annual water flow over the recent decades compared to the baseline period of 1960–1979 were observed in 7 of the 13 rivers analyzed. In the remaining six rivers a trend of decreasing runoff prevailed: in 4 rivers, the decrease in the water flow was, on average, −30.2% (from −20.8% to −44.2%) between 1960–1979 and 2002–2016; in two rivers, on the contrary, there was a trend of increase in the water flow – 15.2% to 18.4% (on average, 16.8%) (Table 3). No geographical patterns in the specified distribution of trends in the mean annual water flow were found in the region studied.

4.1.1.2. The seasonal water flow changes. Compared to the aforementioned redistribution in the mean annual water flow between the monitoring periods, the changes in seasonal water flow were more regular and distinct, viz:

(1) In all the analyzed rivers there was a statistically significant ($p < 0.05$) decrease (on average, by 77.2 ± 4.5%) in the intra-annual irregularity (N) of river water flow. At the same time, the smallest reductions in N occurred in the south-west of the study region, on the Volga Upland within the Ulyanovsk Oblast (−62% to −66%), the largest – in the middle zone of this region, from the Kubnya River basin to the Bolshoy

Table 3
The period-to-period changes in the mean annual water flow (Q_{an}, m^3 s^{-1}) recorded at the studied rivers (see Fig. 1).

Rivers	SGS at (see Table 1):	Monitoring periods		±Δ, %	p
		1960–1979	2002–2016		
Aktai	Karavayevo	2.04 ± 0.34	2.04 ± 0.33	0	≫0.05
Bolshoy Cheremshan	Novocheremshansk	22.40 ± 3.91	15.47 ± 2.14	−30.9	$0.001 < p < 0.01$
Bolshoy Kinel'	Timashevo	35.55 ± 5.18	36.82 ± 5.31[a]	+3.6	>0.05
Chagra	Novotulka	2.91 ± 0.78	2.36 ± 0.51[a]	−18.9	>0.05
Kazanka	Arsk	3.60 ± 0.41	2.71 ± 0.40	−25.0	$0.001 < p < 0.01$
Kichuy	Utyashkino	6.61 ± 0.76	6.57 ± 0.94	−0.6	≫0.05
Krasnaya	Krasnaya Reka	1.04 ± 0.14	0.58 ± 0.04	−44.2	<0.001
Kubnya	Chuteyevo	3.91 ± 0.78	3.56 ± 0.50	−9.0	>0.05
Maliy Cheremshan	Abalduyevka	4.49 ± 0.72	3.89 ± 0.60	−13.4	>0.05
Myosha	Pestretsy	17.31 ± 1.51	13.70 ± 2.29	−20.8	$0.01 < p < 0.05$
Sheshma	Sloboda Petropavlovskaya	12.52 ± 1.36	14.83 ± 1.53	+18.4	$0.01 < p < 0.05$
Syzranka	Repyovka	13.51 ± 1.49	15.57 ± 1.10[a]	+15.2	$0.01 < p < 0.05$
Tushonka	Sergeyevka	1.17 ± 0.14	1.12 ± 0.11	−4.3	>0.05

SGS – streamflow gauging stations; ±Δ – relative changes between the corresponding average Q_{an}-values; p – the probability of statistically significant differences between the corresponding average Q_{an}-values (the Student's t-test).
Note. The Sviyaga River at Koromyslovka has not been included in the analysis since its available Q_{an} time series was only until 1995.
[a] Until 2015.

Cheremshan River basin (–83.9% to –88.3%) (Table 4, Fig. 1). These evident changes were associated with a redistribution in the water flow between the main hydrological phases (snowmelt-induced flood, and low-water (baseflow) period). As a visual example of year-to-year changes in the water flow, we present the data on the Myosha River basin (Fig. 4) where the studied small catchment is located.

(2) Almost in all the analyzed rivers there was a statistically significant ($p < 0.05$, excluding three rivers) decrease in the snowmelt-induced flood water flow ($Q(f)$) by, on average, 37.4 ± 9.8% (for only statistically significant decreases – by 42.2 ± 11.0%) between 1960–1979 and 2002–2016. This resulted in the fact that the average share of the snowmelt-induced flood flow in the total annual water flow of the rivers also decreased significantly – from 59.5 ± 9.1% to 38.9 ± 8.2%, that is, there was the aforementioned 'degradation' of the river snowmelt-induced flood that was previously (up to the current climate change) the leading component of the total annual river water flow in the region. The maximum water discharges in all the rivers studied were statistically significantly reduced, on average, by 58.6 ± 6.0%. As a consequence of all these changes, the overall intensity of the snowmelt-induced flood flow (Z) of all the analyzed rivers also greatly and statistically significantly decreased between the monitoring periods – by 40.4 ± 8.2% (Table 4).

(3) An important contribution to the reduction of the intra-annual irregularity of water flow was made by a rather noteciable increase in the volume of river flow during the low-water (baseflow) phases of hydrological regime – during the winter and river-ice-free periods. Particularly tremendous and statistically significant changes have occurred over the past decades in winter water flow: from 1960–1979 to 2002–2016 the winter minimum water discharges of the rivers increased, on average, by 145.2 ± 57.6% (or 90.3% ± 20.7%, excluding the Aktai River and Kubnya River with super extreme changes in this flow) (Table 4). The minimum water discharge changes during the river-ice-free period were also great – the discharges increased between the same monitoring periods by 94.9 ± 39.7% (or 110.1% ± 40.5% for only statistically significant increases). These water discharges were reduced slightly (statistically insignificant changes) only in the Krasnaya River basin (Fig. 1).

(4) The obtained results are generally consistent with the overall trends identified earlier (Frolova et al., 2015; Blöschl et al., 2017, 2019, etc.) for the East European Plain.

4.1.2. The changes in suspended sediment yield

Despite the data on river suspended sediment yield, compared to water flow, are not complete in the period under study, and are not presented for all the studied rivers, nevertheless, its analysis gives a good idea of the current trends in changes of the general erosion intensity in river basins of the region.

Myosha River and Kazanka River. These two adjacent rivers in the north of the region under consideration clearly demonstrate a significant decrease in the general erosion intensity on their interfluves, near the border with the forest landscape zone. The mean annual suspended sediment yields of the rivers from 1960–1979 to 2002–2016 decreased with a high statistical significance: by 11.8 times in the Myosha River, and in 16.3 times in the Kazanka River (Fig. 5). This was due primarily to a great decrease in suspended sediment yields in April, the month with a maximum (snowmelt-induced) water flow/runoff. The suspended sediment concentration (mean annual, and in April) of the rivers, that is one of the indicators of the environmental state of their water, also significantly decreased (with a high statistical significance) between the time intervals under consideration (Fig. 5). The yield/-concentration of suspended sediment in these rivers began to decline most markedly since the first half of the 1980s.

Kichuy River. The following temporal dynamics in the mean annual suspended sediment yield were observed in this river: in 1963–1979 – 4.28 ± 1.05 kg s^{-1}, in 1980–1998 – 1.83 ± 1.19 kg s^{-1}, and in 2003–2012 – 0.92 ± 0.14 kg s^{-1}, i.e the yield reduced ($p \ll 0.001$) by 4.7 times from 1963–1979 to 2003–2012.

Sviyaga River, Tushonka River and Syzranka River. An even more essential reduction in suspended sediment yield was recorded in the south-western part of the study region, on the Volga Upland within the Ulyanovsk Oblast. There, in the basin of the Tushonka River (see Fig. 1), for example, the mean annual suspended sediment yield/concentration decreased (with a high statistical significance) by almost 28/26 times from 1960–1979 to 2002–2016. Moreover, this dynamics began to appear there most clearly since about 1983 (the upper reaches of the Sviyaga River), and after 1985 (the Tushonka River) (Fig. 6). In the adjacent (larger) basin of the Syzranka River (Fig. 1), this sediment reduction was manifested smaller – by less than 16 times: in 1963–1975 – 110 Mg km^{-2} y^{-1}, in 2008–2016 – 7 Mg km^{-2} y^{-1}. As in the cases of the Myosha River and Kazanka River, the mean annual suspended sediment yield/concentration in these rivers also began to reduce most markedly since the first half of the 1980s.

Bolshoy Kinel' River. In the basin of this river, located in the steppe south-east of the study region, the mean annual suspended sediment yield/concentration decreased (with a high statistical significance) less greatly – only by about 4/5 times from 1965–1979 to 2002–2015 (Fig. 7). Apparently, the most noticeable decrease in the yield/concentration in this river began in the second half of the 1980s.

Krasnaya River. The following temporal dynamics in the river mean annual suspended sediment yield were observed in this river (the Trans-Volga Region of the Ulyanovsk Oblast): during 1967–1979 (without 1969) – 0.89 ± 0.47 kg s^{-1}, in 1980–2001 (without 1987 and 1998) – 0.39 ± 0.17 kg s^{-1}, and in 2002–2016 (without 2002, 2006, 2010, and 2014) – 0.006 ± 0.002 kg s^{-1}, i.e. the yield reduced ($p \ll 0.001$) by 148.3 times from 1967–1979 to 2002–2016. This is the largest reduction in the mean annual suspended sediment yield that we have identified in the study region. It began to appear most significantly since 1984, and was the result of a favorable combination of changes in climate (the greatest decrease in the intensity of snowmelt-induced water runoff (see Table 4)) and land use/cover (the greatest decrease in the area of cultivated land in the Ulyanovsk Oblast compared to other studied administrative regions (see below)) with geological structure (mostly sandy and sandy-loam alluvial deposits of the palaeo-Volga River valley) in that part of the Ulyanovsk Oblast where the basin of this river is located.

Chagra River. The following temporal dynamics of the mean annual suspended sediment yield were observed in this river flowing mainly in the south-west of the Samara Oblast (see Fig. 1): during 1965–1980 – 11.5 Mg km^{-2} y^{-1}, in 2008–2015 – 0.9 Mg km^{-2} y^{-1}, i.e. between these periods the yield reduced ($p \ll 0.001$) by 12.8 times. The similar rates of reduction in the yield were also noted in the extreme west of the Samara Oblast (to the west of the Volga River valley), in the Usa River basin, upstream of the village of Bayderyakovo (GPS coordinates: 53.460000 N, 48.560000 E), F = 1940 km^2, that was not included in our overall analysis: in 1963–1979 – 0.34 ± 0.13 kg s^{-1}, in 2002–2016 – 0.035 ± 0.007 kg s^{-1}, i.e. the yield reduced ($p \ll 0.001$) by about 10 times.

Thus, from the data obtained it might be concluded that there was a significant decrease in the mean annual suspended sediment yield (concentration) in the river network of the Middle Volga Region since the 1980s.

Table 4
The period-to-period changes in seasonal water flow recorded at the studied rivers (see Fig. 1).

Characteristics	Monitoring periods				p
	Before 1960	1960–1979	1980–2001	2002–2016	
Aktai River at Karavayevo (690 km²)[a]*, since 1951*					
Q(f), mm y^{-1}	86.0	74.1	71.3	59.6	>0.05
D, days	20	29	26	28	>0.05
P, %	79	78	65	57	<0.001
Z, mm per day	4.1	2.9	2.8	2.3	$0.01 < p < 0.05$
Q_{max}, m^3 s^{-1}	166.5	185.5	133.7	84.8	$0.001 < p < 0.01$
$Q_{min}(1)$, m^3 s^{-1}	0.04	0.10	0.31	0.50	<0.001
$Q_{min}(2)$, m^3 s^{-1}	0.21	0.19	0.37	0.54	<0.001
N, times	792.9	976.3	361.4	157.0	$0.01 < p < 0.05$
Bolshoy Cheremshan River at Novocheremshansk (6050 km²)					
Q(f), mm y^{-1}	–	81.9	79.6	36.9	<0.001
D, days	–	42	35	40	>0.05
P, %	–	69	60	41	<0.001
Z, mm per day	–	2.0	2.3	1.1	$0.01 < p < 0.05$
Q_{max}, m^3 s^{-1}	–	585.1	472.8	199.1	<0.001
$Q_{min}(1)$, m^3 s^{-1}	–	3.47	6.72	6.60	<0.001
$Q_{min}(2)$, m^3 s^{-1}	–	2.73	6.34	6.87	<0.001
N, times	–	214.3	74.6	29.0	$0.01 < p < 0.05$
Bolshoy Kinel' River at Timashevo (12,000 km²), since 1934					
Q(f), mm y^{-1}	58.0	54.2	57.0	44.2	>0.05
D, days	35	39	39	56	$0.001 < p < 0.01$
P, %	62	55	47	41	$0.001 < p < 0.01$
Z, mm per day	1.7	1.4	1.5	0.8	$0.001 < p < 0.01$
Q_{max}, m^3 s^{-1}	653.4	609.7	526.5	263.5	$0.001 < p < 0.01$
$Q_{min}(1)$, m^3 s^{-1}	5.68	8.59	16.12	16.08	<0.001
$Q_{min}(2)$, m^3 s^{-1}	7.70	11.15	18.47	17.28	<0.001
N, times	84.9	54.7	28.5	15.2	<0.001
Chagra River at Novotulka (2550 km²), since 1933					
Q(f), mm y^{-1}	34.6	29.6	33.4	16.0	$0.01 < p < 0.05$
D, days	26	32	29	32	$\gg$0.05
P, %	70	72	66	53	$0.01 < p < 0.05$
Z, mm per day	1.5	0.9	1.2	0.5	$0.01 < p < 0.05$
Q_{max}, m^3 s^{-1}	161.1	131.7	108.2	53.9	$0.01 < p < 0.05$
$Q_{min}(1)$, m^3 s^{-1}	0.40	0.31	0.57	0.80	$\ll$0.001
$Q_{min}(2)$, m^3 s^{-1}	0.39	0.37	0.60	0.72	$\ll$0.001
N, times	454.3	321.2	193.1	76.3	<0.001
Kazanka River at Arsk (650 km²)					
Q(f), mm y^{-1}	–	114.2	88.5	58.9	<0.001
D, days	–	28	27	32	>0.05
P, %	–	66	50	40	$\ll$0.001
Z, mm per day	–	4.4	3.4	1.9	<0.001
Q_{max}, m^3 s^{-1}	–	182.8	123.2	59.2	$\ll$0.001
$Q_{min}(1)$, m^3 s^{-1}	–	0.53	1.01	1.00	<0.001
$Q_{min}(2)$, m^3 s^{-1}	–	0.64	1.03	0.97	<0.001
N, times	–	377.0	138.5	66.4	$0.001 < p < 0.01$
Kichuy River at Utyashkino (1330 km²), since 1935 (1935–1939, and since 1948)					
Q(f), mm y^{-1}	62.3	68.0	60.1	44.2	$0.001 < p < 0.01$
D, days	26	30	30	33	>0.05
P, %	50	43	32	27	<0.001
Z, mm per day	2.4	2.3	2.1	1.5	$0.001 < p < 0.01$
Q_{max}, m^3 s^{-1}	124.4	159.6	93.7	63.9	<0.001
$Q_{min}(1)$, m^3 s^{-1}	1.12	2.04	3.45	3.12	$0.01 < p < 0.05$
$Q_{min}(2)$, m^3 s^{-1}	1.28	2.67	4.87	4.33	$0.001 < p < 0.01$
N, times	97.2	59.8	19.2	14.8	<0.001
Krasnaya River at Krasnaya Reka (311 km²), since 1961					
Q(f), mm y^{-1}	–	50.8	36.8	9.9	<0.001
D, days	–	25	21	24	$\gg$0.05
P, %	–	46	36	17	<0.001
Z, mm per day	–	2.2	2.0	0.5	<0.001
Q_{max}, m^3 s^{-1}	–	50.1	28.1	5.7	<0.001
$Q_{min}(1)$, m^3 s^{-1}	–	0.23	0.40	0.38	<0.001
$Q_{min}(2)$, m^3 s^{-1}	–	0.38	0.41	0.37	$\gg$0.05
N, times	–	131.8	68.5	15.4	$0.01 < p < 0.05$
Kubnya River at Chuteyevo (930 km²), since 1947					
Q(f), mm y^{-1}	91.5	95.8	66.4	62.9	$0.01 < p < 0.05$
D, days	28	31	31	32	$\gg$0.05
P, %	73	74	59	50	<0.001
Z, mm per day	3.6	3.4	2.2	2.1	$0.01 < p < 0.05$
Q_{max}, m^3 s^{-1}	174.3	172.3	91.3	76.2	<0.001
$Q_{min}(1)$, m^3 s^{-1}	0.13	0.19	0.35	0.81	<0.001

(continued on next page)

Table 4 (*continued*)

Characteristics	Monitoring periods				p
	Before 1960	1960–1979	1980–2001	2002–2016	
$Q_{min}(2)$, $m^3 s^{-1}$	0.06	0.13	0.25	0.49	<0.001
N, times	2905	1325.4	365.2	155.5	<0.001
Maliy Cheremshan River at Abalduyevka (1230 km²), since 1941					
Q(f), mm y^{-1}	95.0	95.1	93.6	70.3	$0.01 < p < 0.05$
D, days	24	31	31	34	>0.05
P, %	77	83	70	65	<0.001
Z, mm per day	3.9	3.3	3.1	2.2	$0.01 < p < 0.05$
Q_{max}, $m^3 s^{-1}$	228.7	241.4	144.9	104.0	<0.001
$Q_{min}(1)$, $m^3 s^{-1}$	0.29	0.28	0.59	0.59	<0.001
$Q_{min}(2)$, $m^3 s^{-1}$	0.37	0.24	0.70	0.46	$0.001 < p < 0.01$
N, times	618.1	1005.8	207.0	226.1	$0.001 < p < 0.01$
Sheshma River at Sloboda Petropavlovskaya (3110 km²), since 1940					
Q(f), mm y^{-1}	67.2	59.2	63.4	44.6	$0.01 < p < 0.05$
D, days	29	35	32	40	>0.05
P, %	51	46	34	28	<0.001
Z, mm per day	2.2	1.8	1.9	1.1	<0.001
Q_{max}, $m^3 s^{-1}$	267.1	223.3	179.6	108.9	$0.001 < p < 0.01$
$Q_{min}(1)$, $m^3 s^{-1}$	2.77	4.08	8.72	7.27	<0.001
$Q_{min}(2)$, $m^3 s^{-1}$	3.32	5.16	10.65	9.44	<0.001
N, times	80.4	43.3	16.9	11.5	$0.01 < p < 0.05$
Syzranka River at Repyovka (4380 km²), since 1947					
Q(f), mm y^{-1}	40.0	40.4	36.1	30.0	>0.05
D, days	24	33	29	34	≫0.05
P, %	40	40	29	25	>0.05
Z, mm per day	1.7	1.2	1.3	1.0	<0.001
Q_{max}, $m^3 s^{-1}$	371.7	268.0	206.9	157.0	$0.01 < p < 0.05$
$Q_{min}(1)$, $m^3 s^{-1}$	3.94	4.14	7.49	10.18	≪0.001
$Q_{min}(2)$, $m^3 s^{-1}$	4.32	5.21	8.11	8.91	<0.001
N, times	86.0	51.4	25.5	17.6	$0.001 < p < 0.01$
Tushonka River at Sergeyevka (309 km²), since 1961					
Q(f), mm y^{-1}	–	37.6	31.2	21	$0.001 < p < 0.01$
D, days	–	33	28	33	≫0.05
P, %	–	31	21	18	<0.001
Z, mm per day	–	1.2	1.1	0.7	$0.01 < p < 0.05$
Q_{max}, $m^3 s^{-1}$	–	20.4	16.7	9.7	0.05
$Q_{min}(1)$, $m^3 s^{-1}$	–	0.38	0.61	0.70	<0.001
$Q_{min}(2)$, $m^3 s^{-1}$	–	0.63	0.83	0.79	>0.05
N, times	–	32.4	20.1	12.3	$0.01 < p < 0.05$

Q(f) – the total depth of surface water runoff for the spring (snowmelt-induced) flood period; *D* – duration of the spring (snowmelt-induced) flood period; *P* – the share of the spring (snowmelt-induced) flood surface water runoff in the total annual surface water runoff; *Z* – the average intensity of the spring (snowmelt-induced) flood 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 river-ice-free period (*2*); *N* – the average dimensionless ratio between Q_{max} and $Q_{min}(2)$; *p* – the probability of statistically significant differences in the corresponding average values between 1960–1979 and 2002–2010/2016 (the Student's *t*-test).
Note-1. The data on *P* and *Z* are until 2010. *Note-2*. The information on the Myosha River is in Fig. 4.
[a] River basin area.

4.2. Changes in sedimentation rates

In the modern sediment of the bottom of the dry valley Temeva Rechka, two peaks of ^{137}Cs are clearly distinguished (Fig. 8) – the peak of the maximum global fallouts (1963), and the Chernobyl-derived peak (1986). In two sediment sections, the peak of 1959, the second largest peak of the global fallouts, is also identified. It should be noted that the ^{137}Cs peak of 1963 almost everywhere in the temperate climate zone is in the range of 15–20 Bq kg^{-1} (taking into account the ^{137}Cs half-life is about 30 years) (Golosov, 2006). The period-to-period dynamics in sedimentation rates in the bottom indicate a significant decrease in the rates of soil erosion mainly within the arable part of the catchment (Fig. 2) in the recent decades. So, if during 1963–1986 the average rates of accumulation of washed-out soil material were 0.92–1.81 cm per year, then during 1987–2015 – only 0.17–0.50 cm per year, i.e. they decreased by at least 3.0–5.4 times (Fig. 8) (Gusarov et al., 2018a). If we compare the rates of annual sedimentation over the sediment sections at the dry valley bottom, then the difference in these rates increases generally between the first and second periods from the upper reaches to the lower ones: the sediment section I – by 4.3 times, section II – by 3.7 times, section III – by 5.3 times, and section IV – by 6.8 times (Sharifullin et al., 2018). This fact suggests that during the formation of surface runoff from the catchment slopes in the period after 1987, most of the sediment was deposited immediately at the exit from the arable part of the catchment, and downstream the runoff was less saturated with sediment. At the same time, the bottom gully located downstream of the sediment section IV (Fig. 2) has grown over the period since 1987, as a whole, by about 200 m (about 6–7 m per year): this fact means that the water runoff from the catchment area was still considerable during this time (Sharifullin et al., 2018). The increase in the erosion potential of concentrated episodic streams in the dry valley bottom, containing less and less erosion products (sediment) from the early period to the late one (at least in the 1980s–1990s), contributed to the above-mentioned active growth of the bottom gully. The rapid development of this erosion incision was also due, most likely, to several extreme rainfall events in the region.

It is noteworthy that in that part of the Republic of Tatarstan, where the small catchment is located, almost 60% of the studied gullies stopped their linear growth between the 1960s–1970s and 2009–2016 (Medvedeva et al., 2018).

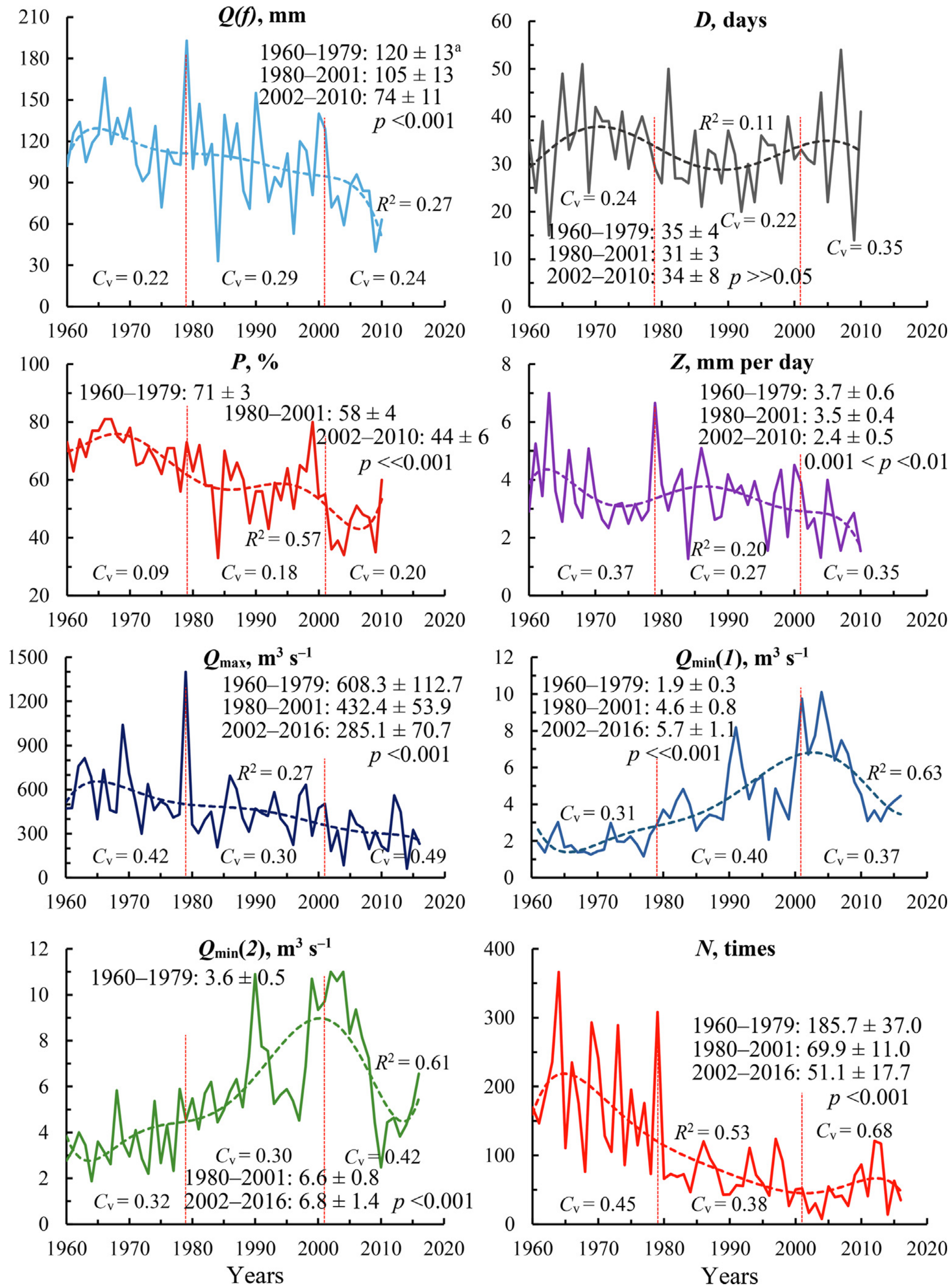

Fig. 4. The year-to-year changes in water flow recorded at the Myosha River at the village of Pestretsy (the Republic of Tatarstan, European Russia, see Fig. 1) during 1960–2016. *Q(f)* – the total depth of surface water runoff during the spring (snowmelt-induced) flood period in the river basin; *D* – duration of the spring (snowmelt-induced) flood period; *P* – the share of the spring (snowmelt-induced) flood surface water runoff in the total annual surface water runoff; *Z* – the average intensity of the spring (snowmelt-induced) flood surface water runoff; Q_{max} – maximum (per year) water discharge timed to the spring (snowmelt-induced) flood period; Q_{min} – minimum water discharges during the winter period (*1*) and river-ice-free period (*2*); *N* – the average dimensionless ratio between Q_{max} and $Q_{min}(2)$; C_v – the coefficient of variation; R^2 – the coefficient of sixth-degree polynomial trend approximation; *p* – the probability of statistically significant differences in the corresponding average values between 1960–1979 and 2002–2010/2016 (the Student's *t*-test). *Note.* No data on *Q(f)*, *D*, *P*, and *Z* for 2011–2016 were available. [a]Hereinafter, a 95% confidence interval.

5. Discussion

5.1. Climate/climate-induced changes

5.1.1. The changes in snowmelt water runoff

According to the results of field measurements on runoff plots and slope catchments (Surmach, 1992; Barabanov, 1993; Litvin et al., 1998; Kuznetsov and Demidov, 2002; Petelko et al., 2007), in the forest-steppe zone of the East European Plain with gray and dark gray forest soils (*Greyic Phaeozems*), leached chernozems (*Luvic Chernozem (Pachic)*), ordinary chernozems (*Haplic Chernozems (Pachic)*), and typical chernozems (*Haplic Chernozems (Pachic)*), there was a clear tendency toward a reduction in the snowmelt water runoff depth on ploughed fields (1–1.3 mm per year) since the 1950s–1960s. It is noteworthy that the reduction rate appreciably increased (to 1.3 mm per year) from the late 1980s (Litvin et al., 2017). For example, the snowmelt water runoff on fall-ploughed fields was 35–38 mm in 1958–1975, and then

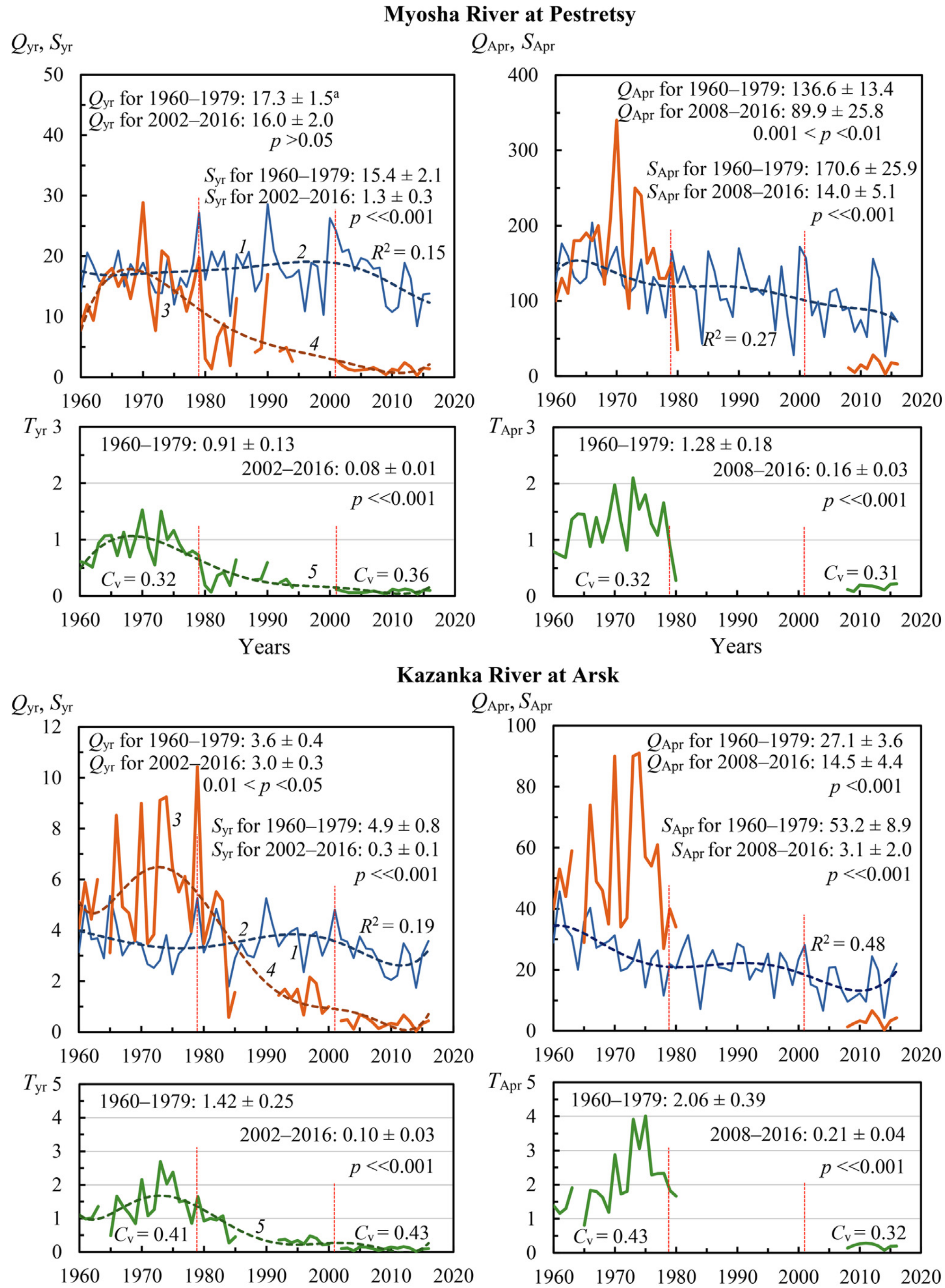

Fig. 5. The year-to-year changes in suspended sediment yield recorded at the Myosha River and Kazanka River (the Republic of Tatarstan, European Russia, see Fig. 1) during 1960–2016. Q_{yr} – mean annual water discharge, $m^3 s^{-1}$; Q_{Apr} – mean monthly water discharge for April (the predominantly snowmelt-induced flood month), $m^3 s^{-1}$; S_{yr} – mean annual suspended sediment yield, kg s^{-1}; S_{Apr} – mean monthly suspended sediment yield for April, kg s^{-1}; T_{yr} – mean annual suspended sediment concentration, kg m^{-3}; T_{Apr} – mean monthly suspended sediment concentration for April, kg m^{-3}; *1* – water discharges; *2* – sixth-degree polynomial trend of the water discharges; *3* – suspended sediment yield; *4* and *5* – sixth-degree polynomial trends for S_{yr} and T_{yr} respectively; C_v – the coefficient of variation for T_{yr} and T_{Apr}; R^2 – the coefficient of sixth-degree polynomial trend approximation; p – the probability of statistically significant differences in the corresponding average values between 1960–1979 and 2002/2008–2016 (the Student's t-test). No data on S_{Apr} and T_{Apr} for 1981–2007 were available. [a]Hereinafter, a 95% confidence interval.

decreased to 5–6 mm in 1995–2005, according to the monitoring data on some runoff plots of the Novosil Zonal Agroforest Experimental Station (ZAGLOS) located in the Orel Oblast, SW European Russia (Petelko et al., 2007). Later observations confirmed this trend. So, according to observations at the experimental drainage sites of the Scientific Research Institute of Agriculture of the South-East (the Saratov Oblast), the surface snowmelt water runoff from cultivated land and compacted autumn plough in 1973–1982 was 10 and 34.5 mm respectively, and then decreased to 1.3 and 9.1 mm in 2004–2014 (Medvedev et al., 2016). According to the data of field monitoring in 1959–2016 in 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., 2018), there was also a reduction in the surface water runoff coefficient during the spring snowmelt period from 0.3–0.5 in the 1960–1970s to 0.01–0.05 in the 2000–2010s. It is

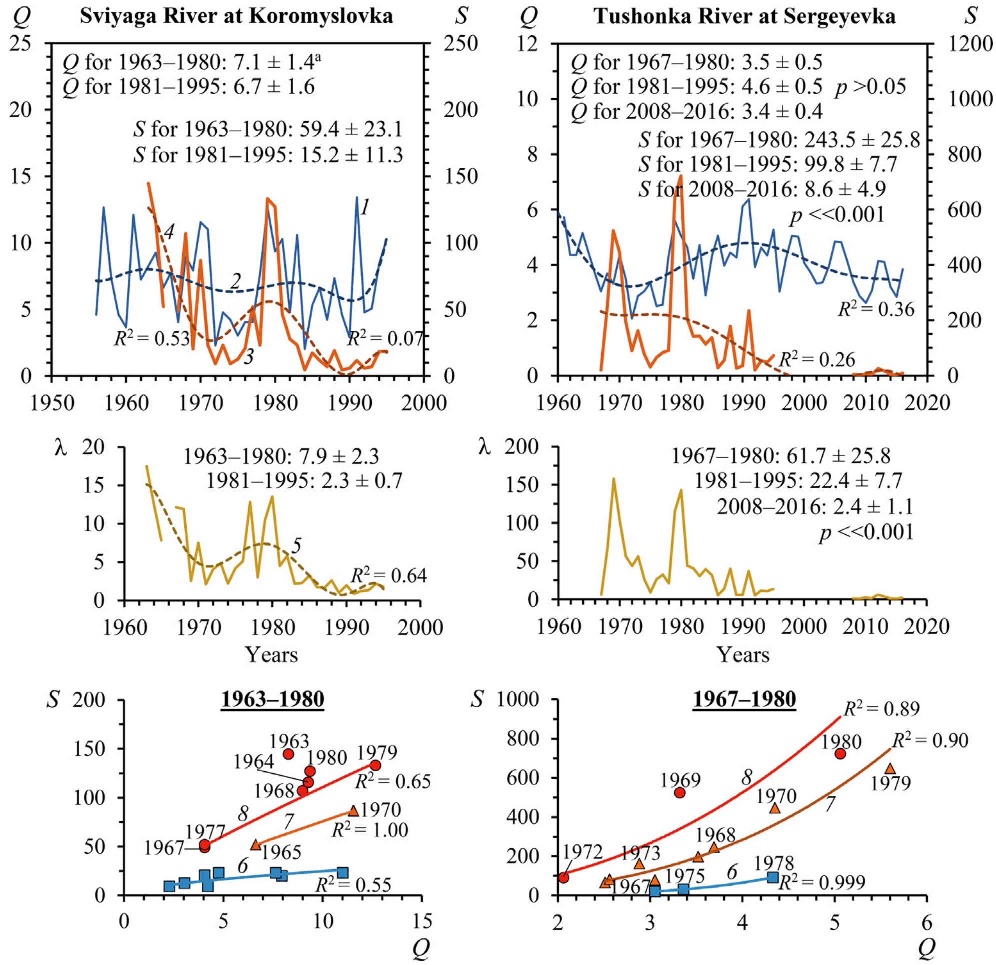

Fig. 6. The year-to-year changes in specific mean annual water flow (Q, L s^{-1} km^{-2}) and specific annual suspended sediment yield (S, Mg km^{-2} y^{-1}) recorded at the Sviyaga River and Tushonka River (the Ulyanovsk Oblast, European Russia, see Fig. 1) during 1963/1967–1995/2016. λ – the ratio between S and Q; R^2 – the coefficient of sixth-degree polynomial trend approximation; p – the probability of statistically significant differences in the corresponding average values between 1967–1980 and 2008–2016 (the Student's t-test). *1* – water discharges; *2* – sixth-degree polynomial trend for Q; *3* – suspended sediment yield; *4* and *5* – sixth-degree polynomial trend for S and λ respectively; *scenarios for: 6* – relatively weakened erosion, *7* – relatively normal erosion, and *8* – relatively intensive erosion. No data on S and λ for the Tushonka River for 1981–2007 were available. [a] Hereinafter, a 95% confidence interval.

quite obvious that this snowmelt water runoff 'degradation' could also have been observed in the Middle Volga Region, since their causes are of a common nature – an increase in spring temperatures of the soil in the study region (Park et al., 2014) (a decrease in the depth of freezing of the soil) (Table 5) against the background of regional climate warming. This warming, including an increase in the number of winter thaws, was most statistically expressed in the northern part of the study region (Fig. 9, Table 6). In the environment of the forest-steppe and steppe zone of European Russia, the water runoff on the soil can be almost completely absent, regardless of the level of autumnal soil moisture, if the soil is frozen to a depth of no more than 30–50 cm (Barabanov et al., 2012). Komissarov and Gabbasova (2014) showed that, in the years when the freezing depth of leached chernozem on arable slopes of the Southern Cis-Ural was within the range of 30–38 cm, the surface water runoff was absent regardless of water reserve in the snow, soil water content, and soil protection by plants. In the continental climate of the centre and east of the plain, this critical depth for almost complete filtration of the snowmelt water runoff is decreased. The warming of the soil results in formation of cellular structures of the distribution of thickness of the temporally frozen zone with a predominance of weakly frozen areas. It causes an increase in losses of the snowmelt water runoff due to filtration and groundwater recharge: the coefficient of snowmelt water runoff from the slopes decreases. All these changes in the snowmelt water runoff on the slopes affected water flow in rivers of the study region – a significant decrease in the snowmelt-induced flood flow and its intensity, as well as in the role of this flow in formation of the annual water flow of the rivers (see Table 4, Fig. 4). The similar tendency of decrease in water discharges during spring (snowmelt-induced) floods over the last decades has also been observed 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), that is, it was a large regional phenomenon. Moreover, the trend towards a decrease in river flood water discharges during 1960–2010 was observed across almost the entire European Mediterranean, in Turkey, while the opposite trend prevailed in northwest (northern France, Belgium, the UK, Ireland, etc.) and northeast (the basins of the Onega River, Northern Dvina River, Mezen' River, etc.) Europe (Blöschl et al., 2019).

On the other hand, frequent thaws in the winter, and increased infiltration of snowmelt waters into the soil in the spring during the last decades resulted in significant increase in water discharges in rivers of the study region, respectively, in the winter months and during the river-ice-free period (especially in the late spring, and the summer) (see Table 4, Fig. 4). The overall decrease in the intra-annual irregularity of water flow in the rivers was largely

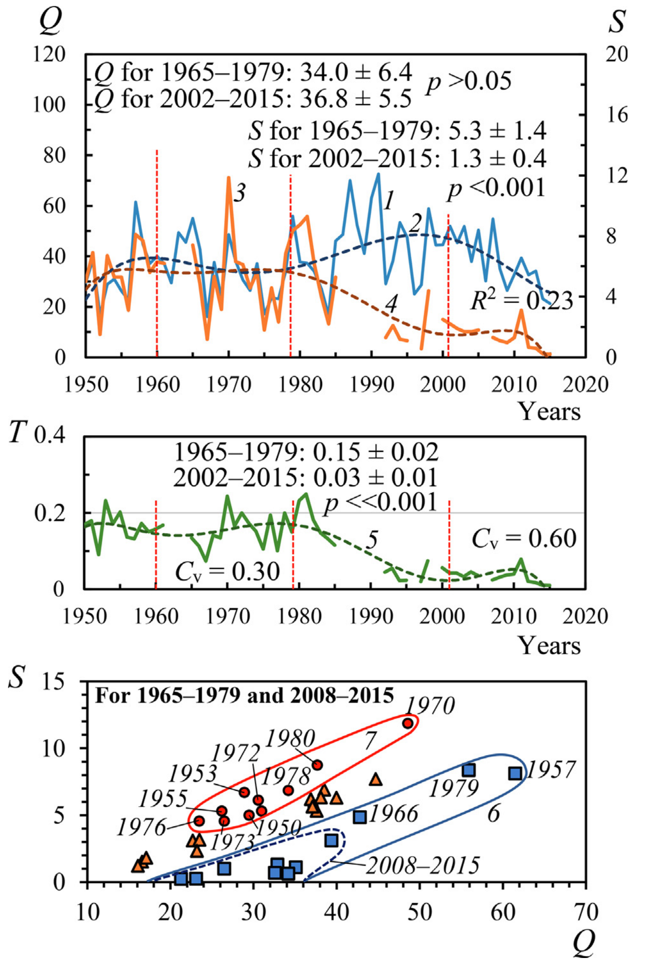

Fig. 7. The year-to-year changes in mean annual water flow (Q, $m^3\ s^{-1}$) and mean annual suspended sediment yield (S, $kg\ s^{-1}$) recorded at the Bolshoy Kinel' River at Timashevo (the Samara Oblast and Orenburg Oblast, European Russia, see Fig. 1) during 1950/1965–2015. T – mean annual suspended sediment concentration, $kg\ m^{-3}$; p – the probability of statistically significant differences in the corresponding average values between 1965–1979 and 2002–2015 (the Student's t-test). *1* – water discharges; *2* – sixth-degree polynomial trend for Q; *3* – suspended sediment yield; *4* and *5* – sixth-degree polynomial trends for S and T; R^2 – the coefficient of sixth-degree polynomial trend approximation for Q; C_v – the coefficient of T-variation; *scenarios for*: *6* – relatively weakened erosion, *7* – relatively intensive erosion. No data on S and T for 1962–1964, 1986–1989, 1991, 1996, 1999, and 2006 were available. [a]Hereinafter, a 95% confidence interval.

due to the 'degradation' of the spring snowmelt water runoff on slopes of the river basins.

The aforementioned significant reduction in river sediment yield was a logical consequence of the decrease in the snowmelt water runoff on interfluve slopes, considering the fact that snowmelt-induced soil-rill-gully erosion was the main source of sediment in the river network of the region prior to the 1980s–1990s. The examples of the Kazanka River and Myosha River (Fig. 5) clearly showed that the decrease in the mean annual suspended sediment yield was due almost entirely to a decrease in suspended sediment yield during the snowmelt-induced flood season (April), which in turn was the result of a sharp decrease in soil erosion intensity in that time in the basins of these rivers. The results of stationary observations, summarized by Butakov et al. (1987, 1988), showed that the main increase in head-gully retreat (70–80%) occurred at that time owing to the meltwater runoff, while the role of heavy rainfalls was only about 10–20% (Sukhoverkova, 1991). The soil masses washed-out from slopes during the spring (snowmelt) time come into rivers more rapidly and in larger amounts than products of rainfall-induced erosion (Golosov, 2006). Moreover, the rainfall erosivity in the East European Plain is less than in most parts of Europe (Panagos et al., 2017a,b). The long-term observations since 1978, for example, in the neighboring Udmurt Republic (see Fig. 1), showed not only a significant decrease in the head-gully retreat rates in this Russia's administrative region, but also reducing the role of the meltwater runoff in these dynamics of the recent decades (Rysin et al., 2017a, b). This trend was also likely continued in the last years in many regions of the southern half of the Eastern European Plain (Gafurov et al., 2018).

5.1.2. The changes in warm-season precipitation

An analysis of the results of long-term observations at three key weather stations in the study region showed the ambiguity of precipitation changes in the recent decades (Table 7). In general, there was a general decrease in the number of rain events from 1966–1979 to 2002–2017; it was accompanied by an increase in their intensity. Particularly noteworthy is the increase in the number of rain events in the southern part of the study region (the weather stations in Inza and Sernovodsk) with precipitation depth of >30 mm, which is the most erosion-hazardous. Some studies have shown (Shi and Wang, 2015; Tang et al., 2015; Panagos et al., 2017a; and others) that the effect of rainfall intensity on soil erosion is even more important than the effect of rainfall amount. However, the number of rains with a depth of precipitation of 30–50 mm in the northern part of the region, on the contrary, has decreased. It is important to note that the bulk of liquid precipitation (including heavy rains) falls in the region from late May to September, when the soil is reliably protected by natural sod-meadow vegetation, or is covered by more or less dense cultivated vegetation. The analysis of redistribution of precipitation in these months showed a statistical insignificance of their changes from 1966–1979 to 2002–2017 (Fig. 10). In general terms, the results obtained for the three weather stations are confirmed by a more detailed regional analysis of current climate change (Perevedentsev et al., 2011, 2013). Consequently, there is no reason to talk about any important role in the variability of liquid precipitation in the noted general hydrological and erosion changes in the river basins across the region of the study. This is also confirmed by the absence, in general (with the exception of reducing the maximum water flow of the Kazanka River), of statistically significant changes in rainfall-induced river water flow (at least in the northern part of the study region) (Fig. 11) that directly depends on liquid precipitation, especially on heavy rains.

5.2. Land use/cover changes

Over the recent decades, the East European Plain has undergone noticeable changes in the use of land resources, that was associated with political and economic changes after the collapse of the Soviet Union in 1991. These changes resulted primarily in a significant decrease in the area of cultivated land, as well as in changes in crop rotation structure. Particularly significant reduction in the cultivated land area has occurred within territories with relatively risky agriculture – in the south of the forest landscape zone, as well as in the arid steppe subzone and semidesert (Fig. 12), while the whole forest-steppe zone and wet steppe subzone were characterized by relatively minimum changes. So, between 1980 and 2012 the reduction area (first of all, the area under grain crops) of cultivated land in the south of the forest zone within European Russia was, on average, 55.6%, in the forest-steppe zone – 28.0%, and in the steppe zone – 27.8% (Golosov et al., 2017a). As for all these changes in the study region itself, we summarized them in Table 8. The most significant decrease in the cultivated land area was observed in the Ulyanovsk Oblast,

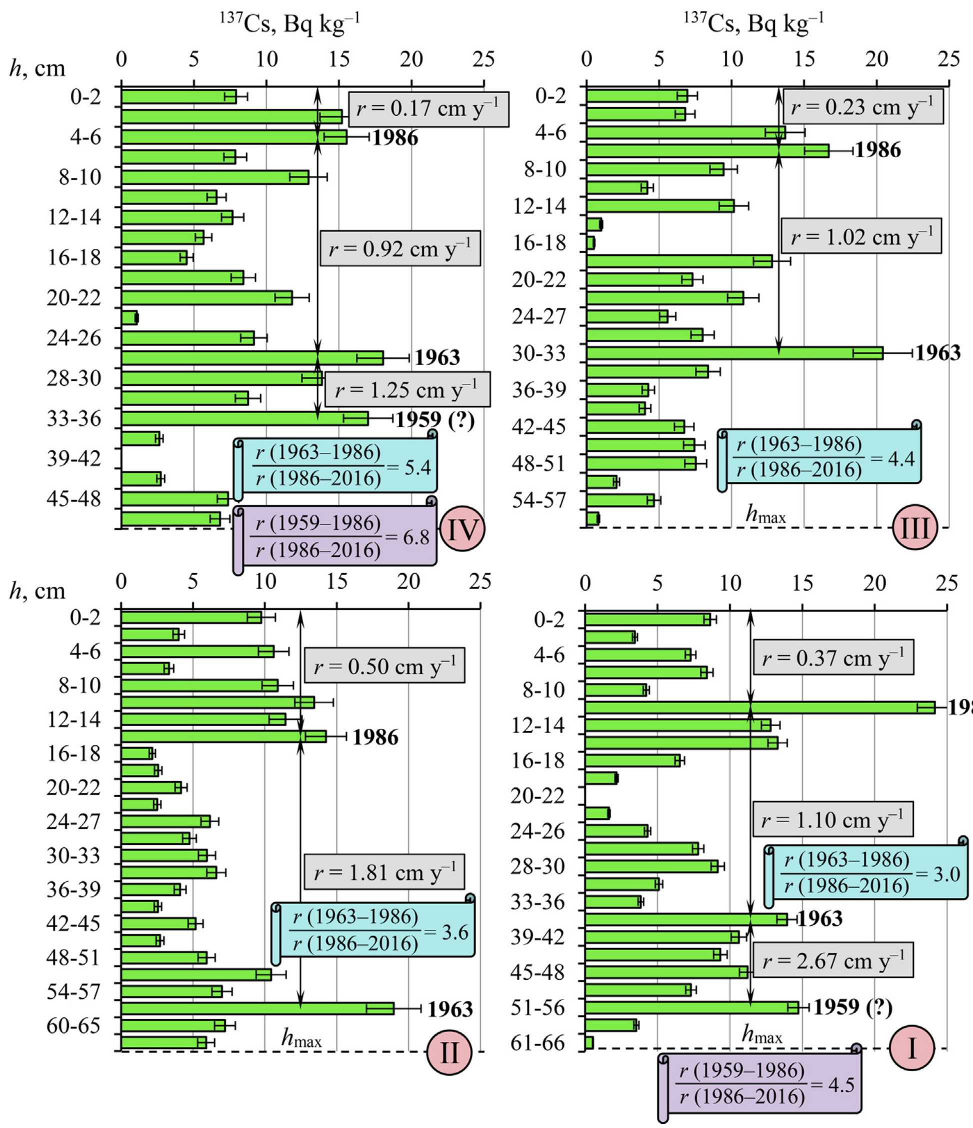

Fig. 8. The vertical ^{137}Cs distribution in the sediment sections I, II, III, and IV within the bottom of the studied dry valley Temeva Rechka (the Tyulyachi administrative district of the Republic of Tatarstan, European Russia, see Figs. 1 and 2), according to Gusarov et al. (2018a) with some changes. *h* – depths (h_{max} – the maximum depth) of sediment sampling (during the summer 2015); *r* – average rates of sedimentation during the corresponding periods; 1959, 1963, and 1986 – the years of the maximum ^{137}Cs fallouts.

Table 5
The period-to-period changes in mean temperature (°C) at different depths of the soil for last 10 days of March (the pre-snowmelt period) during 1963–2011, according to the data from some weather stations in the study region of the East European Plain (see Fig. 1) (based on Gusarov et al., 2018a with changes).

Weather stations (cities, towns)	Monitoring periods and *p*	Soil depths		
		160 cm	80 cm	20 cm
Cheboksary	1963–1986	1.70 (0)[a]	0.40 (20)	−0.41 (100)
	1987–2011	2.00 (0)	0.47 (20)	−0.28 (65)
	p	~0.05	>0.05	>0.05
Nolinsk	1963–1986	2.27 (0)	0.59 (6)	−0.39 (80)
	1987–2011	2.48 (0)	0.94 (4)	−0.02 (46)
	p	~0.05	0.01 < *p* < 0.05	~0.05
Sarapul	1963–1986	1.82 (0)	0.38 (22)	−0.42 (78)
	1987–2011	2.51 (0)	1.06 (4)	0.00 (48)
	p	<0.001	<0.001	>0.05
Bakaly	1963–1986	1.31 (6)	−0.35 (52)	−0.90 (90)
	1987–2011	1.94 (0)	0.62 (15)	−0.30 (58)
	p	0.01 < *p* < 0.05	<0.001	>0.05
Buguruslan	1977–1986	1.94 (0)	0.04 (40)	No data
	1987–2011	2.98 (0)	1.10 (8)	0.19 (36)
	p	0.01 < *p* < 0.05	0.01 < *p* < 0.05	–

p – the probability of statistically significant differences in the corresponding average temperature values between the monitoring periods (the Student's *t*-test).
[a] Hereinafter, in parentheses is the portion (%) of years with negative mean soil temperature at the given depth for the corresponding period.

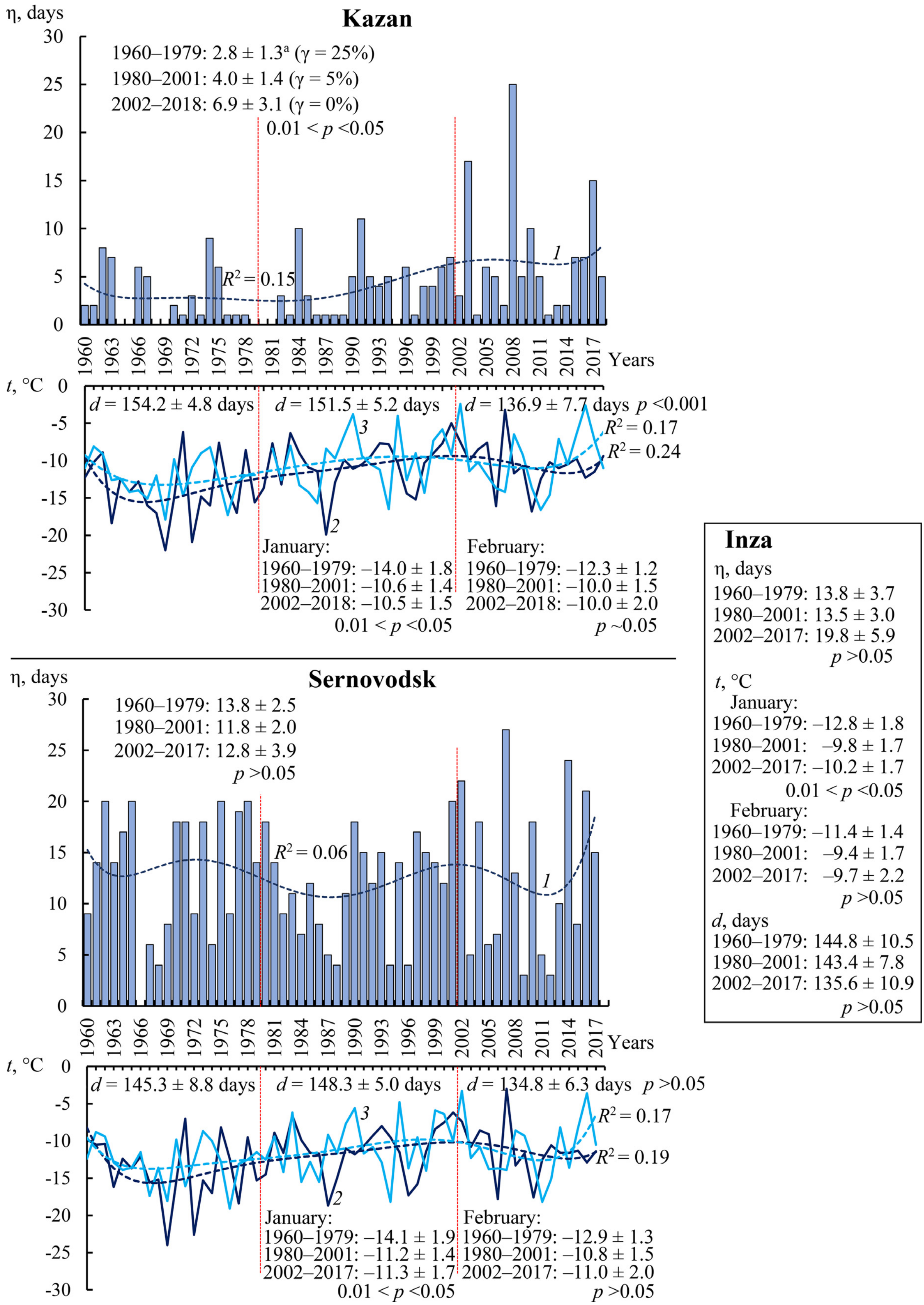

Fig. 9. The year-to-year changes in mean monthly (January and February) temperature (t) and winter (December to February) thaw amount (η) during 1960–2017/2018, according to the data from the weather stations in the cities/towns of Kazan, Inza, and Sernovodsk (European Russia, see Fig. 1). γ – the portion of years with no thaws; d – duration of the cold (frosty) period of year, limited by days with a steady transition of mean daily temperature through 0 °C; *1* – sixth-degree polynomial trend; R^2 – the coefficient of approximation of the sixth-degree polynomial trend; *2* – in January; *3* – in February; p – the probability of statistically significant differences in the corresponding average values between 1960–1979 and 2002–2017/2018 (the Student's t-test). No data on η for Sernovodsk for 1966 were available. [a]Hereinafter, a 95% confidence interval.

Table 6
The period-to-period changes in some early-spring meteorological characteristics at the city of Kazan (the weather station Kazan-Opornaya, the Republic of Tatarstan), the town of Inza (the Ulyanovsk Oblast), and the town of Sernovodsk (the Samara Oblast) (see Fig. 1) during 1960–2017/2018.

Characteristics	Monitoring periods			p
	1960–1979	1980–2001	2002–2018	
Kazan				
Mean temperature (°C) for:				
March	−5.4 ± 1.4	−4.6 ± 0.8	−3.3 ± 1.3	$0.01 < p < 0.05$
April	4.4 ± 1.2	5.4 ± 1.1[a]	5.7 ± 0.8	>0.05
Mean snow cover depth (cm) for:				
March	35.5 ± 7.7[b]	43.8 ± 6.2[a]	48.6 ± 7.7	$0.01 < p < 0.05$
April	8.0 ± 5.2[c]	9.0 ± 3.6[a]	11.1 ± 5.0	>0.05
Precipitation (mm) for:				
March	25.1 ± 7.4	29.1 ± 6.6[a]	40.6 ± 11.2	$0.01 < p < 0.05$
April	36.2 ± 8.8	31.7 ± 7.9[a]	34.1 ± 8.0	≫0.05
Inza				
Mean temperature (°C) for:				
March	−4.8 ± 1.3	−4.3 ± 1.2[d]	−3.0 ± 1.5[f]	>0.05
April	5.3 ± 1.1	5.6 ± 1.2[d]	5.7 ± 0.9[f]	≫0.05
Mean snow cover depth (cm) for:				
March	31.1 ± 8.0[b]	39.5 ± 9.6[d]	26.6 ± 8.6[f]	>0.05
April	4.7 ± 2.7[c]	6.7 ± 3.1[d]	3.2 ± 2.1[f]	>0.05
Precipitation (mm) for:				
March	22.6 ± 6.6	25.6 ± 5.8[e]	29.1 ± 6.7[f]	>0.05
April	29.9 ± 7.2	31.2 ± 9.2[e]	35.2 ± 6.2[f]	>0.05
Sernovodsk				
Mean temperature (°C) for:				
March	−5.5 ± 1.4	−5.4 ± 1.0	−3.8 ± 1.3[f]	>0.05
April	5.8 ± 1.3	6.0 ± 1.4	6.3 ± 1.2[f]	≫0.05
Mean snow cover depth (cm) for:				
March	32.3 ± 6.6	37.8 ± 6.8	32.5 ± 6.7[f]	≫0.05
April	4.5 ± 2.3	6.5 ± 2.9	4.4 ± 3.0[f]	≫0.05
Precipitation (mm) for:				
March	23.8 ± 6.8	22.2 ± 5.8	28.3 ± 7.2[g]	>0.05
April	25.7 ± 7.7	28.7 ± 7.7	29.4 ± 10.3[g]	>0.05

p – the probability of statistically significant differences in the corresponding average values between 1960–1979 and 2002–2018 (the Student's t-test).
Note. All the average values are with a 95% confidence interval.
[a] Without data for 1980.
[b] Without data for 1966, 1970, 1972, and 1975.
[c] Without data for 1967–1974, and 1976.
[d] Without data for 1982, 1983.
[f] Without data for 2018.
[g] Without data for 2016–2018.

especially in its least wetted and low-lying (eastern) part (the Trans-Volga Region) where the most significant decrease in the river mean annual suspended sediment yield was noted (for example, the Krasnaya River).

Considering the environmental conditions in the region, these changes had the following important consequence: the conversion of significant areas of land from the category of erosion-hazardous (cultivated land) to the category of erosion-free and/or low-hazardous lands (abandoned cultivated lands transformed into post-agrogenic meadows, sometimes overgrown with young trees, with the presence of sod that has a high erosion resistance). Additionally, on the abandoned lands, the conversion of surface (snowmelt-induced and rainfall-induced) water to underground runoff increases. It also suppresses erosion processes and increases river water flow during the low-water (summer–autumn) season. That is what we noted on the above material. Expansion of crops of perennial grasses (especially in the Republic of Tatarstan (in its northern part) and the Chuvash Republic), having a high erosion resistance with respect to the spring (snowmelt-induced) water runoff, could further weaken erosion processes in the region in the last decades. The perennial seeded grasses protect the soil against erosion, holding it together with its roots to a depth of 20 cm or more. In terms of projective coverage in 85–95% it completely protects the soil against any erosion (Shakirov, 1978). According to the earlier studies of I.A. Kuznik in 1961 (Mozzherin and Kurbanova, 2004), in the forest-steppe of the Trans-Volga Region, the washing-out of soil material under crops of perennial grasses was 50 times less than on cultivated land. On slopes with a gradient of 16–25° under the perennial grasses, there was no erosion, whereas on a tillage, even with a gradient of slopes of 9°, the soil wash-out reached 120 m^3 ha^{-1} (Cherkosova, 1957). The difference between the intensity of erosion on cultivated land and natural (and also abandoned arable land – post-agrogenic meadows) sodden meadows was even greater (Mozzherin and Kurbanova, 2004; Golosov, 2006). On the other hand, new sunflower crops in the Samara Oblast and Ulyanovsk Oblast (Table 8) could have resulted in some relative increase in soil erosion in the area of their cultivation, since the sunflower is a crop with relatively low erosion resistance than cereals. The general increase in the soil erosion resistance of crops in the warm (rainfall) season in the study region can be confirmed by a decrease (by 24–40%) in the C-factor (Table 8). The greatest increase in the resistance has occurred in the Ulyanovsk Oblast where the aforementioned greatest relative reduction in river suspended sediment yield was also noted (the Krasnaya River and Tushonka River).

The trend of the total cultivated land area reduction was continued in the study region over the past two decades: between 1996–2004 and 2005–2017 the area has reduced by 20.7% (16.8% – the area of cereals) in the Ulyanovsk Oblast, 18.0% (13.6%) in the Chuvash Republic, 9.0% (21.3%) in the Samara Oblast, 6.5% (10.8%) in the Orenburg Oblast, and 2.5% in the Republic of Tatarstan (the area of grain crops in this republic has even increased a little (by

Table 7
The period-to-period changes in April-to-October precipitation at the weather stations in the cities/towns of Kazan, Inza, and Sernovodsk (see Fig. 1) during 1966–2017/2018.

Precipitation depths, mm	Kazan (monitoring periods)								
	1966–1979			1980–2001			2002–2018		
	Σ	*m*	γ	Σ	*m*	γ	Σ	*m*	γ
Total	3542	1418	2.5	3504	1060	3.3	3501	1000	3.5
<10	2497	1355	1.8	2267	983	2.3	2251	923	2.4
10–20	651	49	13.3	867	64	13.5	847	62	13.7
20–30	213	9.3	22.9	179	7.7	23.2	306	13.1	23.4
30–40	103	2.9	36.2	120	3.6	32.9	22	0.6	34.9
40–50	32	0.7	44.5	20	0.5	44.4	0	0.0	0.0
>50	46	0.7	62.4	51	0.9	56.3	75	1.2	59.9
	Inza (monitoring periods)								
	1966–1979			1980–2001			2002–2017		
	Σ	*m*	γ	Σ	*m*	γ	Σ	*m*	γ
Total	3565	1588	2.2	3095	926	3.3	3869	1061	3.6
<10	2535	1526	1.7	1962	861	2.3	2215	967	2.3
10–20	634	46	13.8	688	50	13.8	1005	72	14.0
20–30	304	12.9	23.6	272	11.8	23.1	354	14.4	25.6
30–40	92	2.9	32.3	57	1.8	31.5	177	5.0	35.3
40–50	0	0.0	0.0	80	0.8	44.0	118	2.5	47.2
>50	0	0.0	0.0	36	0.5	78.8	0	0.0	0.0
	Sernovodsk (monitoring periods)								
	1966–1979			1980–2001			2002–2017		
	Σ	*m*	γ	Σ	*m*	γ	Σ	*m*	γ
Total	2636	1177	2.2	3173	1028	3.1	3118	938	3.3
<10	1976	1125	1.8	2165	966	2.2	2082	876	2.4
10–20	499	46	10.8	685	51	13.4	653	49	13.3
20–30	138	5.7	24.2	187	7.7	24.3	199	8.1	24.6
30–40	23	0.6	31.9	61	1.8	33.9	124	3.8	33.1
40–50	0	0.0	0.0	20	0.5	44.7	26	0.6	41.9
>50	0	0.0	0.0	55	0.9	60.2	34	0.6	54.6

Σ – mm for 10 years of the corresponding period; *m* – the number of rainfall events for 10 years of the corresponding period; γ – the average rainfall depth (mm per one rainfall event, γ = Σ/m).

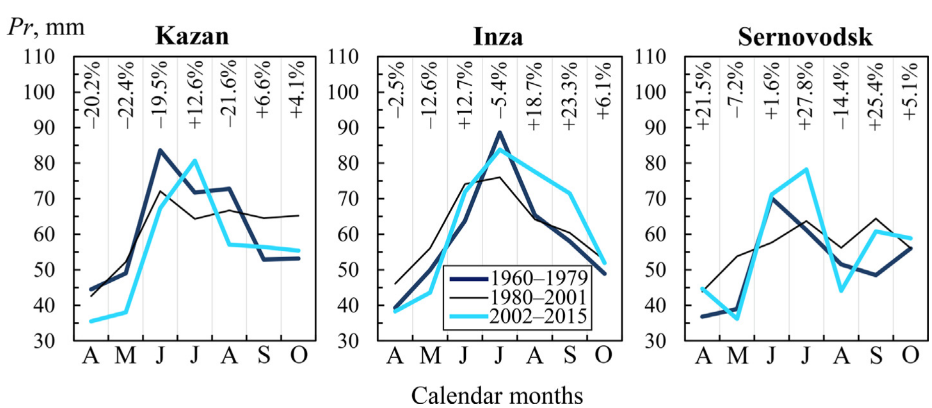

Fig. 10. The period-to-period changes in monthly precipitation (*Pr*)[a] during the warm (April to October) season of year, recorded at the weather stations in the cities/towns of Kazan, Inza, and Sernovodsk (see Fig. 1) during 1960–2015. *Note.* The probability (*p*) of statistically significant differences in the average precipitation between 1960–1979 and 2002–2015 (−20.2%, −22.4% ..., etc.) for each month at each weather station is >0.05 or ≫0.05. [a]Only monthly precipitation ≥20 mm.

1.1%), being a consequence of some improvement in the economic situation there).

There is a large number of examples of the influence of land abandonment on changes in hydrological regime of rivers and erosion activity in their basins, including Europe (Kosmas et al., 2000; Taillefumier et al., 2000; van Rompaey et al., 2000; Lach and Wyżga, 2002; López-Moreno et al., 2006; Bakker et al., 2008; Cebecauer and Hofierka, 2008; Keesstra et al., 2009; Kozak, 2009; Wyżga, 2008; Zorn and Komac, 2009; García-Ruiz, 2010; García-Ruiz et al., 2010; Baumann et al., 2011; Wyżga et al., 2012; Spalević et al., 2013; Latocha et al., 2016; Wyżga et al., 2016; and others). Their comparison requires a further separate detailed analysis.

The decrease in the cultivated land area, that was caused by serious economic problems in Russia, was not the only reason that contributed to the decrease in erosion and sediment yield in the river basins of the study region. In the late USSR's period, mainly in the 1970s–1980s, anti-erosion-processes measures began to be actively conducted on the most agriculturally developed part of the East European Plain, especially in the territories most affected by these processes. For example, in the Republic of Tatarstan (the area is 67,847 km^2), the following dynamics of the areas of artificial anti-erosion plantings within gully/dry-valley systems of this region were noted: in 1946–1955 – 10,120 ha, in 1961–1970 – 10,800 ha, in 1971–1990 – 43,687 ha. The dynamics were

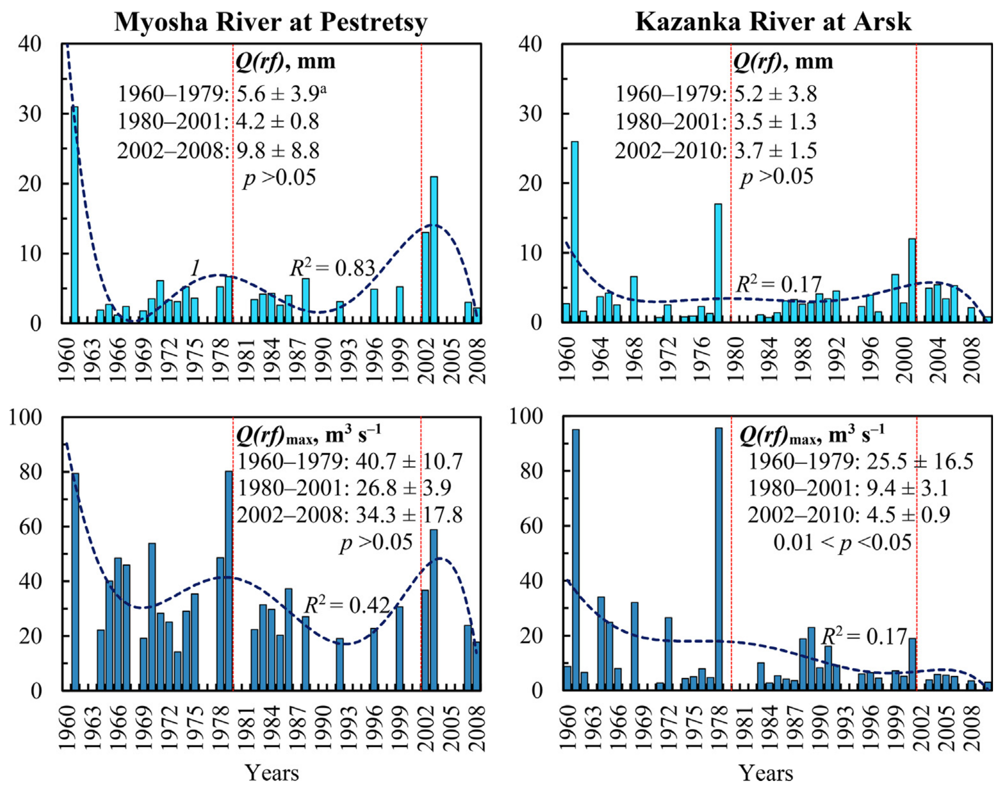

Fig. 11. The year-to-year changes in rainfall-induced water flow recorded at the Myosha River and Kazanka River (the Republic of Tatarstan, European Russia, see Fig. 1) during 1960–2008/2010. *Q(rf)* – the total depth of surface water runoff during the rainfall-induced flood period in the basins of the rivers, $Q(rf)_{max}$ – maximum water discharges during the rainfall-induced flood period; R^2 – the coefficient of sixth-degree polynomial trend (*1*) approximation; *p* – the probability of statistically significant differences in the corresponding average values between 1960–1979 and 2002–2008/2010 (the Student's *t*-test). No data for 2009/2011–2016 were available. [a]Hereinafter, a 95% confidence interval.

continued later, in the post-Soviet period, albeit on a somewhat smaller scale: in 1991–2010 – 27,209 ha (Forestry Development Strategy, 2018). The cumulative effect of these activities, carried out in the region in the 1970s–2000s, could make a significant contribution not only to reducing the erosion rates and river sediment yields, but also to redistribution of water flow in the rivers, noted earlier, through a change in the ratio between surface and subsurface water runoff on interfluve slopes. The same hydrological changes in the Baltic countries (Estonia, Latvia, and Lithuania) might also be partially due to the afforestation of their territory mainly owing to the abandonment of cultivated land (Jogiste et al., 2015).

An additional contribution to the decrease in erosion activity on the fields being cultivated after the collapse of the USSR could be a reduction (especially in the 1990s and the early 2000s) in the regional agricultural machinery park, as we showed with the example of the Saratov Oblast located southward from the study region (Gusarov, 2019).

Fundamental changes in the area of cultivated land within the Temeva Rechka catchment, that could potentially affect the noted reduction in the accumulated sediment in the bottom of the dry valley after 1986, were not detected based on our analysis of Landsat space images (Sharifullin et al., 2018). Consequently, within the boundaries of this catchment, the main role in the dynamics of erosion/sedimentation rates was likely played by the climate change described above.

5.3. How representative are the results for European Russia?

The aforementioned hydrological and erosion changes were traced over the last decades almost everywhere in the forest-steppe and steppe landscape zones 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; Gusarov et al., 2018a,b,c; Medvedeva, 2018; Sharifullin et al., 2018; Gusarov, 2019; Gusarov et al., 2019b; Gusarov and Sharifullin, 2019; Sharifullin et al., 2019; and others). So, for example, in the basin of the Samara River (the upper reaches, 22,800 km^2, the western part of the Orenburg Oblast (see Fig. 12), European Russia), located in the southeastern steppe sector of the plain, annual suspended sediment yield has reduced at least twice over the last 30 years compared to the 1940–1960s (Gusarov and Sharifullin, 2019). The marked decreasing trend in the intensity of soil-gully erosion in the Samara River basin is confirmed by a decrease (by 3.0–3.6 times as a minimum) in the rates of accumulation of products (sediment) of the erosion over the past 60 years within dry valley bottom of one of the small catchments of the river basin (Gusarov et al., 2018b). The similar rates of decrease in the erosion intensity were found (Golosov et al., 2017b) in the western sector of the forest-steppe and steppe zones of European Russia, within the Voronezh Oblast (see Fig. 12). A more significant decrease in the intensity of erosion was noted by us in the central sector of the steppe zone of the plain, within the Volga Upland, in the western part of the Saratov Oblast (see Fig. 12): the quantification of the rates of sedimentation in one of the local small dry valley catchments during two time intervals (1963–1986 and 1986–2017), based on the sediment dating using ^{137}Cs as a chronomarker, indicates their decrease at least by 4–6 times after 1986; this points to a proportional reduction in erosion rates on the ploughed slopes of the catchment (Gusarov et al., 2018c). An analysis of the temporal variability of suspended sediment yield in some rivers of the western part of the Saratov Oblast (the Medveditsa River and Khopyor River) during the period since 1940 to the present time has confirmed this conclusion (Gusarov, 2019).

Table 8
The period-to-period changes in the area of cultivated land within the European Russia's administrative regions where the studied river river basins are situated.

Characteristics (×10³ ha)	Administrative regions[a]				
	Republic of Tatarstan	Chuvash Republic	Orenburg Oblast	Samara Oblast	Ulyanovsk Oblast
The total region area	6785	1834	12,370	5356	3718
The total area of cultivated land	3502/3002 − 14.3%	805/615 − 23.6%	5825/4206 − 27.8%	2859/1972 − 31.0%	1713/1033 − 39.7%
The share of the total area of cultivated land in the total region area, %	51.6/44.3	43.9/33.5	47.1/34.0	53.4/36.8	46.0/26.4
Cereals	2233/1525 − 31.7%	442/258 − 41.6%	4295/2884 − 32.9%	1904/1133 − 40.5%	1093/586 − 46.4%
Perennial crops[b]	366/542 + 48.1%	139/204 + 46.7%	294/415 + 41.2%	120/151 + 25.8%	91/123 + 35.2%
Annual crops[c]	316/272 − 13.9%	70/59 − 15.7%	443/223 − 49.7%	244/118 − 51.6%	202/89 − 55.1%
Crops of:					
Sunflower	0/26	0/1.7	0/419	138/337 + 144.2%	51/97 + 90.2%
Potato	140/88 − 37.1%	80/50 − 37.5%	46/26 − 43.5%	57/37 − 35.1%	52/27 − 48.1%
Sugar beet	50/58 + 16.0%	0/0	0/0.34	16/2.5 − 84.4%	15/12 − 20.0%
Other crops	397/491 + 23.7%	74/42 − 43.2%	747/239 − 68.0%	380/193 − 49.2%	209/99 − 52.6%
C-factor[d]	0.43/0.32 − 25.6%	0.40/0.25 − 37.5%	0.45/0.34 − 24.4%	0.46/0.32 − 30.4%	0.45/0.27 − 40.0%

Note. In numerator is the average area of cultivated land during the late USSR's period (averaged over 1970, 1975, 1980, 1985, 1986, and 1987), in denominator – during the Russian Federation's period (averaged over 1996–2017); the percentage is relative change in the cultivated areas between the periods.
[a] See Fig. 1.
[b] Medicago sativa L., Onobrychis viciifolia, Agropýron, and others.
[c] Sorghum sudanense L., Setaria italica, and others.
[d] The generalized erosion resistance index (*C*-factor) of agricultural crops (calculated only for cereals, perennial and annual crops, as well as crops of potatoes, sugar beet, and sunflower; these crops totally occupied in these regions 87–91% in 1970–1987, and 84–94% in 1996–2017 of the total area of cultivated land) for the warm (rainfall) season of year. *Note 1.* The lower the *C*-factor, the better one or other crop (or agrocenosis) protects the soil against erosion; *Note 2.* The generalized *C*-factor values for individual crops were obtained from Catchment (2017); *Note 3.* For 1996–2017, the generalized *C*-factor was calculated totally within the cultivated + abandoned land area.

The same trends were also found in the south of the forest zone (the southern taiga) of the East European Plain. For example, in one (the Kuregovo dry valley catchment) of the small dry valley catchments located in the south part of the Udmurt Republic (see Fig. 12, the mixed forests zone) within the Izh River basin, there was also a noticeable decrease (by 2.5–3 times as a minimum) in sedimentation rates of washed-out slope soil material at the valley bottom of the catchment over the past 60 years: from 1.8–2.5 cm per year during 1954–1986 to 0.15–0.75 cm per year in 1986–2016 (Gusarov et al., 2018a; Gusarov et al., 2019b). This trend is well consistent with a decline of the average retreat rates of gully headcuts within cultivated lands in the Udmurt Republic over the past 40 years – from 1.3 m per year in 1978–1997 to 0.3 m per year in 1998–2014 (Rysin et al., 2017a,b).

Thus, in the Middle Volga Region, the greatest (among recorded at the moment) rates of decrease in the erosion intensity in European Russia (at least in its central and eastern parts) have been observed, judging by the data of river suspended sediment yield. As mentioned earlier, the long-term average erosion rates and river suspended sediment yield amounts were also the greatest just in this region of the East European Plain in the 1950–1970s.

We also discussed earlier some of the possible environmentally-positive consequences of the same identified hydrological and erosion changes using the example of the Don River basin, SW European Russia (Gusarov, 2019).

6. Conclusion

As a result of the study made it was revealed that significant hydrological and erosional changes took place over the recent decades in the Middle Volga Region. These changes have resulted in the significant decrease in the intra-annual irregularity of river water flow due to the reduction in spring (snowmelt-induced) water runoff (flow) and the increase in low-water flow (baseflow) in the winter and summer-autumn months. Together with these events in the region, there was the significant decrease in the intensity of erosion and its products, mainly suspended sediments, in the regional river network. The main reason for all these changes was the redistribution of surface and subsurface water runoff within regional interfluves, that was due to both climate change (the decrease in the depth of soil freezing during the snowmelt period caused by the increase in air temperature mainly in the winter and spring months; the increase in winter thaws frequency, especially in the northern part of the region) and changes in economic (primarily agricultural) activity (mainly the reduction in cultivated land area, especially in the 1990s and the early 2000s). At the present time, an accurate quantitative assessment of the contribution of each mentioned factor to the noted changes seems methodologically difficult, since the influence of these factors manifested itself almost simultaneously. In addition, the absence of reliably established regional patterns of interaction in the functioning system "winter freezing of the soil → spring (snowmelt-induced) surface water runoff → soil/rill erosion → mobilized sediment (→ river sediment yield)" limits the reliable use of modelling and statistical methods in such the assessment at different scales of research.

The main regularities obtained in the paper (the 'degradation' of snowmelt-induced river flood water flow, the increase in river water flow during the winter and river-ice-free periods, the decrease in the intra-annual irregularity of river water flow, the decrease in the intensity of soil-rill-gully erosion and its products including river suspended sediment yield, etc.) can be considered in general terms as a comparatively representative scenario of

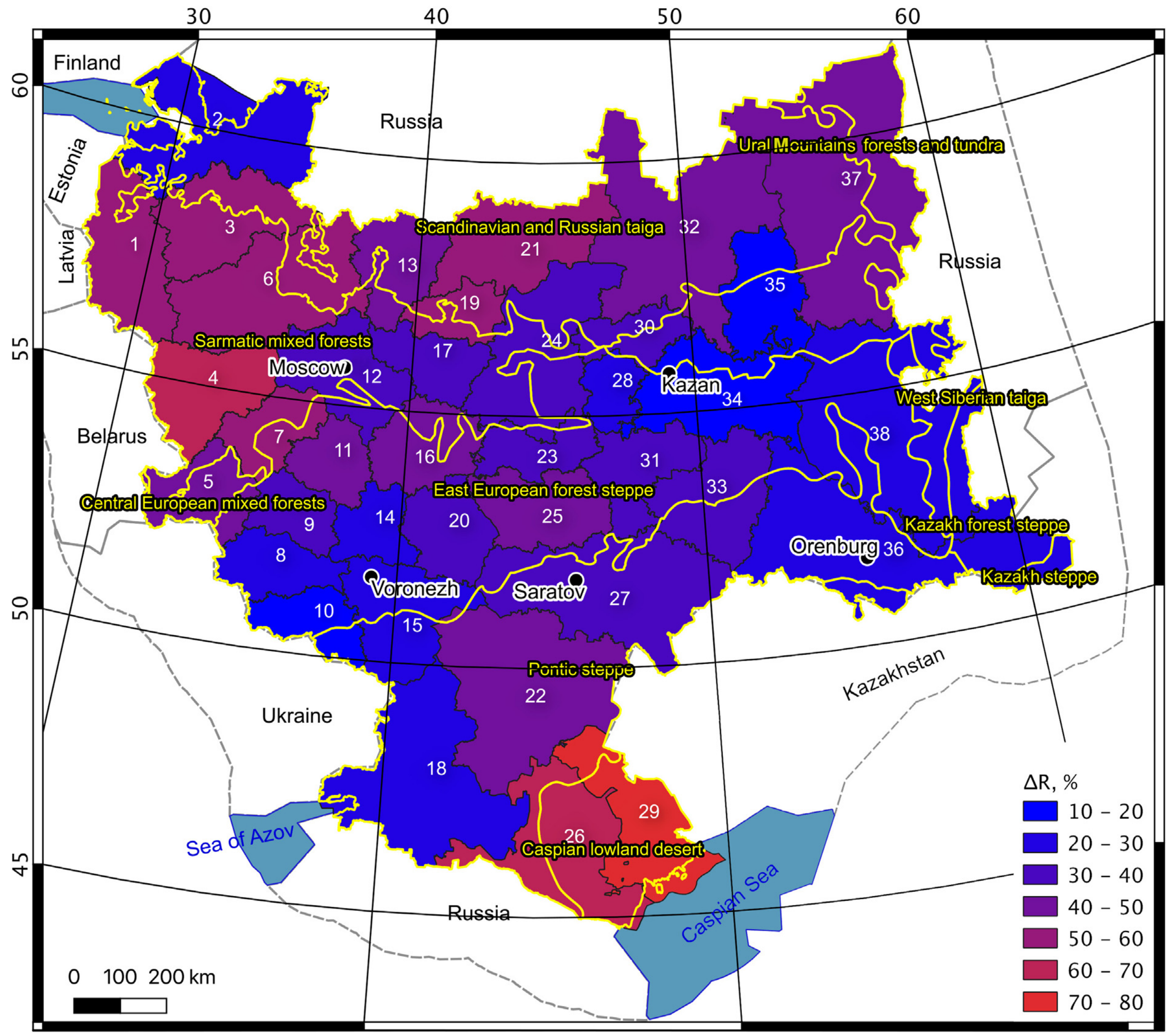

Fig. 12. The map of relative reduction (ΔR) in the total area of cultivated land between the late USSR's period (averaged over 1970, 1975, 1980, 1985, 1986, and 1987) and the Russian Federation's period (1996–2017) within the most populated and agriculturally developed administrative regions of European Russia (without the semi-exclave of the Kaliningrad Oblast), according to Gusarov, 2019 (based on 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 landscape zones are given according to Olson et al. (2001).

the fluvial system response to contemporary climate and land use/cover changes in the East European Plain, at least for most of its southern half.

The prospects of the study. Although a number of issues have been analyzed and discussed much remains to be done in the field of quantitative assessing the impact of changes in climate conditions and land use/cover on the dynamics of the delivery of sediments from hillslopes (primarily cultivated) to the river network (river suspended sediments) of the study region. This is of great methodological significance, and requires expanding the number of research objects (including small catchments, river floodplains, etc.) and the range of applied (including interdisciplinary) methods.

Declaration of Competing Interest

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The author is grateful to Dr.Sci. V.N. Golosov, Faculty of Geography, Lomonosov Moscow State University (Russia), and PhD A.G. Sharifullin, Institute of Environmental Sciences, Kazan Federal University (Russia), for help in the field data collection in the summer 2015 (also special thanks to A.G. Sharifullin for help with collecting meteorological data), as well as to PhD student A.S. Tsyplenkov, Institute of Geography, Russian Academy of Sciences, Moscow (Russia), for providing some hydrological data. The author also thanks the anonymous reviewers who comprehensively contributed to the paper providing valuable reviews.

Funding sources

The work was performed according to the Russian Government Program of Competitive Growth of Kazan Federal University, and was also partly supported (the study of the Temeva Rechka catchment) by the Russian Science Foundation (Russia), project no. 15-17-20006.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2019.134770.

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