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Assessment of soil loss by water erosion in small river basins in Russia

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ABSTRACT

Prolonged and intensive agricultural exploitation in the European territory of Russia has resulted in extensive soil erosion, which has led to anthropogenically induced degradation of arable land. The extensive agricultural development of the region stems from the presence of plains suitable for plowing, which feature fertile chernozem (Luvic Chernozems) and grey forest (Luvisols) soils. The majority of the land in the small river basins (70–80%) are plowed. In addition, this macroregion of Russia is the main agricultural territory that provides food for the entire country. The total arable area comprises approximately 600,000 km^2. Approximately 95 million people, the majority of the population of Russia, live in this region. This research aims to provide a quantitative assessment of the soil lost by erosion in the arable lands of the macroregion using an USLE empirical mathematical model modified to suit the harsh climatic conditions of Russia. The calculation was performed using a raster model of the data that includes a model of the slope angle, slope length, soil erodibility, rainfall erosivity factor, water content of the snow, annual distribution of precipitation, and types of land use. The location of arable lands of the territory were determined by remote sensing measurements and the TerraNorteRLCv.3 (2014) map compiled by the Space Research Institute of the Russian Academy of Science. For the first time, the intensity of soil erosion over periods of snowmelt and storm runoff, as well as the total annual soil loss, were determined for this territory at a regional scale (1:500,000). The results of these calculations were generalized for small river basins. For this generalization, we used a grid we had previously designed that features over 50,000 river basins.. The average soil erosion in the territory studied amounts to 4.04 t ha^{-1} year^{-1}, considering the soil-protective coefficients of agricultural vegetation. In the annual soil loss by erosion, storm runoff erosion prevails at 3.78 t ha^{-1} year^{-1} and the erosion by snowmelt is considerably lower at only 0.26 t ha^{-1} year^{-1}.

As expected, due to the higher values of the relief (length-slope) factor, soil erosion increases from the lowland plains (3.65 t ha^{-1} year^{-1}) to the high plains (5.38 t ha^{-1} year^{-1}), peaking in the mountains (12.88 t ha^{-1} year^{-1}). The rate of soil erosion of arable lands consistently decreases from the taiga and forest landscape subzone to the steppes. An east–west trending zone featuring the highest soil erosion was distinguished. This zone of high soil erosion coincides with the mixed and broad-leaved forests subzone, which is highly used for plowing. Moreover, a western longitudinal sector of high soil erosion that includes the forest and forest-steppe landscape zones was also determined.

1. Introduction

The qualitative assessment of soil and gulley erosion rates is one of the key issues in attempts to preserve the efficiency of land use and provide the population with food supplies. The lowland landscapes of the European part of Russia (EPR) are well suited for plowing, feature fertile soils and are the main agricultural areas of the country. Historically, these factors played a major role in the extensive agricultural development of the region. The majority of the small river basins are more than 70–80% plowed. Almost all suitable areas are cultivated. The continuous and intensive agricultural interventions have led to intensive natural-anthropogenic soil erosion over a significant area where the rate of soil erosion exceeds that of natural soil formation.

Quantitative assessments of the intensity of soil erosion and its spatial development have been extensively developed using erosion modeling at different levels of generalization, from small watershed to continental scales (Karydas et al., 2014). Currently, geoinformational systems are widely used to calculate the erosive soil loss. These systems allow large amounts of data to be processed and help evaluate the

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amount of erosion at an acceptable accuracy at different levels of generalization. Advances in modern geoinformational technologies have allowed us to evaluate the erosion of unprecedentedly large territories and create cartographic models of soil erosion.

Different erosion models have been developed and applied to evaluate soil erosion rates. Modeling is widely used in erosion studies (Boardman and Poesen, 2006). There are different classifications of erosion models. Overall, they are divided into empirical and process-based models. USLE (Wischmeier and Smith, 1978), RUSLE (Renard et al., 1997), MUSLE (Kumar et al., 2015) and modified versions of these models are examples of empirical models. Over the past five years, nearly 1,000 articles featuring these models were published in the international Web of Science database. Examples of process-based erosion models include LISEM (Grum et al., 2017), WEPP (Pieri et al., 2007), SWAT (Vigiak et al., 2015), MMF (Morgan et al., 1984; Shrestha and Jetten, 2018), WATER/SEDEM (Quijano et al., 2016), and EUROSEM, (Morgan et al., 1998) among others.

Russian and post-Soviet models use formulas of Genrich Shvebs (Shvebs, 1974), Tsotne Mirtskhulava (Mirtskhulava, 1970), Georgiy Surmach (Surmach, 1979), the equation and model of the State Hydrological Institute (Larionov, 1993; Litvin, 2002). Of particular note are the stochastic (Sidorchuk et al., 2006) and probabilistic models, which represent soil erosion by water as a probabilistic process (Sukhanovskii, 2013).

This study is not the first to assess soil loss due to erosion in the EPR and present the results in a map model. Soil erosion in this territory has been mapped at various times as part of projects covering larger areas. We highlight the main previous studies here:

- World map of the status of human-induced soil degradation (GLASOD) (Oldeman et al., 1990);
- Map of human-induced soil degradation in Central and Eastern Europe (SOVEUR) (Van Oost et al., 2007);
- The map of spatial variation of soil erosion by water (Van Oost et al., 2007);
- Global Land Degradation Information System (GLADIS) (Nachtergaele et al., 2011);
- Soil-erosional map of USSR scale 1:5,000,000 (Sobolev, 1968);
- Project Digital Georeferenced database of soil degradation in Russia (1998 г.) (Stolbovoi and Fischer, 1998);
- State soil-erosional map of Russia and neighboring countries (Kashtanov et al., 1999);
- National Soil Atlas of Russia (Shoba, 2011).

Particular attention should be paid to the soil erosion assessment and mapping based on the latest Revised Universal Soil Loss Equation and the model of the State Hydrological Institute (1985–1995) covering all of Russia at a small scale (1:1,500,000) (Litvin, 2002; Litvin et al., 2017).

Additionally, within this territory, previous work has assessed the intensity of water erosion and the degree of erosion in individual parts of the study area. For example, at the end of the 20th century, medium-scale soil erosion maps were provided for many regions in the EPR. The maps were designed based on data from large-scale soil surveys that had been conducted more than 50–60 years ago; therefore, these maps need to be adjusted (Ermolaev, 2002; Yermolaev, 2017). Current research studies employ GIS technologies for different regions of this large territory. For example, there are map models of soil erosion for the Belgorod, Voronezh, Lipetsk, Tambov, and Kursk regions (Spesivyy and Lisetskiy, 2014). Long-term average annual soil loss by erosion was also quantified and mapped based on the river basin approach for the Middle Volga Region (the Republic of Tatarstan, Republic of Mari-El, Chuvash Republic, Ulyanovsk Region) (Yermolaev, 2017; Maltsev and Yermolaev, 2008; Golosov et al., 2018a).

The map of a river basin is often used in combination with modeling and GIS to assess the rate of soil erosion and conduct erosion control measures. Therefore, second and the third order small river basins according to (Strahler, 1952) are used as the operational territorial units of soil erosion for the final presentation of our results.

A few publicly available cartographic products of watershed models that cover the study territory currently exist. Publicly available products primarily include HydroSHEDS (Lehner et al., 2011), CCM2 (Vogt et al., 2007) and ECRINS. These models were designed both for the fluvial network and temporary streams. Several Russian river basin models and corresponding geodatabases were previously designed for particular regions in Russia (Ermolaev, 2002; Lisetskii et al., 2014; Rysin, 1998; Korytny, 2001) and only one database presents a cartographic model of small rivers in the all study area (Ermolaev et al., 2017).

Therefore, materials published in the past have not provided a regional-scale (1:500,000) quantitative assessment of modern soil loss by erosion in the arable lands in the EPR using the river basin approach and GIS technologies. Hence, the goal of our research is to develop an up-to-date map model of the intensity of soil erosion in the arable lands of the EPR at a higher spatial detail (a scale of 1:500,000) using a spatial analysis that features results generalized for small river basins.

To achieve this goal, the following steps were taken:

1) Source information was collected and a geodatabase was prepared for the factors that affect the water erosion of soil for future calculations;

2) The calculations were performed and a cartographic-geoinformational model of the water erosion of soil for the arable lands studied was created;

3) The intensity and spatial development of soil erosion in the given macroregion of Russia were analysed; **and**

4) The fidelity of the resulting cartographic model was assessed.

The main novel findings of the research are as follows:

1) The first calculations of soil erosion losses in this territory were conducted using the best spatial detail at the given time, in comparison with previous studies, using modern data on land use and precipitation intensity;

2) In addition, the basin approach to synthesize erosion data was used in first time for all study area. Using this approach to present data on geosystem formations, such as small river basins, enables plans to combat soil erosion at the local (municipal) level;

3) A quantitative assessment of soil erosion and mapping was obtained over a large portion of Russia.

In addition, the work presented here is based on the same methodological approach for calculating soil erosion losses that is used in Moscow State University (Litvin, 2002), (Litvin et al., 2017).

2. Methods & materials

2.1. The research territory

The EPR covers an area of approximately 4 million km^2 and is situated over several landscape zones, from tundra to temperate zone deserts (Fig. 1). According to the Land Cover Map obtained in 2014 from satellite data from TerraNorte RLC v.3 (Bartalev et al., 2015), which was designed by the Space Research Institute of the Russian Academy of Science (RAS), the total area of arable lands in the EPR comprises approximately 600,000 km^2. Approximately 95 million people live in this region, which is the majority of Russia's population. The environmental conditions that accompany soil erosion in this vast territory are diverse. We created and published an online dedicated geoportal called ‘The River Basins of the European Territory of Russia’ (http://bassepr.kpfu.ru/) that displays the environmental conditions of the territory (terrain, climate, hydrology, soils, land use, human-induced impact).

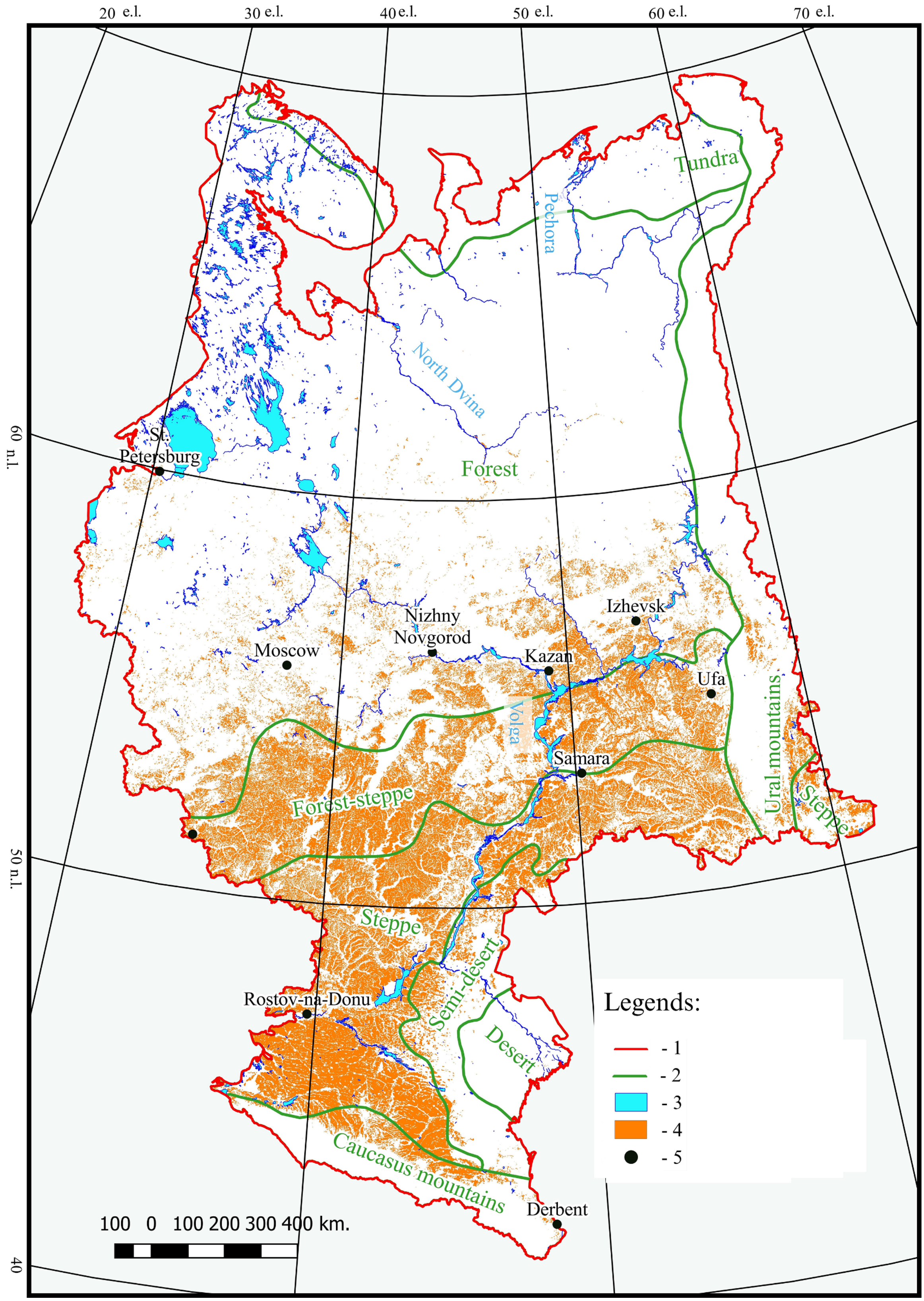

Fig. 1. The territory of research, (1 - study area; 2 – borders of landscape zones; 3 - lakes and reservoirs; 4 – arable lands; 5 - cities).

2.2. The technique for delineating river basins

The Global Multi-resolution Terrain Elevation Data 2010 (GMTED2010) and the raster model of the hydrographic network were used to construct the boundaries of the river basins in the entire area of study and to generate a corresponding electronic vector map. The boundaries were delineated in the automatic mode using an algorithm implemented in the Whitebox Geospatial Analysis Tools GAT software product (Lindsay, 2016). A series of test calculations were preliminarily conducted within areas with different topographic features. The basins were planarly delineated; that is, not only the catchment areas of small rivers but also their inter-basin spaces were delineated.

The results show that in the selected test areas the mean difference between the indicators of the river basin areas identified automatically and manually was 3.6%. For areas with weakly dissected lowland topography this error did not exceed 5%, while in areas with relatively dissected, elevated topography, the error was approximately 2%. The automatic construction of the river basin boundaries used for the cartographic model thus developed is quite satisfactory. Such an error can be deemed acceptable because delineating the borders manually does not produce perfect accuracy either. The technique for delineating river basins is presented in detail in previous studies (Ermolaev et al., 2017). Hence, an electronic map of the river basins was created for the EPR. A geodatabase comprising information about the natural-anthropogenic conditions in which the soil erosion develops in the basins was formed.

2.3. The technique for calculating the potential soil erosion

Considering the climatic conditions that accompany the formation of the superficial slope runoff in the EPR (during a long and snowy winter), the assessment of the soil erosion by water should include a combination of soil erosion assessments performed during periods of storm and snowmelt runoff. Rainfall plays a dominant role in the annual precipitation. The annual precipitation decreases to the north and to the south of the forest zone (Table 1). Rainfall prevails over snowfall in all zones. In the tundra, this difference is minimal (29%). The further south of the forest zone, the less snowfall, and the larger the difference between the snowfall and the rainfall. The difference is nearly three and four times larger in the semi-desert and desert zones, respectively.

We used empirical mathematical models that consider both snowmelt and storm runoff erosion to calculate the potential soil loss. These values were assessed using empirical dependence widely known in Russia (Larionov, 1993). The model includes such additional factor as surface flow during snowmelt.

All model calculations for the territory of the EPR are performed in raster layers containing cells 200 m in diameter and later generalized for river basins. Model calculations were performed as follows:

- The factors of soil erosion included in the storm runoff erosion model and in the snowmelt erosion model were calculated;
- The potential storm runoff soil erosion (E_{rain}) was calculated;
- The potential snowmelt soil erosion (E_{snow_melt}) was calculated;
- The annual intensity of soil erosion was calculated by summing the intensity of storm runoff and snowmelt erosion (E_Y) using formula 1 as follows:

$$E_Y = E_{rain} + E_{snow\_melt} \tag{1}$$

Table 1
The distribution of precipitation according to landscape zones.

Landscape Zone	Rmean*, mm	Rcold*, mm	Rwarm*, mm
Desert	204	43	161
Semi-desert	298	78	220
Steppe	420	124	296
Forest-steppe	474	136	338
Forest	525	161	364
Tundra	376	157	219
Ural mountains	505	185	320
Caucasus mountains	768	137	631

Rcold – snow (sold precipitation).
Rwarm – rainfall.
* Rmean – The amount of annual precipitation.

2.3.1. Rainfall soil erosion

The annual rainfall soil erosion rates were calculated for croplands with an empirical model that used a modified version of the USLE-based approach (2) (Larionov, 1993). Modifications of the initial USLE model included an improved set of equations to determine topographic factors, a novel approach for calculating and mapping the rainfall erosivity index for European Russia (Krasnov et al., 2001), as well as the adaptation of land use factors and soil protection techniques specific to the Russian agricultural system. E_{rain} was calculated as follows:

$$E_{rain} = f(R, K, LS, P, C) \tag{2}$$

where E_{rain} is the annual average rainfall soil loss (t ha^{-1} year^{-1}); R is the rainfall erosivity factor (t mm) /(ha min) year $^{-1}$; K is the soil erodibility factor (t ha min/((t*m) ha mm); C is the land-use factor (dimensionless); LS is the slope length and slope steepness factor (dimensionless); and P is the crop factor (dimensionless).

2.3.2. Rainfall erosivity factor

To calculate the potential soil loss for the arable lands of the EPR, we need information on the weather conditions, in particular, on the rainfall erosivity of the maximum 30-minute intensity and its annual distribution. The previously drawn EPR map of this weather parameter (Larionov, 1993; Litvin, 2002) reflects the situation as it was in the mid-1980s. However, the climatic system has undergone significant changes over the past few decades. The annual precipitation in the spring–-autumnal period has increased (Groisman et al., 2005). Research studies (Golosov and Yermolaev, 2019) have established that despite the differences in the nature, frequency, and magnitude of heavy precipitation in each landscape zone during the warm period, it is possible to distinguish a number of general tendencies among zones: (a) there has been a major increase in erosion-threatening precipitation, with a daily rainfall depth of 50 mm in all forest areas; (b) the forest-steppe and steppe zones are characterized by non-linear changes in the frequency and amount of precipitation and feature a daily rainfall depth of 10–30 mm; in addition, the frequency and amount of precipitation has increased, with a daily rainfall depth of 40–50 mm; (c) the area south of the steppe zone and the foothills of the Caucasus has experienced a decrease in the frequency and amount of precipitation, with a daily rainfall depth of up to 40 mm, and an increase in the frequency of precipitation, with a daily rainfall depth of 40–50 mm. Overall, in the warm seasons from 1960 to 2015, precipitation that can cause soil erosion (with an intensity of > 10 mm/day) has tended to increase (Golosov et al., 2018a).

These factors led us to attempt to create a map model of the modern spatial distribution of erosive rainfall potential in the EPR to perform calculations. The intra-annual redistribution of liquid precipitation was assumed to have remained approximately the same. An up-to-date rainfall erosivity model was created based on daily observation data from meteorological stations from 1965 to 2015. The data have been uploaded from the official website of RIHMI-WDC (http://meteo.ru/). The raster model of the rainfall erosivity was designed in two stages using software developed in the R Programming Environment (Bivand et al., 2015).

During the first stage, to calculate the rainfall erosivity at every meteorological station, we used formula 3 (Kanatieva et al., 2010) as follows:

$$R = 3.19e^{0.006P} \tag{3}$$

where P stands for the long-term average annual sum of the daily rainfall depth over 10 mm during the warm season (the warm season is determined to be the time during which the average daily temperature is above 0 °C).

During the second stage, we calculated the raster model of the long-term average annual rainfall erosivity in 1965–2015 using the MBA spatial interpolation technique (Finley and Banerjee, 2014) and the rainfall erosivity data obtained at meteorological stations.

2.3.3. Soil erodibility factor

Currently, there are several publicly available databases of soil characteristics that could be used to calculate the soil erodibility factor for the region under study. For example, one of the most recent global databases containing the soil characteristics of the study area was created within the framework of the SoilGrids project (Hengl et al., 2017). The cartographic models from this database were designed based on global soil profile data and modeling. We could have used this database for our calculations as it is consistent with the level of spatial detail featured in the research. However, it was not used in the modeling work because it lacks open source information regarding the origin of the source data for the soil profiles in the research area and does not employ a map of soil type distribution in Europe as a covariate for modeling.

Therefore, the 'Unified State Register of Soil Resources of Russia' was used as the main source of information on soil parameters to prepare data on the properties of the soil, which are presented on the website http://egrpr.esoil.ru. The registry consists of two parts: a spatial database of the soil section properties and a map of soil types. A detailed description of the creation of a geoinformational database for this registry is presented in articles written by employees of the Soil Institute V.V. Dokuchaev (Rukhovich et al., 2011).

Not all soil types were used in the calculations. Hydromorphic soils were excluded since their locations exclude the possibility of slope erosion.

The erodibility (K-factor) was calculated using formula 4 as follows:

$$K = [16.67 * \{d * (100 - e)\}^{1.14} * (10^{-6}) * (12 - a) + 0.25 * (b - 2) + 0.193 * (4 - c)] * z \quad (4)$$

where d is the fraction content of particles 0.1–0.001 mm in size, %; e is the fraction content of particles $<$ 0.001 mm in size, %; a is the organic matter, %; b is the classes for structure; and c is the classes for permeability.

2.3.4. Length-Slope factor

Currently, there are several techniques commonly used to calculate the Length-Slope (LS) factor. First, the LS factor can be calculated following the methods in USLE. However, this technique largely overestimates the LS factor values for steep slopes, which is why the RUSLE model for slopes with a gradient of more than 9% employs a different calculation technique. There are also other techniques for calculating the LS factor suggested by some authors (Moore and Nieber, 1989) and (Bosco et al., 2008). The Moscow State University (MSU) considered the terrain of Russia and developed an equation to calculate the LS factor that differs from other techniques reviewed because it better smoothed the LS outliers in areas of elevated terrain and rugged topography.

The LS factor was calculated according to formula (5) (Larionov, 1993) as follows:

$$LS = 22,1^{-p} L^{p} \frac{18,62 \sin\left[arctg\left(\frac{1}{100} I\right)\right]}{1 + 10^{0,339 - 0,06I}} + 0,065 \quad (5)$$

where I is the slope, %; L is the slope length, m; and p is determined by formula (6), as follows:

$$p = 0,2 + 2,352(p_0 - 0,2)L^{-0,15} \quad (6)$$

where p_0 – slope percent $<$ 1% is 0.2, 1–3% is 0.3, 3–5% is 0.4, and > 5% is 0.5.

2.3.5. Land use and crop factors

All soil erosion values were calculated only for arable land in European Russia. The location of arable land was obtained from TerraNorte RLC v.3 'Map of Land Cover Types' developed by the Space Research Institute of the RAS. This model is updated annually and has a scale of 1:500,000. We used the 2014 model version in our studies. A full description of the methodology for creating this model is given by Bartalev and co-authors (Bartalev et al., 2015).

According to the data obtained, arable land almost completely disappears north of 60° (Fig. 1). According to agro-climatic conditions, these territories are unfavorable for agriculture and arable land distribution is limited. The territories are heavily forested and marshy; therefore, the plowing of river basins here does not exceed 26%.

The calculations were made only for arable lands and conventional tillage is used in most of European Russia. There are serious attempts protect soil from erosion in several EPR regions. Therefore, in the Belgorod region (forest-steppe, steppe), which is the most eroded region and has a predominance of chernozem soils (chernozems occupy 78% of the area, the area of eroded soils is 50%), an unprecedented modern Russia National pilot program to protect soils from erosion was realized in 2015. This program is based on the concept of basin environmental management. More than 100 projects for soil–water protection in the catchments of 63 river basins were developed as part of this program. Each project includes improvements to the organization of crop rotation, the transfer of arable land for conservation, tinning of ephemeral gullies, and the creation of contour forest belts (Lisetskii et al., 2014). Another example is the territory of the Republic of Tatarstan (forest, forest-steppe zone). Here, from 1994 to 2005, approximately 16 billion rubles (approximately 200 million €) were allocated under the program to construct anti-erosion measures to increase soil fertility and protect soils from erosion. Approximately 4% of arable land with a slope of more than 5° was transferred to hayfields and pastures. This led to a sharp slowdown in the linear growth of gullies and a decrease in the rate of gullies dissection (Medvedeva, 2018).

In addition, there was no direct data on changes in the intensity of soil erosion on arable land obtained from the field stations in recent decades for the whole European Russia. Available observations are very contradictory and are not regular in time or space. Therefore, it is difficult to determine how the measures taken to protect soil from erosion in the local territories will globally affect the quantitative assessment of soil erosion throughout the EPR.

Because there is no free available spatial information about how to cultivate land over such a large territory, C, the land-use factor in the calculations of rainfall erosion and snowmelt erosion, was assumed to be 1.

Information about the crop factor (P) was taken from an article by Litvin (Litvin et al., 2017) based on information from the Russian State Committee on Statistics of typical crop rotations in each landscape zone (http://www.gks.ru).

2.4. The snowmelt erosion

The modified Russian State Hydrological Institute (SHI) model (Larionov, 1993), which estimates erosion from snowmelt, was used for calculations in this study (7). The data required for the SHI model inputs include detailed topography, local soil properties (similar to the USLE), depth of overland surface flow during snowmelt and land-use, and crop information. The depth of the overland flow depends on the water content in the snow, the precipitation and the coefficient of slope runoff during snowmelt, as follows:

$$E_{snow\_melt} = f(h, K, I, L, P, C) \quad (7)$$

where E_{snow_melt} is the annual average snowmelt soil loss (t ha^{-1}) per year; h -is the overland surface flow during snowmelt; K is the soil erodibility factor; C is the land-use factor; I is the slope; L is the slope length; and P is the crop factor.

Considering the specifics of the erosion model in use, in which the share of the snowmelt runoff in the annual soil loss by erosion is relatively small (approximately 10%), calculations were based on the water content map of the snow created in the 1970s (Larionov, 1993). The value of the spring runoff layer is calculated based on the dependence (8) as follows:

Table 2
The value of D and E coefficients for different landscape zones and soil textures (Larionov, 1993).

Landscape zone	Soil texture	D	E
Forest	clay, loam	2.6953	0.89836
	sandy loam	2.1118	0.63475
Forest-steppe	clay, loam	3.1219	0.96103
	sandy loam	2.4472	0.73120
Steppe	clay, loam	3.0235	0.99758
	sandy loam	1.37	0.60474

$$h = HDI^{E}; \tag{8}$$

where: H – water content in the snow, mm.; I – slope, %; and D and E are coefficients, which depend on the landscape zone and soil texture (Table 2) (Larionov, 1993).

3. Results and discussion

3.1. The spatial analysis

The main result of this research is the quantitative assessment of the potential current soil loss by erosion on arable lands of the EPR, as reflected by the corresponding thematic map (Fig. 2). The results obtained have been generalized to the network of small river basins (Fig. 3) previously developed to enable river basin land use management of large territories (Ermolaev et al., 2017). The advantages of using these two cartographic models relative to those previously created are as follows:

1) A quantitative assessment of the intensity of potential soil losses in European Russia was realized, in contrast to the results of projects such as: «World map of the status of human induced soil degradation (GLASOD)» (Oldeman и др., 1990). «Map of human-induced soil degradation in Central and Eastern Europe (SOVEUR)» (van Lynden, 1997), and «The map of spatial variation in soil erosion by water» (Van Oost et al., 2007), which provide qualitative assessments of the degree of erosion relevant at the time of map creation;

2) Our cartographic models quantify the intensity of erosion in the entire EPR and are spatially more detailed in comparison with other models (Sobolev, 1968), (Shoba, 2011), (Litvin et al., 2017) based on the scale of the cartographic models and the detail of the source spatial data;

3) This study uses the most modern spatial data on land use in the study area and a modern author's model of precipitation intensity.

Having analysed the results obtained, the amount of potential erosion of arable lands in the EPR widely varies, with 99% of values ranging from 0 to 40 t ha^{-1} year^{-1}. In addition, the average potential soil loss amounts to 4.04 t ha^{-1} year^{-1}.

The spatial distribution of potential soil erosion is also highly heterogeneous. Several zones with high soil loss values have been determined. Within the plain territories, there are two characteristic erosion zones; these zones are the western longitudinal sector and the eastern subzone in the latitude of 50–55° N, which stretch along the right banks of the rivers Volga (Nizhny Novgorod–Kazan) and Kama (Kazan–Izhevsk). Other areas with high soil erosion values are situated in the foothills of the Caucasus and the Urals.

As expected (due to the higher values of the erosive potential of the terrain), soil erosion increases from the lowland plains (3.65 t ha^{-1} year^{-1}) to the high plains (4.90 t ha^{-1} year^{-1}), peaking in the mountains (12.88 t ha^{-1} year^{-1}) (Table 3). High values of potential soil losses are observed in the regions that are mostly situated in the forest landscape zone and have low suitability for plowing and high erosivity of the sod podzol and podzolic soils (Albic Retisols (Ocric) and Albic Podzols) that prevail in those regions (Table 4).

Table 4 shows that the soil erosion rates in the arable lands consistently decrease from the forest landscape zone (4.49 t ha^{-1} year^{-1}) to the semi-deserts (2.15 t ha^{-1} year^{-1}) and the deserts landscape zone (0.61 t ha^{-1} year^{-1}). For the annual soil loss by erosion, erosion by rainfall prevailed at 3.78 t ha^{-1} year^{-1}, while snowmelt runoff showed significantly smaller values, at only 0.26 t ha^{-1} year^{-1} (Fig. 4). The east–west trending zone featuring the highest soil erosion is clearly distinguished on the thematic map (Fig. 2). This zone coincides with the mixed and broad-leaved forest subzone, which has high levels of plowing. Moreover, a western longitudinal sector of high soil erosion that includes the forest and forest-steppe landscape zones was also determined. In our opinion, soil erodibility plays a main role in decreasing southward soil loss, and also naturally decreases south of the EPR due to the widespread development of chernozems in the steppe zone and a significant reduction in melt runoff.

In contrast, the arable lands of the forest landscape zone feature sod podzols and podzolic soil (AlbicRetisols (Ocric) and AlbicPodzols), which have a pulverescent structure and low resistance to the superficial slope runoff. The lowest erosion values observed in semi-deserts (2.15 t ha^{-1} year^{-1}) and deserts (0.57 t ha^{-1} year^{-1}) are associated with the generally flattened nature of the terrain, low superficial runoff amounts and the areal nature of farming. Soil deflation processes are the major type of soil degradation in this area.

3.2. Accuracy of the results of the calculation of soil erosion in the landscape zones of the EPR at different levels of spatial detail

To evaluate the accuracy of the results we used previously published data for this territory. In particular, according to the data by Golosov (Golosov et al., 2017) obtained for 12 local drainage basins of the EPR using the radio-cesium method to determine the intensity of soil erosion, the average annual rate of erosion in 2012 amounted to 4.1 t ha^{-1} year^{-1} in the forest zone, 3.3 t ha^{-1} year^{-1} in the forest-steppe zone, and 3.3–4.6 t ha^{-1} year^{-1} in the steppe zone. These results were in good agreement with the speed of erosion obtained in this research (see Table 4).

The obtained erosion values were also verified by the same calculation method that used highly detailed materials on local territories situated in the main agricultural areas of the EPR. The main objective is to assess the role of generalization in the obtained results. The small river basins from different landscape zones used for verification are as follows: Izh (southern and middle taiga zone); Mesha (subzone of mixed forests); Ulema (forest-steppe); Medveditsa (southern forest and steppe zone); Veduga (southern forest and steppe zone); Samara (steppe); and Kuma and Kalaus (steppe). The source information for the river basins used for calculations was significantly larger and corresponded to a scale of 1:50,000. Upon analysing the erosive soil loss data obtained during the verification, the erosion values for arable lands we obtained for the whole territory of the EPR at a scale of 1:500,000 are consistent overall with results calculated for the key areas that have more detailed information with which to calculate erosion. The observed discrepancies in the majority of the test territories (Table 5) (Maltsev and Yermolaev, 2019) are within 1–19% (except for the catchment area of river Izh). The discrepancies in the data are mostly associated with relief parameters, which is consistent with the generalization of the terrain in the global terrain model is used in the calculations relative to the relief parameters obtained from large-scale maps.

The map of erosive soil losses in the territory of the EPR was compared to a similar soil erosion map for the European Union designed using the same calculation methods (Bosco et al., 2015) (Panagos et al., 2015). Erosive soil losses for the whole European Union, according to various estimates, generally vary between 2.46 and 2.76 t ha^{-1} year^{-1}. These values are slightly different from the results obtained here (4.04 t ha^{-1} year^{-1}). In addition, the values for soil erosion are comparable with those for the arable lands of the European Union and the EPR in similar landscape conditions. For example, erosive soil losses vary between 0.5 and 2 t ha^{-1} year^{-1} within the Polish,

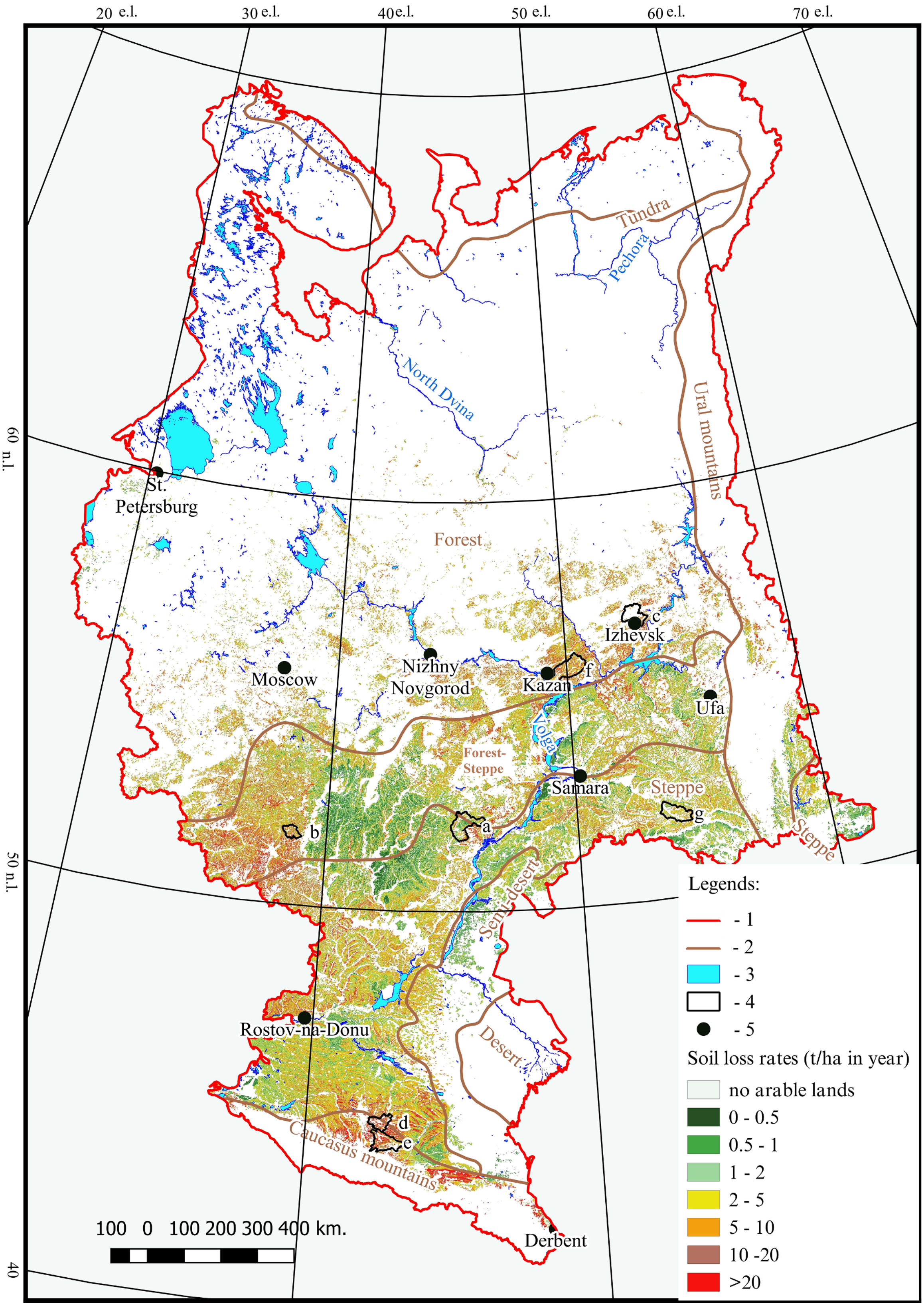

Fig. 2. The soil erosion map of European Russia, 1 - study area; 2 - borders of landscape zones; 3 - lakes and reservoirs; 4 - borders of test basins; 5 – cities.)

North German, Middle, and Lower Danube lowlands. The soil erosion in the plains of the middle and lower streams on the right bank of the river Volga, the Oka-Don Lowland, and the Caspian Lowland have the same values. The soil erosion values for the high plains of Germany, the Czech Republic, Bulgaria, Romania, etc. are 5–10 t ha^{-1} $year^{-1}$ on average. We received the same results for soil erosion across the arable lands of the EPR that have similar conditions (the Volga, Smolensk–Moscow, Central Russian Uplands, etc.). The mountainous areas

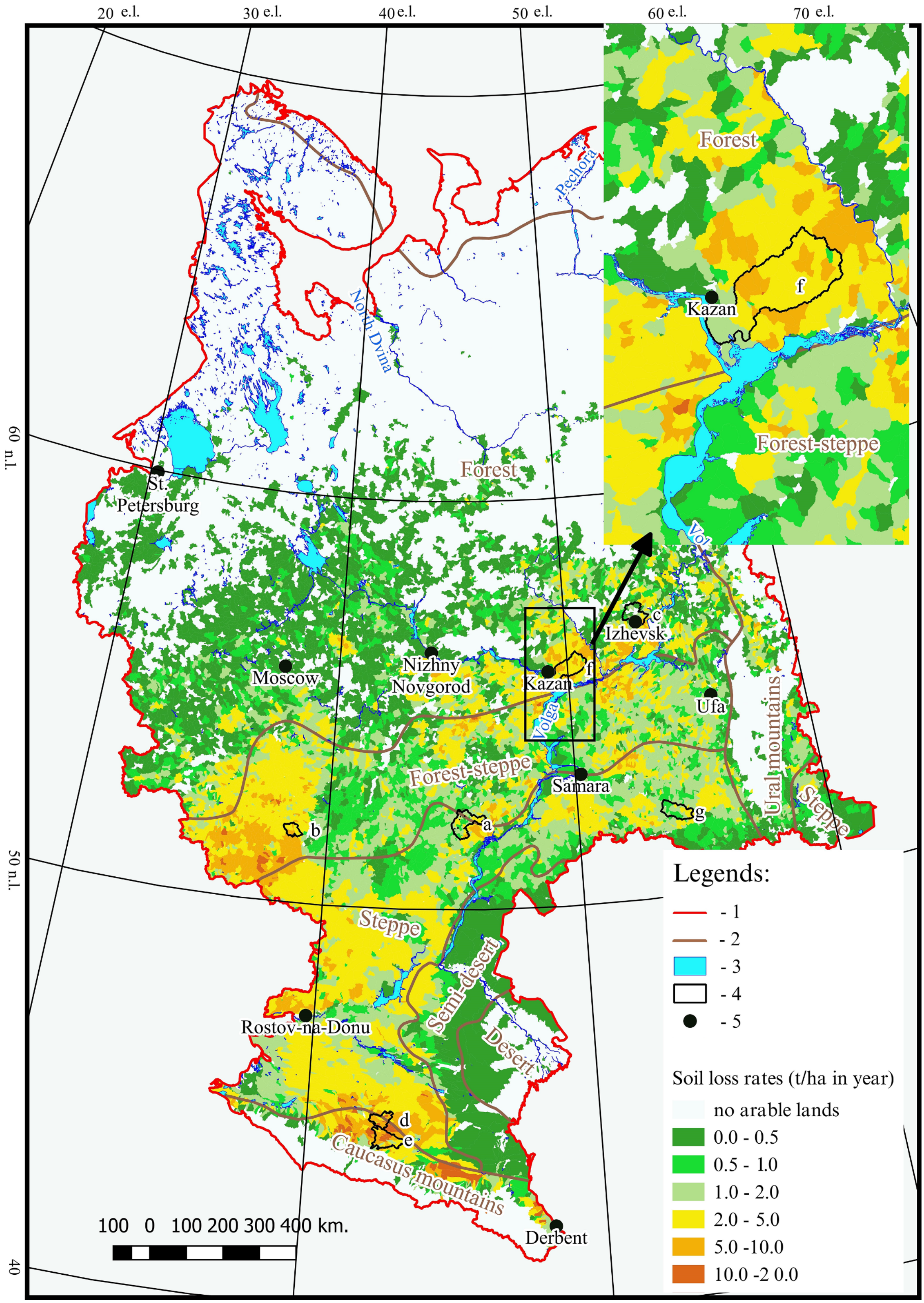

Fig. 3. The soil erosion map within river basin of European Russia, 1 - study area; 2 - borders of landscape zones; 3 - lakes and reservoirs; 4 - borders of test basins; 5 – cities.)

Table 3
Soil loss statistics within different types of terrain.

	Average, t ha^{-1} year^{-1}	Standard Deviation
Lowland Plain (< 200 m)	3.65	7.79
High Plain 200–500 m	4.90	11.21
Mountains > 500 m	12.88	26.77

of Western Europe (the Alps, the Carpathians) and the EPR (the Caucasus and the Urals) also have similar soil erosion values that vary from 10 to 20 t ha^{-1} year^{-1} to greater values.

3.3. Analysis of the temporal dynamics of potential soil losses in European Russia

The total annual soil losses decreased from 436 Mt in 1980 to 245 Mt in 2012, according to research by Golosov and Yermolaev (Golosov et al., 2018). Based on the spatio-temporal analysis of the potential losses of soil from water erosion within the administrative units, which was performed by the team from the laboratory of soil erosion and channel processes at Moscow State University (Litvin et al., 2017), we conclude the following:

- there was a significant (43%) reduction in soil erosion on arable land within administrative units located in the forest zone;
- there was a reduction (19%) in soil erosion on arable land within the administrative units located in the forest-steppe zone;
- there was an increase (19%) in soil erosion on arable land within administrative units located in the steppe zone.

The potential soil erosion values in the EPR calculated at a small scale (1:1,500,000) by Litvin for the mid-1980s (Litvin, 2002) within the various landscape zones are as follows: 6.7 t ha^{-1} year^{-1} in the forest zone, 4.6 t ha^{-1} year^{-1} in the forest-steppe zone, and from 2.2 t ha^{-1} year^{-1} to 6.5 t ha^{-1} year^{-1} in the steppe plain zones and the elevated areas. Our calculations show a decrease in the intensity of soil loss across the forest and forest-steppe landscape zones of the EPR (Table 3) relative to the intensity of soil erosion in the 1980s (Litvin, 2002). In addition, based on this comparative analysis, it is not possible to determine the direction of change in soil erosion within the steppe zone of the EPR.

Currently, the average annual intensity (4.04 t ha^{-1} year^{-1}) of water soil erosion in the research area is 15% smaller relative to that from the 1980 s (4.7 t ha^{-1} year^{-1}) (Litvin et al., 2017). Apparently, such a change is associated with the climatic change that led to a reduction in the share of snowmelt runoff in soil erosion. Seasonal snow cover is not currently formed south of the steppe and southwest of the forest-steppe zone, where arable lands are mostly situated; therefore, there is no snowmelt runoff (Golosov and Yermolaev, 2019). The change in the speed of erosion-accumulative processes over two periods (1954–1986 and 1986–2017) in small river drainage basins situated in different landscape zones of the southern part of the area allow us to assume that the main cause of the decrease is the change in the hydrometeorological conditions in the region. The general climate warming mostly impacted the increase in the temperatures in winter and in March. This led to a decrease in the depth of soil freeze and, consequently, to a decrease in the surface runoff and sediment runoff during spring snowmelt (Golosov and Yermolaev, 2019).

Another influence on the ambiguity of changes in soil erosion in the steppe zone was an increase in the crop factor in several administrative units south of the EPR.

In addition, it is difficult to determine how the intensity of erosion in the study region will change further, since it is affected by two multidirectional factors. As a result of global warming, the fraction of soil erosion from meltwater runoff will continue to decrease (Golosov et al., 2018a); however, in our opinion, this will not lead to a significant reduction in erosion intensity, since the fraction of erosion from this phenomenon in the southern intensively plowed part of the European Russia is small. In addition, a significant increase in the frequency of extreme rainfalls can cause soil erosion.

Soil cultivation methods may also significantly impact the intensity of erosion in the future. Thus, according to several studies (Golosov et al., 2018) in this territory, subsurface tillage are increasingly applied, and according to other studies (Litvin et al., 2017) in the southern highly plowed area, tilled crops have been sown more over the last 30 years.

3.4. Discussion and perspectives

This research allows us, for the first time, to obtain quantitative data on the intensity of soil erosion across arable lands within small river basins at a regional scale. All previous studies conducted in this area were limited to particular territorial subjects of Russia or performed at a small scale, with high spatial generalization. In addition, our research can also be considered a pilot project. The limitations associated with the sources of information, quality, and level of detail of the original data, as well as unresolved methodical objectives, are clearly visible as follows:

- Unfortunately, there is no national DEM for Russia; therefore, we used the global freely distributed DEM GMTED2010, which does not have the highest spatial resolution among global freely distributed models. Our use of a more detailed terrain model (for example, “AW3D30”) was not possible due to the limited computational capabilities at our disposal. As a result, the calculation of the LS-factor from the used DEM may be underestimated;
- We used the only cartographic model of soil types available on the public domain for Russia, which has a scale of 1: 2 500 000, to calculate the soil factor (K). This model greatly simplifies the spatial distribution of soil properties and, accordingly, soil erosion;
- The sparseness of the existing hydrometeorological stations (200 stations) in the study area also limits the spatial detail of erosion calculations;
- There are also methodological limitations in the work. The modified

Table 4
Soil loss statistics within different types of landscape zones.

Landscape Zone	Average, t ha^{-1} year^{-1}			Standard Deviation			99% - percentile			Area of arable land, km^2
	Year	Rain	Snow melt	Year	Rain	Snow melt	Year	Rain	Snow melt	
Forest Zone	4.91	4.77	0.49	8.82	7.78	1.96	40.32	34.23	7.18	97,321
Forest-Steppe Zone	3.91	3.67	0.29	8.91	7.73	1.55	41.35	37.19	4.60	187,251
Steppe Zone	3.37	3.26	0.16	6.86	6.26	0.92	30.42	28.43	2.41	248,728
Semi-Deserts Zone	2.15	2.14	0.08	3.81	3.67	0.25	17.39	16.47	1.09	28,208
Deserts Zone	0.61	0.60	0.003	1.14	1.13	0.01	5.15	5.13	0.05	47
The Caucasus Mountains	11.23	11.07	0.41	22.97	21.46	2.32	106.08	99.27	7.00	19,865
The Ural Mountains	3.85	3.46	0.43	14.61	10.0	5.36	43.95	37.94	5.66	13,106

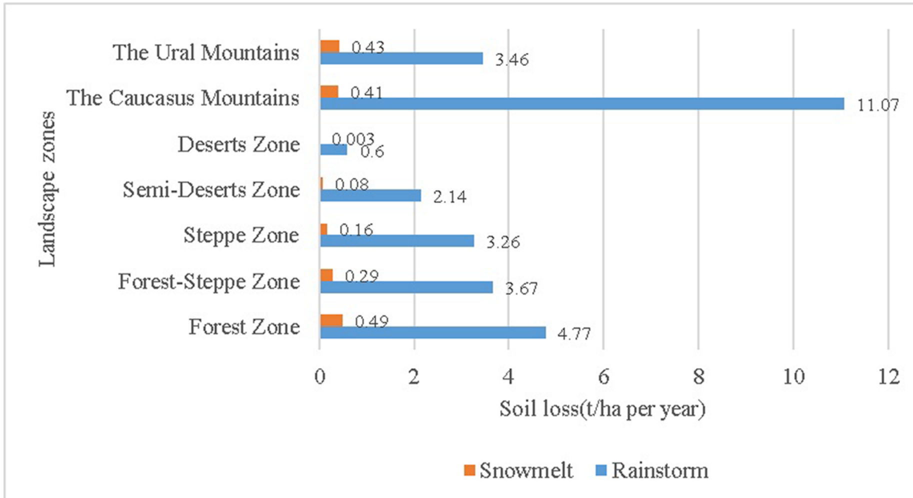

Fig. 4. Distribution of erosion soil loss within landscape zones of European Russia.

SHI equation used appears to underestimate the fraction of soil erosion from snowmelt runoff. According to the existing equation, it estimates the proportion of thawed flush to be approximately 10% of the annual soil loss. In addition, the resulting cartographic model does not evaluate the accumulation of the part of the soil that is washed away on arable slopes, which may overestimate the spatial estimates of potential soil losses in this cartographic model.

Therefore, it is necessary to obtain more realistic assessments of soil erosion during the next research stage. To outline the perspectives here, we define the following lines of research.

1. The rainfall erosivity (R) factor is one of the leading predictors in the equation of erosive soil losses. Our current research features a spatial model (R) that was based on the regression obtained earlier for the central part of the study area, which can cause discrepancies in the edges of the area under study. Therefore, it is necessary to obtain more realistic and up-to-date assessments of this input factor in the model of erosive soil loss in the future. This objective is also relevant given the changes that have occurred in the climatic system over the past 40 years. Over the past few decades, the amount of precipitation during the warm season of the year has tended to increase (with an intensity of > 10 mm/day), which can cause soil erosion (Zolina, 2011). Bayesian spatiotemporal models, one of the most modern and advanced approaches to modeling, will be used to solve the problem in the future. INLA, the statistical system of Bayesian modeling, will be used for this purpose.

2. Building a spatial distribution model of the managemental and agronomical factors (crop factors - P) for the EPR is also a relevant scientific objective that remains unsolved for now. Remote sensing data is the most adequate source of information to solve this issue. A new approach to automatically determine the vegetation factors based on remote sensing data will be employed. Then it will be possible to consider differentiation across the expansive area of the EPR and the within-year variability in the structure of the agricultural lands that differs from static data, within the limits of the landscape zones that we used in the current study to calculate the intensity of soil loss.

3. Erosion and accumulation occur simultaneously at every subcompartment of a slope. Therefore, the value of soil losses caused by water erosion depends on the balance between erosive and accumulation on the slopes of river basins. However, this research only assesses water erosion on slopes and does not consider the accumulation of soils in areas situated downhill. Therefore, a method to calculate erosive soil losses with regard to the accumulation of soil washed away on the slopes of local watersheds will be relevant, as will the creation of a cartographic model of soil losses caused by water erosion that considers this accumulation.

4. Conclusions

Against the background of the climatic changes that have occurred over the past 30 years (reduction in the share of snowmelt runoff in erosion), the intensity of soil losses in the EPR decreased by nearly 15% on average, from 4.7 to 4.04 t ha^{-1} year^{-1}. Erosion by rainfall prevails in terms of annual erosive soil loss, with 3.78 t ha^{-1} year^{-1} lost, while the snowmelt runoff causes significantly lower erosion, with only 0.26 t ha^{-1} year^{-1} lost.

In the future, the cartographic model of the erosive soil loss can be adjusted by creating models with more detailed spatial rainfall erosivity factors (R factor) and crop factors (P factor) with regard to the accumulation of the soil washed away on the slopes of river basins.

Table 5
Average soil loss from erosion for 1965–2015 within test river basins (Maltsev and Yermolaev, 2019).

River basin, regions Russian Federation	Soil loss, t ha^{-1} year^{-1}		Differences, %
	Scale 1:50,000	Scale 1:500,000	
Medveditsa, Saratov region (a - Fig. 3)	2.10	2.12	0.9
Veduga, Voronezh region (b - Fig. 3)	5.55	6.57	18.4
Izh, Udmurt Republic (c - Fig. 3)	4.51	6.13	35.9
Kalaus, Stavropol region (d - Fig. 3)	14.34	13.83	3.6
Kuma, Stavropol region (e - Fig. 3)	15.55	12.57	19.2
Mesha, Republic of Tatarstan (f - Fig. 3)	7.30	7.91	8.4
Samara, Orenburg region (g - Fig. 3)	2.52	2.27	9.9

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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