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DEGRADATION, REHABILITATION, AND CONSERVATION OF SOILS

Gully Erosion Zoning in the Middle Volga Region

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Abstract—The study presents a new scheme of zoning of modern gully erosion in a large region of the Russian Federation. Automated landscape zoning by means of artificial neural networks was carried out in order to determine the natural and anthropogenic conditions for the development of the gully network. Erosion zoning was implemented on the basis of large-scale geoinformation mapping of gullies with visual interpretation of high- and ultra-high-resolution satellite images for 2017–2021. The basins of small rivers (1314 in total) with an average area of 91 km^2 were taken as operational territorial units. 22688 gullies (including their lateral branches) were identified in the study area; their average length was 65 m, and the total length of the gully network was about 1500 km. The mean density of the gully network constituted 12 m/km^2, and the maximum density reached 301 m/km^2. This indicator indirectly reflects the intensity of gully formation and was used for the zoning of gully erosion. Most of the studied river basins (84%) had either no gully dissection or very weak and weak gully erosion. The main reasons for the widespread damping of gully erosion are related to changes in land use and in the climate system, as well as to an evolutionary factor—the transition of many gully forms to the balka stage of development.

Keywords: gully dynamics, automated zoning, geoinformation mapping, spatial analysis

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INTRODUCTION

The first thematic map of the gully–balka systems of Russia was compiled by Koz`menko at the beginning of the 20th century [2]. In the late 1940s, under the leadership of S.S. Sobolev, a map of the length of gully–balka networks was created for the European part of the Soviet Union. To compile it, sheets of a 10-verst map (scale 1 : 420000) were processed, illustrating gully–balka landforms at this generalization level. The length of the gully–balka systems was measured using a curvimeter and a magnifying glass [25]. The spatial development and zoning of gully erosion in the former USSR and Russia (including the Middle Volga region) with a cartographic generalization of the results was carried out by a number of researchers [5, 10, 16, 18, 20, 22, 28]. For these purposes, topographic maps of different scales (1 : 420000, 1 : 100000, 1 : 50000, and 1 : 25000) were most often used. As a rule, for large areas, generalization of data on gully dissection was carried out based on studies performed at key areas. Using this method, maps of the length of gully network and the number of gullies were compiled for the entire territory of Russia on a scale of 1 : 8 000000 and for the European part of Russia on a scale of 1 : 2500000 [5, 25].

The Middle Volga region, from the point of view of the intensity of the development of gully erosion, has always been considered a region with intense soil and gully erosion, the so-called "erosion pole" of Russia. The results of studies of the gully erosion in this region have a long history dating back to the middle of the 20th century. The study of gullies, including their mapping using topographic maps, is discussed in [7, 8, 26]. Much less often, remote sensing data (large-scale aerial photographs 1 : 17000–1 : 25000) were used for mapping because of the lack of free access and complexity of image analysis. in In the 1980s, large-scale work on mapping gullies in the east of the Russian Plain was carried out by Kazan geographers under the leadership of A.P. Dedkov [19]. The assessment of gully erosion was carried out for elementary basins (catchments of rivers of the second or third order) within large physiographic regions. Unfortunately, no map of the zoning of gully erosion zoning was made. and the results of this work are largely outdated, since mapping was carried out using aerial photography of the 1950s–1970s. Later, these materials were laid in the basis of the first map of erosional zoning of the Middle Volga region developed in the early 2000s [7, 8]. Thus, the existing maps of gully erosion zoning in the study area are made either with a high generalization level or reflect the situation observed 50–70 years ago. The introduction of geoinformation technologies in thematic mapping and spatial analysis, as well as free access to and availability of high-resolution satellite images space allow us to revisit the problem of modern gully erosion in large areas. There are a number of reasons for this: firstly, the changes that have taken place in the climate system since the 1980s; secondly, a significant transformation of land uses and management systems following the disappearance of the Soviet Union from the geopolitical arena; thirdly, a time factor that determines the natural morphological and genetic evolution of gully landforms.

At present, geoinformation mapping of modern gully erosion using high-resolution satellite images, which are not inferior to aerial photographs in terms of detail and the ability to display linear forms of erosion on slopes, has been completed [12, 17, 31].

The main purpose of this study is the typological zoning of modern gully erosion in the Middle Volga region using the basin approach and the determination of the natural and anthropogenic factors of gully development.

OBJECTS AND METHODS

The study area is a part of the Middle Volga region (Fig. 1) and includes three federal subjects of the Russian Federation (the Chuvash Republic, the Tatarstan Republic, and the Ulyanovsk oblast) with a total area of 123 300 km^2. Valleys of the Volga River and its largest tributary Kama River—divide the territory into four unequal physiographic regions. The largest one is the Cis- Volga region; then, in descending order of area, the Trans-Kama, Cis-Kama and Trans-Volga regions follow.

Landscape conditions for the development of gully erosion. Since gully erosion is a multifactorial process, the assessment of both natural and anthropogenic factors is necessary to identify the spatial patterns of this process. A comprehensive physiographic zoning of the Middle Volga region was carried out to solve this task.

In any thematic zoning, typological and regional approaches are distinguished. The typological approach takes into account the most significant features for a certain taxonomic level of regions [1, 14] and omits many of their particular features. In this case, the characteristic is not given to each delineation, but to a group of delineations of the given type. The regional approach implies such a differentiation of territorial units, each of which is identified on the basis of the homogeneity principle and is characterized by a clearly expressed individuality, so that their properties differ in adjacent regions [21]. In the present study, typological zoning was carried out in order to identify territorial units that are homogeneous in terms of a set of features at the district rank. At the regional level, in the conditions of the East European Plain, three main types of natural—territorial structures are developed: (1) cellular (physiographic and geomorphic regions and provinces); (2) isopotential, with vector fields (bioclimatic zones and subzones); and (3) basin type [15]. As units of spatial zoning and structural—functional analysis, small river basins were used; for each of them, exact location and length of gullies were determined.

When zoning, the following basic principles were observed. Firstly, it was carried out taking into account morphological features that reflect the most important patterns in the spatial variability of landscape conditions due to the interaction of zonal and azonal natural factors. Secondly, the requirement of proportionality of the territorial complexes assigned to the same rank was followed at each stage of zoning. Thirdly, zoning was carried out according to the bottom-up principle, i.e., from the particular to the general.

The Middle Volga region has repeatedly served as an object of landscape (physiographic) zoning. This is evidenced by the existing zoning schemes [14, 23, 26]. Most authors recognize that geological and geomorphic conditions, which are azonal factors, play a significant, often decisive role in the intrazonal differentiation of landscapes. This is especially noticeable at the lower levels of the landscape classification, when the lithomorphic factor is the determining criterion for distinguishing genera and types of landscapes. In all existing zoning schemes, the most controversial issue is the drawing of zonal and subzonal landscape boundaries, which are most complex in terms of a combination of discrete and continual types of boundaries (in this study, this is the boundary of the forest and forest-steppe zones).

The proposed landscape zoning scheme takes into account, to the fullest extent possible, not only the factors that directly affect erosion but also the conditions that have an indirect effect. Priority was given to features that have a sufficient variety of their values and are available for measurement in order to obtain mass discrete material. Both zonal and regional factors of territorial differentiation were taken into account. The well-known "black box" principle was used in the informational assessment of geocomplexes at the regional level. In accordance with it, landscape-geophysical, geomorphic, and biotic features were selected as input parameters that determine the spatial differentiation of landscapes. For example, the landscape—geophysical features were the annual total radiation; mean annual and flood discharge; rainfall erosivity (for 10- and 30-min rainfalls), hydrothermal coefficient; runoff and climate continentality coefficients; maximum snow cover depth; underground and surface river runoff; annual precipitation; precipitation of the warm season; gross moistening of the territory; water reserves in the snow cover; radiation balance; and sum of biologically active temperatures. The geomorphic features included the length of valley dissection; soil texture, parent material, mean steepness of the basins; depth of erosional dissection, mean length of the slopes of river valleys and balkas, area distribution by absolute heights; minimum, maximum, and mean height, and standard deviation of absolute heights in the basin; soil humus content and

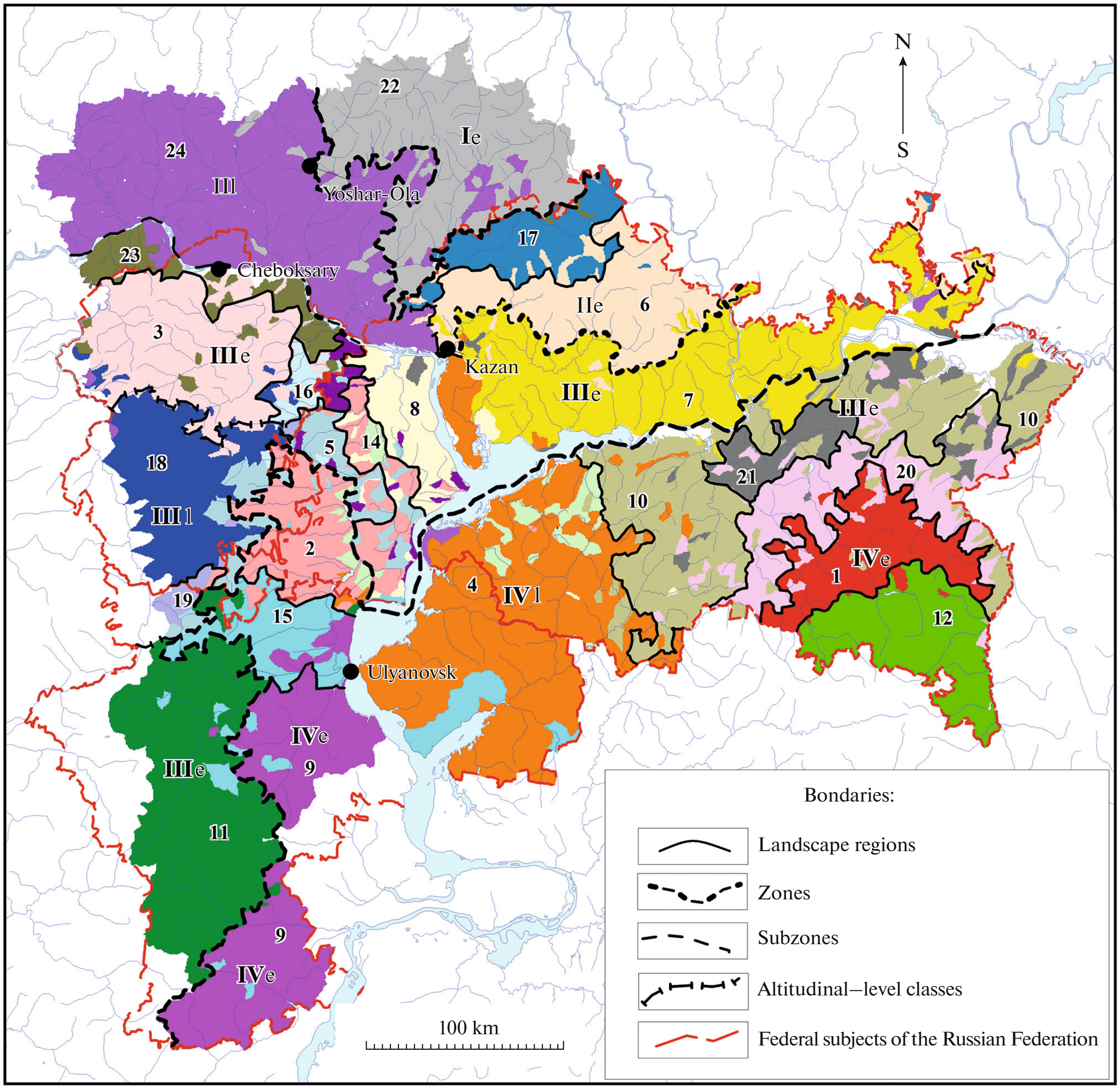

Fig. 1. Landscape zoning of the Middle Volga region. Symbols: (I) boreal moderately continental (southern taiga); (II) boreal moderately continental (subtaiga); (III) subboreal northern semihumid (broadleaved); (IV) subboreal northern semihumid (forest-steppe); l is subclass of low plains; e is subclass of elevated plains; numbers indicate the numbers of landscape areas (Table 1).

stocks; thickness of the cover of deluvial–solifluction loams. Information on the primary productivity of landscapes was included in the biotic block and was considered an integral landscape-geophysical parameter of the functioning of geosystems.

The output block of characteristics of geocomplexes at the regional level included the length of balka network, soil cover features (at the level of soil subtypes), percent of forest area, and percent of meadow area in the basins. These parameters are important diagnostic features of landscape types at the zonal and regional levels.

Overall, more than forty different parameters were involved for the purposes of landscape zoning of the region., Information sources for this geodatabase were published [9].

The automated selection of homogeneous regions, due to the detail and multidimensionality of the initial information corresponding to the river basin and the combination of features from particular to general, made it possible to get away from the subjective approach in generalizing the results that occurs with the manual zoning method. As a zoning method, artificial neural networks [30] were involved with the initial division of the entire sample into 121 classes. Such a number of classes further allows, using the hierarchical classification methods, to group them into relatively homogeneous entities or regions suitable for analysis. The zoning area in the northern part of the Middle Volga region was somewhat expanded. This was due to the need to more accurately establish the southern boundary of the forest zone, since it separates two bioclimatic zones of temperate latitudes: boreal (taiga-forest) and subboreal (forest-steppe and steppe). After the identification of core areas and the subsequent procedure of class merging, twenty one landscape regions were identified (Fig. 1). The resulting landscape boundaries correspond to the boundaries of the regions; their sinuosity is determined by the configuration of the river basins. When drawing zonal boundaries, areas, consisting of several small basins, typologically homogeneous, but located apart from the core area, were generalized. The boundary between the boreal and subboreal zones was drawn taking into account the distribution of the sum of biologically active temperatures (in the range of 2100–2150°C); annual radiation balance (1500–1550 MJ/m^2) [3]; and radiation index of dryness (in the range of 1.0–1.05).

In accordance with the zoning of the study area, each identified region can be attributed to the following altitudinal–layer classes and zonal–sector types of landscapes:

—boreal (Eastern European) moderately continental elevated subtaiga landscape (regions 6, 17);

—subboreal northern semihumid (Eastern European) elevated broad-leaved landscape (regions 3, 5, 7, 8, 11, 14, 16, 19, 23);

—subboreal northern semihumid (Eastern European) broad-leaved moderately continental lowland landscape (region 18);

—subboreal northern semihumid (Eastern European) moderately continental forest-steppe landscape (region 4);

—subboreal northern semihumid (Eastern European) moderately continental elevated forest-steppe landscape (regions 1, 2, 9, 10–12, 15, 20, 21).

The main characteristics of the landscape conditions of the studied region, are summarized in Table 1. Soddy-podzolic soils (Albic Glossic Retisols (Abruptic, Loamic, Ochric)) predominate in the of the northern part of the region in lowland, fully forested areas of Chuvashia and Cis-Kama region of Tatarstan. Light gray forest soils (Luvic Retic Greyzemic Phaeozems (Loamic)) are widespread in the northern part of the Volga Upland and in the Cis-Kama region of Tatarstan. Leached chernozems (Luvic Chernic Phaeozems and Luvic Chernozems) (604 basins) predominate in river basins in the central part of the Volga Upland and in the Trans-Kama region of Tatarstan.

Methodology for the analysis of modern gully dissection. Mapping of modern gully erosion was carried out by visual interpretation of high and ultra-high resolution satellite images for the period 2017–2021 provided by Yandex, Google, Bing, ESRI, and Nokia resources. A system of interpretation features was formed to determine gully landforms on the images. These landforms are characterized by (a) sharp geometrically well-defined boundaries, (b) characteristic shape of a gully, (c) linear and dendritic patterns with a clearly defined rim and thalweg, and (d) some indirect signs (shadows that allow determining the transverse profile of the gully; color and hue indicating the presence of bare areas). During interpretation and subsequent mapping, the gullies were subdivided according to their origin into primary (on slopes and river banks) and secondary (developed in the bottoms of the already existing erosional landforms) gullies. The methodology of interpretation of gully landforms was described in more detail in [11, 12, 29].

Based on the results obtained using the basin approach (the previously created layer of small river basins was taken from the Kazan Federal University geoportal http://bassepr.kpfu.ru/ [32]), the modern gully dissection of the study area was mapped. For each basin (there are 1314 in total), the total length of the gully network and the degree of gully dissection of the territory were determined using parameters of the density of gully network (total length and number of gullies per unit area).

Using GIS, the zoning of modern gully erosion in the study area was carried out. For the zoning of gully erosion, the following intervals were identified for the length of gully network: (1) 0 (absence of gullies), (2) up to 5 m/km^2 (very weak), (3) 5–20 m/km^2 (weak), (4) 21–50 m/km^2 (moderate), (5) 51–100 m/km^2 (strong), and (6) 101–500 m/km^2 (very strong). Each interval on the map corresponds to a specific color. It should be noted that, when identifying regions with different intensity of gully erosion, researchers sometimes use other qualitative criteria. For example, on the best-known published map of gully erosion in Russia [5], the regions are distinguished by other intervals: very weak (<0.01 km/km^2), weak (0.01 to 0.02 km/km^2), moderate (mean value of 0.06 km/km^2); significant (mean value of 0.3 km/km^2), strong (mean value of 0.9 km/km^2), and very strong (mean value more than 1.3 km/km^2). This map reflects the development of gullies 30–40 years ago and is based on other methodological rules and sources. In particular, as topographic maps were used at the main source of information, the density of gully network was somewhat overestimated, because large runoff cuts were assigned to gullies. In addition, it is inappropriate to include zero values of gully length in the first (weak gully erosion) interval. It seems reasonable to single

Table 1. Mean values of the water and thermal regime parameters for landscape regions

Region number on the map	Radiation index of dryness	Hydrothermal coefficient	Climate continentality coefficient	Annual precipitation, mm	Specific annual river discharge, mm	Water reserves in the snow, mm	Sum of biologically active daily temperatures, °C	Mean slope steepness, min	Rock types	Texture	Soil	Forest cover percent, %
Boreal (Eastern European) moderately continental subtaiga elevated landscapes												
17	1.05	1.75	2.22	605	148	101	2061	68	1	0	3;1	23.5
6	1.04	1.75	2.21	590	144	108	2143	91	1	0; 1	3;1	11.9
Subboreal northern semihumid (Eastern European) broadleaved elevated landscapes												
8	1.14	1.72	2.22	611	113	93	2195	126	1	0	4; 3	19.7
16	1.05	1.82	2.10	622	135	80	2163	100	1	0	4	5.9
19	1.06	1.66	2.11	622	144	69	2297	172	3	0	4; 5	5.5
7	1.05	1.67	2.27	589	135	114	2191	87	1; 5	0; 1	3; 1	23.5
23	1.10	1.77	2.15	619	118	90	2190	164	1	0	3; 4	18.7
11	1.11	1.55	2.37	598	113	77	2304	259	4	0; 1	4; 5; 3	43
5	1.10	1.72	2.19	617	124	82	2241	100	1; 3	0; 2	4; 6	12.3
14	1.08	1.62	2.16	615	114	85	2256	54	5	0	6	11.3
3	1.07	1.84	2.10	625	155	91	2208	109	1; 3	0; 2	3; 4	16.5
Subboreal northern semihumid (Eastern European) broadleaved moderately continental lowland landscapes												
18	1.03	1.79	2.10	632	158	90	2242	79	6; 3	0; 3	1	70.7
Subboreal northern semihumid (Eastern European) moderately continental forest-steppe lowland landscapes												
4	1.14	1.56	2.25	615	108	79	2285	4	48	0; 1	6; 5	24.3
Subboreal northern semihumid (Eastern European) moderately continental forest-steppe elevated landscapes												
1	1.15	1.54	2.45	567	109	87	2183	155	1; 2	0	6; 8	29.4
2	1.13	1.68	2.25	608	110	75	2263	69	3; 1	0; 2	6	5.2
9	1.22	1.38	2.25	564	85	84	2412	318	4; 3	0; 1	6; 9; 5	21.4
20	1.14	1.53	2.45	575	113	81	2190	123	1; 5	0	6; 8	23.6
21	1.09	1.57	2.39	588	121	88	2181	108	1; 5	0	4; 3	27.0
12	1.13	1.61	2.19	616	108	99	2128	143	1; 2	0	6; 8	23.4
15	1.16	1.52	2.30	595	101	67	2314	141	3; 4	0; 1	6; 8	13.1
10	1.10	1.54	2.35	587	118	87	2195	56	5; 1	0	6	13.8

Characteristics are not given for regions 22, 24, as they are out of the study area.
Rock types: (1) clayey–marly and clayey–limestone member of the Tatar stage, Belebey suite and Ufimian stage of the Permian–Triassic systems (P_2^{t-u}); (2) limestones and dolomites of the Carboniferous and Permian (P_2^{kz}); (3) sandy–clayey deposits of the Jurassic and Lower Cretaceous (J_3–K_1); (4) chalky–marly and sandy–siliceous sequence of the Upper Cretaceous and Paleogene (P_g–K_2); (5) sandy–loamy member of the Neogene and Pleistocene (N–Q); (6) sands and loamy sands of the Neogene and Pleistocene (Q_p). In the first place, symbols of predominate rocks (>60% of the territory) are indicated.
Soil texture groups: (0) clay and clay loam, (1) silt loam, (2) sand loam, and (3) loamy sand and sand. Soils: (1) soddy-podzolic s (Albic Glossic Retisols (Abruptic, Loamic, Ochric)), (2) soddy-calcareous s (Eutric Rendzic Mollic Leptosols), (3) light gray forest (Luvic Retic Greyzemic Phaeozems (Loamic)), (4) gray forest (Luvic Retic Greyzemic Phaeozems (Loamic)), (5) dark gray forest (Luvic Retic Greyzemic Phaeozems (Loamic)), (6) leached chernozems (Luvic Chernic Phaeozems and Luvic Chernozems), (7) podzolized chernozems (Luvic Greyzemic Chernic Phaeozems), (8) typical chernozems (Haplic Chernozems (Pachic)), and (9) typical carbonate chernozems (Haplic Chernozems (Pachic)).

Table 2. Number of gullies and their total length

Parameter	Slope gullies	Bank gullies	Bottom gullies	Total gullies
Number of gullies	19861	1628	1179	22668
Total length, km	1287	22.9	139.2	1449.1
Mean length, m	65	14.1	118.1	–

Table 3. Statistics of the length of gully network in erosion regions

Parameter	Length of gully network, m/km^2				
	>0–5	>5–20	21–50	51–100	101–500
Mean	2.1	11.4	32.5	67.4	161.8
Median	1.9	10.9	32	65.1	137.5
Standard deviation	1.4	4.4	8	13.3	60.4

out regions with a complete absence of gullies. The remaining gradations of gully parameters are in many respects close to the classification proposed in this paper.

RESULTS AND DISCUSSION

The total length of the gully network in the study area is 1449 km, the mean length of gullies is 65 m (Table 2), and the mean density of gully network for the entire study area is 31 m/km^2. Most of the gullies (88%) are gullies developing on slopes. Gullies dissecting river banks constitute 7%; bottom gullies, 5%.

Areas without gully dissection, or with weakly or very weakly developed gully network predominate (84% of the basins). Areas with very strong gully erosion occur only in 2% of the basins (Fig. 2, Table 3).

Spatial development of gullies and landscape conditions of the region. *Strong and very strong gully erosion* (Fig. 3) is almost universally developed in the western Cis-Kama region on elevated positions in the subtaiga zone (regions 6, 17). The same gully erosion is typical for the elevated broad-leaved landscapes of the Cis-Volga and Cis-Kama regions of Tatarstan (regions 3, 5, 7, 8, 14, 16, 19, 23). Another area with strong and very strong gully erosion is located in the Cis-Volga region in Ulyanovsk oblast in the subboreal elevated forest-steppe landscapes (region 9). Here, gullies occur on steep (>5°) slopes composed of the well-eroded sandy–clayey Jurassic and Lower Cretaceous deposits and chalk–marl and sandy siliceous rocks of the Upper Cretaceous and Paleogene. Leached, podzolized, and typical carbonate chernozems (Luvic Chernic Phaeozems and Luvic Chernozems, Haplic

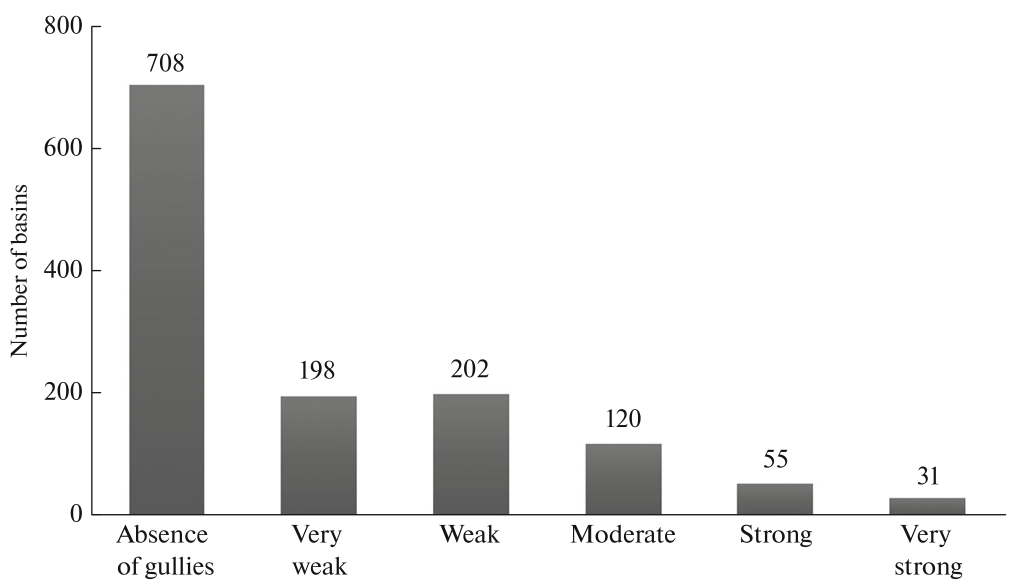

Fig. 2. Distribution of basins according to the degree of gully erosion.

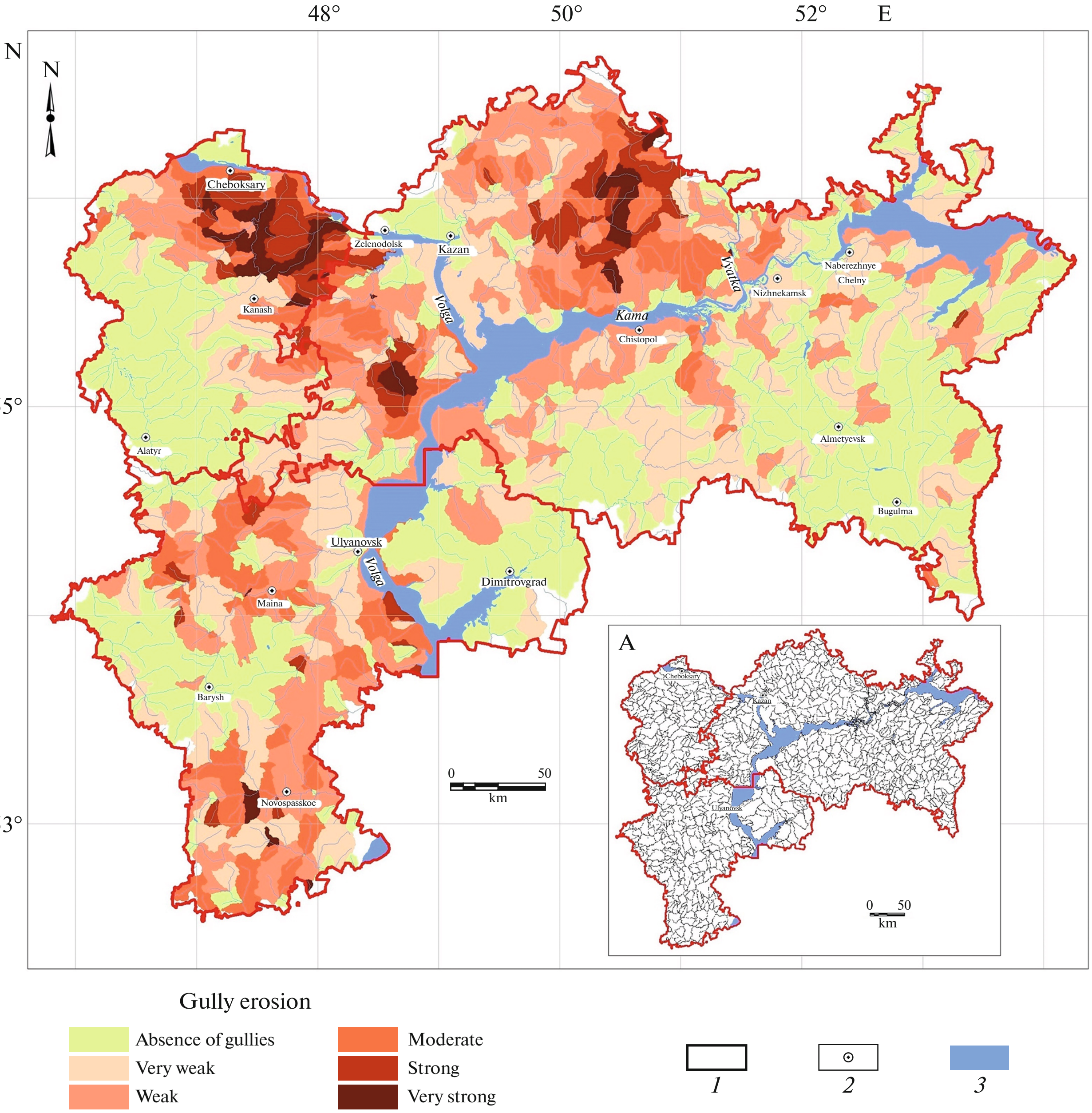

Fig. 3. Zoning of the modern gully network in the study area: (*1*) borders of the Republic of Tatarstan, Chuvashia and Ulyanovsk oblast, (*2*) settlements, and (*3*) water bodies; inset map (A) shows the boundaries of small river basins.

Chernozems (Pachic)) are subjected to gully erosion. Locally (in the north of landscape region 11), strong gully erosion is observed in the subclass of elevated landscapes in the southern part of the subzone of broad-leaved forests with high values of the mean steepness of slopes (4.5°) on chalk–marl and sandy–siliceous rocks of the Upper Cretaceous and Paleogene. Light gray and gray forest soils (Luvic Retic Greyzemic Phaeozems (Loamic)) are eroded. However, gullies completely disappear in the central and western parts of this region with continuous forest cover with one of the highest mean forest cover percent (43%) (Table 4, Fig. 4).

Regions with moderate gully erosion generally repeat the spatial patterns characteristic of regions with strong and very strong gully erosion. The greatest development of moderate gully erosion is manifested in subtaiga landscapes in the eastern part of region 6 and in the zones of broad-leaved forest (region 5) and elevated forest-steppe landscapes (regions 2 and 15).

The intensity of gully erosion sharply decreases in the forest-steppe zone on the left-bank part of the Volga and Kama valleys, regardless of the subclass of landscapes. Moderate gully erosion is developed on terraces of these large rivers. In region 12 confined to the Bugulma–Belebey Upland, *gully erosion is very*

Table 4. Natural–anthropogenic conditions for the development of gullies in river basins [33]

Parameter	Length of gully network, m/km^2					
	0	>0–5	>5–20	21–50	51–100	101–500
	absence of gullies	very weak	weak	moderate	strong	very strong
Total area, km^2	47 149	28 218	24 076	12807	5031	2572
Mean area, km^2	66.6	142.5	119.2	106.7	91.5	83
Mean length of the gully network, m	0	292	1325	3427	6086	12258
Number of gully heads	0	1049	4186	6149	5569	5742
Mean height, m	138	155	150	164	150	140
Mean steepness of slopes, deg.	1.63	1.71	1.73	1.92	1.85	2.04
Erosion potential of the relief	0.72	0.72	0.72	0.82	0.76	0.90
Mean annual precipitation, mm	522	524	525	522	530	528
Mean precipitation for the cold season, mm	162	163	163	159	162	160
Mean precipitation for the warm season, mm	360	361	362	363	368	368
Forest cover percent, %	27.4	21.4	15.3	18.3	9.6	7.6
Arable area, %	31.1	46.5	49.2	45.7	49.8	43.2
Meadow area, %	36.6	30.5	33.9	34	38.8	47.7
Specific runoff. m^3/(s km^2)	0.0036	0.0037	0.0036	0.0037	0.0038	0.0038
Specific annual discharge, mm	113	116	113	116	119	120

weak or absent. Despite the high steepness of the slopes, manifestations of gully erosion are local because of the high percent of forest areas (23.4%) preserved on the nonarable slopes of the upland with hardly eroded Carboniferous and Permian limestones and dolomites.

Thus, though the spatial development of gullies is generally controlled by the landscape conditions, it does not manifest clear zonal features, because the the key factors of gully formation—relief and composition of rocks—are essentially azonal factors. At the same time, hydroclimatic conditions responsible for the formation of surface runoff and erosion do have zonal pattern. However, in the studied region, which includes the southern boundary of the boreal forests and part of the forest-steppe zone, zonal changes in these conditions are not that contrasting as changes in the geological and geomorphic conditions, so the zonality of gully erosion is poorly pronounced.

Dynamics of gully erosion. The modern gully erosion in the region as a whole correlates with regions of different length of gully dissection half a century ago [10, 19, 31], with the only difference being that this parameter has decreased by at least an order of magnitude. For example, the modern length of gully dissection in Tatarstan has decreased, on average, by 230 m/km^2 in comparison with that in the 1950s. Within the Volga region, the greatest length of gully network is observed in Ulyanovsk oblast. A noticeable decrease in the number of gullies erosion is noted in the eastern Cis-Kama region of Tatarstan, while more than half a century ago there were gully regions with a length of gully dissection typical for the western Cis-Kama region.

An important role in the dynamics of gully erosion is played by changes in the land use of the territory. For example, the reason for the high growth rates of gullies in the eastern Trans-Kama region of Tatarstan, despite the significant forest coverage of this part, is the later development of the territory (deforestation, tillage, intensive exploitation during oil and gas production), and, therefore, the later establishment of gullies compared to other regions [19]. Differences between the eastern and western Cis-Kama, identified by modern studies can also be explained by the transfer of arable land to the category of land occupied by industrial facilities (the creation of the Alabuga free economic zone in the eastern Cis-Kama), which led to a sharp decrease in the number of actively growing gullies.

An assessment of land use changes and its role in the dynamics of gully erosion was carried out for a part of the territory (the Cis- Volga region and the western Cis- Kama region of Tatarstan) in 458 basins with a total area of more than 20 300 km^2 using Landsat imagery archives. An assessment of changes in land use in 2019 relative to 1985 showed a decrease in the arable land area by almost 10%, while the share of forests increased by 40.9%, while hayfields and pastures decreased by 8.7%. In 2003–2019, the arable land area practically did not change. An overlay of gully thal-

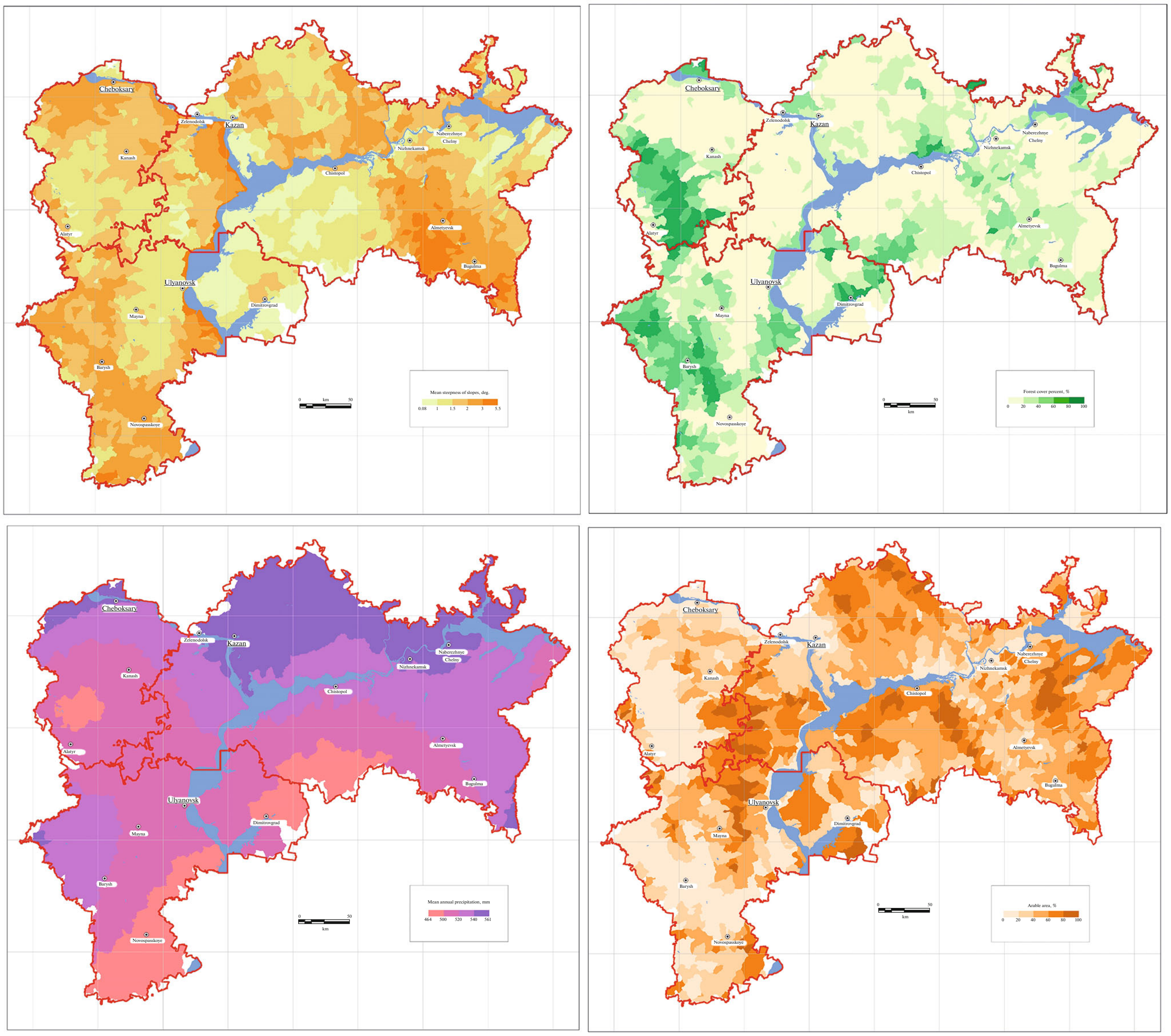

Fig. 4. Natural–anthropogenic conditions for the development of gullies in basins [33].

wegs on the land use map (2013–2019) indicates that a large number of gullies fall into the meadow category, and some of the gullies are located within settlements. However, the correlation analysis between the change in the length of gully network and changes in the arable area and in the percentage of forests and meadows indicates no significant correlation (the correlation coefficients are 0.014, 0.005, and 0.003, respectively) [12]. It is possible that the role of land use dynamics on the gully erosion of the territory becomes noticeable with more significant changes in these parameters. The applied methodology of the analysis of gully network for particular basins also affects the results of statistical analysis. All parameters, as well as the gully erosion, are expressed as mean values for the entire basin territory, whereas gully formation is a localized process. Therefore, for a more detailed analysis, a test basin in the Cis-Volga region with very strong gully erosion was chosen. In 50 years, the length of gullies within it decreased by 2.3 times (Table 5). Since 1985, the arable land area has decreased by about the same as the increase in the area of meadows and forests.

An aerial photograph (1969) and a satellite image (2022) of a fragment of the studied basin are shown on Fig. 5. Their analysis confirms the results of the land use change assessment. Over the past period, a forest shelterbelt crossing the arable land in its central part has been created. A change in the state of erosional landforms bordering the arable land is clearly seen. On the aerial photo of 1969, the gullies have a well-defined rim, thalwegs, and ungrassed slopes. The satellite image of 2022 indicates the cessation of the

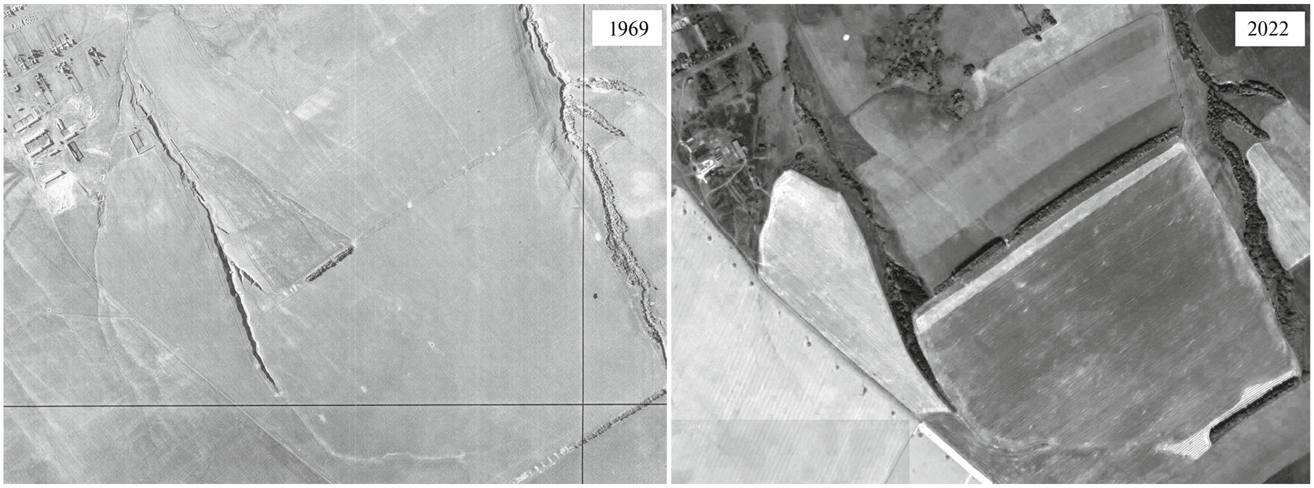

Fig. 5. Changes in the gully network from 1969 (aerial photography) to 2022 (satellite image) on the territory of the Republic of Tatarstan (village of Yambukhtino, 55°04′10″ N, 48°44′43″ E).

active phase of their growth: erosional forms are covered with trees and shrubs, thalwegs are not pronounced, and the phase of active growth of gullies is completed. Some reduction in the area of arable lands should also be noted. Over the past 53 years, the intensity of gully erosion has decreases. Former gullies of various types, in fact, have been transformed into balka landforms. The reduction of gullies presented in this fragment of the territory occurred due to the protective action of forest plantations, overgrowing of gullies with grasses, and some decrease in the arable land area. The same tendency is typical of other areas of intensive agriculture in the European part of Russia. For example, a detailed spatial analysis of changes in the area and location of forests was carried out on the basis of satellite data of 1970 and 2014–2015 for 63 gully–balka systems with a total area of 10310.2 ha in the south of the Central Russian Upland (Belgorod oblast) [27]. It demonstrated an increase in the area of forests from 3.6 to 22.7% (i.e., by 6.3 times) over the past 50 years. These data may also indicate stabilization and damping of gully formation.

The reason for the development of gullies is the concentration of surface slope runoff. Changes that occur during periods of snowmelt and rainstorm runoff are, of course, the most important factor controlling the appearance of new gullies and the development of existing gullies. Another important factor of the dynamics of gully erosion is changes in the climate system. In the studied region, there is a trend towards an increase in the mean monthly air temperatures in winter with most pronounced changes in in January [6]. Milder winter conditions decrease soil freezing depth and, as a result, snowmelt runoff. In the 1950s–1970s, the most active increase in the length of gullies was observed during the snowmelt runoff season.

Table 5. Characteristics of the studied basin [12, 31].

Basin area, km^2	52
Length of gully network (1970s), m/km^2	507
Length of gully network (2017–2021), m/km^2	222
Change in arable area from 1985 to 2019, %	–5.3
Change in forest area from 1985 to 2019, %	2.1
Change in meadow area from 1985 to 2019, %	3.4

At present, according to long-term field monitoring data on the growth of gullies in the territory of Udmurtia, snowmelt runoff has significantly decreased because of the less deep soil freezing in winter. The growth rate of gullies in 1998–2014 was four times lower than that in 1978–1997 [24]. Over the past decades, the volumes of snowmelt runoff have changed significantly. This can be indirectly proved by the amount of water reserves in the snow (Table 6). The most significant decrease in water reserves in the snow (and hence in the volume of snowmelt runoff) is observed in the forest and forest-steppe zones (24 and 18%, respectively). Apparently, the large-scale reduction of the gully network that occurred in the basins in the northern and southwestern parts of the region is largely due to this factor.

In the warm period of the year, rainfall intensity is the decisive factor of gully growth. It is expressed by the rainfall erosivity factor R. For the region, studies on the temporal and spatial variability of rainfall erosivity for 10-min maximum intensity were carried out for 1966–2019 [31]. The studied 53-yr-long interval was divided into two approximately equal periods (1966–1990 and 1991–2019). For each period, the mean long-term annual R factor and the mean long-term monthly R factor were calculated and compared on the basis of data from weather stations. The spatial pattern of changes in the R factor is rather complex

Table 6. Changes in water reserves in the snow within agricultural zones of the European part of Russia in 1960–1980 and 2006–2021 (% from 1960–1980) [31]

Natural zone	Mean	Median	Minimum	Maximum	Standard deviation
Forest	22	24	–12	100	11
Forest-steppe	17	18	–22	46	12
Steppe	17	14	–48	60	17

and multidirectional. In the west and east of the region, a slight (10%) increase in the R factor took place. However, these are the areas of weak and very weak gully erosion. A significant (by 10–30%) decrease in the R factor took place along the meridional part of the Volga River valley, in the areas with strong and very strong gully erosion. However, it we compare our data with previous estimates based on the materials obtained 50–70 years ago, we can see a considerable reduction in the density of gully network (by about 200–800 m/km^2).

The above reasons for the reduction in gully erosion, in our opinion, are quite debatable and require confirmation. Note that the evolutionary factor may be also important: after reaching the peak of active development and the state of dynamic equilibrium in the mid-20th century, the gullies have passed into the balka stage. Changes in land use and climate (first of all, a significant decrease in snowmelt runoff) launched an accelerated transition of gullies into balka systems.

CONCLUSIONS

The development of gully erosion is largely determined by the landscape features of the territory. An automated multiple physiographic (landscape) zoning was carried out using artificial neural networks to identify these features. The application of this method, in comparison with the traditional manual method of physiographic zoning, makes it possible to take into account the maximum number of parameters. With traditional zoning, the researcher, as a rule, works with a maximum of 4–5 information layers, while the neural network can use the entire available set of features. In addition, the neural network landscape zoning has a number of advantages over traditional statistical modeling methods. Its main difference is a large number of the degrees of freedom, which allows one to build arbitrarily accurate models, as well as the ability to self-learning, i.e., the correction of the structure and behavior of neural network with due account for the new data. A valuable quality of neural networks is their ability to generalize, which is expressed in the construction of satisfactory models based on incomplete or highly distorted data.

In the area of intensive agriculture in the Middle Volga region, several geographical centers of gully development are clearly distinguished. Moderate and high gully dissection within relatively small areas is characteristic of the right-bank parts of the Volga, Kama, and Vyatka valleys. Gullies are formed under conditions of elevated and rugged topography and the development of well-eroded Permian clay–marly and sandy–marly deposits and chalky–marly and sandy–siliceous Cretaceous deposits. The forest-steppe zone to the south of the Volga and Kama rivers and the western part of the studied region are characterized by the weak development of gullies or their absence. In the west, this is primarily favored by high (>50%) percent of forest vegetation; on the left-bank slopes of the Volga and Kama valleys, by the widespread development of erosion-tolerant chernozems on the interfluves, Neogene sands and loamy sandy on river terraces, and poorly erodible Permian limestones and dolomites in the southeast.

Conservation measures and changes in land use are important controls of gully erosion. The conversion of arable land into other land categories, the cessation of tillage, and the restoration of forests are limiting factors for the growth of gullies and the development of new erosional forms.

Modern gully erosion in the region has declined significantly since the middle of the 20th century. The reasons for this reduction are the significant changes in land use and in the climate system that have affected surface runoff. However, the key factor may be related to the natural evolution of gullies with their transition into the balka stage of development, which is much more tolerant towards the action of concentrated runoff flows.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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