EARTH SURFACE PROCESSES AND LANDFORMS
Earth Surf. Process. Landforms (2018)

Published online in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/esp.4435

Mapping and spatial-temporal assessment of gully density in the Middle Volga region, Russia

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Received 20 January 2017; Revised 19 May 2018; Accepted 29 May 2018

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ABSTRACT: A large-scale mapping of gully density was carried out for the Middle Volga region of the Russian Plain (188 000 km^2) based on the interpretation of aerial photographs (scale 1:17 000; surveys undertaken during 1956–1970). In addition, spatial-temporal dynamic of gully density were assessed for some parts of the study area (the Udmurt Republic and the Mesha and Ulema River basins of Tatarstan), based on the interpretation of aerial photographs (survey 1986–1991) and high resolution satellite images (2012–2015). Information on factors potentially controlling gully formation and development were collected and a geographic information system (GIS) analysis was conducted. Results show the strong development of gullies in the study area over the 1956–1970 period with an average gully density of 0.21 km km^{-2}. For the Udmurt region, we found that gully densities varied little in the period 1956–1986, during which the total active gully length reduced with only 2%. This period was characterized by low variable climatic conditions and a stable fraction of arable land with a relatively continuous crop rotation system. However, gully dynamics seems to have changed more strongly during recent decades. We found a strong (order of magnitude) reduction in active gully density for the period 2010–2015 as compared to 1986–1991. The main reason for this is likely the increasing winter air temperatures. This leads to a significant reduction in surface runoff during spring as a result of snowmelt. Nonetheless, in some regions (i.e. the Udmurt Republic in the taiga zone), the abandonment of arable land after 1991 likely plays a significant role. Likewise, a decline in the frequency of extreme rainfall events (> 50 mm) may have played a role. All of these factors contribute to a reduction of surface runoff to the gullies and their subsequent stabilization. © 2018 John Wiley & Sons, Ltd.

KEYWORDS: gully density; gully mapping; spatial-temporal dynamic; satellite image interpretation; snowmelt; Middle Volga region

Introduction

Gullies are a central link of fluvial networks, as connectors between slopes and river valleys (Makkaveev, 1955; Leopold *et al.*, 1964; Poesen *et al.*, 2003). As such, active gullies are not only an important source of sediment, but also serve as a transit pathway for runoff and sediment from uplands to valley bottoms and permanent channels (Hughes et al., 2001; Poesen, 2011; Poesen *et al.*, 2003, 2011; Vanmaercke *et al.*, 2016; Zhao *et al.*, 2016). However, stable gullies are often zones of sedimentation, in which eroded sediments are redeposited (Golosov, 2002; Poesen *et al.*, 2003). Alternating phases of activation and stabilization of gullies within temperate climates have been attributed to land use and/or climate changes (Golosov, 2006).

Overall, gully erosion is often closely related to climate and land-use changes (Vanwalleghem *et al.*, 2003, 2005; Torri and Poesen, 2014). While topographical and soil-lithological factors certainly also play a role (e.g. Rysin, 1998; Valentin *et al.*, 2005; Torri and Poesen, 2014), anthropogenic land-use changes are often a key driver of gully erosion (e.g. Stankoviansky, 2003; Vanwalleghem *et al.*, 2005). Gully initiation is typically closely linked to land-use conversions such as the enlargement of cultivated lands or urbanization (Brierley and Stankoviansky, 2002; Guerra *et al.*, 2007; Torri and Poesen, 2014; Imwangana *et al.*, 2015). Also, on the Russian Plain, the expansion of arable land areas and cultivation intensification during the last three centuries were a main reason for the acceleration of gully erosion (Sidorchuk and Golosov, 2003). Likewise, gully expansion rates have been reported to be closely linked to rainfall intensities (e.g. Vanmaercke *et al.*, 2016) and, in some areas, snow melt (e.g. Ionita *et al.*, 2015).

Nonetheless, the effects of land-use and climatic conditions on gully erosion remain hard to quantify and, sometimes, even to identify. For example, a global compilation of gully headcut retreat rates worldwide demonstrated that variability in these rates are mainly attributable to differences in rainfall intensity (Vanmaercke *et al.*, 2016). On the one hand, Vanmaercke *et al.* (2016) could not identify a clear land-use effect on gully headcut retreat rates. On the other hand, Torri and Poesen (2014) showed that gully slope-area thresholds, and by extension, gully initiation and maximum gully densities, clearly depend on land use, while effects of climate appear to be much less strong. Likewise, other recent studies have found no significant correlation between gully density and climatic factors (e.g. Zhao *et al.*, 2016).

These seemingly contradicting results are potentially attributable to several reasons. Firstly, gully erosion is generally the result of different processes, such as gully initiation and gully expansion (Poesen *et al.*, 2003). These processes are, at least partly controlled by different and interacting factors (Rossi *et al.*, 2015). As such, gully initiation and the expansion of existing gullies may indeed be more strongly controlled by respectively land-use and climate conditions. In addition, other controlling factors of gully erosion such as topography and soil characteristics may also obscure existing impacts of land use and climate, as they are often intercorrelated. Finally, it should be acknowledged that gully erosion is a highly erratic process. Its threshold-dependent nature often results in highly variable erosion rates, both in space and time, causing difficulty in quantifying the importance of different controlling factors (e.g. Rossi *et al.*, 2015; Vanmaercke *et al.*, 2016; Zhao *et al.*, 2016). By consequence, understanding the importance of climate and land use for gully erosion rates, typically requires a large number of observations, preferably over a sufficiently long measuring period (Torri and Poesen, 2014; Vanmaercke *et al.*, 2016; Hayas *et al.*, 2017). Only then, robust and statistically meaningful results can be obtained.

In order to better understand the magnitude and controlling factors of gully erosion, several studies have mapped and monitored active gullies and their densities, using aerial photographs and high-resolution satellite images (e.g. Mitchel, 1981; Ries and Marzolff, 2003; Vrieling *et al.*, 2007; Bouaziz *et al.*, 2009; Shruthi *et al.*, 2011, 2014; Torri and Poesen, 2014; Vanmaercke *et al.*, 2016; Hayas *et al.*, 2017). Recent studies use object-oriented analyses, methods of pixel identification and self-organizing neural networks for the detection of ravines and gully networks (Vrieling, 2006; Vrieling *et al.*, 2007; Bouaziz *et al.*, 2009; Desprats *et al.*, 2013; Johansen, 2010). While these techniques are important and promising tools; the relatively limited spatial extent of gullies often inhibits its detection using satellite imagery. Given their spatial resolutions, Landsat and SPOT imagery can at best be applied for identifying individual large- and medium-sized gullies (Langran, 1983; Latz *et al.*, 1984; Millington and Townshend, 1984) and do not allow gully growth analysis using sequential imagery (Bocco and Valenzuela, 1993). In general, automatic detection of gullies from satellite images may provide fast insight in the importance of gully erosion and the consequent loss of productive land over large regions. Nevertheless, some authors have questioned the feasibility of this exercise due to the spectral heterogeneity of gullies themselves and of their surroundings (King *et al.*, 2005).

Considerable climate (Park *et al.*, 2014) and land-use (Lyuri *et al.*, 2010) changes have occurred over the past 30 years in the European part of Russia, which may have strongly influenced gully erosion and gully densities. For example, Rysin *et al.* (2017b) report a significant reduction in mean annual gully head-retreat rates over the past 20 years, based on the long-term monitoring of over 150 gully heads in the Udmurt Republic, located in the north-western part of the Middle Volga river basin. From a geomorphic perspective, the Middle Volga region is representative for European Russia, with a high proportion of arable land and annual erosion rates that correspond well to mean values of the Russian Plain (Sidorchuk *et al.*, 2006; Yermolaev, 2017).

A large advantage of this region for the study of gully erosion, is the long-term availability of gully data on a massive scale. During the former Soviet Union, gully density maps were published for many regions in the former USSR, including the Middle Volga region (Yermolaev, 2002). However, these maps were based on information collected from topographic maps of different scales (1:100 000, 1:50 000 and 1:25 000) (Sobolev, 1948; Aver'yanova and Petrov, 1961; Sementovskiy, 1963; Kosov and Konstantinova, 1973; Zorina, 2003; Nikol'skaya and Prokhorova, 2005). The application of such medium-scale topographic maps resulted in relatively inaccurate and crude gully network mapping, while more detailed large-scale topographical maps were only used for gully mapping in some key areas. Comparisons of such gully maps with field observations and interpretation of large-scale aerial photographs have shown that topographic maps do not fully reflect the spatial pattern of gully development (Kosov and Konstantinova, 1973). This is, of course, due to the generalization of topography in the cartographic preparation of topographic maps. As shown by comparative measurements of the gully network lengths derived from aerial images and large-scale topographical maps (1:25 000 scale), estimated gully network densities based on maps can strongly deviate (50–300%) from those based on aerial photograph interpretation (Zorina, 2003; Nikol'skaya and Prokhorova, 2005).

Despite these limitations, the long-term availability of gully density observations in the Middle Volga region, provides an excellent (if not unique) opportunity to better understand the controlling factors of gully erosion and the relative importance of land-use and climate change, in particular. Hence, the objectives of this study are: (1) to analyze the spatial distribution and dynamics of gully network densities in the Middle Volga region for the past six decades; and (2) to identify the main factors responsible for the observed changes of gully density in the Middle Volga region.

Materials and Methods

Description of the study area

The Middle Volga region is located in the eastern part of the Russian Plain and includes five administrative units of Russia (the Republic of Mari El, Udmurt Republic, Chuvashia, Tatarstan and Ul'yanovskaya oblast') with a total area of 188 000 km^2 (Figure 1). Average slopes in the river basins range from 0.5° (Mari Polesie) to 5.3° (south of the Prilozhskaya uplands). Elevations range from 120 to 237 m. The study area is divided into several geomorphological regions based on their morphological characteristics and lithology (see Figure 2).

The Middle Volga region is characterized by a temperate continental climate with cold winters and warm summers. Annual precipitation ranges from 560 mm in the south to 640 mm in the north. A significant proportion of this precipitation falls as snow. The snow water reserves before the annual period of snow-melting (March–April) increase from 65–75 mm in Predvolzhye (central and southern part) to 100–115 mm in the eastern and northern part of the region.

Within the region, taiga, mixed forest and forest-steppe landscape zones follow each other from northwest to southeast. The gray forest soils (humus content 2.9–3.5%) and medium leached chernozem (humus 5.6–7.6%) are the most typical soils in the mixed forest and forest-steppe zones respectively. The most prevalent soil type in the taiga zone is sod-podzolic soil (albeluvisols according FAO World Reference Base) with average humus content of 1.5%. Soil textures are typically loam to clay-loam. In the north-western part of the region, sandy soils also occur frequently. In terms of land use, the northern, north-western and western parts of the study area are mostly forested (Figure 2). Cropland is the dominant land

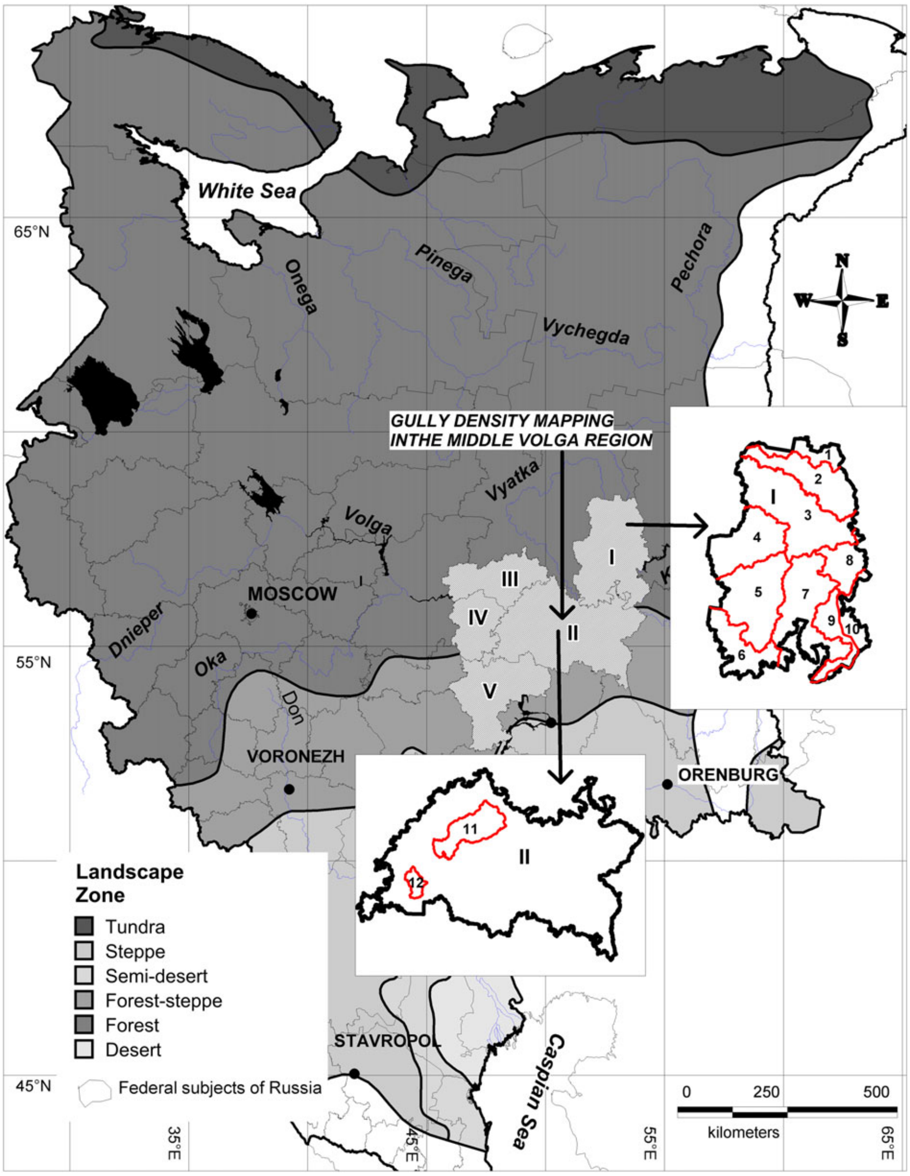

Figure 1. Location of the Middle Volga region within the Russian Plain, administrative units and key study river basins. Legend: Administrative units: I – Udmurt Republic, II – Tatarstan Republic; III – Mari-El Republic; IV – Chuvash Republic; V – Ul'yanovskayaa oblast. River basins: 1 – upper Vyatka and Kama; 2 – the right bank of Cheptsa; 3 – the left bank of Cheptsa; 4 – the Kilmez; 5 – the Vala; 6 – the left bank of Vyatka and Toima; 7 – the Izh; 8 – the Siva; 9 – the right bank of Kama; 10 – the left bank of Kama; 11 – the Mesha; 12 – the Ulema. [Colour figure can be viewed at wileyonlinelibrary.com]

use for the rest of the Middle Volga region with proportions of arable land typically in the range of 60 to 67%.

Sheet, rill and, in some places, ephemeral gully erosion is commonly observed on cropland. This erosion typically takes place during periods of snowmelt (March–April) and heavy rainstorms (mainly in the period from May to September). Estimated mean annual sheet and rill soil erosion rates range between 3 and 10 Mg ha^{-1} yr^{-1}, but show large spatial variability in relation to relief and soil characteristics (Sidorchuk *et al.*, 2006; Yermolaev, 2017). Gully erosion is observed across the whole study area, but mostly associated with agricultural activity. The proportion of urban, road and other technogenic gullies is about 10% of the total number of active gullies (Grigor'ev *et al.*, 2016).

Gully density mapping in the Middle Volga region

General information

Mapping gullies in the Middle Volga region was a large undertaking. In total, an area of 171 700 km^2 was mapped (Figure 2). Aerial photographs of sufficient quality and detail were only available for different time periods, because the aerial surveys were conducted in different years (1956–1970; 1986–1991). The used satellite images were taken in the period 2012–2015. In total, about 30 persons participated during the different stages of processing and interpreting these aerial photographs and satellite images, as well as with the collection of data on controlling factors, geographic information system (GIS) mapping and data analysis and interpretation. These persons, including 20 post-doctorate and PhD students and 10 staff members (assistant professors, associate professors and professors), had the necessary background to conduct the mapping. More specifically, they had a thorough knowledge of geomorphology and gully erosion and received training to identify gullies and other geomorphic features from aerial photographs.

Overall, the work took place in several stages:

- Mapping of active gullies based on the interpretation of aerial photographs obtained between 1956 and 1970 for the entire Middle Volga Region (55 person-months).

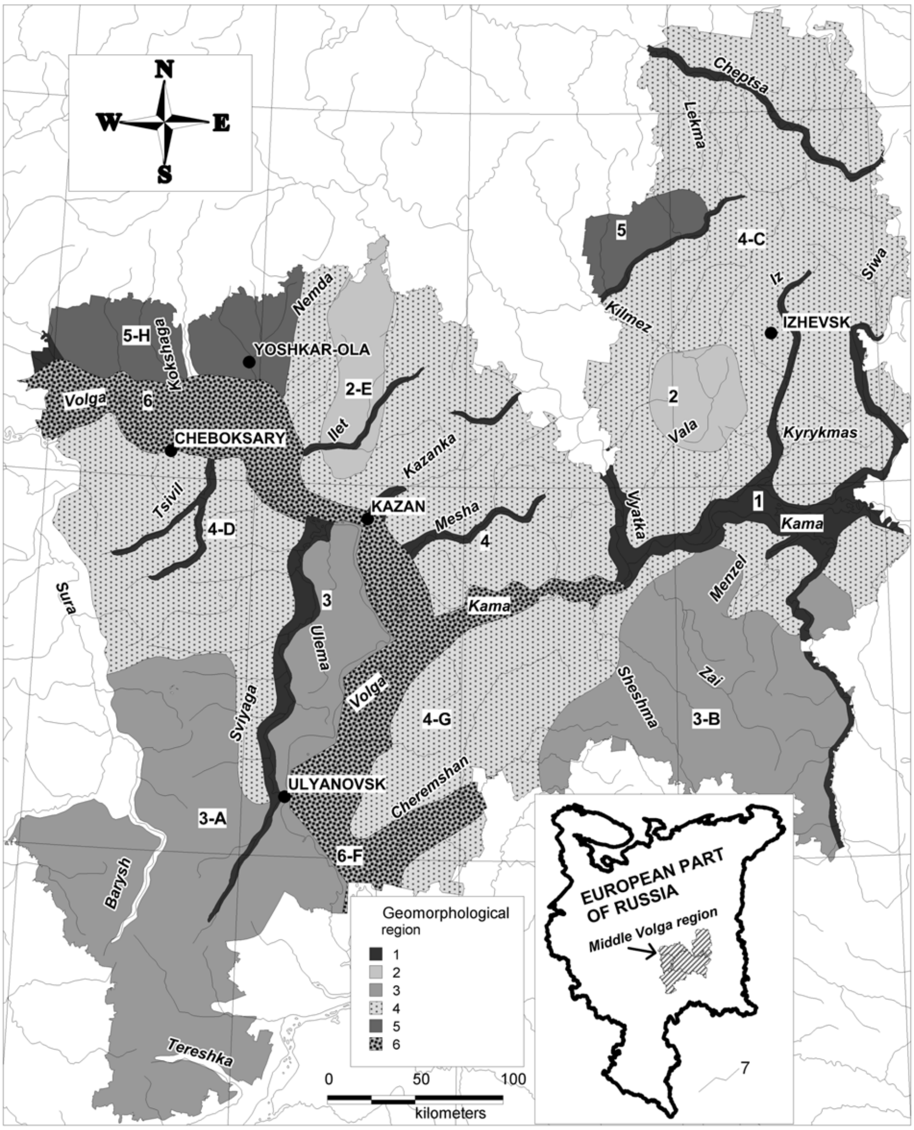

Figure 2. Map of geomorphological regions (Gerasimov and Aseev, 1986) and the main physical geographic areas (between brackets) of the Middle Volga region: 1 – Alluvial river valleys; 2 – Structural-denudation stepped plains on sedimentary rocks (2-E – Vyatka Ridge upland); 3 – Structural-denudation stepped-tiered plains on sedimentary rocks (3-A – Privolzhskaya upland; 3-B – Bugulmino-Belebeevskaya upland, Zakamie); 4 – denudational tiered plains on sedimentary rocks (4-D – Predvolzhie; 4-C – Verkhnekamskaya upland; 4-G – Zavolzhie); 5 – denudational sub-horizontal plain on sedimentary rocks (5-H – Mari Polesie); 6 – valley bottom (terraced plains) of the Volga and lower Kama Rivers, alluvial neogen-holocene sediment (6-F – western Zavozhie); 7 – location of the Middle Volga region on the European part of Russia.

- Mapping of active gullies based on interpretation of aerial photographs obtained between 1986 and 1991 and satellite images obtained between 2012 and 2015 for the Urmurt Republic (see Figure 1; 25 person-months).
- Mapping of active gullies based on the interpretation of satellite images obtained between 2012 and 2015 for the Ulema and Mesha River basins in the Tatarstan Republic (see Figure 1; 6 person-months).
- GIS processing of mapped gully densities and compilation of data on potentially controlling factors (12 person-months).

Identification of active gully length on the basis of aerial photograph and satellite imagine interpretation

As indicated earlier, our analyses were based on aerial photographs (scale 1:17 000) and multispectral satellite images of high and very high spatial resolution (ranging between 0.5 and 1.0 m; GeoEye, QuickBird, and IKONOS). The resolution of the aerial photographs used allowed to identify the gully length with accuracies of about 1 to 1.7 m.

Before the mapping began, it was necessary to select the most appropriate periods for photograph and satellite image acquisition. Based on the comparison of images for the different seasons and field verification, autumn and spring images were found to be the most informative for the study of gully erosion in the study area. The thalwegs of the gullies can be traced well using the winter images, but (due to snow cover) it is difficult to distinguish the edges of gullies, impeding the accurate assessment of gully development. However, summer pictures generally show denser vegetation cover, making it more difficult to identify the bottoms of active gullies but easier to distinguish the stage of development of slope and bank gullies. Images from spring and autumn provided an excellent trade-off.

In the next stage, the satellite images and the aerial photographs were georeferenced. This was done using the GIS software MapInfo. The coordinate system UTM – Mercator (WGS -84), UTM zone 39, Northern hemisphere was used. Minimum seven fixed points (e.g. road crossings, single trees, corners of buildings and other marks that do not change their position over time) were used for georeferencing. Where possible, additional fixed points were used, in order to improve the accuracy.

The identification and mapping of gully forms was carried out based on visual interpretation by trained scientists (see earlier), using several interpretation signs (Burkard and Kostaschuk, 1997; Vandaele *et al.*, 1997; Labutina, 2004; Knizhnikov *et al.*, 2004). The main interpretation signs of active gullies were the following: (a) characteristic shapes with sharp, geometrically well-defined boundaries; (b) linear and branched forms on the image; (c) the clear edge and the line of the thalweg; (d) contrast photograph tone on different sides of the gully, occurring typically with V-shaped gullies; (e) the presence of local bright areas on the slopes of the gullies, corresponding to areas unprotected by vegetation and testifying the activity of the erosion form. Some examples of features of visual interpretation of the gullies are shown in Figure 3.

When mapping gullies, it is also important to distinguish active gullies from other linear forms, such as ephemeral gullies and dry valleys, which were not mapped in the context of this study. Characteristics of ephemeral gullies are different from the classical active gully (Kirkby and Bracken, 2009). The depth of an ephemeral gully does not exceed 1.5 m, while their width typically does not exceed 3 m. Dry valleys (balkas, in the Russian terminology) usually have a trapezoidal transverse profile with a pronounced flat bottom. They are completely covered with vegetation (grass, tree, shrub). Accordingly, such forms have fuzzy edge at their banks and poorly expressed thalwegs. Balka have a linear pattern and a blurry form on satellite images (Figure 4).

Field verification of the results of image interpretation was undertaken for several locations within the different landscape zones in the study area. The field verifications allowed evaluating the correctness of determining the boundary between active gully sections and gully sections in transition to dry valleys stabilized by vegetation. It was found that the uncertainty in determining this boundary varied between 10 and 15%. In addition, this field verification showed that very short bottom gullies (length < 5 m) were usually missed in the aerial mapping because they were covered by vegetation. However, their proportion in the total active gully length was estimated to be only 1–2%. In addition, our field surveys confirmed that almost all gullies under the secondary forests (former abandoned cultivated fields) transformed into dry valley with vegetated banks and bottoms.

Mapping gully densities and controlling factors

Next, catchments and inter-catchment areas, were selected and delineated on topographic maps of 1:50 000 and 1:100 000. These selected units correspond to second- and third-order streams according to the Strahler-classification (Strahler,

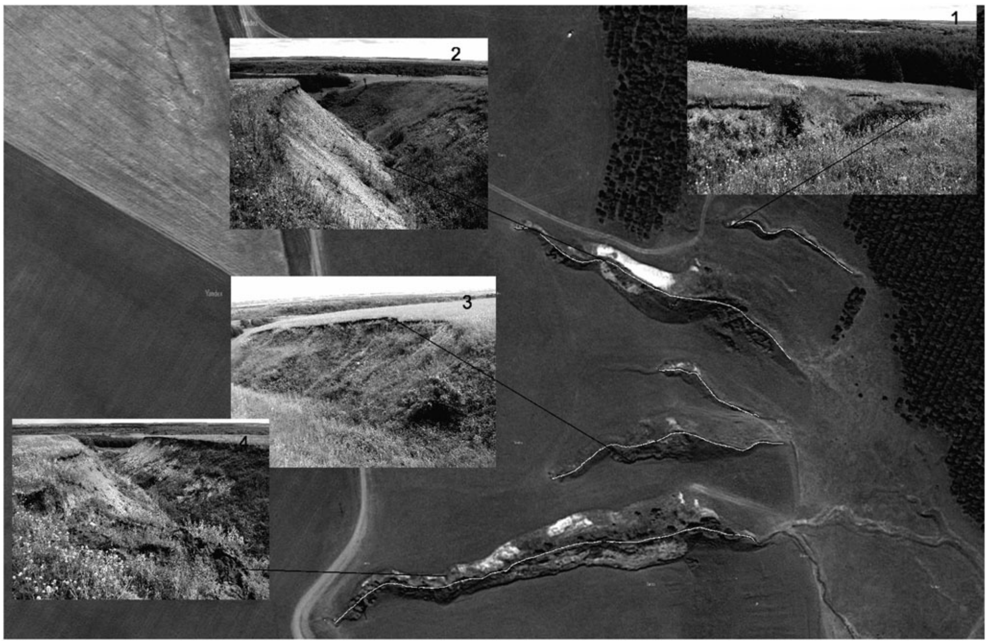

Figure 3. Dry valley (balka) on satellite image (left) and on the ground (right).

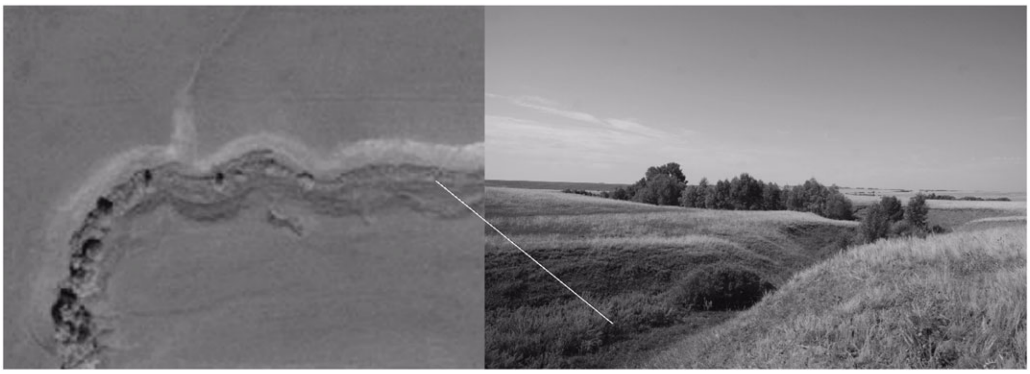

Figure 4. Gully forms and their morphological characteristics on satellite image and on the ground.

1957). The inter-catchment areas represent groups of smaller catchments and slopes, which are located on the valley banks of the basins with a Strahler-order larger than three. The size of the delineated catchments and inter-catchment areas varied between 15 and 145 km^2. For simplification purposes, we use the term 'catchment' for both catchments and inter-catchment further in the text. The gullies digitized from the aerial photographs or satellite images were converted into gully density by dividing the sum of the total length of mapped gullies (in kilometers) by the total area of the corresponding catchment (in km^2). This gave a gully density measurement of kilometers of gully length per square kilometer of area (km km^{-2}). Overall, this approach allowed us to study regional variation in gully density over our extensive study area. While using (inter-) catchment units contrasts somewhat with the commonly used principle of determining the gully density at equal areal units (Zinck *et al.*, 2001; Hughes *et al.*, 2001), we preferred this approach as the delineated (inter-)catchments correspond to meaningful geomorphic units that can actually be detected in the landscape.

The boundaries of all (inter-)catchments were vectorized and, to each unit, a number of characteristic features were assigned: a territory code number, the geographic location, coordinates and a unique identifier (ID). In total, we determined the gully density for 4575 units. (Figure 5). Catchments of the Middle Volga region were divided in eight classes according their overall gully density (Figure 5) for the evaluation and the detailed description of gully development in the different parts of the study area. It allowed to identify areas with catchments having no significant gullies (classes 0–0.005 km km^{-2}), very low gully densities (0.005–0.01 km km^{-2}), high gully densities (0.5–1.0 km km^{-2}) and extremely high gully density (> 1.0 km km^{-2}). The three other classes represented catchments with intermediate gully density (Table I).

Next, information on factors potentially controlling gully formation and development were collected for each of the delineated units. Considered factors included: the fraction of arable land and forest (i.e. the two dominant land-use types in the study area), the average slope length and gradient, the depth of dissection or local relief (differences between maximum and minimum absolute heights in the catchment), an erosion index of precipitation, average water reserves in the snow cover before snow-melt, the lithology of the underlying rocks, the predominant soil type and the soil texture. Land-use information was derived from land-use maps that were constructed for the different timeframes (1960–1970; 1985–1991 and 2012–2015) based on the interpretation of aerial photographs, satellite images and topographical maps (1:25 000 or 1:50

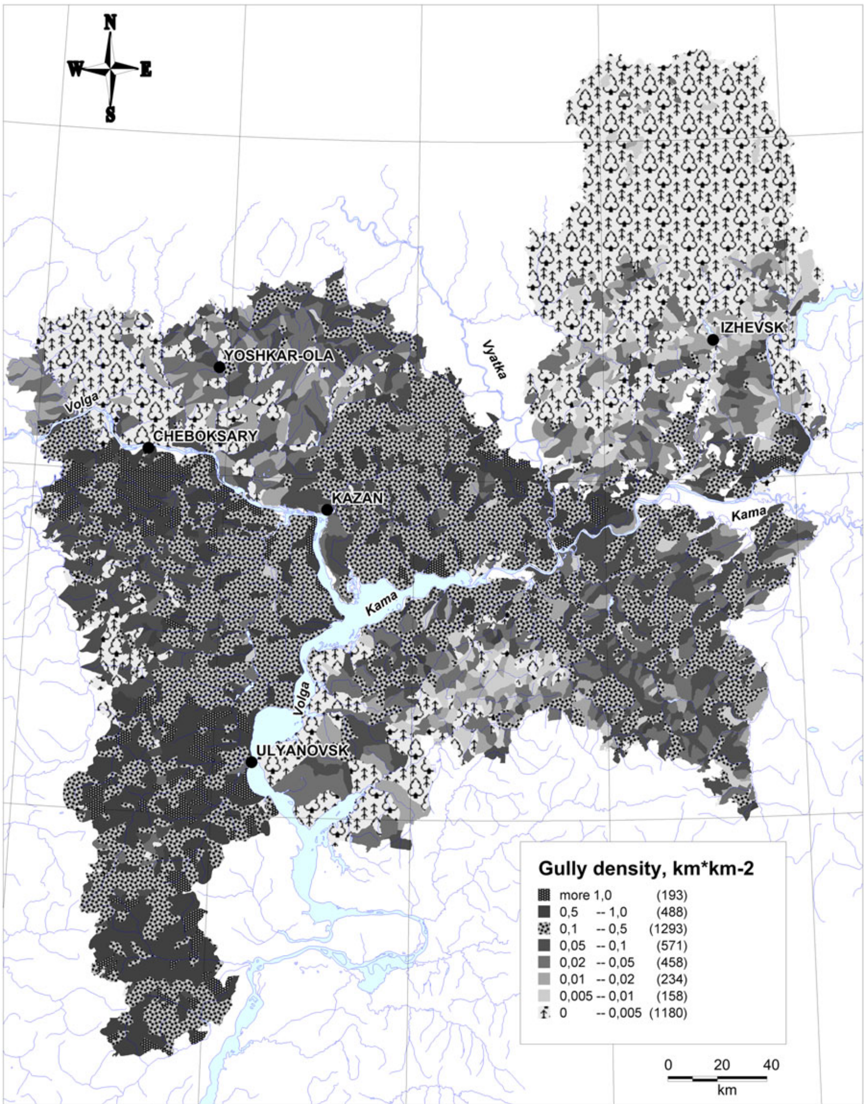

Figure 5. Gully density map for the Middle Volga region for the timeframe 1957–1970. See Figure 1 for the rivers names and administrative regions borders (the number between brackets indicates the number of catchments with the indicated gully density). [Colour figure can be viewed at wileyonlinelibrary.com]

Table I. Some natural and anthropogenic characteristics of the areas of the Middle Volga region with different gully density (see Figure 5)

Area with gully density ($km\,km^{-2}$)	Number of catchments	Local relief (m)	Cultivated area (%)	Forested area (%)	Average steepness of catchment slopes (deg)
0–0.005	1180	67	28	71	3.5
0.005–0.01	158	93	50	38	3
0.01–0.02	234	82	45	41	2.5
0.02–0.05	458	103	51	34	2.5
0.05–0.1	571	108	50	33	2.5
0.1–0.5	1293	115	61	20.5	2
0.5–1.0 and > 1.0	681	120	66–70	11–17	3.5

000). The morphological characteristics (i.e. slope lengths and gradients, depth of dissection) were derived from topographical maps (scale 1:25 000 or 1: 50 000) (Main Department of Geodesy and Cartography of the USSR). Hydro-meteorological information for 1960–2015 was collected from State meteorological stations, located within the study territory. Water reserves in snow were determined for each meteorological station for areas with constant snow cover based on the regular (weekly) measurements of snow depth and snow-density at several points along transects crossing open areas (agricultural fields or/and meadows/pastures) and/or forested areas. Only data for periods with maximum water reserves before the beginning of snow-melt (March–April) were collected. The erosion index of precipitation was derived from the map of Universal Soil Loss Equation (USLE) rainfall erosivity index for the former USSR (Larionov, 1993). The USLE rainfall erosivity index of precipitation was calculated, using the maximum 30-minute rainfall intensity of rains during the summer season (May–September). Kinetic energy of rain was calculated using the formula suggested by Wischmeier *et al*. (1958) and adapted to the metric system (Larionov, 1993). Soil data were derived from soil maps (scale 1:200 000 and 1:300 000) which were produced based on field surveys undertaken by the State company Giprozem for the entire area of USSR during the 1970s and 1980s. Geological information was derived from state geological maps (scale 1:200 000).

Individual GIS layers were created for each of the considered factors, using MapInfo GIS version 8 (e.g. Figure 6).

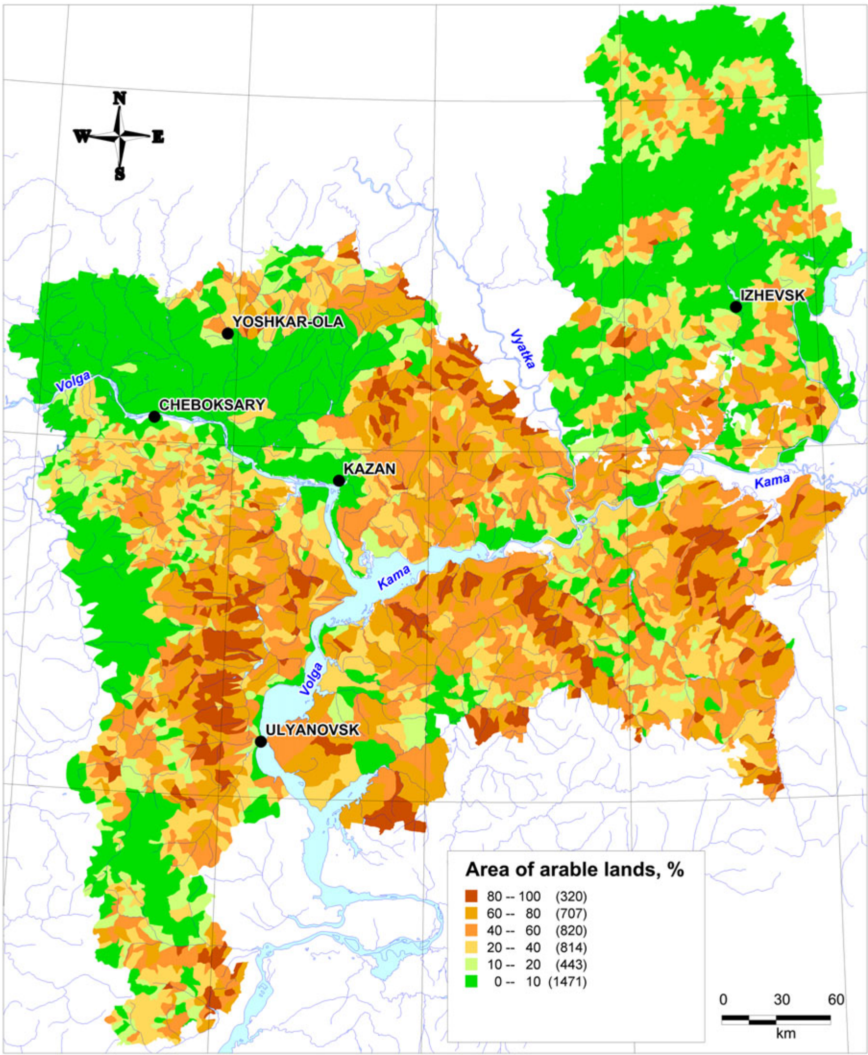

Figure 6. Map of the proportion of arable lands for the Middle Volga region (the number between brackets indicates the number of catchments with given percent of the arable land). [Colour figure can be viewed at wileyonlinelibrary.com]

Topographic maps with a scale of 1:200 000 (Gauss–Krüger projection; coordinate system; Pulkovo, 1942) were used as the basis for creating these layers. The process of creating basic vector electronic maps (maps of the catchments, the gully density, factors of gully erosion, etc.) and extracting environmental factors were carried out following standard GIS methods. The result of this work was a geospatial database of gully densities and relevant potential controlling factors of gully erosion per identified (inter-)catchment, covering the entire study area at a scale of 1:200 000.

Statistical analyses of the correlations between gully density (dependent variable) and potential controlling factors were undertaken by considering all catchments, as well as by grouping all catchment based on the eight observed gully density classes described earlier (Figure 7). It is necessary to underline, that anthropogenic factors (road construction, field boundaries, cattle and sheep pathways, etc.) may also influence the occurrence of gullies and, hence, gully density. However, due to a lack of data, these factors could not be quantified in our analyses. Nonetheless, given that this study focuses on a regional scale, the influence of these anthropogenic factors is expected to be limited.

Assessing spatial-temporal variations in gully density

Quantifying gully density dynamics

Apart from assessing regional differences in gully density, also the dynamics of gully networks were assessed for some parts of the study territory, considering different time periods and by using a number of indicators. Firstly, the gully density and the number of gully heads were determined for each catchment of the Udmurt Republic.

To characterize changes in gully network in the selected catchments between different time periods we used an indicator '*R*', corresponding to the ratio of the total length change of the active gullies (ΔL, in meters) and the number of gully heads (*n*) within the catchment, divided by the number of years in the considered time interval (*T*, i.e. number of years elapsed between the first and subsequent aerial photograph or satellite image):

$$R = \left(\frac{\Delta L}{n}\right)/T$$

This indicator reflects the joined effect of several processes: the rate of growth of existing active gullies, the appearance of new gullies and the revegetation of existing gullies (leading to their potential stabilization and transformation into dry valleys). Therefore, the value *R* can be both positive and negative, with positive values indicating the predominance of actively expanding and new gullies. If the total length of gullies that stabilized over the period (*T*) exceeds the length of active gully expansion and the length of newly formed gullies, this will result in negative *R*-values. Apart from *R*, also the total length change of active gullies over time ($\Delta L/T$) was used as an indicator for gully dynamics.

Results

Spatial variation in gully density

According to our aerial photograph interpretation, the gully density within the Middle Volga region for the period 1956–1970 ranged between 0 and 4.19 km km^{-2}, with a mean value 0.21 km km^{-2}. The ranges of gully density and generalized environmental characteristics for each gully density class are presented in Table I.

Nearly one quarter (23.7%) of the catchments have no or only sporadic (patchy) gullies, resulting in gully densities between 0 and 0.005 km km^{-2} (Figure 5). These areas include territory of the southern forest zone (see Figure 1) which are

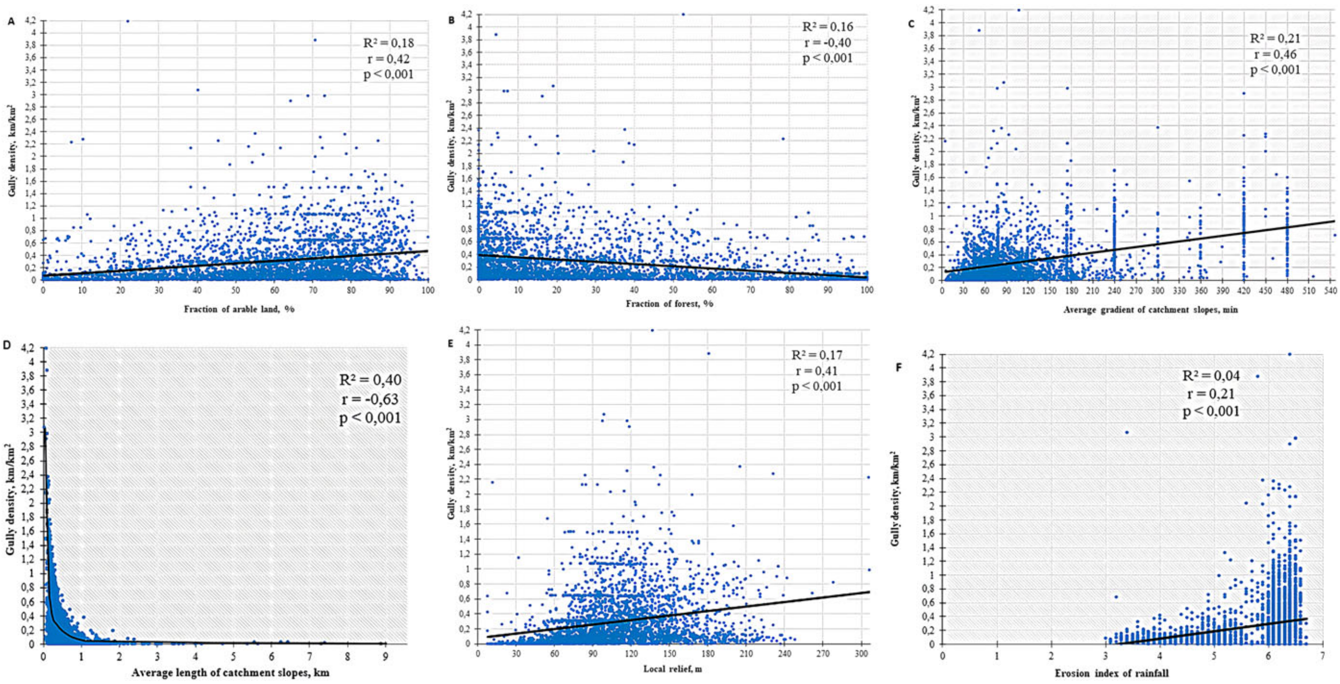

Figure 7. Scatter plots showing the gully density (GD) in catchments and various potentially explaining factors (see Table II): (A) the correlation between GD and fraction of the arable lands; (B) the correlation between GD and fraction of forest; (C) the correlation between GD and the average catchment slope gradient; (D) the correlation between GD and the average length of catchment slopes; (E) the correlation between GD and the relief (dissection depth); (F) the correlation between GD and the erosion index of precipitation. [Colour figure can be viewed at wileyonlinelibrary.com]

characterized by densely forested and swampy landscapes (Figure 2) (Rysin, 1998). About 3.5% (158 catchments) have very low gully densities (0.005–0.01 km km^{-2}). They are generally located on the left bank of River Kilmez, the right bank of the River Vala, and in the Siwa and Cheremshan River basins (Figures 2 and 5). Likewise, 234 catchments have low gully densities (0.01–0.02 km km^{-2}), mainly located in the middle reaches of the Siwa and Izh River basins and in the upper reaches of the River Cheremshan (Figures 5 and 2). About 10% of the units (458 catchments) have a moderate gully density (0.02–0.05 km km^{-2}). These gully densities mainly occur in the Kokshaga and Ilet River basins and parts of the Izh and the Kama River basins (Figures 2 and 5). About 12.5% of the units (571 catchment) have moderate to high gully densities (0.05–0.1 km km^{-2}). These gully densities were mainly observed in the basins located on the right bank of the Kama River (the mouth of the River Siwa), in the upper reaches of the River Carismas and in the Zay and Mensel River basins, on the right bank of the River Sura and in the upper River Nemda (Figure 5). High gully densities (0.1–0.5 km km^{-2}) were observed in 1293 of the catchments (28.3%); mainly located in the interfluve area of the Rivers Volga and Sviyaga, in the southwest part of the region and in the Kazanka and Mesha River basins (Figures 2 and 5). Of the selected catchment, 681 (15%) have very high (0.5–1.0 km km^{-2}) to extremely high (> 1.0 km km^{-2}) gully densities. Most catchments with a high gully density were located in the middle and lower reaches of the Sviyaga and Tsivil Rivers and on the right-hand side (when looking downstream) of the largest rivers of the study region, i.e. the Volga, Kama and Vyatka (see Figures 5 and 2). These higher densities on the right banks are attributable to the fact that the topography at this side is more pronounced with typically steeper slopes.

The correlation analyses indicated that observed patterns of gully density are mainly correlated to topographical factors and land use (Table II; Figure 7). Also, a very strong relation was found between the average gully density and the average fraction of arable land of each gully density class (Figure 8). This indicates that most of the gullies are closely linked to agricultural activity. Similarly, very high correlations were found between the average local relief and the corresponding average gully density of each class (Figure 9). Overall, gully densities strongly increase in catchments having average height differences exceeding 100–110 m.

The considered hydro-meteorological parameters showed no strong correlations with the observed gully densities (Table II). However, the overall range was limited due to relatively smooth changes in climatic characteristics within the East European Plain as a whole and in particular in its eastern part, where the Middle Volga region is located. Soil-lithological factors appeared to have some influence on the gully formation in the Middle Volga region (Table II).

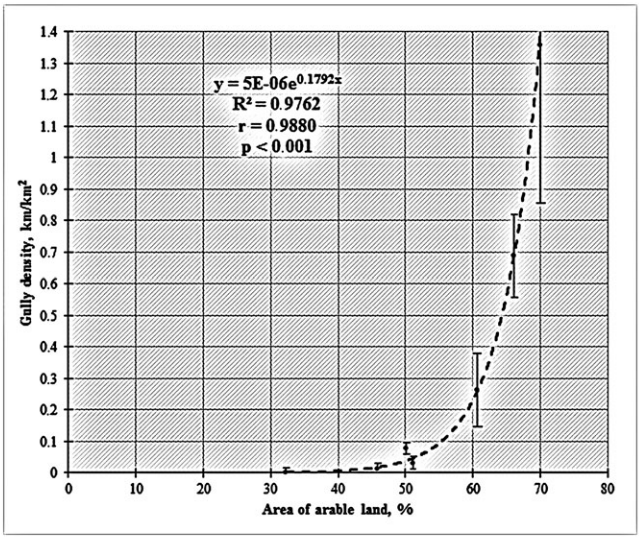

Figure 8. Correlation between gully density and average arable land area for each category of gully density.

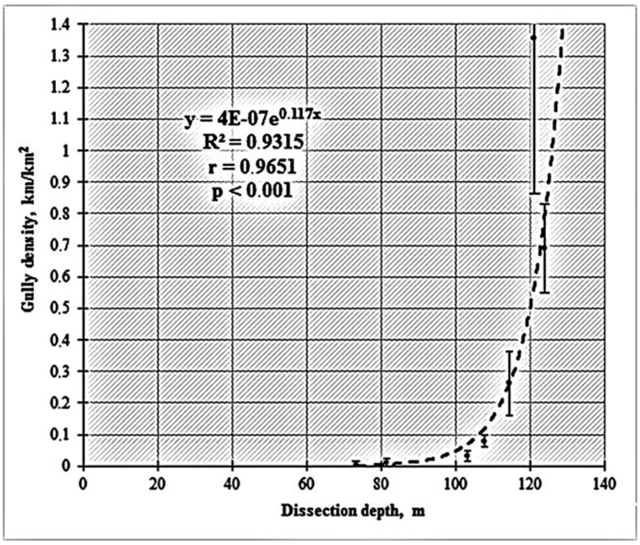

Figure 9. Correlation between gully density and average relief for each category of gully density for the Middle Volga region (without Udmurt Republic).

Temporal dynamics of gully density

Analysis of the data in the Udmurt Republic shows that during the first period of observation (between 1957–1960 and 1986–1991) there was a 2% reduction in total gully length (i.e. as

Table II. Results of the correlation and dispersion analysis of gully density of catchments (n = 3331) and considered environmental factors for the Middle Volga region (without Udmurt Republic)

Factor	r	R^2	H	η^2	Minimum	Maximum
The mean length of slope (km)	–0.63	0.4	0.62	0.38	0.04	11
The average gradient of slope (minutes)	0.46	0.21	0.47	0.22	5	547
Local relief (m)	0.41	0.17	0.47	0.22	8	306.4
Forested area (%)	–0.40	0.16	0.45	0.20	0	100
The dominant type of parent (underlying) rocks			0.57	0.33		
Soil type			0.47	0.22		
Soil grain size			0.44	0.19		
Area of arable lands (%)	0.42	0.18	0.42	0.18	0	100
USLE erosion index of precipitation (I max 30 minutes)	0.21	0.04	0.42	0.18	3	6.7
Water storage in the snow before snowmelt	–0.09	0.01	0.22	0.05	58	147

Note: r, coefficient variation; R^2, Spearman coefficient; H, Blackman statistics; η^2, influence power.

compared to the gully length observed between 1957 and 1960). The most significant change in gully length was observed on the right bank of the Kama River and in the Vala River basin (Figures 10 and 1). River basins located in the north part of the Republic, with relatively short cultivation periods did show increased gully erosion, while a decreasing trend was observed in the other basins.

Overall, for the majority of the territory, no significant changes in gully length occurred during this time interval. The largest group of catchment (713) showed zero change in the *R*-indicator (Figure 8). Positive *R*-values, indicating gully erosion were observed in 268 catchments (21% from total number of catchments). Relatively high gully dynamics rates (indicator $R > +6\,\mathrm{m\,yr^{-1}}$) were observed in 194 catchments (15% of the total number of catchments). Negative *R*-values (indicating gully stabilization and/or transformation to dry valleys) were observed for 304 catchments (24%). In total, the total gully length showing vegetation overgrowth was slightly higher than the total gully head retreat during the considered time period (1957–1960 to 1986–1991).

However, there has been a significant reduction in the total length of active gullies and the number of gully heads in the Udmurt Republic over the past 25–30 years (from 1986 to 1991; see Tables III and IV). Active gullies were identified in only 26 catchments of the 160 catchments on the right bank part of the Cheptsa River basin (Table IV; see Figure 1 for location). The number of actively expanding gully heads reduced 2.7 times, while the length of the active gully network decreased 1.7 times. Likewise, the gully density ($0.932\,\mathrm{m\,km^{-2}}$) and gully head density ($0.006\,\mathrm{units\,km^{-2}}$) decreased, although the average gully length increased from about 100 to 147 m.

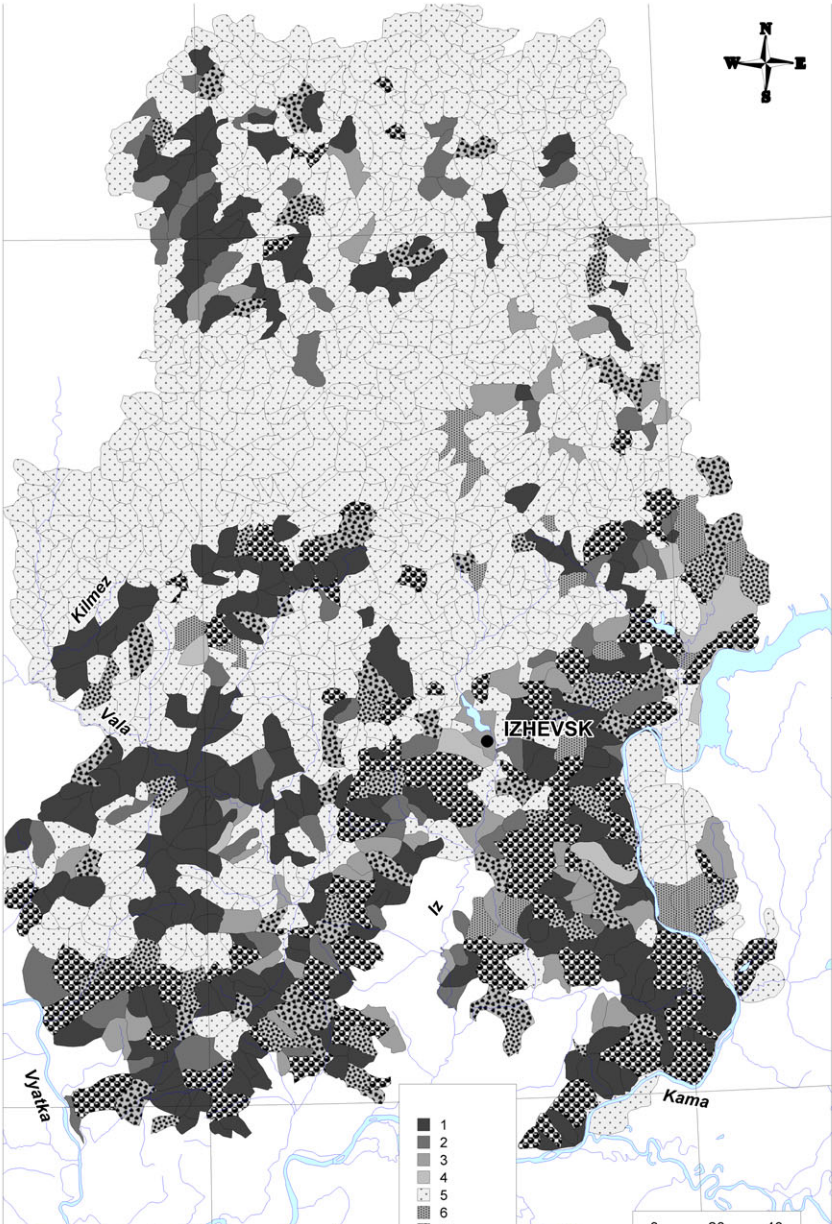

Figure 10. Map of gully development dynamics in the Udmurt Republic between 1957–1960 and 1986–1991, based on the *R*-indicator (see text). *R* values (in m $\mathrm{yr^{-1}}$) (number of catchments in parentheses): 1 ≥ +6 (194); 2 = +3 to +6 (55); 3 = +1 to +3 (48); 4 = +0.1 to +1 (7); 5 = ±0 (713); 6 = −0.1 to −1 (16); 7 = −1 to −3 (33); 8 = −3 to −6 (49); 9 ≤ −6 (129). [Colour figure can be viewed at wileyonlinelibrary.com]

Table III. Average values of gully development (indicator *R*, see text) for the main river basins of Udmurt Republic based on aerial photographs interpretation for two timeframes (1957–1960 and 1986–1991) (see Figure 1 for locations of river basins)

River basins	Number of catchments: Total	Number of catchments: With recently and formerly active gullies	Average value of gully development for the river basin (indicator *R*; m yr^{-1})
Upper Vyatka and Kama	66	—	—
The right bank of Cheptsa	160	32	1.73
The left bank of Cheptsa	250	58	1.74
Kilmez	150	22	3.12
Vala	184	93	2.62
The left bank Vyatka and Toima	103	85	–0.47
Izh	208	157	0.47
Siva	71	51	–0.86
The right bank of Kama Камы	68	68	–1.77
The left bank Kama	25	6	–1.54
Total	1285	572	–0.17

The left bank part of the Cheptsa River basin is characterized by the lowest reduction in gully network length (17.2% decrease) and number of active gully heads (52.3% decrease), which may be due to the latest agricultural development of this part of the Udmurt Republic. Active gullies were observed in 57 catchments. Almost all of these were also active during the previous period (Tables III and IV). The mean gully density has changed slightly (1831 km km^{-2}), which is 1.2 times smaller than for the previous period. Gully head density decreased with a little more than a factor two, while average gully lengths were about 1.7 times higher as compared to the previous period. It should be noted that, in the Cheptsa River basin, actively growing gullies commonly have a technogenic origin (road construction, oil production, etc.) while agricultural gullies are relatively rare.

More substantial reductions in total gully network length and the number of active gully heads occurred in the Kilmez River basin (Table IV, Figure 1). The total length of the gully network was reduced by a factor 4.8 and the number of active gully heads by a factor 4.6. Also, the mean length of the gullies decreased slightly (to 168 m).

Even more significant changes of gully density were observed in the Vala River basin (Table IV, Figure 1). The total length of the gully network reduced by a factor 37.5, while the number of actively growing heads was 23 times lower. Also, the average length of gullies decreased with a factor 1.6 (to an average of 150 m).

On the left bank of the Vyatka River and in the Toima River basin, gully densities decreased by a factor of five and gully head densities with a factor 2.3. The mean length of gullies decreased with more than 100 m, reaching 83 m (Table IV, Figure 1).

Also, the Izh River basin showed a sharp decrease in gully network length (Table IV) and a somewhat smaller decrease in active gully heads. Similar results are observed in the Siwa River basin draining the Eastern part of the Udmurt Republic. Here, the total length of the gully networks was reduced to 7.4% compared to the previous time period, and the number of the gully heads to 6.8%. The mean gully length (133 m) increased almost 10 m (Table IV, Figure 1).

During the period 1986–1991, the highest gully densities were observed at the right bank part of the Kama River basin. The interpretation of satellite imagery from 2012 to 2015

Table IV. Characteristics of contemporary (2012–2015) active gully networks and their change as compared to 1986–1991 for the main river basins of the Udmurt Republic (see Figure 1 for locations of river basins)

Main river basin*	Number of catchments: Total	Number of catchments: With active gullies	Area of river basins with active gullies (km^2)	Number of active gully heads in 2012–2015	Proportion of active gully head (AGH) in 2012–2015 as compared to AGH in 1986–1991 (%)	Total average length of active gullies in 2012–2015 (km)	Proportion of the total length of active gully (TLG) in 2012–2015 as compared to the TLG in 1986–1991 (%)	Mean gully density in 2012–2015 (km km^{-2})	Mean density of gully heads in 2012–2015 (number km^{-2})	Mean length of active gullies in 2012–2015 (m)	Average value of gully development for the river basin (*R*-indicator) (m yr^{-1})
Upper Vyatka and Kama	66	0	0	0	0	0	0	0	0	0	0
The right bank of Cheptsa	160	26	1030	32	37.6	4.69	59.1	0.932	0.006	147	–4.42
The left bank of Cheptsa	250	57	2193.6	106	47.7	14.588	82.8	1.831	0.013	138	–1.24
Kilmez	150	14	405.3	23	21.9	3.874	20.8	0.775	0.005	168	–27.9
Vala	184	9	272.3	20	4.3	2.994	2.7	0.461	0.003	150	–234.5
The left bank of Vyatka and Toima	103	26	1176.7	262	48.3	21.689	20.0	5.569	0.067	83	–14.4
Izh	208	35	1327.1	114	11.1	9.755	52	1.317	0.015	86	–3.43
Siva	71	4	136.7	12	6.8	1.596	7.4	0.653	0.005	133	–72.4
The right bank of Kama	68	18	800.4	79	4.7	8.637	1.8	3.614	0.033	109	–25.9
The left bank Kama	25	0	0	0	0	0	0	0	0	0	0
Total	1285	189	7342.1	648	15.1	67.823	7.1	1.551	0.015	105	–59.5

showed that the length of active gullies reduced by 1.8%, while the number of active gully heads decreased by 4.7% (with respect to the 1986–1991 observations).

Overall, between the two first observation periods (1957–1961 and 1986–1991), very little change occurred to gully density (Figures 11A and 11B), whereas over the last 25 to 30 years, the total length of active gullies has decreased dramatically in all parts of the Udmurt Republic (Figure 11C). Presently, there are no catchments with gully densities $> 0.1\,\text{km km}^{-2}$, while the number of catchments with moderate gully density (0.02–0.05 km km^{-2}) reduced almost 10 times (from 133 to 16). However, the number of catchments with no or only sporadic gullies (0–0.005 km km^{-2}) strongly increased (Figure 11).

The Ulema River and the Mesha River basins are two other sites, located in the forest-steppe zone of the Republic of Tatarstan (see Figure 1 for location of basins). A comparison of gully densities was undertaken for two timeframes (1960–1970 and 2012–2015). Overall gully development in 1960–1970 was more intense (see Figure 5) than in the Udmurt Republic, which is overall more forested. However, also here, very strong reductions in gully density were observed. This is illustrated by the changes in distribution of gully density classes in the Mesha and Ulema River basins (Figure 12). For example, 4.7 times less catchments had a strong (0.1–0.5 km km^{-2}), very strong (0.5–1.0 km km^{-2}) or extremely strong ($> 1.0\,\text{km km}^{-2}$) gully density in 2015 as compared to the 1960s and 1970s, whereas the proportion of catchments with a low gully density was almost in 17 times in 2015 than in the 1960s and 1970s (Figure 12).

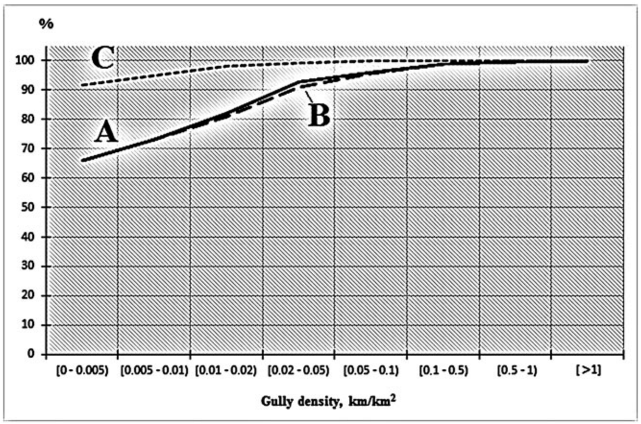

Figure 11. Distribution of catchments according to their gully density in the Udmurt Republic for the three time periods: (A) 1957–1960; (B) 1986–1991; (C) 2012–2015.

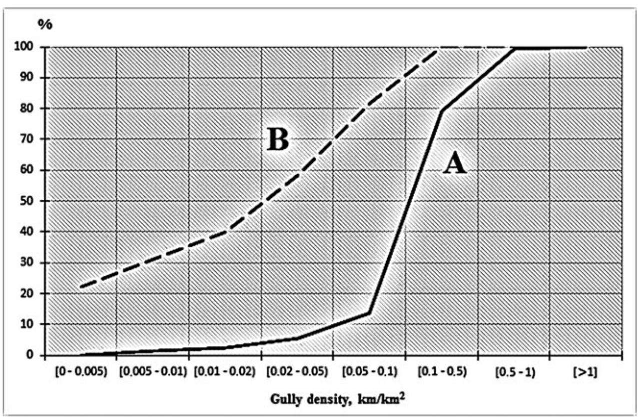

Figure 12. Distribution of catchments according to their gully density in the Mesha and the Ulema River basins (the Tatarstan Republic) for the two time periods: (A) 1960–1970; (B) 2010–2015.

Discussion

Spatial variation of gully density

Our results showed that mainly topographic and land-use characteristics of the catchments strongly correlated to the observed gully densities. This concurs with our understanding that topography and the fraction of arable land are the key factors controlling surface runoff in the Middle Volga region. Previous studies showed that runoff coefficients under forest and meadow are typically between 0.1 and 1%, depending on soil texture and the depth of frozen soil during the period of snowmelt (Koronkevich, 1990). Runoff coefficients under arable land conditions are typically much higher, although they may strongly vary (between 0 and 100%), depending on the hydro-meteorological conditions (Golosov, 2006). The overall low correlation between gully density and hydro-meteorological parameters (Table II) can probably be explained by the overall low variability across the Middle Volga region in meteorological conditions (Table I). For example, the considered catchments are characterized by an overall very similar rainfall erosivity. However, it is necessary to underline that some climatic effects may be present that could not be quantified in the context of this study. For example, based on long-term monitoring of gully head retreats, Rysin *et al.* (2017b) found that intensities of gully erosion are typically higher on slopes with a southwest aspect, due to the less regular (and often faster) snow melting on slopes with these exposures (Rysin *et al.*, 2017c). In contrast to mountain regions, where lithology is typically a central factor for explaining differences in active gully density (Poesen and Hooke, 1997), also the influence of soil and lithology on gully densities in the Middle Volga region was found to be only limited. Nonetheless, they may explain some of the observed regional variations (Rysin, 1998).

In general, the findings of our correlation analyses correspond well with those of other studies, illustrating the great control of land use and topography on gully initiation and gully densities, while climatic and soil conditions appear of lesser importance (e.g. Torri and Poesen, 2014; Zhao *et al.*, 2016). While weather and climate conditions can have a clear impact on gully expansion and gully retreat (e.g. Ionita *et al.*, 2015; Vanmaercke *et al.*, 2016; Rysin *et al.*, 2017b; Hayas *et al.*, 2017) they appear to be less significant in explaining spatial patterns of gully density at regional scales.

Overall, the average observed gully density for the Middle Volga is about 1.7 times higher than reported gully densities in the agricultural areas of Australia, which are also located predominantly within elevated plains (Hughes *et al.*, 2001). Overall, the spatial variation of gully densities in the Middle Volga region is very typical for plains with a high proportion of arable lands. Gully densities are mainly correlated to local relief with the highest densities occurring in uplands and hilly areas and the lowest in lowlands (Burkard and Kostaschuk, 1997; Poesen, and Govers, 1990). The forested area of the Middle Volga region is characterized by extremely low densities of active gullies (Figure 5). Long-term monitoring of gully head retreats in these areas demonstrates that new gullies are typically stabilized in a few years following the abandonment of arable lands (Rysin *et al.*, 2017a). This strongly differs from the situation observed in the Piedmont of the south-eastern United States where deep active gullies were found in under forested areas (Galang *et al.*, 2007).

Spatial-temporal dynamics of gully density

Three main factors may potentially help explain the observed sharp reduction in active gully density since 1991: an increase of the winter air temperature, land-use changes and decreases in the contributing areas of gully heads.

Table V. Changes in cultivated land area for the administrative units of the Middle Volga region for three time periods (1975, 1990 and 2015; based on http://www.gks.ru/ and *Sel'skoe khozhyastvo*, 1988)

Administrative unit number	Administrative unit	Landscape zone	Cultivated lands		
			In 1975, 10^3 ha/%	In 1990 10^3 ha/%	In 2015 10^3 ha/%
I	Udmurt Republic	South of forest zone	1422.3/100%	1400.8/98.5%	1028.9/72.3%
II	Tatarstan Republic	South of forest and forest-steppe zones	3676.6/100%	3402/92.5%	3000.9/81.6%
III	Mari El Republic	South of forest zone	633.9/100%	603/95.1%	393.4/62%
IV	Chuvash Republic	South of forest zone	818.2/100%	800/97.7%	575.7/70.3%
V	Ul'yanovskaya oblast'	Forest-steppe zone	1773.1/100%	1643.8/92.7%	1010.2/57%
	Total Middle Volga Region	South of forest and forest-steppe zones	8324.2/100%	7849.6/93.4%	5908.1/70.3%

Note: See Figure 1 for location of administrative unit within the Middle Volga region.

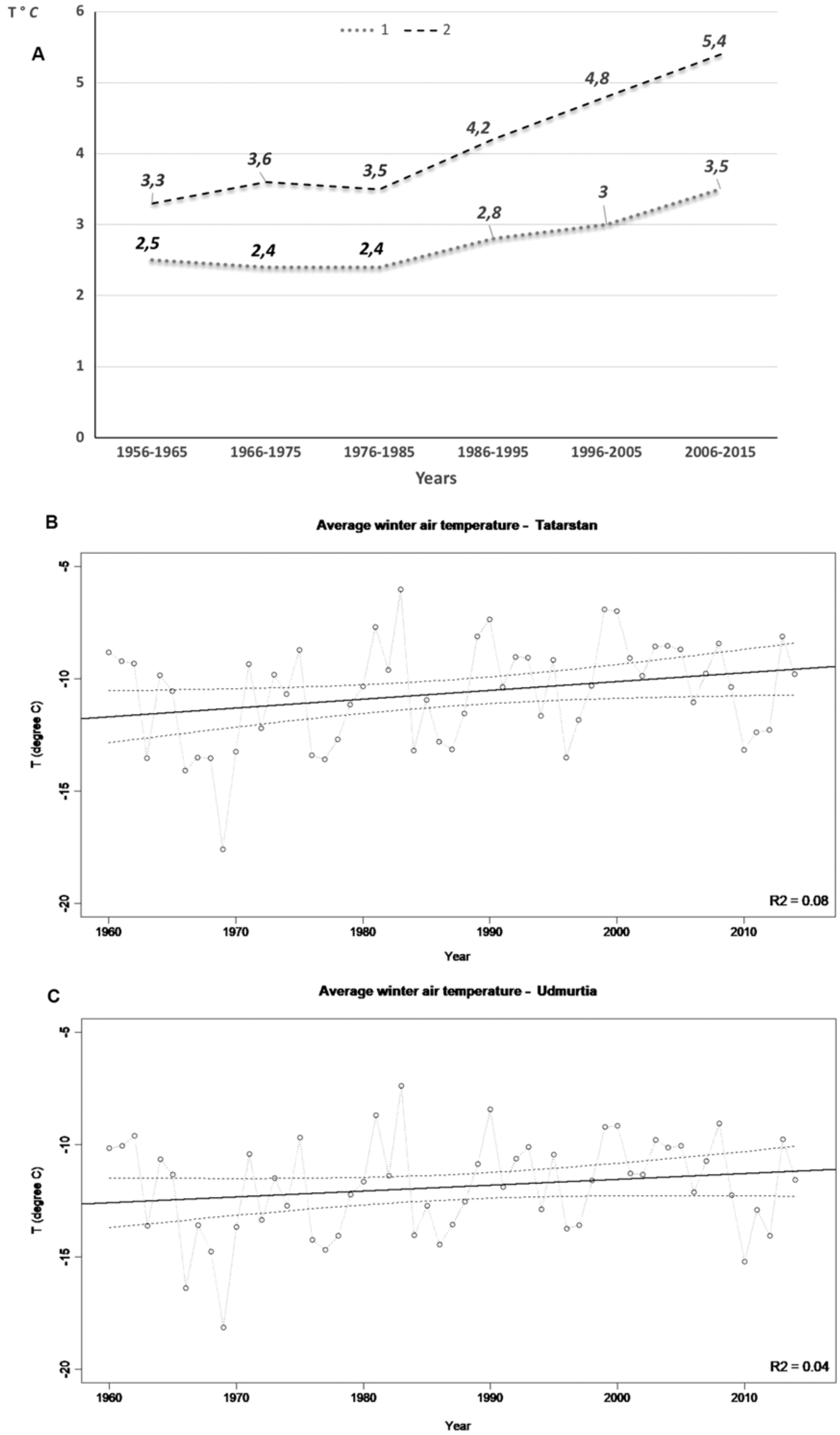

Figure 13. Dynamic of air temperature in the Middle Volga region during the last 60 years: (A) mean annual temperatures per decade (1 – Udmurt Republic; 2 – Tatarstan Republic; based on Gafurov *et al.*, 2018); (B) mean winter temperature for Tatarstan; (C) mean winter temperature for Udmurt Republic (based on http://meteo.ru/it/178-aisori).

Earlier research analyzing the correlation between average headcut retreat and contributing area indicated that the latter factor alone is likely unable to explain the observed reductions (Vanmaercke *et al.*, 2016). Nonetheless, it may play a role in some cases, in particular when climate and land-use changes are insignificant. This may be the case in the Middle Volga region for the period 1970–1990, when arable land area changes were minimal (Figure 1, Table V). Likewise, no clear trend in air temperature was detected during that period (Perevedencev *et al.*, 2014). However, the lack of a clear trend in the dynamics of gully density within Udmurt Republic during this period (Figure 10; Table IV) confirms that reductions in contributing area probably have no strong effect on the observed gully dynamics.

With respect to land-use changes, the abandonment of arable land has most likely contributed to the decline in active gully density during the past 25 years. The abandonment of arable land has strongly increased since 1990 in all the administrtive units of the Middle Volga region (Table V). The cessation of ploughing within areas prone to gullies, their gradual overgrowth by vegetation and their subsequent transformation into meadow or forest resulted in significant reductions of runoff coefficients (Koronkevich, 1990). It also resulted in the revegetation of previously active gullies, which lead to a fixation of the gully walls (Rysin *et al.*, 2017a). Similar processes are observed in the other parts of the taiga zone (Ryzhov, 2015), while the stabilizing effect of vegetation (and especially root systems) have been well-discussed in recent literature (e.g. Stokes *et al.*, 2014; Vannoppen *et al.*, 2015). Nonetheless, it should be noted that the decline in cultivated land during the past 25 years are relatively limited in Tatarstan Republic (Table V), which comprises the studied Ulema and Mesha River basins (Figure 12). This clearly indicates that the observed declines in active gully density are not attributable to land use alone. Hence, also climate change likely plays an important role.

The contribution of climate change can be evaluated based on the results of the long-term monitoring of gully head retreats in 28 sites located in the different parts of Udmurt Republic during 1978–2015 (Figure 1; Rysin, 1998; Rysin *et al.*, 2017a, 2017b, 2017c). Average air temperatures increased on the territory of European Russia since the middle of the 1970s, including the Middle Volga region (Figure 13A). Also air temperature during winter months increased (Perevedencev *et al.*, 2014; Figures 13B and 13C), which promoted also an increase in soil temperatures (Park *et al.*, 2014). This may have contributed to a significant reduction of snowmelt runoff from the tilled slopes during spring snowmelt. In addition, according to meteorological observations, the total amount of water stored as snow before the start of the snowmelt (i.e. during the last 10 days of March) were 20–30% higher in the period 1986–2015 as compared to the period 1966–1986. These changes likely resulted in significant reductions of soil freezing depths. Frozen soils generally have very low infiltration rates due the formation of ice in soil pores (Komarov and Makarova, 1973). Hence, higher soil temperatures during winter time promote a reduction in soil freezing depth and therefore may result in reduced runoff production (Gray *et al.*, 2001). This is supported by the results of the surface runoff monitoring from arable lands during spring snowmelt undertaken at the Novosil experimental station (the north of the forest-steppe zone, to the west of the Middle Volga region), which showed a ten-fold reduction in runoff coefficients since 1990 as compared to the period 1955–1980 (Petelko *et al.*, 2007). This trend concurs with observed reductions in gully headcut retreat in the Udmurt region, based on long-term observations (1978–2015; Figure 14; Rysin *et al.*, 2017a, 2017b, 2017c). For gullies within cultivated catchments, it was found that average annual headcut retreat rates reduced from 1.5 m yr^{-1} (1978–1997) to 0.3 m yr^{-1} (1997–2015).

Figure 14. Mean annual gully head retreat rates for the period 1978–2015, based on results of the field monitoring of 168 gully heads in Udmurt Republic (Legend: 1 – mean annual rates; 2 – mean rate over five-year periods; after Rysin *et al.*, 2017c).

Analysis of retreat events during the first observation period (1978–1997) showed that 81% of the linear gully head retreat occurred during the snowmelt period between March and April (Figure 15). Only 19% of the retreat occurred as a result of rainfall during the warm part of the year (May–September) (Rysin *et al.*, 2017c). During the period 1997–2015, the contribution of snowmelt to gully headcut retreat became clearly lower and is now more or less equal to retreat rates during the warm part of the year (Rysin *et al.*, 2017c).

Apart from changes in snowmelt regimes, changes in rainfall intensity should also be considered. Earlier studies have shown that rainfall intensity is a dominant factor of gully erosion (Poesen *et al.*, 2003; Capra *et al.*, 2009; Vanmaercke *et al.*, 2016), with higher intensities resulting commonly in (drastically) higher gully erosion rates. Based on information collected from meteorological stations evenly distributed across the area, a significant decrease was observed in heavy rainfall events (> 50 mm; Figure 16). The frequency of such rainfall events was 0.27 per year in the period 1960–1990, but dropped to 0.04 events per year in the period 1990–2015. Hence, this decrease in heavy rainfall events may certainly contribute to the observed declines in gully erosion. However, this decrease in heavy rainfall event was not clearly detected in the Udmurt Republic (i.e. the sub-region of the Middle Volga). This suggests that the decrease in snowmelt-related runoff is

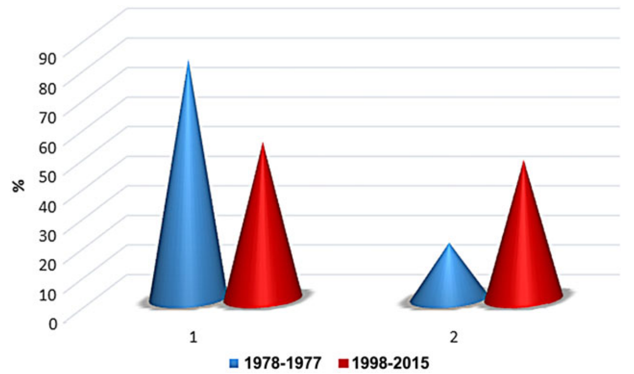

Figure 15. The mean contribution of snow-melting (1) and rainstorms (2) to mean annual gully head retreat rates (expressed as percent of the mean annual retreat rate) for two timeframes of monitoring: 1978–1997 and 1998–2014. Percentages are based on the results of monitoring campaigns in Udmurt Republic for sites located nearby Izhevsk (see Figure 1) (after Rysin *et al.*, 2017c). [Colour figure can be viewed at wileyonlinelibrary.com]

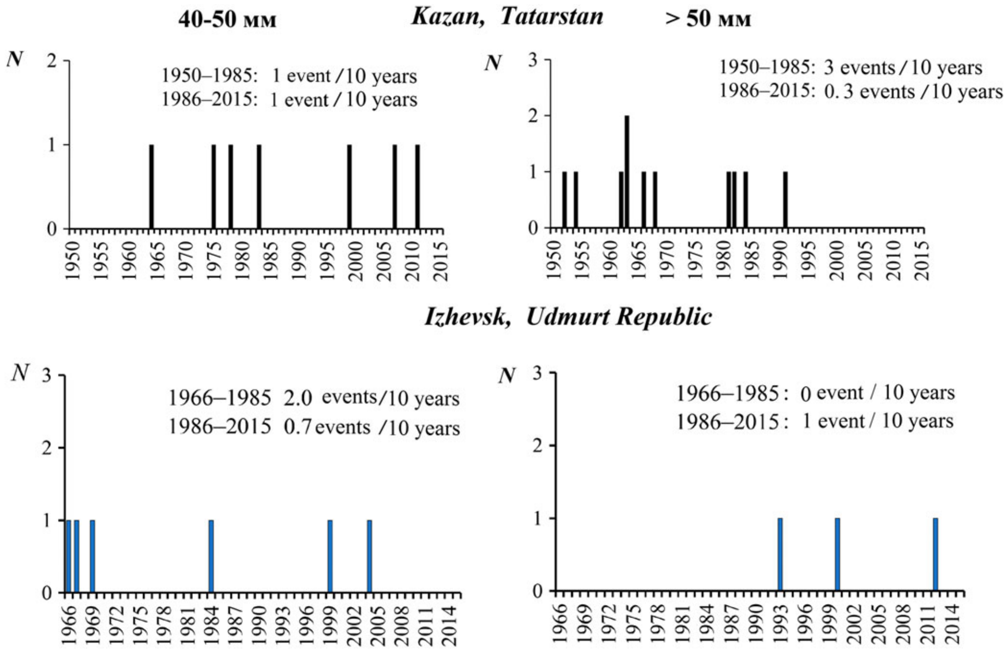

Figure 16. Frequency of rain-storms (with layers 40–50 mm and > 50 m) during the warm part of the year (May–September) for some meteorological stations in Tatarstan and Udmurt Republics since the middle of the twentieth century. [Colour figure can be viewed at wileyonlinelibrary.com]

probably more important in explaining the observed decreases in gully erosion.

Nonetheless, it is uncertain if this decline in gully erosion as a result of changing climatic conditions will continue in the future. Studies overall predict a strong increase in air temperature for northern Eurasia (Deser *et al.*, 2012). It remains unclear if this warming trend will continue to result in a decline in snowmelt-related runoff (due to reduced soil freezing depths) or may result in higher snowmelt runoff peaks (e.g. due to rapid snowmelt events). Likewise, rainfall intensities are expected to increase worldwide in the following decades, including in the Middle Volga region (Polade *et al.*, 2014). Earlier studies showed the high sensitivity of gully erosion rates to rainfall intensities (e.g. Vanmaercke *et al.*, 2016). As such, both the relative and absolute importance of rainfall-related gully erosion may increase.

Conclusion

For the first time, a digital vector map of gully density was composed for the Middle Volga region. The map was prepared on the basis of a complete large-scale mapping of gullies using aerial photographs from the period 1956–1970. The results of the mapping indicate a very strong gully development in some parts of the Middle Volga region in 1956–1970, when this area was intensively cultivated. The average gully density for the entire area of the Middle Volga region was 0.21 km km^{-2}. The highest gully densities (2–2.3 km km^{-2}) occurred in catchments located at the confluence of the Rivers Volga and Tsivil, on the right bank of the Kama River and right slope of the valley of the upper Sviyaga River, which were characterized by a generally steeper topography. It was found that gully densities were mainly correlated to average relief and the fraction of arable land.

We also studied the long-term dynamics of gully densities, based on the interpretation of aerial photographs and satellite imagery over three timeframes (1956–1960, 1986–1991 and 2010–2015) the Udmurt Republic and the Mesha and Ulema River basins in the Republic of Tatarstan. We found that the total length of the gully networks reduced by only 2% in the Udmurt Republic during the period 1956–1986. This period was characterized by low variable climatic conditions and a stable fraction of arable land with a relatively continuous set of crops included in the crop rotation. However, we observed a very sharp (order of magnitude) reduction in active gully densities for the period 2010–2015 as compared to 1986–1991. The main reason for this sharp reduction in the gully erosion is likely the increase in winter air temperatures and, associated with this, a decrease in soil freezing depths, which results in a significant reduction in surface runoff during spring. Nonetheless, in some regions (i.e. the Udmurt Republic in the taiga zone), arable land abandonment after 1991 likely also played a significant role. Likewise, a decline in the frequency of extreme rainfall events (> 50 mm) may have contributed. All these factors likely lead to the reduction of peak surface runoff to gullies and their subsequent stabilization.

Nonetheless, climate change scenario studies indicate that rainfall intensities may increase in the region, while it remains unclear how a further warming of air temperatures in the study area will affect snowmelt-related runoff. As such, while gully erosion rates in the Middle Volga have strongly declined over the past decades, it remains unclear to what extent this trend will continue or be reversed in the future.

Acknowledgement—The work (methods, analysis and results) was funded by the Russian Science Foundation (project number 15-17-20006).

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