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Long-term monitoring of gully erosion in Udmurt Republic, Russia

Ivan Rysin[1,2], Ivan Grigoriev[2], Mariya Zaytseva[2], Valentin Golosov[1,3], and Aidar Sharifullin[1]

[1]Department of the Landscape Ecology, Kazan Federal University, 18 Kremlyovskaya street, Kazan, 420008, Russia
[2]Department of the Environment and Ecology, Udmurt State University, 1 Universitetskaya, Izhevsk, 423064, Russia
[3]Laboratory for Soil Erosion and Fluvial Processes, Lomonosov Moscow State University, GSP-1, Leninskie Gory street, Moscow, 119991, Russia

Correspondence to: Aidar Sharifullin (luleo123@mail.ru)

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Abstract. This article presents results from the long term-monitoring of gully headcut retreat rates (GHRR) between 1959 and 2015 in different parts of the Udmurt Republic and is based on the use of historical aerial photographs and field observations (measuring the distance from the gully head to a fixed reference point) (Vanmaercke et al., 2016). It was determined that GHRR decreased from 2.4 to 0.3 m yr^{-1} during the 1959–1997 observation period and the 1998–2015 period, respectively. Measurements of GHRR were made once per year for most of the monitoring sites, and twice per year (after snow-melt in May, and after the rainy season, October–November) for gullies located in the eastern part of the study area that contain high proportions of arable land. 80 % of GHRR occurred during the snowmelt period (1978–1997), and decreased to 53 % since 1997. Spatial patterns of GHRR resulting from changing hydro-climatic factors for different regions of the Udmurt Republic, as a whole, were determined based on the analysis of long-term observations at 6 meteorological stations and 4 gauging stations. The main reason for decreasing GHRR appears to be due to reductions in winter frozen soil depth. The influence of stormwater runoff more clearly occurred within the east and north parts of the Vyatka-Kama interfluve, whereas higher correlations between GHRR and frozen soil depth were found for the western parts of the Republic. The most significant increases in GHRR appear to have occurred during the warm part of the year (June–July), after > 40 mm rainstorms.

1 Introduction

Gully erosion is an important soil degradation process in the southern half of the Russian Plain. The dissolution of the USSR at the end of the 20th and beginning of the 21st century led to significant changes in land use in forested areas, including the taiga and broad-leaf forests; large areas of arable land were abandoned. These changes coincided with global warming during the last decades of the 20th and early 21st centuries. Recent decades have been characterized by significant climatic changes that resulted in substantial reductions in surface water runoff in the European territory of Russia (ETR) and Western Siberia (Bazhenova et al., 1997; Dedkov, 1990; Petelko et al., 2007).

2 Materials and methods

The research area is located in the Eastern part of the Russian Plain in the southern part of the Vyatka-Kama interfluve (Fig. 1). This area of the Udmurt Republic is located south of the taiga zone. Elevations in the study area are in the range of 120–250 m a.s.l. with maximum relative elevations occurring along the river valleys. This area of the Udmurt Republic is characterized by a temperate continental climate with annual precipitation in the range of 550–600 mm; mean annual temperatures in January and July are −12.3 and +19° respectively (Perevedencev et al., 2014). The amount of arable lands in the Udmurt Republic slightly decreased from 38.5 %

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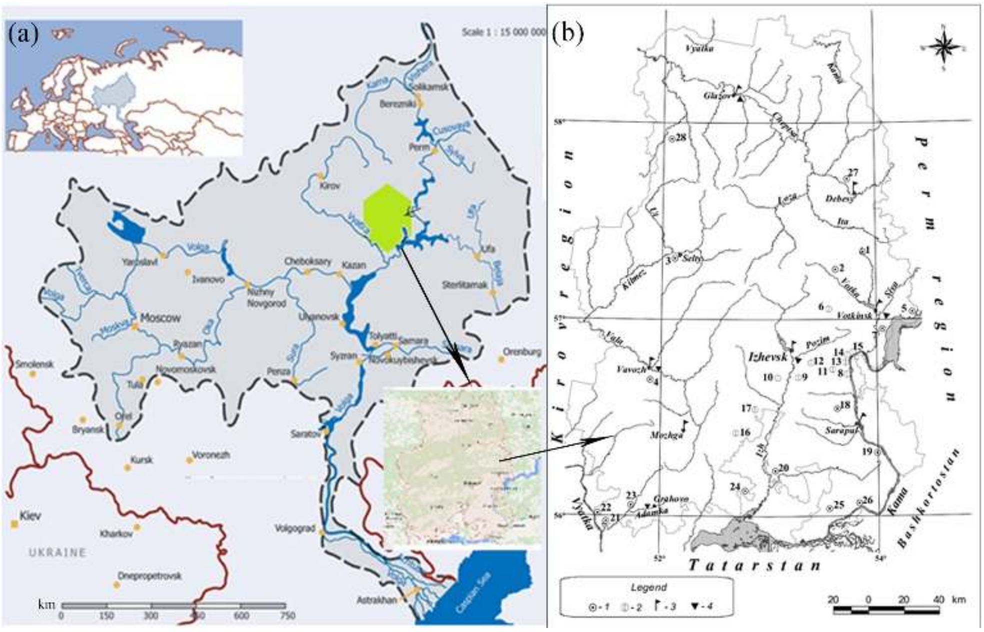

Figure 1. Map of the Volga River basin showing the location of the Vyatka-Kama interfluve **(a)** and Udmurt republic **(b)**. (Legend: 1 – study sites with annual measurement of gully head retreat, 2 – study sites with measurement of gully head retreat twice per year (after snow-melting, May; after rain-storm season, October), 3 – meteorological stations, 4 – gauging stations.

in 1955, to 35 % in 2014, with the maximum reduction occurring after the dissolution of the USSR between 1991–1996.

Gully erosion was studied by using two approaches. Firstly, high resolution aerial photographs (surveys 1959, 1970 and 1980) were used for evaluation of mean annual GHRR for the 1959–1970 and 1970–1980 periods; we used images with scales of 1 : 17 000. Gully heads were identified in all the aerial photographs and the rate of gully growth was measured (Rysin, 1998). Secondly, 168 gully heads, located at 28 sites within different parts of the study area were monitored since 1978 (Fig. 1). The actual number of monitored gully heads varied during this period because some gullies stabilized whereas new gullies became active. Different types of gullies, including slope, bank and bottom, in mostly cultivated catchments, were included in the monitoring program. GHRR was determined once per year for the majority of the sites by measuring the distance from the gully head to a fixed reference point. However, 34–40 gully heads, located in the Eastern part of the study area that contained high proportions of arable land, were measured twice per year (after snowmelt in May, and after the rainy season in October–November).

3 Results

It is important to note that the monitoring period for GHRR coincided with climate warming, which began during the second half of the 1970s (Rysin, 1998). Based on aerial photographs, the mean linear GHRR decreased from 2.4 m yr^{-1} in 1959–1970 to 1.9 m yr^{-1} in 1970–1980 for the entire study area (Fig. 2). These changes may have been due to the stabilization of the catchment area of the gully. Similar observations were noted until the mid-1990s, partly because some gullies stabilized, some arable land was abandoned during 1991–1996, and some gullies were levelled (Rysin, 1998; Rysin and Grigor'ev, 2010).

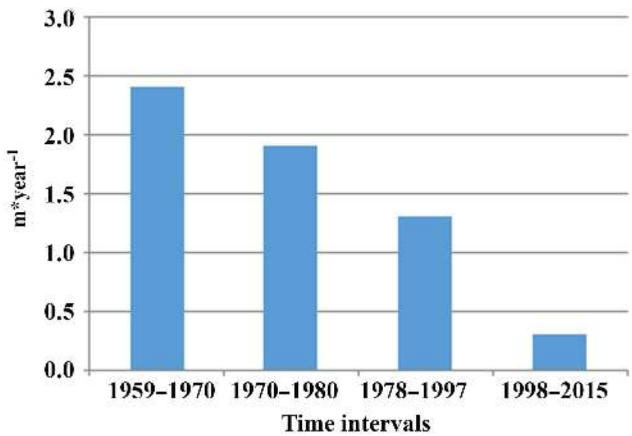

Figure 2. Mean annual gully head retreat rates for different time intervals within Udmurt Republic (time intervals 1959–1970 and 1970–1980, based on aerial photograph comparisons; time intervals 1978–1997 and 1998–2015, based on monitoring data).

There has been a considerable decrease in the mean annual rate of linear GHRR since 1997 (Fig. 3). During the 1978–2015 observation period it is possible to identify 3

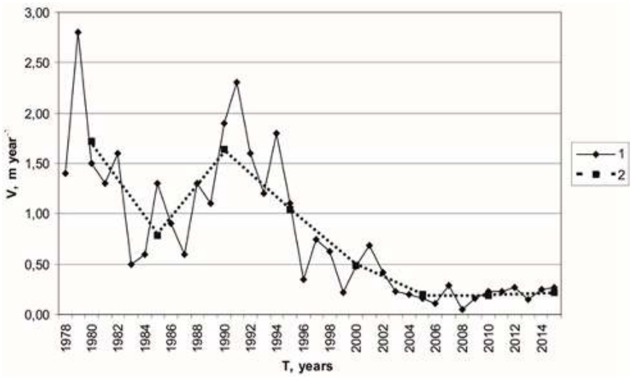

Figure 3. The mean annual gully head retreat rates for the period 1978–2015, based on results of the field monitoring of gully heads at 28 sites (for site location see Fig. 1) (Legend: 1 – mean annual rates; 2 – mean rate for five-year periods).

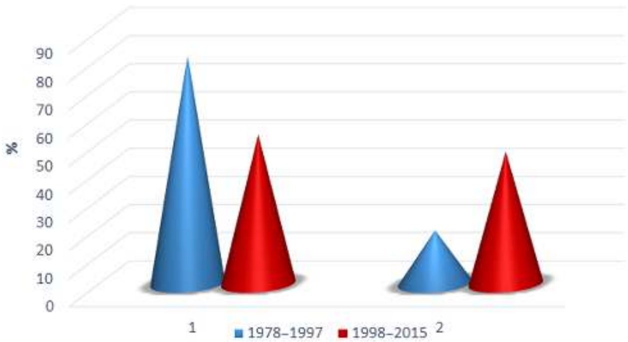

Figure 4. The mean contribution (in %) of snow-melting and rain-storms in annual gully head retreat rates for periods of monitoring 1978–1997 and 1998–2014 (Legend: 1 – period of snow-melting; 2 – rain-storms period).

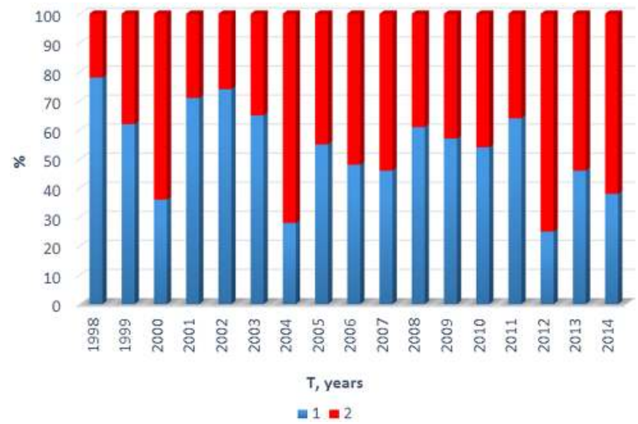

Figure 5. Annual contribution (in %) of snow-melting and rain-storms in annual gully head retreat rates for the period 1998–2014 (Legend: 1 – period of snow-melting; 2 – rain-storms period).

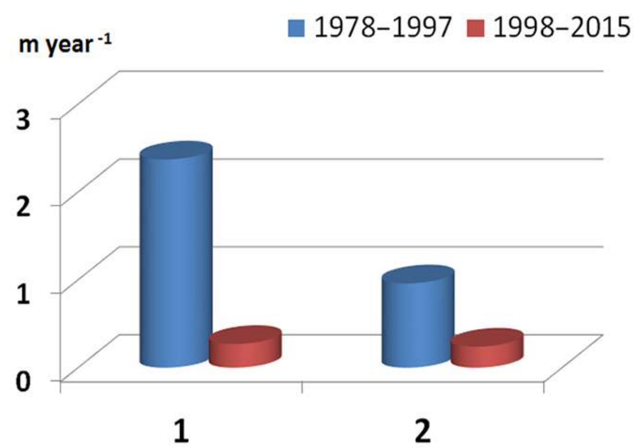

Figure 6. The mean gully head retreat for gully catchments with "warm" and "cold" aspects for the periods 1978–1997 and 1998–2015 (Legend: 1 – gully catchment with "cold" aspects (N, NE, NW and E); 2 – gully catchment with "warm" aspects (S, SW, SE, W).

peaks, with maximum values occurring in 1979 (2.8 $m\,yr^{-1}$), between 1990 and 1991 (1.9 and 2.3 $m\,yr^{-1}$), and in 1994 (1.8 $m\,yr^{-1}$). Increased rates of GHRR in these years were associated with increases in surface runoff during the spring snowmelt period (Rysin, 1998).

Based on the results of the first monitoring phase of this study (1978–1997) it is possible to conclude that 81 % of linear GHRR occurred during the snowmelt periods between March and April (Fig. 4), with the remainder occurring during the warm season. The second monitoring period (1997–2015) was characterized by a sharp decline in the mean linear GHRR (0.3 $m\,yr^{-1}$). This tendency was observed for all gully types. Further, there is a clear increasing trend in GHRR for bottom gullies since minimum values were observed in 2006.

The main reason for the substantial reductions in gullying since 1997 appears to be increasing winter air temperatures due to global warming. This led to substantial reductions in surface water runoff from the surrounding slopes during snowmelt because of an increasing frequency of years where the frozen soil depth was $<$40–50 cm. The impact of snowmelt for annual GHRR appears to have declined by some 53 %, with relatively high interannual variations (Fig. 5). It also is important to note that during the warm part of the year, serious GHRR occurred in conjunction with intense rainstorms where precipitation exceeded 40 mm. The maximum number of such rainstorms were observed within the Vyatka-Kama interfluve between 1990–1994. Since 2003, the number of extreme rainstorms ($>$40 mm) has declined in the study area (Rysin et al., 2017).

There is reason to believe that GHRR also depends on slope aspects relative to solar radiation. For the observation period, most gullies developed on the slopes that favored cold aspects (North, North–East, East, North–West; Fig. 6). In fact, the overall water resulting from snowmelt on the southern slopes is lower than on the northern slopes, where evaporation is relatively low. Also, during the second monitoring period (1998–2015), there was a noticeable reduction in GHRR for the slopes with cold aspects. The reason for this decrease probably is an increase in March temperatures during snowmelt.

Finally, it is possible to conclude that a limited number of factors influenced mean annual GHRR between 1959 and 2015, these include: land use changes, declining gully catchment areas, and climate warming. However, the latter factor appears to have led to the most notable declines in mean annual GHRR after 1996. A positive trend in mean annual GHRR has been observed for bottom gullies within the Vyatka-Kama interfluve area after 2006, and may be the initial indicator of some changes in the conditions of surface and subsurface runoff within the gullied catchments.

4 Data availability

The paper used data from a united database of gullies in the territory of the Republic of Udmurtia (Vanmaercke et al., 2016). Also we used of the database of gullies of the Udmurt Republic data, which is patented in Russia.

Competing interests. The authors declare that they have no conflict of interest.

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