Long-term dynamics of erosion and channel processes on the territory of Udmurtia

Rysin Ivan[1,*], *Grigoriev Ivan 2, and Permyakov Maksim 2*

[1] Department of Ecology and Nature Management, Udmurt State University, Izhevsk, Russia
[2]Department of Geography, Cartography and Geoinformatics, Udmurt State University, Izhevsk, Russia

Abstract. This paper presents the data of long-term observations of gully erosion (1978-2023) and channel processes (2000-2023) on the territory of Udmurtia. Quantitative indices of gully top growth rates at 28 sites for different periods have been compared by types and composition of eroded. Average and maximum rates of their growth are given here. The study of river channel scour at 55 sites in different landscapes has been resulted. To analyze the results, the rivers have been divided into 4 groups according to the magnitude of their orders (according to A. Scheidegger's model). Linear, area and volume indices of scour in ravines and channels of small watercourses have been calculated on the basis of geodetic surveys using electronic total stations and unmanned aerial vehicles.

In this article we aimed to analyze changes and identify trends in the development of gully erosion and channel erosion of river banks on the territory of the Udmurt Republic (UR) over a multi-year period, that is quite relevant in the context of modern global climate change. The relevance of this study is also related to the great economic damage caused by erosion and channel processes to agricultural production and social sphere (residential and industrial buildings, roads, pipelines and other communications). The results of this study will be used for scientific substantiation of techniques and ways of protection from erosion and channel processes as well as their forecasting.

We started the examination of erosion processes on the UR territory as early as 1976 [1]. Gully erosion has been monitored since 1978 [2]. The main results of gully erosion studies for the period from 1978 to 1997 were presented in our monograph [3]. A great contribution to the study of the mechanism and dynamics of gully erosion in the east of the Russian Plain was made by scientists of Kazan, Perm, Udmurt and Ulyanovsk Universities [4, 5]. Since the middle of the 19th century, researchers of the Laboratory of Soil Erosion and Channel Processes at the Faculty of Geography of Lomonosov Moscow University have been successfully engaged in studies of gully erosion processes in various landscape zones of the former USSR and Russia [6-10, etc.].

We have found no publications on studies of channel processes on the UR territory in the last century. We started to study channel scouring of banks in 1999 under the assignment of

[*] Corresponding author: rysin.iwan@yandex.ru:

the State Committee on Subsoil of the UR [11-14]. Otherwise, on the territory of neighboring regions, the channel processes studies have been carried out quite actively [15-17].

The paper firstly presents the results of long-term (1978-2023) field observations of linear growth of gullies within the south of the Vyatka-Kama interfluve on the territory of the UR. For 2023 the monitoring system on agricultural lands has included 169 gullies tops located in 28 key sites in different landscape conditions in the south of the Vyatka-Kama interfluve (Fig. 1).

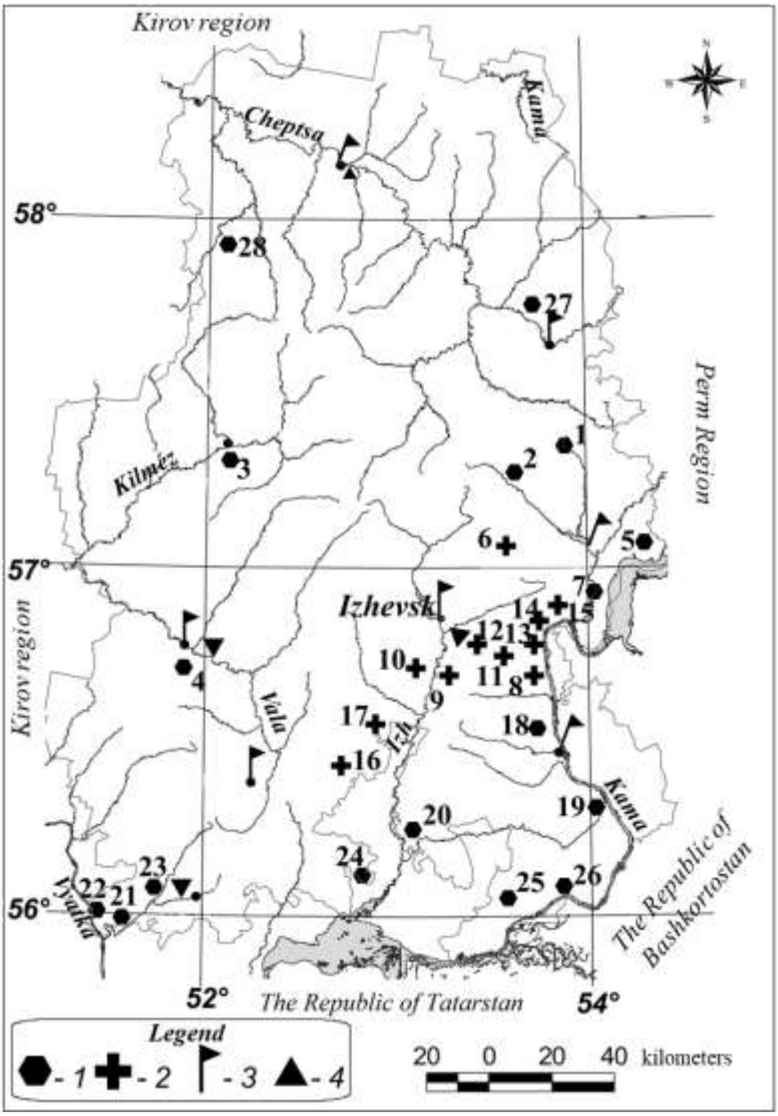

Fig. 1. Map of the Udmurt Republic.
Legend: 1 –study sites with annual measurement of gully head retreat, 2 – study sites with measurement of gully head retreat twice per year (after snow-melting, May; after rain-storm season, October), 3 – meteorological stations, 4 – gauging stations.

The linear growth rate of gullies is determined by measuring the distance from the top of the gully to a pre-determined reference point. At most sites (127 gully tops) observations are carried out once a year (in summer), and at nine key sites (42 gullies) measurements are made twice a year (after snowmelt in May and after the end of the summer-autumn rainy season in October or early November) [1].

Over the entire 46-year observation period on the background of the general downward trend, 4 maximum values peaks have been clearly distinguished. All of them refer to the first stage of observations in 1978-1997: 1979 (2.8 m/year), 1990 and 1991 (1.9 and 2.3 m/year), and in 1994 (1.8 m/year) (Fig. 2). Increased rates of gully top retreat in the following years were due to the intensity of flood runoff and a significant share of arable land in their catchments [2]. After 1997 the average annual rates of gully tops retreat decreased sharply and only in 1998 and 2001 exceeded the value of 0.5 m/year reaching a minimum in 2008 (0.05 m). Epigenetic gullies are characterized by more active growth [3].

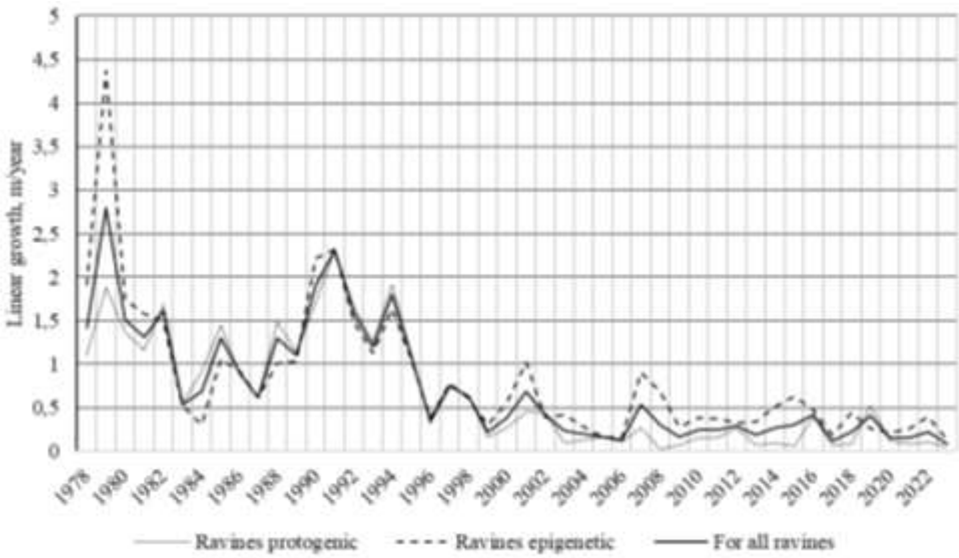

Fig. 2. Dynamics of average annual growth rates of protogenetic, epigenetic and all types of ravines in the south of the Vyatka-Kama interfluve in 1978 – 2023

The monitoring data assay shows that the greatest differences in average annual linear growth rates have been observed among protogenetic gullies (0.59 m/year) as epigenetic gullies have these differences slightly higher, which is 0.74 m/year. Reduction of growth rates of protogenetic gullies by types differs insignificantly, from 5.5 to 6.5 times, as well as in epigenetic gullies the differences are more significant, from 2.65 times for bottom gullies to 5.12 times for top beam gullies, while there is an increase of 3.57 times in the development of floodplain gullies (Table 1).

Among the protogenetic gullies, the slope gullies develop most intensively. Their average multiyear velocity for the period under consideration amounts to 0.83 meters. The maximum velocity was recorded in 1985 near Mushak village, Kiyasovsky district of the UR, and amounted to 80.3 m. The second maximum was registered in the same ravine in 1984 (63.2 m). The average multiyear velocities of the slope of beam gullies (0.57 m) and valley slope gullies (0.42 m) are much lower (Table 1). The maximum velocities of these types are also much lower: in the valley slope gullies they are 18.8 m (2002), and in the slope of beam gullies - 5.1 m (1999).

Table 1. Average long-term growth rates of different types of ravines in Udmurtia (m/year)

Types of gullies *	Quantity, units	1978-1997 years	1998-2023 years	Rate reduction, number of times	1978-2023 years
Protogenetic gullies					
GSB	16	1.04	0.19	5.47	0.57
SG	52	1.56	0.24	6.50	0.83
GVS	31	0.77	0.13	5.92	0.42
Epigenetic gullies					
GTB	43	1.28	0.25	5.12	0.72
BG	25	1.38	0.52	2.65	0.93
FG	2	1.69	6.03	+3.57 (increasing)	3.86

* Types of gullies: GSB – Gully on the slope of the beam, SG – Slope gully, GVS – Gully on the valley slope, GTB – Gully at the top of the beam, BG – Bottom gully, FG – floodplain gully

Epigenetic gullies develop more actively than protogenetic gullies. While the average perennial velocities of bottom gullies are higher than those of top beam gullies and floodplain gullies, in terms of maximum velocities the highest values for top beam gully (84.58 m) were recorded in 1979 at the site near Varzi-Yatchi village, Alnashsky District. For bottom gullies, the maximum (13.8 m) was recorded in 2001 near Kuregovo village, Malopurginsky District. For the floodplain ravine, the maximum value of annual growth was recorded in 1991 and amounted to 2.64 m. It should be taken into account that since 2007 we have been observing a new floodplain gully that appeared on the high left-bank floodplain of the Varzinka River near the village of Yumyashur, Alnashsky District. The gully has been developing due to the frequent breaches of two earth dams at the mouth and in the middle part of the beam created for the accumulation of melt water for cattle watering in summer periods. Thus, in the first year of the breach of the earthen dams in 2007 it grew by 53 meters. The second maximum growth (38 m) was registered in the following year, 2008, which was associated with the repeated dam breaching (Fig. 3) [4, 5].

A B

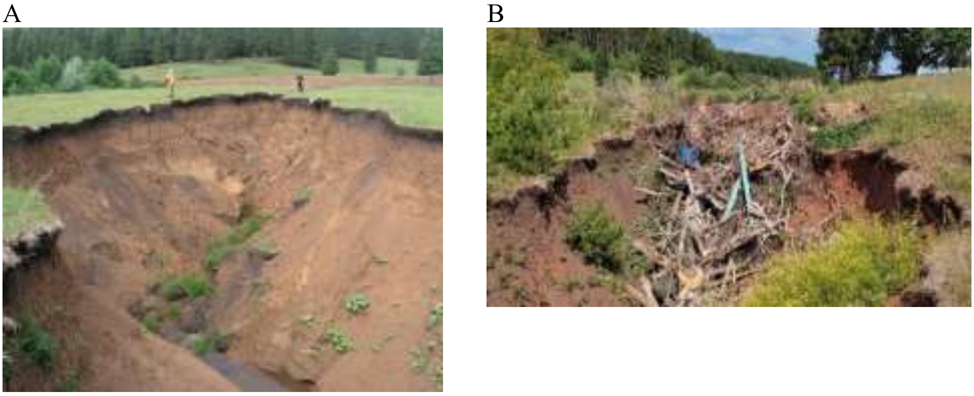

Fig. 3. Gully on the floodplain of the Varzinka River resulting from the breach of two earthen dams of the ponds: A - photo in July 2008; B - photo in July 2023

The lithologic and geomorphologic structure of the territory, the depths of local erosion bases, the morphometric characteristics of slopes and their exposure as well as the size of the catchment area, width and depth of the gully at the top are among the most important conditions affecting the processes of gully erosion. Here in this article we have studied the data on the assay of the importance of these factors in gully development for the time interval of 1998-2020 [6].

To study the peculiarities of horizontal channel deformation development on the territory of the UR, we have identified 55 key sites covering rivers of different sizes using large-scale topographic maps. Field work on the studied rivers has been carried out annually (since 1999) in summer, and at some sites (near Izhevsk) in spring and autumn additionally. To determine scour rates at all key sites, about 300 marks and stamps have been laid, and within 30 of them a total station survey of the eroding bank is being carried out [7].

The analysis of 24-year field data indicates a large range of lateral scour rates of rivers. According to the field expedition observations, the highest scour rates are typical for the rivers with an order higher than the 9th, according to A.E. Scheidegger [8]. The maximum values of scour observed on such rivers reach 6-8 m and more, the average annual scour rates vary in the range of 0.8-3.1 m/year. On the Vyatka River, which has the 15th order, the average annual scour rates exceed to 3-5 m/year, and the maximum values recorded are 12-15 m/year. Horizontal channel deformations are quite active on the Cheptsa River near Yar village (the 12.3rd order): average annual scour rates here are usually 1-3 m/year, and the maximum of 7.1 m was recorded in 2005.

Fig. 4. Tachymetric survey of the eroding section on the Kyrykmas River in July 2023

For small rivers (the 6-9th order) average rates of bank retreat are 0.3-0.5 m/year. But at some sites scour rates are much higher. On the Kyrykmas River (the left tributary of the Izh River) near Tavziamal village in 2012, the maximum scour rate was 5.05 m, in 2017 it was 5.35 m (Fig. 4). On the Pyzep River (near Bani village) in 2012, the maximum scour at one of the sites amounted to 4.8 m. And in 2019 this indicator reached a record for this group and made up 5.5 m (Fig. 5).

Fig, 5. Intensively eroded area on the Pyzep River (a tributary of the Cheptsa River) near the Bani village, Balezinsky District, the Udmurt Republic

For very small rivers (below the 6th order), the average scour rates are 0.1-0.3 m/year, although in some areas 1 m or more of bank displacement has been recorded. Thus, at the section of the Sharkan River near Titovo village (the 5.6th order), the average maximum scour in 2000 and 2003 exceeded 2 m. On the Adamka River near Grahovo village (the 3.8th order) in 2011, the average maximum scour was 4.2 m, and on the Agryzka River near Bagrash-Bigra village (the 4.5th order) in 2003, the maximum scour was 8.1 m, that was caused by the breach of the earthen dam above the pond.

The analysis of average annual and maximum scour rates (excluding tachymetric survey data) for the 24-year period has shown that in recent years there has been a tendency for scour rates to decrease. At the same time, this trend is less pronounced for the group of small rivers with the 6.1-9.0th order. This is likely to be connected with the decrease in the intensity of flood flow in the rivers under study. The areas of active scour are supposed to have shifted over time from the locations with reference observations to the downstream bends. As the example, the observations on the Kerzhenets River in the Nizhny Novgorod Volga region indicate the displacement of the maximum scour areas towards the lower wing of the bend [24].

The results of the total station survey show the opposite picture. On the contrary, the values of scour (linear, area and volume) have a positive trend. The highest scour rates for many rivers were recorded in 2012, 2013, 2016 and 2021 when they experienced the highest floods. At the same time on the Kyrykmas River (the 8.4th order) in 2021, a record for the entire observation period of erosion value of 8.14 m was recorded.

Thus, over the considered long-term observation period on the background of the general downward trend, 4 maximum values peaks referring to the first observation period (1978-1997) have been clearly distinguished. High growth rates of ravine tops in these years were caused by the intensity of flood runoff and a significant share of arable land in their catchments. The most active growth of secondary gullies is noted, among which the bottom and apex gullies with extensive catchment areas are predominant. Among the primary gullies, the maximum growth rates are typical for drivable (slope) gullies eroding diluvial soliflectional loams.

The analysis of long-term (2000-2023) field studies of horizontal channel deformations on the rivers of Udmurtia has revealed that the rates of lateral bank displacement vary in a large range from a few centimeters to many meters (10-15 m/year). The intensity of scour depends primarily on the water content of the river often determined by the watercourse order. Maximum scouring is characteristic of rivers with the 14th order and higher (according to A. Scheidegger's model), reaching 12-15 m/year as well as average annual values are 3-5 m/year. For medium-sized rivers (with the 9-14th order), the maximum scour values are 6-8 m/year as well as the average annual values are 1-3 m/year. For small rivers with the 6-9th order, maximum scour values were as high as 5.5 m/year and annual averages ranged from 0.4-0.6 m/year. In very small rivers (the 6th order and less), maximum bank scour rates reached up to 4.2 m/year under natural conditions and up to 8.1 m/year under anthropogenic interference, with average annual scour rates typically 0.1-0.3 m/year.

The study was carried out at the expense of the Russian Science Foundation grant no. 23-27-00194, https://rscf.ru/project/23-27-00194

References

1. G.P. Butakov, I.I. Rysin, *Second All-Union Interuniversity Conf. on the problem "Regularities of manifestation of erosion and channel processes in different natural conditions", Moscow, January 27-30, 1976,* 186-187. (1976)
2. I.I. Rysin, *The Third All-Union Scien. Conf. "Regularities of manifestation of erosion and channel processes in different natural conditions", Moscow, December 22-24, 1981*, 230-232. (1981)
3. I.I. Rysin, *Gully Erosion in Udmurtia* (Udmurt State un-ty: Izhevsk, 1998)
4. A.P. Dvinskikh, N.N. Nazarov, I.I. Rysin et al. *Ravine erosion in the east of the Russian Plain* (Kazan, 1990)
5. V.N. Golosov, O.P. Ermolaev (eds.) *Spatio-temporal patterns of contemporary processes dynamics of natural and erosion on agricultural lands of the Russian Plain* (Kazan, 2019)
6. E.F. Zorina, Geomorphology, **4**, 62 - 67. (1987)
7. E.F. Zorina, *Gully erosion: regularities and development potential*. (Moscow, 2003)
8. B.P. Lyubimov, I.I. Nikolskaya, S.D. Prokhorova, Soil erosion and channel processes. **12**, 96-100 (2000)
9. B.F. Kosov, Vestnik Mosk. un-ta. Ser. Geogr., **1**, 37-44. (1971)
10. B.F. Kosov, I.I. Nikolskaya, Erosion processes, 97-103 (Moscow, 1984)
11. I.I. Rysin, L.N. Petukhova, Sixteenth plenary interuniversity coordination meeting on the problem of erosion, channel and estuary processes, 183-184 (St. Petersburg, Oct. 2-4, 2001)
12. I.I. Rysin, L.N. Petukhova, *Proc. of the Intern. Symposium held at Moscow, from 2 to 6 August 2004*, 261–268. (2004)
13. L.N. Petukhova, I.I. Rysin, Vestnik of Udmurt un-ty, Ser. Earth Sciences. **11**, 153-168. (2005)
14. L.N. Petukhova, I.I. Rysin, Channel processes in the rivers of mountains, foothills and plains, 119-131 (Jagiellonian University, Cracow, 2006)
15. O.V. Korableva, A.V. Chernov, *Proc. of the State Natural Biosphere Reserve "Kerzhensky",* 5 (Nizhny Novgorod, 2012)
16. V.I. Mozzherin, S.G. Kurbanova, *Human activity and erosion-channel systems of the Middle Volga region* (Kazan, 2004)
17. N.N. Nazarov, S.S. Egorkina, Rivers of the Permian Kama Region: Horizontal channel deformations (Perm, 2004)
18. I.I. Rysin, I.I. Grigoriev, M.Yu. Zaitseva, V.N. Golosov, Vestnik Mosk. un-ta, Ser. 5. Geogr., **1**, 63-72 (2017)

19. V.N. Golosov., O.P. Yermolaev, I.I. Rysin, M.Vanmaercke, R. Medvedeva, Earth Surface Proc. and Landforms, **43(13),** 2818-2834. (2018)
20. I.I. Grigoriev, I.I. Rysin, Geomorphology, **53**, **4**, 56–74. (2022)
21. I.I. Rysin, M.I. Zaitseva, and D.A. Syntsov, Vestnik Udmurt un-ty, ser. Biol. Earth Sciences, **31**, **1**, 76 -87. (2021)
22. I. Rysin, L. Petykhova Channel processes on the rivers of Udmurtia (Izhevsk, 2006)
23. A.E. Scheidegger, *Theor. Geomorphology* (Moscow, 1964)
24. O.V.Korableva, A.V. Chernov, *Scientific problems of improvement of Russian rivers , and ways of their solution*, 172-176 (Moscow, 2019)
25. I.I. Rysin, I.I. Grigoriev, L.N. Petukhova, O.N. Andreev, Erosion and channel processes, **7**, 269 - 280 (2020)