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Distribution and development of gullies in Southern East Siberia (Russia)

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Abstract: Large catchment basins (the Yenisei, Angara, Lena, Selenga, and Amur) within southern East Siberia are characterized by weak gully dissection, and by a very uneven distribution of gullies. The varied natural conditions, combined with anthropogenic impacts, produce a highly mosaic pattern in the spatial distribution of gullies. For the last 230–300 years, four intensification stages of gully erosion were identified, which were associated with periods of abrupt changes in nature management. The growth rates of the gully heads in different areas of southern East Siberia vary from 0.1 to 26 m yr^{-1}, the mean long-term linear growth rates of gullies are 0.5–2.5 m yr^{-1}. Extreme meteorological phenomena: torrential rains (over 30 mm hr^{-1}), abundant rains (over 50 mm day^{-1}), and rapid snow thawing in the spring are responsible for gullying.

Keywords: gully erosion, degree of frequency and density of gullies, south of East Siberia, gully development

Introduction

Gully erosion causes extensive damage to the national economy largely because of the resulting withdrawal of lands suitable for cultivation and for the construction and laying of various facilities and has a negative influence on landscapes and environment. Successful linear erosion control requires a knowledge of the conditions and degree of gully occurrence (Mironova 1971) and of their growth rate at different development stages. For the southern areas of East Siberia the published general purpose maps (Mironova 1971, Kosov & Konstantinova 1972, 1974) show highly schematically the areas with different gully frequency, and every so often their boundaries do not coincide. Therefore, the obtaining of an objective picture of the distribution of erosional forms, zoning of the territory according to gully frequency and density, and assessment of the rates of erosion-accumulation processes hold significance in gaining insight into the distinguishing features relating to the location and evolution of the gully network and in developing the package of antierosion measures in different spatial settings (regional, indigenous, local).

Study area

The study area lies between 49-58°N and 88–122°E and includes the zones of the middle and southern taiga, forest-steppe and steppe, numerous mountain ranges, and intermontane and intramontane depressions, where latitudinal zonality and altitudinal zonality are clearly pronounced. Orographically, it is largely a mountainous territory with heights more than 1,000 m a.s.l. Plains and plateaus occupy a subordinate place and are concentrated in the western and northeastern parts of the study area. The southern part of East Siberia is home to the main agricultural lands, where the major areas of erosion loss and scouring of soils were recorded (Litvin 2001, Bazhenova et al. 1997, Ryzhov 2003). The territory under consideration lies at the heart of Eurasia and is characterized by varied types of landscapes, and by a high contrast of the natural conditions.

Materials and methods

The map of the occurrence frequency and density of contemporaneous gullies was compiled by using topographic maps and aerial photographs at scales of 18,000–100,000, and field measurements made in the Angara region, Baikal region and Western Transbaikalia. The first stage involved assembling and summarizing published data on the gully network and studying the sheets of 1:100,000 topographic maps which were used to take inventory of (slope and bottom individually) large (more than 400–500 m) gullies. This was followed by the stage of selecting for 1:100,000 map sheets large-scale (1:25,000 and larger) topographic maps and aerial photographs and high-resolution space images, whereupon measurements were made. Account was taken of all forms of scouring longer than 100 m and deeper than 1 m. The total length and the number of slope and valley gullies were calculated for each sheet of the maps. The growth rates of the gullies were inferred from field survey data spanning the time interval 1985–2009, different-time topographic maps, aerial photographs, and from high-resolution space images. The sediments of the gully fans were studied by lithologo-stratigraphic, isotopic (radiocarbon, and cesium) and dendrochronological methods.

Development stages of gully erosion

A dramatic increase in pressure on landscapes occurred in the latter half of the 17th – first half of the 18th century; it was due to settlement and economic development of the southern part of East Siberia by Russians. Gullying in southern East Siberia was triggered by plowing up of lands, cutting of forests, laying of engineering structures, pasturing of livestock, and redistribution of runoff. An abrupt decrease in the degree of vegetation cover or its total devastation, combine with compaction of soils, act to enhance the unevenness of the runoff and increase the air and soil temperature fluctuation amplitude. Four stages of intensification of linear erosion were identified in the southern part of East Siberia, associated with periods of drastic changes in nature management. All of them, with the exception of the first stage, started concurrently with plowing up of extensive areas of land and were accompanied by a dramatic enhancement of the rates of erosion loss, scouring and deflation of soils. The first period corresponded to development of the vast expanses of the region by Russians and spanned the 17th–19th centuries. The second stage (1875–1930) relates to active development of southern areas of Siberia, the construction of the Trans-Siberian railroad, and to the resettlement of peasants. The third stage includes the 1930s – first half of the 1950s. It is notable for a significant increase in the area of agricultural lands, especially during the 1930s. Small plots of arable lands belonging to peasants, which were delimited by stretches of the taiga, alternating with fallow land, began to turn into large open fields owned by collective farms and used largely for cereals (Zulyar 2002). The next (fourth) stage of development of linear erosion encompasses the latter half of the 20th century. The southern part of East Siberia during that period was subjected to saw an abrupt intensification of erosion caused by plowing up of virgin and fallow lands.

Distribution of gullies

Most gullies in southern East Siberia has been formed during the last 100 years on arable lands, in cutover areas, pastures, populated localities, and along the ruts and ditches at the sides of cart roads under favorable geologo-geomorphological conditions (dense network of ephemeral streams, wide occurrence of readily erodible loose Neogene-Quaternary deposits, and convex and straight slopes of a steepness of 3–10°). Areas with a density of scouring forms of 1–10 and 11–25 100 km^{-2}, and with a dissection frequency of 0.02–0.1 km km^{-2} predominate.

On steep eroded slopes, in the bottoms of valleys of ephemeral and perennial streams, and on escarpments of the river and mountain terraces there occur natural gullies. Usually, they are locally distributed and are produced at the time of infrequent heavy rains and abundant precipitation with a rare (not higher than 5%) recurrence rate in areas of drifting, debris flows, landslips, cryogenic fissures, and forest fires where there are taking place a dramatic decrease in the degree of density of vegetation cover, and a disturbances of soil cover. Gullies occur in areas of river bank caving, an expansion of piping and sinkholes, and collapsing of subterranean galleries. In mountainous areas, gully-ravine systems typically originate and evolve on the boundary of bedrocks that are more resistant to scouring, and loose adjacent Quaternary features (Ivanov & Budayev 1974).

According to calculations, the number of scouring forms is 122,500, the extent is 35,500 km, and the area is 397.5 km^2 (Ryzhov 2003). The mean gully density is 5.63 100 km^{-2}, and the dissection frequency is 16 m km^{-2}. A calculation of the mean areas of gully catchments was performed by the formula:

$$S = 0.4 l_c^2$$

where S is the area of the gully catchment [km^2], and l_c is the length of the slope [km] (Nezhikhovsky 1971). Assuming the mean length of the slopes, on which there occurs gullying, to be 0.5–0.6 km, we obtain the total area of the catchments of the gullies, 14,700 km^2, or merely 0.7% of the area of the southern part of East Siberia. In recalculating for the areas of gully catchments, the dissection density and frequency increased by a factor of 150. This indicates that a dense network of scouring forms is concentrated on relatively small territories. Primary (slope) scouring forms predominate, and the secondary (bottom) forms account for 27% of the erosion forms. Their extent is identical. The area and volumes of bottom gullies, respectively, are by a factor of 1.6 and 1.5 larger than those of the slope forms of scouring. The mean calculated length of the slope is 290 m, and the mean length of the slope and bottom gullies, is 210 and 490 m respectively.

Gully erosion is the most intense in forest-steppe landscapes. The gullies in the intermontane depressions in the southern part of East Siberia are notable for concentric zonality (Salyukova 1976), and for the occurrence of the main gully areas along the slopes and river valleys of order 3–4 or higher. This regularity is explained by the fact that the river valleys and slopes are home to forest-steppe and steppe landscapes that have been modified the most by the economic activities; by the widespread occurrence of loose Neogene-Quaternary deposits, and by a significant (more than 6°) steepness of the slopes and depth of erosion dissection (more than 100 m). Human activity of various kinds led to an active development of scouring forms in the cities of Krasnoyarsk, Irkutsk, Chita, Ulan-Ude, and others. The highest density of scouring forms is usually recorded in suburbs; in rural areas, the density of scouring forms usually increases by a factor of 2–3 as one approaches populated localities. An intensification of gully erosion was promoted by the construction of large hydroelectric power stations (Krasnoyasrakaya, Sayano-Shushenskaya, Irkutskaya, Bratskaya, and Ust-Ilimskaya).

The Figure 1 presents the map of regionalization of the southern part of East Siberia according to the dissection frequency and density of the gully network. The dissection frequency and density were used to identify 6 categories of areas (Ryzhov 2009).

Territories with almost no gullies do not have a wide occurrence. They account for 75% of the area. They include vast undeveloped forest-clad spaces of watersheds and slopes. In some areas, gullies occur singulary, yet their density and dissection frequency are very low. Territories of a very rare occurrence of gullies (less than 2 100 km^{-2}) are characterized by small stretches (a few tens of km^2) of concentration of gullies amongst extensive gully-free territories. Typically, they represent poorly developed, largely taiga landscapes. Gullies can be found in local areas with modified natural vegetation on the slopes of the river valleys, in cutover areas, geological profiles, and near populated localities.

Territories of a rare (island) spread of gullies are characterized by the occurrence of scouring forms in small areas in many geomorphological countries, provinces, and regions. Areas of low, moderate and high dissection frequency and density of gullies are characteristic for treeless developed territories of the intermontane and intramontane depressions, plains, plateaus, and river valleys. Critical to the development of gullies of these three categories are the geologic-geomorphological (existence of steep slopes, widespread occurrence of loose Neogene-Quater-

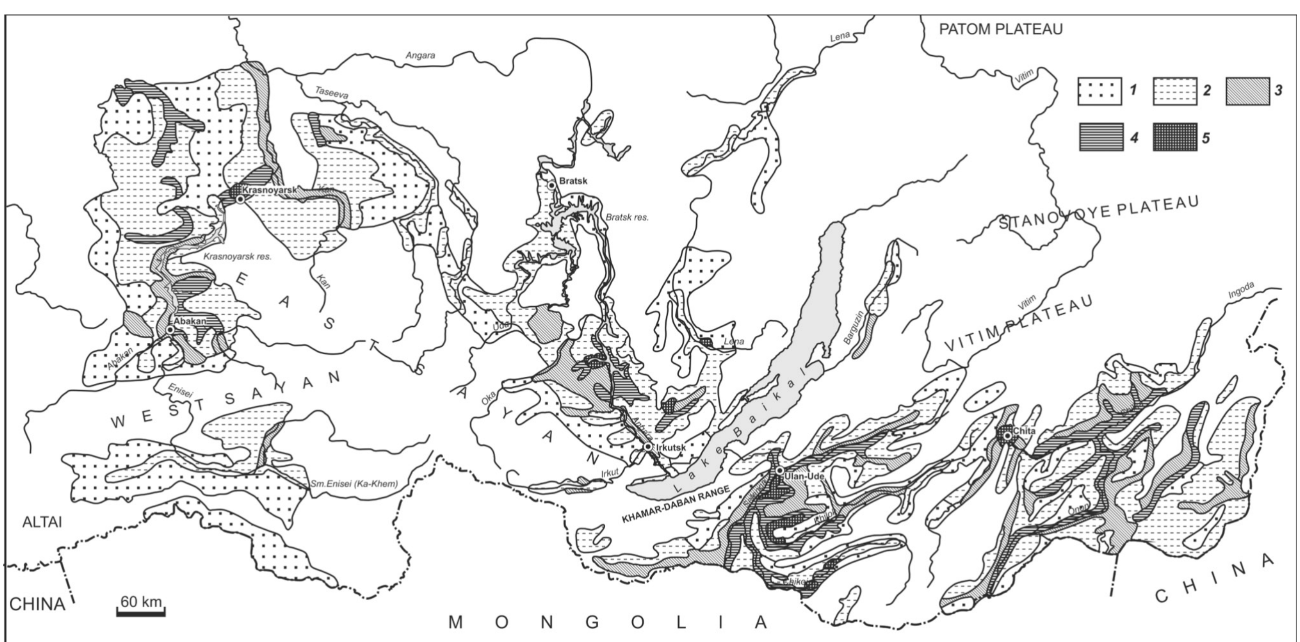

Fig. 1. Map of regionalization of East Siberia according to the occurrence frequency [km km^{-2}] and density [units km^{-2}] of gullies: 1 – very rare occurrence (0.003–0.006 km km^{-2}; 0.011–0.020 units km^{-2}); 2 – rare island occurrence (0.006–0.030 km km^{-2}; 0.021–0.100 units km^{-2}); 3 – weak occurrence (0.031–0.100 km km^{-2}; 0.101–0.250 units km^{-2}); 4 – moderate (0.101–0.200 km km^{-2}; 0.251–0.500 units km^{-2}); 5 – high (>0.201 km km^{-2}; >0.051 units km^{-2}); 6 – white background – no gullies or gullies occur exceptionally rarely (<0.003 km km^{-2}; <0.010 units km^{-2})

nary, not infrequently loessal, deposits) and anthropogenic (a high degree of agricultural development) conditions. Some of the catchment basins of rivers show an increase of the values of the frequency and density of gullies downstream as the result of an increase in slope steepness, frequency and depth of erosion dissection, the thickness of loose deposits, and the area of agricultural lands.

Areas of high gully density lie in the valleys and on the slopes of rivers within the basins of the Yenisei, Selenga and Amur rivers and their large tributaries. They encompass agricultural lands with erosion-denudation, lacustrine-accumulative topography. A moderate and high gully density is observed along the river valleys, in deeply dissected areas of the Yuzhno-Minusinskaya and Sydo-Yerbinskaya depressions, along the shores of the Bratsk reservoir composed by loessal loams, on the escarpments of the river terraces and deluvial-proluvial aprons in the river valleys and depressions within the basins of the Selenga, Onon, Shilka and Ingoda rivers. For instance, the gully density in the catchment area of the Kuitunka river (Selenginskoye middle mountains) in thick loessal loamy sands and loams is 390 100 km^{-2}, and the dissection frequency is 0.890 km km^{-2} (Reimkhe 1986).

The highest occurrence rate of linear erosion corresponds to well-developed areas with dissected topography, with slopes of a steepness of 3–18°, and with the occurrence of thick Quaternary, largely loessal, deposits. The relief, along with lithogenic composition of deposits, is the main factor governing the occurrence of gullies.

Development of gullies

Over the last 50–100 years, many researchers pointed out a substantial increase of the number and extent of gullies (Bazhenova et al. 1997, Vasiliev et al. 1988). In the Republic of Buryatia, from 1984 to 1980, the length of the scouring forms increased by a factor of 2.7 (Tarmayev et al. 2004). Within the Kuitunka river basin (Selenginskoye middle mountains) 127 new gullies appeared during 40 years (1933–1973), and in the summer of 1988 there arose 42 new gullies (Batuyev 1977, Tarmayev et al. 2004). In the depressions of the Southwestern Baikal region during the past 50 years, and in the Barguzinskaya depression during the time interval 1984–1991, the number of scouring forms increased twice (Bazhenova et al. 1997). An abrupt increase of the number of gullies for several years in the catchment areas of small rivers and creek valleys was recorded in the Transbaikalia (Golosov et al. 1996).

The growth rates of the gully heads in different areas of southern East Siberia vary from 0.1 to 26 m yr^{-1} (Bazhenova et al. 1997). The mean long-term linear growth rates of gullies are 0.5–2.5 m yr^{-1}. In dry years (with precipitation less than 200–300 mm), no increment in the head is observed for some of the gullies. In steppe landscapes with a wide occurrence of sands in the springtime there occurs filing of the gullies at the time of dust storms. Extreme meteorological phenomena: torrential rains (over 30 mm hr^{-1}), abundant rains (over 50 mm day^{-1}), and rapid snow thawing in the spring are responsible for gullying. The time of their manifestation is accompanied by the production of erosion forms with an extent of up to 1,000 m, and the growth rates increase several times.

The contemporaneous intensity of gully evacuation can be estimated quantitatively by the volumes of earth material arriving through the exit locations of the evolving gullies at larger components of the erosion network in a unit time from a unit area, m^3 km^{-2} yr^{-1}. The modulus of gully evacuation in southern East Siberia fluctuates from 0.01 for the basins of rivers with a very sparse network of gullies to 100 m^3 km^{-2} yr^{-1} for heavily gullied catchment basins of draws and small rivers in the Western Transbaikalia. The mean values of the modulus of gully evacuation typically do not exceed 10 m^3 km^{-2} yr^{-1}.

Erosion manifests itself actively at the gully head. Transit and accumulation of sediments are taking place in the middle and lower parts. When the slope is convex in shape, extended erosion forms are produced; erosion and accumulation alternate on straight and especially concave slopes, and there occurs a series of short discontinuous gullies separated by gully fans and bridges. The accumulation rates in the bottom of the erosion forms are 2–50 cm yr^{-1}. On the gully fans the thickness of proluvial sediments reaches 4 m, and the mean accumulation rates, according to dendrochronological and isotopic data, vary from 1.8 to 15 mm yr^{-1}. Sediments are transported from the gullies to the bottoms of the draws, and to the river floodplains and terraces.

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