ORIGINAL PAPER

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Geomorphological process development under the impact of man-made reservoir operation, a case study: Bratsk reservoir, Baikal-Angara hydroengineering system, Russia

Oksana Mazaeva [1] · Viktoria Babicheva [1] (ORCID) · Elena Kozyreva [1]

Abstract

The Bratsk reservoir is one of the constituents of the Baikal-Angara hydroengineering system. Large hydropower reservoirs created worldwide produce anthropogenic pressure that provokes substantial changes in the environment and land use practice, as well as different natural hazards, such as induced seismicity, activation of landslides, karst, and shore and bluff erosion processes. Creation of the Bratsk reservoir was followed by a burst activation of shore erosion, karst, aeolian processes, gully, and landslide formation. We monitored the short- and medium-term dynamics of process development in the context of reservoir water level change, which involved the comparative analysis of large-scale aerial photos and field measurements at four key sites. A complex (interaction) of processes can be observed in the shore zone. Based on the monitoring data, models of the geomorphological process evolution in the next years are presented. By investigations, we identified the mechanisms of karst-erosional, aeolian-erosional, and shore- and gully-erosional processes. The case study has shown that the response of dynamics of the processes, their interaction, and environment change are characterized by a certain cyclicity corresponding to water level fluctuations.

Keywords Bank gully · Shore erosion · Karst · Landslide · Aeolian processes · Reservoir water level change

Introduction

Since the 20th century, many large hydroelectric stations and water storage reservoirs created worldwide produce anthropogenic pressure that induces substantial changes in the environment and land use practice (vegetation, hydrochemistry of water, etc.), as well as different natural hazards, such as induced seismicity (Ruiz et al. 2006; Gahalaut et al. 2007), landslides (Qi et al. 2006; Jian et al. 2009; Xia et al. 2013), karst activation (Pecherkin 1969; Ovchinnikov et al. 1999; Milanović 2011;

Khak and Kozyreva 2012; Gutiérrez et al. 2014), and shore and bluff erosion.

During the exploitation of reservoirs of different types, the seasonal and annual (multi-year) water level fluctuations have been recorded. The main geomorphologic processes in the shore zone comprise wave erosion, bluff erosion, landslides (Collins and Sitar 2008), cliff retreat, and aeolian processes (Vilmundardóttir et al. 2010).

In Russia, the comprehensive study of coastal processes was of vital importance in mid-20th century due to the extensive creation of hydroelectric stations in the European territory of Russia and in Siberia.

After the creation of the Angara reservoirs, the hydrogeological conditions changed, which entailed rise of the groundwater level and increase of hydrostatic pressure of waters filling the fissures in the soil mass; the technogenic level variations lead to the alternating watering and dewatering of rock massifs and increase in the infiltrating flow of groundwater.

The backwater influence zone of the Irkutsk reservoir ranges from 0.2 to 0.4 km; in loose deposits, it can reach 23 km. For the Bratsk reservoir, the smallest values (0.3–0.5 km) are observed in low-permeable clay rocks. The greatest width of the reservoir backwater influence zone

✉ Viktoria Babicheva
khak@crust.irk.ru

Oksana Mazaeva
moks@crust.irk.ru

Elena Kozyreva
kozireva@crust.irk.ru

[1] Laboratory of Engineering Geology and Geoecology, Institute of the Earth's Crust, Russian Academy of Sciences, Siberian Branch, Lermontov Street 128, 664033 Irkutsk, Russia

reaches 25 km in sulfate-carbonate deposits. The width of the Ust-Ilimsk reservoir backwater influence zone is mostly localized in a narrow coastal strip, which is explained by the low permeability of rocks distributed in the coastal zone. The maximum width of the backwater influence zone is 46 km in areas that are composed of sulfate-carbonate and terrigene red deposits of the Ordovician and Carboniferous.

In the case of the Bratsk reservoir created during the period 1961–1967, the water level fluctuations determine the activation of landslides (Trzhtsinskii 1978) and the dynamics of shore erosion and aeolian processes (Ovchinnikov et al. 1999). Similar conditions were observed in the region of the Blöndulón hydroelectric reservoir in Iceland. The continued redistribution of aeolian sediments and processes of bluff erosion was controlled by water level fluctuation in the reservoir (Vilmundardóttir et al. 2010).

Investigations of the landslides on the Geheyan reservoir (Qi et al. 2006) and the Three Gorges reservoir (Li et al. 2010) in China and Canelles reservoir in Spain (Pinyol et al. 2012) showed that the landslide process is closely associated with water level variations. Investigation of the Maoping landslide at the Geheyan reservoir in China (Qi et al. 2006) has revealed reactivation of the landslide process after filling of the reservoir. However, further observations showed that the shore deformation is due to the sharp drawdown rather than to the sharp rise of the reservoir water level.

Investigations at the Bratsk reservoir showed that, during the first years of its existence, shore erosion was not the cause of the formation of landslides or their renewed activity. Perhaps this was controlled by the level regime, which decreased by 4 m in 1967–1969. Small landslides were formed as a result of undercutting. The main cause of the renewed activity of old landslides and origination of new ones in the shores of the Angara reservoirs is the decrease of clayey rocks in strength on flooding (Trzhtsinskii 1978). Further investigations of the landslide dynamics revealed decrease of their activity during periods of low water in the reservoir (Ovchinnikov et al. 1999). The landslides present a certain hazard to areas of land use and water protection zones, though the landslide-affected areas are sparsely inhabited. Therefore, landslides in this territory are considered as those of medium (or, rarely, high) hazard.

The creation of Bratsk reservoir has considerably changed the hydrogeological conditions and activated karst processes. A burst of karst activity was observed during the first period of the reservoir's exploitation (Ovchinnikov et al. 1999). Large-sized collapse forms, such as sinkholes etc., originated on the land surface (Filippov 1988; Kuskovsky et al. 2000; Litvin 1989; Litvin et al. 1996; Trzhtsinsky et al. 2003). Up to now, open karst forms have occurred immediately on the shoreline; the shore slopes covered by a mantle of loose deposits are marked as covered karst.

In this paper, we present the results of the short- and medium-term monitoring of geomorphological processes in the shore zone of the Bratsk reservoir. The main objectives of the research were: (1) to estimate the dynamics of the processes in relation to the water level change as a result of reservoir exploitation and (2) to investigate the conditions, factors, and environment of the shore processes, analyze their temporal dynamics, and define the development mechanisms.

We selected key sites that are in the reservoir backwater influence zone and marked by a complex of geomorphological processes. These processes showed active dynamics after creation of the reservoir or had not been observed in the areas previously. They are indicators of the influence of a technical object (reservoir) on the geological environment.

Study area

The Bratsk reservoir is located in the area of valleys of the Angara, Oka, and Iya rivers (southern part of the Central Siberian Plateau, westwards of Lake Baikal) at an elevation of 400–600 m a.s.l. (Fig. 1). This is one of four reservoirs of the Angara hydroelectric complex (including the Irkutsk, Ust-Ilimsk, and Boguchan reservoirs). By its volume of 170 km^3, the Bratsk reservoir ranks as second in the world, with the water surface area amounting to 5470 km^2 (Odintsov 1963); the total length of the shore line extends for 6013 km (Ovchinnikov et al. 1999).

The reservoir strikes for over 600 km in the meridian direction and occupies the steppe, forest-steppe, and taiga landscape/climate zones. The shores are marked by steep high slopes of the Angara river and its tributaries. Along with the erosion-denudation and structural-denudation relief, the presence of relic accumulative and accumulation-erosion terraces (of 10–20 m and 12–80 m heights, respectively) that appeared in Quaternary can be observed (Palshin 1963). Most accumulative river terraces have the common gently sloping surface leveled out by denudation (some terraces were flooded after the creation of the Bratsk reservoir).

Rassvet site

Rassvet is the study site that presents a 2-km-long zone of the Osa bay's left shore; it is located on a 2–8° slope of an accumulative-erosional terrace of loose alluvial-deluvial deposits of loams, sandy loams, fine-grain dusty sands, and mean-grain sand. The shore slope is subject to intense shore erosion during periods of high water level stand in the reservoir. Since the time of the reservoir creation, the 40–95 m shore edge retreat and, in places, the maximum shore edge retreat of ~140 m have been recorded (Ovchinnikov et al. 1999). The erosion forms are presented by scours and small-sized gullies of the 315° NW to the 70° NE strike, with the length ranging from 2 to 30 m. The gullies and scours of the
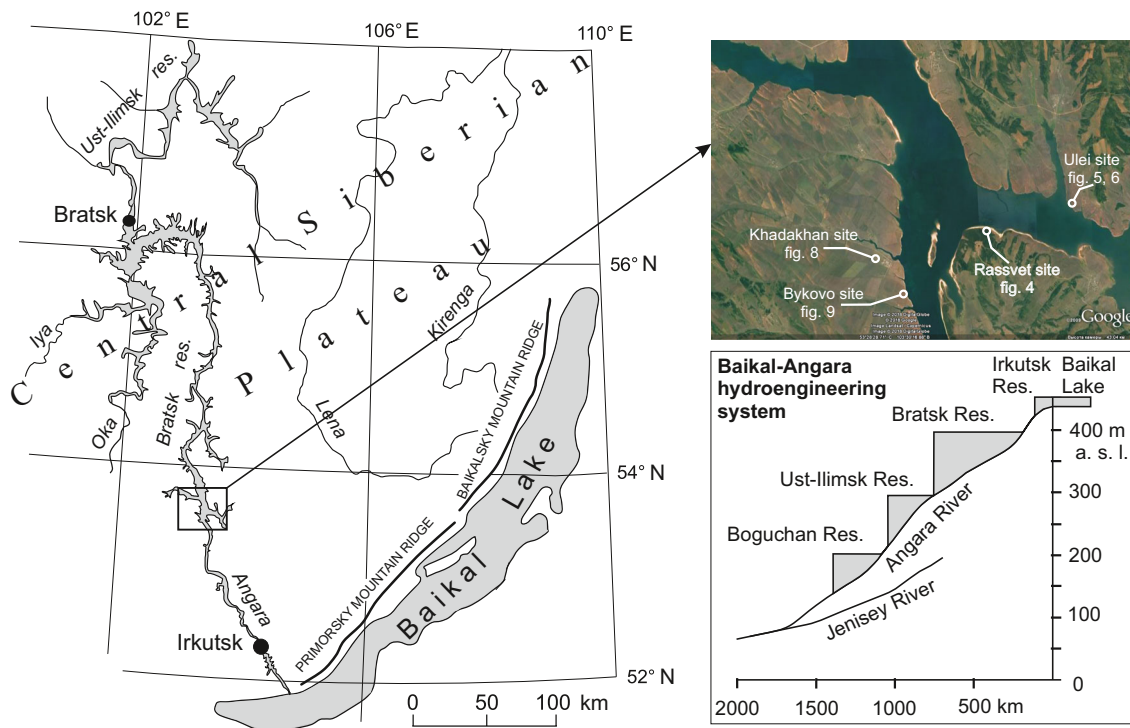
Fig. 1 Location of the study area

NW strike involve the native deflation basins, serving as the channels for sand transport to the shore slope. In the mouth areas of some gullies, small aeolian ridges arise (Mazaeva et al. 2011, 2014a).

Ulei site

Ulei is the investigation site which presents a 1.6 km-long zone on the right shore of Osa bay. The territory is composed of Middle-Upper Cambrian sandstones and aleurolites overlain by eluvial-deluvial loose deposits (2–5 m), affected by slope erosion. In the site, the short SW-exposed shore slopes of straight profile with 31 gullies of 65–200 m length can be observed. The shore area belongs to the abrasion-talus type; during the period of reservoir exploitation, the shore edge retreat reached 10–20 m (Ovchinnikov et al. 1999).

Khadakhan site

Khadakhan is the investigation site on the right shore of Shaloty bay. The karst-erosional form develops on the erosion-denudational slope of 10–15° inclination, which changes into the steep (40°) abrasive cliff at the contact with the reservoir. This site locates in the area of covered karst occurrence. The karst-erosional gully develops in the 2–10-m-thick deposits of loam and loess-like deluvial sandy loam overlying the sulfate-carbonate-gypsum rocks of Cambrian.

Bykovo site

The Bykovo area is in the left shore of the Bratsk reservoir. It is an NE-exposed 250–300-m shore slope, affected by landslides, gully, and shore erosion. The coast and abrasive scarp areas are composed of the gypsum-saliferous-carbonate rock formations of Lower-Middle Cambrian ($\mathrm{C}_{1\text{-}2lt}$), consisting of dolomites, limestones, gypsum, anhydrite, and carbonate breccias. The bedrock outcrops occur in bench scarps of southern and northern parts of the site. In some places, the occurrence of the Middle-Upper Cambrian deposits of the Verkholensk suite's Osa member ($\mathrm{C}_{2\text{-}3vl11}$) is recorded; it consists of marl, dolomite, argillites, and aleurolite intercalations with thin gypsum lenses. The lower part of the suite is composed of clays with red and green breccias. The landslide process develops in the Mid-Quaternary grounds (a^{QII}) of the erosion-accumulative terrace that consists of sand, sand with pebbles, sandy loams, and loams.

Methods

We monitored the short- and medium-term dynamics of geomorphological processes, which involved the comparative analysis of large-scale aerial photos and field measurements at four key sites. The investigation strategy is based on three stages: (1) determination of key sites, analysis of conditions and factors of the processes by the interpretation of aerial photos, published and archival materials on geological

processes prior to and after the reservoir creation; (2) monitoring of the process dynamics at the key sites by geodetic-topographical survey; and (3) analysis of the obtained data and creation of three-dimensional cartographic models of the relief. Temporal dynamics were estimated by the comparative analysis of cartographic models based on the data of repeated theodolite surveys and defining of the development mechanisms (Mazaeva et al. 2014b).

For investigation of the water level and climate factors, the data from the Balagansk weather station (N 54°; E 103.33°; 427 m a.s.l.) were used.

At the Bykovo site, a geodetic-topographical survey was carried out using T-30 theodolite in the summer months of 2003–2007. A system of six benchmarks was set up on the landslide-affected slope; two hanging benchmarks were also allocated in the coast zone. For the landslide processes, the landslide scar brows, the rear joint, and foot of the landslide slope were surveyed.

At the Rassvet site, to estimate the dynamics of aeolian processes, aerial photographs of scales 1:10,000, 1:7200, and 1:10,000 made in 1953, 1969, and 1980, respectively, were used. The shore edge retreat and dynamics of gully length at the Ulei key site were assessed by the comparative analysis of photographs (1:6500) made in 1971 and 1980. GIS software was used to rectify and analyze them. The dynamics of karst development was estimated using the aerial photographs (1:10,000) made in 1980 and field survey. The rates of volumetric dynamics of gullies were estimated by detailed morphometric field measurements. Surveying in several cross-sectional profiles (width of the gully bed, spacing of the upper gully edges and gully depth, total length of the gully) were carried out once a year in 2004, 2007–2013 at the Rassvet site, and in 2001, 2004, 2008, and 2012 at the Khadakhan site. For the measurement purposes, the Leica DISTO A8 laser distance gauge with accuracy ranging from ± 1.5 mm (for up to 30-m distance measurements) to ± 10 mm (for less than 30-m distance measurements) was used. The volume of each gully was calculated by Popov's formula (Popov 1951).

Conditions of the shore processes development

Climate

The climate belongs to the continental type with severe dry winter conditions and warm summer with abundant precipitation. The annual averages of sub-zero temperature vary within the range − 1.1 to − 3.2 °C in winter time, with January being the coldest month (temperature variations within − 22.9 to − 26.8 °C). The temperature in July reaches 17–18 °C. The transition of average daily air temperature through 0 °C

towards negative values happens on October 8–15 and towards positive ones on April 12–20. Within the year, the number of above-zero temperature days reaches 112 (Belyh and Znamensky 1978). The depth of seasonal ground freezing reaches 2.5–3.0 m (Leshchikov and Shats 1983).

The temperature conditions influence the depth of the seasonal freezing (2.5–3.0 m) and, thus, the intensive weathering of the ground. The dominant winds are of the W and NW directions, which are most active in spring and summer.

The total annual precipitation of the forest-steppe region amounts 350–500 mm year^{-1}, with irregular yearly distribution. Vast precipitation (60–70%) occurs in May–September (as rainfall); this is the period of the largest erosion hazard caused by storm runoff. By Wishmeer and Smith, the studied area is characterized by an erosional precipitation index in the range 2.5–5.0 (Bazhenova et al. 1997).

During the period 2004–2011, the amounts varied from a minimum of 226.2 mm in 2007 to a maximum of 413 mm in 2006, and the rainfall volume did not exceed 35–40 mm per day. The maximum number of days (5 days) with an amount of rainfall not less than 30 mm per day was observed in 2006. The highest intensity of rainfall reached 1–2.12 mm min^{-1}. These torrential rains occurred only in 2006–2007.

The solid precipitation amounting to 45–78 mm a year occurs in November–April. In spring, erosion development is induced by a rapid snowmelt runoff in the context of seasonal freezing-defrosting of ground. The snow cover varies from 10 to 25 cm. The water content in the snow cover generally reaches a maximum in March, and, in the analyzed period, it constituted 39–67 mm. The snow thawing begins in the first week of April; by April 26–27, the ground surface becomes free of snow cover. The vegetation period begins normally during May 15–25.

Water level fluctuations in the reservoir

The Bratsk reservoir is of energy-generating importance, with multi-year drainage regulation, in the context of yearly level fluctuations in the range of 2–3 m and lowering by up to 10 m. The annual level fluctuation regime is marked by the highest level in autumn and the lowest level in spring. Reservoir drawdown cases take place, i.e., the duration of definite level stand is short, lasting from several days to a month.

The reservoir level regime is one of the factors that influence the groundwater dynamics in the backwater zone. The water level fluctuations determine the dynamics of shore erosion and aeolian processes; it controls landslide processes and continued redistribution of aeolian sediments. The amplitude of level variations, rates of level rise and lowering, duration of high or low level stands, and the annual and multi-year variation trends are the determining parameters of this influence (Ovchinnikov et al. 1999).

Lithology

The Bratsk reservoir and adjacent territories belong to the Irkutsk amphitheater, composed of thick Paleozoic sediments overlying the old pre-Cambrian basement (Odintsov 1963). The bedrocks consist of Lower-Middle Cambrian dolomites, limestones, gypsum, anhydrite, and carbonate breccias; the Middle-Upper Cambrian rocks consist of marl, dolomite, argillites, and aleurolite intercalations with thin gypsum lenses. The alluvial deposits include sand, with clays and loam intercalations, sand dust, loams, and pebble, and are covered by a thin layer (10–15 m) of deluvial loams and sandy loams.

The most favorable conditions for the shore slope erosion occur in the areas where the bedrocks lie below the water edge level. The erosion process affects the Quaternary deposits of sand dust, loams, locally the loess-like loam, or loams in combination with detrital-platy material. The shore line length extending within the area of loose rock deposits constitutes 2277 km (i.e., 38% of the total length of the reservoir shores) (Ovchinnikov et al. 1999). The shore slopes of the Bratsk reservoir originating due to shore erosion are widely affected by landslides and bank gullies.

The landslides along all the Angara reservoirs have been investigated in detail (Odintsov 1963; Trzhtsinskii et al. 1969). Landslide deformations are extended to the area from 483.4 to 627.2×10^3 m^2 on the Irkutsk and Bratsk reservoir shores. The landslides on the Bratsk reservoir shores occur in terrigene and clayey deposits of Ordovician and in gypsum-anhydrite and terrigene-carbonate deposits of Cambrian age. Landslides in the Quaternary deposits are less frequent. Many large landslides in the Jurassic sandstones on the Irkutsk reservoir were flooded.

Most of the landslides observed in the shore zone of the Bratsk reservoir have been reactivated. They are block-type landslides, dislocated as a result of deep, slow creeping and rock fall, with a so-called deep creeping zone. The dominant type are lateral spreading landslides, which develop on slopes composed of two geological layers, where plastic, easily deformed silty-clay deposits lie at the bottom of the firm deposits. Less often, a shallow flow of material on the massive substrate is observed. The areas of landslide-damaged shores are described in Table 1.

The southern part of the Bratsk reservoir is located in the 100-km-wide zone of karsting rocks of dolomite formation (presented by dolomites, limestones, anhydrite-dolomites, and gypsum) of the WE stretch. The sulfate-carbonate karst is typical of gypsiferous and anhydrite-dolomite rocks of the Angara suite of Cambrian. The presence of karsting rocks overlapped by the erosion-pliable rocks determines origination of the karst-erosional forms. The co-occurrence of karst and erosion processes is determined also by their formation in the zones of regional jointing. In the area of covered karst, the gullies appear as a sort of "fissured massif", facilitating the infiltration of surface waters into the karsted rocks through the gully bottom and the subsurface drainage into the reservoir during periods of abundant rainfall.

Results and discussion

Rassvet site

The shore zone in the Rassvet site is formed by shore and gully erosion and aeolian processes. Pre-reservoir (1953) aerial photographs (which have poor resolution overall) show the absence of aeolian sediments and gully forms at the site. The aeolian process has developed here since the reservoir impounding in 1967. The cyclic character of aeolian processes was determined primarily by the duration of the low water stand. The existence of aeolian forms in shore slopes was associated with the intensity of shore erosion processes (Ovchinnikov et al. 1999).

Permanent increase of the number and volume of gullies was observed in the period 2004–2009. In 2004, investigations revealed the development of 16 gullies; in 2007, their number reached 21; in 2008, it reached 38; and in 2009, it reached 47 (Mazaeva et al. 2011).

The period 2004–2007 was marked by the minimum of total volumetric increment of gullies (317.22 m^3) and the average volumetric increment rate (5.04 m^3 year^{-1}) due to shore erosion and aeolian processes.

Hanging thalwegs (i.e., the gully mouth is located over the level of the in-shore shoal) in the major gully forms prove the prevalence of shore erosion over the vertical erosion, which is verified by the comparative analysis of digital models of the relief in the Rassvet site in 2006 and 2007. The total loss of ground material due to the shore retreat amounts to 13,860 m^3 year^{-1}; the retreating shore edge width varies along the studied zone in the range 0 to 8 m year^{-1} (Khak et al. 2009).

The abrasive destruction of the shore scarp lead to the increase of its height, hanging of the gully mouth part, and the break of the gully longitudinal equilibrium profile. Thus, the small-volume gullies are marked by a deficient energy for washing out of the bench between the gully mouth bottom and the in-shore shoal surface. This resulted in the volume decrease of the majority of the gullies.

The negative dynamics of major gullies can also be provoked by the aeolian processes. In 2006–2007, the increment of the aeolian deposit massif area (3620 m^2) and the increase in thickness of aeolian deposits over the topsoil layer on the slope area were observed (Khak et al. 2009). In spring, it is also the period of minimal water level in the reservoir; an increase of shoal width and intensive sand transportation are observed. On the large scale, the activation of aeolian processes in the shore area was preconditioned by the permanent water level lowering between autumn 2006 and summer 2008.

Table 1 The characteristics of landslide-damaged shore areas of the Bratsk and Irkutsk reservoirs

Landslide	Alongshore length (m)	Width of landslide (m)	Landslide-covered area (m²)	Land category
Bratsk reservoir				
Bykovo	250	50	12,500	Agricultural land use
Balaganski	370–400	120	44,400–48,000	Agricultural land use
Monastyrski	480	100	48,000	Forest lands
Kazachinski	700	160	112,000	Forest lands
Strelkinski	600	50–250	30,000–150,000	Forest lands
Imbeyski	120–200	50–60	6000–12,000	Forest lands
Barsunski	150–170	50–70	7500–11,900	Forest lands
Shaloty	250	50	12,500	
Tynkobski	100	120	12,000	Forest lands
Novo-Oktyabrski	250	82–120	20,500–30,000	Forest lands
In solid rocks	100	60	6000	Forest lands
Okinski	40–50	30	1200–1500	Forest lands
In loess-like rocks	60	30	1800	Forest lands
Silotski	300	120	36,000	Forest lands
Other sites	100–400	50–200	80,000	Forest lands
			In total: 430,400–574,200 m²	
Irkutsk reservoir				
Ershovski	250	100	25,000	Urban areas
Other sites	280	100	28,000	Forest lands
			In total: 53,000 m²	

July 2007–June 2008 was the period of maximum material loss from gullies (in total, 627.66 m³) and the average volumetric increment rate was 16.5 m³ year⁻¹. This happened due to the increasing number of gullies. The lowering of the reservoir water level contributed to the intensification of vertical and retrogressive erosion, and the gully bottom reached the level of the in-shore shoal. The low water level is the reason for the activation of aeolian processes in the shoal. This process has been described by Vilmundardóttir et al. (2010) in the region of the Blöndulón hydroelectric reservoir in Iceland. They observed that aeolian transport mainly occurred when the sediment was exposed at low water level. The gullies, partially or entirely filled with wind-blown sand, are temporarily (at the low water level) marked by low negative dynamics.

In summer 2008, the aeolian processes prevailed over erosion. Therefore, during the period of June 2008–May 2009, numerous gully forms were marked by low negative dynamics. Within a year, the total loss of ground material from gullies amounted to 418.59 m³ and the average growth of gully forms reached 16.05 m³ year⁻¹, which conforms to the former period (Fig. 2).

Investigations of the gully mouth profiles at the Rassvet site showed that gully water erosion dominated in the period 2009–2010, which was induced by heavy rainfalls (340–330 mm in April–September) and the maximum water level stand in autumn 2010, which caused the maximum shore edge retreat (Fig. 3). During 2011–2013, aeolian processes prevailed over erosion, and the gullies accumulated aeolian material and decreased in volume (Fig. 4). This was determined by a small rainfall amount of 210–230 mm and the minimum shore edge retreat by 0.45–0.95 m at low water level in the reservoir.

Ulei site

Gullies existed in the Osa river slopes before the creation of the Bratsk reservoir, as could be seen in photos taken in 1953 (Fig. 5). After the creation of the reservoir, the conditions and factors of gully development changed considerably: the gully mouth parts were submerged, the catchment areas reduced in size and were reshaped, the base level of erosion decreased in depth, and the shore erosion processes induced the retreat of shore scarp edges.

Based on the interpretation of aerial images (1971–1980), the mid-term dynamics of the linear growth of gullies at the Ulei site ranged from 0 to 44 m, and the average growth rate accounted for 1–2 m, with a maximum of 4 m per year.

The first field investigation (1999) of the Ulei site showed that the gullies cut down the shore scarp up to its foot, reaching the shoal (Fig. 6a). This period followed the low level cycle of 1990–1993 and 1996–2000 in the context of the multi-year level trend.

During 1980–2007, the shore erosion at the Ulei site reached 33.4 m. In 1984–1989, 1994–1995, 2002, 2004, and 2006, the reservoir water was at its high level marks. The
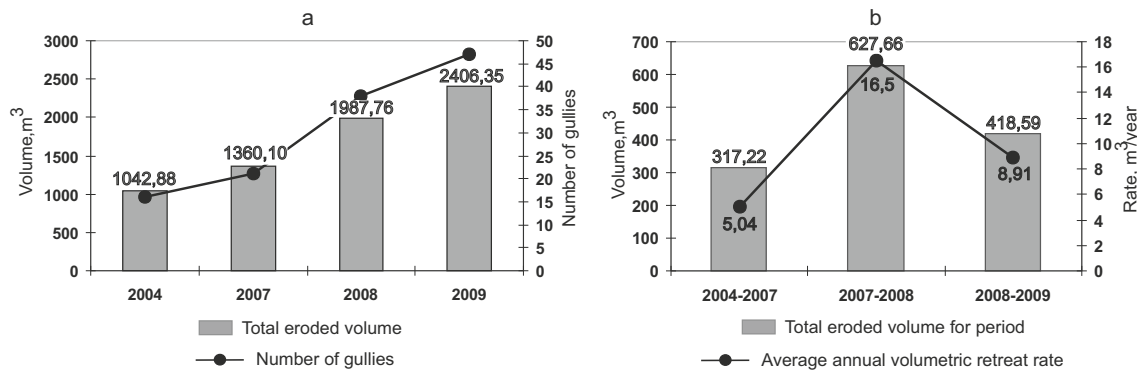
Fig. 2 Dynamics of gully development at the Rassvet site: **a** increase of the volume and number of gullies; **b** differences in the total eroded volume of gullies between two monitoring measurements and average annual volumetric retreat rate

shore erosion rates exceeded those of the erosion process, which entailed the decay of gullies and decrease in length.

The field works in 2013 revealed a small (0.3 m) shore edge retreat since 2007; it was found that the gullies in that location were marked by inactive head parts overgrown with grass, hanging mouth parts (Fig. 6b), in thalweg parts the secondary bottom gullies of 1.17–8.32 m in length with maximums of 9.36 and 10.59 m. The gully mouth parts in accumulative shore areas were not hanging and reached the shoal.

Thus, the long-term investigations proved that rejuvenation of the erosion process in thalweg parts of inactive gullies followed the shore edge retreat, hanging of gully mouth parts and formation of wave-cut niches at high water level, and failure of ground blocs over the niches.

Investigation of the gullies on the Isle of Wight, UK, showed that coastal gullies are influenced by terrestrial and marine processes, and sea cliff erosion causes rejuvenation of their channel network (Leyland and Darby 2008, 2009).

The mechanism of gully development in abrasive shore areas depends on the reservoir water level; this conforms to I.A. Pecherkin's scheme for the Kama reservoirs (Pecherkin 1969). The gully development in the shore zone is, to a large extent, influenced by wave erosion. The wave undercutting of shore slopes caused the formation of shore scarps of different heights. The failure of ground blocs over wave-cut niches induced the origination of regressive cuts in the gully bottom. Activation of the erosion process occurred in the convex areas of the gully's longitudinal profile. During low water periods,
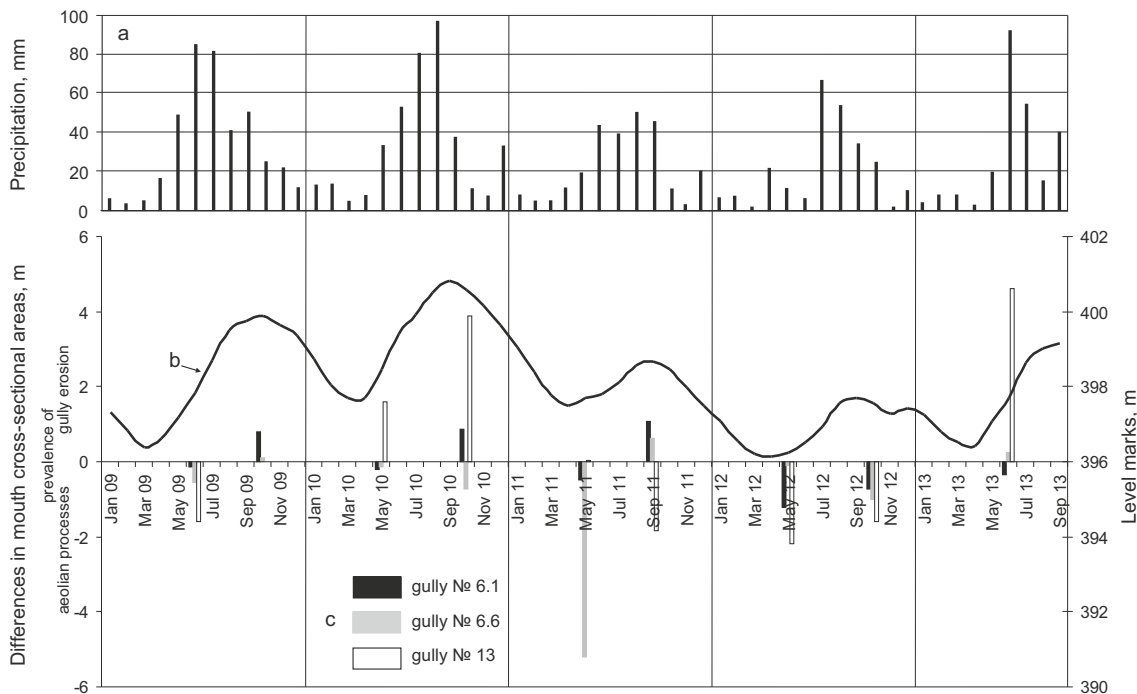

Fig. 3 Monitoring data of the Rassvet site during the period 2009–2013: **a** mean monthly precipitation (data of the Balagansk weather station); **b** water level fluctuations (data of the Balagansk weather station); **c** differences in mouth cross-sectional areas (differences in the areas of mouth cross-sectional profiles) between two morphometric measurements
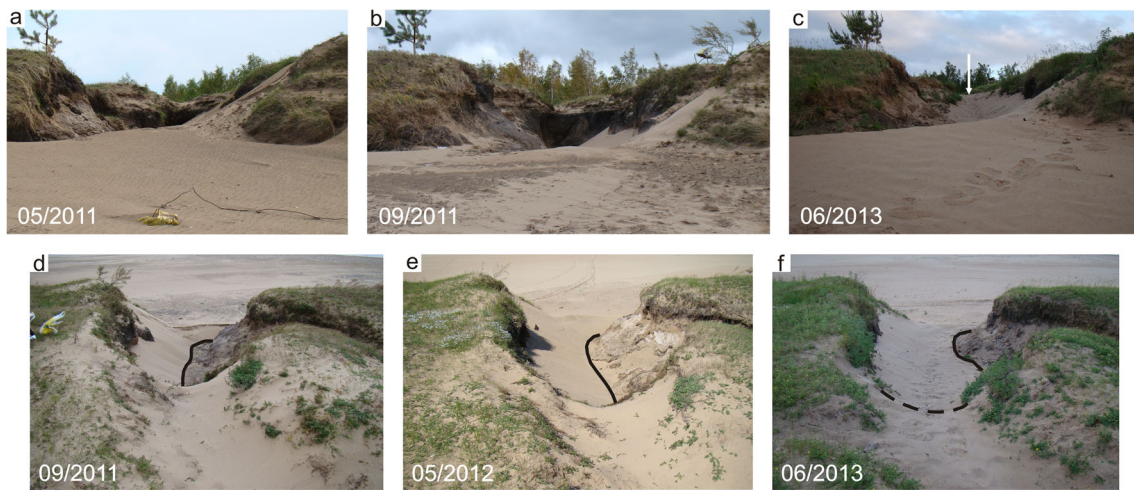
Fig. 4 Images showing the activity of aeolian-erosional processes in gully no. 6.1 at the Rassvet site: **a**, **b**, **c** beach view at the gully mouth part; **d**, **e**, **f** shore slope view at the beach. Note that there is aeolian material in the gully mouth part in **a** and there is alluvial fan from the gully in the beach in **b**. **c** Aeolian deposits in the gully head (*arrow*) as a result of aeolian transport from March 2012 to June 2013 at low reservoir water level. **d**, **e**, **f** Increase of the aeolian ridge near the left gully side. Note that the gully head cut is buried by aeolian material (*dashed line*)

the vertical erosion was more intense in the context of increased erosion rate and depth of the base level of erosion, stimulated by heavy rainfalls.

The dynamics of gully development at the Ulei site represents shore erosion-induced reactivation of the erosion process in thalweg parts of decayed inactive gullies.

Khadakhan site

After the reservoir's creation, formation of new karst forms at the site was registered in 1976 and 1979–1980 in the context of multi-year (until 1982) drawdown of the reservoir water level (Ovchinnikov et al. 1999).
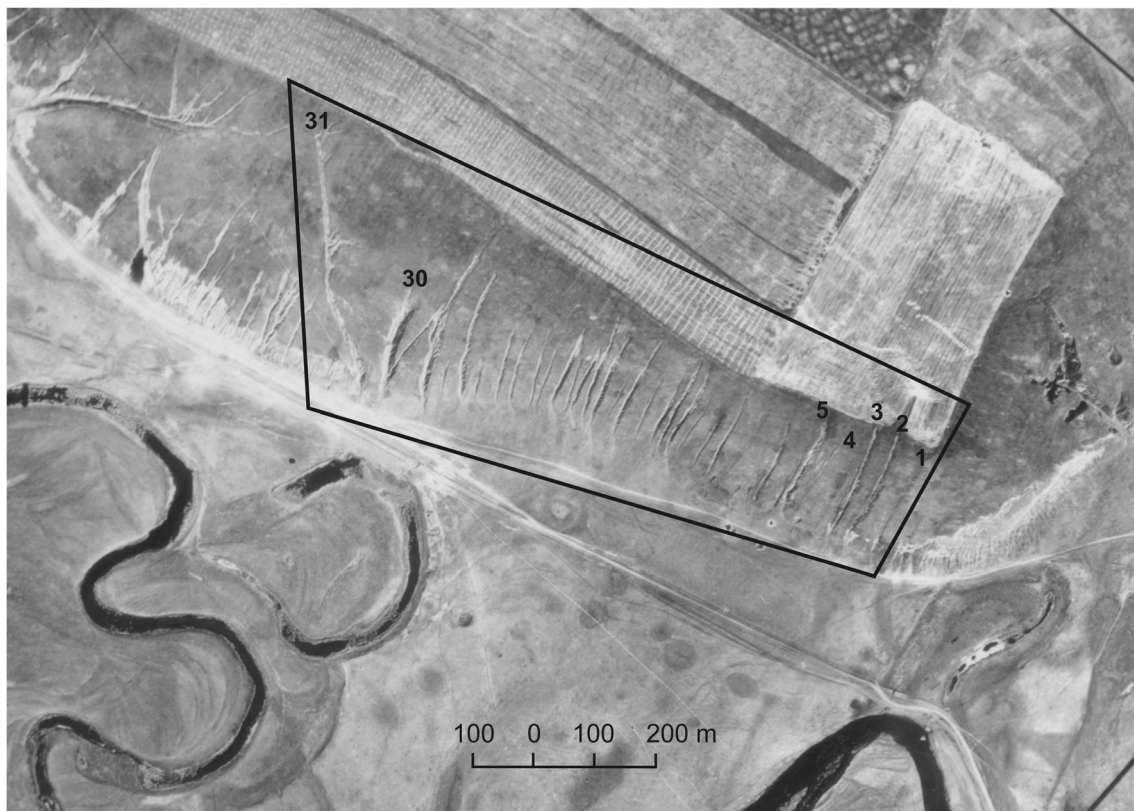

Fig. 5 Gullies at the Ulei site before the creation of the Bratsk reservoir. In the 1953 photo, gullies cut the Osa riverbank. The selected area shows the location and numbers of the investigated gullies
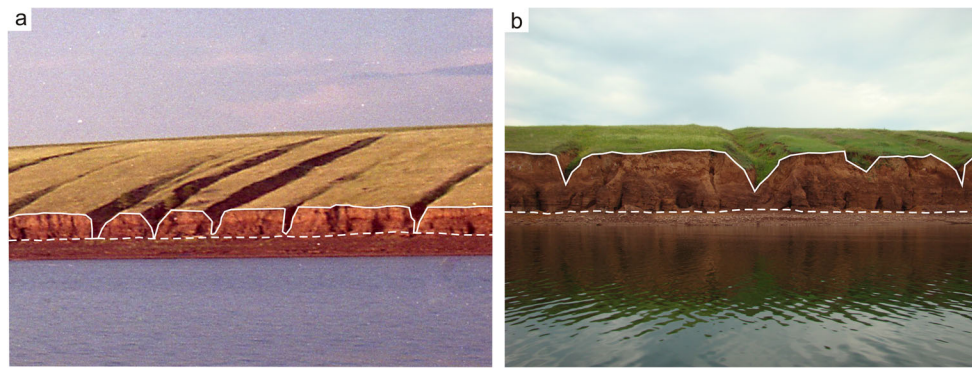
Fig. 6 View of gullies on the Ulei site: **a** 1999; **b** 2013. Note that there is a prevalence of gully erosion over shore erosion at low water level marks in **a**; there are hanging mouth parts after high water level marks in **b**. The *dashed line* indicates the location of the shore scarp toe and the *continuous line* shows the configuration (outline) of the crest and the gully mouth cross-sectional profile

The karst-erosional form has been investigated since 1976 after the origination of a karst hole in the Khadakhan-Zakulei motor road 6 months after its exploitation began. The regular ground filling did not prevent the area from permanent damage. In 1982, the investigations revealed the presence of two collapse holes in both roadside areas. In this period, the lowest water level marks in the reservoir were recorded.

The aerial photos of the Khadakhan site taken in 1980 showed the presence of several sinkholes on the slope, which later developed into gullies. Our first investigations at the site in 2001 revealed two successively arranged gullies (Fig. 7).

By July 2004, both gully forms fused into a 123.5-m-long karst-erosional gully; it was associated with the activation of

karst-suffosional processes in the context with lowering of the water level since autumn 2001 (Fig. 8). The maximum of gully increment (4486.34 m³) occurred during the 2004–2008 period (Kozyreva et al. 2008; Kaczmarek et al. 2016). The high water level regime of autumn 2006 was followed by a multi-year period of permanent lowering.

Further gully dynamics was associated with activation of the erosion process; the progressive increase of gully volume from 2008 to 2010 was attributed to abundant precipitation (292–342 mm during April–September). The perennial rise of the reservoir water level was recorded at that time.

The negative dynamics of gully growth in 2010 and 2011 was due to the small precipitation amounts and gravitation

Fig. 7 Development of karst-erosional form at the Khadakhan site (2004–2008)
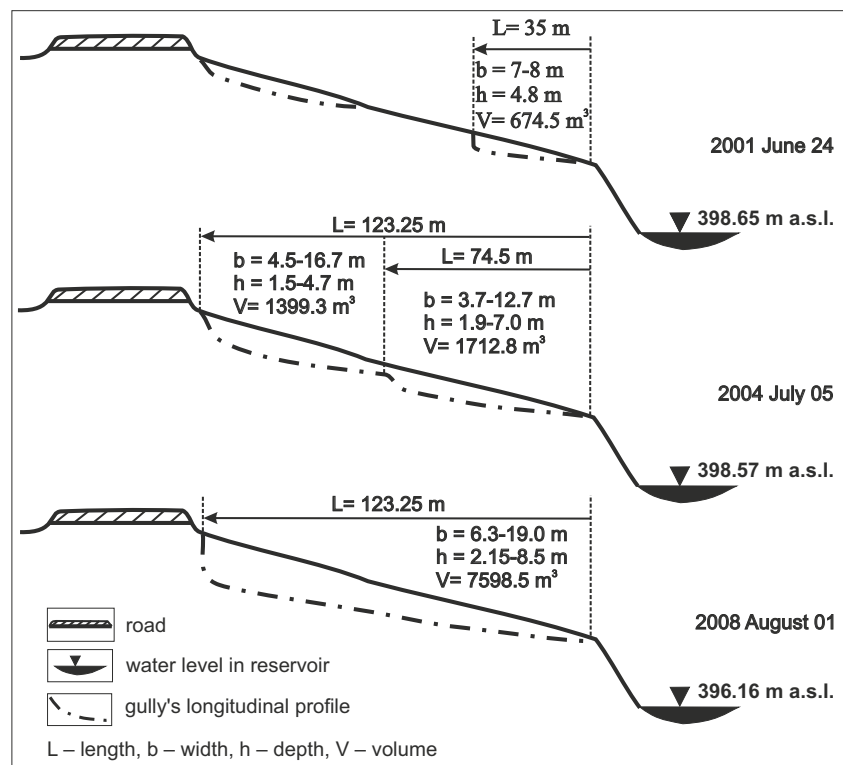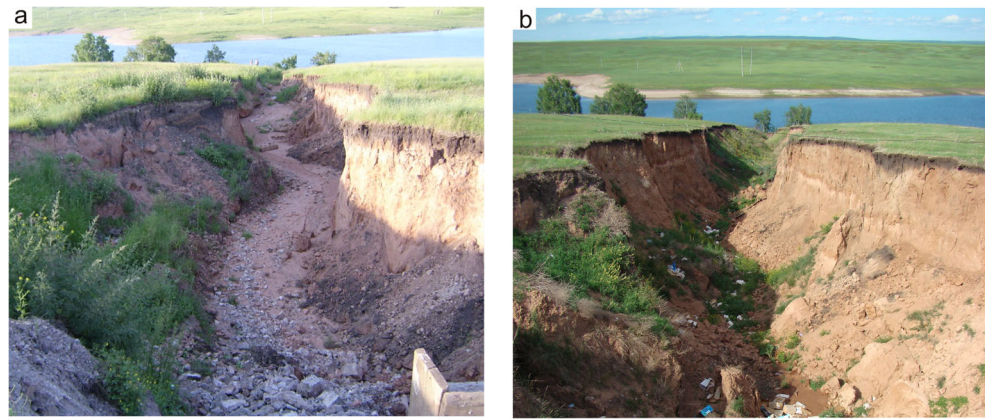
Fig. 8 Karst-erosional gully at the Khadakhan site: **a** 2004; **b** 2008

process in the gully side slopes. The gully volume in 2013 was 7715.18 m³. Thus, karst activation occurred in the long periods of reservoir level lowering after saturation of the shore massif at high water level marks (Kozyreva et al. 2012).

According to the data of hydrogeological investigations, the changes of groundwater level in the Cambrian carbonate and sulfate rock deposits occur with a 48-h delay compared with those in the reservoir (Ovchinnikov et al. 1999). Fluctuations of the reservoir water level entail the development of groundwater backup and are accompanied by the filtration of freshwater into the shore massif, which is affected by its highly aggressive action against gypsum-anhydrite rocks. The technological drawdown of the reservoir water level entails the gradual lowering of the groundwater table (Jia et al. 2009), and, hence, the increase in the groundwater flow gradient through the rock massif, evacuation of soluble and suspended matter, and activation of the karst process in the backwater zone and formation of new karst form (Pecherkin 1969; Milanović 2011; Gutiérrez et al. 2014). The zone of sulfate karst activation in the area of the Bratsk reservoir is 4–6 km wide.

Bykovo site

The aerial photos of the Bykovo site taken in 1953 (prior to the reservoir inundation) show that the slope was not affected by landslide (Fig. 9a). Since 1969 (after the reservoir filling), aerial photos showed evidence of the emergence of sand quarry in the north of the area (Fig. 9b). The deformations are likely to have been caused by the creation of the reservoir, sand quarrying, or their reciprocal influence. The reservoir inundation caused the variations of groundwater level, abundant humidification of sands, sand dust, and loams, which led to deformation of the slope due to landslide (Fig. 9c).

The comparative analysis of digital elevation models based on large-scale topographic surveying at the Bykovo site in 2006 revealed a 746 m² maximal extension of landslide movement area, which was caused by maximum rainfall and the reservoir water level being the highest during the observation period. The areas prone to erosional form development on the landslide slope increased from 100 m² (Mazaeva et al. 2013). Numerous studies

revealed that landslides could be triggered by rainfalls (Saito et al. 2010; Guzzetti et al. 2004; Li et al. 2011; Macfarlane 2009), by reservoir inundation (Jian et al. 2009; Wang et al. 2008), as well as by a sharp drop in the water table (Emery and Kuhn 1982). However, Qi et al. (2006) suggested that the rainfall impacts on the slide deformation increased after reservoir inundation.

During the low water periods, the activation of erosion and stabilization of landslide processes in shore slopes was observed, and landslide occurred on the beach and gully side after heavy rainfall. Gradual lowering of the water level stimulates the formation of secondary shore erosion scarps on the shoal.

The reservoir water level lowering followed by the groundwater level lowering induces the intensive ground water runoff within the shore massif and activation of suffusion-subsidence processes, which also lead to gully activation.

High water level in the reservoir stimulates the activation of landslide processes. Under these conditions, the shore erosion, formation of wave-cut notches, and recession of slope foot cause a decrease of stability in the steep slopes. The excessive soil water saturation attributed to both the climate (abundant precipitation) and hydrodynamic factors (the reservoir water level rise followed by a rise of groundwater level) leads to deconsolidation and decrease of the soil strength properties. Abundant rainfall leads to liquefaction of gully slopes, increase of gully width and decrease of gully depth, and to the jamming of gully mouth parts as well. Loose material containing montmorillonite in the clay fraction forms a sliding zone. Jian et al. (2009) also reported on minerals mainly composed of montmorillonite in the slip zones of the Anlesi landslide (Three Gorges Reservoir, China). This implies that this material is marked by swelling capacity and low shear strength properties. During the dry period, the volumetric shrinkage of soils leads to cracking, sheeting, and disintegration of rocks and decrease of soil massif stability. All these factors stimulate landslide processes, which originate in the form of landslide terraces, the upslope displacement of the existing landslide scar, slide of fluid soil on the inshore shoal, or in the increasing landslide terrace number, development of secondary deformations inside the landslide body, and origination of new fractures.

Fig. 9 Images of the Bykovo site: **a** aerial photo taken in 1953; **b** aerial photo taken in 1969; **c** view of landslide slope (2007)
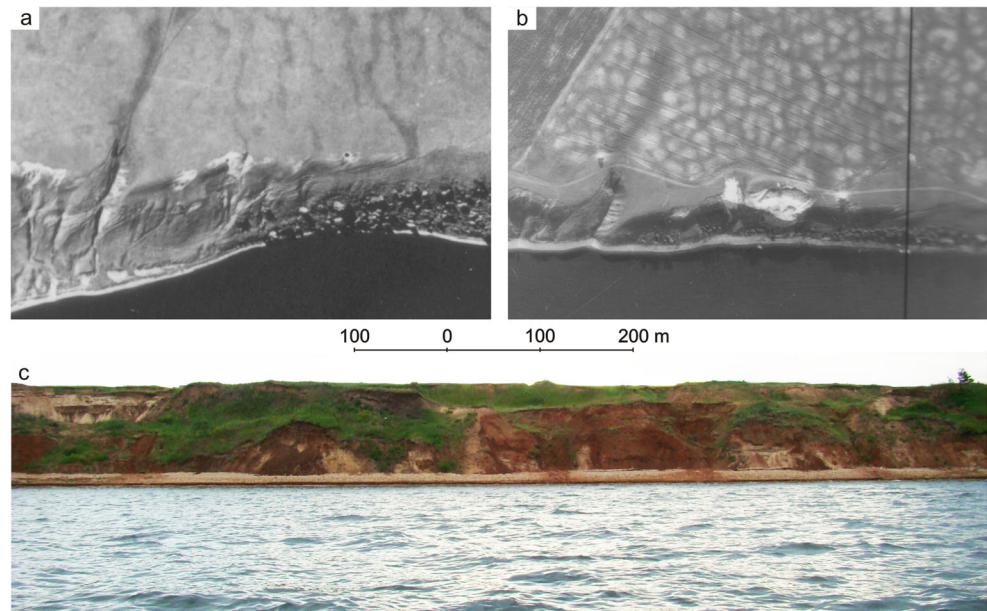
Geomorphological process evolution in the next years

Khadakhan site

According to the results of monitoring studies, the evolution model of the karst-erosional form of the Khadakhan site is presented in Fig. 10. The logarithmic approximation most accurately reflects its dynamics: a linear growth of the erosion form, an extreme increase in volume as a result of the activation of karst-suffusion processes, and following stabilization of growth (a low increase in volume). The model shows that, in the next years, a permanent growth of the karst-erosional form with a small rate is expected.

However, with repeated cases of technological drawdown after high reservoir water level marks, the activation of karst-suffosional processes and sharp increase in the volume of this form are possible. We can also expect the formation of new erosion-karst forms on the same coastal slope along the dense network of meridional cracks in the Lower and Middle Cambrian gypsum salt-carbonate deposits. This should be considered in engineering practice.

Rassvet site

In the Rassvet site, similar scenarios may be expected (Fig. 11). A logarithmic trend line was used to demonstrate the gully evolution model. The total eroded volume of gullies would increase

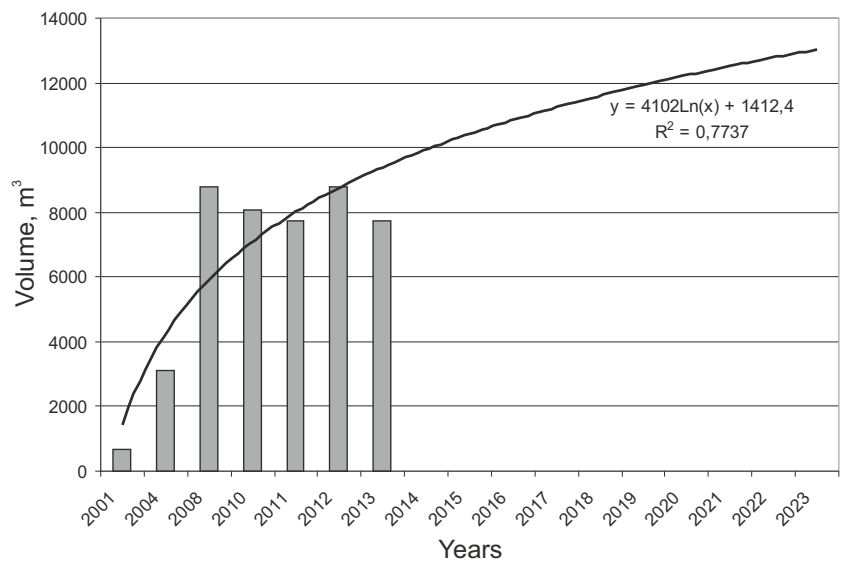**Fig. 10** Prediction of the karst-erosional gully development at the Khadakhan site based on monitoring data
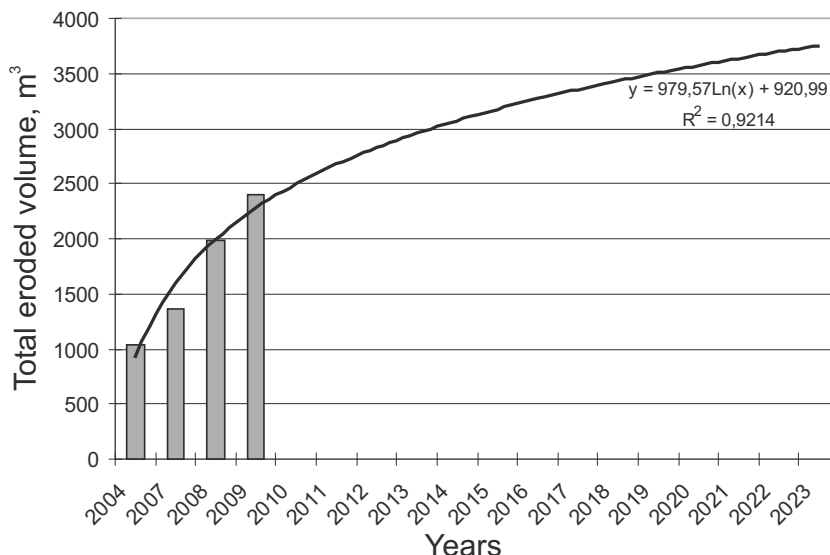

$$y = 4102\,\mathrm{Ln}(x) + 1412{,}4$$
$$R^2 = 0{,}7737$$

Fig. 11 Prediction of the gully development at the Rassvet site based on monitoring data

$$y = 979{,}57 Ln(x) + 920{,}99$$
$$R^2 = 0{,}9214$$

under the influence of erosion factors; however, the gully stabilization can be disturbed under the impact of the reservoir water level fluctuations according to the scheme of shore erosion-induced reactivation of the erosion process in thalweg parts of decayed inactive gullies, as revealed for the Ulei site.

Bykovo site

The causes for the activation of this landslide type are undercutting due to shore erosion and differential weathering. The prediction of shore erosion at the Bratsk reservoir made by Ovchinnikov (2003), based on the data for the entire operational period, showed that further shore erosion development is expected on the shore slopes forming in loose deposits, whereas the shores in firm rock are marked by erosion slowdown.

The combination of climatic factors and significant operational fluctuations in the reservoir water level contribute to the preparation of coastal slopes for landslide deformations. Slopes of steepness more than 20° are potentially susceptible

to landslides. In areas where landslide deformations have already occurred, relative stabilization and shore erosion of landslide masses is expected. The landslide process in loose Quaternary deposits in conditions of periodic abrasion is more accurately described by polynomial regression, which is characterized by variable increase and decrease in values (Fig. 12).

Therefore, the evolution of these landslides will be characterized by periods of activation at high reservoir water levels, alternating with periods of preparation of the slide zone (disintegration and weathering) and the relative stabilization of the process at low reservoir water levels.

Conclusions

In the course of investigations, the influence of reservoir exploitation (particularly the large water level fluctuations) on geomorphological process development has been noted.

Fig. 12 Mathematical model of landslide dynamics at the Bykovo site based on monitoring data

$$y = -128{,}08x^3 + 1054{,}1x^2 - 2289{,}8x + 4800{,}4$$
$$R^2 = 0{,}8388$$
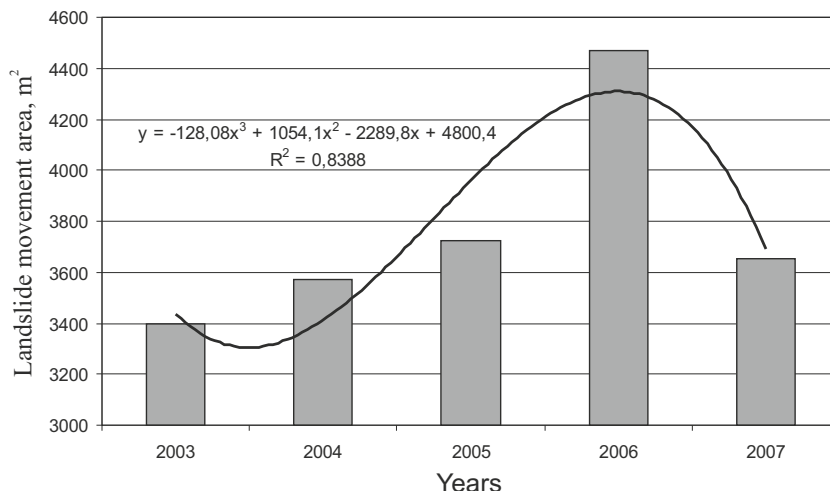
The Bratsk reservoir, a 51-year-old man-made reservoir, is the second largest in the world in terms of volume (170 km^3) and a natural model for the investigation of geomorphological and environmental change around large reservoirs. Different reservoir water level favors the activation of such geomorphological processes in the shore zone as shore and gully erosion, aeolian, landslide, and karst processes. A complex (interaction) of processes can be observed in the shore zone. By investigations, we identified the mechanisms of karst-erosional, aeolian-erosional, and shore- and gully-erosional processes.

The gully development in the shore zone is, to a large extent, influenced by the shore erosion process. Shore erosion disturbs the longitudinal gully profiles, whose mouth parts reach the inshore shoal areas. High water levels caused shore erosion, shore edge retreat, hanging of gully mouth parts, formation of wave-cut holes in the foot of shore scarp, and, finally, the rejuvenation of retrogressive erosion in gully thalweg parts. The lowering of the water level stimulates vertical erosion.

The activation of landslide processes in the reservoir shores follows periods of high water level stands. The disturbance of shore slope stability is induced by shore erosion of the slope foot and inundation of the slide zone.

Long periods of reservoir water level lowering was marked by the activation of karst that followed the water saturation of shore massif at high level marks. Combined action of karst and gully erosion processes excited the highest rates of gully growth.

The low water level conditions stimulated the positive dynamics of aeolian processes (area size, thickness of deposits). Aeolian material accumulated in the gullies and they decreased in volume.

Thus, the annual and seasonal water level fluctuations affected the dynamics of geomorphological processes in the reservoir shore areas. The dynamics and relationships of shore processes are marked by definite cyclic recurrence according to the reservoir level regime. The investigation revealed the influence of new aspects of reservoir exploitation on the environment.

It was found that large water level fluctuations will play a key role in the activity of geomorphological processes in the shore zone for the next decades, highlighting a need to understand the role of the large reservoir in future projections of landscape evolution.

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