Landform Analysis, Vol. 17: 117–123 (2011)

The short-term changes of gully erosion forms in the context of the water level fluctuations in the Bratsk reservoir (Russia)

Oksana Mazaeva[1], Halina Kaczmarek[2], Victoria A. Khak[1], Elena A. Kozyreva[1]

[1]*Institute of the Earth's Crust Russian Academy of Sciences Siberian Branch, Laboratory of engineering geology and geoecology, Russia*
[2]*Institute of Geography and Spatial Organization, Polish Academy of Sciences, Poland*
e-mail: moks@crust.irk.ru

Abstract: The results of investigations ascertain the influence of the water level regime on the erosion dynamics that was estimated according gullies volume change within the space-time between two measurements. The development of gullies in the shore zone is to a large extent influenced by the abrasion of shore slopes, which is intense at high water level in the reservoir. The minimum rate of gully development (4.5–54.7 m^3 yr^{-1}) was due to the action of shore abrasion and eolian processes within the period of 2004–2007. A large positive dynamics can be attributed to the increasing number of erosion cuts. The maximum material loss from gullies (in total 627.66 m^3) and the average volumetric retreat rate for all gullies (16.5 m^3 yr^{-1}) were recorded at the permanent lowering of the reservoir water level during the 2007–2008 period. Water level fluctuations cause cyclic changes in the dynamics of processes and initiate the new mechanism of erosion that is not typical of regular conditions.

Keywords: gully erosion, short-term dynamics, abrasion, reservoir, water level fluctuation

Introduction

The gully forms in the territory of Southeastern Siberia are marked by rather irregular occurrence, observed primarily in the regions of intense agricultural land use. The Unga-Osa shore areas of the Bratsk reservoir can be cited as an example where a large density and diversity of erosion forms exists. The Bratsk reservoir was created in 1967 westwards of Baikal Lake; it occupies the watershed area of the Angara, Oka and Iya rivers. The reservoir exploitation has induced a rapid change of the environmental conditions with reference to the geological time scale. Its volume constitutes 170 km^3, ranking as the world second among the artificial reservoirs.

The rise of the erosion base level, after the reservoir impounding, stimulated a radical change in the erosion pattern, including the ultimate impact on the gully forms that had developed in the river shores prior to the reservoir construction. Alongside the water level rise, the gully mouth areas were submerged; the activated abrasion process in the reservoir shores induced the dislodging of the shore edges, which caused changes of definite factors such as the size reduction and watershed reshaping, the decrease of erosion base level. The influence of the technogenic factors has increased due to the expansion of economic development of the region accompanied by forest cutting and creation of additional infrastructure.

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 2,277 km (i.e. 38% of the total length of the reservoir shores) (Ovchinnikov et al. 1999).

The role of gully forms as the source of material delivery into the reservoir has been investigated by numerous researchers (i.e. Poesen et al. 2003, Vandekerckhove et al. 2001). Other investigations revealed that the gully systems provide connectivity between the dominant hillslope sources and the reservoirs, being, however, the small contributors of sediments (Foster et. al. 2007).

The shore conditions of artificial reservoirs, unlike those of rivers, lakes and even seas, are marked by larger seasonal and annual water level fluctuations. The reservoir water level determines a new basis for erosion forms that develop in the shore areas. The development of gully forms in the shores of artificial reservoirs is characterized by some peculiar features.

Along with the abrasion, landslide, rockfall, crumbling, karst and other exogenic processes, the gully erosion is the source of material for the onshore deposits and underwater sediments, as it has been reported by I.A. Pecherkin (1969) concerning the shore dynamics of the Kama reservoirs; his investigations have also shown that the rate of the gully volume increase in the loess-like loam shore areas is 2–3 times higher than those of the abrasive destruction of the shore slopes.

The Bratsk reservoir is a large reservoir with 3-4 m seasonal and up to 10 m annual water level fluctuations. In the course of its exploitation, three cases of maximum (up to 10 m) water level drop entailed the activation of exogenic geological processes. Such a pattern of the water level drop determines a large-scale influence upon the surrounding territories, including the activity of coastal processes. Since these processes have got large effects in the course of a year, the short-term observations are vital, aiming to reveal the changes in the dynamics and mechanisms of erosion form development in the context of the reservoir water level fluctuations, and to evaluate the erosion effect on coastal processes.

Study area

The study area occupies a forest-steppe territory in the mid-elevation part (600–750 m a.s.l.) of the Lena-Angara plateau with a 150–200 m-deep ruggedness of the relief. The native rocks include argillites, aleurolites, marles and the Middle-Upper Cambrian terrigene sandstone formations.

The initial gully forms develop in loose alluvial-deluvial or eluvial-deluvial deposits of the gently sloping abrasive reservoir shores. The gully forms extend a few dozen meters within the cliff zone.

Detailed investigations have been carried out in a 2 km-long zone of the left Osa Bay shore area, in the vicinity of the Rassvet settlement (Fig. 1A). The studied shore area lies aslope of the accumulation aggradation-denudational terrace (2–8°) composed of loose alluvial-deluvial deposits of loams, sand dust, fine- and medium-grain sands. The microrelief of the area has been formed due to eolian, abrasion, erosion and karst processes. In the course of the reservoir exploitation (1967–1999) the shore retreat reached 40–95 m, with a 130 m width of the maximum hollow-out of the shore area.

The erosion forms include grooves, scours and small-size gullies (of 2–30 m length and 315° NW to 70° NE strike). The gullies and scours of NW-strike involve native deflation basins which serve as channels for sand transport to the shore slope. In the mouth areas of some gully forms, small eolian ridges have been formed.

Materials and methods

A comprehensive study of the dynamics of coastal processes was carried out in a 2 km-long shore zone in the vicinity of the Rassvet settlement.

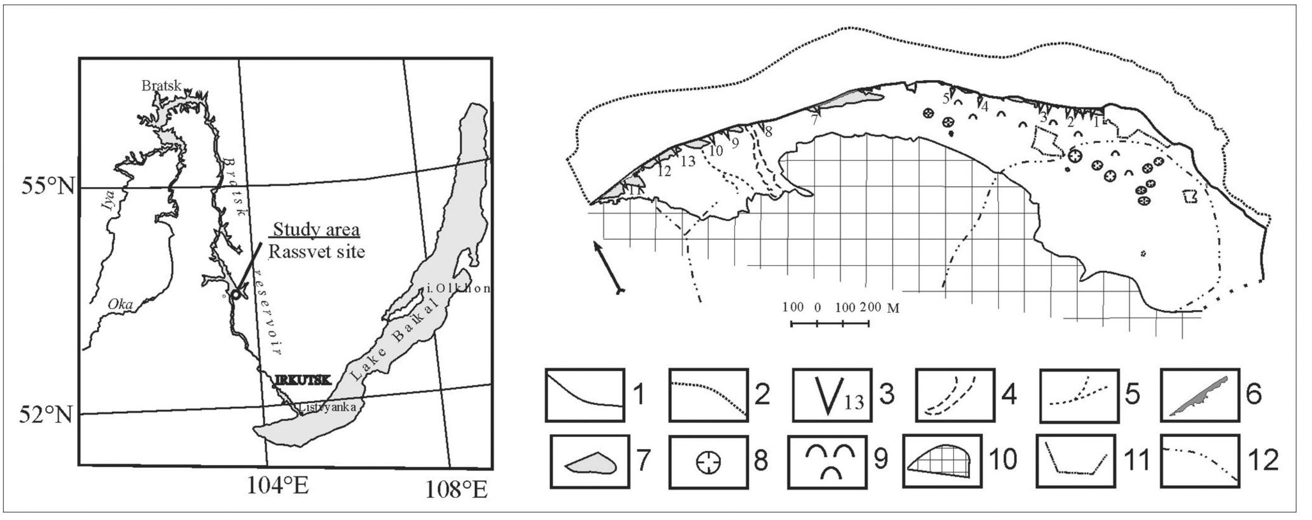


Fig. 1. Map of the study area (A) and the exogenic geological processes in the Rassvet site (B)
1 – shore cliff; 2 – shoreline; 3 – active scours and gullies (with the observation point number); 4 – ravine edge; 5 – drainage rill; 6 – eolian areas (by the time of 1969); 7 – eolian areas (by the time of 1980); 8 – karst funnel; 9 – hummock-and-hollow microrelief; 10 – forest land; 11 – quarry border; 12 – earth road

The dynamics of the development of gullies was estimated according to their volume change within the space-time between two measurements. The detailed morphometric surveys of gullies (i.e. survey in several cross-sectional profiles: the width of gully bed, distance between the upper gully edges, gully height; the total gully length) were carried out once a year in 2004, 2007, 2008 and 2009. The volume of each scour and gully was calculated by the Popov's formula (Popov 1951). For measurement purposes, the "Leica disto A8" laser distance gauge with the accuracy ranging from ± 1.5 mm (for up to 30 m distance measurements) to ± 10 mm (for shorter than 30 m distance measurements) was used.

The monitoring of the dynamics of aeolian fields and the retreat of abrasive scarp edge was performed by means of the GPS-survey methods in a kinematic regime: two 2-frequence "Ashtech Z-Xtreme" GPS detectors and two "Chokering" aerials (antennas) were used. Processing of the GPS data was made by means of a licensed "Ashtech Solution v.27" program pack, with the 0.01+1 ppm accuracy.

During the period of 2006–2007, a series of route surveys was performed in the areas of the shore zone basic morphological elements. By means of this method the retreat of the beach scarp edge, the morphometric characteristics of gullies (contours and thalweg outlines), the boundaries of the occurrence of active aeolian fields along the shore slope were estimated.

Results and discussion

Factors of erosion form development

Climate is one of the factors that determines the development of exogenic geological processes in the coastal area. The temperature conditions have a definite influence upon the depth of the seasonal freezing (2.5–3.0 m) and thus the intensive weathering of the ground. The dominant winds of the W- and NW direction, their recurrence and speed evoke an ultimate influence on the water surge formation and the intensity of processes such as abrasion and aeolian activity in the reservoir shore area. The monthly distribution of atmospheric precipitation within the period of 2004–2009 is shown in Figure 2.

Annual atmospheric precipitation amounts to 350–500 mm yr^{-1}. Vast precipitation (60–70%) occurs in the period of May–September (as rainfall); this is the period of largest erosion hazard caused by the storm runoff. The highest amount of liquid precipitation falls on June-August (25% of annual amount). During the study period the amounts varied from the minimum of 226.2 mm in 2007 to maximum of 413 mm in 2006 and the rainfall volume did not exceed 35–40 mm per day. Maximum number of days (5 days) with an amount of rainfalls 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 up to 45–78 mm a year occurs in the period of November–April. In spring the influence on the erosion development is induced by a rapid snowmelt runoff in the context of a deep seasonal ground freezing and the regime of its defrosting. The thickness of snow cover varies from 10 cm 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 ten-day period of April; by April 26–27 the land surface becomes free of snow cover. At this time, the land surface has no plant cover (the vegetation period begins normally in May 15–25). Furthermore, a deep ground freezing impedes the thaw-water infiltration.

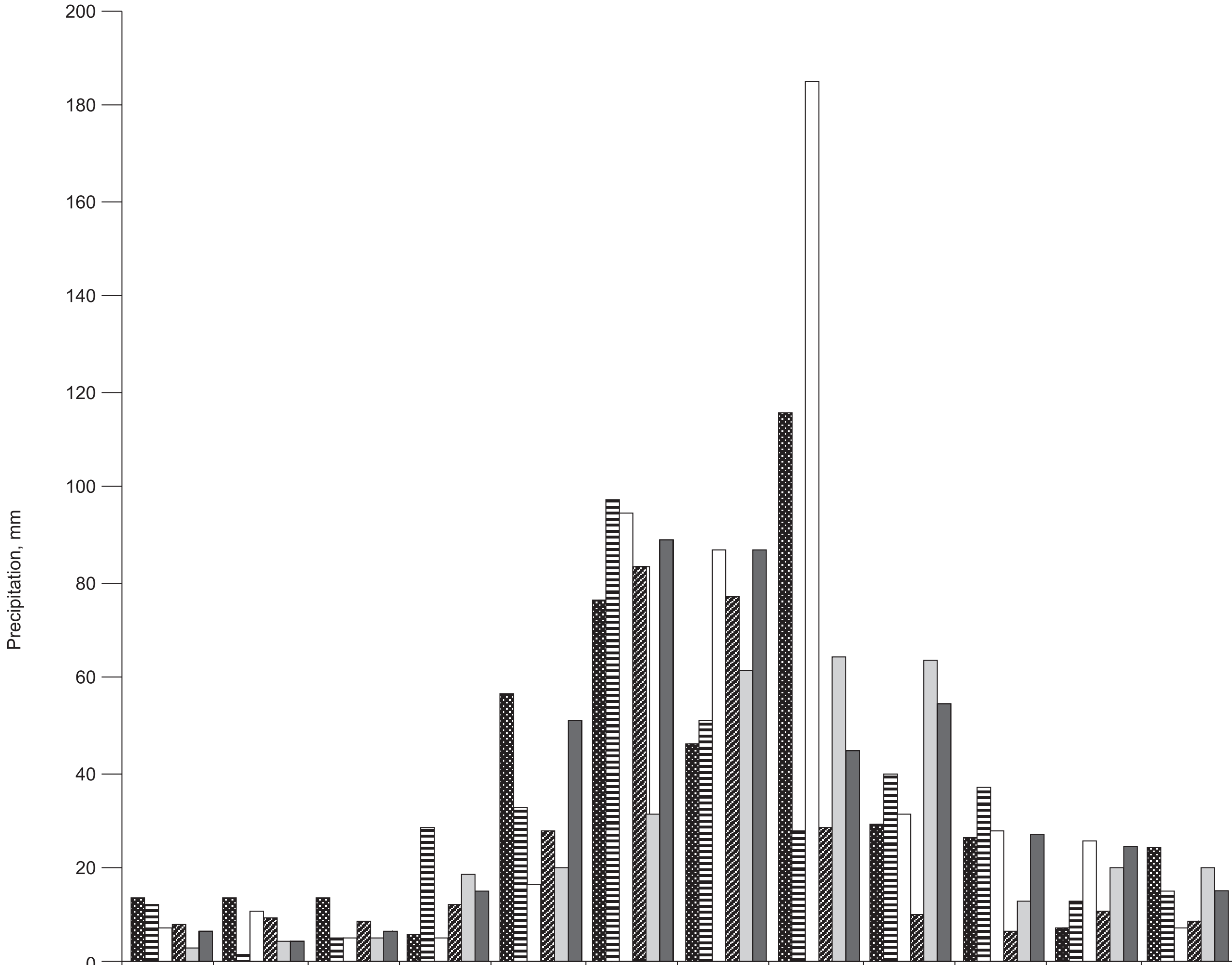
The lithology of gully development sites was studied in the areas of a natural outcrop in 1.6–2.3 m deep erosion forms in the Rassvet-site (Grobelska et al. 2007). The thickness of modern eolian deposits covering the 0.5 m-thick topsoil layer, amounts to 0.2–0.4 m. The profile section displays the interchangeable underconsolidated sandy loam and sandy layers in the periodically freezing-thawing area. The laboratory study of the composition, structure and physical-mechanical and chemical ground features shows the following factors that determine the gully development: the lithological stratification of underconsolidated loess-like sandy loams overlying the sand layer; high siltiness of sandy loam, primarily of a skeletal-aggregated microstructure; the sulphate salinization; low physical-chemical activity and low cohesion of grounds that easily get sodden, lose their strength and acquire the features of shrinkage and subsidence. The sand interlayer is salinized (sulphate salinization), low humid and friable; in humid conditions the grounds become unstable and flowing (the angle of the submerged natural slip decreases from 33° to 26.5°).

The water level regime of the Bratsk reservoir is one of the main factors that influence both the groundwater dynamics in the backing zone and the development of geological and geomorphological processes in the neighboring territories. Within a year, the maximum water level of the Bratsk reservoir is recorded in autumn period, and the minimum level in April. In the context of perennial trend, the level regime in 2004–2007 was marked by high water that reached the normal headwater level of 401.15 m in September 2006 (Fig. 3). The maximum amplitude of the water level rise cases (4.5–5.0 m) were recorded in the summer-autumn periods of 2004 and 2006; the minimum amplitude (~1 m) occurred in 2007.

The period of July 2007–June 2008 was marked by a permanent water level lowering. At the open water period of 2007, the level was approx. 2.0–2.5 m lower than in 2006, varying at monthly average level marks of 398.5–399.0 m. The lowest water level in spring–summer 2008 slightly exceeded the level mark of 395 m, that is approx. 4 m lower in comparison with a similar period of 2007. In the period of July 2008–May 2009 the tendency of the water level rise up to the average of 397.5 m was observed.

Mechanisms of erosion form development

The initial stage of erosion form origination is presented by desiccation fissures, frost clefts and tension cracks filled with eolian sand, snow, thaw water and rainwater (depending on the season). In these fissured areas, located along gully slopes and parallel to the edge of abrasion bench, the processes of ground subsidence, rockfall, landslide and crumbling occur. The capillary water rise (which reaches 1.5 m above the reservoir water edge in sandy loams) induced the soaking, water saturation, swelling and



month	1	2	3	4	5	6	7	8	9	10	11	12
2004	13,8	13,3	13,6	6	56,2	76	45,6	115,4	28,7	26,4	7,1	24,2
2005	12,1	1,6	5,2	28	32,4	97	50,7	27,5	39,2	36,4	13	15
2006	7,1	10,7	4,8	5,2	16,6	94,1	86,8	184,7	30,8	27,8	25,4	7,5
2007	7,8	9,5	8,4	12,4	27,9	83,1	76,7	28,2	10,3	6,4	10,7	8,5
2008	3	4,4	5,1	18,6	19,6	30,8	61,4	64	63,6	13	20,1	19,7
2009	6,7	4,1	6,6	14,9	50,7	88,9	86,5	44,2	54,5	26,6	24,6	14,5

Fig. 2. Monthly precipitation within the period of 2004–2009 (data of the Balagansk weather station)

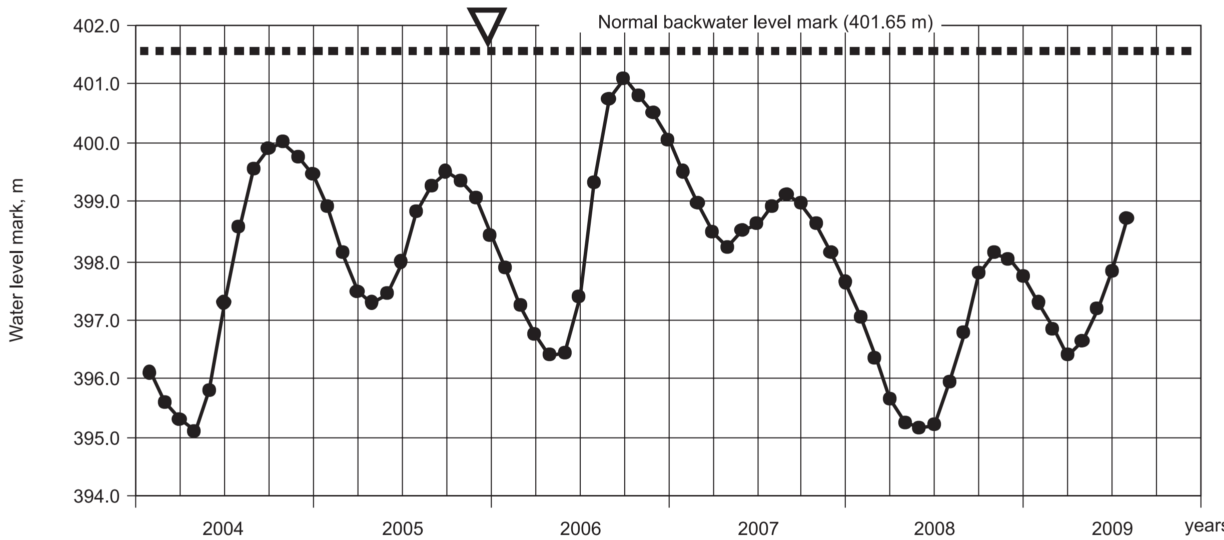


Fig. 3. Average monthly water level marks for the Bratsk reservoir (data of the Balagansk weather station)

subsidence of the ground. The frost weathering leads to the damage of the structural bonds and decrease of the ground resistance against erosion and deflation.

The analysis of the structural properties of sandy loams and sands in the Rassvet site revealed a high degree of erosion-pliability of the ground. One of the mechanisms of erosion form development is the sand mass saturation and flow from underneath the topsoil layer, and formation failure of the overhanging benches in the gully heads.

In the eastern part of the discussed site, the main factor stimulating the erosion increment in the area of mantled karst is the suffosion-subsidence mechanism. Over the head cuts of the gully branches and in the thalweg areas the suffosion funnels appear due to the mechanical transport of soil particles into the fissured and karsted areas. The growth of funnel size and merging of the erosion forms lead to the gully lengthening.

The spring snow thawing stimulates the subsidence of underconsolidated dust-like macroporous sandy loam soils, fissuring, disintegration and subsidence of soil blocks. The additional inundation results in the gravitational block fall. A similar mechanism also applies to the origination of additional erosion cuts in the edges of the abrasion scarps. The subsidence and block caving induce the formation of overhanging topsoil benches in the gully head areas.

Another factor inducing the destruction of gullies and abrasive benches is the process of solifluction of the melted ground layer. The deformation processes of this kind are attributed to the revealed ground properties.

The field investigations carried out in 2008 during the heavy rainfalls (11.4 mm) revealed that the mechanisms of erosion form development are various. The erosion forms developing in the discussed territory can be tentatively subdivided into 3 groups.

In gullies of larger size (Group 1) developing in the western part of the studied territory, the heavy rainfalls caused the formation of plunge pools in the gully head areas, and the washout channels in the beds with 100 m-long alluvial fans in the beach. The abrasion scarps are in a developing condition, preventing the accumulation of near-scarp aeolian deposits. The gullies of this group are marked by the following characteristics: the volume ranging from 75 m^3 up to 150 m^3; a 0.6–1.55 m gully headcut height (predominantly of 1–1.2 m.). After the rainfall of similar abundance (11.8 m) in June 11, 2007, large amount of soil (ranging from 16.6 m^3 to 77 m^3) was deposited from these gullies; moreover, the gullies increased in length (from 0.95 m to 8.0 m).

The gullies of Group 2 are of smaller size: their volume is ranging from 20 m^3 up to 40 m^3 0.6–10 m (predominantly 5–10 m) in length; with small headcuts (h = 0.2–0.4 m) and small heights in the mouth areas; here the sand saturation and washout in the mouth area (with a 9 m-long sand cone) and scouring in the thalweg area were recorded. The abrasive scarp is of small height (1.6–3.7 m). In this part of the shore area the scarp is composed of alluvial-colluvial sand deposits; due to the grass-bushy and soddy surface, the scarp is in a stable condition.

The gullies of Group 3 develop in a smaller area of shore slope that is marked by the active aeolian phenomena (the near-scarp aeolian deposits, aeolian deposits in gully beds, fields over the shore slope edges). The heights of gully headcuts and gullies volume are of 0.42–0.65 m and 10–30 m^3 respectively. The rainfalls did not cause any erosion process, nor any formation of alluvial cone was observed due to a natural intake of the rainwater by aeolian and sand deposits.

It has been observed that large amount of material was lost from gully forms of larger volume and length. This conclusion conforms to that obtained by the investigation of the increment rate of gully forms along the shore area of Huron Lake (Burkard & Kostaschuk 1997). Furthermore, this conforms to the relation between the annual average volumetric erosional retreat rate, the present drainage-basin area and the elevation of the gully headcut revealed by the study of short-term bank gully retreat rate in the Mediterranean environment (Vandekerckhove et al. 2001). It should be noted, however, that the presence of aeolian deposits in the gully forms of Groups 2 and 3 (i.e. lithological features of eroded deposits) is the determining factor for the difference of erosion mechanisms.

Dynamics

Monitoring of the dynamics of erosional processes carried out during the period of 2004–2009 revealed a permanent increase of the number and volume of erosion forms, with some exceptions though. In 2004, the development of 16 erosion forms within the studied area was revealed by the field investigations; the persistent increase reached the number of 21 erosion forms in 2007, 38 – in 2008 and 47 – in 2009.

The maximum material loss from gullies (in total 627.66 m^3) and the average volumetric retreat rate for all the gully forms (16.5 m^3 yr^{-1}) were recorded during the period from July 2007 to June 2008. This large positive dynamics can be attributed to the increasing number of erosion cuts as a result of abrasive, collapse and subsidence processes that occurred in fissured areas along edge of abrasive scarp in 2006–2007. Mechanism of initiation of the additional erosion cuts in the abrasion scarp is described in the section "Mechanisms of erosion form development". Another important factor of the material loss is the activation of vertical erosion occurred in the abrasive shore areas, where the undercutting of the gully bed mouth areas and the break of the longitudinal profile appeared as a result of an intense shore abrasion during the high water level (401.2 m) in autumn 2006. This entailed the washout of the bench between the shoal surface and the hanging mouth areas of the gully bottoms. The mouth areas of major erosion forms reached the level of the in-shore shoals. The decrease of reservoir water level followed by the groundwater table lowering could intensify the flow of the infiltration water within the shore massif, and cause the reasonable activation of the pipe and subsidence processes.

During the 2004–2007 period marked by abundant atmospheric precipitation and intense abrasion, the minimum of total volumetric increment of gully forms (317.22 m^3) and the average volumetric increment rate (5.04 m^3 yr^{-1}) were recorded.

The negative dynamics and a low rate of volumetric increment of major erosion forms (4.5–54.7 m^3) can be attributed to the process of shore abrasion. A prevalent occurrence of abrasion was verified in 2006 and 2007 by the comparative analysis of digital models of the relief in the Rassvet site. The total loss of ground material due to the shore retreat amounts to 13,860 m^3 yr^{-1}; the retreating shore edge width varies along the studied zone in the range from 0 to 8 m a year.

The prevalence of shore abrasion over the vertical erosion is proved by the presence of hanging thalwegs in the major gully forms (i.e. the gully mouth is located over the level of the in-shore shoal (Grobelska et al. 2007). 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.

The negative dynamics of major gully forms can also be the consequence of the aeolian effects. The aeolian processes were marked by the positive dynamics in terms of both the spatial distribution of sand material (the 3,620 m^2 increment of aeolian deposit massif area during the 2006–2007 period), and the increasing thickness of aeolian deposits over the topsoil layer on the slope area.

Aeolian processes are most active during spring and summer, when high winds are observed. In spring this windy period concurs with the period of minimal water level of reservoir. Consequent increase of shoal width is accompanied with an intensive sand transportation. An important prerequisite for eolian process activation in the shore area, on long terms, is the long-duration low water level mark of the reservoir. As a result of constant water level decrease between autumn 2006 and summer 2008, there developed more and more favorable conditions on the site.

However, two large-size gullies (200 m^3 and 300 m^3) should be noted, which considerably increased in volume (by 103 m^3 and 173 m^3 respectively) during the period of 2004–2007. The rate of erosion and volume increase of these gullies due to abundant rainfalls in 2004 (with 426 mm annual precipitation, and 321.9 mm liquid precipitation during May–September), and in 2006 (with 501 mm a year precipitation amount, and 313 mm liquid precipitation in the period of May–September) exceeded those of the shore retreat.

The average rate of volumetric gully increase (amounting to 5.04 m^3 a year) during the 2004–2007 period is the measure of gully development in the described territory in the context of abundant rainfalls, high water level in the reservoir, active abrasion and aeolian processes. In summer 2008, the aeolian processes prevailed over the erosion. At the low water level the increase of shoal width was accompanied by an intensive sand transportation. Therefore, during the period of June 2008–May 2009, numerous gully forms were marked by a low negative dynamics.

Within a year, the total loss of ground material from gullies amounted to 418.59 m^3, the average growth of gully forms reached 16.05 m^3 a year, which conforms to the former period.

In comparison with the bank gullies of the Mediterranean region (Vanderckhove et al. 2001) the gullies of the Rassvet-site are marked by a larger dynamics of development, not as striking, however, as that of gullies developing in black soils of the Northeast China (Hu et al. 2007).

Conclusions

1. Formation of the shore zone in the Rassvet-site is contributed by abrasion, erosion and aeolian processes.
2. The development of erosion forms in the shore zone is to a large extent influenced by the abrasion process. The high water level in the reservoir is accompanied by an intense abrasion of shore slopes. Within the period of 2004–2007, the minimum rate of gully development was due to the antagonistic action of abrasion and aeolian processes. 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. This resulted in the volume decrease of the majority of the erosion forms.
3. Further lowering of the reservoir water level during the 2007–2008 period contributed to the vertical erosion intensification in the bottom areas and stimulated the activation of the retrogressive erosion. In the course of the vertical erosion the gully bottom cut reached the level of the in-shore shoal, which in this case is the erosion base level.
4. The low water level is the reason for activation of aeolian processes in the shoal. The erosion forms, partially or entirely filled with wind-blown sand, are temporarily (at the low water level) marked by a low negative dynamics. The presence of aeolian deposits near the gully head edges and in the bottoms produced the erosion-protection effect (as stated by field investigations after heavy rainfall in July 25–26, 2008).
5. During the period of 2007–2008, the maximum loss of gully material was attributed to the growing number of erosion forms.
6. In the area of the Rassvet-site, the principal source of alleviation is the abrasion process at the high water level, and erosion at the low water level. The results of investigations ascertain the influence of the water level regime on the erosion dynamics. Water level fluctuations inhibit the stabilization of erosion processes, which can relatively suspend for a definite time, and resume the development with the following water level change. This causes cyclic changes in the dynamics of processes and initiates a new mechanism of erosion that is not typical of regular conditions. The level regime is practically considered as a main factor for the development of coastal processes in the reservoir area.

References

Burkard M.B. & Kostaschuk R.A., 1997. Patterns and controls of gully growth along the shoreline of lake Huron. *Earth Surface Processes and Landforms*: 901–911.

Foster I.D.L., Poesen J., Boardman J. & Keay-Bright J., 2007. Sediment tracing and environmental history for two small catchments, Karoo Uplands, South Africa. 90, 1–2: 126–143.

Grobelska H., Mazaeva O.A. & Hak V., 2007. Conditions of development of erosion forms in the shore zone of Bratsk reservoir (Angara-river, Russia). In: *Funkcjonowanie geoekosystemow zlewni rzecznych*, *4. Procesy ekstremalne w srodowisku geograficznym*: 275–285 (in Polish).

Hu Gang, Wu Yongqiu, Liu Baoyuan, Yu Zhangtao, You Zhimin & Zhang Yongguang, 2007: Short-term gully retreat rates over rolling hill areas in black soil of Northeast China. *Catena* 71: 321–329.

Ovchinnikov G.I., Pavlov S.Kh. & Trzhtsinsky Yu.B., 1999. *Change of the geological environment in the Angaro-Yenisei reservoir-affected areas*. Nauka, Novosibursk: 254 pp. (in Russian).

Pecherkin I.A., 1969. *Geodynamics of the shore areas of the Kama reservoirs. Part 2. Geological processes*. Perm: 308 pp. (in Russian).

Poesen J., Nachtergaele J., Verstraeten G. & Valentin C., 2003. Gully erosion and environmental change:importance and research needs. *Catena* 50: 91–133.

Popov I.V., 1951. *Engineering Geology*. Geolizdat, Moscow: 444 pp. (in Russian).

Vandekerckhove, L., Poesen, J., Oostwoud Wijdenes, D. & Gyssels, G., 2001: . *Catena* 44, 2: 133–161.