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The importance of geological-geomorphological factors in the development of abrasion processes on the coasts of the Bratsk Reservoir, in the SE part of Russia

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Abstract: The construction of the Bratsk Reservoir, which is on the Leno-Angarskoje Plateau, favoured the active development of many exogenous geological processes, among which the abrasion of coasts is the most important, both in intensity and scale. Over the period of operation of the reservoir (1967–1998) the length of abraded coasts was 2160 km, or 36% of the total length of the coastal line. The maximum width of abrasion of the coast varies from 200 m to 750 m in unconsolidated sediments and is up to 90 m in rocks. The total area of abraded territory is about 5000 h. Nearly 131 000 000 m³ of the ground entered the reservoir basin due to abrasion. Geological-geomorphological factors are particularly important controls of the abrasion process.

Key words: abrasion process, abrasion of coasts, the Bratsk Reservoir

Introduction

The study of the processes of abrasion and the factors, which affect their scale and intensity, is one of the most important tasks relating to the problems of how reservoirs change their coastlines and how this should be managed. Millions of cubic meters of sediment are mobilised along and across the coast as a result of the abrasion. The changing water levels and wave energy regimes over the period of operation are not conducive to the long-form stabilization of the abrasive processes, especially on coasts composed of unconsolidated sediments. The alternating periods of high and low water levels abrade the coastal slopes, corresponding to a water level 1.5–2.5 m lower than the normal height of damming (NHD). Owing to intensive abrasion, a number of settlements, arable lands and forests were directly affected in the abrasion zone. Accordingly, some settlements had to be removed.

The periods of significant intensification of the process of abrasion in development of the coasts of the reservoir are related to variations in its hydro-engineering management. Rock weathering, which is related to a regular soaking and exposure of the rock is an important contributory process.

In order, a system of permanent observation sites was installed to study the processes of abrasion on the reservoir since it started to fill (1961) and, subsequently, the period of normal operation (1967–1998), in the first years of the operation of the reservoir the measurements were made 3–5 times in the periods of open water, and subsequently, one or two times.

The investigations of the reservoir shorelines allowed us to determine the relationship between the abrasion and geological-geomorphological and geodynamical factors.

General characteristics of the reservoir and the geological-geomorphological conditions of the coastal zone

Bratsk Reservoir has a very complex configuration owing to the relief of the flooded river valleys and the local geological structure. It is the second stage of the Angarsky cascade scheme for hydroelectric power generation. Its filling began in 1961, and in

October 1967 it reached the NHD mark. The area of the water surface is c. 5 500 km^2; the body of water mass is c. 170 km^3; the coastline is >6000 km long; the average depth is 31 m, and the maximum depth is 150 m.

The reservoir is located in the southern part of the Middle Siberian Plateau. In the upper part, as far as Ust-Uda-steppe and forest-steppe zone prevail whereas the middle and lower parts lie in the taiga zone. The basin relief formed during a long geological epoch as a result of both fluvial erosion and tectonic processes. The shorelines coasts of the reservoir are situated along high and steep marginal slopes of the Angara and its tributaries. The erosional-denudational and structural-denudational forms of relief, and forms of relief dated from the Quaternary – the remnants of accumulative and accumulative-erosional terraces 10–12 m and from 12 m to 80 m high are distinguished on the reservoir coast according to the genetic feature (Palshin *et al.*, 1963; Logatchev *et al.*, 1964). The erosional-denudational forms of relief are distributed along almost the whole coast. Structural-denudational forms are identified in the northern part of the reservoir within the Angarsky mountain-ridge.

A specific feature of the Bratsk Reservoir is that the type of its basin relief, the surface of the Middle Siberian plateau eroded by the valleys of large rivers and their tributaries, and large erosional incision determined a substantially jagged coastal line and the distribution of high, mostly steep slopes.

The intensity of abrasion of the coasts and the composition of drifts depend on the geological structure of the coastal zone, which is formed by Palaeozoic and Mesozoic rocks and Quaternary deposits (*Bratsk Reservoir...*, 1963) (Fig.1; Table 1). The weathered rocks in coastal slopes are easily abraded.

In the northern part of the reservoir, the coastal zone consists of trap-rocks, which are both intrusive and extrusive forms. These are not normally abraded incoastal slopes, but the abrasion of deluvial deposits, which includes trap debris, provides a cover, which protects the coast from abrasion. Trap outcrops form only a small part of the reservoir coast and they are restricted in the northern part of the Reservoir. Unconsolidated sediments of various composition and genesis represent the Quaternary forms.

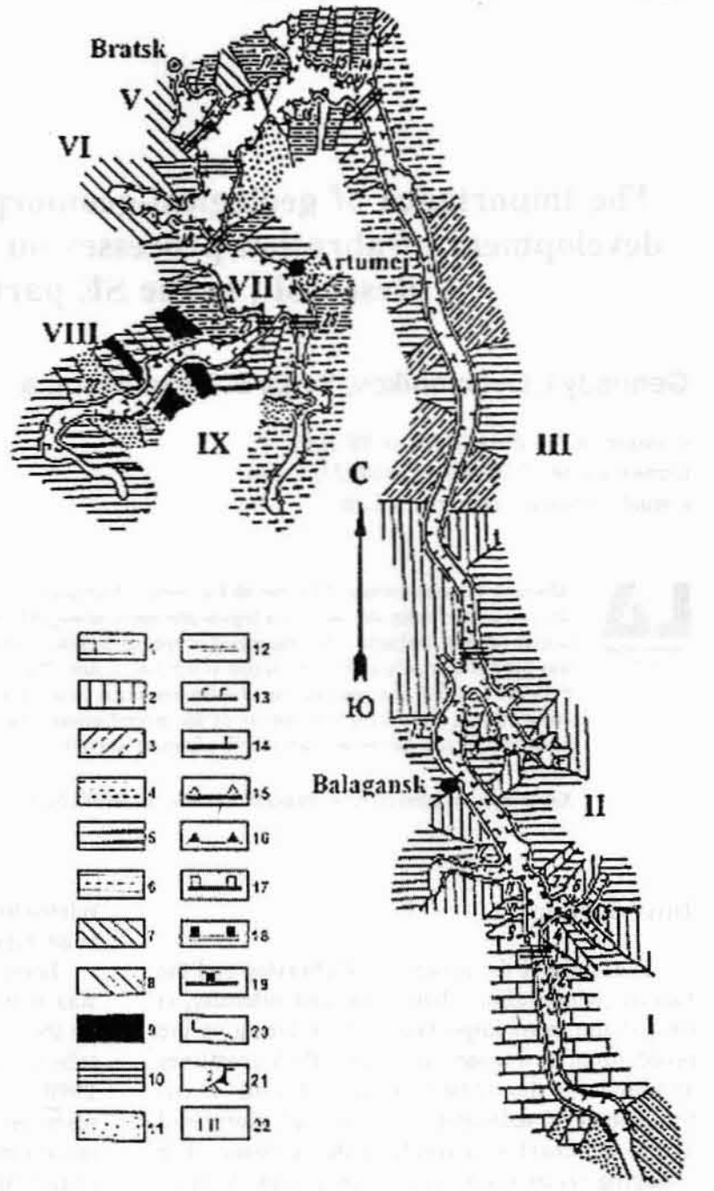

Fig. 1. The map of zoning of the coasts of the Bratsk Reservoir according to the intensity of abrasion over the period of operation (1967–1998). Prepared by G. I. Ovchinnikov

Geological structure: 1 – Cambrian sediments of the Angarsky Suite; 2 – Cambrian sediments of the Verkholensky Suite; 3 – Ordovician sediments of the Ust-Kutsky Suite; 4 – Ordovician sediments of the Iisky Suite; 5 – Ordovician sediments of the Badaranovsky Suite; 6 – Ordovician sediments of the Mamyrsky Suite; 7 – Ordovician sediments of the Bratsky Suite; 8 – Jurassic sediments; 9 – traps; 10 – loams; 11 – sands. Abraded coasts with width of abrasion: 12 – up to 10 m; 13 – from 10 m to 20 m; 14 – from 20 m to 30 m; 15 – from 30 m to 50 m; 16 – from 50 m to 70 m; 17 – from 70 m to 100 m; 18 – from 100 m to 130 m; 19 – more than 130 m; 20 – unabraded coasts; 21 – observation sites; 22 – areas of the reservoir: I – Verkhneangarsky; II – Balagansky reach; III – Angarsky narrow; IV – Zayarsky reach; V – Near-Dam; VI – Dolonovsky reach; VII – Kaltuksky reach; VIII – Iisky Bay; IX – Okinsky Bay

Table 1. Extension (km) of coasts of the Bratsk Reservoir in rocks of various age

Stretch	Quaternary	Jurassic	Bratsky Suite	Mamyrsky Suite	Badaranovsky Suite	Iisky Suite	Ust-Kutsky Suite	Verkholensky Suite	Angarsky Suite	Basaltic traps
Main	1035	14	85	130	150	400	131	205	126	36
Bays	1242	–	220	702	264	525	233	438	53	11
In total	2277	14	305	832	414	925	364	643	179	47

The coastal zone occurs predominantly in rocks (3723 km [62%] of 6013 km of the entire shoreline, 1277 km [21,9%] of which falls on the main reservoir structures and 2466 km [40,8%] in the bays). In unconsolidated sediments, the shoreline is 2277 km long (38%), 1035 km (17,3%) of which belong to the main reservoir (Table 1).

After the Reservoir had been filled, the abrasion platform along the shorelines was as wide as 750 m on certain outcrops of unconsolidated sediments and 90 m on rocky shores.

Level and wind-wave regime of the reservoir

Hydrodynamic factors – level and wind-wave regime – are important in the development of abrasion forms. The scale of the abrasion relates to the various water levels during the history of the reservoir.

The Bratsk Reservoir is the reservoir of many-year regulation. The variation of the level during drawdown has been as much as 10 m. The filling of the reservoir began in 1961 and this took 6 years, during which the slopes of river valleys were flooded along with an initial formation of its coasts. In an annual regime, the maximum abrasion levels are typical of the autumn (Fig.2). A prolonged high level, and storm conditions promote active abrasion of the rocks on the coastal slopes or exposed shallows. In April, the level of water is usually a minimum. A plot of variations of water level shows that the process of filling of the reservoir is closely followed by its drawdown (Fig. 2). Thus, the level does not normally reach the NHD or even close to it.

The many-year regime of water level in the reservoir over the period of its operation (1967–1998) was cyclic with relative stability at certain levels and with regular variations of amplitude. A high water level is typical of the first cycle (within the NHD) and was attained in the periods 1967–1968, 1971–1974, 1984–1989, and 1994–1995. The amplitude of variation of the water level within any particular cycle varied from 1.2 m (1989) to 4 m (1971). With respect to the NHD, this value varied from 2.1 m to 4.3 m. The second cycle was characterized by low water level, 1 m lower than the NHD (1991) and the minimum, 7.2 m lower than that in (1990). In the third cycle, during 1975–1983 and 1996–1998, there was a continuous fall of the water level in the reservoir. Taken over a several-year-long period, it resulted in maximum amplitude of 9.7 m (1982) relative to the NHD, and a minimum,

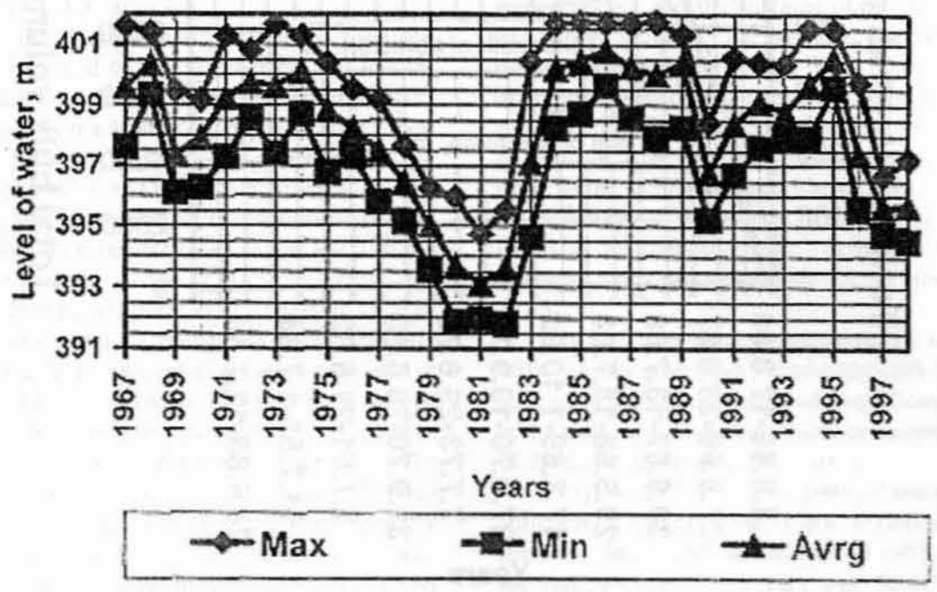

Fig. 2. Variation of the level of water in the Bratsk Reservoir over the period of its operation

1.2 m (1983). In an annual variation at continuous lowering of the level the amplitude changed from 1.3 m (1976) to 4 m (1980) in respect of the minima and maxima.

Wind turbulence is one of the main factors, which affects the intensity of abrasion of the reservoir shorelines. It is of variable character and relates to the morphological differences of different parts of the reservoir, and the velocity and persistence of wind of various directions. The south-to-north reach of the reservoir is more then 600 km long. The wind regime varies perceptibly over the whole territory, both in respect of prevalent windflows directions and velocities. Most of the moderate and strong winds are those from the W, NW and SW (56–57%), and each of the rest – for 4 – 9%. SW and NW windflows prevail in the southern part of the reservoir; NW and N in the middle part and W in the northern part. The strongest winds are equinoctial (*Bratsk Reservoir...*, 1978). The variable windflows across the reservoir also produce variable wave conditions in the coastal zone. In storms, the maximum height of waves in open parts of the reservoir is as much as 3.5 m though it rarely exceeds 1 m in the narrower parts. The energy of agitation varies in the range from 10 000 tons per meter to 1 100 000 tons per meter (Pulyaevsky *et al.*, 1976).

Abrasion of coasts

Over the period of its operation, several distinct episodes can be identified in the formation of coastal abrasion zone of the Bratsk Reservoir. These relate to the level of water in the reservoir and the intensity of the abrasion processes, i.e. to years of high water level: 1967–1968, 1971–1974, 1983–1989 and 1994–1995; to those of low level of water – 1969–1970 and 1990–1993, and to the years of continuously falling level – 1975–1982 and 1996–1998.

The first significant year of abrasion was, the maximum amount, in loessal loams, being 50 m, and the volume of abraded material averaging 300 m³/m shoreline. The shoreline retreated mainly as a result of landslipping. Of particular interest is that part of the reservoir coast located on the right bank of the Oka valley at Artumey. At the end of the period of filling of the reservoir (1966) the coast was composed of fine sand, which receded there 470 m in relation to the NHD. In volume of rocks, abraded over the period of 1966–1968 along just one of the cross-sections, was c. 11 000 m³/m shoreline but in the following years of high water level in the reservoir the recession did not exceed 1–8 m a year (Fig. 3).

The abrasions of rocks have occurred in the weatherworn zone. The resulting sediment was

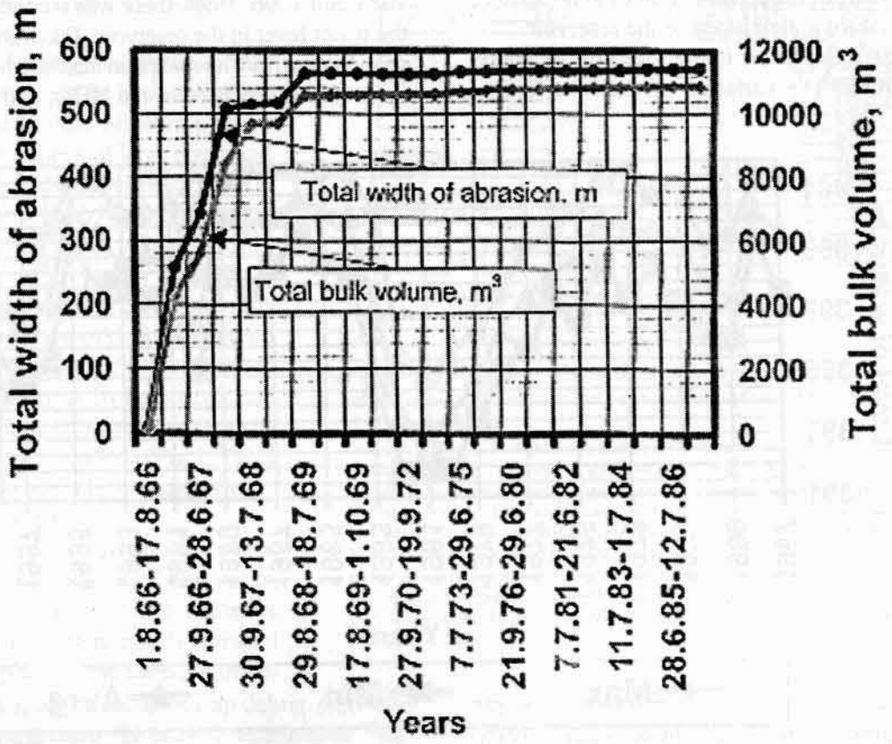

Fig. 3. Relationship between the bulk volumes and width of abrasion on the Artumay site

transferred to deep water though some of it was incorporated into the littoral drift. The maximum recession of the edge of the coast was 25 m, and the volume of abraded rocks – about 100 m³/m shoreline. The abrasion touched the coastal line within extensions (Pulyaevsky *et al.*, 1971). The most of coastal scarps in rocks and half-rocks decomposed in the form of collapses.

The formation of abraded platforms and mobilisation of large amounts of abraded ground led to long shore drifting. Up to 80% of the volume of the abraded rock material was deposited on the outer edges of the platforms. Large accumulation forms began to develop at the mouth of the bays (Ovchinnikov & Karnaukhova, 1985).

During the second period (1969–1970) the water level in the reservoir fell (Fig. 2). Slopes composed of rocks were not abraded at that time, but substantial abrasion of the previously formed platforms took place. These became much narrower due to abrasion of the deposits on the outer edges. The volumes of abraded drifts were c. 60 m³/m. The abrasion of the exposed platforms resulted in the formation of secondary scarps, up to 2.5 m high. The recession of the edge of the secondary scarps was 10–22 m in sandy loams and 6–10 m in sands (Ovchinnikov, 1970). The shoreline thus acquired a double-step profile. Almost all the drifts of the exposed platforms were abraded in the autumn of 1970, and the line between the level of water and the coast receded towards the foot of coastal scarps. The coastal slopes were abraded on some windward parts formed from unconsolidated sediments. The abrasion amounted to 0.5–2.5 m, and the volume of abraded material was c. 10–20 m³/m.

As a result of abrasion of the exposed zone, the shallows deepened to 2.5 m in sands and loessal loams; to 2.0 m in sandy loams; from 0.7 m to 2.0 m in sandstones of the Mamyrsky Suite; from 0.7 m to 1.0 m in aleurolites, argillites and sandstones of the Verkholensky suite, and to 1.0 m in limestones. The deepening led to an intensive abrasion of coastal slopes when the reservoir filled to the NHD in the succeeding period.

In the third period, 1971–1975, the high level of water and the previous deepening of the abrasion platforms made the process of abrasion more active over the decametres. The maximum abrasion was, as before, observed in the loessal loams – from 8 m to 50 m. The volumes of abrasion were about 350 m³/m of the coast. In sandy loams and sands, the abrasion varied from 12 m to 34 m; in rocks of the Angarsky Suite it was 1.5–3 m; Verkholensky Suite – 1.0–3.0 m, and in the Mamyrsky Suite – 4.0–15 m. Near the end of the period, the process of abrasion tended to slow down on the coasts formed in sands and rocks. Though this was not observed on the coasts composed of loessal loams. Gentle coastal slopes (less than 4°) began to be abraded and form abrasion scarps up to 1 m high.

A significant widening of the platforms and a decrease of their inclination characterized this period. An extensive drifting occurred along the entire coastal line. Some parts of the shallows began to develop in accordance with an accumulative type (Pulyaevsky *et al.*, 1974).

In the fourth period (1975–1982), the coastal zone formed during a protracted fall of the reservoir level (Fig. 2). Abrasion of the original coast ceased entirely landslips developed along the fractures, which separate the block from the coastal slope. Owing to further abrasion, the previously deposited drifts gradually shifted to deeper water. All the drifts had been removed by the end of this period. All the shallows within the exposed zones became completely stripped of drift on the slopes composed of rock outcrops and the process of erosion abruptly intensified on the abraded coasts where the thalwegs of ravines and gullies had been cut. This occurred not only on the slopes of old ravines but also on the drained shallows with the ravines, which opened the drift units.

Those exposed platforms affected by abrasion, were 7 m to 40 m wide, and the volume of abraded rocks – varied between 20 m³/m and 100 m³/m shoreline. The secondary scarps, formed on the drained shallows, were up to 1.5 m high. The previously deposited drifts and deposits of the bedrock were abraded. All the drifts deposited in the previous period were abraded, and the surfaces of the shallows became more inclined. The outcrops were rapidly attacked by weathering agents. With progressive fall of the reservoir level, the shoreline acquired a multi-stepped profile. The accumulation forms were abraded, and the material, which previously comprised those forms, drifted inside the bays. In loessal loams the platforms deepened by 4 m; c. 3 m in sandy loams; c. 2.5 m in sands, c. 1.5 in rocks of the Verkholensky Suite, and from 1.5 to 3.0 m in the Mamyrsky Suite.

This fourth period is characterized by a deficit of drifts, an intensive rock weathering both in coastal scarps and shallow deposits, and a significant abrasion of the platforms. These conditions promoted abrasion of the coasts in subsequent years.

A high water level, 1983–1989, characterized the fifth period. The abrasion of coastal slopes was then intensive. In summer and autumn of 1983 almost all the shallows were abraded at a water level 1.5–2.0 m lower than the NHD, and the line between the level

of water and the coast receded towards the foot of scarps. They were intensively abraded at some places. In unconsolidated sediments the amount of abrasion was 5–18 m, and the volume of abraded rocks – 30–100 m³/m shoreline. In the weathered zone of the Lower Mamyrsky Sandstones, the abrasion was 0.5–3.0 m, and the volume of abraded material as much as 25 m³.

In subsequent years, the maximum amounts of abrasion were mostly typical of extensions and related to the coasts formed in loams and sandy loams. Thus, abrasion amounted to 7–22 m between the measurements of 1984 and 1985. The bulk volumes of abraded material were 80 m³/m shoreline. The recession of coast composed of the Ordovician rocks was 0.5–8.0 m, and the maximum amount of abrasion – up to 50 m³/m shoreline. It did not exceed 3 m in the Cambrian rocks. That period saw the beginning of abrasion of gentle (< 2°) slopes. Only in the period 1983–1985, the recession of the coast was 7–30 m in loessal loams, 0.1–8.5 m in sandstones of the Mamyrsky Suite, and 0.4–4.0 m in sandstones, aleurolites and argillities of the Verkholensky Suite.

Over this period the coast receded up to 50 m in sandy loams, up to 60 m in sands, up to 70 m in loams and loessal loams, up to 6 m in rocks of the Angarsky Suite, up to 8 m in the Verkholensky Suite, and up to 18 m in rocks of the Mamyrsky Suite.

In the sixth period (1990–1993), a 6 m fall of the water level in 1990 caused the abrasion of the platforms, which varied in width from 30 to 250 m. The wave effect mostly intensified the beginning of abrasion of the unit of drained drifts accumulated on an outer edge of the shallows in the previous period. Over the spring-summer periods (1990–1993) the width of abrasion of the drained shallows was 2–10 m in sands and 20–50 m in loams. The secondary scarps mainly occurred in pebble drifts on the exposed platforms, which emerged in the Cambrian rocks in spring-summer periods. The bedrock was abraded in the autumns. In the summer-autumn period of 1991, the exposed platforms underwent intensive abrasion and, at the end of August, were completely abraded on the windward coasts formed in weathered rocks of the Verkholensky Suite. The line between the level of water and the coast receded towards the foot of scarps (the level of water was 2.5 m lower than the NHD).

The rise of the level of water to 400.50 m resulted in the beginning of abrasion of the coastal slopes. In certain sectors, the amount of abrasion was 5–7 m. In 1993, the water level was low (2.5 m lower than the NHD). In June, the line between the level of water and the coast was at the foot of scarp on a number of windward sectors, and the abrasion of coast began in the autumn storm period.

The seventh (1994–1995) was characterized by high water levels in the summer-autumn periods and small values of turbulence of agitation, factors which were not favourable to an intensive abrasion. The talus at the foot of scarps and some parts of the coastline

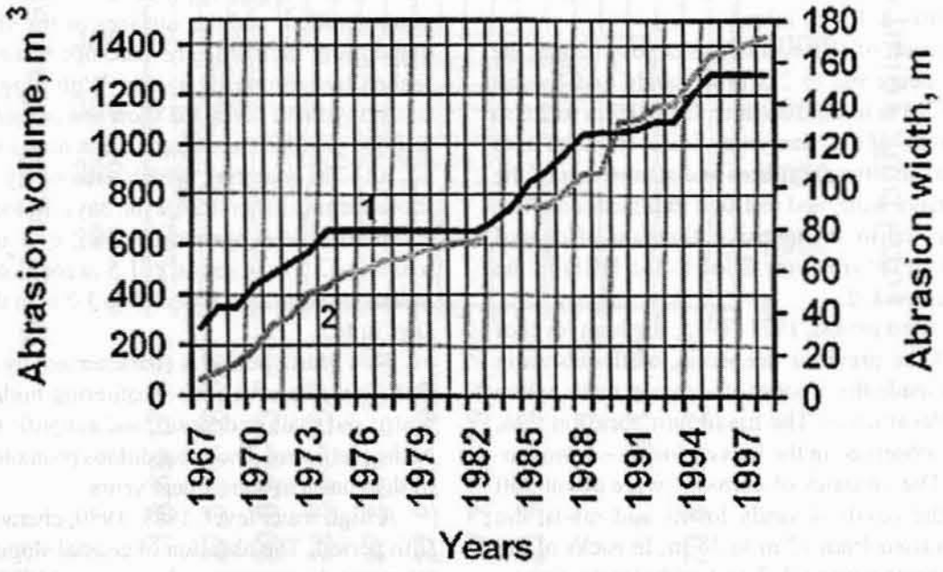

Fig. 4. Relationship between the width of abrasion in loose sediments and the level of water in the Bratsk Reservoir over the period of 1967–1998
1 – abrasion width; 2 – abrasion volume

affected by eastward agitation were abraded, but the amount of abrasion was not greater than 10–20 m.

In the eighth period (1996–1998), at a low water level, the erosional and eolian processes were mostly typical of the exposed platforms with some 300 m - wide sectors. The deposits of the platforms were abraded.

Over the period of operation of the reservoir, from 1967 to 1998, the total length of the abraded coasts was 2160 km (about 36% of the entire coastline). 1608 km of this belongs to the Angarsky Stretch; 390 km – to the Okinsky and 162 km – to Iisky. Along the main stretches of the reservoir the coasts are abraded over a length of 1649 km, and along the bays – at least 511 km. In the initial period of the operation of the full reservoir the abraded coasts were extended regularly, and at a high rate. In 1966, the length of eroded coasts was no greater than 700 km. In 1975, it then extended to 1300 km and from 1984 to 1998 it increased by 860 km.

The maximum abrasion of coasts (up to 200 km) was recorded in large sectors of the reservoir margins and is mainly related to the slopes composed of unconsolidated sediments. In narrow bays the amount of abrasion on short single sectors, does not exceed 10–20 m. The intensity and dynamics of abrasion is shown in Fig. 1,4. The total amount of material abraded over the entire period of operation of the reservoir is more than 130 000 000 m³ (Table 2). About 40% of this volume remained in the shallow waters of the reservoir, and the rest was transported to deep water.

Table 2. Bulk volumes of the rocks abraded at the Bratsk Reservoir in 1967–1998

Area		Above-water abrasion (m³)	Underwater abrasion (m³)	Total bulk volume
Verkhneangarsky		4847139	2086070	6933209
Balagansky extension		23483125	13920000	37403125
Angarsky narrow		2768750	981250	3750000
Zayarsky extension		7182034,7	4512843,8	11694878,45
Near-dam		2173750	1566875	3740625
Angarsky stretch	In total	40454798,7	23067039	63521837,45
Dolonovsky extension		4880500	3298850	8179350
Kaltuksky extension		25907500	21170250	47077750
Okinsky bay		4193750	2096875	6290625
Okinsky stretch	In total	34981750	26565975	61547725
Iisky bay		3940000	1970000	5910000
Over the reservoir as a whole		79376548,7	51603014	130979562,5

Conclusion

The coasts of the Bratsk Reservoir continue to evolve. The history of their development consists of certain periods determined by the different level regimes of the reservoir: the period of an intensive processing at a normal operation of the reservoir at a high level of water and a gradual attenuation of abrasion to the end of a deep cycle, when the profile of dynamic balance begins to form for a certain stage of development of the coast, and the period of dynamics of the coastal zone at continuously lowering level (Ovchinnikov, 1997).

Over the period of the operation of the reservoir it is concluded that the coasts composed of rocks are characterized by some slow down of the process of abrasion, which is due to incision of the coastal profile in more monolithic sedimentary units. It does not occur on the coasts composed of loose sediments. Over the period of operation, the volumes of abrasion in some sectors are more than 2000 m³/m shoreline. The volumes regularly increase from year to year with some insignificant deviations. If the edge of the coastal slope does not actually recede in shallow years, then the volumes of abrasion increase in these periods; this is due to abrasion of the exposed platforms.

The periods of high water level, alternating with lows, controlled the abrasion of coastal slopes at the levels of water 1.5–2.5 m lower than the NHD.

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