RESULTS OF INSTRUMENT OBSERVATIONS AND ADAPTIVE PREDICTION OF THERMOABRASION OF BANKS OF THE VILYUI RESERVOIR

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Quantitative data derived from observations of reformation of the thermoabrasive banks of the Viliyui Reservoir in Yakutia during the service period from 1972 through 2011, and results of analytical prediction of bank formations over the next 20 years for purposes of monitoring the ecological safety of this water body are presented.

Keywords: cryolithozone; reservoir; banks; thermoabrasion; observations; prediction.

The land surrounding the Vilyui Reservoir is confined to the eastern margins of the structurally denuded Vilyui traprock plateau, and is a disintegrated, slightly rolling surface with absolute elevations ranging from 350 to 400 m.

The mean-multiyear air temperature in the region varies from –7.5 °C (Tuoi-Khaya) to –10.4 °C (Syul'dyukar), and the lowest temperature is observed in January (–30.9 °C), and the highest in July (+17 °C).

The permanently frozen rocks range from 300 to 500 m in thickness, and 800 m based on certain predictions. Moreover, data derived from evaluation of the geocryologic setting, are based on studies conducted in a section within the area containing the site of Vilyui HPP, and characteristics of the frozen stratum may vary over the length of the reservoir, depending on the lithologic composition and moisture content of the deposits, the relief, vegetation, and exposure of the slopes. The mean-annual temperature of the rocks in the lower sections of slopes ranges from –6 to –7 °C, increasing to –1 °C toward the water sheds. The thickness of the snow cover does not exceed 0.5 – 0.7 m. In the forested sections where the density of snow is light, the rocks are characterized by somewhat higher temperatures.

The reservoir has a complex configuration in plan, and alternation of lake-like broadening and canyon-like sections. The area of the water surface is 2170 km^2 at the normal support level (NSL) of 244.0 m (Baltic system); the area of the flooded land is 1112 km^2, of which approximately 700 km^2 is in the zone of periodic flooding when the drawdown level is 8 m (according to the design). The reservoir had been filled by 1973, and has operated until now in its normal regime.

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The wind conditions in the littoral zone of the reservoir were studied at the Vilyuisk Permafrost Scientific-Research Station (VPSRS), where the wind vane of the remote meteorological station was located at a height of 40 m above the NSL. Data from observations during three ice-free seasons (1972 – 1974) indicated that for the average 120-day duration of observations in a season, the number of days with winds was 99.7 (83%). Slight winds of 1 – 2 m/sec (50.8%, and 3 – 5 m/sec (33.5%) predominated. The percentages of stronger winds was: 6 – 8 m/sec — 11.7%, 9 – 11 m/sec — 3.2%, and 12 m/sec and higher — 0.8%. September and October had the greatest number of days with winds. Storm-generated winds are observed on average once or twice per season, primarily in the fall and at the beginning of summer. Two storms with wind speeds of 15 – 17 m/sec were noted in 1972, a similar one was noted once in 1973, and a storm with a wind of 12 – 14 m/sec was observed in 1974. The most pronounced destruction of the banks of the reservoir has occurred during storms.

Maximum ice thickness was recorded by the VPSRS on 14 May 1974 in the central portion of the reservoir, and was 107 cm. Average ice thickness is 92 cm.

With impoundment of the reservoir, the water level in the near-dam area had risen by 70 m, as a result of which all terraces above the river are flooded at a distance 300 – 350 km above the site of the hydroproject. The banks of the reservoir vary in steepness, legend, and lithologic composition of the rocks.

A characteristic feature of the geologic formation of the land occupied by the reservoir is the existence of numerous traprock intrusions occurring among Cambrian, Ordovician, Permian, and Triassic sedimentary strata. Comparatively widespread development of precipitous rocky banks is associated with this on the reservoir. Thus, the narrowing that

Fig. 1. Precipitous rock banks along Vilyui Reservoir in area of Kusagan "pipe."

Fig. 2. Rock slopes of left bank in Dyraninskoe broadening of Vilyui Reservoir, which are covered by layer of Quaternary deposits.

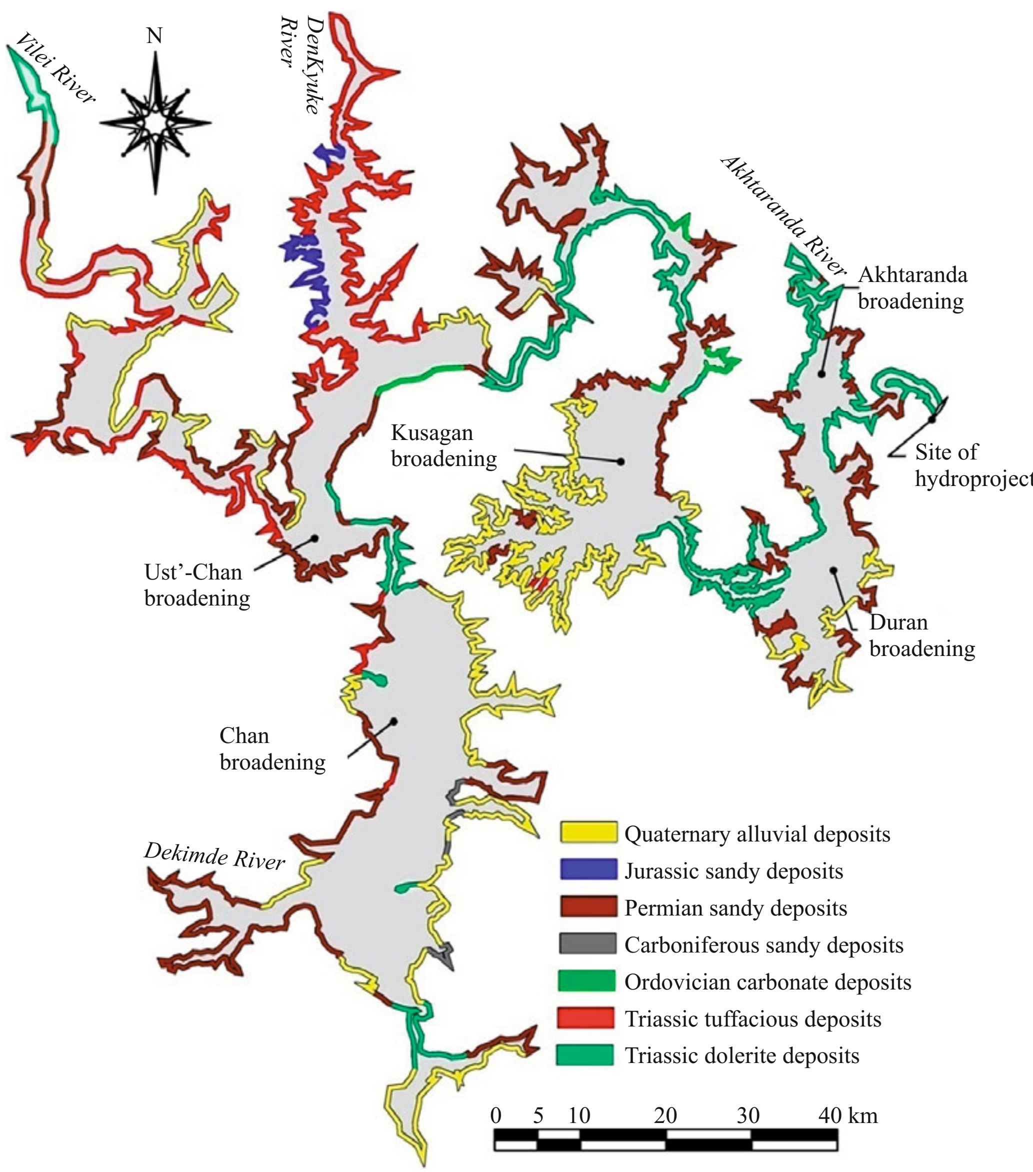

Fig. 3. Diagram showing geologic structure of banks along Vilyui Reservoir.

TABLE 1. Indicators of Banks Along Vilyui Reservoir After Decade of Normal Service Based on VPSRS Data [4]

Rocks comprising bank	Quaternary alluvial deposits	Jurassic sandy deposits	Triassic deposits: tufas	Triassic deposits: dolerites	Permian sandy deposits	Sandy deposits of Carboniferous Age	Ordovician carbonate deposits	Total
Shoreline expanse, km	814	22	400	455	583	45	57	Up to 2500
Characteristic slope of bank, deg	<5 and up to 10	5 – 10	15 – 20 and more	5 – 10	5 – 10	10 – 20	—	
Expanse of scoured banks, km	50.3	3	12.5	86	55	3.5	2	320 (13 %)

connects the Duran and Kusagan broadenings, as in the majority of narrowings along the entire reservoir, is a canyon 300 – 500 m wide, which cuts into the traprock plateau. The majority of the banks are steep with large-lump talus, and are frequently vertical. On the surface, the bedrocks (dolerites) are weathered, jointed, and weakly resistant to mechanical action (Fig. 1).

Over a large portion of the length, the shore slopes of the reservoir in the zone of water-level fluctuation have thin Quaternary deposits of alluvial-deluvial origin, which are underlain by bedrocks (Fig. 2).

Sloping banks (1 – 6°) are spread over all broadenings of the reservoir, and are confined to outcropping sections of Permian sands and weakly cemented sandstones. Drainage is good despite the shallow slopes. They are covered by a deciduous-coniferous forest.

Initial investigations of the banks of the Vilyui Reservoir were conducted during its filling in the summer of 1968 by Shrokov [1]. In the Akhtaranda, Duran, Kusagan, Ust'-Chan, and Chan broadenings, the VPSRS station equipped 17 observation sections where bank reformation was measured with respect to profiles in 1972, 1978, 1982, 1983, 1984, and 1985). The banks were systematized with respect to geologic structure on the basis of a 1:100,000 topographic map, field investigations, and theoretical developments of Finarov [2] and Ermolaev [3] (Fig. 3), and standardized by type with respect to groups (neutral, thermodenudation, thermoabrasion, and thermokarsting), and their condition after 10 years of normal reservoir service was recorded (Table 1).

A thermoabrasion group of banks is observed in the lake-like broadenings of the reservoir, and is represented by the following types:

— collapsing-crumbling thermodenudation-thermoabrasion bank. Composed of weathered and jointed dolerites and tufas. Rocks are broken down by thermodenudation and are removed under wave action;

— collapsing-block thermoabrasion bank. Comprised of limestones, dolomites, and marls. Wind-driven waves scour the rocks that have thawed directly in the zone of action; and

— collapsing-crumbling thermoabrasion bank. Composed of Jurassic, Permian, and Carboniferous sandstones, and upper-terrace alluvium. The deposits exhibit high mechanical strength. They are thawed by the thermal energy of the water, and are then mechanically broken down by waves [4].

In August – September 2011, the Nizhny Novgorod State Architectural and Civil-Engineering University (NSACEU) performed an expeditionary series of instrument measurements of bank profiles in Sections No. 1 – 7, which made it possible to continue the series of bank-reformation parameters previously observed. Characteristic examples of development of thermoabrasion banks of the reservoir in these sections are cited below.

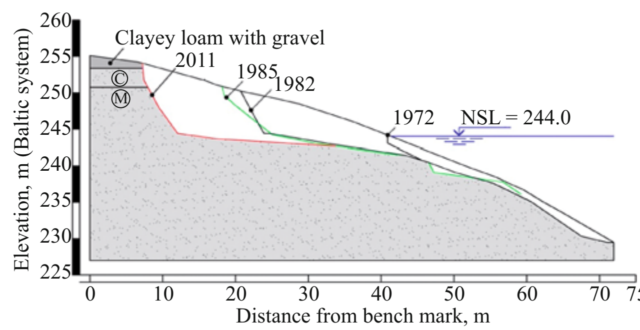

Fig. 4. Observed bank profiles in Section No. 2 at Site No. 1 in Duran broadening of Vilyui Reservoir: NSL, normal support level.

Section No. 2 of the former VPSRS in the Duran broadening. Exposure of the slope varies from south to southwest, and the steepness ranges from 26 to 16°. The collapsing-crumbling thermoabrasion bank is comprised of Permian-age sandstones and sands. The mean annual wave energy is 240,000 kJ/year per running meter of bank. Six observation sites are noted in the section. Data for Site No. 1, which was reestablished in 2011, are presented in Fig. 4 and Table 2.

Section No. 5. Situated is on the right bank of the Duran broadening. The slope has a southwestern exposure, and its steepness is 7°. The bank is comprised of yellowish-grey, fine-grain, well-graded sands: collapsing-crumbling thermoabrasion. The mean-annual wave energy is 631, 040 kJ/year

TABLE 2. Characteristics of Bank Reformation at Vilyui Reservoir in Section No. 2 at Site No. 1.

Years of observations	Recession of brow of bank		Volume of scoured rock	
	m	m/year	m^3	m^3/year
1972 – 1978	15.24	2.54	2525.4	420.9
1978 – 1982	6.14	1.54	1694.7	423.6
1982 – 1985	2.7	0.9	607.9	202.6
1985 – 2011	11.7	0.45	4655.3	179.0
1972 – 2011	35.78	0.91	9483.3	243.1

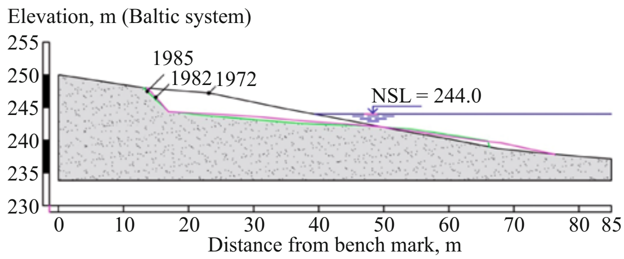

Fig. 5. Observed profiles of bank in Section No. 5 at Site No. 1 in Duran broadening of Vilyui Reservoir: NSL, normal support level.

TABLE 3. Characteristics of Bank Reformation of Vilyui Reservoir in Section No. 5 at Site No. 1

Years of observations	Recession of brow of bank		Volume of scoured rock	
	m	m/year	m^3	m^3/year
1972 – 1982	9.03	0.9	2169.6	216.9
1982 – 1985	0.56	0.28	338.1	112.7
1985 – 2011	4.94	0.19	1235.0	47.5
1972 – 2011	14.53	0.37	3742.7	95.9

per running meter of bank. In the section, there is one observation site; measurement data acquired at this site are presented in Fig. 5 and Table 3.

Section No. 6. Located on the right bank of the Kusagan broadening near the “Kusagan” hydrometeorological station (Fig. 6). The bank with a northerly exposed slope and steepness of 1 – 6° is composed of fine alluvial sand, and is collapsing-crumbling thermoabrasion. The wave energy is 247, 960 kJ/year per running meter. Bank profiles were measured with respect to five cross sections. The results are presented in Fig. 7 and Table 4.

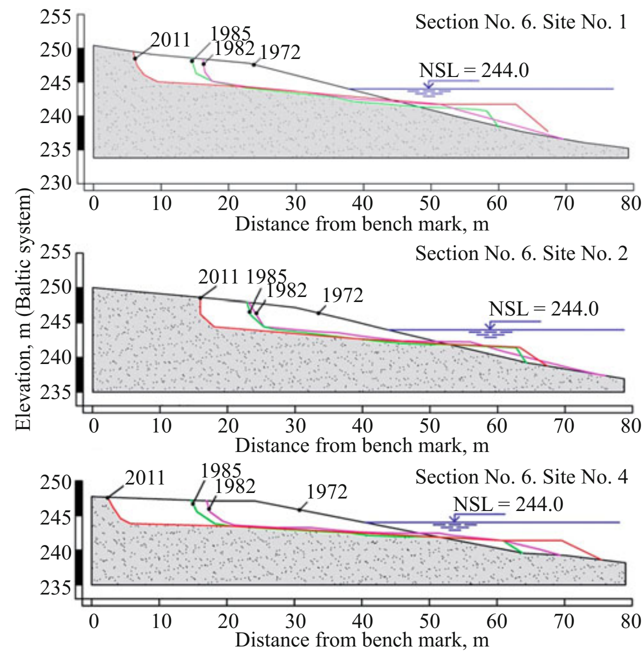

Fig. 7. Bank profiles observed in Section No. 6 at Sites 1, 2, and 4 in Kusagan broadening of Vilnyi Reservoir: NSL, normal support level.

Section No. 7. Located on the right bank of the reservoir near the mouth of the Ust’-Chon “pipe” (Fig. 8). The slope has a southwestern exposure and its steepness increases from 5 to 11° from south to north. The bank is composed of highly weathered limestones and sandstones (Ordovician carbonate rocks), and is collapsing-lumpy and thermoabrasion. In the section, there is one observation site, data from which are presented in Fig. 9 and Table 5.

Fig. 6. Thermoabrasion right bank of Vilyui Reservoir at Section No. 6 in Kusagan broadening; bank is composed of fine sands.

Fig. 8. Thermoabrasion right bank of Vilyui Reservoir in Section No. 7 near mouth of Ust'-Chon "pipe" composed of highly weath-

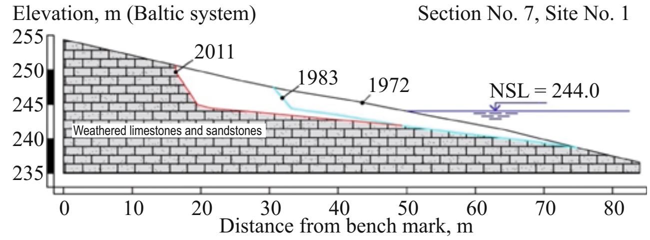

Fig. 9. Bank profiles observed in Section No. 7 at Site No. 1 near mouth of Ust'-Chon "pipe" of Vilyui Reservoir: NSL, normal support level.

It follows from the data presented (see Tables 2 – 5) that the average rate of failure of the thermoabrasion banks of the reservoir during a long period of service (1972 – 2011) ranged from 0.35 to 1.41 m/year.

The thermoabrasion process in Section No. 6 with an observed pattern of bank-brow recession rate typical of the Vilyui Reservoir (Fig. 10) will be subject to analysis and prediction. Numerical-analytical [5] and adaptive [6] methods of analyzing reformation of the thermoabrasion banks of the reservoir, which were developed at the VPSRS were verified on the basis of field data acquired from this section. Figure 11 shows the result of adaptive modeling of bank reformation in Section No. 6. The adaptive model of the dynamics of the process in the section is compiled on the basis of linear, polynomial, and logarithmic trends with the following set of weighting factors for quality of the approximation: 0.307, 0.368, and 0.325. The result of the prediction definitely indicates continuation of slowing of the rate of thermoabrasion as the length of the bank shoal increases (under steady climatic conditions). Where in the course of the

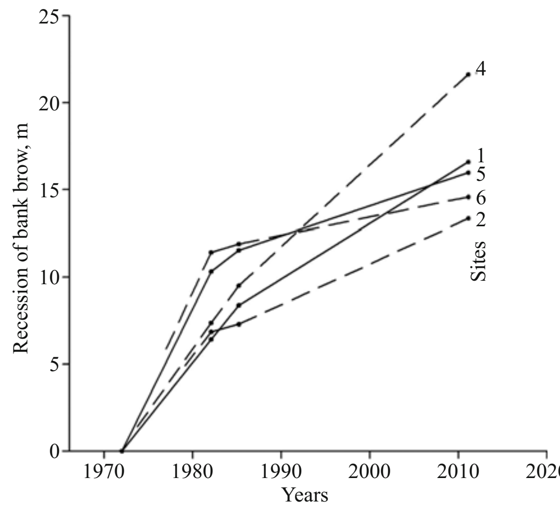

Fig. 10. Plots showing observed recession of brow of thermoabrasion bank of Vilyui Reservoir at Sites No. 1 – 6 in Section No. 6.

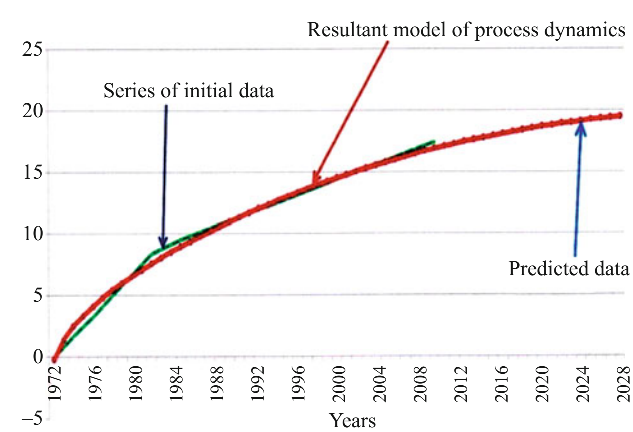

Fig. 11. Adaptive model of dynamics of brow recession of thermoabrasion bank of Vilyui Reservoir in Section No. 6.

TABLE 4. Characteristics of Bank Reformation of Vilyui Reservoir in Section No. 6 at Sites No. 1 – 6

Site	Years of observations	Recession of brow of bank		Volume of scoured rock	
		m	m/year	m^3	m^3/year
1	1972 – 1982	6.55	0.65	2083.1	208.3
	1982 – 1985	1.72	0.57	406.4	135.5
	1985 – 2011	8.3	0.32	1211.8	46.1
	1972 – 2011	16.57	0.42	3701.3	94.9
2	1972 – 1982	6.81	0.68	1931.5	193.1
	1982 – 1985	0.23	0.07	404.8	134.9
	1985 – 2011	6.85	0.26	976.2	37.5
	1972 – 2011	13.89	0.35	3312.5	84.9
4	1972 – 1982	7.1	0.72	2367.1	236.7
	1982 – 1985	2.3	0.76	614.6	204.8
	1985 – 2011	12.3	0.47	1747.8	67.2
	1972 – 2011	21.7	0.55	4729.5	121.2
5	1972 – 1982	10.13	1.02	3376.9	337.7
	1982 – 1985	1.21	0.4	421.5	140.5
	1985 – 2011	4.66	0.18	1770.6	68.1
	1972 – 2011	16.2	0.41	5569.0	142.7
6	1972 – 1982	11.22	1.12	2931.3	293.1
	1982 – 1985	0.55	0.18	419.6	139.8
	1985 – 2011	2.83	0.11	1541.8	59.3
	1972 – 2011	14.6	0.37	4892.7	125.4

past 25 years (1985 – 2011), the average recession rate of the brow of the bank was 0.32 m/year in a section, it is expected to be 0.24 m/year in the next 20 years.

CONCLUSION

For the insignificant expanse of scoured banks (over 13% of the length o the shoreline (Table 1), bank reformation at the Vilyui Reservoir will not result in an essentially significant change in the area of its water surface over time. However, study of thermoabrasion of the banks of the Vilyui Reservoir — the first of the large-scale reservoirs impounded in the cryolithozone — assumes scientific and practical significance for assurance of the ecological safety of artificial water bodies during advancement of water-power and water storage construction in northeastern Russia.

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