Assessment of Geoecological Processes of the Volga River Shoreline on the Territory of the Saratov Reservoir

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Abstract: The article analyzes the current geoecological state and gives an assessment of the conditions for the development of hazardous natural processes in the shoreline area of the Saratov reservoir. As a result of the monitoring, it was established that the geological structure of the shoreline area of the reservoir is complex. Tectonic instability of the earth's strata in the area under study can lead to unpredictable consequences, which requires the implementation of bank protection measures.

Keywords: Saratov reservoir, shoreline area, shoreline geoecological processes, geoecological risk, riverbank protection.

Introduction

The Saratov Reservoir is a valley-type flatland body of water within the Volga-Kama reservoir cascade lying within the Samara, Ulyanovsk and Saratov Regions. The reservoir surface total area in flooded condition exceeds 1,950 sq.km, its average area being 1,728.5 sq. km, its volume ranging between 10.04 and 13.4 cub.km, its length reaching 357 km during the overflow stage and maximum width achieving 14.5 km, while its average width and maximum depth are 5.1 km and 35 m respectively.

The Saratov Reservoir construction started in November 2, 1967 when the Volga river was dammed near Balakovo town. The reservoir was filled in two stages: that of the November-December of 1967 when the Volga River surface was elevated above the natural level to achieve the +24 m mark, to be later on raised still 4 meters higher during the following year's flood period. The reservoir construction caused the water level of the upstream-located Volga Hydroelectric Station to raise 3 m above the low water one. Nowadays the reservoir normal water surface level exceeds the Volga pre-damming low water level by 13 m. This level has been established as the normal water surface (NWS).

The reservoir flooded such Volga tributaries as the Samara river, Sok, Chagra, Chapayevka, Bezenchuk, Bolshoy Irgiz and Syzranka, their lower reaches forming the reservoir's bays [1].

The reservoir provides limited daily and weekly flow control. By its hydrographical appearance the Saratov Reservoir belongs to the single-reach type. The reservoir is distinguished by morphological and morphometrical complexity brought about by its planimetric configuration combining both large lacustrine-type expansions and elongated narrow stretches of considerable length bending at some points in nearly 90° corners, as well as vast shallow water areas in the reservoir's central and left-bank parts.

The Saratov Reservoir can be divided into three areas each having its distinctive scope of morphological features and hydrographical regime peculiarities, namely: the lower (lake) one, the middle (lake-river) one and the upper (river) one. The lower area stretches from the hydroelectric station dam to the reservoir's narrowed part in the vicinity of the Samara Region's Ekaterinovka settlement. It features 95 km navigable length and 695 sq. km surface area. The middle area with its 70 km navigable length is confined to the section between Ekaterinovka settlement and Oktyabrsk town. The upper area expands from Oktyabrsk town to the Samara Hydroelectric Station dam, thus having the navigable length of 176 km.

The key determinants for the lake area shoreline transformation are the reservoir's water level, wind and wave regimes throughout the navigation season. The reservoir's minimum wave length fluctuations are 0.6-0.8 m.

The reservoir construction has drastically changed the Middle Volga valley bottom landscape. One of the most prominent outcomes of the reservoir formation are the the abrasion activities and the resulting landslides and other slope-related processes [2].

These days witness intensive utilization of the reservoir's shoreline area by residential, recreational, agricultural and fishfarming facilities boosting the geoecological situation changes and entailing various deformations and even total destruction of the existing installations. The riverbank deterioration renders the shoreline areas permanently unavailable for utilization and prone to accidents resulting in human casualties and significant economic damage [3]. All this emphasizes the urgency of ecological risk assessment including quantitative estimation of the destruction caused by wave processes, landslides and rockfalls, as well as by waterlogging brought about by flash floods. Such assessment is aimed at development of the preventive activities intended to decrease the shoreline's transformation by the processes described above, as well as at solving crucial geoecological issues.

Materials and Methods

The study is intended to evaluate the conditions for the development of hazardous natural processes in the Saratov reservoir area by the geoecological risk level.

This objective was addressed with a series of field and desktop geoecological researches studying the Saratov Reservoir shoreline area within the vicinity of Balakovo town including the nuclear power station dam and of Volsk District's Shirokiy Buerak settlement. The Saratov Reservoir shoreline was examined in cooperation with the Volgageologia Federal State Unitary Geological Enterprise Saratov Hydroecological Expedition.

The reservoir shoreline survey route was plotted according to 1:50000 scale European Russia's Unified Deep Water System Atlas (volume 6). The survey team was transported by UAZ PATRIOT motor car, Progress motor boat and Yaz inflatable boat. The visual evaluation of stationary surveillance by moving on foot along the shoreline scarp was performed to describe the reservoir banks, encroached and widened tributaries' mouths, walls of large ravines and minor caves, detect and measure the cliff, scree and beach, register the new crevices along the scarp crest, describe the rockfall forms and scree erosion patterns. A routine geotechnical examination of landslide formation area was performed in the vicinity of the Saratov Region Volsky District Shirokiy Buyerak settlement.

The examination included evaluation of the landslide trends on the slopes and detailed description of both activated old deformations and newly emerging ones. Alongside with that efforts were made to describe manifestations of other economically significant locations which may affect landslide processes.

The cross-sections of the plotted combined profiles provided such morphometric quantitative data on the scarp as: linear terrace edge failure, dissociated rock volume, abrasion scarp distance and beach width. Examination of the underwater part yielded the quantitative details of the submerged shoal profile, namely its width, steepness, front edge, type and formation dynamics.

The summer (first) scope of stationary surveillance monitoring transformation of the reservoir left and right banks became the principal activity for obtaining from the earlier established cross-sections (benchmarks) of the main shoreline erosion parameters, namely linear and volumetric erosion values. These studies also revealed the parameters of the submerged shoal.

The second surveillance series took place in November of 2020 and covered a number of the Saratov Region shoreline areas where several bottom measurements are insufficient to identify the parameters of the submerged shoal due to the latter's extensive width (over 100 m). In summer the river bottom at such areas was measured up to the +26.0 mark, i.e. 2 m below the NWS.

It is worth mentioning that the measurements performed within the autumn scope of surveillance studies ensure comprehensive profiling of the shoreline area and identifying the trends of the bottom processes, which is due to the lower water level as compared to spring. Apart from that the second surveillance cycle enables detection of the reservoir's bank scarp absence during the autumn gale period.

The primary processing of the field data obtained by the surveillance was instrumental in plotting of combined profiles by cross-sections which included the results of the initial cycle of surface and underwater measurements of the shore and bottom. Failures to recover a survey stake which had been installed in the summer of 2020 were addressed by laying out the relevant cross-section anew in the spring of 2021 to enable plotting of combined profiles.

Findings and Discussions

Surveying of the reservoir's shoreline areas resulted in identification of types and manifestation modes for abrasion, erosion, landslides and other exogenous processes, as well as in more detailed definition of the abrasion scarp's lithologic composition for a number of locations and cross-sections.

The Saratov Reservoir shoreline's distinctive peculiarity consists in the diversity of stratigraphical lithological and genetical types of bank-forming rocks (semi-rock and sandy-clay varieties of Carboniferous, Jurassic, Cretaceous, Neogene and Quaternary ages). There are also differences between the geomorphological conditions of the right and left banks of the reservoir. The physical, chemical and mechanical properties of rocks belonging to different ages bring about the difference in the types of shoreline transformation processes. Reservoir shoreline transformation is intended to signify their destruction by a scope of exogenous geological processes (shoreline erosion, landslides, screes, rockfalls, ravine formation, etc.) resulting from construction and usage of water reservoirs [4].

In morphostructural attitude the right bank terrain is distinguished by large latitudinal steps forming its structure, the most prominent being the upper step featuring the absolute elevation of 130-210 m and two lower ones with the elevations of 90-120 and 50-80 m. The low left bank is recognizable for presence of multiple fragments of multiple-aged Volga terraces. The processes playing the most significant part in shaping the Saratov Reservoir's bank scarps are: alluvium accumulation, wave abrasion, underflooding, landslides and ravine erosion [5].

The Saratov Reservoir right bank has been found highly prone to rockfalls and landslides which destroy the shoreline areas favorable for land development and forests, deform and destruct installations located thereon, and impede large-scale construction of residential, industrial and recreational facilities. The multiple-area landslide cirques virtually cover the whole shoreline area between the Saratov Hydroelectric Station dam and the city of Syzran, which makes about 140 km. The scale of the reservoir shoreline transformation is shown in Table 1.

The shoreline section between the Saratov Hydroelectric Station dam and the city of Syzran can be conventionally subdivided into two landslide-prone regions, namely the reservoir lake area landslide-active region and reservoir lake-river area landslide-active region.

The reservoir lake area landslide-active region stretches over 90 km from the Saratov Hydroelectric Station dam to the Agrafenovskaya mountain, wherein relative landslide safety is demonstrated only by the Alekeseyevka-Khvalynsk shoreline section. The region features significant complexity due to its rugged terrain, high degree of separation and presence of variable-sized landslide cirques. The region's generally unfavorable geotechnical

TABLE 1.
The Saratov Reservoir Shoreline Transformation Dynamics

Item #	Shoreline type	Location	Shoreline length, km		Area lost due to riverbank failure, ha	Total scope of shoreline destruction, MM cub.m	Linear erosion, m	
			Total	% of total shoreline			average	maximum
1	Abrasion landslide	Shirokiy Buerak, Merovka, Khvalynsk, B. Fedorovka, Agrafenovsky land plot, Ershov, Cherny Zaton, Obraztsovoye, Kashpirka Mouth land plot, Semyonovka (Kashpir), Novokashpirsky, Syzran	43.0	5.0	105.4	7.7	24.5	59.5
2	Abrasion rockfall	Perevoloki, Pecherskoye, Pervomaysky, Oktyabrsk	146.5	16.9	51.3	4.1	3.5	7.0
3	Abrasion rockfall and scree	Alekseyevka, Ivanovka, Davydovka, Fedorovka, Privolzhye, Sofyino, Ekaterinovka, Vladimirovka, Krasnoyarsky plot, the M. Irgiz river mouth, Nizhneyablonovsky	184.2	21.3	1160.5	63.6	63.0	122.5

environment is further aggravated by large ravines headed with terrain formations which explicitly manifest landslide nature. The geological structure is formed by Lower (less frequently Upper) Cretaceous and Quarternary deposits.

The 3 km long shoreline strip from the Saratov Hydroelectric Station dam towards Shirokiy Buyerak settlement features abrasive nature while the shoreline immediately belonging to the settlement area demonstrates abrasive-landslide nature. The bulk of the ancient landslide incorporates more recent slumps and minor landslides with front width ranging from 30 to 50 m, and an active landslide can be clearly seen 500-700 m downwards of the ravine mouth whereupon three landslide terraces are clearly identified.

The upper part features overturned appearance, the rocks are deconsolidated, and there is an abundance of hydrophilous vegetation along the inner margin. The base of the second landslide terrace was found subject to waterlogging. The lower landslide terrace is subject to intensive wave wash erosion, with an abrasion undercliff up to 1 m high formed in the front part. Erosion of the lower landslide terrace lead to destabilization of the entire landslide body.

Upstream, within the territorial limits of the Shiroky Buerak settlement, the slope is affected by an extensive landslide cirque with the length of the landslide along the displacement axis reaching 350-360 m, the width of about 2,100 m, and the total area of the displaced rock of approximately 650,000 sq.m. On the slope, there is the so-called "drunken forest" (a stand of trees displaced from their normal vertical alignment towards the slope) featuring breaks in tree trunks, large cracks along the trunk, as well as an inclined position (noticeable deviations from the vertical) of the pillars of various service lines. In addition, the houses and fences located in the vicinity are also slightly inclined. The survey of the river banks revealed cracks in the blind area and on the edge of the slope, and the formation of undercliffs (terraces) and soil mounds in the lower zone of the slope, as well as a noticeable increase in the humidity at the slope base leading to area swamping and the emergence of springs under the slope.

The conditions and reasons for landslide formation are complex and diverse. The main contributing factors include high altitude and steepness of bank slopes and of the slopes of large ravines; geological and hydrogeological conditions of the shoreline, and the anthropogenic impact which increased significantly after the water reservoir was established.

Examination of the Nuclear Power Plant dam revealed that the site is located on the surface of an artificial sand ridge which separates the closed reservoir of the Balakovo Nuclear Power Plant from the Saratov Reservoir. The length of the dam section along the shoreline is 6 km. There is a road going along the cooling pond on the left side of the sand ridge, and the inner part of the ridge facing the pond is reinforced with a concrete slope and a retaining wall. The width of the ridge is about 30 m. Towards the reservoir, the ridge is covered with gravel and rises over the 3 meters long underlying artificial floodplain section of the bank, to which it descends at an angle of 30-45 degrees. The floodplain shoreline section has a length of 80 to 120 m, and at the moment it is densely overgrown with trees and shrubs, namely, poplar, willow, and elk trees. There is also a sandy opening 5 to 7 meters long in front of the water line.

The bank erosion at the dam site was studied along 8 fixed sections oriented towards the reservoir. For sections No.1-6 the average annual retreat of the edge of the artificial sand ridge ranged from 0.0 m for section No. 1 to 2.3 m for section No. 3 in 2020–2021, whereas the erosion ranged from 0.03 to 2.5 cub. m per 1 running meter of the shore. It must be mentioned that both the retreat of the shoreline and the erosion rated almost zero in the above-mentioned time interval. This might be accounted for by the fact that the sloping sandy floodplain is overgrown with trees and shrubs that formed an insurmountable barrier for the exogenous processes of abrasion and ashing activity of the wind.

The northern part of the site near cross-sections No. 7 and 8 has retained a bank section featuring discernible abrasion. The retreat of the coastal strip ranged from 26.75 m to 33.35 m (section No. 7), and up to 24.5 m (section No. 8), which makes an average of 2.2-2.8 m per year. It should be noted that the average annual retreat of the edge in this area ranged from 1.5 to 2.6 m, and from 2.9 to 3.7 m in the spring of 2021, which indicates a clear acceleration of the shoreline retreat. In addition, there is a number of residential and industrial buildings, as well as forests located in the area of potential collapse along the Berezovka River which flows into the Volga near the Nuclear Power Station dam.

Assessment of the reservoir water level's weekly dynamics demonstrated that the inflow to the Saratov node is higher on weekends (Saturday-Sunday) relative to other days. There could be two factors contributing to the phenomenon: the amount of water discharged from the top of the Zhigulevskaya Hydro Power Plant, and lateral inflows from small rivers. The total average inflow is 28,575 cubic meters per second.

The analysis of the shoreline profiles of the Saratov reservoir enables evaluation of the undercliff erosion intensity, as well as the dynamics and increase in the riverbed-forming processes on the underwater horizon. Shoreline erosion is understood as the retreat of the banks of an artificial reservoir inland as a result of hydrodynamic impact brought about mainly by wind waves. Table 2 presents the data on shoreline erosion in the areas under survey.

The indirect environmental impact of abrasion is likely to include the activation of slope processes virtually bound to be accompanied by the retreat of cliffed (rocky) shores. Erosion of the cliff base by waves inevitably entails the development of rockfalls, talus or landslides (depending on the geological structure of the undercliff) that significantly increase the rate of shore retreat. In this case, the influence of abrasion on human activities is manifested through slope processes that impede the development of shore slopes and pose a threat to the erected buildings.

It is imperative to reduce the speed of abrasive processes and prevent the erosion of the shoreline area with bank protection works. Today there are a large number of bank protection methods with different designs and materials used depending on the purpose and local hydrotechnical situation. The highest practical expediency is offered by bank reinforcement with supports. This method involves implementation of well-compacted gravel with a layer thickness of about 15 cm or a mixture of concrete and stones. A retaining wall over one meter high will take the load of the soil and water behind it. Since the soil is quite mobile near the body of water, the retaining walls must be mounted to a depth of 1.5 times greater than the width of the structure. Gabions are

TABLE 2.
The Saratov Reservoir Marginal Erosion Dynamics

Cross-section #	Monitoring period	Lithologic composition	Marginal erosion parameters															
			Scarp height, m as of 2020/2021	Shoreline retreat, m					Erosion volume, cub.m/running m					Shelf parameters				
				for 2000	2020–2021	since the beginning of monitoring	monitoring period average	2020-2021 average	for 2020	2020–2021	since the beginning of monitoring	monitoring period average	2020–2021 average	width, m	depth at outer edge	Slope angle	
																	initial	2021
Shirokiy Buyerak settlement																		
1	2020	Loams, clays, siltstone	18.2/18.8	32.3	4.2	36.5	1.2	0.5	383.4	60.2	443.6	14.3	7.5	50	2.9	5°00'	1°30'
2	2020	Loams, clays, siltstone	19.8/19.9	21.1	1.8	22.9	0.8	0.4	127.0	–	127.0	4.5	0.0	40	3.0	3°50'	3°55'
3	2020	Loams, clays, siltstone	6.4/7.6	17.9	2.8	20.7	0.7	0.4	214.6	23.4	238.0	7.7	2.9	>38	2.5	2°20'	2°10'
Average for location				23.8	2.9	26.7	0.9	0.4	241.7	41.8	269.5	8.8	3.5				
Nuclear power station dam																		
7	2020–2021	Sands	3.0/3.0	18.8	14.5	33.3	2.8	2.9	55.0	40.0	95.0	7.9	8.0	>125	0.8	0°45'	0°30'
8	2020–2021	Sands	3.7/3.7	8.4	18.4	26.8	2.2	3.7	45.6	47.6	93.2	7.8	9.5	>105	1.3	0°40'	0°40'
Average for location				13.6	16.4	30.0	2.5	3.3	50.3	43.8	94.1	7.8	8.8				

often employed to fill the spans between the base plates, thus anchoring and ensuring additional strength. This technology supports the reservoir slope relief building and the landscape designing, thereby ensuring the safety of the water-adjacent territories.

Apart from the foundation, bank reinforcement procedures can use Reno mattresses, i.e. planar gabion structures made of double-twisted metal mesh with zinc or polymer coating. Internal diaphragms divide the structure into sections to ensure better rigidity. It must be noted that the strength and stability of these structures increase over years due to vegetation growing therein.

Bank protection can also be achieved by installing geogrids. This rigid plastic mesh structure has sufficient elasticity and resilience to compensate for the settlement of soft soil along river banks, as the material does not decompose and features resistance to aggressive chemicals, temperature changes and ultraviolet rays.

Another bank reinforcement method that is gaining increasing popularity is geotextiles, a non-woven fabric made from continuous polypropylene fibres (rayon). Due to its high chemical resistance and resistance to thermal oxidative aging, geotextiles are not subject to decomposition, fungi and mold, rodents and insects, and root germination.

Using PVC (plastic) sheet piles to reinfornce river, sea and reservoirs' shoreline is a relatively inexpensive, viable and reliable alternative. The service life of plastic piles is up to 100 years. The Larssen sheet pile is a steel sheet pile, a metal bar of the given profile used for ground penetration. Locks (piles) allow the profiles to be connected to each other. When immersed, each pile is turned over 180 degrees and locked to the previous one. The assembled structure is a sealed steel fence known as "a sheetpile retaining wall". In some cases, it is recommended to add a sealant to reduce filtration in the interlock space.

In addition to artificial materials traditional methods of bank protection with woody vegetation are of no small importance. This method is suitable not only technically and economically, but also in terms of aesthetics point of view as it does not infringe the natural landscape.

Yet another method is the bioengineering protection of the reservoir bank from erosion. The main concept behind the biological method, also referred to as the bioengineering method, is to use the natural ability of the soil to self-purify and protect its upper layer from erosion. A water protection zone is formed by grassing (sodding) the slope and shrub planting, as well as macrophyte planting in the near-water zone.

This technology has a number of advantages, namely it helps to consolidate the soil in the shoreline area and prevents erosion; forms a water protection zone in the shoreline area and contributes to the purification of polluted effluents; and improves the water quality in the body of water.

Conclusion

Geoecological monitoring has established that the shoreline area of the Saratov reservoir is subject to abrasion of landslide, rockfall or rockfall-talus nature. Therefore, an action plan has been developed to improve the geological situation of the Saratov reservoir to include the following steps:

1. determine the boundaries of water protection zones and shoreline protection zones, and comply with their protection regime;

2. establish a 20-meter shoreline strip of public water bodies;

3. remove industrial enterprises out of shoreline and water protection zones;

4. move garages and outbuildings out of the coastal and water protection zones and into the eastern residential area;

5. implement bank protection measures at the site of the Balakovo Nuclear Power Plant dam using stone-crushed structures which help protect the coastal line from erosion and purify the polluted water of the reservoir by filtering during wind surge and landwash.

In the areas of human settlements, the recommended solution includes the bioengineering protection methods due to their significant aesthetic advantage.

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