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Assessment of the landslide process intensity on the bank of the Kuybyshev Reservoir using instrumental methods

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Abstract. The aim of the work was to survey and monitor dangerous exogeodynamic processes on the shoreline of the Kuibyshev reservoir. Field instrumental studies were used as the main method, including topo-geodetic survey of key morphological elements of the slope with ground control points, video and photo recording of the processes. Since 2019, unmanned aerial vehicle surveys have been chosen as the main method of research. The paper presents the results of long-term studies of the local landslide near Tetyushi, Republic of Tatarstan. As a result of 2003-2006 situational plans processing and results of UAV survey in 2019 quantitative data on the intensity of slope processes in the mass landslide were obtained.

1. Introduction

The creation of reservoirs leads to a fundamental restructuring of natural systems. The water runoff of the river, the flow of suspended sediments is changed, a special microclimate is created and shoreside landscapes are transformed. Abrasion and landslide processes increase their rate due to the large area of the water mirror [1]. This very complex relief-forming processes (together with erosion and gravity) usually is called reservoir bank transformation. Approximately 78% transformed shores of water reservoirs in Russia are destroyed by abrasion type, and the remaining 22% – by abrasion-slide, abrasion-karst and other types [2]. Almost all inherited (i.e. existing on the river banks before the creation of the reservoir) landslides after reservoir creation by an increase in displacement [3]. As a result of long-term observations, it was noted that landslide activation occurs with varying degrees of intensity and is often determined by the level regime of the reservoir. Subsequent long-term researches of landslide dynamics on reservoirs showed that in periods characterized by low water levels, landslide activity decreases [4]. But there is another point of view. For example, studies of the oldest landslide in one of China reservoirs [5] have shown that it activated after reservoir filling and landslide deformations are closely connected with water level fluctuations. However, subsequent observations revealed that the deformations were more closely related to the reservoir level lowering than to its raising.

The study of landslides all over the world is an urgent problem due to their high catastrophic nature, leading to huge social and economic losses, deterioration of engineering and geological conditions of construction, facilities and land use management [6]. During the destruction of the shores, a large amount of sediment enters the reservoir. This leads to rapid siltation, depth reduction and deterioration of the ecological state of the reservoir.

The object of the study is Kuybyshev Reservoir – one of the largest reservoirs in the world. The research is focused on abrasion and landslide processes as the most significant by area and intensity of bank transformation. The development of abrasion and landslide slope processes near settlements often leads to emergencies related to the destruction risk of buildings, structures and communications, disturbance and withdrawal of agricultural and other lands from land use. Therefore, it is necessary to develop effective methods of monitoring of these dangerous exogenous processes.

In Russia, study of bank transformation is a very topical task due to the large-scale construction of hydroelectric power plants on large rivers in the European part of Russia and Siberia in the first half of the XX century. Specially equipped monitoring stations and test sites were set up and observations were made.

Currently, there is a large set of methods for measuring and evaluating the intensity of exogenous processes. One of the most widely used and well-known methods of landslides monitoring is ground survey with total stations. The use of permanent reference points, on the basis of which the base station is positioned, makes it possible to measure the dynamics of the landslide process with millimeter accuracy. The advantage of this survey method is high accuracy, the disadvantage is that the survey takes a long time; hence a limited number of points located in accessible places can be surveyed.

None of classical methods gives comprehensive information about quantitative characteristic and mechanism of dangerous processes on slopes [7,8]. The most effective methods for studying landslide processes are the methods providing modelling of relief of inaccessible landslide areas, and possibility to carry out repeated survey through precise georeferencing of multitemporal data.

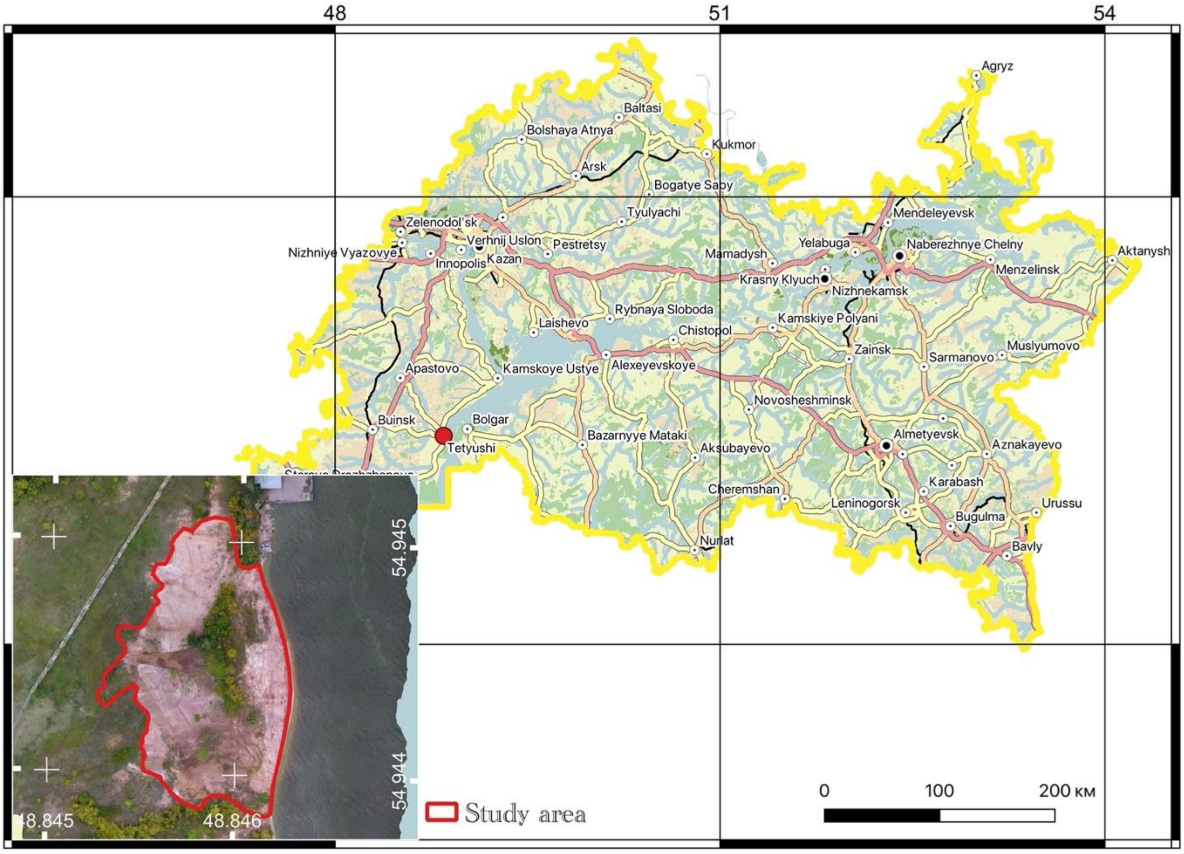

Figure 1. Study area.

Among all modern technics of exogenous processes monitoring, methods using unmanned aerial vehicles are rapidly developing. The possibility of obtaining three-dimensional (3D) information about terrain with high accuracy and high spatial resolution provides new horizons for studying landslide processes [9]. The use of modern global navigation satellite systems (GNSS) receivers for registration of ground points and new GNSS drones allows to reach the georeferencing error not exceeding 3-5 mm in height which is more than enough for the tasks of terrain modelling of intensively developed coasts.

The paper shows the results of the assessment of the intensity of abrasion and landslide processes on the site located on the right bank of the Kuibyshev Reservoir near the pier of Tetyushi (Republic of Tatarstan) (figure 1). In the XI-XIV centuries Tetyushi was one of the cities of the Volga Bulgaria [10], and then the Bulgar ulus of the Golden Horde, the archaeological remains of which are located within the modern city. The emergence of the settlement on this cape was also related to the presence of a water source nearby.

The city is located in the depression between two massifs of the middle plateau of the right bank of the Volga. This depression is associated with Pliocene valley of one of the upper parts of the Ulema River (right tributary of Sviyaga), cut by the Volga slope in the process of its retreat to the west. The Volga slope near Tetyushi reaches 90 m in height with steep (up to 25-30 degrees) slopes. Such heights, interrupted by gullies, have a mountainous nature, which is reflected in the local titles (Tetyushi Mountains).

The main geological attraction of Tetyushi is the development of well-defined linear folds in the upper part of the Permian system, which has long been studied, and their origin has been discussed by scientists for many decades. The steepness of the Volga slope also caused intensive development of slope gravity processes of landslides, as well as rockslides and scree. Especially widespread are landslides of different types that endanger certain structures in the coastal part of the urban development. In 2002, a large landslide happened here (figure 2), which led to interest in the study of this slope.

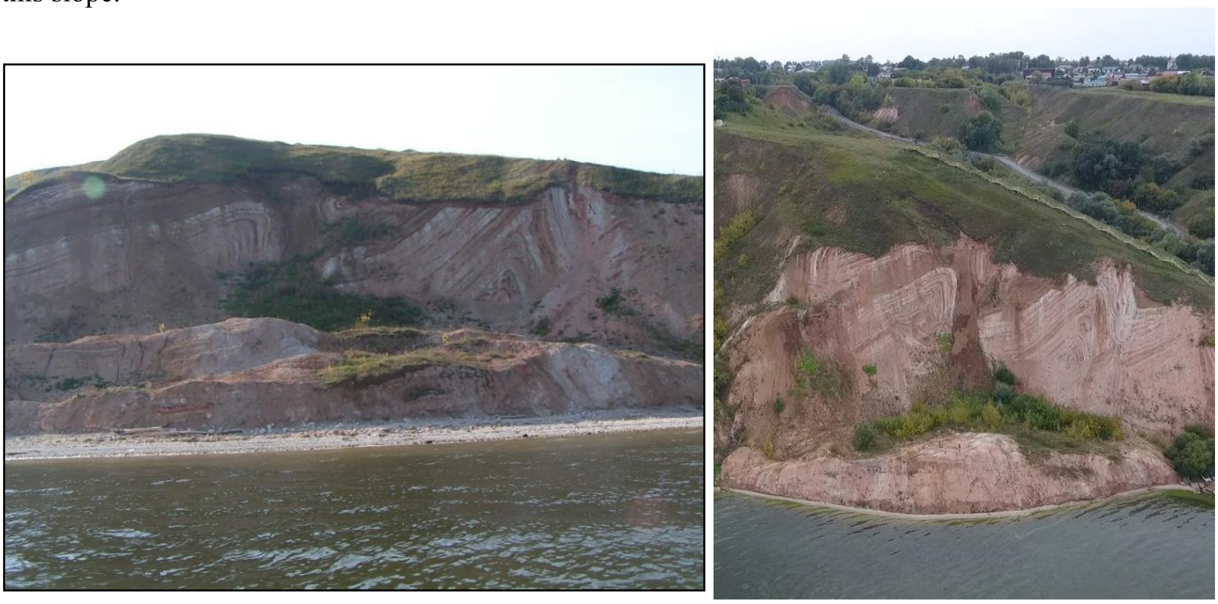

Figure 2. An observation site in 2006 (left) and 2009 (right).

2. Materials and methods

A variety of information sources and observation methods were used to assess the intensity of abrasion and landslide processes on the reservoir shores. Analysis of the landslide scarp displacement was chosen as the main method to study the shore transformation. In 2002, 2003, 2005, and 2006, a topographic survey was made in a relative coordinate system. To ensure repeatability of the survey, a reference point network was created, on the basis of which the positioning was carried out. The coordinates of the reference points were determined with a Trimble M3 total station, which ensured high accuracy of the repeated survey results referencing.

Since 2019, a DJI Phantom 4 unmanned aerial vehicle (UAV) has been used to survey the site. The survey was performed using ground control points. Their position was obtained using the Emlid Reach RS+ GNSS receiver working in real-time kinematic mode from a base station located no more than 20 km away. UAV control and surveying was performed in automatic mode by loading the flight task into the instrument controller [11]. The flight task included such parameters as instrument flight height from the takeoff point, percentage of images overlap. In order to carry out works on landslide assessment with the UAV according to the annual monitoring data, the flight height should be 100-150 m for the vehicle with the installed camera with a resolution of 12 megapixels, the images overlap should be 65-75% [12]. Specified parameters obtain 5 cm spatial resolution, which is more than enough for registration of even insignificant changes.

The Digital Shoreline Analysis System (DSAS) as an extension module of ArcGIS software was used to quantify planar displacements of the landslide boundary line.

Based on the comparison of shoreline positions, a number of statistical measures of shoreline change are compiled: shoreline position change (NSM), shoreline change envelopes (SCE), endpoint rate (EPR), linear regression rate (LRR), and weighted linear regression rate (WLR) [13]. This module is effective for simplifying the analysis of shoreline position changes [14].

A geodatabase was created in ArcGIS and the shorelines were entered into it. The line of the 2003 landslide scarp boundary was taken as a baseline. The following parameters of the transect-sections were selected: distance between transects - 1 m, search radius - 300 m. Linear velocity indicators (m/year) were calculated in automatic mode.

3. Results and discussion

Due to the steepness of the studied slope and the clay-mergel composition of the deposits, a wide range of exogenous geodynamic processes (EGP) is active here (figure 2). Along the outcropped steep ledges of the coastline, the soil is crumbling and collapsing. However, a complex set of landslide processes dominates. A large body of an old landslide from 2002 were observed at the bottom of the slope. Analysis of the combined 2003, 2005 and 2006 toposchemes showed, that in comparison to 2003-2005, when the shoreline had retreated by 1 to 6 m, in 2005-2006 the shore had moved by a very small distance, 0.5-1 m. The average shoreline retreat rate near the Tetyushi pier during the monitoring period was between 0.5 and 2 m/year. Land loss rates in the Tetyushi pier section decrease from 1,798 m^2 in the year of the landslide, to 208 m^2/year between 2003 and 2005, and finally to 31 m^2 in 2006. The land loss rate for 2019 was 820 m^2 over 13 years, or 63 m^2/year, which means that the landslide site, in general, reduce the intensity of land loss.

Combining the 2019 UAV orthophoto with observations from 2003-2006 (figure 3A) provided a geodatabase of the upper boundary of the landslide retreat scarp, which was used to calculate changes in the landslide scarp retreat rate (figure 3B). Comparison of the multi-temporal slices showed a trend of slowing average landslide scarp retreat rates – for example, from 2003 to 2005, the average retreat rate was 0.98 m/yr, decreased to 0.75 m/yr by 2006, and further decreased to 0.48 m/yr by 2019. Estimating area changes per year, the denudation rate was 0.87 m^2/m/year between 2003 and 2005. In the following period, the landslide velocity decreased to 0.24 m^2/m/year and increasing slightly to 0.37 m^2/m/year in 2019 (table 1).

The reduce in the intensity of landslide development is also confirmed by the dynamics of the average scarp retreat – 2 times from 2003-2005 period – to 0.44 m/year by 2019. As well, the rate of scarp maximum retreat from 3.22 m/year to 1.53 m/year by 2019 has proportionally decreased.

The old landslide body of is degraded by the action of waves and the ground masses move down the abrasion scarp with a height of 3-4 m. The steepness of the slope is 40-80 degrees. According to the field data, the scarp edge has shifted towards the reservoir as a result of landslide body washout. The products of abrasion processes are transported into the reservoir and accumulated and formed a coastal shoal at the abrasion scarp foot.

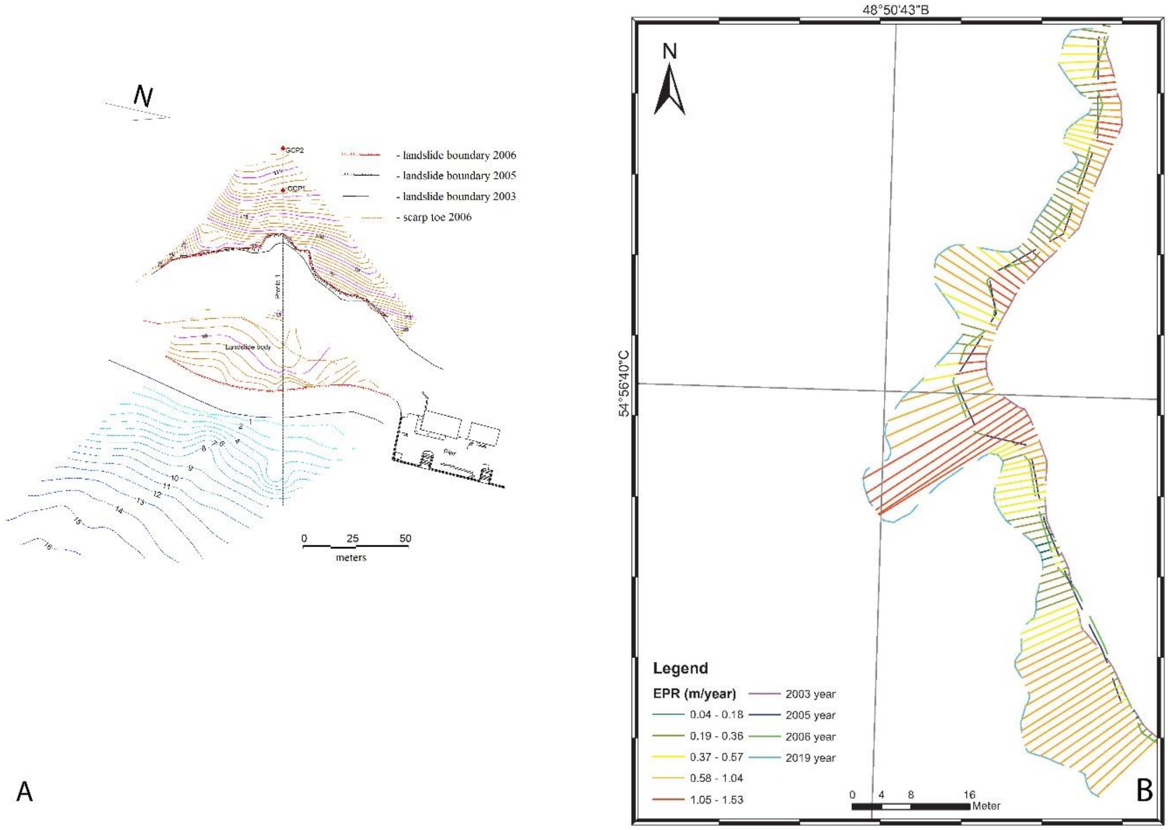

Figure 3. The results of the total station survey in the 2003-2006 period (A) and measurements of landslide slope retreat rates in 2005, 2006 and 2019 (B).

Table 1. Indicators of landslide slope dynamics in the study area.

Indicators	Period		
	2003-2005	2005-2006	2006-2019
Area (m^2)	208	31	820
Area per unit (m^2/m/year)	0.87	0.24	0.37
Average retreat rate (m/year)	0.99	0.75	0.44
Maximum retreat rate (m/year)	3.22	2.20	1.53

4. Conclusion

The studies showed that the spatial dynamics of the landslide scarp boundaries in the studied area has a steady trend of decreasing retreat rate, which began in 2002-2006 due to gradual leveling of the slope profile after a large landslide that occurred in 2002 and relative stabilization of the slope processes. Nevertheless, new observations have shown that the slope is still not stabilized, keeping the potential for destruction.

Acknowledgments
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