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Using multitemporal remote sensing data for evaluation of the Kuibyshev reservoir bank transformation (Laishevo and Ostolopovo archaeological sites, Tatarstan, Russia)

Bulat M. Usmanov*[a], Iskander I. Gainullin[b], Konstantin A. Rudenko[c],
Artur M. Gafurov [a], Maxim A. Ivanov [a]
[a] Institute of Environmental Sciences, Kazan Federal University, Kazan, Tovarisheskaya st. 5, Russia 420097; [b]Autonomous Non-Commercial Organization "Scientific Research Rentre "Country of Cities", Kazan, 8 Marta st. 12, Russia 420029; [c]Kazan State Institute of Culture (Russian Federation), Kazan, Orenburg tract st. 3, Russia 420059

ABSTRACT

The paper presents the results of studies of medieval archaeological sites, the Laishevsky and Ostolopovsky settlements, and the Ostolopovsky hillfort, using multitemporal remote sensing data and modern field research methods. The studied sites are located in the zone of active bank transformation and have been destroyed since the creation of the Kuibyshev reservoir. To assess the dynamics of the coastline, multitemporal remote sensing data were used. Shoreline positioning for the historical period of the 1950s was interpreted from archival aerial images (Kazan University Library). 1975 satellite images obtained during the Corona reconnaissance space program KeyHole-9 Hexagon satellite (10.06.1975). For their georeferencing very high-resolution satellite images were used (2019). The maximum errors of georeferencing are less than 3 pixels for both sites. In 2018-2019, field surveys of the shoreline fragments at the Ostolopovsky and the Laishevskoe settlements were carried out in 2020 – at Ostolopovo hillfort placement. For field studies, a DJI Phantom 4 drone and GNSS receiver with real-time kinematic corrections were used. The Digital Shoreline Analysis System (DSAS), as an extension module of the ArcGIS software, was used to quantify shoreline displacement. Shoreline indicators such as linear retreat rate (m/year), shoreline displacement (m) were automatically calculated. A quantitative assessment of the Kuibyshev shoreline transformation makes it possible to evaluate the damage caused to archaeological sites and the risk of their further destruction.

Keywords: multitemporal remote sensing data, reservoir bank transformation, archaeological sites, UAV, DSAS, CHM

1. INTRODUCTION

Many studies deal with vulnerability[1,2,3], risk assessment[4,5], conservation strategies6, management[7], and sustainability issues[8], regarding the cultural heritage of the coastal areas of seas and oceans. However, there is a lack of studies dealing with shorelines of large artificial reservoirs. Over the last decades, the number of artificial reservoirs around the world has considerably increased. This leads to the formation of new shorelines, which are highly dynamic regarding abrasion processes.

Reservoir bank erosion is a result of the combination of different factors – both natural and human-induced. In any case, damages caused to cultural heritage sites situated near the shoreline are most of the time irreversible, and data with significant cultural and archaeological value is being lost. The high intensity of reservoir bank erosion leads to the destruction of large areas. Therefore, it is necessary to assess the danger of banks transformation. To assess the intensity of shore retreat, it is optimal to use multi-time remote sensing data[9,10]. Archival aerial and satellite photographs are precious for assessing shoreline displacement over a long period. Since archival materials often do not get a spatial reference, georeferencing tools realized in much modern GIS are used to solve this task. Such tools implement an extensive list of methods of transformations (from affine transformations to various splines) and interpolation. Modern satellite images with equal or higher resolution are most often used as reference data.

*busmanof@kpfu.ru

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The main hazard indicator of shoreline degradation is the intensity of the process, defined as the average long-term linear, areal or volumetric rates of shoreline retreat per unit time (m/year, ha/year, m3 /m*year, etc.) The most obvious characteristic of the intensity of shoreline change in seas and reservoirs is the linear rate of shoreline retreat. The use of GIS to assess the dynamics of shoreline change for reservoirs and seas makes it possible to obtain reliable and reproducible information and assess the intensity of shoreline degradation. The use of GIS tools makes it possible to use a variety of remote sensing data sources and manual and automated methods of calculations. Dewidar and Frihy (2010) used multitemporal Landsat imagery to quantify erosion and accretion along the Nile Delta shoreline[11]. Multi-temporal satellite images of the coastal zone at different resolutions are used to assess cyclic shoreline changes[12,13,14]. Remote sensing data can provide a preliminary assessment of change and is a unique tool for coastal and deltaic research and monitoring[15,16]. Both manual and automated methods are used for coastal line delineation. And if the classical method of manual extraction is essentially reduced to the detection and drawing of the coastline as a polygon or polyline by an expert operator, the automated methods are usually related to an automated or semi-automated classification of the image into two classes - water and non-water. Such automated methods include the ISODATA method[17], maximum likelihood method[18], various machine learning methods such as Random Forest[19], reference vector method[20], CART[21], and semantic detection using convolutional neural networks[22]. Quantitative analysis of shoreline dynamics using GIS is performed both manually and automatically. The manual method involves measuring the distance between different time positions of the shoreline using a "ruler" tool at the most representative points. This method allows getting an approximate picture of shoreline degradation rates. Automated methods are used to assess fluvial and abrasion processes along the entire coastline. The most popular tool for such analysis is the Digital Shoreline Analysis System (DSAS). DSAS has been an essential component of the U.S. Geological Survey's Coastal Change Hazards project which provides a robust suite of regression rates in a consistent and simply repeatable method so as to execute on large volumes of data collection at various scales. The software is proposed to assist the shoreline change-calculation process and also to give rate-of-change information and the arithmetical data essential to set up the consistency of the computed results[23]. DSAS is also appropriate for any general purpose that calculates positional transformation over time, for instance assessing change of glacier limits in chronological aerial photos, river edge borders or land use/land-cover changes[24]. It has three main components that define a baseline, generate orthogonal transacts which determine separation along the coast and compute rates of changes like linear regression rate, endpoint rate, average of rates etc. by means of several models or methods[25].

2. STUDY AREA

Kuibyshev reservoir is the largest in the Volga-Kama cascade system. Among artificial water reservoirs of Russia, almost according to all indicators, it is noted for the highest values of shore zone transformation. That is why it is necessary to continually collect information about the state and tendencies of developing dangerous exogenous processes, which are hazardous for shoreline destruction. One of the effects of the development of such processes is the destruction of archaeological monuments. It is impossible to establish the exact number of various archaeological monuments, which turned out to be in the flood zone of Kuibyshev reservoir. It is only possible to guess how many objects of archaeological heritage located in the floodplain of the Kama river were not found and lost forever. Especially it concerns the settlement monuments - camps of Stone and Bronze ages and medieval settlements without specific features in the relief as hillforts fortifications.

After the Kuibyshev reservoir filling in 1957, since 1961, regular research of the archaeological monuments in the zone of active bank erosion began. During the 20 years of active research, about 1500 monuments under the negative influence of the Kuibyshev reservoir were discovered. It should be recognized that this number is very approximate because at the level of research methodology of those years and the lack of operational information, often there was a duplication of monuments, dividing the territory of one monument into several, etc. In addition, the number of monuments identified in that period, but to date wholly destroyed, has not been established.

Since 2008, the article's authors have conducted a comprehensive study of archaeological sites in areas of intensive shore-forming processes using multi-temporal remote sensing data and modern geodetic research methods [26,27,28,29].

This article presents the results of studies of medieval archaeological monuments, Laishevskoye and Ostolopovskoye settlements, as well as Ostolopovskoye fortified settlement using the data of multi-temporal remote sensing and modern methods of field research (Fig. 1). The studied sites are in the zone of active transformation of the banks and destroyed since the creation of the Kuibyshev reservoir[30].

Figure 1. Overview map: Laishevsky settlement (1), Ostolopovsky settlement (2) and Ostolopovo hillfort (3)

The choice of objects is caused by both settlements' unique monuments of the Bulgar period. The destruction of which will be an irreparable loss to science and the cultural and historical heritage of the peoples of the Republic of Tatarstan.

Ostolopovskie settlement and hillfort are located in the Alekseevsky district of the Republic of Tatarstan, on the left bank of the Kama river. The monuments date back to the beginning of the XI - the second half of the XII century is known since the XIX century, archaeologically described and recorded in 1965. In 1997-2017, stationary research on Ostolopovo settlement was conducted by K.A. Rudenko. The settlement covers a remnant of the native terrace, stretched in the north-northeast-south-southwest direction (190-120 x 25-80 m). From the south, it is separated from the shore by a deep ravine; from the west, northwest, and northeast, it is surrounded by a flooded floodplain of the Shentalka River. Its surface is flat and soddy. The Ostolopovo is not an ordinary rural settlement but a center of jewelry production, manufacture, and repair of weapons and horse equipment and had a relatively high social status. The comparison of cartographic data and excavations and collections of materials from the destroyed cultural layer allowed to determine the specificity of the settlement, which controlled the estuary of the Shentala River, a tributary of the Kama, an important trade route connecting the central districts of Volga Bulgaria to a significant river route[31].

The Laishevskoe settlement is located on the right bank of the Kama River and dates back to the X-XIV centuries. Regular studies of the monument began in the 1960s. During the XI century, the Laishevskoe settlement was a local center of iron metallurgy and blacksmithing production. After the Mongol invasion, the settlement was still an active supplier of blacksmith's products for the domestic market32. Both settlements were associated with foreign and domestic trade. The western part of the settlement at the end of the 1990s was built entirely up with dacha communities and became inaccessible for research. The eastern part of the settlement was almost completely eroded by the end of the 2010s, except for a small section on the left bank of the Bolshaya Chakma balka.

3. MATERIALS AND METHODS

To assess the dynamics of the shoreline, data from multi-temporal remote sensing were used (Fig. 2). The position of the shoreline for the period of the 1950s was recognized using archival aerial photographs at a scale of approximately 1:17000 (Kazan University Library). The data for 1975 were satellite images KeyHole-9 Hexagon obtained as part of the Corona reconnaissance space program with a spatial resolution of 6-9 m from the open archive of the US Geological Survey. To assess the current position of the shoreline, field studies were carried out at the Ostolopovsky (2018) and Laishevskoe (2019) settlements, and in 2020 - at the Ostolopovo hillfort. DJI Phantom 4 PRO v2, equipped with a 20-megapixel camera was used.

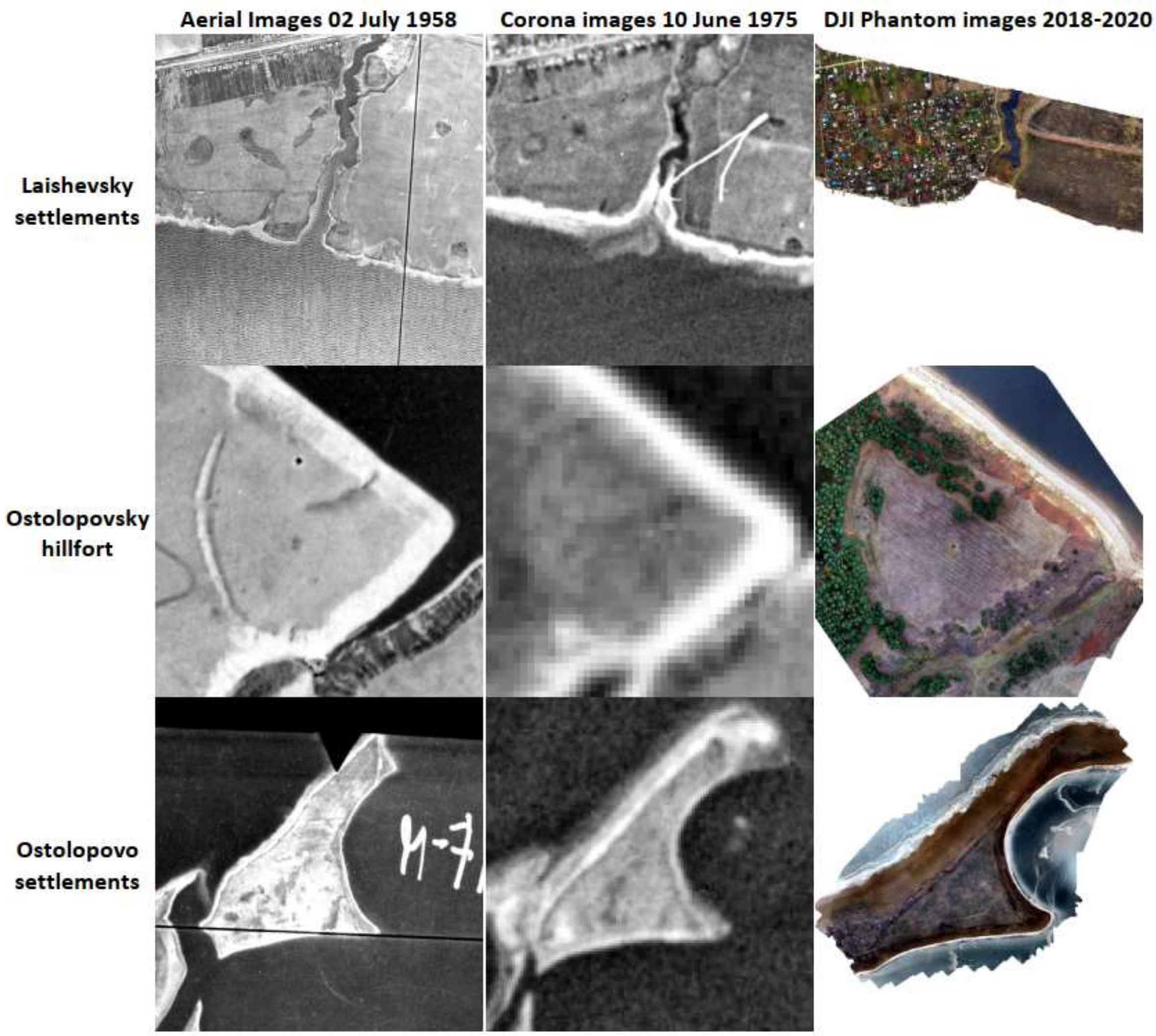
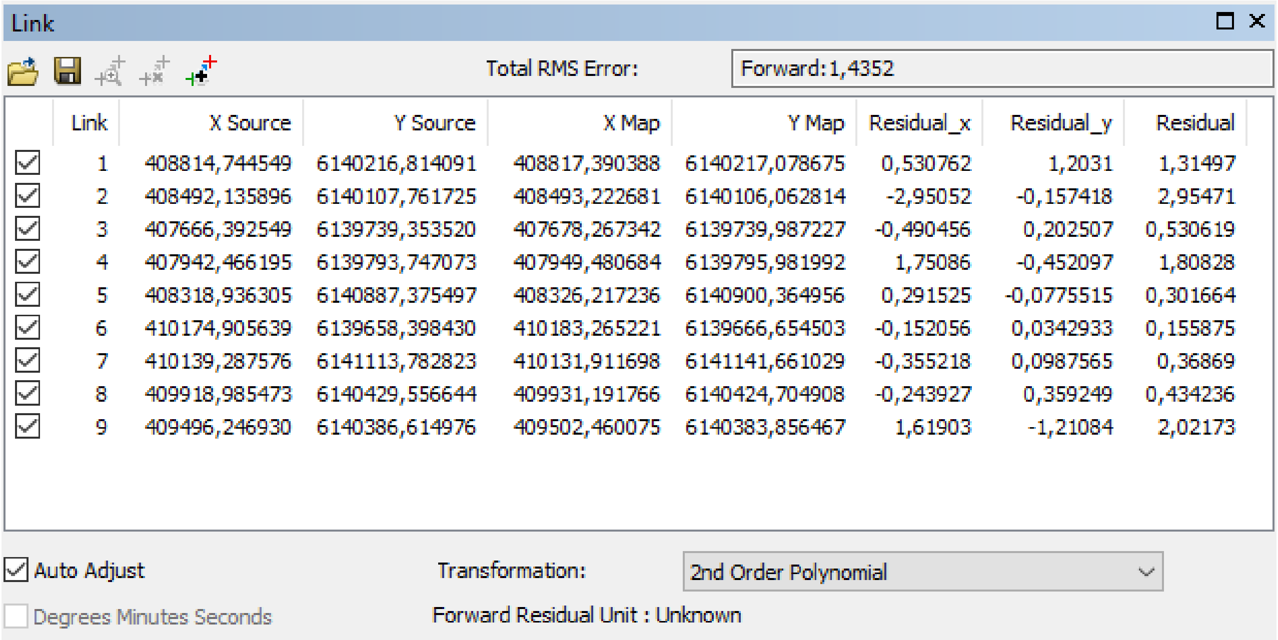


Figure. 2. Input materials. Laishevsky settlement, Ostolopovsky settlement and Ostolopovo hillfort on the different images

Since the historical images are not georeferenced, it was done using the Georeferencing module in ArcGIS. All work was carried out in the projection WGS 84/UTM 39 Northern Hemisphere. Modern (2018-2019) very high-resolution satellite images were used as reference data. These images are available as global basemaps from Google and ESRI in the QGIS module - HCMGIS. Crossroads and unchanged objects (houses, churches, detached trees) were chosen as reference points, both in archival and modern images. Fragments of the Corona images on the medieval Laishevsky settlement and the Ostolopovsky complex were referenced separately to achieve maximum accuracy. The 2nd and third-order polynomial transformation and bilinear interpolation were used. The maximum georeferencing errors for both sites were less than 3 pixels (Figure 3).



	Link	X Source	Y Source	X Map	Y Map	Residual_x	Residual_y	Residual
☑	1	408814,744549	6140216,814091	408817,390388	6140217,078675	0,530762	1,2031	1,31497
☑	2	408492,135896	6140107,761725	408493,222681	6140106,062814	-2,95052	-0,157418	2,95471
☑	3	407666,392549	6139739,353520	407678,267342	6139739,987227	-0,490456	0,202507	0,530619
☑	4	407942,466195	6139793,747073	407949,480684	6139795,981992	1,75086	-0,452097	1,80828
☑	5	408318,936305	6140887,375497	408326,217236	6140900,364956	0,291525	-0,0775515	0,301664
☑	6	410174,905639	6139658,398430	410183,265221	6139666,654503	-0,152056	0,0342933	0,155875
☑	7	410139,287576	6141113,782823	410131,911698	6141141,661029	-0,355218	0,0987565	0,36869
☑	8	409918,985473	6140429,556644	409931,191766	6140424,704908	-0,243927	0,359249	0,434236
☑	9	409496,246930	6140386,614976	409502,460075	6140383,856467	1,61903	-1,21084	2,02173

Figure. 3. Aerial photo georeferencing Errors (Laishevskoe settlement).

Then, using the georeferenced images and orthophoto plans, the shorelines in the studying areas were manually vectorized. It should be noted that due to the different resolutions, the vectorized lines have different smoothness. So generalization grows in the series Orthophoto plan - Aerial image - Corona image.

The Digital Shoreline Analysis System (DSAS) was used to quantify shoreline movement as an add-on module to the ArcGIS software. This module is effective for simplifying the analysis of shoreline position changes. The main implementation of DSAS is the use of polylinear layers as a representation of a particular shoreline feature at a particular point in time. A number of statistical measures of shoreline change are generated by comparing shoreline positions: net shoreline movement (NSM), shoreline change envelope (SCE), endpoint rate (EPR), linear regression rate (LRR), and weighted linear regression rate (WLR)[24].

A geodatabase was created in ArcGIS, into which shoreline layers were entered as .shp files. The shoreline of 1958 was taken as the baseline. (right after the filling of the reservoir). In the automatic mode, transects were built within the extreme positions of the shoreline, and indicators such as net shoreline movement (m/year) and shoreline shift (m) were automatically calculated from these transects.

4. RESULTS AND DISCUSSION

3.1 Ostolopovo monument complex

The Ostolopovo settlement is a unique monument of archaeology. However, research opportunities are limited because part of the settlement was destroyed by the Kuibyshev reservoir, which has been washing away the shoreline since 1955. Research by K.A. Rudenko on the Ostolopovo settlement provided an opportunity to record objects and finds in controlled conditions and determine the features of cultural deposits in this part of the settlement. At present, this part of the bank is still destroyed by the reservoir. Regular excavations revealed the dependence of the bank destruction on several objective factors, such as the intensity of water level fluctuations in the reservoir. According to K.A. Rudenko's observations from 1997 to 2011, at least 30 m of the shoreline was destroyed on the western part of the shore alone, with 1 to 3 m of the shoreline collapsing in the erosion zone of the monument every year[31]. It should be noted that the protective excavations in the erosion zone have stabilized the process of shoreline collapse to some extent. The intensity of the latter has slowed down, according to archaeologists.

Fig. 4. The Ostolopovo settlement shoreline retreat during the entire period

Table 1. Degradation rates of the shoreline at the Ostolopovo settlement

Years	**1958-1975**				**1975-2018**			
Statistics	Mean	Min	Max	STD	Mean	Min	Max	STD
NSM (m/y)	0.40	0.00	1.26	0.33	0.57	0.01	3.09	0.58

The Ostolopovo settlement site, unlike all other sites, is represented by a pattern of increasing intensity in the modern period (Fig. 4, Table 1). This is probably due to the activity of turbulent flows occurring in the estuary at the confluence of the Shentala River into the Kama River. The main degradation of the shoreline occurred here on the side of the Kama River (~1 m/year throughout the study period) in the direction of straightening the mouth of the tributary in the period, according to multi-temporal images of Google Earth, from 1975 to 1985. On the side of the Shentala River the rate of degradation of the shoreline is several times less and does not exceed 0.5 m/year, which, in turn, affected the overall average intensity of destruction of the monument. For a detailed analysis of the reasons for the increase in the intensity of shoreline retreat, it is necessary to use high-resolution images during this period, which is planned to be done in the future.

Fig. 5 Shoreline retreat at the Ostolopovo hillfort

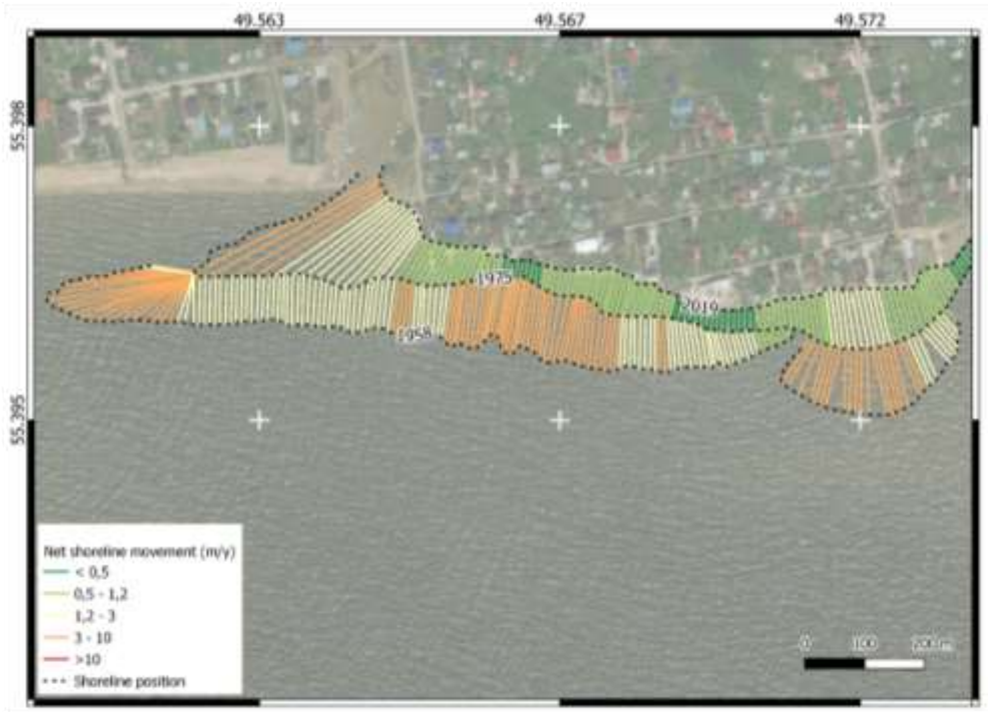
Table 2. Degradation rates of the shoreline at the Ostolopovo hillfort

Years	**1958-2020**			
Statistics	Mean	Min	Max	STD
NSM (m/y)	0.16	0.05	0.27	0.06

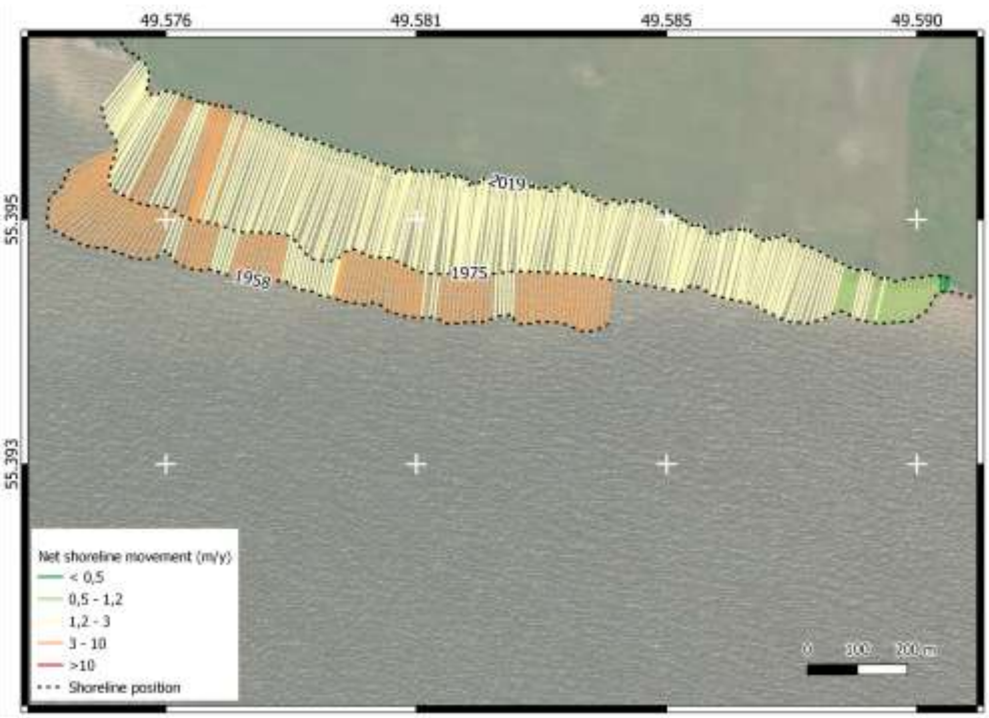
Unfortunately, no good quality intermediate images could be found for the site near the Ostolopovo hillfort, which does not provide an opportunity to assess the variability of the shoreline dynamics. However, since at this site, located on the left bank of the Kuybyshev reservoir and formed by bedrock, the average intensity of degradation is insignificant (Fig. 5, Table 2), the intermediate measurements can be disregarded. The main destructive action occurs due to colluvial processes, which, according to the overgrowing slopes, reduce their present intensity.

3.2. Laishevskoe settlement

The Laishevskoe settlement, at the time of 1988, was much more destroyed than the Ostolopovo settlement and it is still unclear what part of it was destroyed by the reservoir before regular archaeological research began to be conducted there[32].



A



B

Figure 6. Shoreline retreat at the Laishevskoe settlement for the whole period at Site 1 (A) and Site 2 (B)

Since the area of Laishevskoe settlement was partially built up, the shoreline in this area was divided into two sections along with the mouth of the unnamed river. The right-bank part was built up with dacha communities and partially reinforced with engineering structures when the bank came close to the buildings (Fig. 6, A). The left bank part was not reinforced and is used for agricultural purposes (Fig. 6, B).

The combination of these factors affected the nature of abrasion processes at these sites - in the first 17 years after filling the Kuibyshev reservoir, the average intensity of degradation at both sites exceeded 3 meters per year (Table 3-4). However, due to reinforcement of the right bank part (Site 1), the intensity of shoreline retreat here is almost 3.5 times less. The unstrengthened part has a retreat rate of more than 2 meters per year. The decrease of the modern intensity of the retreat in comparison with the period after the filling of the reservoir is due to the regulation of its level, which somewhat reduced the wave effect, especially during the flooding period, but cardinally did not reduce the rate of retreat.

Table 3. Degradation rates of the shoreline at the Laishevskoe settlement in Site 1

Years	**1958-1975**				**1975-2019**			
Statistics	Mean	Min	Max	STD	Mean	Min	Max	STD
NSM (m/y)	3.14	0.29	8.53	1.30	0.92	0.24	4.49	0.73

Table 4. Degradation rates of the shoreline at the Laishevskoe settlement in Site 2

Years	**1958-1975**				**1975-2019**			
Statistics	Mean	Min	Max	STD	Mean	Min	Max	STD
NSM (m/y)	3.37	2.07	5.21	0.61	2.14	0.33	3.07	0.57

5. CONCLUSION

As a result of the research, an assessment of shoreline retreat was carried out by interpretation of remote sensing data and field observations with the use of UAVs. Quantitative assessment of the transformation of the Kuybyshev shoreline makes it possible to assess the damage caused to the archaeological monuments and the risk of their further destruction.

Reservoir shore changes are a complex process, which depends on many natural and anthropogenic factors. The high intensity of their transformation leads to negative consequences. That is why it is necessary to carry out a continuous collection of information about tendencies of exogenous processes development, which lead to the destruction of banks. This problem is actual for cadastral activity as well. Thus, to keep track of changes taking place and update information on cadastral maps properly, it is advisable to apply algorithms and tools implemented in modern GIS.

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