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Study of fluvial processes impact on archaeological sites of the Volga Bulgaria period using remote sensing data

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ABSTRACT

This work is a part of the research aimed at developing a system of analysis of the risks of destruction of archaeological sites on the territory of the Republic of Tatarstan. Most of fortified settlements of the Volga-Bulgarian period (X-XIII centuries AD) are located on the small river banks. In order to identify the risk of archaeological sites transformation by fluvial processes, the river dynamics in the area of Lukovskoye, Bolsheklyarinskoye and Zelenovskoye fortified settlements was assessed. Field studies were conducted using UAV and GNSS techniques to describe the relief and current state of the site's territory. The measured data were analyzed using the GIS to evaluate intensity of bank erosion. Historical maps, archival remote sensing data and orthophotomaps compared to get quantitative characteristics of monument territory damage. In addition, as a result of photogrammetric image processing, the DEM of monuments territory were constructed and analyzed. As a result, maps of the river dynamics and quantitative characteristics of the intensity of the site's destruction were obtained. The main factors affecting bank erosion are the meandering of the riverbed, the height of the bank and its component rocks. The study showed the importance of using remote sensing and 3D-modelling methods to study and predict the dynamics of river processes as a factor in the destruction of archaeological sites. Results of the research will help to reveal tendencies in cultural heritage objects condition and to estimate risks of their destruction.

Keywords: Remote Sensing, Geoinformation Systems, Exogenous Processes, Cultural Heritage, Fortified Settlements

1. INTRODUCTION

Archaeological sites are formed under the influence of human activity and natural processes during a long historical development and consist of interacting natural and anthropogenic components. Therefore, it is important to obtain quantitative characteristics of modern changes in the state of the territories where medieval objects are located. One of the important tasks in this context is the study of fluvial processes, since water plays a large role in formation and transformation of the modern relief, an integral part of which are the archeological sites. Because rivers kept changing their course and networks due to avulsion, the sedimentary sequences in these areas are archives of both fluvial geomorphological and archaeological development[2]. Rivers are notoriously effective at reworking their past fluvial archives, eroding and redepositing their alluvium including the archaeological materials contained here. River researchers benefit from the interdisciplinary incorporation of geoarchaeological data since it leads to age-control on the phasing, and archaeologists benefit since it enables them to develop a more detailed insight in autogenic landscape change. In this manner this interdisciplinary approach enables more complete explanations of the timing and duration of successive patterns of human settlement observed along the former river.

Since always the main criterion for finding a suitable place for settlement was the availability of water and natural fortifications (gullies, ledges, etc.), most archaeological sites are usually located on the banks and terraces of small rivers, where fluvial and other exogenous processes are possible[3]. Even the usual activities of permanent and temporary streams, and even more anomalous and catastrophic processes, can lead to damage or complete destruction of cultural heritage objects. The study of human-fluvial landscape interactions requires an interdisciplinary approach integrating geographical and archaeological datasets. Worldwide, developing a cultural heritage conservation strategy based on advanced methods is an integral part of modern archaeological research[1].

Fluvial processes are studied using various methods, which can be divided into several groups according to the source information. For example, there are methods based on the use of ready-made archival (old books and descriptions,

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historical maps[4,5], archival aerial images) and cartographic information (state topographic and thematic maps[6,7]). Archival information is especially important because it reflects changes in the study area over a long period of time, and allows to predict their further development. Other methods aimed at obtaining native information, include field and desk-based methods. Desktop methods include the use of Earth remote sensing data from space – satellite imagery and digital elevation models. As an example, multispectral images of Landsat[8] (30 m resolution) and Sentinel[9] (10 m resolution) missions can be mentioned, as well as non-spectral images of Corona[10] mission. All these missions are global and cover major part of the Earth. Sentinel and Corona images can be used for assessment of coastline degradation; Landsat images are not suitable for this purpose due to their insufficient resolution. However, Landsat images can be used to monitor meandering[11] and other river bed changes. Of course, it is not possible to survey small rivers in this way, but medium rivers can be studied[12]. The advantages of the Landsat mission also include the fact that it is the most long-term project to obtain satellite images of the planet Earth. The first satellite under the programme was launched in 1972; the last, to date, Landsat, was launched on 8-11 February 2013. In 2020, it is planned to launch satellites of the Landsat 9 mission. Such a long series of observations allows estimating long-term dynamics. Digital elevation models also allow studying riverbeds, but not all missions allow estimating the dynamics of the process due to the unavailability of multi-temporal digital elevation models (DEM) of one mission. Among global DEMs used to study fluvial processes, the missions ASTER GDEM[13], SRTM[14], ALOS AW3D30[15] are worth mentioning.

Field methods include various instrumental approaches. For example, coastal processes are studied using the method of recording shoreline retreat from a ground control point. The method is the easiest to implement, however, because of the discrete arrangement of peers the results are very generalized[16]. To solve this problem, total station surveys[17,18] or, as in recent years, surveys with GNSS instruments[19,20] are used. The accuracy of such a survey reaches up to a centimeter[21], at that the problem of setting continuous observations is solved, and the probability of interrupting a number of observations due to the loss of a reference point is minimized. However, these approaches have a drawback due to the high cost of the instruments and the impossibility to estimate volumetric changes of the relief.

For the solving of the problem of estimation of volume losses of soil from fluvial processes various methods are used[22]. Laser scanning and unmanned aerial vehicles (UAV) survey considered as the most advanced and effective. The result of such equipment is a three-dimensional model of the surface; however, approach to a model construction is different. To obtain an initial point cloud using a laser scanner, the relief of the area of interest is scanned by laser light to determine the coordinate of each point of the surface with a resolution equal to the scanning step. When building a terrain model using UAV, the point cloud is created using the Structure-from-Motion or SfM[23] algorithms. The accuracy of that model is comparable to the model obtained by laser scanning[24]. In order to determine the volume loss of soil, multi-temporal models are built for the same area and then subtract the later model from the one obtained earlier[25]. This approach allows to estimate not only the total volume of changes, but also to identify areas with the highest intensity of coastal processes. When using the UAV approach, in addition to the model obtaining, it is possible to construct orthophotoplans[26] that helps to evaluate the planar dynamics and to compare the current state of the object with historical orthophotoplans or satellite images.

This work is a continuation of research aimed at developing a system of archaeological sites of the Volga-Bulgarian period (X-XIII centuries AD) state analysis[27]. At present, 2751 objects of cultural heritage (historical and cultural monuments) in the Republic of Tatarstan (RT), Russia, are influenced by negative natural and anthropogenic factors. Settlements with a system of defensive fortifications (ramparts, ditches), were selected as objects of this study, since they are easily identified by remote sensing data. 121 fortified settlements were described on the territory of the Republic of Tatarstan. Authors of the article found approximately 100 sites by remote sensing data (Fig. 1).

The Republic of Tatarstan is located in the eastern part of the East European Plain at the merge of the Volga and Kama rivers (Fig. 1). The area of the Republic is 68,000 square kilometers and its terrain is a wavy plain. With an average altitude of 170 m above sea level, some parts of the Republic's territory rise to 300-350 m. The East-European Plain gradually rises from the Volga River to the spurs of the Ural Mountains, where the Bugulma-Belebey Upland was formed. In addition to four major rivers – the Volga, the Kama and its tributaries Belaya and Vyatka – there are about 500 small rivers over 10 km long. The Pre-Volga of the Republic of Tatarstan (RT) with maximum altitudes of 276 m occupies the northeastern part of the Volga Upland, characterized by a very high level of agricultural development – 76.4% of plowed and 40% of eroded land. The most developed erosive forms created by temporary streams are erosion strips up to 30 cm deep, and ephemeral gully with 1-2 m deep. The average density of permanent gully heights in the Pre-Volga region is 0.34 heights per sq. km, the average length is 0.7 m/sq. km. The most common gullies in the Pre-Volga RT are in the Apastovsky district. The average eroding of the arable part of the territory is 64%, the territory belongs to the zone of average washout. Average forest cover of the Pre-Volga region is 9,7%, prevailing soil type is grey forest (Haplic Greyzems).

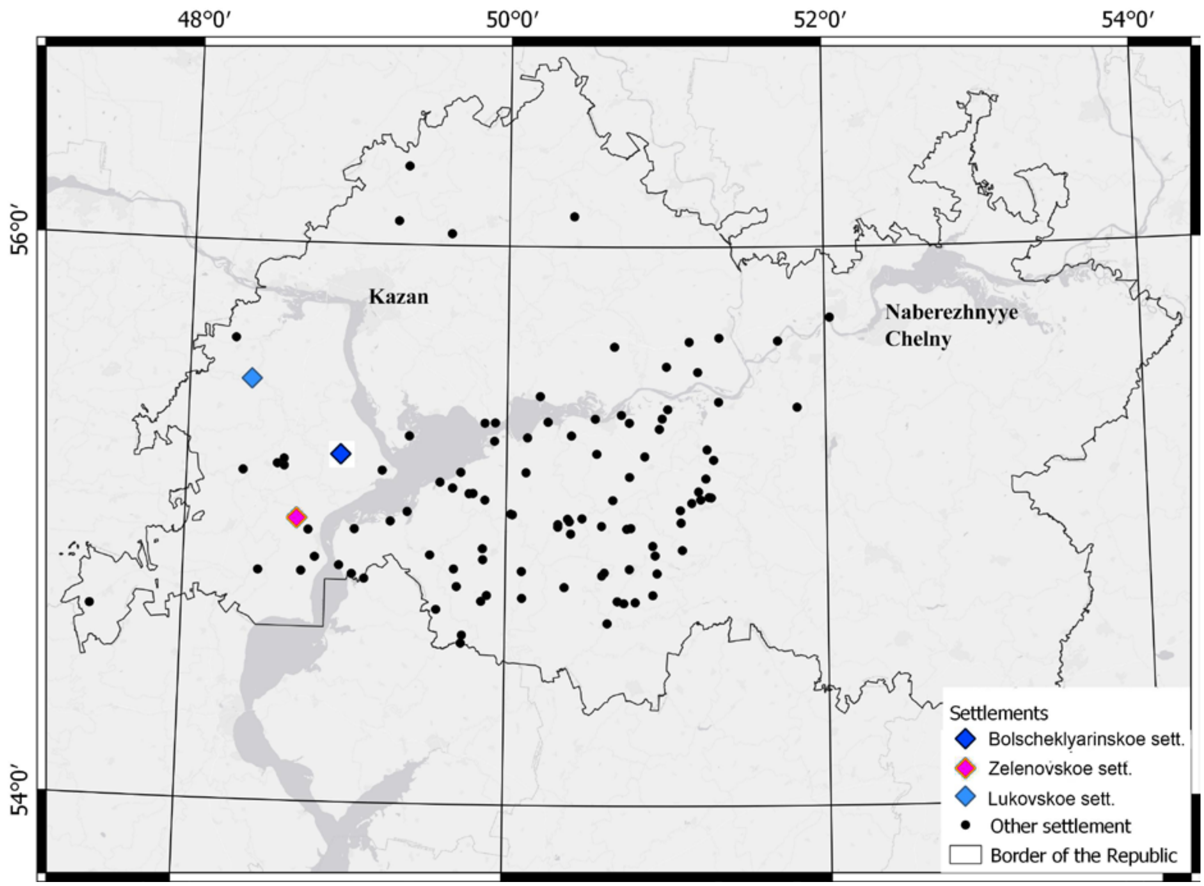

Figure 1. Study area and selected settlements.

The Sviyaga River, which flows for 195 km, is the longest river in the Pre-Volga region of the Republic. In total, the average length of the rivers in the Pre-Volga region is 16 km, excluding the Sviyaga River. To assess the dynamics of fluvial processes, we selected three settlements – Lukovskoye, Bolsheklyarinskoe and Zelenovskoe, from 15 remaining on the Pre-Volga RT territory (Fig 1.).

2. METHODS

To study the degradation of archaeological sites due to the dynamics of fluvial processes, authors used historical and topographic maps, archival aerial images of the middle of the last century, and field studies using UAVs and GNSS; all spatial data was georeferenced and included in the GIS database. Old maps and aerial photographs dating back to the Soviet period proved to be useful in many regions of Russia for assessing of archaeological sites degradation and cultural heritage management. For better understanding of fortification system, river dynamics and negative exogenous processes, a 3D model was created based on UAV images taken during field work in 2019. The model was made using AgiSoft Photoscan software. Aerial shooting was performed using a multi-rotor UAV DJI Phantom 4 with 12-megapixel camera, controlled by DronDeploy software. The following flight parameters were used: height – 50-100 m; pictures overlapping – 60-80%; camera position – 90°; coverage – area survey; meteorological conditions – no precipitation, wind no more than 15 m/s.

In order to improve UAV data processing accuracy and provide precise X, Y, Z coordinates, GCPs centers were measured with a double frequency GNSS receiver Leica Zeno 20 with external antenna. Survey was performed in RTK regime in WGS84 with real-time corrections by satellite reference stations.

Figure 2. Quadrocopter DJI Phantom 4 (left), special mark georeferencing by GNSS receiver (right).

DEM analysis, mapping and calculations were conducted in Golden Software Surfer 13 software. A digital terrain model (DTM) with a step of 0.5 m showing the altitude characteristics of the settlement territory was generated by the point cloud. Profiles, inclination and aspect maps were built to describe the morphometric characteristics of settlement relief. Models were used to simulate a situation when water level in the river rises during seasonal flood. To do this, water level at the time of the UAV survey (summer low water) showed on the model, and then – the average long-term seasonal flood level according to hydrological observations.

Ultra-high resolution orthophotos with a pixel size of 5 cm were also created. They were used to create electronic layers for topographic plans construction.

3. RESULTS

3.1 Zelenovskoe fortified settlement (X–XIII AD)

Located 2 km east from Zelenovka v. in Tetyushsky municipal district at the right bank of the Lyubimovka river, the right tributary of the Ulema river on subdued relief (Fig. 3). The form of the settlement is oval, the occupied area – 4,06 ha. The line of fortifications consists of two ramparts and a ditch between them, arranged in one belt. Zelenovsky settlement was first mentioned in "Notes on fortified settlements, burial mounds and other ancient earth mounds in Kazan governorate" by N. Vecheslav in 1874. He noted that the shafts have not been preserved in some places. Kalinin, as a result of research in 1949, also noted washed-out ramparts and a hollow that cuts the settlement longitudinally.

Figure 3. Moderm view of the Zelenovskoe fortified settlement on the Lyubimovka river.

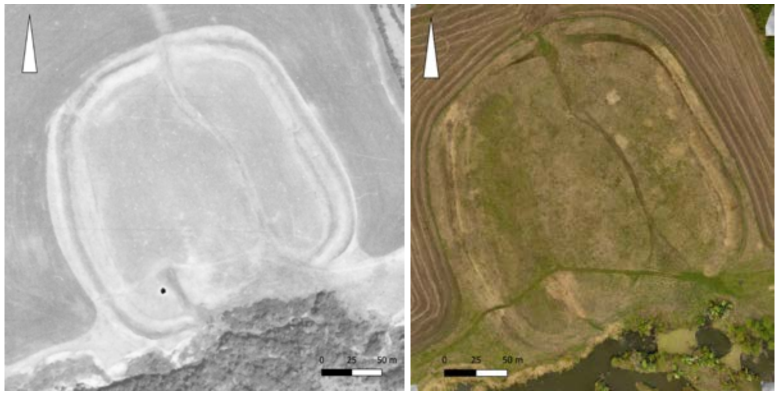

Figure 4. Zelenovskoe fortified settlement on multi-temporal images (left – 1958; right – 2019).

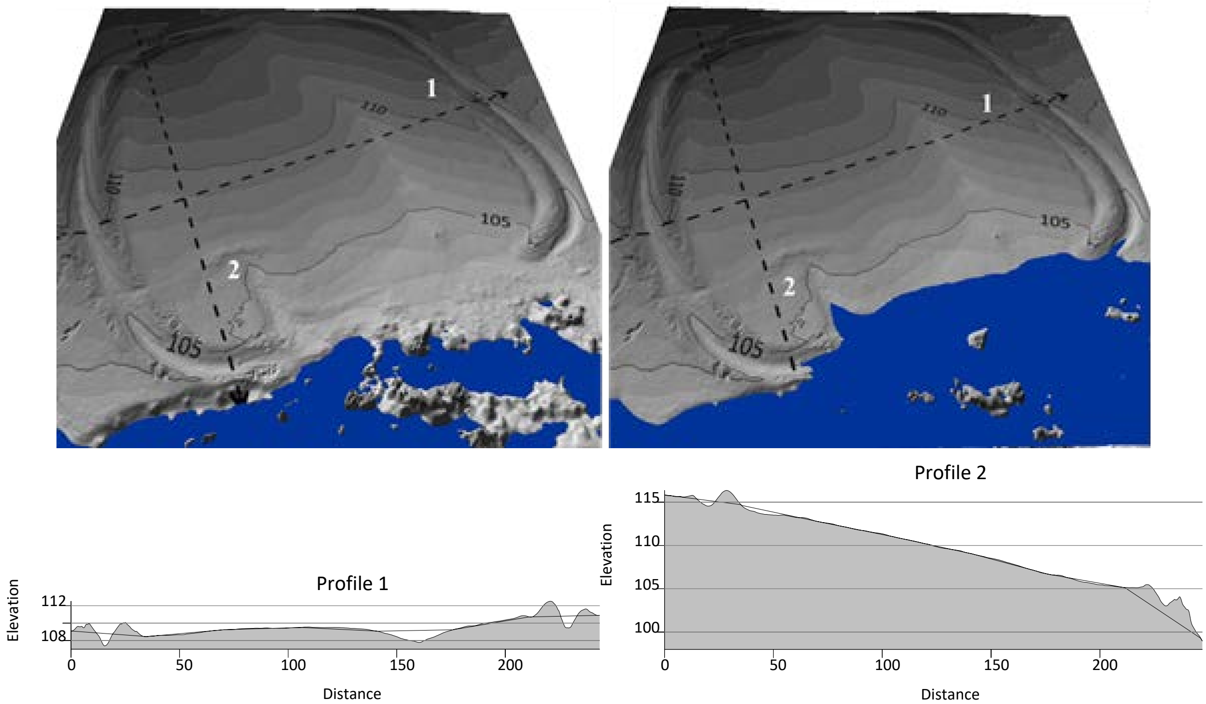

Figure 5. Zelenovskoe fortified settlement 3D-model. Lyubimovka river level rise simulation (left – 98,5 m; right – 99,5 m).

Although the river does not meander near the fortifications, changes in the defensive structures near the shore are clearly visible from multi-time images (Fig. 4). A fragment of the outer rampart at the southern border is almost completely destroyed, despite the fact that it is located above the water level. As can be seen from the 3D model (Fig. 5), the shore in this place is steep, which indicates the wash-out and collapse of the slope. The intensity of exogenous processes is low, but nevertheless this affects the settlement. During floods, water reaches the defensive structures and erode them (Fig. 5). As a result, the fortifications near the shore became less defined in relief in comparison with 1958 image. Most likely, the ancient settlement had a closed system of fortifications, which was constantly washed by the river before it was discovered. Also, the shape of the gap in the fortifications, probably passage, in the northern part of the settlement, changed; it became wider due to the temporary stream. The scour begins on a cropland higher up the slope and "cuts through" the settlement territory in its eastern third. It looks like a path on aerospace images and only the DEM made it possible to detect a hollow. Its width varies from 30 to 50 m, the depth – 1.5-2 m. It not only destroys archaeological site territory and fortifications, but also accumulates sediments, on the one hand changing relief of the settlement, and on the other – protecting it from river waters impact.

3.2 Bolsheklyarinskoe fortified settlement (X–XIII AD).

Located 1 km north-north-west of from Bolshie Klyari v. in Kamsko-Ustyinsky district at the left bank of the Sukhaya Ulema river, the right tributary of the Sviyaga river on subdued relief (Fig. 6). The form of the settlement is round, the occupied area – 3.3 ha. The lines of fortifications are three rampats and three ditches, arranged in one belt. Bolsheklyarinskoe settlement was first mentioned in "Notes on fortified settlements, burial mounds and other ancient earth mounds in Kazan governorate" by N. Vecheslav in 1874. It is noted that the fortifications on the eastern side are annually destroyed due to water level rising as a result of seasonal floods of the Ulema River. Archaeological surveys were first conducted in 1949 by N. Kalinin, who indicates that the river bed is 120 meters from the site.

Figure 6. Moderm view of the Bolsheklyarinskoe fortified settlement on the Sukhaya Ulema river.

It has intensively plowed since the 1980s, now as a result about 70% of ancient settlement occupied by arable land (Fig. 7). In the eastern part, fortifications are partially destroyed by old river channel. The floodplain form shows that earlier the river was actively meandering and the crescent incision on the eastern side of the settlement was the result of the river valley development.

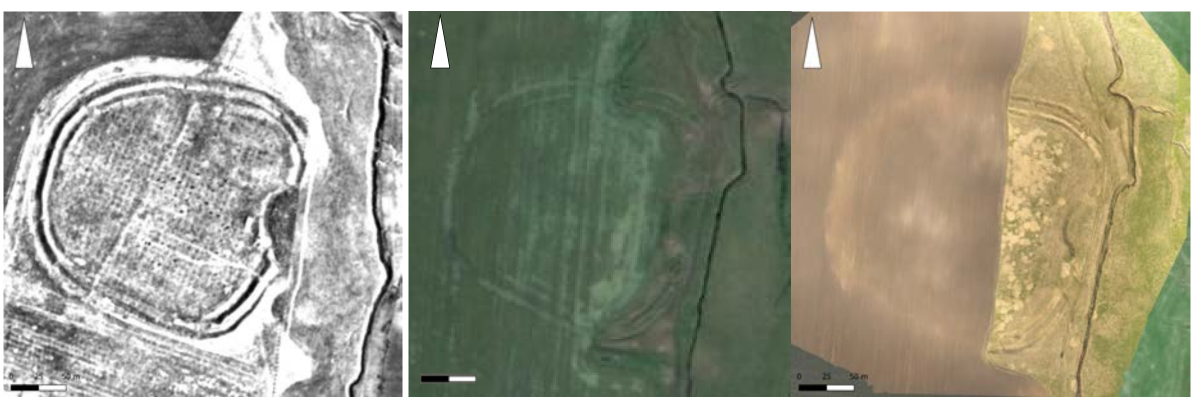

Figure 7. Bolsheklyarinskoe fortified settlement on multi-temporal images (left – 1958; middle – 2002; right – 2019).

If we compare the historical plan with a 1958 image, the channel displacement was about 25-35 m (2.7-3.8 m/year). From 1958 to 2002 the Sukhaya Ulema river channel has change position from east to west by 60-80 meters (1.4-1.8 m/year), and is currently 10-15 m from the site (Fig. 8). Since the river was turned into a shallow channel at the end of the last century, it does not change position at least the last 17 years, currently there is no risk of further destruction of the settlement by fluvial processes. Despite this, the DEM analysis showed that during the seasonal flood the river rises by 1 m and reaches the settlement (Fig. 9), which causes the risk of destruction of the archeological object in this period.

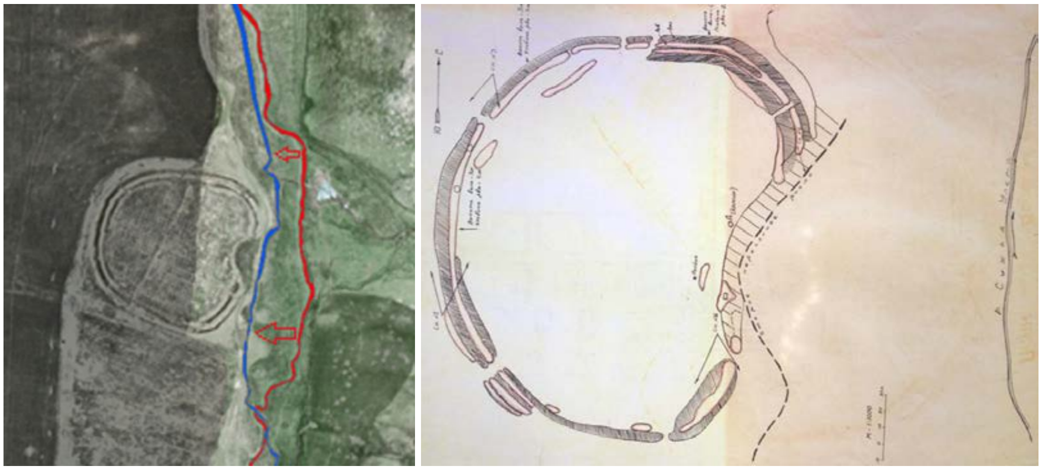

Figure 8. Bolsheklyarinskoe fortified settlement. Sukhaya Ulema riverbed shift 1958-2019 (left), historical plan 1949 (right).

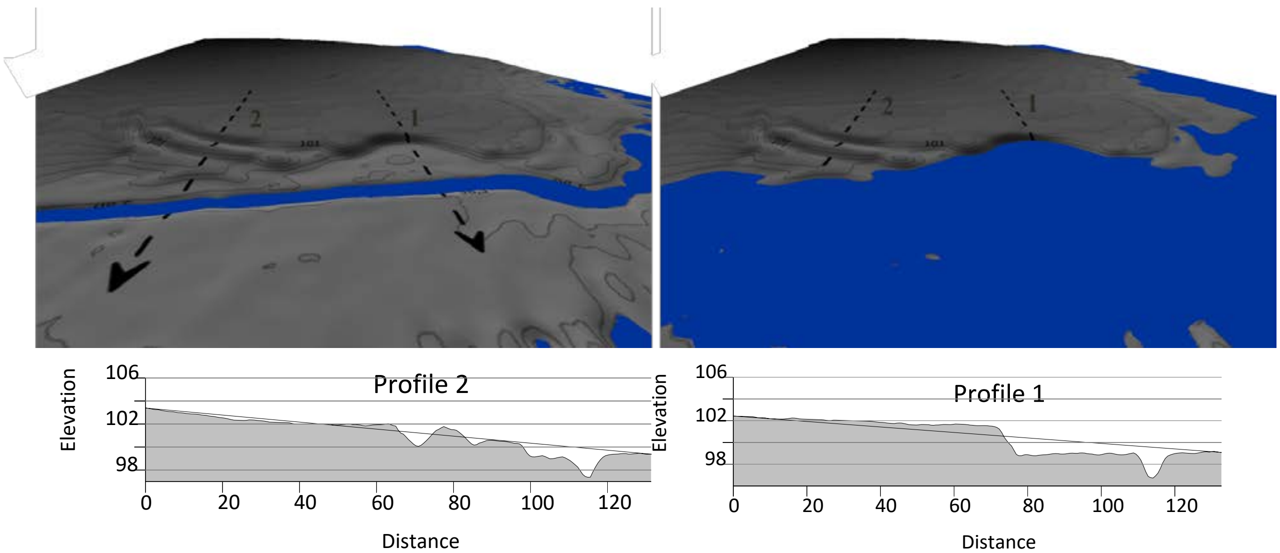

Figure 9. Bolsheklyarinskoe fortified settlement 3D-model. Sukhaya Ulema river level rise simulation (left – 98,5 m; right – 99,5 m).

3.3 Lukovskoe fortified settlement (X–XIV AD)

Lukovskoe (Yapanchino) fortified settlement (Fig. 10) dates from two periods in the history of Volga Bulgaria – pre-Mongol and Golden Horde (X-XIV centuries). The settlement was first described in the 70s of the 19th century by N.N. Vecheslav (1874) and S.M. Shpilevsky (1877). Even then, they noted the settlement territory erosion by the waters of the Kubnya river. This fact is confirmed by the historical map of that period (1879), which shows a significant destruction of the Lukovskoe settlement territory (Fig 11, left). Unfortunately, a historical map cannot be geographically linked in order to compare with modern maps and remote sensing data. The first quantitative data on the level of settlement damage indicated by the results of a survey by Akhmerov, who describes the destruction of the settlement by fluvial processes and specify the fortifications length – 240 m in 1891. In 1945 the village was investigated by N.F.Kalinin. According to him, defenses have been reduced by 40 meters since the first inspection in 1891. Thus, the shoreline retreat rate was at least 0.67 m/year.

Figure 10. Moderm view of the Lukovskoe fortified settlement on the Kubnya river.

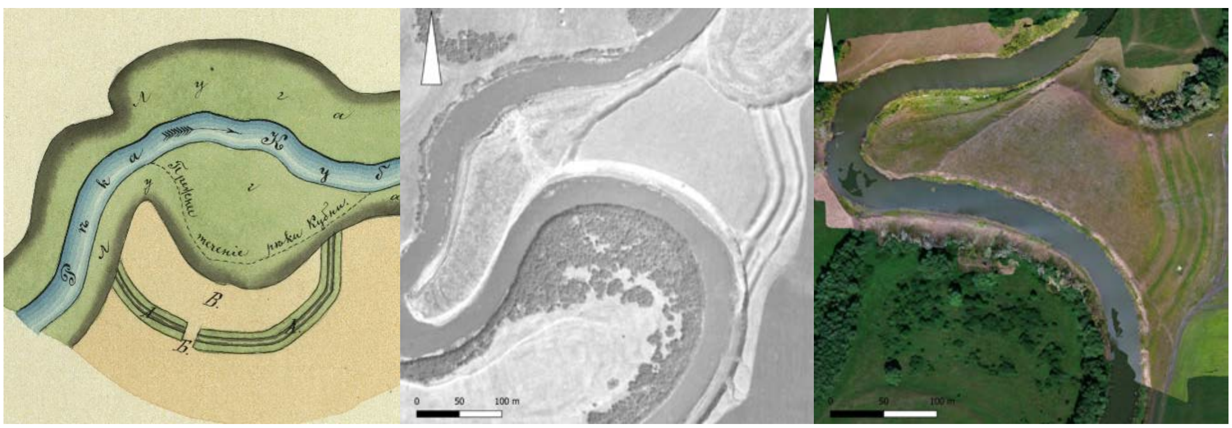

Figure 11. Historical map (1879), aerial image (1958) and modern orthophoto (2019) of the Lukovskoe fortified settlement.

As seen from the remote sensing data (Fig. 11), the site and the fortifications were previously destroyed as a result of channel deformations from the northern side, as evidenced by the presence of a crescent lake. Its convex side, on which the main energy of the stream falls, is directly adjacent to the territory of the settlement and forms a ledge. At present, the southern part of the settlement is influenced by the movement of the Kubnya river.

From 1958-2019 (Fig. 12), the river bank retreated by an average of 18.8 m (0.32 m/year). In total, 5530.5 m^2 of territory was removed by the river that constitute approximately 18 % of the settlement area in 1958. At present, the length of fortifications is 180 m, that is, to date, the length of the defensive structures has decreased by 20 m (0.29 m/year) in comparison with Kalinin data (200 m). In the middle of the 1990s, due to the cut of the meander the riverbed "shifted" 254 m to the northeast. Therefore, displacement of the river Kubnya in the south-east direction (0.15 m/year) can be observed in the northern part of the settlement, which may soon lead to the resumption of the bank caving processes by the channel flows at this area.

Modeling of the seasonal flood situation (Fig. 13) showed that the Kubnya river, rising to a maximum of 3 m, reaches the settlement level, which explains the collapse of the sod ledge in the northern part of the archaeological site. Flood also contributes to the slope processes intensification in the southern part of the Lukovskoe fortified settlement.

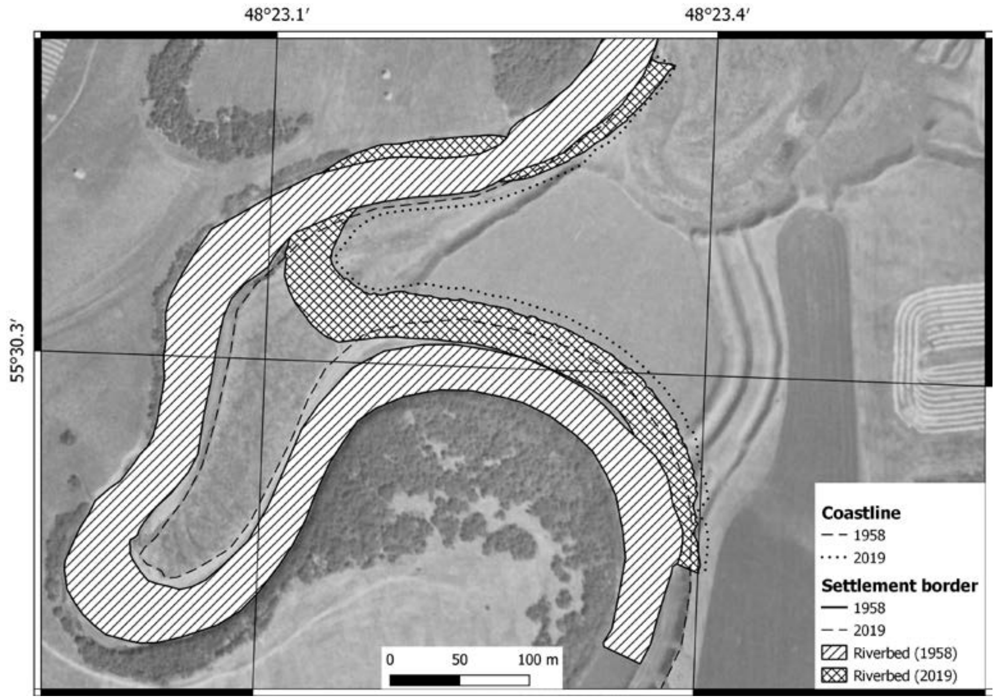

Figure 12. River channel change at the Lukovskoe fortified settlement (1958-2019).

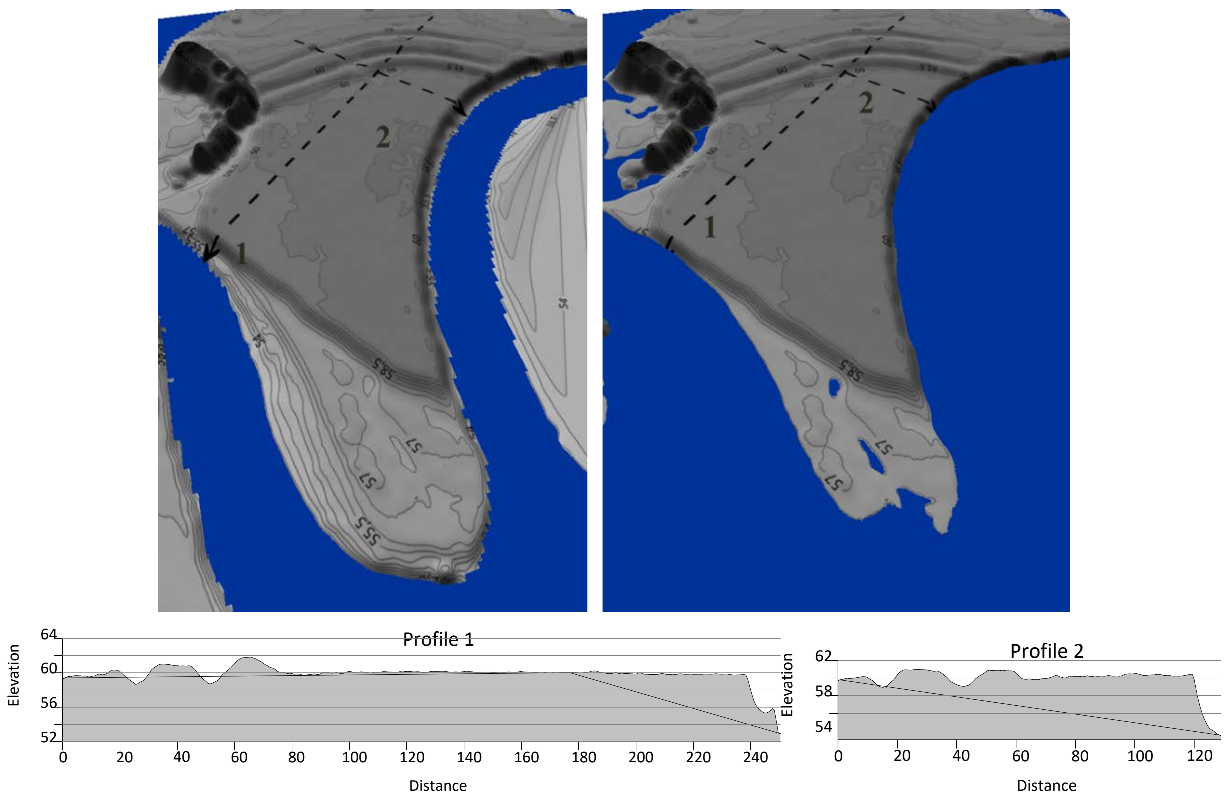

Figure 13. Lukovskoe fortified settlement 3D-model. Kubnya river level rise simulation (left – 53 m; right – 56 m).

4. CONCLUSION

Modern studies on the risks of destruction assessment of archeological objects located in close proximity to water objects are mainly devoted to the study of seas and oceans coastal processes intensity. In our opinion, there are not given enough attention for archaeological sites exposed to rivers and temporary streams. Conducted studies have shown the need for a comprehensive study of archaeological sites under impact of fluvial processes. Multidisciplinary approach allows us to study various aspects of this problem and to assess the risk of archaeological sites destruction. We can make the following conclusions as a result of study of several settlements located in small rivers valleys:

1. The rates of horizontal deformations of small rivers channels flowing in loose sediments vary, typically from 0.1 to 2 m/year. This is 2-3 times less than average rate and 15-20 times less than the extreme values of bank erosion on large rivers. The mechanism of shoreline retreat on small rivers is erosion of the lower part of the slope, which consists of channel facies sand, by the stream and subsequent collapse of the upper part with floodplain facies. At the same time, concave banks are eroded predominantly, which leads to an increase in their curvature. Modeling confirms historical data about impact of seasonal changes.

2. Historical maps and plans show great importance as sources for historical knowledge of studying area. Due to the use of archival sources, data were found that helped to specify the shape of ancient settlements, including the already destroyed parts, and to reveal changes in the riverbed position that led to the partial destruction of archeological sites. The study of historical maps and archival plans is a very promising direction in the study of fluvial processes affecting archaeological sites.

3. The use of UAV and GNSS technologies in field survey allowed the study of medieval settlements with a high accuracy degree. This method quickly and efficiently, at a previously inaccessible detail level, receives information that allows to describe the processes that lead to the archaeological sites' destruction. Therefore, we consider the use of UAV as a serious alternative to other, more traditional approaches to field research of archaeological sites.

4. The construction of high-resolution DEM allowed a more detailed study of the fortified settlements territory and defensive structures. This helped to correctly describe modern exogenous processes that affect the archeological monuments relief and to identify the most susceptible places to negative natural and anthropogenic impacts. In addition, textured 3D models published in the World Wide Web will increase the public interest in problems of archaeological heritage preservation.

The research methods proposed in this article can be used in cultural heritage management and monitoring of archeological sites current state. An integrated approach using historical data, multi-time remote sensing data and modern methods of archaeological field survey gives us a vision of the negative processes at archeological sites and allows us to identify areas for necessary security and rescue works. We believe that systematic work on the study of destructive processes at archaeological objects will help to create a negative processes map for effective management of cultural heritage.

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