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GIS-BASED SPATIAL ANALYSIS OF THE KAKASVÁR ARCHAEOLOGICAL SITE

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Abstract: The Battle of Muhi, widely regarded as a major national catastrophe in Hungarian history, has been a focal point of archaeological research for over seven centuries. Investigating the battlefield landscape and the associated 13th-century settlement system requires an interdisciplinary approach. This study presents a new GIS-based analytical method that integrates a high-resolution light detection and ranging (LiDAR)-derived digital elevation model and a Relative Elevation Model (REM), which were applied to enhance subtle micro-topographic contrasts within the low-relief floodplain environment. These tools were used to reconstruct former hydrological systems, enabling the precise spatial identification of the Kakasvár archaeological site, which had previously remained imprecisely defined.

***Keywords**: GIS, Battle of Muhi, LiDAR, REM, spatial analysis, hydrological datasets*

1. INTRODUCTION

Research on the Battle of Muhi has constituted a defining component of archaeological and historical scholarship for more than a century. Over recent decades, this field has undergone a marked methodological shift towards increasingly integrative and data-driven approaches. Non-destructive survey techniques (e.g., metal-detecting survey), community archaeology, and LiDAR-based terrain modeling have become integral elements of analytical practice, significantly expanding both the empirical basis and interpretative potential of research (Laszlovszky J. 2003, P. Szabó S. 2022). As a result, a growing corpus of professional databases and synthetic studies is now available (Négyesi L. 1997, Wolf M. 2014; Laszlovszky J. et al. 2014; Pusztai T. 2014). Today, the events of the battle, which took place in the mid-thirteenth century, are documented through detailed and multidimensional analyses focusing on battlefield reconstruction, contemporary settlement networks, and a range of related thematic questions. Despite these advances, significant research potential remains unexploited, particularly regarding the systematic analysis of foreign textual sources (Laszlovszky J. et al. 2014, P. Szabó S. 2022). At the same time, the comprehensive investigation of the entire battlefield remains an open research challenge, for which advanced digital methodologies may offer promising solutions (Laszlovszky J. and Rácz T. 2020). One possible response to this demand is provided by the methodology of Archaeological GIS, or Archaeo-GIS for short (Sarris, A. 2024). To date, however, the number of GIS-based foundational studies related to the Battle of Muhi remains limited, and existing works have primarily focused on descriptive and visual analyses or relatively simple spatial queries. Notably absent are studies employing complex spatial databases, surface-related indices, or explicitly formulated analytical questions, such as those addressing catchment areas, hydrological networks, or terrain-driven accessibility. These limitations can be attributed in part to the high cost or restricted availability of high-resolution digital elevation models and other relevant spatial datasets (e.g. flood inundation boundaries or flood models), as well as to the specialised expertise required to extract meaningful information from such data. Consequently, the analytical potential of GIS-based approaches and associated spatial databases has not yet been fully exploited in research on the battle. The present study represents a further stage in a multi-phase research programme that integrates physical geographical and archaeological data through the application of advanced GIS techniques. While closely connected to other ongoing investigations, its primary objective is not to intervene directly in existing archaeological interpretations, but rather to explore spatial and environmental relationships using the Archaeo-GIS methodologies. The study therefore focuses on identifying environmental and spatial patterns (particularly those related to terrain morphology, hydrology, and accessibility) and on applying methodological solutions that may contribute to a more detailed contextualisation of archaeological data. In addition, this study asks whether REM-enhanced LiDAR and Archaeo-GIS techniques can reliably identify anthropogenic micro-topography, thereby enabling a more precise localisation of human-made features and their discrimination from natural fluvial forms.

2. MATERIALS AND METHODS

2.1. Study area

The study area (Figure 1.) is located within the Sajó–Hernád Plain. The mesoregion is an alluvial fan plain situated at an elevation between 89.5 and 160 m a.s.l. Its northern part lies at a lower elevation, while the southern areas rise island-like by 8–10 m. The surface morphology has been shaped primarily by the Sajó and Hernád rivers. As a result of fluvial erosion, the area has developed into a piedmont-type landscape dissected by low interfluves, with an average relief of approximately 5 m/km². The Muhi Plain, forming the floodplain area of the two rivers, is characterized by low relative relief and consists of a gently undulating plain covered by loess deposits (Dövényi Z., 2010). The geological evolution of the area is highly complex; however, this study focuses on the key stages relevant to the formation of the Sajó alluvial fan. The development of this section of the Sajó Valley was strongly influenced by the structural evolution of the Bükk Mountains and the Cserehát Hills, as well as by their tectonic changes and the northwestward shift of the Tisza River during the Pleistocene. The formation of the present-day channel orientation of the Sajó River was largely controlled by the gradual but intensive uplift of the northern foreland of the Bükk Mountains, which began in the Miocene (Gábris Gy. 1970).

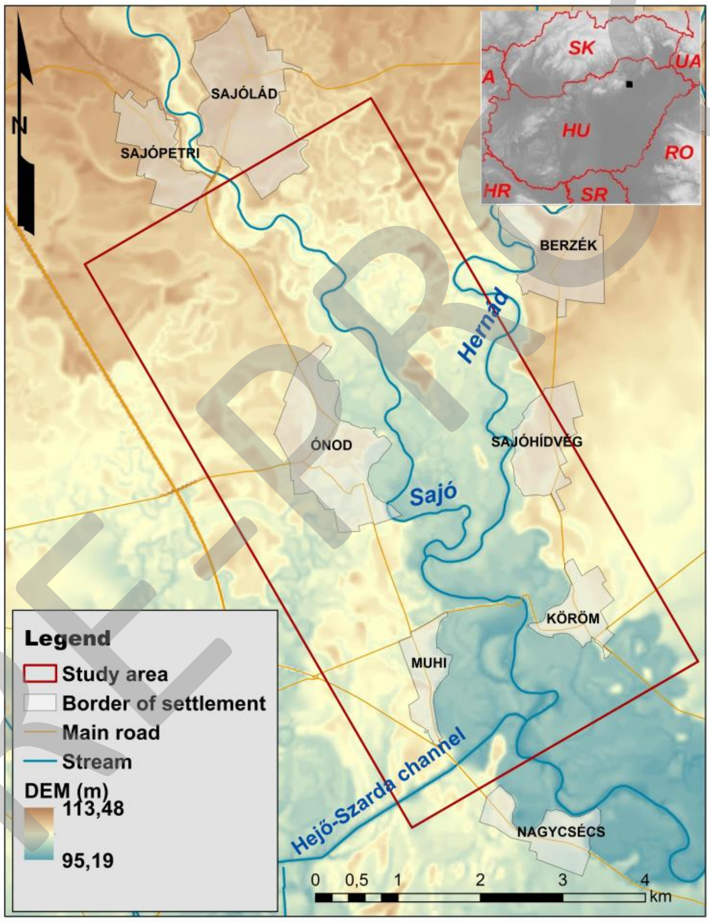

Figure 1.
Location of the study area

The establishment of the main channel direction of the Sajó started in the Late Miocene and continued into the Pliocene following Miocene volcanism (Mike K., 1972, Láng S. 1944). During this period, the Sajó and Hernád rivers joined the Tisza approximately 120 km south of their present confluence (Vadász E. 1960, Somogyi

S. 1961). Due to the Pleistocene uplift of the initial section of the Sajó Valley, the river began gradual incision north of the Miskolc Gate, while strong aggradation commenced toward the south–southeast during the Pleistocene (Láng S. 1944). As a result of these processes, the lowland alluvial fan constructed by the two rivers was formed (Franyó F. 1966). During this period, the Sajó built an alluvial fan extending far into the Great Hungarian Plain. Surface aggradation of this fan was largely completed by the end of the Pleistocene, whereas sediment accumulation within the valleys continued until the Early Holocene. The development of the present hydrographic network of the Sajó River dates to the Holocene and, based on previous studies, is estimated to be approximately 5,000 years old (Láng S. 1944). During the same period, both the Sajó and the Hernád rivers began to incise into their own alluvial fan deposits (Dövényi Z. 2010). The unified alluvial fan extends across the entire mesoregion. Its apex is located near Miskolc, and it stretches approximately 30 km southward with an average width of about 3 km (Dövényi Z. 2010, Csoma J. 1972). The section of the alluvial fan can be subdivided into several units representing different channel generations (Figure 2.).

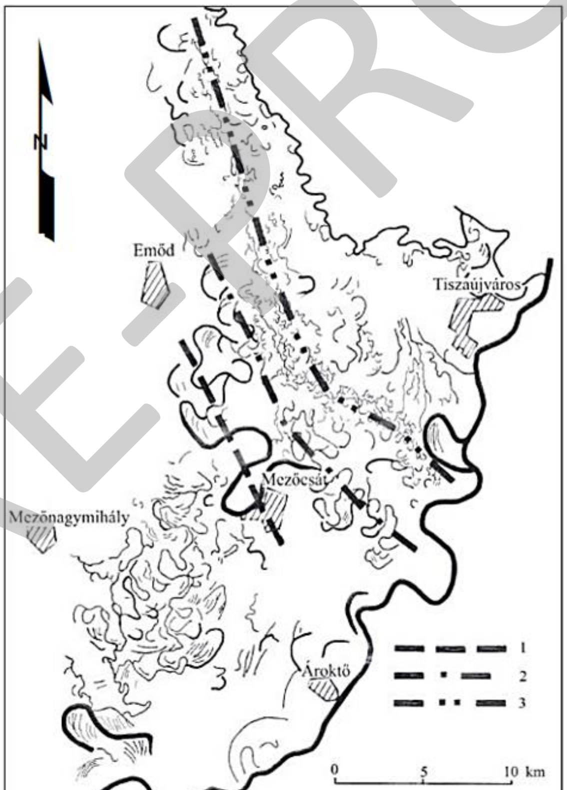

Figure 2.
Palaeodrainage directions on the Sajó alluvial fan during the Late Pleistocene–Holocene (Gábris Gy. 1970)

These form three distinct levels, separated by two phases of incision. The individual levels are delineated by well-defined erosional scarps. From the perspective of this study, the third channel-generation unit is of particular importance, as it demonstrates that during the subboreal humid phase of the Holocene, the Sajó–Hernád river system already flowed within its present channel. In subsequent periods, increased precipitation led to renewed incision into the alluvial fan on two occasions; however, neither the Sajó from the east nor the Hejő Stream from the west was able to completely breach the fan (Csoma J. 1972). Traces of these incision phases have been preserved despite aeolian modification and can be clearly identified on aerial imagery. The climate of the mesoregion is moderately warm and dry. The annual duration of sunshine ranges between 1,850 and 1,900 hours. Mean annual air temperature varies from 9.3–9.6 °C in the northern part of the area to 9.7–9.9 °C in the southern part. Approximately 60% of the annual precipitation falls between May and October, with maximum values occurring in June and minimum values in January–February. The spatial distribution of annual precipitation ranges between 540 and 580 mm. The aridity index is 1.20 in the northern part of the region and 1.30 in the southern part. The prevailing wind direction is from the north to northwest, with an average wind speed of 2.5 m/s (Dövényi Z. 2010). Soil types within the area show considerable spatial variability. Soils in the Sajó Valley are predominantly acidic, whereas those along the Hernád River are carbonate-rich or weakly acidic. On gravelly substrates, alluvial meadow soils and meadow soils have developed, with small patches of saline soils and steppe-like meadow solonetz soils. On loess-covered terraces, meadow chernozems and calcareous meadow chernozems are dominant, while brown forest soils occur toward the piedmont surfaces. Land use in the region is largely agricultural and closely reflects the natural environmental conditions described above (Dövényi Z. 2010).

2.2. Review of previous GIS-based studies in the study area

As an initial step, all available cartographic sources of the study area (land-use maps, historical military surveys, flood inundation boundaries) were integrated into a GIS database. A drainage network of the wider study area was derived from Hungarian Water Directorate's digital elevation model (HydroDEM) with a spatial resolution of 5 m, (DEM) with a spatial resolution of 5 m which, after filling surface artefacts (fill), was suitable for representing surface runoff. A 5 m spatial resolution DEM was selected as an optimal compromise between spatial detail and noise reduction in the low-relief floodplain environment. While higher-resolution datasets (e.g., 1 m) provide greater micro-topographic detail, preliminary tests indicated that they also amplify local surface irregularities related to vegetation remnants, ploughing patterns, and minor anthropogenic disturbances, which may obscure broader geomorphological structures. Conversely, coarser resolutions (e.g., 10 m) resulted in the loss of subtle elevation differences critical for identifying low-amplitude fluvial and anthropogenic landforms. The 5 m resolution therefore ensured sufficient sensitivity to micro-relief variations while maintaining geomorphological interpretability at the landscape scale. Based on these datasets, a geospatial framework was established for an area of approximately 140 km², including sub-catchments associated with the Hejő, Szinva and Sajó watercourses, as well as a vector dataset of flood inundation heights was obtained from the Flood Risk Management Plan prepared by the Hungarian Water Directorate (ÉMVIZIG, 2014), representing the maximum inundation extent of the 2010 flood event. Areas not affected by the Highest Recorded Flood Level (HFL) were delineated and interpreted as permanently dry zones under present hydrological conditions. . These areas were proposed as potential targets for archaeological research. While several zones coincide with previously investigated sites, additional areas were newly identified (Dobai A. and Dobos E. 2022). The spatial distribution of these zones corresponds well with the known structure of early medieval settlement networks, characterized by inter-settlement distances of approximately 2–3 km (P. Fischl K. and Pusztai T. 2018). Building upon these results, the second step of the research involved hydrological analyses focusing on narrower areas considered key for investigating the presumed site of the Battle of Muhi and early medieval settlement patterns. These analyses were conducted using a corrected DEM, from which present-day surface features (e.g., linear infrastructure) were manually removed, resulting in a new DEM. The new database was supplemented with DEM-derived parameters, including slope gradient, surface flow accumulation, and the topographic wetness index (TWI). In addition, sub-catchments associated with right-bank outflow points of the Sajó River were identified and analysed (Dobai A. and Dobos E. 2023).

The results demonstrate that the extracted drainage branches are not artefacts produced by flow accumulation algorithms, but represent real, former drainage paleochannels. Along the Hungarian reach of the Sajó River, floodplain basins are predominantly located on the left bank; however, the investigated Szirma–Sajóörös basin represents a right-bank floodplain system. Within this basin, three former Sajó branches were identified, which may become reactivated during flood events exceeding the HFL. One of these channels, referred to as the Sajó III–Ónod branch, emerges at river km 34+100 of the Sajó River, near the flood protection levee of Ónod settlement. The channel crosses Ónod over approximately 3.5 km in a northeast–southwest direction and connects to a southward-flowing channel that does not rejoin the Sajó River. Instead, the multi-branch drainage system can be traced to the administrative border of Szakáld (Dobai A. and Dobos E. 2023). Several segments of these former channels are also identifiable on maps of the First Military Survey. A former confluence of the Bársonyos Stream is located approximately 1.2 km northeast of the Sajó III–Ónod palaeochannel. No research has yet been conducted on the relationship between the two channels. It should be noted that a more detailed survey of the former Hernád catchment warrants a separate investigation, as it reveals extensive, continuous drainage networks that in several locations are connected to the contemporary floodplain of the Hernád River at river kilometres 3+500 and 5+100. The results of József Laszlovszky's investigation into the shared channel system of the Hernád and Sajó pertain to the area between river kilometre 34+000 of the Sajó and 2+500 of the Hernád (Laszlovszky J. and Nagy B.

2023). The size of the catchment is also explained by the presence of a multi-order flow network within the area.

Based on the analysis of the vector datasets, it was determined that certain right-bank sections of the river can typically be regarded as suitable for the establishment of bridgeheads providing a river crossing. This suitability is attributed to the presence of the Sajó River's channels (Sajó I, II, III), which, in the absence of modern flood protection structures, drain excess floodwater more efficiently during high-flow events. Consequently, the hydraulic force of the flood wave is reduced, relieving a substantial portion of the riverbanks from flood-related stress. This pattern is corroborated by the flood inundation boundaries recorded by the North Hungarian Water Directoriate during the 2010 flood event.

As a third step of the research, the narrowed study areas were subdivided into 3 km x 3 km zones (A, B, C, D) and 1.5 km x 1.5km subzones (A1, B2, C3, etc.), reducing the examined sample area to 36 km². In the following, the steps undertaken for the identification of the site located in subzone D1 are presented (Figure 3.).

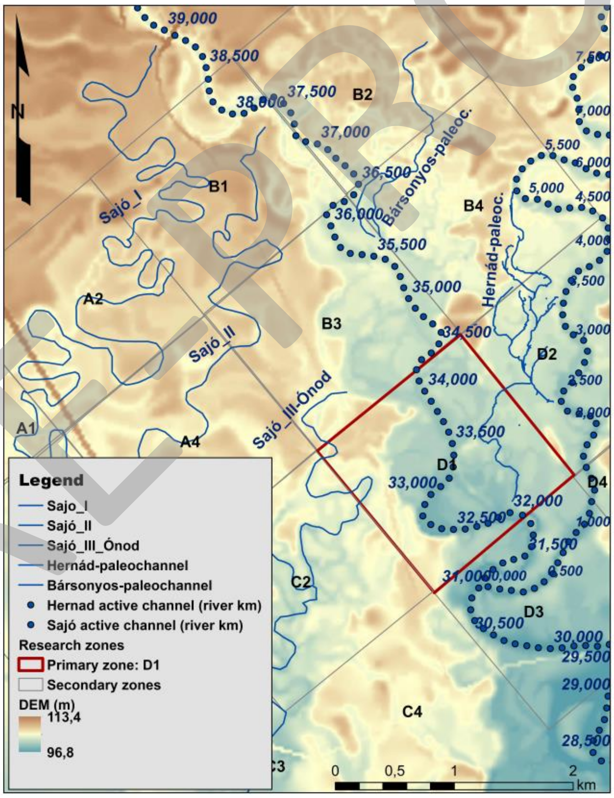

Figure 3.
Summary map of previous GIS-based analysis in the study area

2.3. Presentation of the new GIS methodology

In the present study, the database containing the previously presented datasets was supplemented with additional raster layers and terrain-descriptive indices. As a first step, different flood stages (Grades I–III), as well as the Highest recorded Flood Level (HFL) of 2010, were delineated on t* a pre-produced digital elevation model (DEM) provided in geoTIFF format by Envirosense Ltd., derived from a UAV-based LiDAR (Light Detection and Ranging) survey. The study relied exclusively on this ready-made DEM product, as the raw LiDAR point cloud and detailed preprocessing metadata were not accessible, the underlying technical parameters of the dataset could not be fully assessed.These flood inundation boundaries define the spatial extent of floodplain dynamics within the Sajó River corridor and identify areas that are no longer regularly flood-affected. For subsequent analyses, these areas were designated as *stable banks*, adopting terminology from practical water management, a concept essentially equivalent to *high banks* (HGD 147/2010), as this term more precisely captures the functional characteristics relevant to the objectives of the present study. The delineation of stable banks was necessary to enable the measurement of distances between riverbank sections defined by the maximum observed inundation extent and associated discharge conditions. These straightforward calculations can provide an adequate basis for identifying potential crossing points along the Sajó River, as such locations may play a key role in analyses of both the 13th century settlement network and issues related to the Battle of Muhi. In addition, a Relative Elevation Model (REM) was generated for the study area. The REM is a spatial data model that represents variations in surface elevation relative to a defined reference level rather than absolute elevation values (John M. R. et al. 1998; Kairis and Rybczyk 2010). The REM used for geomorphological analysis was computed as the difference between the working DEM and a smoothed floodplain reference surface (REM = DEM − reference_surface). The reference surface was produced by applying a low-pass smoothing filter (moving-window mean: 50 m window) to the DEM to remove micro-topographic noise while retaining the regional floodplain slope. To account for the scale-dependent expression of floodplain landforms, additional REM layers were generated using different window sizes. Smaller window sizes (10–20 m) enhanced short-wavelength features such as levees and scroll bars, while intermediate windows (30–60 m) emphasized abandoned channels and depressions. Larger windows (>80–100 m) progressively suppressed local relief and highlighted broader floodplain gradients. This multi-scale approach allowed us to distinguish geomorphological units of different spatial extents and ensured that the interpretation was not biased by a single smoothing scale (Greco, S. et al. 2008). The application of the REM facilitates the identification of geomorphological features such as valleys, ridges, and slopes, and, in combination with the delineated flood inundation boundaries, supports further spatial analyses.

3. Results

The examination of the riverbank zones was conducted based on previously established 2-3 km distance criteria and the results of the Relative Elevation Model (REM). According to the REM analysis, on the left bank of the Sajó River, approximately 240 m from the river's centerline, 683 m southeast of the Ónod Castle, and 623 m from the remains of the Sajóhídvégi Church, a topographically distinct, isolated landform was identified (Figure 4.).

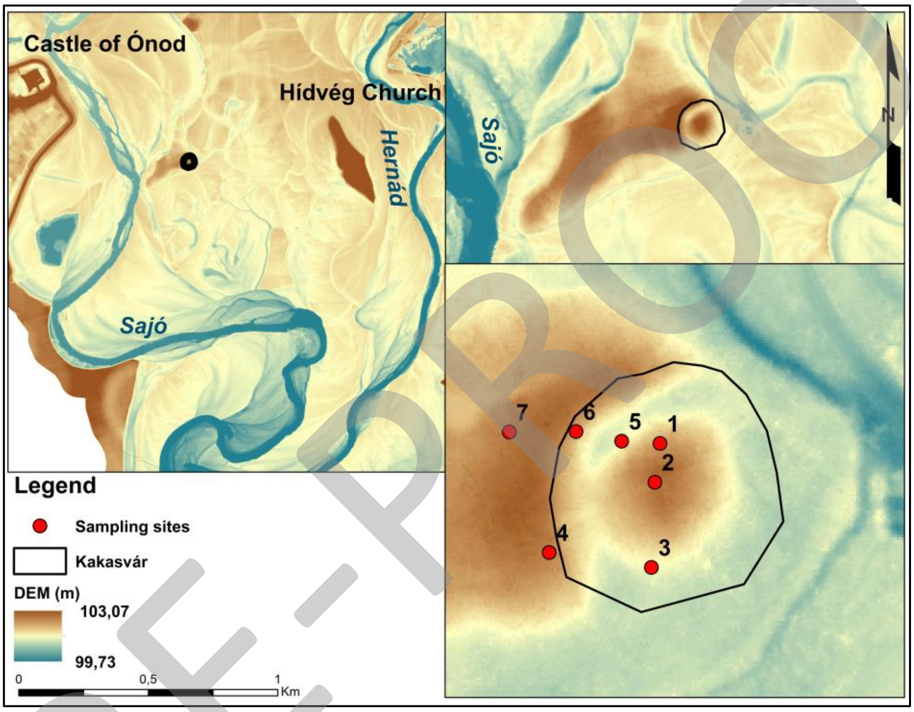

Figure 4.
Result of the REM analysis and location of Kakasvár archeological site

The Sajó–Hernád Plain is generally characterized by a low-relief, monotonous flat surface (Dövényi Z. 2010). In contrast, the investigated landform rises on average about 2 m above its surroundings, showing stronger erosional features on its southern and eastern slopes. It is located within a stagnant flow zone that is only minimally affected by floods, exhibiting flow velocities of merely 0.0–0.5 mm/s even under extremely high-water conditions. This velocity range is insufficient to generate channel-forming discharge. The delineation of flow zones is based on sand transport and deposition velocities, providing a suitable basis for interpreting historical channel migration processes in the area (Kiss P. 2018).Based on the I., II., and III. Military Survey maps, as well as archival aerial imagery from fentrol.hu and Google Earth, the area appears to have been continuously forested over an extended period. The landform is situated on the outskirts of Ónod, on plot number 0159, within the area referred to as Kakasvár (Ónod Urban Development Plan, 2014). The site remains forested with dense undergrowth; consequently, only approximate dimensions can be provided until further excavations are conducted. The principal characteristics of the site are summarised in Table 1.

Table 1.

Morphometric and spatial characteristics of the Kakasvár site

Parameter	Value	Parameter	Value
Total site area	2006 m²	**Inner circular area**	~496 m²
Highest elevation of inner area (m, a.s.l.)	102.8	**Outer circular + moat area**	1510 m²
Lowest elevation of outer area (m, a.s.l.)	100.7	**Percentage of inner area**	~24.7%
Elevation difference (inner–outer)	2.1 m	**Length of semicircular ridge**	~60 m

The site comprises a near-circular central platform enclosed by a surrounding moat and an outer, higher-elevated zone (Figure 5.). The inner plateau represents the feature's highest ground, while the moat forms a pronounced depression around it. A semicircular ridge borders the circular form along a north–south sector; this ridge is composed of clay-rich deposits with progressively sandier layers at depth. The circular feature is sharply separated from the outer ridge, indicating deliberate detachment, and a connecting sector on the western side appears to have developed secondarily through deposition of eroded material. Although the site's position and sandy substrata might initially suggest an alluvial origin, its morphology and structural relationships are more consistent with anthropogenic construction. The landform occupies remnants of an alluvial fan and lies adjacent to palaeochannel traces, and field observations therefore also recorded characteristics typical of former flow channels. While the size and moat configuration could be compatible with a tell-type feature, artefactual evidence recovered during a non-invasive survey does not support a Neolithic or Bronze Age attribution. Overall, the morphostratigraphic evidence points to a constructed feature whose function and chronology remain to be established through targeted subsurface investigation.

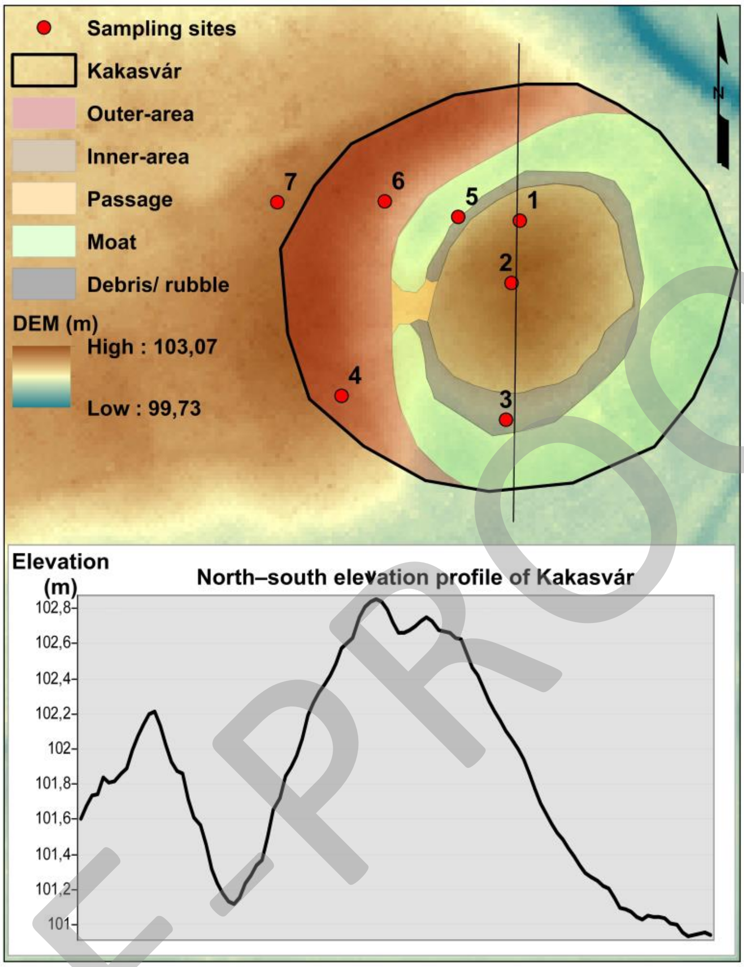

Figure 5.
Structure of Kakasvár and north–south longitudinal elevation profile

On May 2, 2024, field survey, non-invasive examination (metal detector survey), and soil sampling were carried out at seven points. Only cores exhibiting soil-relevant differences were photographed, as most cores contained homogeneous material. The surface layer is predominantly clayey loam, transitioning sharply to sand at a depth of approximately 60 cm in the central area (points 1, 2, and 4). Within the moat (point 6), humic material, eroded from surrounding higher terrain, was observed down to 1 m depth; it was compacted but had a well-developed root structure. In the southern (point 3) and northern (point 6) areas, smaller debris was encountered from 60 cm depth, while at point 5, brick material appeared from 90 cm depth onward (Figure 6).

***Figure 6*.**
Artefacts unearthed at the Kakasvár site

The non-invasive survey covered a larger area than that accessed by coring. During this survey, construction nails and wooden fasteners were recovered from the inner zones, while various metal fittings and other iron artifacts (e.g., keys, blade-shaped objects) were found in the outer zones. At point 7, horseshoes, hoes, and other recent artifacts were concentrated within the upper 10–15 cm of the surface. The surveyed area was designated as *Kakasvár* based on the name appearing in the urban development plan of Ónod. The site was further validated using the map from 1791 (HU MNL BAZML IV.501.e. 2393/1791) by the National Archives of Hungary, which shows a precise correspondence with the location. Based on the analysis of both archival and digital sources, it can be concluded that the identified area likely held a prominent significance in the region. The relationship between flood inundation limits and the site's proximity to Hídvég Church indicates a potential role in facilitating river crossings along the Sajó, possibly contributing to the local socio-economic functioning of the area. Consequently, given its location, the site may have held considerable strategic significance, and its potential role in the Battle of Muhi cannot be excluded; however, further investigation is needed to confirm this. The precise localization of the Kakasvár site represents a significant achievement, as previous archaeological research was unable to delineate the site with such accuracy.

4. DISCUSSION AND CONCLUSIONS

Despite several centuries of scholarly research, the reconstruction and interpretation of the Battle of Muhi and its contemporary settlement network continue to pose significant challenges to researchers in the field. The aim of the present study was to demonstrate how Archaeo-GIS methodologies based on high-resolution topographic data and complex spatial analyses can contribute to a more precise understanding of spatial and environmental relationships, thereby providing a foundation for the spatial reconstruction of the Battle of Muhi and the re-evaluation of the 13th-century settlement network. Previous archaeological investigations were unable to precisely localise the Kakasvár site, largely due to the absence of high-resolution topographic modeling and a systematic clarification of hydrological conditions. Earlier interpretations relied primarily on historical maps, surface observations and approximate spatial correlations, which proved insufficient in the geomorphologically subtle environment of the Battle of Muhi. In contrast, the integration of REM analysis and hydrological zoning enabled the identification of a morphometrically coherent landform and its clear separation from surrounding fluvial units.

The integration of high-resolution LiDAR-derived DEMs, flood inundation data, Relative Elevation Models (REM), and hydrological indices enabled the identification of subtle terrain features that are not discernible through traditional cartographic sources or conventional field observation alone. In a low-relief floodplain environment such as the Sajó–Hernád Plain, even minor elevation differences of 1–2 m may have had substantial functional significance in terms of flood safety, accessibility, and visibility. The REM-based analysis proved particularly effective in highlighting isolated relict landforms embedded within an otherwise monotonous alluvial surface, enabling the clear spatial separation of the Kakasvár feature from surrounding geomorphological units. The applied workflow is transferable to other floodplain analysis along major river systems such as the Tisza River and the Danube River, provided that DEM resolution is carefully selected and hydrological parameters are locally calibrated. In such environments, reliable identification of anthropogenic features is contingent upon the joint interpretation of relative elevation and flood dynamics rather than on morphological observation alone.

The identified landform at Kakasvár exhibits a combination of characteristics that strongly suggest an anthropogenic origin. Its circular morphology, moat-like depression, outer elevated zone, and spatial detachment from surrounding sedimentary structures cannot be satisfactorily explained by fluvial or aeolian processes alone. The available evidence points toward a later, possibly medieval construction, the function of which remains to be clarified through future targeted excavation. From a functional perspective, the site's location is of particular interest. The site lies within a hydrodynamically stable zone, minimally affected even by flood events. Such settings are consistent with locations suitable for river crossings, bridgeheads, or controlled access points, all of which may have been strategically relevant during the medieval period. This environment would have provided favourable conditions for river crossing, movement control, or temporary refuge during periods of flood event.

In methodological terms, the study highlights the value of Archaeo-GIS approaches that move beyond descriptive mapping and apply analytically defined spatial criteria. The integration of flood inundation boundaries, stagnant flow zones, and relative elevation as interpretative variables offers a replicable workflow applicable to other lowland battlefield and settlement studies. At the same time, the research also underscores current limitations, particularly the need for higher-resolution subsurface data (e.g., Ground-penetrating radar (GPR), magnetometry) and systematic archaeological verification to complement GIS-based interpretations. While the exact function and chronology of the site remain open questions, the GIS-based analyses presented here provide a robust spatial and geomorphological toolkit for future investigations. The results support the view that interdisciplinary integration of archaeology, physical geography, and geoinformatics is essential for advancing the understanding of medieval conflict landscapes, especially in geomorphologically subtle lowland environments.

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