RESEARCH ARTICLE – VÝZKUMNÝ ČLÁNEK

Digital spatial modelling for encampment localisation related to the Battle of Mohi (1241), Hungary

Digitální prostorové modelování lokalizace tábora spojeného s bitvou u Mohi (1241), Maďarsko

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The Battle of Mohi in 1241 was a major clash between the Kingdom of Hungary and the Mongols invading Europe. Recent research on the battle has increasingly refined our understanding of the events surrounding the confrontation. Although these studies build on a shared scholarly foundation, they rely on heterogeneous spatial datasets, as no unified GIS database is yet available. This limits the full use of tools such as Historical GIS (HGIS), which can integrate these heterogeneous datasets into a unified, archaeologically oriented database to facilitate analysis and interpretation. The present study introduces a high-resolution potential-mapping approach aimed at identifying the likely position of the Hungarian camp. The analysis integrates archaeological, military–historical, and relevant environmental data, weighted through the Analytic Hierarchy Process (AHP), resulting in a five-meter-resolution potential map. The findings contribute to a more spatially grounded reconstruction of the battle and offer a methodological basis for future archaeological investigations.

GIS – Battle of Mohi – AHP weights – REM – LiDAR

Bitva u Mohi roku 1241 představovala zásadní střet mezi Uherským královstvím a Mongoly postupujícími do Evropy. Nedávné výzkumy této bitvy zpřesnily naše chápání událostí spojených s touto konfrontací. Ačkoli tyto studie vycházejí ze společného badatelského základu, opírají se o heterogenní prostorová data, protože dosud neexistuje jednotná databáze GIS. To omezuje plné využití nástrojů, jako je historický GIS (HGIS), který by mohl tato různorodá data integrovat do jednotné, archeologicky orientované databáze a podpořit jejich analýzu a interpretaci. Tato studie představuje přístup založený na tvorbě detailního potenciálového modelu, jehož cílem je identifikovat pravděpodobnou polohu uherského tábora. Analýza propojuje archeologická, vojensko-historická a relevantní environmentální data, vážená metodou analytického hierarchického procesu (AHP), přičemž jejím výsledkem je potenciální mapa s rozlišením pět metrů. Zjištění přispívají k prostorově ukotvenější rekonstrukci bitvy a poskytují metodologický základ pro budoucí archeologický výzkum.

GIS – bitva u Mohi – váhové koeficienty AHP – DMR – LiDAR

Introduction

One of the most consequential processes in the 13th-century Eurasian realignment of power was the expansion of the Mongol Empire, which from the 1230's onward posed an increasingly direct threat to Eastern Europe. The Mongol invasion of Europe was grounded in a complex strategic system based on rapid mobility, a unified command structure, and the multi-layered use of intelligence (*Jackson 2017*, 92–94). Their operations against the Rus' principalities demonstrated this efficiency vividly: between 1237 and 1240, the Mongols systematically conquered and devastated the fragmented Rus' polities, while

https://doi.org/10.35686/AR.2026.320

simultaneously seeking to integrate local political networks into the imperial system as tribute-paying client structures (*Halperin 1987*, 3–6). After consolidating their dominion over the eastern Slavic territories, the offensive shifted westwards, where the Carpathian Basin held key strategic importance both militarily and economically.

The Hungarian Kingdom at this time was experiencing a period marked by internal tensions, especially concerning the settlement of the Cumans and the balance of power among the nobility (*Engel 2001*, 99). Prior to the campaign, the Mongol leadership dispatched envoys to King Béla IV demanding his submission, a request the king rejected while seeking diplomatic support from the papacy, which ultimately did not translate into effective military assistance (*Berend 2013*, 34). In the spring of 1241, Mongol forces entered Hungary from three main directions, overcoming the defensive structures constructed at the Carpathian passes, which in any case did not constitute a coherent or adequately organised system (*Kristó 2007*, 226). The Mongol army had advanced as far as the Danube line, reaching the region of Pest by mid-March 1241, prompting Béla IV to mobilise a rapidly assembled Hungarian force composed largely of cavalry. Avoiding a pitched battle, the Hungarian army followed the Mongols eastward and on April 10 reached the Sajó River, where the Hungarian camp was established along the riverbank.

The reconstruction of the battle is nevertheless constrained by the scarcity of near–contemporary narrative sources, chiefly Rogerius and Thomas of Split. Both sources provide descriptions of the battle with differing levels of detail and perspective. However, two locations stand out as particularly important: the Hungarian camp, located close to the Sajó River, and the bridge over the Sajó, which is considered the site of the initial engagement. The two sources are somewhat confused regarding the location of the camp and the bridge. They mention a bridge crossed by the Hungarian army, but do not always specify the river. They also indicate that the camp was on the left bank when advancing from west to east. At first glance, this seems contradictory, because the Hungarian forces are also reported to have repelled a Mongol detachment at the Sajó Bridge on the night of April 10, which, according to the description, should have been either near the Hungarian camp or even to its west. In that case, continuous military supplies would not have been able to reach the Hungarian camp from the west. In this context, it is important to add that the distance between the Hungarian camp and the Sajó Bridge may have been substantial.

Négyesi (*1997*, 296) offered a detailed discussion of the events preceding the clash at the Sajó Bridge on April 10. According to his calculations, sunset on that day likely occurred at 18:29, with suitable visibility lasting until approximately 19:30. Even so, the bridge may have been located roughly 7 km away, while the engagement there reportedly took place around midnight. The return from the clash to the camp then followed around 3 a.m. In the subsequent Hungarian defeat at the bridge on April 11, it is striking that reinforcements were apparently not sent from the theoretically nearby Hungarian camp, and that neither the sounds nor the sight of the battle were perceived by the camp itself or by Hungarian soldiers patrolling the area. This observation underlies one of the conceptual bases of the present study, namely the establishment of an average audiovisual range of approximately 1 km. As a result, the exact locations associated with the battle cannot be fixed with full certainty, and both the reconstruction of the battlefield and the estimated size of the armies have long remained matters of scholarly debate.

The battle itself, fought on 12 April 1241, ended in a devastating defeat for the royal Hungarian army. Fragmented command, the tactical limitations of heavily armoured cavalry, and the Mongols’ concentrated ring of mounted archers all contributed to the disaster (*Pow 2022*, 185–186). Following the battle, the Mongols quickly occupied significant parts of the Great Plain and Transdanubia, during which numerous towns and ecclesiastical centres were destroyed. The scale of demographic losses remains debated: while contemporary chronicles report widespread destruction, archaeological evidence indicates that the settlement network suffered unevenly and certain areas remained largely unaffected (*Laszlovszky et al. 2016a*, 189–191; *Wolf 2018*, 138). The Mongol withdrawal in the spring of 1242 has traditionally been explained by the death of the Great Khan and the ensuing internal political transitions; however, environmental factors such as the freezing of the Danube may also have influenced strategic decision–making (*May 2012*, 25–28). The long-term consequences of the Mongol invasion in Hungary included a royal castle-building programme, the emergence of new types of stone fortifications, and a transformation of settlement policies, all of which strengthened royal authority and partly reoriented the kingdom’s subsequent medieval development.

The localisation of the Battle of Mohi and the Hungarian camp

Research into the location of the April 1241 battle and the possible position of the Hungarian camp remains a prominent topic in both archaeology and military history. The complexity of the issue arises partly from uncertainties in reconstructing contemporary conditions such as road networks and settlement patterns, and partly from natural geographical factors including ambiguities surrounding the former channels and drainage systems of the Sajó and Hernád rivers. Nevertheless, contemporary European and Chinese sources consistently place the events of the battle within the same broader area (*P. Szabó 2022*, 114). This includes the Sajó Bridge on the right bank of the river, where the first clash occurred, the sites of several smaller clashes in the vicinity of the settlement of Muhi (Mohi) and the Hungarian camp, where the final battle unfolded. However, the exact locations of both the bridge and the camp remain unidentified. Although the medieval settlement of Mohi has been excavated, the investigations have not yielded a quantity or type of finds that would conclusively demonstrate that the area was directly involved in the military events (*Wolf 2018*, 136–139).

Determining the chronology and assessing involvement in the battle pose significant challenges even at the international level, despite the application of modern methodologies and careful analyses (*Krapiec – Piekalski 2019*, 323–324; *Piekalski 2023*, 125–127). The Mongol invasion was brief yet unfolded abruptly across dispersed regions, while its effects lasted for years, complicating the stratigraphic record. As a result, the secure identification of layers attributable specifically to the invasion, as opposed to other destructive events or later rebuilding activities, becomes methodologically problematic.

Even though many fundamental questions concerning the Mohi battle have persisted for centuries, the continuous processing and interpretation of an expanding corpus of textual, archaeological, and interdisciplinary sources has allowed research to advance steadily toward a more nuanced, realistic, and methodologically grounded reconstruction of the event (*P. Szabó 2022*, 114). On the basis of growing knowledge, it has become possible to refine estimates of the number of participants, the circumstances surrounding the establishment of the camp, and the possible scenarios of the engagement itself (*Bánlaky 1932*, 369–372; *Veszprémy 1994*, 28–35; *Wolf 2014*, 139). Two key areas of investigation are the reconstruction of contemporary physical–geographical conditions and the assessment of the medieval settlement network (*Laszlovszky et al. 2016b*, 32; *Pusztai 2014*, 29). Despite technological advances, research aimed at localising the battlefield and the encampment still has not fully exploited the potential offered by modern geoinformatics and high-resolution spatial data (*Négyesi 1997*, 295; *Laszlovszky – Nagy 2023*, 950; *Négyesi 2024*). This is largely due to the absence of unified, GIS-based databases that would enable the widespread application of archaeological GIS methodologies and geostatistical analyses. As a result, several important analytical perspectives and evaluative opportunities remain underutilised, even in cases where high-resolution datasets (e.g. LiDAR) and maps are available.

To address these deficiencies, we launched a multi-stage research programme that employs the framework of the Geographic Information System. GIS databases and tools provide a framework for integrating heterogeneous spatial, temporal, and archaeological data into a coherent research platform, enabling high-resolution analysis and predictive modelling. This framework is complemented by Historical GIS (HGIS), which treats GIS not merely as a mapping tool but as an analytical approach that integrates spatial, temporal, and attribute information to address historiographical questions (*Gregory – Ell 2007*, 64–65; *Sarris 2024*, 9–10). Within this framework, the project examines the potential inundation (flood) limits of the Sajó River on the basis of morphological and hydrological indices derived from a digital elevation model (DEM) with a spatial resolution of five metres (such as the Topographic Wetness Index – TWI, slope, flow accumulation, and watershed analysis), as well as data from the Flood Risk Management Plan by the Hungarian Water Directorate (*ÉMVIZIG 2014*).

Our previous analyses enabled the delineation of the local catchment areas of the Hejő, Szinva, and Hernád streams within the 140 km² study area, and identified potential flow branches on the right-bank watersheds of the Sajó that could be reactivated during flood events and form a coherent hydrological system. These were designated by the study as Sajó I, Sajó II, and Sajó III flow branches (*Dobai – Dobos 2022*, 103–104; *2023*, 360). In the absence of modern flood control, these former channels would likely still be active today (e.g. Sajó–III, which even now requires pumping within the urban area of Ónod). This suggests that in the event of flooding, crossing the Sajó as described 'then encamping on its left bank' would have been possible, since one of the Sajó's branches was indirectly connected to the Hejő marshlands. The encampment on the left bank is, in fact, confirmed by both Rogerius and Thomas of Split (*Wolf 2018*, 138). From a geological perspective, this concerns flow processes along the former branches of the Sajó within Late Pleistocene to Early Holocene deposits (fQ_{h1hal}, fQ_{h2alh}) belonging to the third river-generation, which can be identified at three locations on the DEM (*Gábris 2022*, 55–56; *Csoma 1972*, 10–13).

The primary aim of the present study is to produce a potential map of locations suitable for encampment, using the databases assembled by earlier research. In addition, the investigation addresses the evaluation of spatial characteristics of the identified archaeological site. The GIS-based Encampment Suitability Map (ESM), which integrates archaeological perspectives, provides a solid foundation for the future spatial analysis of artefacts (*Laszlovszky – Rácz 2020*, 186–187). Furthermore, it may contribute to the interpretation of archaeological finds and help confirm potential alternative hypotheses regarding the location of the camp, including the predominantly eastern camp location between the Hejő and the Sajó, as well as the debatable but not entirely dismissible possibility of a campsite along the Hejő (*Wolf 2018*, 138).

Materials and methods

Study area

The analysis was carried out within the study area extending between Sajópetri, Emőd, and Kesznyéten, based on a comprehensive GIS database. The study area lies on the Sajó–Hernád alluvial fan plain in northeastern Hungary. The region is a Late Pleistocene, filled, low-relief alluvial plain formed by the Sajó and Hernád rivers through the deposition of gravelly, sandy, and silty sediments during the Quaternary. Its surface is generally very uniform, interrupted only by minor depressions, abandoned channels, and weakly expressed levees (*Dövényi 2010*, 215–216).

Presentation of GIS Database input data

The criteria for identifying an optimal campsite were fundamentally based on Tamás Pusztai's research on the early medieval settlement network (*Fischl – Pusztai 2018*, 84–85). The geographical interpretation is built upon our previous results and the studies of József Laszlovszky and Balázs Nagy, as well as the relevant military-historical literature (*Veszprémy 1994*, 30; *Dobai – Dobos 2023*, 360; *Laszlovszky – Nagy 2023*, 950–961; *Négyesi 2024*, 13). To define the environmental characteristics of a suitable campsite, such as a secure position, defensibility, and protection from flooding, we classified multiple geospatial layers, including slope, TWI, the relative elevation model (REM), potential drainage density (*Dobos – Daroussin 2005*, 40–42), and estimated flood-inundation boundaries (*Kiss 2018*, 46). Analysing the hydrological conditions of the study area and expanding the associated knowledge remains an ongoing task. In this context, an archival document HU MNL BAZML IV.501.e. 2393/1791 detailed, coloured map (*Fig. 1*) was digitalised and then analysed. The map was dated 1775 and originally created to establish the territorial affiliation of Alberek Forest, situated between Ónod, Sajóhídvég, and Köröm on the Sajó and Hernád floodplains (*Bodnár 2021*).

The map's features provided crucial guidance for localising the former church site of the Sajóhídvég settlement. This site is particularly important because the place name itself (*Sajó* – referring to the river, *híd* – bridge, *vég* – end; literally meaning 'end of the bridge over the Sajó') implies the former existence of a bridge associated with the Sajó River. However, the present–day settlement is located along the Hernád River, which suggests a possible shift in the fluvial or settlement context. Therefore, the related information is essential for expanding our understanding of the historical landscape (*Bodnár 2021*). For this reason, sites located in the area between the Sajó and Hernád rivers (e.g. churches) can be used as reference points for the reconstruction of the contemporary settlement network. The scanned map was first georeferenced and then converted to vector format, producing a digital dataset that served as a reliable validation tool for the previously identified archaeological sites.

Among the DEM-derived variables employed in this study, particular attention was given to the Topographic Wetness Index (TWI) and the Relative Elevation Model (REM)

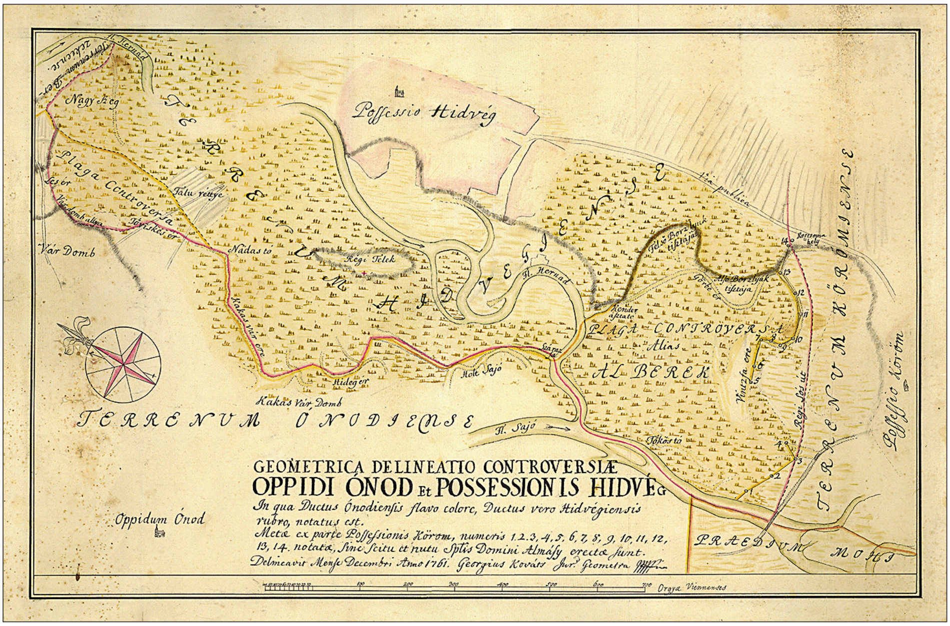

Fig. 1. Original 1775 map of the Alberek Forest (*National Archives of Hungary, HU MNL BAZML IV.501.e. 2393/1791*).

(*Mohamed 2020*). The TWI is fundamental for characterising the spatial distribution of surface moisture and the organisation of runoff processes. Within the mapping framework, its classification proved especially valuable, as it enables the identification of topographic controls on runoff as well as areas susceptible to water accumulation. High TWI values delineate convergent landforms with enhanced water-retention capacity, whereas low values correspond to divergent slope segments associated with rapid drainage. As a result, the TWI is effective not only for delineating potential flow pathways but also for supporting the spatial differentiation of surface–water features in relation to local terrain properties.

The TWI quantifies the potential for soil–moisture accumulation (*Mohamed 2020*, 10–11). Its classical formulation is expressed in the equation:

$$\mathrm{TWI} = \ln\left(\frac{a}{\tan\beta}\right),$$

where,

a denotes the upslope contributing area per unit contour length ($m^2\,m^{-1}$), and

β is the local slope angle (radians).

The Relative Elevation Model (REM) is a terrain-derived metric that expresses the elevation of each surface point relative to a reference line or surface, most commonly an interpolated riverbed level or drainage baseline. Rather than absolute altitude, the REM highlights fine-scale topographic variation within floodplains and low-relief landscapes by quantifying how much a location rises above the hydrologically relevant reference elevation (*Greco et al. 2008*, 71). This makes the REM particularly effective for identifying microrelief, distinguishing geomorphic units, and analysing floodplain morphology in situations where absolute elevation values offer limited contrast. Its computation is based on a simple elevation difference, expressed by the following formula:

$$\mathrm{REM}(x, y) = \mathrm{DEM}(x, y) - E_{\mathrm{ref}}(x, y),$$

where,
DEM(x, y) represents absolute terrain elevation
$E_{\mathrm{ref}}(x, y)$ is an interpolated reference surface at the same location.

Beyond these physical parameters, we also delineated perceptual and spatial factors relevant to the battle, such as the approximate one-kilometre impact zones of battlefield noise, smoke, and fire effects, including the shooting range by siege engines. Moreover, travel-time and distance calculations were performed to model horse-based movement between the bridge and the potential campsite (*Markku 2023*, 9–11). As outlined above, the Hungarian army was composed primarily of highly mobile cavalry and had pursued the Mongol forces for several days, thereby rendering cavalry movement the most appropriate basis for evaluating distance, mobility, and response time between relevant locations. The determination of this distance assumes that the sounds of battle (e.g. weapons firing, distant rumble, echoing noises) and visual signals (such as fire or smoke) could have been perceived in this latitudinal range during the early vegetation period, particularly around April 10. The low canopy cover and wet environmental conditions likely facilitated the propagation of both auditory and visual cues over greater distances. The maximum distance of 3 km was derived from the realistic distance that could be covered while riding at a gallop on horseback, fully equipped for battle. It should be noted that the actual distance from the right bank of the Sajó River to the marshy boundary of the Hejő–Szinva area averages 3.5 km, which thereby defines the upper limit of the potential movement range within the study area. As an additional component, a hypothetical 500-m-wide epidemiological buffer zone was assigned to the reconstructed medieval settlement network (*Fischl – Pusztai 2018*, 84). This experimental buffer, defined as half of the approximate one-kilometre impact zone, serves as a conservative spatial threshold for assessing the limits of encampment possibilities in relation to the medieval settlement network. The primary GIS vector and raster datasets employed in this study are illustrated (*Fig. 2*).

In the next phase, the GIS database layers were weighted using the AHP-derived weights. The Analytic Hierarchy Process (AHP) is a multidimensional decision-support method developed by Thomas L. Saaty. In this approach, the criteria and alternatives are evaluated through pairwise comparisons on a predefined scale, expressing their relative importance (*Choudhury et al. 2022*, 121). The weighting of the rasterised map classes followed the scale proposed by Saaty, and the resulting AHP-based class weights reflected the relative suitability of each layer for camping. The pairwise comparison matrix $\mathrm{A}=(\mathrm{a}_{\mathrm{ij}})$ of the decision hierarchy for a set of n elements was constructed such that a_{ij} expresses the relative importance of objects i and j, where $\mathrm{a}_{\mathrm{ij}} > 0$ and $\mathrm{a}_{\mathrm{ij}} = 1/\, \mathrm{a}_{\mathrm{ij}}$. The weight vector (w) is obtained using the eigenvector method:

$$\mathrm{A\ w} = \lambda_{\max} * \mathrm{w}$$

where,
W represents the principal eigenvector,
A stands for pairwise comparison matrix (a_{ij});
λ max denotes the largest eigenvalue of the eigenvector.

	DEM indices	Hydrology	Flood ind. boundary	Landuse – Landcover	Visibility (1km)	Route distances
DEM indices	1.0	1.8	3.30	6.3	13.5	15
Hydrology	0.55	1.0	1.82	3.60	7.4	8.5
Flood ind. boundary	0.30	0.5	1.0	2.04	4.5	5.4
Landuse – Landcover	0.15	0.27	0.49	1.0	2.3	2.6
Visibility (1km)	0.07	0.13	0.21	0.42	1.0	1.15
Route distances	0.06	0.11	0.18	0.37	0.8	1.0

Tab. 1. Analytic Hierarchy Process (AHP) comparison matrix for GIS layers.

Finally, the weights are normalised according to $\Sigma W_i = 1$, yielding the final priority weights (*Salomon – Gomes 2024*, 8–9). The evaluation process results (*Tab. 1*) in a comparison matrix that serves to calculate weights and determine priorities, enabling the numerical ranking and weighting of the input variables relevant to the study. The method also incorporates the consistency ratio (CR), which ensures the internal coherence of the pairwise comparisons (*Eroglu – Meral 2021*, 505). In this approach, complex problems are represented within a hierarchical structure: the overall decision goal (in this case, defining the characteristics of an optimal campsite) occupies the highest level, followed by the relevant criteria and alternatives (secondary environmental attributes of the campsite). The internal coherence of the pairwise judgements was evaluated using the Consistency Index (CI):

$$\mathrm{CI} = \frac{\lambda_{\max} - n}{n - 1},$$

where,
CI represents the Consistency Index;
λ_max is the principal eigenvalue of the pairwise comparison matrix;
n stands for number of criteria;
and the Consistency Ratio (CR).

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}},$$

where,
CI represents the Consistency Index;
RI denotes Random Index for a matrix of size *n*;

The CI measures the deviation from perfect consistency (λ_max = n) and quantifies the degree of logical inconsistency in pairwise comparisons; the closer the CI is to zero, the more consistent the judgment structure. CR value below 0.10 was considered acceptable (*Salomon – Gomes 2024*, 6). The derived DEM indices used in this study include slope, maximum and minimum DEM, and REM, etc. (*Tab. 1*). Hydrology was assigned as a separate category based on hydrological information. This is followed by datasets representing the flood boundaries of the Sajó River branches. The Landuse–Landcover group integrates the relevant DEM (maximum and minimum), TWI, hydrological feature (Hejő–Tisza Marshland), settlement network, and road network datasets. The visibility group includes perceptual distances of 1 km, 2 km, and 3 km, while route distances define the limits based on potential accessibility and travel–time calculations.

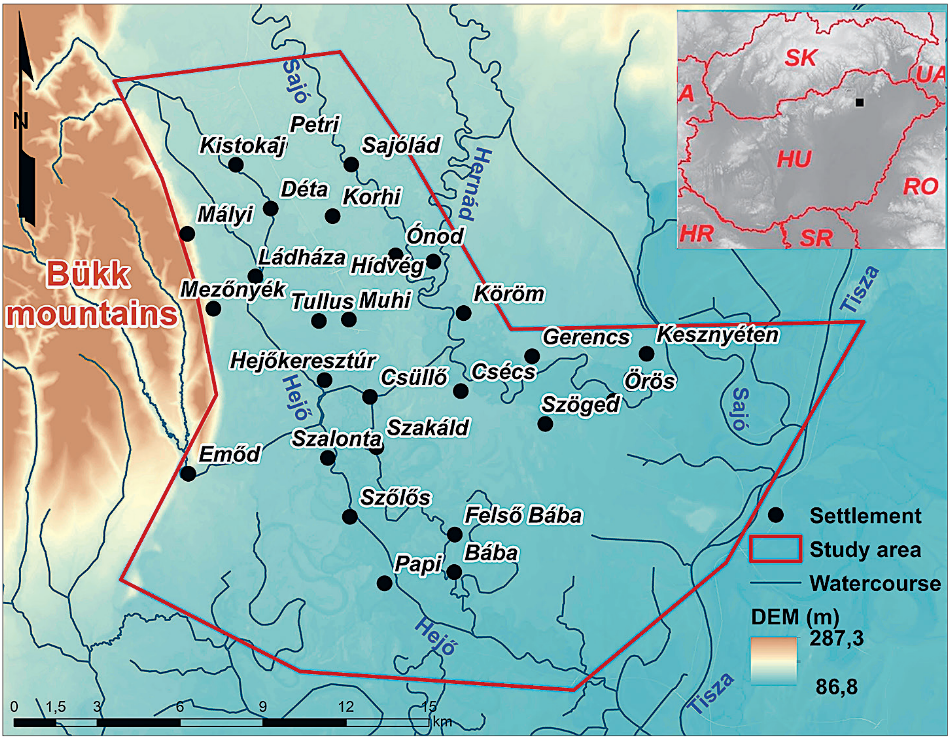

Fig. 2. Map of the study area.

Based on the considerations outlined above, the rationale for selecting the applied methodological framework becomes evident. The AHP method was selected because the encampment localisation problem involves heterogeneous criteria whose relative importance cannot be derived directly from quantitative measurements. As emphasised by *Malczewski* (*1999*, 414–415), AHP is particularly useful in such cases, as it allows expert knowledge to be expressed through structured pairwise comparisons rather than direct weighting. This form of consistency control is not available, for example, in the simple additive weighting (SAW) approach (*Malczewski 1999*, 419–420). While the SAW method was considered, it requires predefined weights without a formal mechanism to test their logical coherence. According to Malczewski (*Malczewski* 1999, 419), SAW is more appropriate when weights are empirically derived or relatively unambiguous, which is not the case for historically and environmentally conditioned criteria such as those used here. For these reasons, AHP was considered the most appropriate framework for integrating archaeological, environmental, and military–historical factors in the GIS-based encampment suitability model.

Results and discussion

The consistency statistics of the six-element AHP pairwise comparison matrix are presented (*Tab. 2*). The calculated Consistency Ratio (CR ≈ 7.37%) is below the 10% threshold, indicating that the matrix can be considered consistent (*Eroglu – Meral 2021*, 505). Although the value approaches the upper limit, it is deemed acceptable, particularly because this type of analysis has not previously been applied to the study area.

λ_max	CI	RI (n=6)	CR
6.456	0.091	1.24	0.0737

Tab. 2. Statistics of the Analytic Hierarchy Process (AHP) comparison matrix.

Based on the AHP weighting, an ESM probability map was produced with a spatial resolution of 5 m (25 m²). The distribution of the AHP-weighted GIS classes followed a Jenks natural breaks classification, based on which the ESM map was divided into three suitability categories for settlement: suitable (S1), moderately suitable (S2), and unsuitable (N). The ESM is available to researchers working in this field (*Online Supplementary Material 1*). All maps presented in this study are in the Hungarian Unified National Projection (EOV). The map enables the analysis of areas most suitable for temporary camps and permanent settlement, and can therefore be applied in the further study of early medieval settlement networks (*Fischl – Pusztai 2018*, 84). Subsequently, the estimated minimum–maximum size ranges of the camps were examined at spatial extents of 3 km², 1 km² and 0.4 km² (*Wolf 2018*, 138–139; *Négyesi 2024*, 73–75). To facilitate the spatial analysis, areas labelled as A, B, and C were delineated along historically significant commercial and military routes accepted by archaeologists (*Fig. 3*). In addition, alternative crossing routes were identified along the stable banks of the Sajó River, defined by the flood-inundation boundaries along the coast. These boundaries together constitute a refined version of the perceptual limit. To verify the occurrence of the camp-size categories, we generated a fishnet grid in ArcMap using the previously defined spatial extents (in km²). Finally, based on the *Hungarian National Museum Archaeology Database* (KRÉTA), we extracted the Árpádian-period, early medieval, and undated archaeological sites to facilitate the evaluation of the results and to delimit those areas that are most suitable for further archaeological investigation along previously documented excavation locations.

Nine locations were identified from the areas suitable for encampment, ranging in size from 0.4 to 1 km². Their correspondence with events associated with the Battle of Mohi and with historically documented battle sites (*P. Szabó 2022*, 116) varied across locations. Field surveys have already been conducted in certain parts of the presumed encampment areas labelled A (*Tab. 3*). Additionally, zone B includes the Kerengő–ér near the settlement of Szakáld, which is recognised as one of the currently accepted battle sites (*Négyesi 2024*, 69–70).

Campsite label	Associated research
Areas of zone A	Only a field survey was conducted
Areas of zone B	*P. Szabó 2022*, 116; *Négyesi 2024*, 69–70
Areas of zone C	*Wolf 2018*, 138–139

Tab. 3. Summary of the campsite locations and the associated research.

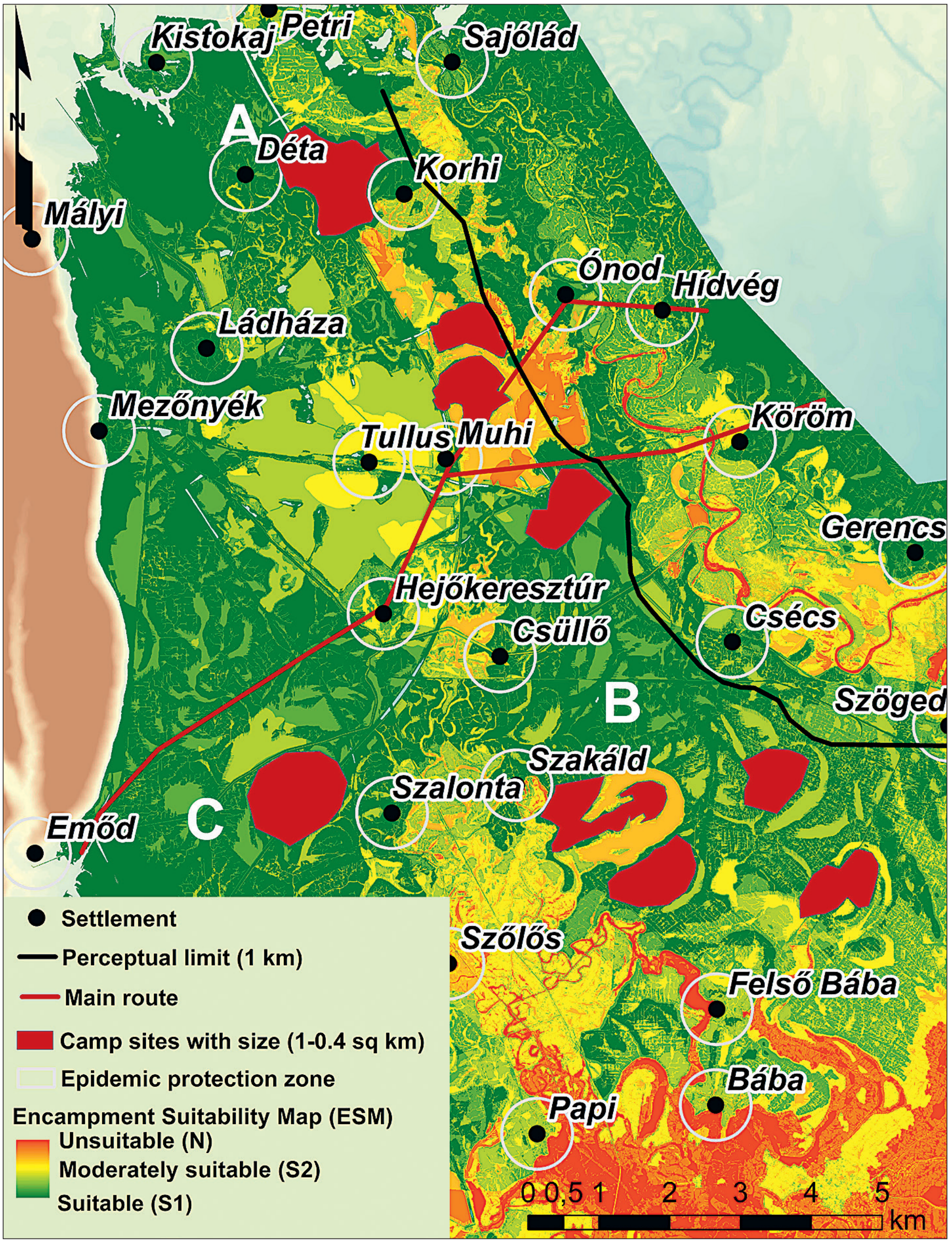

Fig. 3. Resulting Encampment Suitability Map (ESM) for the study area.

A novel aspect of the study is represented by the area designated as C for potential encampment, which was indirectly highlighted through the analysis of the literature. Based on the tactics of the Hungarian army, it cannot be ruled out that the forces did not engage in a frontal confrontation but rather aimed to gain time to consolidate different army units

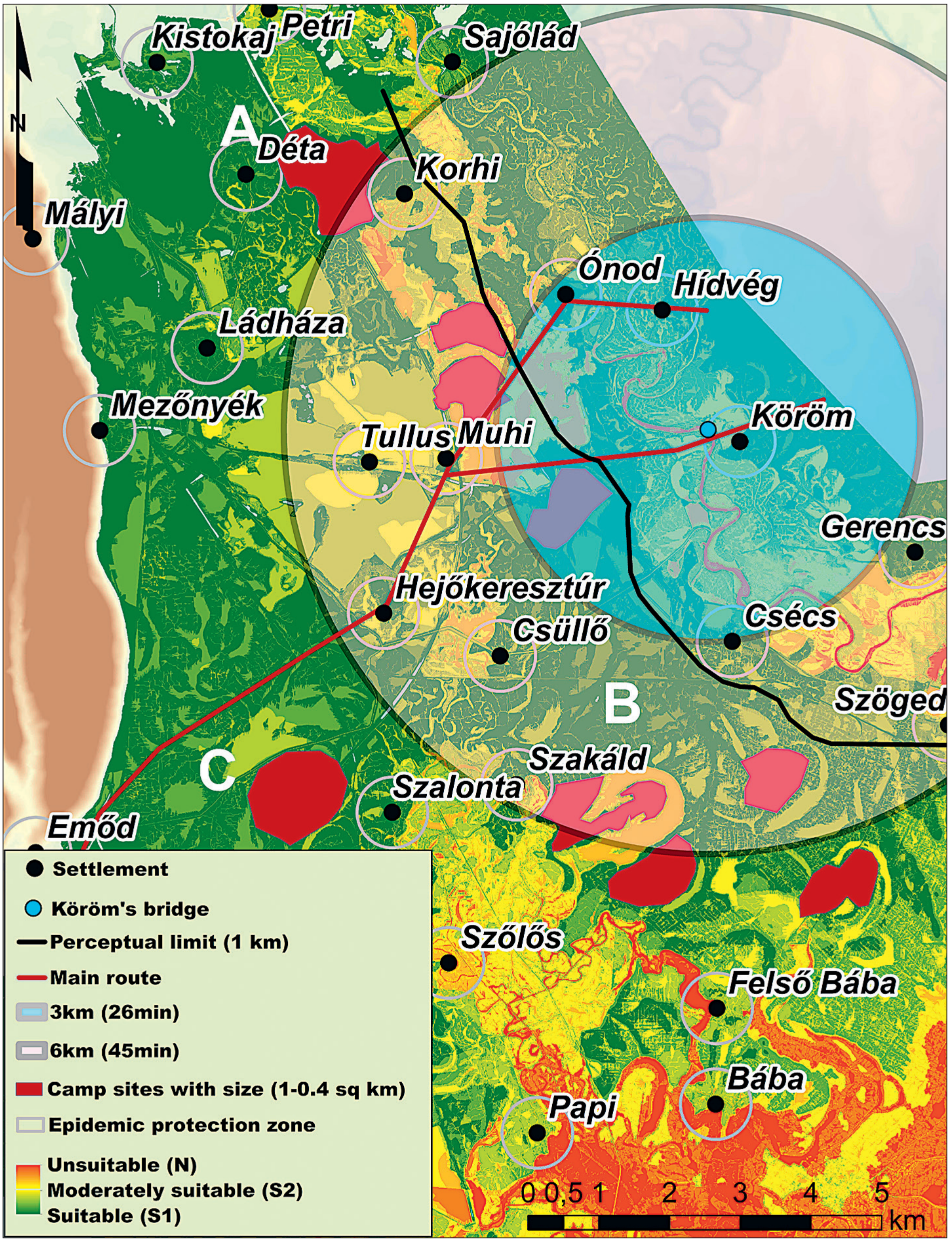

Fig. 4. Encampment Suitability Map (ESM) with travel distances within the study area.

across the country, while also ensuring supply lines (*Négyesi 1997*, 299). Such tactical considerations may have influenced the selection of the encampment site, suggesting that the choice was a deliberate and carefully considered decision, potentially involving several days of encampment (*Veszprémy 1994*, 29).

The initial confrontation of the battle took place at the Sajó Bridge, which, according to Rogerius, was located near the Hungarian camp, whereas Thomas of Spalato's account suggests a camp situated further away both spatially and temporally (*Győrffy 1981*, 111; *P. Szabó 2018*, 119–121). Consequently, average travel times were analysed along the Körömi crossing on the Sajó River. Average travel times were simplified by assuming a medium-quality route to the crossing and considering the movement of heavy cavalry carrying full equipment weighing approximately 50–70 kg. At a gallop, cavalry units could achieve speeds of 8–12 km/h (*Markku 2023*, 15–17). Under worst-case conditions (maximum load and slowest movement), the distance of roughly 3 km from the presumed Körömi zone would be covered in about 26 minutes, whereas 6 km would require approximately 52 minutes on horseback or 1 hour 12 minutes on foot (assuming a walking speed of 5 km/h), reaching the western edge of the Hejő marshlands (*Fig. 4*).

Taking the above-outlined distances into consideration, as well as the fact that no request for reinforcement was made at the bridge, it is worth reassessing the possible location of the encampment during future research. Following the account given by *Négyesi* (*1997*, 296–297), the conditions during the night action before the day of the Battle of Mohi may have affected how well the troops could orient themselves in relation to the bridge. However, if the camp had been located nearby, it is unlikely that no attempt would have been made to call for assistance. It is also important to note that, apart from the marshes, the terrain is essentially flat.

Based on these considerations, the possibility cannot be ruled out that the Hungarian camp was situated near a bridge on the right bank of the Hejő. In this case, the Hejő would have afforded natural protection from the east, while the Bükkalja region, situated approximately 1.5 km to the west, would have constituted additional geomorphological protection. Based on this assumption, a roughly 1 km² area lying west of Hejőszalonta and south of Hejőkeresztúr (along the former course of the Hejő, today corresponding to the Hejő–Szarda drainage channel) may be considered an acceptable location, as its environmental and topographical characteristics align with several of the conditions expected for such an encampment. Although a camp located at such a distance was previously proposed in the research tradition, the currently available archaeological material does not substantiate the establishment of a camp in this sector of the Hejő marshland (*Wolf 2018*, 138–139). A certain area of zone C has been analysed as potentially suitable. However, taking into account the route- and time-related considerations discussed above, a review of the characteristics of zones A and B indicates that more fieldwork and detailed analysis are required.

Localisation of the Kakasvár site

A secondary aspect of the research, based on the GIS input data, should also be noted. While not directly related to the localisation of the camp, it contributes to a better understanding of the study area. Analysis of the REM-based raster layer within the GIS database enabled the spatial delineation and identification of a previously undocumented fortified site, thereby further expanding knowledge of the area (*Dobai et al. 2025*, 128–129). The origin and exact function of Kakasvár are not known; the available sources only indirectly suggest that a former watchtower may once have stood at the site, the remains of which can today be identified only in part (*Édes 1858*). Consequently, the analysis of the area is

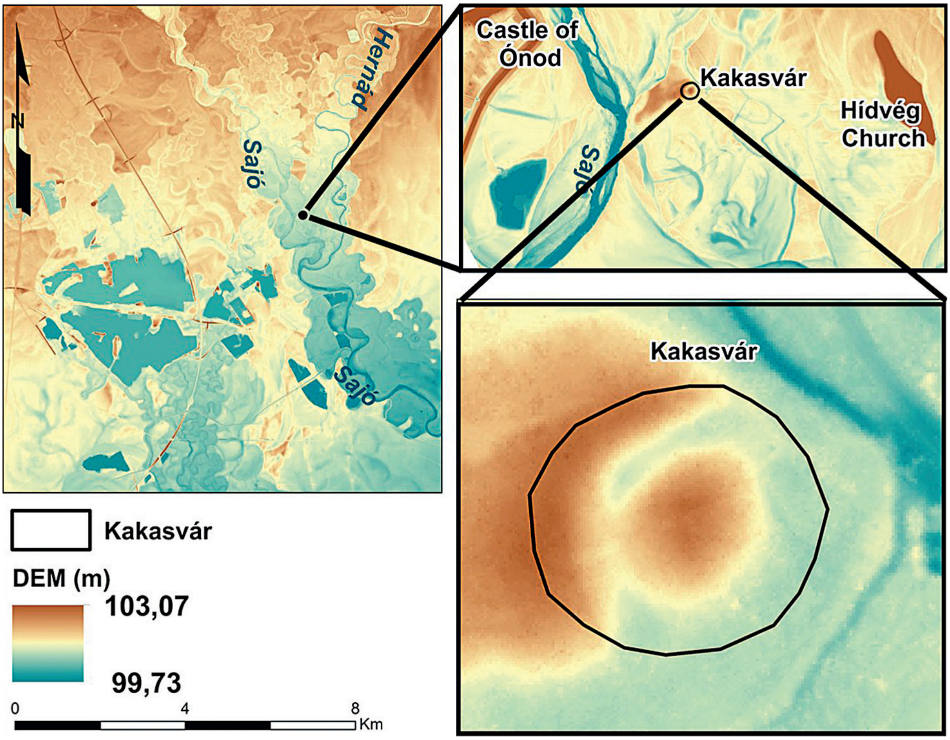

Fig. 5. Location of the Kakasvár site.

justified and may serve as a basis for subsequent archaeological verification. The REM makes it easier to detect topographic features such as elevations, and it can also be used to model changes in water surfaces or territorial stability (*Rybczyk et al. 1998*, 30–34). Based on the analysis of the model, we located an atypical landform on the left bank of the Sajó River, 240 m from the river's centreline, 683 m southeast of Ónod Castle, and 623 m from the remains of the Sajóhídvég church (*Fig. 5*). The area rises on average two metres above its surroundings, with strong erosion visible in the southern and eastern parts. In terms of its location, it lies in a flow stagnation zone only minimally affected by flooding, where even during extreme high-water events the maximum flow velocity is very weak (0.0–0.5 mm/s). Such low velocities cannot generate channel-forming discharges (*Kiss 2018*, 45). The area is located on parcel number 0159 in the outer area of Ónod, within the locality known as Kakasvár (*Ónod Settlement Development Plan 2014*).

Based on the map materials of the First, Second and Third Military Surveys, as well as earlier aerial photographs of the area from fentrol.hu and Google Maps, it was established that the site had been continuously forested. The surface cover of the site is still forest, with dense undergrowth, therefore only the following approximate measurements can be provided until further excavations take place. The site is situated within an area of 2,006 m², consisting of an inner circular area of 496 m², surrounded by a circular ditch and an outer elevated rampart (outer wall). The highest point of the inner area is 102.8 m, while the ditch is generally 5–6 m wide, with its deepest point at 100.7 m. Considering its location within the flood zone and the sandy texture of surface material, the formation nevertheless cannot be linked to an alluvial feature. This is because it is surrounded from the north toward the south (from the direction of the Sajó River) by a semicircular area of loamy but predominantly sandy material, averaging 2 m in height and 60 m in length. This surrounding formation effectively separates or removes the circular feature from its natural environment as a result of anthropogenic activity. Between the outer and inner sections, on the western side, there is a narrow connection, although this may simply result from the accumulation of eroded material. The site is the remnant of a former alluvial fan, which is bordered in several places on the eastern side by former flow channels (*Dobai et al. 2025*, 135–137).

The areas of Kakasvár and the church at Sajóhídvég can be clearly identified based on the vectorised reconstruction of the 1775 map. These features served as reliable reference points for the further interpretation of the cartographic content, enabling the identification of previously unrecognised elements. The fluvial channels between the Sajó and Hernád rivers become clearly discernible, and the former bed of the Holt–Sajó can also be distinctly delineated. In the northern section of the map, traces of the former outlets of the Bársonyos stream are observable, while the Szabacs area can be identified in the southern sector. These results substantially expand the dataset underlying the analysis and demonstrate a strong spatial correspondence with the reconstructed cartographic framework. The study of Kakasvár and its surroundings is significant because Sajóhídvég lies in the immediate vicinity of the Battle of Mohi; its earliest written mention, in 1261, already records it as Hídvég. If the battle fought along the Sajó on 11 April 1241 truly took place near Muhi, the bridge that gave the settlement its name must have been located at this site (*Bodnár 2021*).

As part of the subsidiary research associated with the main study, the existing knowledge was expanded and organised into an archaeology-oriented GIS database, thereby increasing the potential for quantitative analyses. The analyses and resulting findings corroborate the earlier research by *Pusztai* (*2014*, 141–150), which aimed to reconstruct the medieval settlement network. Another outcome of the study is that based on the digitised maps of 1775, *Laszlovszky* and *Nagy* (*2023*, 953) refined investigations concerning the former course of the Hernád River and its hydro–morphological characteristics. In addition, the research designates as a new area of archaeological interest the zone situated between the confluence regions of the Hernád and Sajó rivers. Earlier archaeological, geographical, and hydrological literature had interpreted this zone as a floodplain (*Dövényi 2010*, 215) and therefore did not examine it. However, preliminary flood–inundation models challenge this assumption (*Fig. 6*). Second-degree flood levels affect the area only marginally, and even the boundaries associated with third-degree, extreme water levels (*Kiss 2018*, 46–47) do not fully cover it. Flood inundation is primarily determined by local elevation conditions; however, an equally important factor is the extent of additional water supply entering the system from the north. It is also crucial whether the Tisza exerts a backwater effect from the south. During Level I–II flood stages, the Tisza can back up the Sajó as far as the area of Sajóörös. This effect naturally influences the lower Sajó and indirectly causes backwater conditions in the Sajó–Hernád confluence zone as well. Consequently, the occurrence of Level III (Extreme) inundation requires the simultaneous presence of multiple contributing factors (*Kiss 2018*, 47; *ÉMVIZIG 2014*).

Based on these results, new research directions can be defined, including the investigation of the Szabacs area (*Fig. 6*), a site that has likewise not been examined before. This

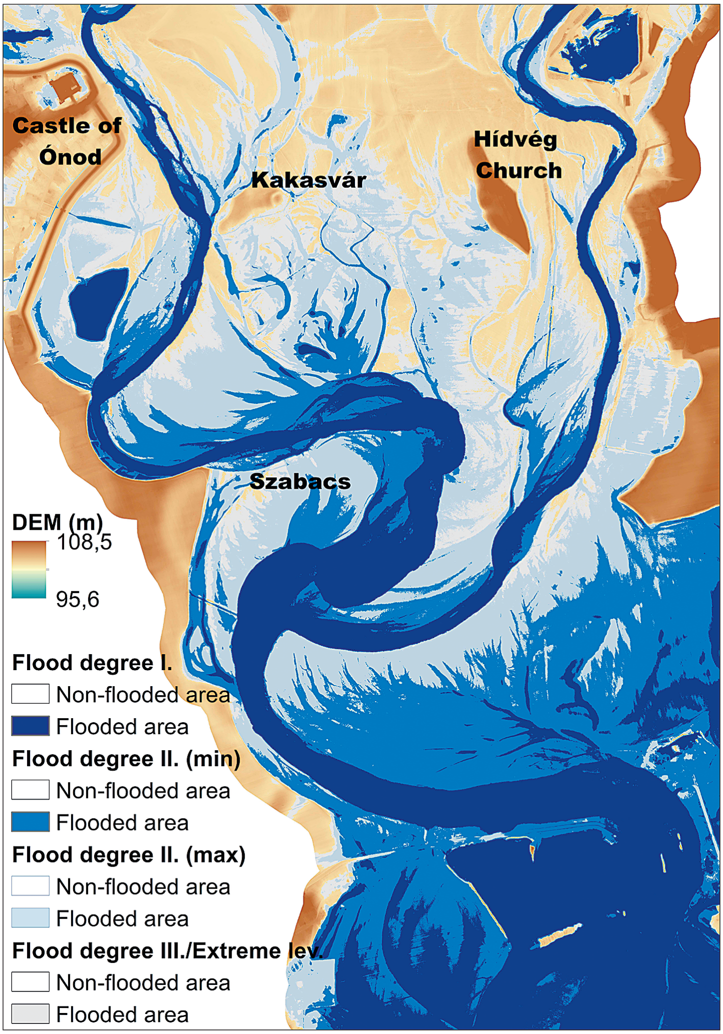

Fig. 6. Degrees of flood inundation (I–III) in the Sajó–Hernád region.

area is marked both on the military surveys and on the digitised map, and it may play a central role not only in the analysis of the landscape but also in the interpretation of the battle itself, as it lies at the core of the investigations along the Sajó. Consequently, it holds considerable research potential.

Conclusion

Although the Battle of Mohi is remembered as a national tragedy in Hungarian history, recent research has enabled a more nuanced understanding of encampment conditions, troop movements, and the psychological dimensions of decision-making. This study developed a GIS-based mapping procedure to identify areas suitable for encampment (ESM) by considering spatial, temporal, and operational factors. The methodological approach intersects with early medieval battlefield research (*Williams 2015*, 352–353; *Bellón Ruiz et al. 2016*, 90–91; *Hewitt 2016*, 143–144) but focuses on an earlier analytical stage: the *a priori* spatial localisation of encampments using environmental, hydrological, and perceptual criteria. This choice is driven by the relatively sparse archaeological record and limited historical source material available for Mohi. Consequently, the research necessarily lacks well-documented sites in terms of identifiable archaeological locations and assemblages. Even with this limitation, while the presented study aligns with landscape-oriented battlefield research (*Hewitt 2016*, 143–144; *Hodgkins 2016*, 108–110) that emphasises terrain analysis and movement constraints, it offers an important advantage in that it extends these approaches by integrating historical GIS, high-resolution DEM-derived indices (e.g. Topographic Wetness Index, Relative Elevation Model), historical flood dynamics, and military-historical considerations within a formal Analytic Hierarchy Process (AHP) framework. The AHP allows explicit weighting and consistency testing of heterogeneous criteria, an approach that has rarely been applied within medieval battlefield archaeology at this spatial resolution. Comparable methodological frameworks and regional battlefield syntheses (e.g. *Foard – Partida 2018*, 30–34) highlight the value of integrating landscape analysis with artefact-based surveys. The present study complements these approaches by prioritising predictive encampment loci for targeted field survey.

Our Encampment Suitability Model (ESM) therefore extends artefact-based methodologies by providing a predictive spatial framework for non-destructive investigation, as exemplified by the identification of the previously undocumented Kakasvár site. ESM outputs broadly corroborate prior findings while expanding analytical scope through additional spatial, temporal, and operational criteria. One methodological limitation is scale sensitivity: the aggregation and normalisation of weighting factors tended to down-rank smaller, locally favourable patches (e.g. Tullus–plain; *Négyesi 2024*, 68). Sensitivity analysis, multi-scale runs, or local recalibration are recommended to mitigate this effect. Despite this limitation, the GIS database and model outputs can be applied to other research (e.g. diachronic settlement–network studies), and the approach has rendered previously unexamined zones discoverable, thereby enriching the empirical dataset and demonstrating the practical value of GIS in battlefield research.

We would like to express our gratitude to Dr. Tamás Pusztai and István Dobai for their professional support, and to Tamás Bodnár, chief archivist of the Borsod–Abaúj–Zemplén County Archives of the National Archives of Hungary, for providing the map materials necessary for the research. Furthermore, we thank Envirosense Ltd. for providing the LiDAR survey data.

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