SPATIAL TECHNOLOGIES IN ARCHAEOLOGY: FROM GIS MAPPING TO SFM-BASED MODELLING

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Abstract: *The development of Geographic Information Systems (GIS) has profoundly transformed archaeological research by enabling precise spatial data acquisition, long-term storage, and advanced analysis. Initially emerging in the 1960s for land-use and urban planning, GIS has evolved into a multidimensional analytical platform supporting complex modelling, pattern recognition, and sophisticated visualisation. In archaeology, GIS facilitates rapid and accurate digital documentation in the field, particularly when integrated with complementary technologies such as UAVs, GPS, and Structure from Motion photogrammetry, as well as the execution of intricate spatial analyses. This paper illustrates its field applications through two case studies: a UAV-based aerial survey around Varbitsa, Bulgaria (2022–2024), investigating the topography of three newly discovered sites, and the use of GIS and SfM modeling during rescue excavations at Schwäbisch Hall-Hessental, Germany (2022–2023), enabling precise documentation of a Middle Neolithic long house. In both cases, GIS supported accurate mapping and the integration of heterogeneous datasets, enhancing interpretative potential. These examples demonstrate that GIS functions not merely as a mapping tool but as a comprehensive platform for archaeological documentation and analysis, which enhances the interpretation of archaeological contexts and ultimately our understanding of past societies.*

ПРОСТРАНСТВЕНИ ТЕХНОЛОГИИ В АРХЕОЛОГИЯТА: ОТ ГИС-КАРТОГРАФИРАНЕ ДО SFM-МОДЕЛИРАНЕ

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Резюме: *Развитието на Географските информационни системи (ГИС) коренно промени археологическите изследвания, като позволи прецизно събиране, дългосрочно съхранение и комплексен анализ на пространствени данни. Първоначално възникнали през 60-те години на XX век с цел управление на земеползването и градоустройството, ГИС се развиха в многоизмерна аналитична платформа, която поддържа комплексно моделиране, разпознаване на закономерности и усъвършенствана визуализация. В археологията ГИС улеснява бързото и точно цифрово документиране на терена, особено когато е интегрирана с допълнителни технологии като безпилотни летателни апарати (БЛА), GPS и Structure from Motion (SfM) фотограметрия, както и при извършването на сложни пространствени анализи. Настоящата статия илюстрира приложенията на ГИС на терен чрез два казуса: въздушно заснемане с БЛА в околността на село Върбица, България (2022–2024), изследващо топографията на три новооткрити обекта, и прилагането на ГИС и SfM моделиране по време на спасителни разкопки в Швебиш Хал-Хесентал, Германия (2022–2023), което позволи прецизна документация на една дълга къща от средния неолит. И в двата случая ГИС подпомага точното картографиране и интегрирането на хетерогенни набори от данни, повишавайки интерпретативния потенциал. Тези примери показват, че ГИС функционира не просто като инструмент за картографиране, но и като всеобхватна платформа за археологическа документация и анализ, която подобрява интерпретацията на археологическите контексти и в крайна сметка нашето разбиране за обществата от миналото.*

The conceptual foundations of GIS were established almost simultaneously in the 1960s, when geographers in Canada and the United States began developing computational tools to assist land-use management and urban planning [1–3]. These early initiatives laid the groundwork for digital mapping and spatial analysis. Prior to GIS, these were manual, time-consuming, and limited in their capacity to integrate diverse datasets. Early GIS overcame these limitations by enabling the digitisation and basic manipulation of geographic information, which allowed the production of simple thematic maps and established GIS as a tool for large-scale environmental and land resource management. The introduction of this technology marked a profound shift in the ways spatial data could be collected, stored, analysed and displayed. Over subsequent decades, as computational capacity and software sophistication increased, GIS evolved into a multidimensional analytical platform capable of complex spatial modelling, pattern recognition, predictive analyses, derived statistics, and advanced visualisation of spatial relationships, fundamentally transforming the field of geospatial research [4, 5].

These advancements in GIS facilitated its rapid expansion into a wide range of disciplines, including environmental and resource management, transportation and infrastructure, public health, as well as tourism and cultural heritage, where the ability to analyse and visualise spatial patterns offered new insights and improved planning and management [6].

One of the fields that has particularly benefited from GIS is archaeology. GIS was first adopted in archaeology in the 1980s, primarily for site location analysis, predictive modelling, and the study of settlement patterns. Its use expanded during the 1990s as advances in computing power and the increasing availability of software enabled archaeologists to apply GIS more broadly in spatial analysis, landscape archaeology, and cultural resource management. By the 2000s, GIS had become an essential tool in archaeological research, often integrated with complementary technologies such as remote sensing, GPS, and LiDAR, thereby facilitating more sophisticated analyses [7–9, 11].

In recent decades, the introduction of open-source GIS software (including Web GIS), combined with the increasing affordability of Differential Global Positioning System (DGPS) receivers, total stations, digital single-lens reflex (DSLR) cameras, computers, unmanned aerial vehicles (UAVs), as well as the improved accessibility of satellite imagery, has rendered GIS a cost-effective and indispensable tool in archaeology [10–12].

Within archaeological fieldwork, GIS has become an indispensable instrument for spatial data acquisition. It enables archaeologists to record locations with exceptional precision and efficiency, while simultaneously allowing rapid mapping and analysis, thereby substantially enhancing both field documentation and subsequent post-excavation research [11–13].

A principal field application of GIS involves the systematic recording, storage and manipulation of spatial information during surface surveys and excavation campaigns. Archaeological data acquired with instruments such as GPS units and total stations are seamlessly integrated into geospatial databases, forming the analytical foundation for subsequent mapping, pattern recognition, and interpretative synthesis [3, 13, 14].

These methods ensure rapid and accurate data capture, while simultaneously allowing the on-site visualisation of basic maps. The recorded data can subsequently be transferred to GIS software, where it can be further processed into detailed distribution maps, analysed for intra-site patterning, and integrated with other spatial datasets [13]. Such analyses are instrumental in delineating the extent of archaeological sites, distinguishing settlement areas across different phases of occupation, and identifying zones of concentrated activity [15, 16]. Furthermore, elevation measurements obtained with the help of DGPS or total stations can be used to construct high-resolution Digital Elevation Models (DEMs), which aid in detecting subtle morphological features such as earthworks or palaeochannels that are often obscured by vegetation [3].

Another major strength of GIS lies in its ability to incorporate heterogeneous spatial datasets, ranging from digitised historical maps and aerial photographs to satellite imagery, geophysical prospection outputs, and LiDAR scans. Through the seamless integration of diverse datasets, GIS facilitates more detailed field documentation and substantially enhances the precision of spatial analysis, thereby facilitating both the discovery of new sites and the investigation of known ones [7, 11, 13, 17].

The rapid development of UAV technology over the past decade rendered aerial photography highly accessible and efficient, enabling its integration into routine archaeological documentation workflows. UAVs facilitate the surveying of extensive areas and the acquisition of data with very high spatial resolution. Beyond single aerial photographs, they also enable the capture of multiple overlapping images that can be processed into large-scale orthophoto maps or digital terrain models. These outputs, once processed, can be seamlessly incorporated into GIS, where they substantially enrich spatial analyses by enhancing site documentation, improving landscape modelling, and supporting comparative investigations across larger regions [18].

A UAV-based aerial photographic survey covering an extensive area around the village of Varbitsa was conducted by Kristian Aleksandrov, Milen Chanev, and Martin Milev in 2022, and subsequently by Martin Milev in 2024. This work was carried out in conjunction with the reconnaissance survey expedition “Plevenski visochini”, directed by Pavel Popov between 2022 and 2023, the results of which have been published elsewhere [19, 20]. During the surface survey, six archaeological sites were identified, three of which were included in the aerial photographic survey, with the aim of studying their topography. The aerial survey was carried out using a DJI Mavic Air 2 UAV equipped with an RGB camera. Flight planning was performed via the DroneLink platform at an altitude of 120 m, with the camera positioned in a nadir orientation. The collected photographs were subsequently processed in Agisoft Metashape 2.2.1 to generate a Digital Elevation Model (DEM).

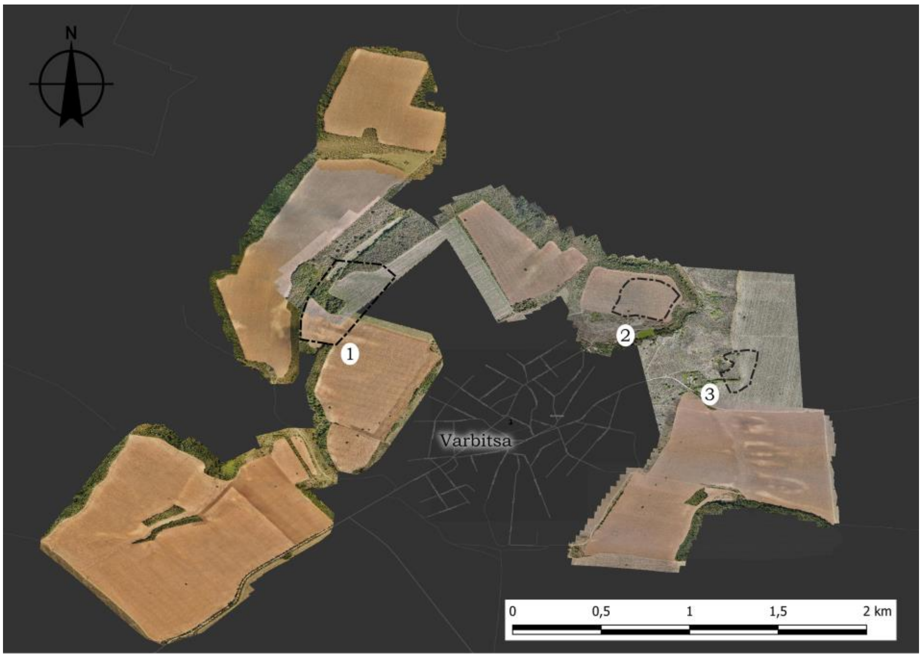

Fig. 1. Orthophoto of the surroundings of Varbitsa village, Pleven Municipality, encompassing three archaeological sites. The orthophoto is derived from a DEM generated from a UAV-based aerial photographs.

The first site, located approximately 1.6 km northwest of the centre of the modern village, in the area called “Suhata Varbitsa” (Fig. 1-1), constitutes a multi-period settlement encompassing an area of 15 ha. The site was occupied during the Iron Age, Classical Antiquity (Roman period), and the Middle Ages. The DEM shows that the settlement is situated on a gentle, northwest-facing slope descending into the valleys of two springs, both originating within the site’s territory. One of these springs shares its name with the toponym of the area. No distinctive morphological features associated with the settlement are visible in the DEM. The second site, located about 1.1 km NNE of the village centre (Fig. 1-2), is a Late Bronze Age settlement covering an area of 5 ha. Immediately southwest of the settlement lies a funerary tumulus. The DEM displays the settlement on a terrace with a slight northeast exposure, overlooking the valley of a small stream that encircles it on three sides. The settlement area exhibits a slightly darker colouration than the surrounding sediment, which allows its approximate boundaries to be delineated. The third site, located at about 1.4 km ENE of the village centre, in the area called “Listachkata” (Fig. 1-3), constitutes a Late Bronze Age necropolis covering an area of ca. 6 ha. In 2024, a small-scale test excavation was conducted, revealing two graves containing skeletons in a crouched position and one grave with disarticulated remains of four individuals. On the DEM, the site appears to be situated on a gently westward-sloping terrace, with no discernible morphological features.

In addition to the ability to swiftly and precisely collect large numbers of spatial measurements, GIS is of great support for the documentation workflow of archaeological excavations with its ability to integrate photographs of flat surfaces with reference points of known coordinates. These photographs can be transformed into orthophotos through georeferencing and orthorectification, providing scaled images suitable as drawing bases and for photogrammetry [10, 11]. Such orthophotos display the natural texture of archaeological features, obviating the need for conventional coloured drawings, and can be collaged to document large areas or confined spaces. This approach reduces field time, ensures greater accuracy, and allows off-site drawing of plans, profiles, and production of reconstructions [11, 12].

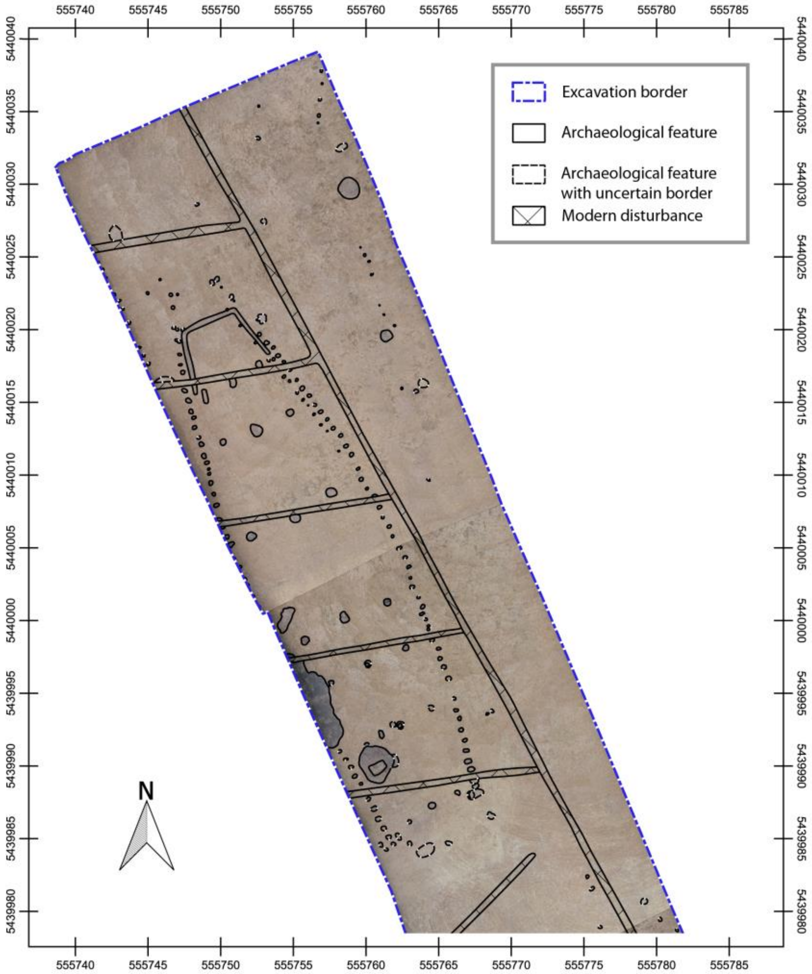

Fig. 2. Plan of a Middle Neolithic house discovered at Schwäbisch Hall-Hessental, Sonnenrein 3 (Germany), compiled from orthophotos extracted from SfM models. Aerial photography by Petru Ciocani; compilation and drawing by Elina Nordwald. Publication rights held by the State Office for Monument Conservation in Baden-Württemberg (Landesamt für Denkmalpflege Baden-Württemberg).

Furthermore, the past decade has witnessed the widespread adoption of Structure from Motion (SfM) photogrammetry, which produces three-dimensional models from overlapping photographs. These 3D models allow the extraction of highly accurate orthophotos, offering superior texture quality compared to collages of orthorectified photographs [11, 12]. SfM has proven particularly valuable in large-scale rescue excavations, where it assists the documentation workflow by enabling the expeditious compilation of planimetric maps and profile drawings. This, in turn, facilitates a comprehensive overview and the monitoring of rapidly evolving field situations, thereby enabling effective planning and enhancement of investigation strategies.

A prime example of the implementation of this documentation technique is provided by the archaeological investigations at Schwäbisch Hall-Hessental, Sonnenrein 3 (Germany), conducted between 2022 and 2023 by the company ArchaeoBW GmbH in collaboration with the State Office for Monument Conservation in Baden-Württemberg (Landesamt für Denkmalpflege Baden-Württemberg [LAD]),[1] leading to the discovery of a previously unknown Middle Neolithic settlement of the Rössen culture [21]. For the documentation of all plans and profiles, SfM models were generated using Agisoft Metashape, on the basis of UAV aerial photographs for the plans and digital single-lens reflex (DSLR) camera photographs for the profiles. Orthophotos extracted from the SfM models were subsequently processed in QGIS for the elaboration of planimetric maps and profile drawings[2].

[1] We wish to express our deep appreciation to Felicitas Schmitt (LAD) and Marcel C. Hagner (ArchaeoBW) for their collaboration and for granting permission to publish the data.
[2] For a detailed description of the profile documentation see [22; 23].

Fig. 3. Profile section of a Middle Neolithic storage pit at Schwäbisch Hall-Hessental, Sonnenrein 3 (Germany), documented by a standard photograph (a.) and an orthophoto extracted from an SfM model (b.). Photography by Katarzyna Szczurek, orthophoto generation and drawing by Elina Nordwald. Publication rights held by the State Office for Monument Conservation in Baden-Württemberg (Landesamt für Denkmalpflege Baden-Württemberg).

As an example of plan documentation, we present the ground plan of a well-preserved Middle Neolithic house situated in the northwestern part of trench 03 (Fig. 2). The building, outlined by rows of postholes, exhibits a distinctly ship-shaped ground plan measuring approximately 41 m in length and 10 m in width. It displays a four-aisled internal arrangement, formed by three longitudinal rows of substantial postholes and two external, curved alignments of smaller postholes that delineate the outer walls. The structure is oriented along a northwest–southeast axis, with the entrance situated at the southeastern end. At the opposite (northwestern) end, a compartment enclosed by three plank-built walls set within a shallow foundation trench formed a separate functional area within the building. This house shows strong analogies with another well-preserved house of the Rössen culture, discovered by Hermann Huber in the 1960s at Schwäbisch Hall-Weckrieden ("Wolfsbühl"), a site located in close proximity to the north [24–25]. For profile documentation, we present the profile section of a roughly circular pit located in the southern part of the aforementioned Middle Neolithic house. The pit cuts through two of the house's postholes, indicating that it was dug after the abandonment of the house. The pit has a depth of 0.70 m and was filled with ashes and a considerable amount of daub fragments, some of which display two straight surfaces (Fig. 3), representing the remains of a burnt structure, most likely an oven. In the eastern part of the profile, one of the postholes cut by the pit is also visible.

The planimetric maps and profile drawings produced in this way are not only more accurate and faster to produce than conventional millimetre paper- or pantograph-based drawing techniques, but they also allow the original colour of the sediment to be preserved, thus providing a much more realistic image of the archaeological situation.

Taken together, these applications illustrate that GIS functions as a comprehensive analytical platform for the collection, organisation, and analysis of archaeological data rather than a mere cartographic tool for archaeology. Whether employed in surface surveys or stratigraphic excavations, GIS facilitates accurate documentation, enables advanced spatial analyses, and ultimately enhances the interpretive potential of archaeological research.

Moreover, GIS enables archaeologists to analyse sites in their broader spatial context or multiple sites within a region through a variety of spatial methods that were previously difficult or impossible to conduct. Landscape and site distribution analyses allow the understanding of the environments in which sites were located as well as the settlement patterns, facilitating the reconstruction of palaeoenvironments, resource use and socio-economic organisation [3, 11, 13]. Cost distance and site catchment analyses assess accessibility, optimal routes, and the exploitation of surrounding resources, often taking into account slope, land cover, and obstacles via raster-based cost surfaces. Thiessen polygons provide a complementary method for delineating site territories in extensively surveyed, synchronous regions, while predictive modelling forecasts probable locations of undiscovered sites based on environmental parameters. Viewshed analysis further contributes to understanding visual relationships within landscape, revealing the visibility and intervisibility of past sites, such as settlements and monuments [3, 7, 11, 26]. Together, these GIS-based methods provide archaeologists with powerful tools for spatial analysis, landscape reconstruction, and the interpretation of past human-environment interactions.

Conclusions

The development and integration of GIS have fundamentally transformed both geospatial research and archaeological practice. From its origins in the 1960s as a tool for land-use management and urban planning, GIS has evolved into a versatile platform capable of complex spatial analyses, modelling, and visualisation. Its applications now extend across diverse disciplines, including environmental management, infrastructure planning, public health, tourism, and cultural heritage. In archaeology, GIS has shifted from initial site location and settlement pattern analyses in the 1980s to becoming an essential component of landscape archaeology, cultural resource management, and advanced spatial analyses by the 2000s. Recent technological advances and increased affordability of UAVs, LiDAR, DGPS, and total stations, coupled with development of GIS software and Structure from Motion photogrammetry, have further expanded GIS capabilities, enabling the rapid collection, integration, analysis and visualisation of high-resolution spatial data.

One of the key applications of GIS in archaeology is the precise acquisition and management of spatial data during surveys and excavations supporting the documentation process. Using a DGPS or total stations, archaeologists can accurately record the locations of artefacts and features and subsequently process the data within GIS to generate detailed distribution maps and analyse intra-site patterns. Recent advances in UAV technology have made high-resolution aerial photography increasingly accessible, enabling the production of orthophoto maps and digital terrain models that can be incorporated into GIS, enhancing landscape modelling and topographic analyses on archaeological sites. GIS also plays a crucial role in the documentation workflow of archaeological excavations through its capacity to integrate photographs of flat surfaces with reference points and to transform them into orthophotos. In recent years, the adoption of SfM photogrammetry in archaeology has further advanced documentation practices by enabling the extraction of detailed orthophotos with superior texture quality from high-precision 3D models. The documentation of plans and profiles in this manner is not only considerably faster and more precise than traditional techniques, but also permits preserving the natural texture of the features and facilitates the off-site production of drawings.

Furthermore, GIS facilitates the execution of intricate spatial analyses encompassing a vast number of sites, thereby enabling the reconstruction of palaeoenvironments, the analysis of site catchments and resource use, predictive modelling, and viewshed studies. This, in turn, fosters a comprehensive understanding of both human-environment interactions and socio-cultural dynamics.

Overall, GIS has evolved from a simple mapping tool into a pivotal platform for the acquisition, processing, and interpretation of archaeological data, thereby enhancing both the precision of documentation and the analytical depth of research. By integrating high-resolution datasets with advanced spatial modelling, GIS enables archaeologists to investigate past landscapes and human activities in ways that were previously unattainable. As such, GIS has become an indispensable instrument within contemporary archaeological science.

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