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Kernel Density Estimation (KDE) Approach in Landscape Archaeological Studies

(Case Study: The Distribution of Middle Paleolithic Open-air Sites in Miankouh Region; Chaharmahal and Bakhtiari Province, Iran)

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Abstract

Today, Kernel Density Estimation (KDE) is one of the most important methods used to illustrate the influence of most important factors (ecotopes) on the distribution of archaeological sites at the local landscape scale. Geographic Information System (GIS), as a core analytical tool, plays a key role in identifying task-specific locations. GIS, in combination with MATLAB toolboxes, topologically enhances our understanding of how environmental factors influenced the resource exploitation patterns of past societies. Focusing on the Middle Paleolithic (MP) statistical dataset, this paper underscores the analytical value of KDE in studying MP open-air sites and localities that were identified during three seasons of archaeological survey in the Miankouh region, located in western Chaharmahal and Bakhtiari (ChB) Province. An analysis of the available dataset (177 points with recorded latitude and longitude coordinates, XY) reveals two probable environmental factors that appear to have contributed to the formation of four major MP open-air site clusters across the Miankouh landscape. The highest concentration of sites occurs on river terraces near the Khersun and Bazoft rivers (Kernel 1), where suitable riverine chert raw materials were available for tool production in the Low Altitude Zone (LAZ). Another significant cluster (Kernel 2) is in the High-Altitude Zone (HAZ), around two natural seasonal pools and the Pootak spring.

Keywords: Kernel Density, Miankouh, Middle Paleolithic, Landscape, Spatial Analysis.

Introduction

Landscape archaeology examines the spatial relationships of cultural materials (stone artefacts) to infer how landscapes were exploited in the past (Zvelebil *et al.,* 1992; Crumley and Marquardt, 1990). Cultural materials in the form of surface scatter findings in open-air environments (as opposed to sheltered areas such as caves) are often undervalued due to assumptions regarding their integrity and informational potential. This tendency is particularly common in arid and semi-arid landscapes, where sediment accumulation is slow and erosion is intense (Ames *et al.,* 2020).

Today, the analysis of such localities is increasingly associated with digital archaeology and its subfield, computational archaeology, as these disciplines facilitate the statistical analysis of cultural material data (see: Mara, 2022; Eiteljorg *et al.,* 2007; Winterbottom and Long, 2006). Among the most widely used digital tools in the humanities and especially in archaeology are GIS and MATLAB, which are employed for modelling socio-ecological and environmental landscapes at multiple spatial scales, as well as for analysing the spatial and temporal distribution of archaeological data (Hughes *et al.,* 2016: 159).

In terms of scale, Geographic Information System (GIS) is typically used to study the spatial relationships of a variety of archaeological elements, from the distribution of pottery and chipped stone artefacts at a single site, to the spatial distribution of archaeological evidence across broader geographic regions (Renfrew and Bahn, 2016: 94–98; Frachetti, 2006: 113).

Recent research contributes to our understanding of the formation processes and distribution patterns of surface scatter findings (i.e., open-air sites) as independent entities at the landscape scale. This is achieved by compiling diverse statistical data and incorporating them into GIS and MATLAB databases to generate spatial representations and digital maps. One of the core tools found in both platforms is the Kernel Density Estimation (KDE) function. In practice, this analytical tool estimates the density of observable data points (Silverman, 1998). As Węglarczyk (2018) notes, KDE allows for more nuanced analysis of probability distributions than traditional histograms. In spatial archaeology, KDE has been used for various purposes, including smoothing point data, creating continuous surfaces from discrete data, integrating point data with other raster datasets, estimating probability distributions, interpolating missing values, and detecting spatial clusters or “hot spots” (Krisp and Špatenková, 2010: 396).

The present study applies two of the most flexible data-driven analytical platforms GIS and MATLAB to model the probable spatial patterning of Middle Paleolithic (MP) open-air sites in the Miankouh region, one of the most mountainous zones in the Zagros range.

Research Importance and objectives

The spatial analysis approach explicitly addresses the use of space in the past. Such analyses are typically conducted at two principal scales: the site scale and the landscape or large-area scale (see: Bintliff, 2000; Zvelebil *et al.,* 1992; Dunnell and Dancey, 1983). Both approaches aim to identify patterns in the spatial distribution of archaeological materials and, ultimately, to reconstruct patterns of human behaviour at a site or within a locality. However, when these analyses are integrated across broader spatial extents using top-down perspectives, they are referred to as inter-site or landscape-oriented analyses (Gaydarska, 2015). With regard to KDE, knowledge of the spatial distribution of stone artefacts across a given region allows researchers to explicitly delineate clusters based on density values observed within specific environmental zones (Dunnell and Dancey, 1983: 273).

Regarding its analytical importance, one could assert that, when juxtaposed with other archaeological data analysis techniques, KDE delivers improved interpretive possibilities by smoothing point data and creating high-resolution, integrated spatial representations of site distributions in the format of density maps. This type of analytical tool represents an informal method of data point clustering which, unlike other techniques, does not impose predefined structural assumptions onto the dataset (Baxter *et al.,* 1997; Beardah and Baxter, 1996a). Another key capability of KDE lies in its ability to assess the degree of overlap between different distributions, thereby facilitating the evaluation of (dis)similarities among archaeological assemblages (De Ceuster and Degryse, 2020).

The primary aim of this study is to introduce KDE as an analytical method for interpreting archaeological evidence at a scale beyond the individual site specifically, at the broader scale (landscape level) in the Miankouh region.

Questions and Hypotheses

What is the role of the Kernel Density Estimation (KDE) tool in intra-site and landscape-scale archaeological research? Furthermore, if kernel densities of sites are observed, what factors have influenced such distributions across the landscape?

Our first hypothesis proposes that the identification of zones with high site concentrations through KDE serves as a foundation for exploring the underlying causes of clustering and localized intensities of past human activities.

Our second hypothesis, informed by research on the Middle Paleolithic (MP) Period, suggests that certain environmental variables particularly ecological ecotopes [1], including the distribution of water resources and accessible stone raw materials have significantly influenced the spatial distribution of sites within the landscape.

Research Background

There are three main orientations in previous research on the KDE. The first category focuses on the theoretical background, literature, and terminology surrounding the formation and conceptual development of KDE (see: Silverman, 1998). The second category deals with the mathematical foundations and technical procedures for building kernel density models using statistical functions (see: Baxter *et al.,* 2000; Baxter and Cool, 2010; Krisp and Špatenková, 2010). The third category compares KDE with other statistical-graphical methods, emphasizing the strengths and limitations of each in identifying horizontal spatial patterns within archaeological datasets (see: Sánchez-Romero *et al.,* 2021; Baxter *et al.,* 1997). The limited application of KDE in archaeological research has often been attributed to a lack of access to the required software or to insufficient familiarity with the method among archaeologists.

In comparison with histograms, Beardah and Baxter (1996a) highlighted KDE's ability to analyse bivariate (X, Y) and even tri-/multivariate (X, Y, Z) datasets rather than being restricted to univariate data. KDE eliminates dependency on the arbitrary selection of the starting point for intervals and produces smoother visual outputs that are better suited for comparative analyses. KDE effectively visualises entire datasets within a single image, facilitating easier interpretation and comparison (Baxter *et al.,* 1997: 347). Although the application of KDE in Paleolithic archaeology can be traced back to the 1950s (see: Binford, 1978), it was not until the late 20th century that KDE was extensively described as a formal statistical method, particularly in quantitative research (Silverman, 1998). Today, it is used across a wide range of disciplines, including archaeology, climatology, banking, economics, genetics, hydrology, and physiology (Sheather, 2004). In the context of Paleolithic studies, KDE has mainly been applied at the site scale to analyse various categories of cultural materials, such as lithic artefacts (Clark, 2017; Neruda, 2015; Pettitt, 1997), stable lead isotope data (Baxter *et al.,* 2000), animal bone remains (Spagnolo *et al.,* 2020; Blasco *et al.,* 2016), or combinations of multiple datasets (Real *et al.,* 2018; Villaverde *et al.,* 2017; Oron and Goren-Inbar, 2014).

A prominent example of KDE applied at both site (intra-site) and landscape (inter-site) scales is the Paleolithic survey conducted by Olszewski et al. (2005) in the High Desert of Abydos, Egypt. There, spatial analysis of the density and average weight of cores, complete and broken flakes, and tool types was used to investigate topographic patterns of accumulation (Olszewski *et al.,* 2005: 293–294). In the Central Levant, near Damascus (Syria), KDE was applied to study Middle Paleolithic site functions, where proximity to water resources was shown to be the key factor influencing kernel densities and the concentration of stone artefacts across the semi-arid landscape (Conard *et al.,* 2010: 142). Perhaps the most illustrative KDE example comes from Quneitra in the Levant, where Oron and Goren-Inbar (2014) used it to examine the spatial distribution and density of lithic and faunal remains on an open-air excavated surface.

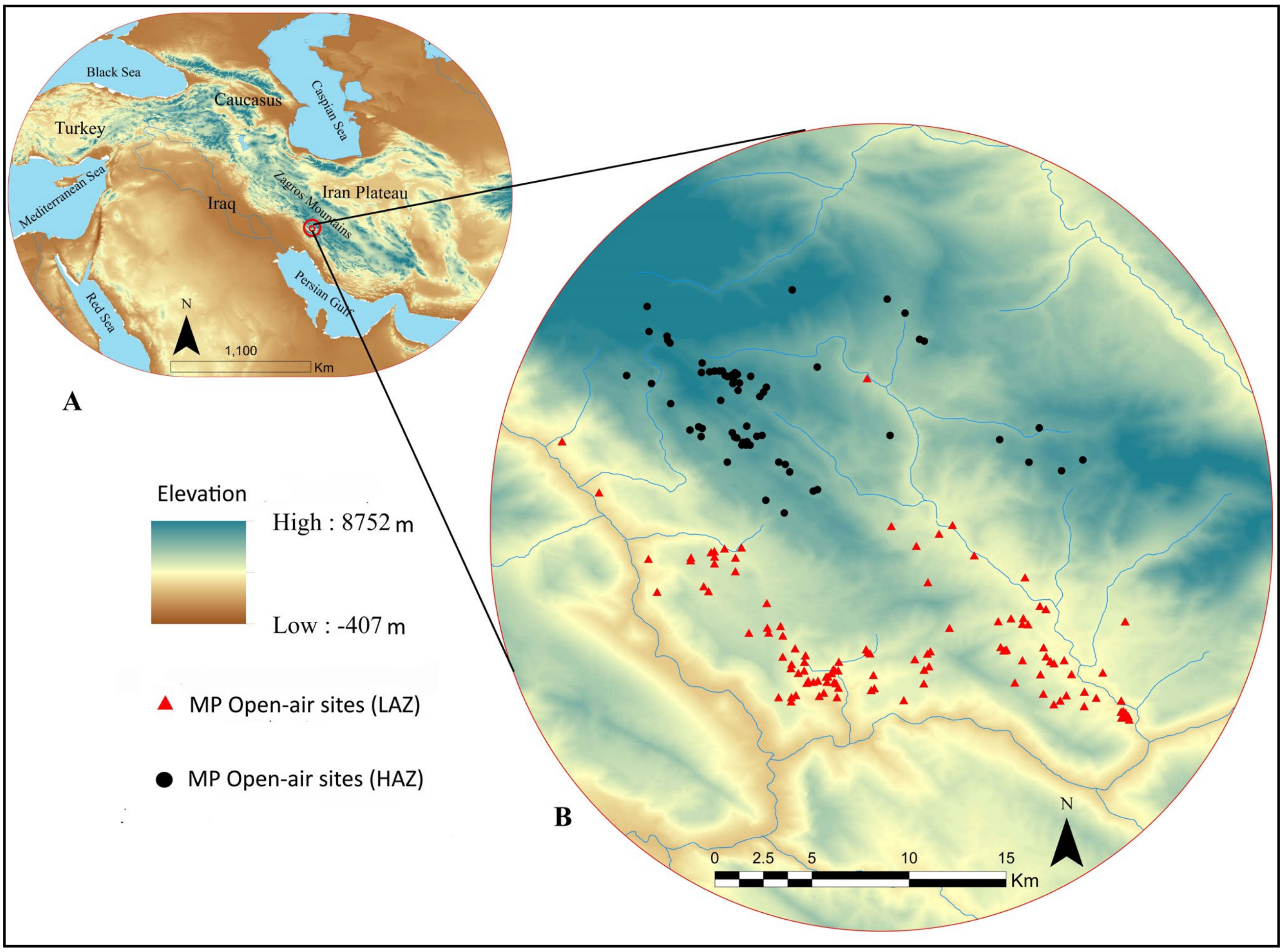
In Europe, Romagnoli and Vaquero (2016) conducted a taphonomic analysis of 11 distinct lithic clusters at the Abric Romaní rock shelter in Capellades, Spain, attributing the distribution patterns to variations in social activity intensity such as group size and occupation duration. Similarly, spatial analysis of lithic and bone remains at the Abrigo de la Quebrada rock shelter near Chelva, Spain, revealed repeated seasonal occupations with intense on-site processing (Villaverde *et al.,* 2017). Clark (2017) investigated seven Middle Paleolithic open-air sites in France to identify behavioural patterns corresponding to zones of high, medium, and low lithic density and to determine the formation processes that produced these distributions.

Recent years have seen a resurgence of interest in spatial patterning in Paleolithic contexts, especially in horizontal clustering of anthropogenic materials identified through GIS-based tools. Current trends in spatial distribution analysis in archaeology increasingly rely on techniques that detect major concentrations of artefacts, including those from the Hotspot family such as Hotspots by Quadrats, K-means, and KDE (see: Sánchez-Romero *et al.,* 2021 and references therein; Coil *et al.,* 2020; Giusti *et al.,* 2018; Blasco *et al.,* 2016).

The study Area

The data presented in the current paper originates from a series of Middle

Paleolithic (MP) open-air sites recorded during field surveys conducted in the Miankouh district of Ardal County, Chaharmahal and Bakhtiari (ChB) Province, within the Zagros Mountains. The survey covered an area comprising two ecological zones, which resulted in two distinct environmental settings spanning approximately 680 square kilometres (Khosrowzadeh, 2011; 2010; 2009) (Fig. 1). These two zones are primarily distinguished by differences in elevation, with the lower zone referred to here as the Low-Altitude Zone (LAZ) and the higher as the High-Altitude Zone (HAZ).



▲Fig. 1. (A) The position of the Ardal County in ChB Province, Southwest Iran and (B) The position of MP open-air sites of the Miankouh region (Authors, 2023).

Both environments were defined through field observation and subsequently confirmed through a review of relevant literature and the use of digital modelling tools. Across the surface of both ecozones, a low density of lithic artefacts ranging from 1 to 36 pieces was recorded at each MP open-air site. The study area yielded a wide range of cultural materials, including lithic artefacts from the MP, Upper Paleolithic (UP), and Epipaleolithic (EP) periods, as well as a substantial quantity of pottery sherds from the Neolithic, Chalcolithic, Medieval, and Late Islamic periods. Focusing specifically on the MP component, 177 open-air sites were recorded in the form of XY coordinate points, comprising a total of 1,454 stone artefacts that were analysed in this study (see details in: Bahraminia *et al.,* 2022).

Materials and Methods

A total of 177 open-air Middle Paleolithic (MP) sites were identified across two distinct ecological zones the LAZ and HAZ) covering approximately 680 square kilometers for KDE analysis. The KDE pattern is determined by the input values and search radius, which vary according to the analytical scale and the size of the statistical population. Within the GIS environment (ArcMap 10.6.1), XY-coordinated point data were inputted using the KDE tool in the software's toolbox section (Fig. 2a). Subsequently, the kernel density of sites was calculated based on the specified search radius and visualized as an output map. The selection of the search radius is data-dependent and influenced by site spatial distribution, directly affecting the accuracy and representativeness of the density results (Sánchez-Romero *et al.,* 2021: 317). To further interpret the kernel density of sites and assess environmental influences on their distribution patterns, a complementary graphical representation was generated using the KDE function in MATLAB R2013a (Fig. 2b). This approach aims to enhance the visual and analytical clarity of the GIS-derived outputs.

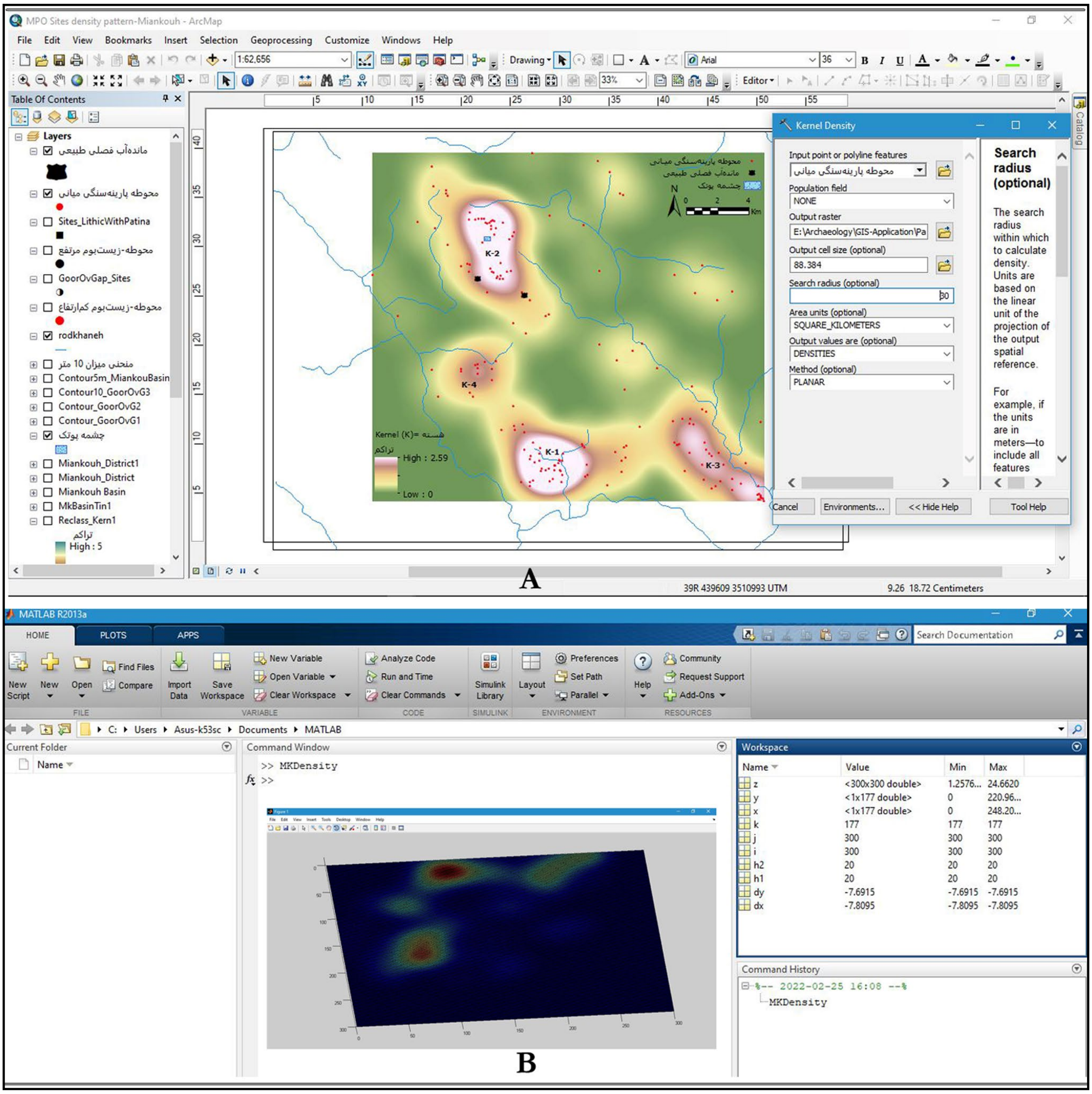
The KDE Mathematical Function

As previously noted, 177 coordinate points corresponding to Middle Paleolithic (MP) open-air sites in the Miankouh region (Khosrowzadeh, 2009; 2010; 2011) were selected for analysis. A search radius of 30 km was applied, determined by the spatial extent of the study area (680 km², encompassing both the LAZ and HAZ), within which the statistical population was evaluated.

The bivariate KDE's mathematical function, central to this study, is expressed by the following formula for estimating K:

$$\hat{f}(x,y) = \frac{1}{nh_1h_2}\sum_{i=1}^{n} k\left(\frac{x-X_i}{h_1},\frac{y-Y_i}{h_2}\right)$$

(Beardah and Baxter, 1996b) where 177 points are statistical population (n), h1 is the bandwidth of X axis, and h2 is the bandwidth of Y axis. Bandwidth value or smoothing parameter based on the extent of the



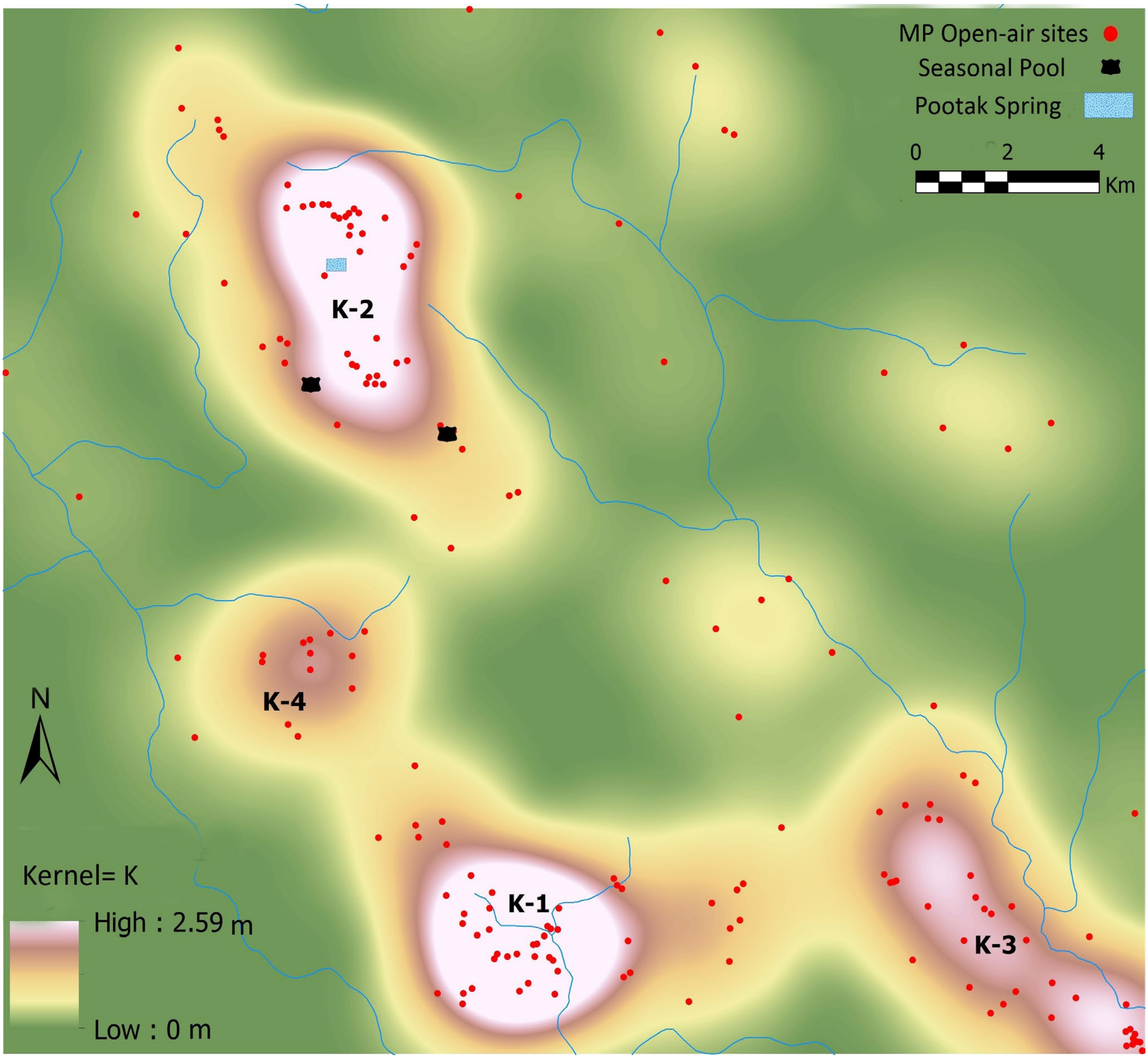
▲ **Fig. 2: General view of GIS (A) and MATLAB (B) work environment (Authors, 2023).**

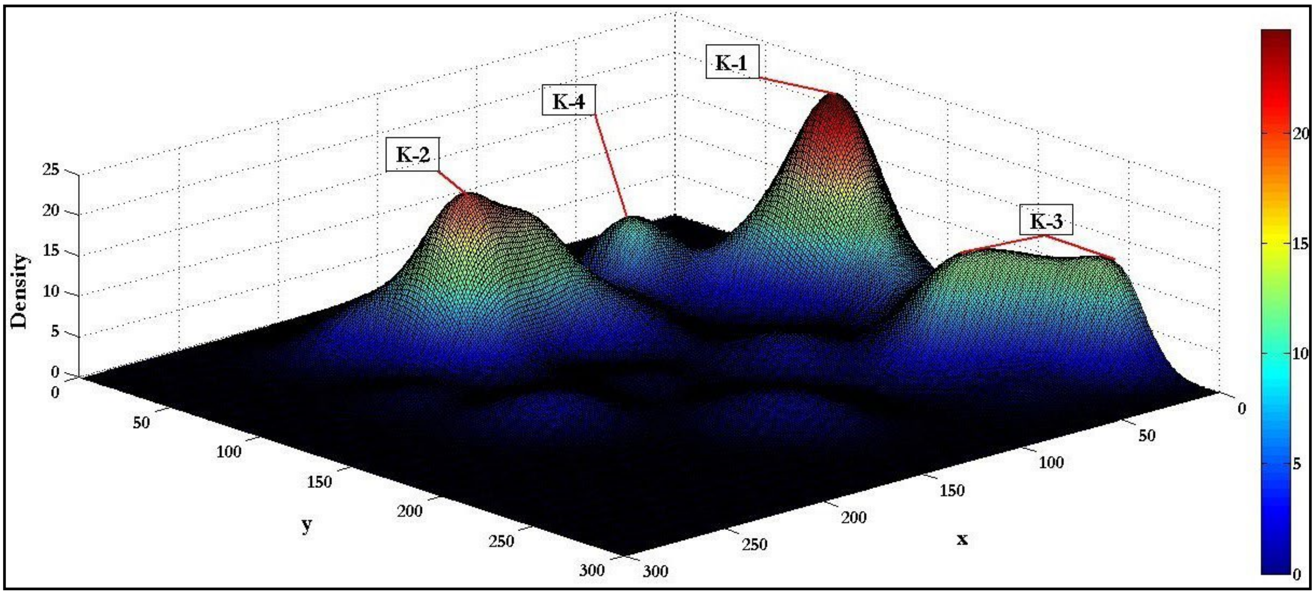
region is 20 rad/time unit for each axis. This complex of orders produces a continuous raster map that is classified based on the colored pixels of the material density on this map (Sánchez-Romero *et al.*, 2021; Giusti *et al.*, 2018).

Discussion

As a result, output of the data indicates that, in general, four density kernels of sites are recognizable according to search radius and using a combination of colors in the form raster/graphical schema (Fig. 3 & 4). Highest concentration of the MP open-air sites (Kernel 1 in Fig. 3 & 4) were seen on the terraces overlooking to Khersun and Bazoft rivers in the LAZ where were found a high frequency of well-rounded pebble chert-based stone raw materials for making artefacts. In this zone, there is also a density with a lower frequency of sites (Kernel 3-4 in Fig. 3 and 4) than kernel 1 on several terraces and slopes overlooking the Sarkhun valley where the valley leads to its narrowest point. Under the influence of three ecotones of Goor Ov Gap, Goor Ov Kuchir, and Pootak spring, the second concentration of sites (kernel 2) in the whole Miankouh are clearly formed near to/or in a close distance of these water resources in the HAZ. Almost

Fig. 3: A raster scheme for the main four kernel density of MP open-air sites in both ecozones of the Miankouh region (by ARC Map), (Authors, 2023). ▼





▲ **Fig. 4. A 3D graphical pick-shaped scheme from the main four kernel density of MP open-air sites in both ecozones of the Miankouh region (by MATLAB). (Authors, 2023).**

a similar density of sites can be seen in the Dehdasht terrace district in the narrowest part of the Sarkhun river valley (Fig 3-4: K-3). Here too, like Serenjak and Goud lalow slopes, the slopes of the Pachatoun and Mazdaki Valley, the highest frequency of river bed rounded stone raw materials can be seen.

Conclusion

Most research on the KDE analytical approach in spatial archaeology has primarily focused on the spatial distribution of cultural materials (such as lithic assemblages and faunal and floral remains) within single sites mainly caves in order to determine the function and duration of site occupation (see: Clark, 2017; Villaverde *et al.*, 2017). For instance, at Quneitra in the Levant, evidence suggests that specific parts of the site were used for particular activities such as knapping, carcass processing, and marrow extraction (Oron and Goren-Inbar, 2014: 201). Clark (2017: 1321) concluded that areas of high artefact density may reflect either multiple occupations or the activity of numerous knappers (see also: Real *et al.*, 2018: 202). Olszewski et al. (2005: 299), drawing on Van Peer's settlement models, particularly for the Nubian Stone Industry Complex, interpreted the MP sites in the Abydos Desert as locations designated for "specific activities." A similar behavioural pattern has also been identified at Kulna Cave (Layer 7a, Micoquian period) in the Czech Republic, where Neanderthals appear to have structured this winter base camp into spatial zones dedicated to specific tasks, possibly including meat processing (Neruda, 2015: 74). In the Central Levant (Syria), in a manner somewhat similar to the Miankouh region, the extensive use of the semi-arid landscape seems to have been directly influenced by natural factors such as variations in precipitation, proximity to permanent water sources as well as by cultural factors like the availability of water transportation methods (Conard *et al.,* 2010: 142).

At the present, we have no absolute data or stratified contexts to identify the function of our MP open-air sites also, reasons for the accumulation of them in four points of the landscape. But on the basis of techno-typological analysis of lithic artefacts, spatial distribution of surface findings, the low frequency of the stone artefacts, and also the absence of cave sites in this region all give us the impression that the MP open-air sites of Miankouh had a very temporary and ephemeral functions such as places for chasing hunting or daily excursions for food sources extraction by hunter-gatherer societies (see details in: Bahraminia *et al.,* 2022). Using the inter-site approach, a method that aims to find relationship between several different sites at the landscape-scale, as opposed to the intra-site approach, which focuses on analyzing a single site (to review the characteristics of each approach, see: Bintliff, 2000; Zvelebil *et al.,* 1992; Dunnell and Dancey, 1983), and by focusing on KDE approach, in general, two important factors have participated in more concentration of the MP open-air sites in 4 Kernels which include: 1- rivers (Khersun and Bazoft) by providing a portion of chert-based stone raw materials for making tools in the LAZ and, 2- the natural seasonal pools/lakes and Pootak permanent spring in highlands of the HAZ.

Endnote

[1] The smallest units of a vast geographical landscape in terms of ecology that can be mapped and classified. In Miankouh, water resources, and natural beds (rocky outcrops/nodules) are sources of raw materials for tool-making represent the most important components of the active ecotopes in the area (for landscape studies and active ecotopes, see: Dash and Dash, 2009; Zonneveld, 1995).

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Observation Contribution

All authors contributed equally to the writing of the article.

Conflict of Interest

The Authors, while observing publication ethics in referencing, declare the absence of conflict of interest.

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«تخمین/ برآورد تراکم هسته» در پژوهش‌های باستان‌شناسی چشم‌انداز (مطالعهٔ موردی: پراکنش محوطه‌های پارینه‌سنگی میانی منطقهٔ میانکوه؛ چهارمحال و بختیاری)

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چکیده

امروزه رویکرد مبتنی‌بر «تخمین یا برآورد تراکم هسته» در تصویرسازی پدیده‌های تأثیرگذار (اکوتوپ‌های اکولوژیکی) بر توزیع فضایی محوطه‌ها در بستر چشم‌اندازهای جغرافیایی از اهمیت بالایی برخوردار است. ابزار مستندنگاری و تحلیلی GIS به‌عنوان یکی از ابزارهای شناسایی محل‌های فعالیت‌های مشخص در کنار خروجی‌های برآمده از نرم‌افزار MATLAB در هرچه ملموس کردن نقش عوامل محیطی در الگوی بهره‌وری از محیط در باستان‌شناسی فضایی-چشم‌انداز نقش دارند. این پژوهش با جامعه‌ای آماری از دورهٔ پارینه‌سنگی میانی از ارتفاعات غرب چهارمحال‌وبختیاری (منطقهٔ میانکوه) شامل ۱۷۷ محوطه که در طول سه فصل بررسی پیمایشی در فاصلهٔ سال‌های ۹۰-۱۳۸۸ شناسایی شده‌اند، به‌گوشه‌ای از اهمیت تخمین/ برآورد تراکم هسته در مطالعهٔ محوطه‌ها/ محل‌ها با فراوانی مواد فرهنگی می‌پردازد. تحلیلی از ۱۷۷ نقطهٔ با مختصات XY نشان می‌دهد که دو عامل رودخانهٔ دائمی با منابع چرت در زیست‌بوم کم‌ارتفاع، و دو ماندہ‌آب یا حوضچهٔ طبیعی فصلی و چشمه پوتَک در زیست‌بوم مرتفع از برخی عوامل احتمالی توزیع محوطه‌ها/ محل‌ها در میانکوه بوده‌اند. نتایج ارزیابی‌ها نشان می‌دهد که به‌طورکلی چهار هستهٔ تراکم محوطه‌ها در طول چشم‌انداز قابل مشاهده است؛ متراکم‌ترین نقطهٔ توزیع محوطه‌ها در زیست‌بوم کم‌ارتفاع دیده شده است، جایی‌که تعداد زیادی از محوطه‌ها (هستهٔ اول) در فاصله‌ای نزدیک از رودخانه دائمی بازُفت و خِرسون در میان دامنه‌ها و تپه‌ماهورهای مشرف به این دو رودخانه با پراکندگی فراوان قلوه‌سنگ‌های چرتی مناسب ساخت ابزار و در محل‌های با آبراهه‌ها و آبکندهای فراوان شکل گرفته‌اند. هستهٔ دوم تراکم محوطه‌ها در زیست‌بوم مرتفع شکل گرفته است. در اینجا محوطه‌ها در کنار دو حوضچهٔ فصلی طبیعی و چشمهٔ دائمی پوتک تمرکز یافته‌اند. هستهٔ سوم در محدودهٔ تراس دهدشت در تنگ‌ترین بخش درهٔ رودخانهٔ سرخون قابل‌مشاهده است. کمترین تراکم محوطه‌ها (هستهٔ چهارم) روی تپه‌ماهورهای تَل‌اُو شکل گرفته‌اند که کاملاً مشرف‌بر رودخانهٔ بازفت هستند.

کلیدواژگان: تراکم هسته، میانکوه، پارینه‌سنگی میانی، چشم‌انداز تحلیل فضایی.

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