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Spatiotemporal Changes and Driving Factors of Prehistoric Sites in the Nihewan Basin Using Geographic Detector*

Qiao Bin¹ Li Jun²(corresponding author)

Abstract: The Nihewan Basin, a key area of continuous prehistoric human activity in East Asia, preserves archaeological remains from the Early Pleistocene to the Holocene (ca. 1.8 Ma), critical for understanding early human adaptation and cultural evolution. This paper uses GIS spatial analysis (clustering, kernel density, and natural factor analysis) and the geographic detector model to systematically examine the spatiotemporal distribution, evolutionary processes, and natural driving mechanisms of Paleolithic and Neolithic sites (Early Paleolithic to Longshan period). Quantitatively, we reveal the environmental adaptation process of prehistoric humans transitioning from mobile hunting-gathering to settled agriculture (1.8 Ma to 40 ka). Results show that the spatiotemporal variation of sites results from the combined effects of climatic fluctuations, geomorphological development, hydrological conditions, and changes in livelihood patterns.

1 Introduction

The Nihewan Basin, located in the northeastern part of the Loess Plateau and the transitional zone from the Mongolian Plateau to the North China Plain, is a core area for prehistoric human activity in East Asia^[1]. In 1921, the French missionary Vincent discovered fossilized vertebrates in the Nihewan strata; from 1924 to 1930, French paleontologist Teilhard de Chardin and British geologist Barbour, among other scholars, conducted multiple investigations here, and were the first to propose the academic term “Nihewan Formation.”^[2] They also named the Early Pleistocene fauna discovered in the Nihewan Basin as the “Nihewan Fauna.”^[3] Since then, the Nihewan Formation has been regarded as the standard Pleistocene geological profile in North China. In 1978, with the discovery of the Xiaochangliang Early Palaeolithic site^[4], the influence of the Nihewan Basin in the international academic community has grown increasingly significant, gradually establishing its important scholarly status in the fields of human evolution^[5], Quaternary geology, and paleontology^[6].

The stratigraphic accumulation within the Nihewan Basin spans from the Early Pleistocene to the Holocene, with complete sequences, densely distributed sites, and a rich variety of artifacts. It is a concentrated area of prehistoric cultural remains and is internationally recognized as a key region for the study of early human evolution. In the Early Paleolithic, the Maquan Gou site^[7], dating back 1.77 million years, was discovered, pushing back the timeline of ancient human activity in East Asia to the early Early Pleistocene. In the Middle Paleolithic, represented by the Xujiayao humans^[8], fossils were unearthed that show the transition from *Homo erectus* to modern humans. In the Late Paleolithic, hematite processing traces were found at the Xima Bei site^[9], and the stratigraphic accumulation at the Youjia Gou site^[10] meticulously records the evolution from Paleolithic to Neolithic cultures. During the Neolithic, discoveries of stone accumulations, sacrificial pits, and cemeteries at the Zhengjiagou and Jiangjialiang sites^[11] marked the migration of the Hongshan culture 5,000–4,300 years ago and the interactions between this region and the Central Plain culture. From the above, it can be seen that the Nihewan Basin comprehensively displays the cultural evolution from nearly 1.8 million years ago to 4,000 years ago, from the

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Paleolithic to the Neolithic, making it a cradle of human evolution comparable to the Olduvai Gorge in East Africa.

The Nihewan Basin is located in the northeastern part of Shanxi Province and the northwestern part of Hebei Province, covering an area of approximately 9,000 square kilometers, with geographic coordinates ranging from 39°10' to 41°50' N latitude and 112°25' to 115°80' E longitude. The northern boundary of the Nihewan Basin ^{[12][13]} connects to the southern edge of the Inner Mongolia Plateau, while the southern boundary adjoins the Hengshan Mountains; the west is bordered by the Guanchen Mountains and Hongtao Mountains, and the Sanggan River flows through the basin from west to east. The concept of the Nihewan Basin used in this study is broad, encompassing regions linked by the Sanggan River and its tributaries, including the Datong Basin, Yangyuan Basin, Yuxian Basin, Zhuolu Basin, and Huailai Basin. (Fig. 1) The tectonics and paleoenvironmental evolution of the Nihewan Basin laid the foundation for human activities. During the Pliocene to Early Pleistocene, tectonic activity in the Nihewan Basin region was intense, forming a new pattern of faulted depressions and uplifted mountains, and the ancient Nihewan Lake subsequently appeared and continued to expand ^[14]. From the Late Middle Pleistocene to the Early Late Pleistocene, tectonic activity remained strong, with ongoing block uplift and subsidence, gradually evolving into the modern landscape of the Nihewan Basin ^[15]. During this period, the ancient lake experienced major transgressive events and underwent large-scale contraction by the end of the Middle Pleistocene. In the Late Late Pleistocene, following a last small-scale expansion, the ancient lake rapidly disappeared, and drainage erosion led to the development of the modern Sanggan River system and its tributaries (such as the Yang River and Huli River), connecting and linking various basins. Human activities in this region appeared as early as the Early Pleistocene and became increasingly frequent by the Late Late Pleistocene ^[16], during the Late Paleolithic, with an increase in the number of sites, broader distribution, and complex and diverse cultural characteristics. The lithic industry not only included the two traditional categories of small tools and microliths, but the large tool tradition represented by the Emao site ^{[17][18]} further enriched the cultural connotation.

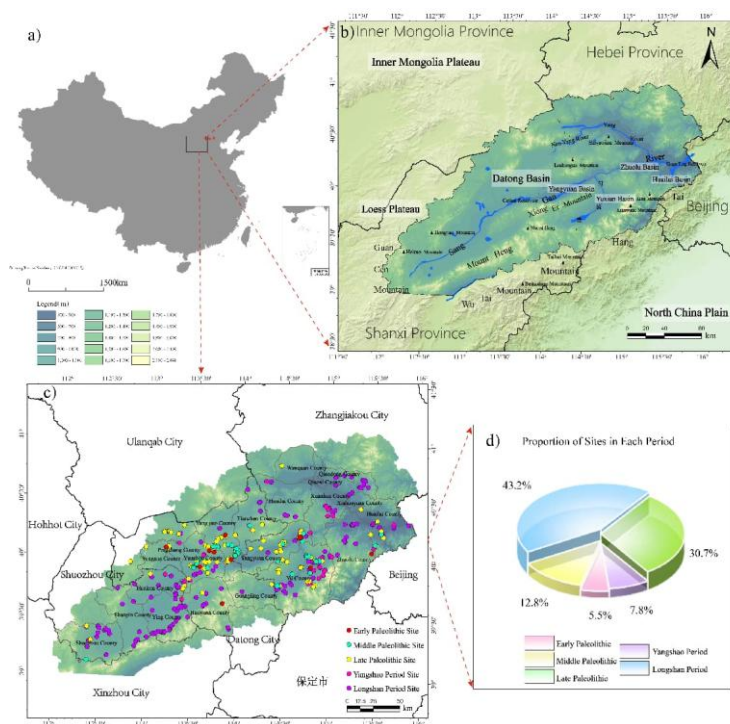


Fig.1 Geomorphology and Site Distribution of the Nihewan Basin

a)Location map of Nihewan b)Topographic map of Nihewan c)Distribution Map of the Nihewan Site d)Site Statistics Chart

This study focuses on the spatial and temporal distribution of prehistoric sites in the Nihewan Basin. By integrating currently published site geographic information and chronological data, and employing GIS spatial analysis and statistical methods, it aims to systematically analyze the distribution patterns and evolutionary laws of prehistoric cultural sites in the Nihewan Basin. Furthermore, based on geographical detectors, it seeks to explore the driving factors of the geographic environment and site distribution, thereby further revealing the adaptability and response mechanisms of ancient humans in the Nihewan Basin to their environment.

2 Methods

2.1 Data Sources

The prehistoric site data of the Nihewan Basin used in this study were selected from the Atlas of Chinese Cultural Relics (Shanxi Volume, Hebei Volume), various archaeological survey reports, excavation reports, and publicly published papers. Geographic coordinates were imported into the ArcGIS Pro geographic information system. A total of 384 sites were collected and organized, including 21 Early Paleolithic sites, 49 Middle Paleolithic sites, 118 Late Paleolithic sites, 30 Yangshao period sites, and 166 Longshan period sites. In addition, the digital elevation model (DEM) data used in this study were sourced from ASTER GDEM V3, with a resolution of 30 meters.

2.2 Research Methods

2.2.1 Average Nearest Neighbor Analysis

The average nearest neighbor analysis is a spatial point pattern statistical method in archaeology, primarily used to quantitatively analyze the distribution patterns of point elements such as sites and artifact find locations, and to determine whether they are clustered, random, or evenly distributed. By calculating the actual average distance from each point to its nearest neighbor and comparing it with the theoretical average distance of a random distribution of the same number of points within the same area, the nearest neighbor index R is obtained. Based on the numerical characteristics of the nearest neighbor ratio (R)^[19], the spatial distribution pattern of sites can be determined. A ratio (R) < 1 indicates a clustered distribution of sites (the smaller the value, the higher the degree of clustering); a ratio (R) = 1 indicates a random distribution; a ratio (R) > 1 indicates a dispersed distribution. At the same time, the method calculates Z-scores and P-values for significance testing to determine whether the pattern occurs randomly or has statistical significance. The specific calculation formulas are as follows:

$$R = \frac{r_1}{r_E} = \frac{1}{n} \sum_{i=1}^n r_1 S_i \times \frac{1}{2\sqrt{\frac{n}{A}}}$$

In the formula: R is the nearest neighbor index, r_1 is the average nearest neighbor distance, r_E is the theoretical average nearest neighbor distance, and n represents the total number of cultural relics within the area; $r_1 S_i$ is the distance from point S_i within the area to its nearest point; A is the area of the Nihewan Basin.

2.2.2 Kernel Density Analysis Method

The kernel density analysis method is an important technical approach in archaeological spatial analysis, used to transform discrete point-type site features into continuous and smooth density surfaces^{[20][21]}. By generating visual density heatmaps, this method can intuitively reveal

hotspot areas and clustering cores of site distributions. The higher the kernel density estimation value, the denser the distribution of point features, which enables a scientific delineation of the core areas of high-intensity human activity in ancient times. The specific calculation formula is as follows:

$$f(s) = \frac{1}{nh} \sum_{i=1}^n K\left(\frac{x - x_i}{h}\right)$$

In the formula, $f(s)$ is the probability density function, which is the result of kernel density estimation; h is the bandwidth; n is the number of points within the bandwidth; K is the kernel function; x is a point within the grid; and x_i is the center of the grid search. The Kernel density in this research was calculated in ArcGIS Pro using the Spatial Analyst tool. The implementation is based on the quartic kernel function described by Silverman^[22].

2.2.3 Standard Deviation Ellipse Analysis Method

The standard deviation ellipse analysis method is a core method used to quantitatively analyze the direction, range, and shape of the spatial distribution of point features^[23], and it has important practical value in archaeological research. Using the mean center of the point data as the center of the ellipse, the standard deviations in the X and Y directions are calculated to determine the lengths of the ellipse axes, thereby generating an ellipse that can encompass a specified proportion of the features. The greater the difference between the long and short axes, the more pronounced the directional tendency of the points. The angle between the long axis and true north indicates the primary trend direction of the distribution, and the value can intuitively reflect the distribution range of the point set. The specific calculation formulas are as follows^[24]:

$$\sigma_x = \sqrt{\frac{\sum_{i=1}^n (\tilde{x}_i \cos \theta - \tilde{y}_i \sin \theta)^2}{n}}, \sigma_y = \sqrt{\frac{\sum_{i=1}^n (\tilde{x}_i \sin \theta + \tilde{y}_i \cos \theta)^2}{n}}$$

2.2.4 Mean Center Analysis Method

The mean center analysis tool calculates the average center of different sites by computing the average x-coordinate and y-coordinate of all site points within a certain range. It is mainly used to track distribution changes and to compare the distribution centers of different site groups^[25]. The specific calculation formula is as follows:

$$\bar{X} = \frac{\sum_{i=1}^n x_i}{n}, \bar{Y} = \frac{\sum_{i=1}^n y_i}{n}$$

2.2.5 Slope Morphology Analysis Method

Slope gradient and aspect analysis are two factors that represent slope morphology, referring to the orientation and inclination of local surface slopes in space. Slope gradient is the angle between the normal at a point on a curved surface (e.g., a site point) and the vertical direction, or it can be defined as the angle between the tangent plane at the ground point and the horizontal plane. Slope aspect refers to the angle between the projection of the slope normal on the horizontal plane and the true north direction. In archaeology, slope gradient analysis can systematically reveal the influence of surface inclination on site selection for human activities, land use patterns, site preservation status, and artifact distribution. Slope aspect is the core terrain feature affecting surface solar radiation distribution, local microclimate formation, and surface runoff direction, and is often used to evaluate sites in terms of sunlight access, avoidance of wind and cold, and drainage conditions. For example, Cui's study used this indicator^[26].

2.2.6 Hydrological Analysis

Hydrological analysis is used to simulate the formation, convergence, and evolution of surface runoff, in order to extract hydrological characteristics of a watershed^[27]. It is widely applied in regional hydrological environment reconstruction. This method first preprocesses DEM data by filling depressions to eliminate data errors, that is, areas where water cannot drain. It extracts core hydrological indicators such as river network distribution, watershed basin extent, and drainage density in the Nihewan Basin, thereby quantifying the impact of the hydrological environment on site selection and distribution density. For example, The study by Yang and others referred to this indicator^[28].

2.2.7 Geographic Detector

The Geographic Detector model is a statistical method for exploring the spatial distribution patterns of research objects and the driving forces of various influencing factors^[29]. The Geographic Detector has been widely applied in studies of driving mechanisms behind various geographical phenomena and can quantitatively identify dominant factors that significantly contribute to spatial distribution. It comprises four core modules: factor detection, interaction detection, risk area detection, and ecological detection. In this study, the factor detection and interaction detection modules of the Geographic Detector model were used to quantify the explanatory power of each evaluation indicator on spatial distribution differences of prehistoric sites, in order to explore the natural factor-driven mechanisms behind the distribution of prehistoric sites in the Nihewan Basin. The Geographic Detector is a spatial research model used to examine the degree of association between research samples (prehistoric sites) and related influencing factors (natural factors). The results are measured using the q value, with the specific calculation formula as follows:

$$q = 1 - \frac{\sum_{h=1}^L N_h \sigma_h^2}{N \sigma^2}$$

In the formula, $h=1, 2, \dots, L$; q represents the degree of explanatory power of the independent variable, with a range of $[0, 1]$ ^[30]. The larger the value, the closer it is to 1, indicating that the influence of the independent factor (X) is greater, the result differentiation is stronger, and the explanatory power for the attribute Y is higher; conversely, the influence is weaker. L represents the stratification of the independent or dependent variable. N_h and σ_h^2 are the number of units and variance in the h^{th} layer, respectively; N and σ^2 are the total number of units and overall variance, respectively.

3 Results

3.1 Spatial Distribution Characteristics

3.1.1 Cluster Analysis

Based on the results of the average nearest neighbor calculation, the clustering pattern of site distribution during all prehistoric periods is a clustered distribution (Fig.2). The analysis indicates (Table 1) that from the Early Paleolithic to the Middle Paleolithic, the nearest neighbor ratio increased from 0.568 to 0.592, showing a slight weakening in clustering, but still remaining highly clustered. From the Middle Paleolithic to the Late Paleolithic, the nearest neighbor ratio decreased to 0.508, with a Z score reaching -8.57, indicating the strongest clustering. During the Yangshao period, the nearest neighbor ratio was 0.650, a significant increase compared to the Late Paleolithic, showing a reduction in clustering. In the Longshan period, the nearest neighbor ratio rose to 0.686, with clustering further weakened, and the Z score was -7.74.

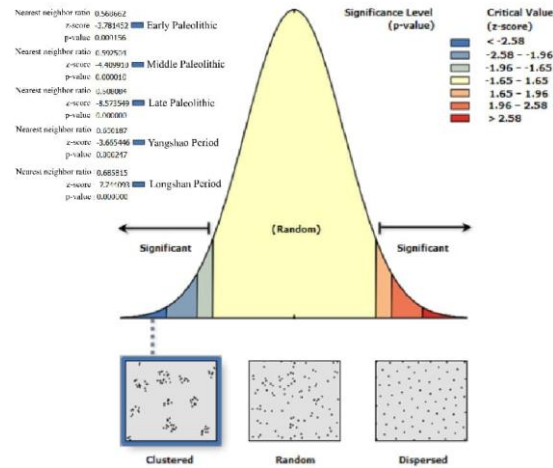


Fig.2 Spatial Distribution Types of Sites in Different Periods

Table 1 Average Nearest Neighbor Analysis

Period	Average observation distance (m)	Expected average distance (m)	Nearest neighbor ratio (R)	z-score	p-value	Clustering mode
Early Paleolithic	14159.5661	24899.8054	0.568662	-3.781452	0.000156	Agglomeration distribution
Middle Paleolithic	11951.4761	20171.1478	0.592504	-4.409910	0.000010	Agglomeration distribution
Upper Paleolithic	6363.5919	12524.6776	0.508084	-8.573549	0.000000	Agglomeration distribution
Yangshao Period	13545.1427	20832.6719	0.650187	-3.665446	0.000247	Agglomeration distribution
Longshan Period	6073.7715	8856.2845	0.685815	-7.744093	0.000000	Agglomeration distribution

3.1.2 Kernel Density Analysis

Kernel density analysis, standard deviation ellipse analysis, and mean center analysis systematically reveal the spatial distribution density characteristics and the changes in distribution centers of prehistoric sites in the Nihewan Basin. Kernel density analysis is used to study the spatial distribution characteristics of point features within a spatial area. The resulting kernel density map of prehistoric sites in the Nihewan Basin can intuitively show the locations and clustering of sites, revealing the spatial clustering orientation of the prehistoric sites in the basin (Fig.3). According to the results of the kernel density analysis, the distribution of sites within the basin does not completely cover the entire Nihewan Basin. Overall, the site distribution shows a clear multi-center distribution pattern.

During the Paleolithic, the kernel density clusters evolved from a single-core cluster, initially centered on Yangyuan County with a secondary area around Yunzhou District and Yanggao County, gradually developing into a dual-core cluster, with internal differentiation and development of sites within the Yunzhou District and Yanggao County cluster, the distribution range of sites expanding significantly, and kernel density markedly increasing. In the early Paleolithic, sites were sparsely distributed along the northern edge of the Yangyuan Basin, forming a single-core cluster centered on Yangyuan County, with extremely low kernel density, and a small number of sites concentrated in Yunzhou District and around Yanggao County. In the Middle Paleolithic, the number of sites slightly increased, with the aggregation cores still centered on Yangyuan County and Yunzhou District–Yanggao County areas, but the distribution center shifted to Yunzhou District and Yanggao County, and a few secondary site points appeared within the Nihewan Basin, with the distribution range slightly expanding outward, and kernel density levels higher than in the earlier period. In the Late Paleolithic, the number of sites increased significantly,

forming two high-density core areas around Yangyuan County and Yunzhou District–Yanggao County, with secondary clusters widely distributed along the northern and western edges of the basin, the overall distribution range greatly expanded, and kernel density levels significantly increased.

During the Neolithic, the distribution pattern of sites in the Nihewan Basin underwent significant changes, showing an overall trend of shifting from scattered to dense distribution and from a single-core to multi-core expansion. In the Yangshao period, sites were mainly concentrated in Wei County, with only sparse site distribution in other areas; the previous Yangyuan core area disappeared, and only a few secondary clusters appeared in Huaiaren City, Hunyuan County, and Yunzhou District, with the distribution center shifting eastward and kernel density at a medium level. In the Longshan period, the number of sites reached its peak; based on the distribution pattern of the Yangshao period, each kernel density cluster expanded outward, forming a multi-core dense distribution pattern, and sites were distributed in an east-west strip along the Sanggan River, with the distribution range covering almost the entire basin and overall kernel density at the highest level.

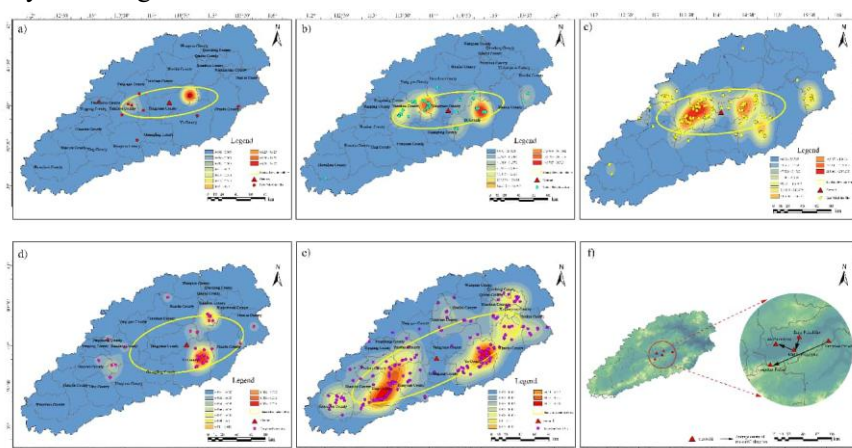


Fig.3 Site kernel density, standard deviation ellipse, and changes in site distribution center

a)Early Paleolithic b)Middle Paleolithic c)Late Paleolithic d)Yangshao Period e)Longshan Period f)Mean center shift

3.1.3 Standard Deviation Ellipse and Mean Center Analysis

According to the standard deviation ellipse and mean center analysis (Table 2), the centers of site distribution are all located in the Yangyuan Basin, situated in the central part of the entire Nihewan Basin.

From the perspective of the Paleolithic as a whole, the center of site distribution in the Nihewan Basin shifted southwestward within the basin, with a relatively short overall movement distance. During the Pleistocene, the climate exhibited alternating fluctuations of cold and warm, wet and dry periods. Compared to the Early Pleistocene, the Middle Pleistocene climate was colder and drier, with significant glacial–interglacial cycles^[31]. The overall environment tended toward aridity, and the site distribution center moved to the warmer southwest by 11.73 kilometers. Since the Late Pleistocene, the climate was predominantly cold and dry, especially during the Last Glacial Maximum when extremely cold and dry periglacial environments occurred. Extensive Malan loess accumulation developed in the region, but improvements in stone tool technology and the use of fire enhanced ancient human environmental adaptability. This led to a shift in activity patterns toward more mobile adaptive strategies, an increase in secondary aggregation points, and a northwestward movement of the site distribution center by 15.39 kilometers.

Entering the Neolithic, with the advent of the Holocene Climatic Optimum, the climate conditions generally became relatively warm and humid, with stable development of rivers, lakes, and marshes, providing a suitable environment for the emergence of primitive agriculture and stable settlement. Compared to the Late Paleolithic, the site distribution center shifted northeast within the basin. Populations gradually transitioned from a highly mobile hunting-gathering lifestyle to a settlement-based lifestyle relying on river terraces and loess plateaus. Site distribution also shifted from being primarily concentrated in river valleys during the Paleolithic to higher terraces and loess plateaus more suitable for agriculture. During the Late Holocene, the climate again tended toward dry and cold conditions, with slight decreases in temperature and humidity, reduced environmental stability, and corresponding adjustments in human settlement and subsistence strategies. Consequently, the site distribution center moved southwestward by 50.89 kilometers.

Table 2 Standard Deviation Ellipse Analysis of the Site

Period	Site center coordinates	Mobile distance (km)	Movement angle (°)	Moving direction
Early Paleolithic	114°20'7"E, 40°7'52"N	--	--	--
Middle Paleolithic	114°17'23"E, 40°2'14"N	11.73	197.22	southwest
Upper Paleolithic	114°6'56"E, 40°4'36"N	15.39	282.53	northwest
Yangshao Period	114°36'42"E, 40°6'40"N	42.71	84.56	northeast
Longshan Period	114°4'13"E, 39°55'33"N	50.89	245.52	southwest

3.2 Influencing Factors of Spatial Distribution of Prehistoric Sites

The natural environment is one of the key factors shaping the distribution of prehistoric humans. The special topography, geomorphology, and water resources of the Nihewan Basin have established the pattern of spatial distribution of prehistoric sites. This section analyzes the natural environment, selecting four key geographical factors: elevation, slope, aspect, and water system, and combines them with the Geographic Detector model to quantitatively test the influence of each factor on site distribution.

3.2.1 Elevation

Based on the illustrative analysis (Fig.4), the terrain in the study area is significantly undulating, with an elevation range of 320–2841 meters, covering basins, valleys, and surrounding mountains. Among them, the mountains have an elevation range of 1700–2841 meters, mainly including Hengshan in the south, Guanchen Mountain in the west, and the Taihang Mountains in the east; the main basin area in the study region has an elevation of approximately 450–1200 meters; depressions are mainly formed by the Sanggan River and reservoirs. Overall, the distribution of sites exhibits a clear vertical differentiation pattern, with elevations concentrated between 800–1200 meters, indicating that ancient humans had a significant preference for specific elevation ranges.

From the spatial distribution shown in the box plot (Fig.4), prehistoric sites in the basin are mainly concentrated in the basin terraces and the gentle slopes in front of the mountains. In the Early to Middle Paleolithic, sites were distributed on higher terraces and plateaus at elevations of 900–1100 meters. In the Middle to Late Paleolithic, sites expanded to terraces at 800–1200 meters, and the proportion of high-elevation sites increased. During the Neolithic, site distribution extended to lower elevations. In the Longshan period, it further spread to gentle slopes at 700–1200 meters. Living resources, safety, and convenience of activity were the main reasons why prehistoric humans chose relatively stable elevation ranges; the variation of elevation within a certain range also reflects the adaptation of prehistoric humans in the Nihewan Basin to climatic

changes and the transformation of their subsistence patterns.

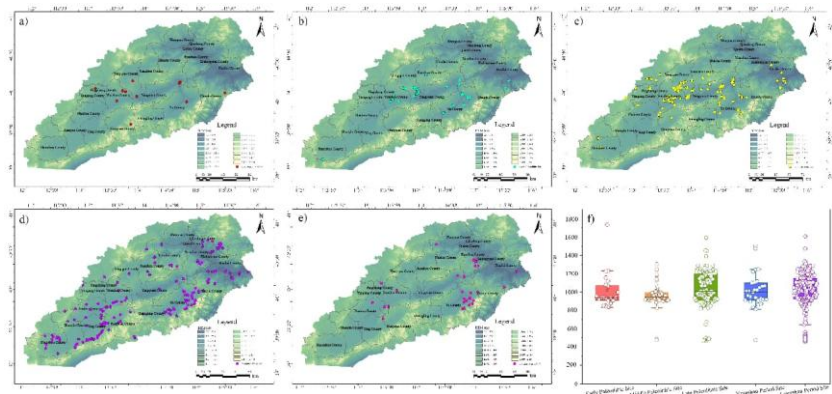


Fig.4 Elevation Analysis of the Site

a)Early Paleolithic b)Middle Paleolithic c)Late Paleolithic d)Yangshao Period e)Longshan Period f)Box diagram

3.2.2 Slope

Overall (Fig.5, Table 3), prehistoric humans in the Nihewan Basin preferred slopes ranging from 0 to 15°. Changes in slope selection at sites reflect the transition of human subsistence from foraging and hunting to settled agriculture. During the Paleolithic period, sites were distributed across flat slopes, gentle slopes, and moderate slopes, with a predominance on flat and gentle slopes, and the largest proportion on gentle slopes. Some sites were found on steeper slopes, indicating a broad adaptability to slope. Paleolithic humans depended on hunting and gathering, had wide activity ranges, and moved frequently, often choosing slopes with open views and steeper terrain, which aligned with their survival strategies. From the Neolithic onwards, site locations shifted towards flat and gentle slopes, with an increasing number and proportion of sites on flat slopes, corresponding to the emergence of agriculture and settled life.

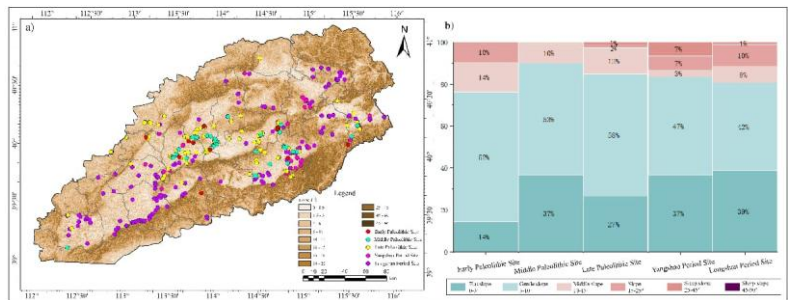


Fig.5 Slope Analysis of the Site

a)Slope Map b)Percentage Stacked Bar Chart

Table 3 Statistics of the Number of Sites with Different Slopes in Each Period

	Flat slope 0-3°	Gentle slope 3-10°	Middle slope 10-15°	Slope 15-25°	Steep slope 25-45°	Sharp slope 45-90°
Early Paleolithic	3	13	3	2	0	0
Middle Paleolithic	18	26	5	0	0	0
Upper Paleolithic	30	66	14	2	1	0
Yangshao Period	11	14	1	2	2	0
Longshan Period	64	69	13	17	2	0

3.2.3 Slope Aspect

Slope aspect, as an indicator for assessing terrain characteristics, indirectly affects the choices of human activities in prehistoric times by influencing local microclimate, sunlight duration, and

water resource distribution, thereby forming a correlation with site distribution. In the Nihewan Basin, winter is heavily influenced by the monsoon, and the region has a temperate semi-humid to semi-arid climate, making the role of slope aspect in shaping the environment more prominent. South-facing, southeast-facing, and southwest-facing slopes generally receive ample solar radiation, have higher ground temperatures and sufficient sunlight, which are conducive to human habitation and crop growth. In contrast, north-facing and northwest-facing slopes receive weaker solar radiation, have lower evaporation, relatively higher soil moisture, insufficient sunlight, and a comparatively colder climate.

From the overall distribution (Fig.6), prehistoric sites in the Nihewan Basin are found on various slope aspects. Due to significant differences in the number of sites from different periods, statistical analysis is presented in terms of percentage (Fig.6, Table 4). Paleolithic sites are mostly distributed on west- and southwest-facing slopes; Yangshao period sites are mainly found on southeast-facing slopes, while Longshan period sites are distributed on southwest, south, southeast, and northeast-facing slopes. Overall, the proportions of sites on north, northwest, northeast, and east-facing slopes are relatively low. During the Paleolithic, when agriculture had not yet developed on a large scale, humans depended on hunting and gathering, and basic survival needs were more critical than microclimatic habitability. In the Neolithic, although sites preferred south-facing slopes to receive sufficient heat and sunlight favorable for settlement and agricultural production, no single slope direction was highly concentrated in any period, indicating that slope aspect had a relatively weak influence on the location selection of prehistoric sites.

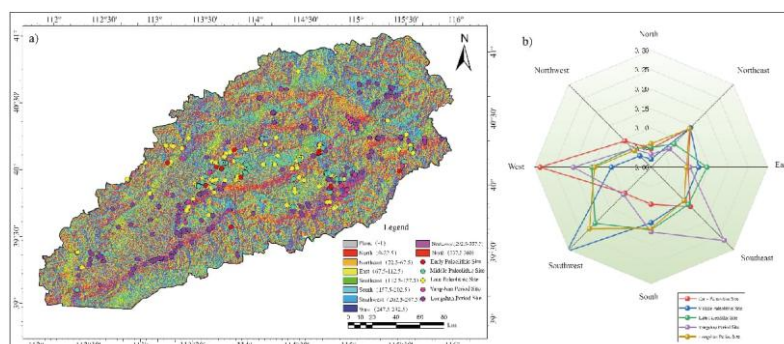


Fig.6 Slope Aspect Map of the Site

a)Slope diagram b)Radar chart

Table 4 Slope Aspect Statistics of Site Numbers in Different Periods

Aspect	Angle (°)	Early Paleolithic	Middle Paleolithic	Upper Paleolithic	Yangshao Period	Longshan Period
north	0-22.5	1	1	6	1	10
northeast	22.5-67.5	3	7	10	2	23
east	67.5-112.5	2	6	17	3	15
southeast	112.5-157.5	3	6	16	8	20
south	157.5-202.5	2	7	19	5	26
southwest	202.5-247.5	2	15	24	3	37
west	247.5-292.5	6	5	18	6	24
northwest	292.5-337.5	2	2	8	2	10

3.2.4 Hydrological Analysis

The abundance of water resources and proximity to water sources are core factors for

production and daily life, and their distribution influences the selection of prehistoric human activity sites. During the early and middle Paleolithic, the ancient lake of Nihewan developed, while the modern Sanggan River system had not yet formed. Therefore, site distribution during this period was strictly controlled by the expansion and contraction of the ancient lake, showing a dispersed distribution along the lake edge and lake terraces. In view of this, the time frame for this hydrological analysis is set after the Late Paleolithic, using the modern Sanggan River and its main tributaries as the baseline, with three buffer zones constructed at gradients of 0–500 meters, 500–1000 meters, and 1000–2000 meters. By overlaying the site point layers with the buffer zones, the results show (Fig.7) that sites in the Nihewan Basin from the Late Paleolithic to the Neolithic generally exhibit a prominent "high density near rivers—low density away from rivers" characteristic, and this feature shows a clear temporal evolution pattern.

At the end of the Late Pleistocene (around 27,000 years ago), with the complete drying of the ancient lake, the modern Sanggan River system continued to erode and cut downwards, forming valleys and multi-level terraces. Site distribution consequently shifted from "around the lake" to "along the river," beginning to cluster in strips along the tributaries and contracting towards the 500–1000 meter buffer zone, with the near-river characteristic initially emerging.

Entering the Neolithic, while sites generally moved closer to the water system and were mainly distributed within the buffer zones, they still exhibited the trait of "near water but not on water," with very few located within the 0–500 meter floodplain, likely to avoid flood hazards. With social complexity and transformations in livelihood patterns, the controlling influence of water systems on site selection significantly increased. During the Yangshao period, following the end of the Last Glacial Maximum, climatic fluctuations warmed, and ecological conditions changed, resulting in further concentration of sites along water systems. The emergence of early agriculture increased the demand for irrigation and domestic water, prompting human aggregation in main river basins. By the Longshan period, the dryland farming system had matured, settlement hierarchy improved, and site density within the 500–2000 meter buffer zone reached its peak, with an increase in the number of sites within the 0–500 meter nearshore zone. At this stage, the relatively mature dryland farming system and the rise of settlements brought human exploitation of water resources to a new level.

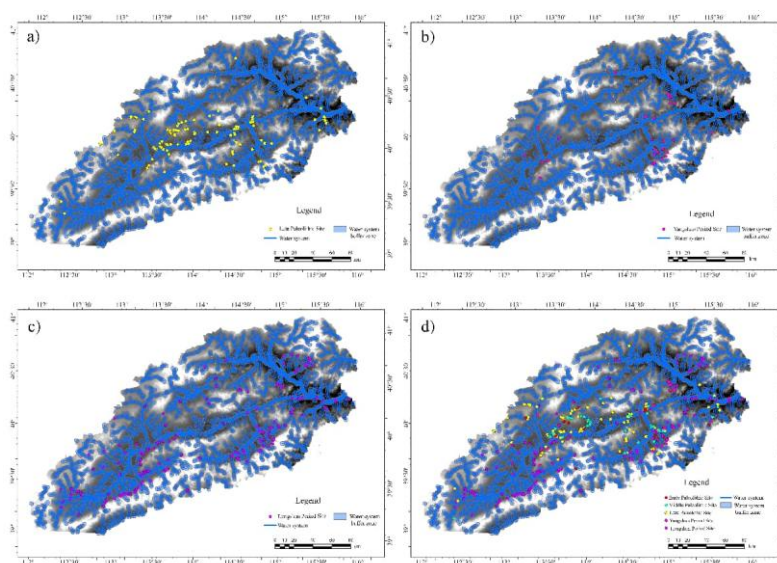


Fig.7 Analysis Map of the Site's Water System Buffer Zone

3.2.5 Geographical Detector

The natural spatial distribution of prehistoric sites in the Nihewan Basin is influenced by multiple factors such as elevation, slope, aspect, and water systems. By using the geographical detector model, the influence of each natural factor on the site distribution and their primary and secondary relationships can be quantitatively analyzed. Elevation (X1), slope (X2), aspect (X3), and water systems (X4) are selected as the four key geographical elements as explanatory variables. Through spatial overlay analysis and correlation testing, the intensity and characteristics of each natural factor's influence on the distribution patterns of prehistoric sites in the Nihewan Basin are explored.

The calculation results show (Table 5) that the influence of natural factors on the spatial distribution of sites in the Nihewan Basin is the same across different periods, in descending order: elevation (X1) > slope (X2) > aspect (X3) > water systems (X4). Among them, elevation has a relatively large impact on the spatial distribution of prehistoric sites, followed by slope and aspect, with water systems having a smaller effect. Elevation (X1) is the decisive factor, with its q statistic always the highest across periods and p-values all 0.000, showing very strong and stable explanatory power. This indicates that prehistoric humans preferred to live within a specific elevation range, namely 800–1200 meters. The influence of slope (X2) is second only to elevation, with a significant q value and p-value of 0.000. Flat and gentle slopes are conducive to Neolithic settlements and agricultural development, making them key favorable terrain conditions. The influence of aspect (X3) is next, with a relatively smaller q value, and in the early Paleolithic period, the p-value is greater than 0.05, making the influence insignificant. The influence of water systems is relatively weak and insignificant in some periods, indicating that the sites are relatively far from rivers.

Table 5 Geographic Detector Analysis

Early Paleolithic			Middle Paleolithic			Upper Paleolithic			Yangshao Period			Longshan Period		
Core	q statistic	p	Core	q statistic	P	Core	q statistic	p	Core	q statistic	p	Core	q statistic	P
factors		value	factors		value	factors		value	factors		value	factors		value
X1	0.1234	0.000	X1	0.6719	0.000	X1	0.5369	0.000	X1	0.2178	0.000	X1	0.0764	0.000
X2	0.0464	0.002	X2	0.4049	0.000	X2	0.4049	0.000	X2	0.0603	0.000	X2	0.0254	0.000
X3	0.0150	0.143	X3	0.0303	0.008	X3	0.0093	0.370	X3	0.0324	0.005	X3	0.0048	0.000
						X4	0.0271	0.007	X4	0.0020	0.834	X4	0.0009	0.224

Interaction detection is used to analyze whether the combined effect of any two natural factors enhances, weakens, or remains independent in explaining the distribution of sites. The values on the diagonal of the table are the q values of individual factors, and the values off the diagonal are the q values following the interaction of two factors. There are five categories of two-factor interaction patterns: nonlinear weakening, single-factor weakening, mutual enhancement, mutual independence, and nonlinear enhancement. (Table 6)

Table 6 Geographic Detector Interaction Diagram

illustration	expression	interaction
	$q(X1 \cap X2) < \min(q(X1), q(X2))$	Nonlinear attenuation
	$\min(q(X1), q(X2)) < q(X1 \cap X2) < \max(q(X1), q(X2))$	Single factor weakening
	$q(X1 \cap X2) > \max(q(X1), q(X2))$	Mutually reinforcing
	$q(X1 \cap X2) = q(X1) + q(X2)$	mutually independent



$$q(X1 \cap X2) > q(X1) + q(X2)$$

Nonlinear enhancement

The interactive effects of geographic detectors on the distribution of prehistoric Nihewan Basin sites show (Table 7) that interaction factors in various periods are almost nonlinearly enhanced, with dual-factor enhancement observed in the Paleolithic. Overall, all interactive q values are higher than the corresponding single factors, which is consistent with the typical characteristics of geographic detectors, indicating a synergistic enhancement effect among factors. Any single geographic factor has relatively low explanatory power for site distribution (q values all < 0.02), suggesting that prehistoric human site selection did not rely on a single environmental element.

The interactions in the Paleolithic show that the q value after any two factors interact is greater than the q value of any factor alone. This proves that natural factors have a significant nonlinear enhancement effect on site distribution, meaning that site distribution is jointly determined by multiple environmental conditions. The overall explanatory power in the early Paleolithic is low, and the low interaction intensity indicates weak constraints of humans on the environment, which aligns with the livelihood patterns of humans in the Paleolithic. The strongly interacting dual factors all involve elevation, indicating that the remnants of early Paleolithic humans were mostly distributed on the basis of elevation, overlaid with other natural factors. In the middle to late Paleolithic, both single-factor and interaction q values increased significantly, indicating enhanced human adaptability and more explicit environmental selection, with elevation, slope, and water systems jointly becoming key factors influencing site distribution.

The interactions in the Neolithic showed that the interaction of any two factors was nonlinearly enhanced. During the Yangshao period, the interaction strength was generally low. In the Longshan period, the interaction strength increased, with an increase in sites and land use, and the distribution of sites depended more evidently on natural resources.

Table 7 Interaction Analysis of Palaeolithic Geographical Probes

Early Paleolithic	X1	X2	X3	Middle Paleolithic	X1	X2	X3	Upper Paleolithic	X1	X2	X3
X1	0.123			X1	0.672			X1	0.537		
X2	0.147	0.047		X2	0.940	0.405		X2	0.796	0.405	
X3	0.184	0.103	0.015	X3	0.730	0.445	0.030	X3	0.565	0.433	0.009

4 Discussion

The nearly 1.8-million-year continuous distribution of prehistoric sites in the Nihewan Basin clearly demonstrates the expansion of ancient human activity spaces. In terms of spatial distribution patterns, sites from all periods exhibit clustered distribution characteristics. Early Paleolithic sites are sparse and scattered, with relatively low clustering intensity; during the Middle Paleolithic, the range of human activity expanded, leading to a slight increase in clustering; by the Late Paleolithic, the number of sites surged, reaching peak clustering intensity. As the Neolithic era began, the shift from mobile hunting and gathering to settled agriculture led to the continuous expansion of human activity spaces, with site clustering gradually decreasing and distribution becoming more balanced.

From the perspective of kernel density distribution, the core areas of prehistoric human activity in the Nihewan Basin evolved from a single core to dual and multiple cores. During the Paleolithic period, the sites in the Nihewan Basin transitioned from a low-density single core in

Yangyuan County during the Early Paleolithic, shifted to the center in Yunzhou District—Yanggao County during the Middle Paleolithic with slight outward expansion, and formed dual high-density cores in Yangyuan County and Yunzhou District—Yanggao County by the Late Paleolithic, with continuously significant growth in site numbers, distribution range, and kernel density. In the Neolithic period, the distribution pattern of basin sites underwent a notable transformation. During the Yangshao period, the distribution center shifted eastward to the Weixian Basin, forming a new eastern core in the Neolithic era. By the Longshan period, site numbers peaked, and kernel density expanded outward, resulting in a multi-core, strip-like high-density distribution across the entire basin along the Sanggan River, marking the expansion phase of human land use and development.

The migration of the site distribution center clearly reflects the adaptive trajectory of ancient humans to the environment. Specifically, during the Paleolithic era influenced by cold and dry climates, the center first shifted slightly southwest and then northwest. With the arrival of the Holocene warm period, the center of the Yangshao culture moved northeast compared to the Paleolithic era. By the Longshan period, the climate became drier and colder again, causing the center to swing back southwest. The changes in the site center are strongly correlated with climatic fluctuations.

The geographical detector quantitatively revealed the influence of natural factors on site distribution, with the natural driving forces ranked as elevation > slope > aspect > hydrography, where elevation was the dominant controlling factor. In terms of elevation, sites were predominantly concentrated in basin terraces ranging from 800 to 1200 meters; slopes were mostly gentle; aspects generally favored southern, southwestern, and southeastern orientations; and the impact of hydrography on site distribution exhibited a phased characteristic. During the early and middle Paleolithic periods, sites were dispersed near ancient lake shorelines under the control of paleolake evolution. In the late Paleolithic period, following the disappearance of the ancient lake, sites aggregated along the tributaries of the Sanggan River, forming a strip-like distribution pattern along these tributaries, with increasingly pronounced near-river clustering. Factor interaction detection indicated that any two factors exhibited a nonlinear amplification effect, with no independent or weakening influence, suggesting that prehistoric human site selection resulted from the synergistic screening of multiple environmental elements rather than reliance on a single condition. In the Paleolithic period, the primary drivers were elevation combined with hydrography or elevation combined with slope; in the Neolithic period, the synergistic effects of multiple factors were stronger, and human environmental selection became more refined.

This study systematically reveals the spatiotemporal distribution changes of the Nihewan Basin as a core region for the continuous evolution of prehistoric humans in East Asia through GIS spatial analysis and the geographical detector model. Overall, the distribution of prehistoric human remains in the Nihewan Basin over the past 1.8 million years is the result of the combined influences of climate fluctuations, geomorphological evolution, and subsistence transitions. The spatiotemporal evolution of these sites records the adaptive process of ancient humans to the environment and also demonstrates the complete trajectory of continuous evolution and cultural persistence of early humans in northern China. During the Paleolithic period, the prehistoric humans in the Nihewan Basin subsisted on hunting and gathering, with activities highly dependent on terrain and water sources. Sites were clustered along high terraces of river valleys and

exhibited strong mobility, with cultural remains dominated by small and fine stone tools. The newly discovered large stone tool tradition at the Emaokou site reflects the expansion of resource utilization methods. In the Neolithic period, the arrival of the Holocene Thermal Maximum provided stable climatic conditions, leading to the rise of early agriculture. Humans transitioned from a nomadic to a settled lifestyle, with sites expanding toward gentle terraces and riverine areas, resulting in a significant increase in the number and scale of settlements. As a "triple junction" region where the Central Plains, Northeast, and Hetao cultures converged, the Nihewan Basin served as a key link in prehistoric cultural exchange in northern China. Studying the spatiotemporal evolution and influencing factors of the Nihewan Basin provides empirical materials for exploring early environmental adaptation in East Asia.

Current research still has limitations. Based on existing archaeological surveys and excavation data, the results exhibit certain deviations due to constraints such as site coordinate accuracy, generalized Neolithic period chronology, and uneven survey coverage in some regions. Future studies could integrate high-precision dating, zooarchaeology and paleoclimate modeling to further refine the chronological sequence of sites, quantitatively reveal the correlation between human activities and environmental changes, and continue regional systematic surveys to improve the site database and deepen research on the Nihewan Basin.

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