Archaeological spatial analysis using GIS: methods and issues

Introduction

Archaeological spatial analysis in a Geographical Information Systems (GIS) context is a relatively new endeavor. Yet, considerable headway has been made using GIS tools to visualize archaeological spatial patterns, to generate new kinds of spatial variables for investigation, to promote objective quantitative analysis, and to model archaeological distributions (e.g., see Allen et al. 1990; Lock, Stancic 1995). The focus of this paper is chiefly on landscape archaeology and on methods for assessing relationships with the environment. Once relationships are established it is possible to combine them with GIS to produce models of archaeological distributions across space, which have come to play an important role for cultural resource management and planning purposes (Kvamme 1990a). A heavy emphasis of this paper lies in quantitative methods. An historical perspective is taken to present their development.

Spatial analysis: visualization versus quantitative methods

GIS graphics readily allow portrayal of spatially distributed information. Simply by displaying multiple spatial variables simultaneously the user can ascertain relationships or associations in the data that might exist. For example, a display of water courses or soil types with known archaeological site distributions might reveal tendencies for site proximity to water or soil preferences. The ease with which a host of data can be displayed with GIS, together with its excellent color graphic displays of two-dimensional or simulated three-dimensional views, enhances this process.

Yet, it should be realized that many patterns in nature are weak - they are not easily visualized - and the human eye can be easily fooled - it sometimes sees pattern when there is none or fails to recognize it when it exists. Objective statistical tests are therefore necessary to detect and verify the existence of pattern. Moveover, we might not be merely interested in the presence or absence of pattern, but in its strength; quantitative indices therefore become important as a means to objectively measure the strength or relationships. It can be seen, then, that both visualization and quantitative analysis of spatial data are complementary; they go hand-in-hand and are equally important to archaeological spatial investigations (Kvamme 1994).

A visualization example

A useful start-point lies in an example where GIS visualization methods alone demonstrate the existence of archaeological pattern. Later examples employ a combination of statistical and visual approaches to the data. The setting is in the high deserts of western Colorado, a region that contains many open lithic sites resulting from prehistoric hunter-gatherer occupations and activities. Owing to sparse vegetation cover the surface visibility of artifacts is excellent. Over the past several years approximately 25,000 surface artifacts have been mapped in a six hectare region of particularly diverse finds and encoded within a GIS. Visualization of artifact counts across the landscape (in 4x4 m grid units) reveals patterns of localized flaking behavior and activity areas (Fig. 1a-c).

The focus of interest here is size distributions of the approximately 24,000 pieces of
mapped debitage. When GIS maps by size class were produced a similar spatial pattern was revealed for all classes. That is, the greatest counts per four meter square for each size class tend to occur in the same place, at the various scatter centers (Fig. 1a-c). In experimenting with GIS visualization of the data in various ways, quite by accident I reexpressed the size data from absolute counts to a proportion of each size grade per four meter grid square. This was accomplished through use of a standard GIS Map Algebra operation that allowed division of each size class layer by a total debitage count layer to achieve the desired proportions results. As can be seen (Fig. 1d, e), with the data portrayed in this manner it seems clear that greater proportions of large debitage tend to occur around the peripheries of each of the flaking concentrations with smaller proportions of large items in the central regions. In other words, spatial sorting seems to exist (see Kvamme 1996 for further details).

Experimental stone working was employed to further investigate this phenomenon. Several experiments showed that in percussion flaking a natural spatial sorting of debitage occurs by size. This pattern arises from the simple mechanics of stone working: greater force is required to detach a large flake than a small one. Larger flakes therefore have an increased likelihood of traveling a greater distance from the stone worker. Although the greatest amount of debitage of any size lands close-by, larger proportions of big items occur at greater distances from the stone working locus (see Kvamme 1997 for further details).

Quantitative locational analysis

Quantitative methods of analysis are the real focus of this paper. In locational analysis problems they may be introduced to supplement, and in some cases replace, simple visualization approaches. The central problem here is to ascertain if locational relationships exist between archaeological distributions and features of the physical environment of a region. In other words, we want to determine if settlements or other archaeological sites tend to show locational preferences for soils, elevation ranges, directional facings (aspect), specific landscape contexts, for proximity to various resources such as water, and the like. In the following a historical-developmental approach is followed that examines the evolution of archaeological quantitative methods for locational analysis, with a specific focus on GIS approaches.

In each of the statistical tests to be examined the basic null hypothesis is that of no association or independence between the archaeological distribution and the environment. It is the empirical evidence gathered that ultimately allows rejection of the null hypothesis if it is untrue. In other words, we can ascertain the probability of obtaining an archaeological sample as different in its characteristics from the background environment as that observed by chance alone.

Example study region

A GIS database is employed that characterizes a small region near Marana, Arizona, located in the American Southwest. The area represented is a prehistoric Hohokam agricultural field complex of the Classic Period (thirteenth-fourteenth centuries, A.D.). This field complex has been intensively studied by Fish et al. (1985, 1990) and contains numerous features related to Hohokam agricultural practices including terraces, check dams, and what is termed the “rock pile” feature. The latter are of interest here.

Rock piles are circular mounds of fist-sized cobbles. Most are less than 1.5 m in diameter and 75 cm in height. They are extremely common throughout the Hohokam territory and several lines of evidence point to their use for growing agave, an important source of food and fiber (Fish et al. 1990).

The plant-growing environment is enhanced by the rock piles. Soils in the region possess a high clay content that inhibits rainfall penetration forcing, instead, considerable run-off and occasional flash floods. The rock piles represent a relatively porous surface that allows absorption of upslope run-off as well as direct rainfall. The mound acts like a mulch where the rocks preserve the interior moisture through the inhibition of evaporation and the blockage of the
A 400x400 m region surrounding the Marana agricultural field complex is employed (Fish et al. 1985; Kvamme 1992a). A random sample of 50 rock pile features from this region forms the basis of this investigation. Aerial photogrammetry was employed to produce an elevation contour map with a 61 cm (two feet) contour interval of the region. This contour map was digitized and GIS methods were utilized to generate a digital elevation model (DEM) and other layers, each with four meters resolution, for subsequent analysis of rock pile locations (Fig. 2a).

Hohokam archaeologists have suggested that the rock piles might be located preferentially to further promote the plant growing environment. One immediate notion is that the rock mounds should be located on inclined slopes in order to be positioned to capture necessary surface run-off during summer and winter rains. This notion is easily tested in a GIS context. A GIS gradient algorithm was employed to compute slope (ground steepness) values from the DEM every four meters in the database region. This result is shown in Fig. 2b with the 50 rock pile locations superimposed. In this figure visualization alone does not seem to provide an answer as to whether there is an association between rock piles and steep slopes: some clearly are located on sloping ground, but others are not. We must therefore turn to alternative procedures and quantitative methods for a clear answer.

The chi-square goodness-of-fit test

The first quantitative test for assessing statistical association between environmental and archaeological distributions was the chi-square goodness-of-fit test, presented in the early 1970’s (Plog, Hill 1971). This test examines archaeological distributions against environmental categories. Each category has an observed number of sites which is compared against an expected number. The latter is determined by the proportion of the study region occupied by a particular category. For example, if one environmental category encompasses ten percent of the total region, then if the null hypothesis of independence is true we would expect about 10 percent of the archaeological sites to occur within it. As the difference between expected and observed numbers of sites increases category-by-category, evidence is accrued that the null hypothesis is false. These accumulated differences can be evaluated probabilistically against the chi-square distribution with \( k-1 \) degrees of freedom (where \( k \) is the number of environmental categories; Shennan 1988).

Since the southern Arizona slope layer is continuous the data must be grouped into categories to meet the requirements of this test. This was easily accomplished through a GIS “reclassification” procedure which produced three classes of equal area: “level,” “mildly sloping,” and “steep.” This tactic alone seems to provide an answer to our question through visualization. Clearly, the vast majority of the rock piles occur in the steepest class with very few occurring on mildly sloping or level ground (Fig. 2c). This is confirmed in Tab. 1 where it’s shown that 28 of the 50 (56%) rock piles occur in the steepest class and only three (6%) occur in the level class. Under the null hypothesis of no association we would expect about one-third (16.67) of the rock piles to occur in each class. The chi-square test gives:

\[
\chi^2 = \sum (O - E)^2 / E = 19.24
\]

where \( O \) is the observed class frequency and \( E = 16.67 \) is the constant expected frequency. Comparing this result against a chi-square distribution with two degrees of freedom (at \( \alpha = .01 \)) yields a critical value of \( \chi^2 = 9.21 \), and the null hypothesis is easily rejected (Shennan 1988).

Two-sample approaches

One drawback of the chi-square test is that the data must be categorical. Although this means that the test is ideally suited for analyzing archaeological distributions against nominal-
level variables like soils, geological, or vegetation classes, such continuous variables as elevation, slope, or distance to water must first be grouped into classes to employ the test. In the latter case this amounts to the throwing away of information, because the scale of measurement is reduced, which can lead to less powerful inferences and reduce analytical options (e.g., mean tendencies or locational variability can no longer be considered).

One solution to this problem in the case of continuous variables is the characterization of the background environment by a random sample of points. The continuous variable of interest is measured at random locations, which represent a sample approximation of the background environment. Measurements made at this sample are then compared against measurements from a sample of archaeological site locations using such two-sample statistical tests as t-tests, Smirnov tests, or Mann-Whitney tests (Kellogg 1987; Shermer, Tiffany 1985).

One-sample continuous tests

A conceptually superior approach, which has the statistical advantage that the background distribution is no longer approximated by a sample, was first illustrated by Hodder and Orton (1976, p. 226). It requires the derivation of the cumulative distribution of a continuous variable over the entire region under study. To accomplish this using the manual methods of pre-GIS days, Hodder and Orton resorted to an approximation. They first categorized their continuous variable, distance to nearest Roman road in southern Britain, into several classes. They then superimposed a fine-mesh grid over their study area and counted the number of grid units that fell into each distance class, which yielded the proportion of the total study area in each class. A graph of the cumulative proportion distribution was then obtained by plotting these values and interpolating the remainder of the graph. The cumulative distribution of the archaeological phenomenon of interest, coin find spots, could then be statistically compared against this background distribution through use of the Kolmogorov goodness-of-fit test (Hodder, Orton 1976, p. 226; Kvamme 1992b, pp. 78-79).

Lafferty (1981) is probably the only other archaeologist who further pursued this methodology using manual methods; his work is noteworthy because it pre-sages GIS developments to come. He divided his study area in Arkansas, USA, into 3,857 grid units (each 200 m square) and measured a variety of continuous variables (e.g., elevation, slope, distance to water) in each one on conventional paper maps. These data were entered into a computer. Simply by sorting the measurements of any variable the cumulative distribution for the entire region could be obtained. Measurements for archaeological site samples were taken from those grid squares in which they were located and the Kolmogorov test was employed to analyze distributional differences.

It should be obvious that a raster GIS readily lends itself to this methodology. An entire study region can be digitally encoded in a grid cell structure. In each grid unit the GIS can provide measurements for continuous or categorical variables over entire regions. Consequently, it is quite easy to obtain the cumulative population distribution of any variable as well as measurements for archaeological sample locations in order to assess whether the sample is unusual through the Kolmogorov or other one-sample tests (see Kvamme 1990b for a summary of testing options).

Returning to the Hohokam agricultural field complex we may now employ these methods to analyze the rock pile locations against the continuous slope landscape of the GIS database portrayed in Fig. 2b. With a raster of 100 rows and 100 columns the cumulative distribution of all 10,000 slope values was first obtained. The slope data were then extracted from the 50 sample rock pile locations. These distributions are plotted in Figure 3a. That there is a difference is readily apparent in the graph. While 60% of the region possess a five percent grade or less only 20% of the rock piles do. This means that 80 percent of the rock piles lie on ground with a grade of five percent or more while only 40% of the region does. Similar differences can be examined along other portions of the graph. The Kolmogorov one-sample test, which requires a test statistic that is simply the maximum difference between the two distributions, yields a highly significant outcome with a difference of D=.41, significant at p < .01 (see Shennan 1988 for an overview of this test).
For comparison purposes, a second variable is also analyzed. This variable is aspect, or the direction the ground faces at any locus (grid cell in the GIS database). Like slope, aspect is easily computed by GIS based on the interrelationships between elevation values in the DEM. Archaeologically, there is some suspicion of a preference for north-facing aspects on theoretical grounds alone: northern slopes will somewhat reduce the intensity of solar radiation in this desert landscape, and therefore evaporation of soil moisture. Nevertheless, the mapping of the continuous aspect surface and the sample of rock pile locations fails to illustrate strong indications of pattern (Fig. 2d) and we must resort to quantitative analysis once again.

A graphical plot of the cumulative distribution of 10,000 aspect values (each scaled between 0 and 180, where 0 is north, 180 represents south, and other values are east or west deviations off a north-south line) and the cumulative distribution of the 50 rock pile aspects reveals somewhat of a preference for north-facing aspects: 40% of the rock piles face north (values less than 90) while less than 30% of the region is inclined in this direction. Yet, this weak tendency is not highly significant by the Kolomgorov test with a maximum difference of D=.14, significant at only p=.11 (Fig. 3b).

**Modeling archaeological distributions**

In recent years archaeologists have shown a great deal of interest in developing models of archaeological distributions over broad areas (e.g., Brandt et al. 1992; Judge, Sebastian 1988; Kvamme, Jochim 1989). This area of focus is a natural outgrowth of the findings of regional locational analyses. If the locational analysis methods of the previous sections can isolate variables against which archaeological sites illustrate pattern, then by combining these variables together it is possible to make powerful statements concerning where archaeological sites may be found. Much of the initial work in this area originally stemmed from cultural resource management projects conducted in the western USA. In that region, with its many large tracts of federally controlled lands, various government agencies required models of archaeological site location to be developed based on knowledge gained from sites discovered in sample surveys. Spatial models were generated from sample data and employed to indicate likely locations of archaeological sites in areas not yet field examined (Judge, Sebastian 1988). These models have been used for the discovery of new sites, much like a prospecting tool, but more importantly they have provided a useful planning mechanism for governmental agencies by their ability to indicate archaeologically sensitive regions where land disturbance or development should be avoided (Parker 1986). Good archaeological models can also serve another purpose: they can provide insight into past land use and settlement patterns by portraying principal trends and eliminating some of the statistical noise in the data. By making the essence of a spatial pattern clearer such models offer great heuristic potential in regional studies (see Kvamme, Jochim 1989).

Although numerous methods and approaches for archaeological modeling have been pursued (see Kvamme 1990a for an overview), GIS probably represents the principal factor that has promoted the growth of interest and applications in this topic. The reason for this is that archaeological models require vast numbers of measurements and considerable computation at regional scales, regardless of approach. To illustrate, a study region located in the Great Plains of southern Colorado, USA, is shown in Fig. 4a. Random sample surveys in this area have discovered 95 archaeological sites, all open-air lithic scatters (hunting camps and temporary habitats). This figure portrays a slope surface, containing nearly 19,000 gradient measurements, which shows the nature of the landscape where several steep-walled canyons dissect the plain. The archaeological sites appear to exhibit locational tendencies near the canyon rims, and the water courses within, but on relatively level surfaces.

These observations can be employed to construct simple site location models through GIS. The first model employs a GIS reclassification function that defines all locations with a gradient less than or equal to 10% as “site favorable.” The mapping of this model principally illustrates the exclusion of the steep canyon wall faces (Fig. 4b). It is a highly accurate model - 91% of the known sites are classified correctly - but it is not very precise or powerful. This stems from the
fact that the model mapping covers approximately 96% of the area of the region. If we consider that a model that covers 96% of the landscape should include about 96% of the sites simply by chance, the above performance is not a significant achievement. We should also note that a model of 100% accuracy can always be obtained simply by formulating a rule that classifies every location as “site favorable”. What is required are models that achieve high accuracy (percent correct classification rates for known sites), but which cover a small area when mapped.

This reduction-of-model-area concept is illustrated in a second model which additionally considers the variable distance to secure water. GIS methods readily allow computation of distance-to-water surfaces based on digitized stream courses, where each grid cell holds a water distance value. The mapping of this model (Fig. 4c) represents all locations that meet the previous condition of level ground and that are simultaneously within 400 m of rank two water courses (i.e., the Boolean intersection of locations with level ground and close to water, achieved through a GIS modeling operation). This model offers about the same level of accuracy (89 percent of known sites correct), but it is much more powerful because its mapping includes only 33% of the study area, representing a considerable improvement over chance.

These models have been rather simplistic in form in order to illustrate the relative ease of archaeological modeling in a GIS context. In practice, many more variables might be considered and multivariate statistical methods employed to yield more powerful results. One such model is shown in Fig. 4d that is based on a logistic regression approach. This model maintains a 95% accuracy rate for the known site sample, but its mapping covers only 20% of the total land area. It is a multivariate function of nine GIS-produced environmental variables: slope, aspect, a terrain form index, a local relief measure, proximity to canyon rims, horizontal and vertical distance to the nearest drainage, and horizontal and vertical distance to rank two drainages (see Kvamme 1988).

In one sense the models in Fig. 4 can be regarded as largely descriptive of the site location tendencies in this region of study. In another they can be considered as predictive tools when their mapping is applied to regions not yet surveyed by archaeologists to indicate likely locations of sites. If the known sites in Fig. 4 are only a sample of sites from that region, then the models represent predictions of site location in unsurveyed areas. Moreover, if the known sites constitute a representative or random sample from the region, then we may expect similar accuracy rates in the discovery of new sites (e.g., in Fig. 4d about 95% of all sites in the study area should occur in the model region; see Kvamme 1988, 1990a for further details).

These examples of modeling illustrate both the power and complexity of results that can be obtained using GIS as a modeling tool as well as the absolute necessity of GIS. Archaeological models generally are functions of environmental data that must be applied systematically across broad regions. Consequently, systematic measurements of environmental data are required over large areas. Raster GIS therefore provide an ideal vehicle for this endeavor. In the example application each variable needed by a model contained about 19,000 measurements at a systematic spacing of 50 m. Besides providing the necessary measurements for the initial analysis, model building, and application, GIS also produced the cartographic results together with important model performance statistics (percent correct rates and model areas). Thus, GIS clearly offers to archaeology a comprehensive means for spatial analysis and modeling.

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Bibliography


Fig. 1 - Mapping of debitage counts per 4 m square in a 250 x 250 m region of western Colorado, USA. a) Count of 5-19 mm debitage. b) Count of 20-29 mm debitage. c) Count of 30–39 mm debitage. d) Proportion of 20–29 mm debitage. e) Proportion of 30–39 mm debitage.

Fig. 2 - Locations of Hohokam rock pile features in a 400 x 400 m region near Marana, Arizona, USA. a) Contour map with 61 cm interval. b) Slope or gradient map. c) Slope in 3 equal-area classes (darkest is steep; white is level). d) Aspect map (white is north-facing; black is south-facing).

Fig. 3 - Cumulative distribution plots of a) slope and b) aspect values showing differences between Hohokam rockpile locations and the background landscape of the region.

Fig. 4 - An 8.5x5.5 km region located in the Great Plains of Colorado, USA, and containing 95 open-air lithic scatter sites. a) The slope surface showing the presence of a steep-walled canyon and the site distribution. b) A simple archaeological model mapping level ground. c) A simple archaeological model mapping the intersection of level ground and proximity to water. d) A multivariate statistical model based on 9 environmental variables.

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Tab. 1 - Hohokam rock pile locations near Marana, Arizona, USA, by slope class.