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Construction of Digital Elevation Models for Archaeological Applications

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CHAPTER SEVEN

Construction of Digital Elevation Models for Archaeological Applications

JON B. HAGEMAN AND DAVID A. BENNETT

The use of interpolation in archaeology is becoming common. As archaeologists incorporate geographic information systems (GIS) and computer mapping programs into their research, questions of interpolation become fundamental considerations in the representation and manipulation of topographic data. To date, however, few archaeologists have dealt with these questions. Uncritical use of interpolation algorithms can result in unrealistic representations of the landscape in a mapping program or can result in an inaccurate digital elevation model (DEM) used in a GIS. This, in turn, can lead to an ineffective predictive model of site location. By carefully selecting an interpolation algorithm that is well suited to the data, statistical pitfalls and wasted effort can be avoided.

7.1 INTRODUCTION

The creation of digital elevation models (DEM) in archaeological applications of geographic information systems (GIS) has, with rare exceptions (e.g., Kvamme 1990; Warren 1990; Wiemer 1995; Madry and Rakos 1996), been largely ignored in print. As Kvamme (1990: 123) has noted, archaeologists are usually concerned with the quality of archaeological data, not the quality of data obtained by computer means. Yet given the same data points, substantively different surfaces can be generated from alternative computer algorithms designed to accomplish the same task. These differences can have significant and unexpected impacts on archaeological investigations.

Consider, for example, the development of a site prediction model in which elevation, slope, and aspect are important independent variables. Available elevation data is likely to be incomplete and/or in a form that is not suitable for the calculation of slope and aspect (e.g., sampled data points or contour lines). To construct a usable DEM (e.g., a lattice of elevation points), an interpolation algorithm must be applied. Yet different algorithms can provide different elevations for the same point in space. Landscapes constructed using alternative interpolation algorithms may superficially appear to be similar, but be both quantitatively and qualitatively different. The implications of this for the predictive modeling of archaeological site locations are critical, as landforms that had been used in the past may be under- or overrepresented in the derived data set. Thus, selecting an inappropriate interpolation algorithm could lead to a low degree of accuracy in the overall predictive model.

Unfortunately, guidelines for selecting a particular DEM or interpolation method do not exist in the archaeological literature. How, then, can the archaeologist determine which interpolation algorithm to use on a given set of points? Is there a single best algorithm? Are vector-based DEMs more accurate than raster-based DEMs?[1]

The purpose of this chapter is to examine these questions. A data set from northwestern Belize will be used to describe methods by which archaeologists can evaluate the results of alternative interpolation algorithms that create DEMs for use in archaeological applications, including predictive models of site location. This comparison of algorithms will be made within the context of ARC/INFO Version 7.0, a commercially available GIS that is commonly used in academic, government, and private-sector applications.

7.2 WHY SHOULD THE ARCHAEOLOGIST CARE ABOUT INTERPOLATION?

Although digital elevation models are becoming increasingly available from government (e.g., USGS) and commercial (e.g., SPOT) sources, there are several reasons why archaeologists should develop a fundamental understanding of interpolation techniques. First, the spatial coverage of such databases is far from complete (Kvamme 1995: 6; Madry and Rakos 1996: 118). This is particularly true for Third World nations, but even in the United States many areas do not have the 7.5-minute quadrangle series in a digital format. For example, less than one-third of the state of Illinois was available in 7.5-minute digital format as of 1 August 1996 (USGS 1996).

As alluded to above, archaeologists work at a variety of spatial scales, from that of the region down to that of a single excavation unit. Available digital data sets tend to provide regional or continental coverage, and thus often lack the spatial resolution and accuracy needed for site-specific work (e.g., Biswell *et al.* 1995; Gaffney and Stančič 1991; Meffert 1995). Accordingly, archaeologists working in areas without existing digital topographic coverages at the appropriate resolution may have to create their own DEMs by digitizing topographic maps or by capturing elevation data using total stations and/or global positioning system (GPS) receivers (Forte 1995: 232; Madry and Rakos 1996: 118; Rick 1996). Points located with total stations or GPS are typically recorded as three-dimensional (XYZ) coordinates, and can be entered into a GIS or mapping program to create a DEM and/or a contour map.

Finally, all DEMs are discrete approximations of a continuous phenomenon. How closely this approximation reflects reality depends on a variety of factors that include:

1 how many sample points were collected;
2 where they were collected;
3 the accuracy of the data collection device;
4 the skill and knowledge of the data collector; and
5 the explicit and implicit assumptions built into the interpolation algorithm (Robinson *et al.* 1995).

Just as the improper use of statistical tools can lead to a misinterpretation of data, the misuse of DEMs and interpolation algorithms can result in a misinterpretation of terrain. To maintain high levels of accuracy, therefore, the archaeologist using automated forms of data recording and manipulation should be aware of the assumptions that these tools bring with them.

7.3 WHAT IS INTERPOLATION?

A brief review of interpolation is appropriate at this point. Burrough (1986: 147) defines interpolation as "the procedure of estimating the value of properties at unsampled sites within the area covered by existing point observations." This is largely based on the rationale that two points that are near one another in space are more similar than two points farther apart (i.e., spatial autocorrelation exists in topographical data[2]). The goal of interpolation is to model variation so that values at unknown locations may be estimated on the basis of known values in the vicinity. For the purposes of this chapter, interpolation algorithms take a set of data points in space and create a digital elevation model (DEM) from which a continuous surface may be inferred. Since the DEM is fundamental to locational modeling in archaeology, it is important to understand (1) the data structure of each method, (2) the assumptions of each method, and (3) how each method manipulates a data set to construct a DEM. Next, four types of interpolation methods will be reviewed. Each of these have either appeared in written reports on the use of GIS within archaeology or are commonly used in the geosciences. In this review we describe the characteristics of each algorithm. These descriptions are derived primarily from Burrough (1986).

7.3.1 Ordinary Kriging

Ordinary Kriging is an algorithm based on stochastic or random surfaces, rather than on mathematical smoothing functions (Ripley 1981: 45). The product of this type of interpolation is a lattice. Kriging assumes that variation across a landscape can be expressed as a sum of: (1) a constant trend; (2) a random, spatially correlated component; and (3) random noise. The technique requires that the random, spatially correlated variation in a data set be relatively homogeneous, so that differences between known points are functions of the distance between those points. The semivariance is calculated from the sample data (often the variance is used). This semivariance is then used to determine weights for interpolation, since it is a function of the distance between sample points (Burrough 1986: 155–6). With Ordinary Kriging it is usually assumed that there is no inherent trend in the data. By considering directional differences in the semivariance, such trends can be incorporated into the interpolation process. In sum, Ordinary Kriging looks to the data set to judge the area to examine for a specified number of known data points around the location to be interpolated. Data beyond this area is assumed to possess little predictive value.

Different semivariogram models can be fitted to the estimated semivariance, and some models fit the data better than others. ARC/INFO provides five different semivariogram models for use in Ordinary Kriging. Since a high degree of homogeneity is assumed between data points, Ordinary Kriging is usually not recommended for use in data sets that contain sharp breaks in the landscape, such as steep cliffs and ridges (Aronoff 1993: 220). Ordinary Kriging can, however, handle even and uneven distributions of points. Ordinary Kriging is a frequently used interpolation method in the geosciences (Cressie 1993; Carr 1995).

7.3.2 Universal Kriging

Universal Kriging is another lattice-based interpolation method. Though similar to Ordinary Kriging in its general assumptions, Universal Kriging has the added assumption of well-defined, though not extreme, local variations or drift within the larger landscape. Accordingly, the random noise within the local variation is assumed to have a semivariogram within the locality (Lam 1983: 133). As such, Universal Kriging is applicable to slightly more complex landforms than Ordinary Kriging. Burrough (1986: 161) suggests that Universal Kriging can be used with smoothly varying landforms. If the local variation is too extreme, such as a cliff or ridge, it may be treated as random noise or residual error (the nugget in semivariograms). If this is the case, data sets with large residual error may stand to gain very little from using Universal Kriging instead of Ordinary Kriging (Webster and Burgess 1980 cited in Burrough 1986: 161). In general, however, Ordinary Kriging has more restrictive assumptions but fewer computational problems, while Universal Kriging has more generalized assumptions but places greater demands on processing time (Lam 1983: 133). ARC/INFO provides two types of Universal Kriging: one with a linear local interpolator and the second with a quadratic local interpolator. As with Ordinary Kriging, Universal Kriging is widely used in geoscience applications of spatial statistics (Cressie 1993).

7.3.3 Inverse distance weighting (IDW)

A third algorithm is known as inverse distance weighting, or IDW. IDW is a lattice-based algorithm that calculates the unknown elevation at a point by computing an average value from a fixed distance, or window, from that point. The influence that a given sample point has on an interpolated value at a different point is weighted by the inverse of the distance between the two points (Burrough 1986: 153). A certain minimum number of points (often $n = 12$) is required to increase accuracy. Thus, as the window "moves" to a cell with an unknown Z-value, the nearest known n points are located and a weighted average is computed. This process is repeated until the elevation for each cell in the lattice has been calculated, resulting in a DEM. IDW assumes a more or less regular distribution of points, since clustering of data may create undesirable results (Ripley 1981: 36-7). In contrast to kriging, which assumes a random component, IDW is more of a smoothing function. IDW was used by Robert Warren (1990) in his creation of a predictive model for archaeological site location within the Shawnee National Forest in southern Illinois.

7.3.4 Triangulated irregular network (TIN)

Triangulated irregular networks (TINs) are often used to construct DEMs for use in archaeological predictive modeling (e.g., Marozas and Zack 1990; Fedick 1994). In contrast to the lattice-based methods of DEM construction described above, the TIN is a vector-based structure. As such, it has a drastically different appearance, and often significantly smaller data storage requirements (Peucker *et al.* 1978). A TIN is composed of a set of triangular facets derived from irregularly spaced data points. TINs often are used to accurately represent stream channels and ridge lines. Accordingly, a major assumption of TIN utilized in this manner is that the digitizing process captures the overall landform as a set of topographically significant points rather than contour-line inflections (ESRI 1995). However, most TIN generation algorithms produce a Delaunay triangulation.

A triangulation is considered to be a Delaunay triangulation if the circle defined by the vertices of each triangle does not contain any other point in the data set. This circle rule generates triangles that are as equilateral as possible and produces a triangulation that is the dual of the Theissen diagram defined by the same data set (Worboys 1995). Edges within a Delaunay triangulation, however, will not necessarily follow such topographically important features as ridge and stream lines. In ARC/INFO, these features (referred to as break lines) must be imposed onto the Delaunay triangulation.

ARC/INFO provides two interpolators for TINs. The first is linear, and represents the landscape surface as the flat face of a triangle. The second is quintic, and can represent each facet with a curved surface, if appropriate. TIN has been used in predictive modeling efforts in Belize (Fedick 1994), in Montana (Marozas and Zack 1990), and in Hungary (Csáki *et al.* 1995).

7.4 SELECTING AN INTERPOLATION ALGORITHM

The description of these four methods for constructing DEMs (Ordinary Kriging, Universal Kriging, IDW, and TIN) answers one of the questions asked above: Is there a single best interpolation algorithm? The answer is that no single algorithm is superior to all others across various applications. The consensus among geographers and others who deal with topographic modeling is that the selection of an appropriate interpolation algorithm depends largely on the type of data being used, whether the data fits the assumptions of the algorithm, the degree of accuracy desired, and the amount of time that can be spent on data processing (Aronoff 1993; Boman *et al.* 1995; Burrough 1986; Houk 1984: 18; Lam 1983: 130). How, then, does one go about choosing between TIN or one of the lattice-based interpolation algorithms for the construction of a DEM?

Previous applications of GIS to archaeological predictive modeling do not provide much guidance in this endeavor. Though Kvamme (1990) has pointed out that different algorithms produce different results, most studies have not provided an explicit rationale behind the use of a particular algorithm in the creation of a DEM (e.g., Kvamme and Jochim 1985; Maschner 1996). Some appeal to "past experience" as the criteria used to select a particular method (Marozas and Zack 1990: 167). Others allude to problems with the interpolation algorithm that was utilized in a particular study (Warren 1990: 211). Otherwise, few guidelines exist in the archaeological literature regarding the selection of a particular type of DEM or interpolation algorithm for use in predictive modeling.

Researchers in other disciplines have conducted studies that compared various interpolation methods in an effort to select one that is best suited to their data set. A qualitative means of doing this is through the use of visualization, which consists of inspecting the DEM for any spurious data or undesirable effects produced by the interpolation algorithm. This allows the user to explore the pattern of error that might result from the creation of a DEM (Weibel and Heller 1991: 285; Wood and Fisher 1993: 55).

Quantitative methods can also be used to compare the relative accuracy of DEMs. This research revolves around applying multiple algorithms to a single data set, and comparing interpolated values with the actual elevations at known reference points (e.g., Monckton 1994; van Kuilenburg *et al.* 1982; Weibel and Heller 1991: 285). Next, the root mean square error (RMSE) for each DEM is calculated; the individual RMSEs are then compared to one another. The RMSE provides an indication of how well interpolation algorithms represent the actual topography. The utility of this index depends in large measure on the number and location of real-world data points and the spatial variability of the terrain.

To ascertain which algorithm is best suited to a particular data set, it is necessary to consider a variety of factors, which include the type of data, algorithm assumptions, desired accuracy, and processing time. Archaeologists should perform the same qualitative and quantitative comparisons between DEMs generated by TIN or different lattice based interpolation algorithms to identify the method that is most appropriate for their data set. To illustrate how this can be done, we will examine a real-world data set generated from paper maps.

7.5 A BELIZEAN CASE STUDY

7.5.1 The data

Data for this exercise was obtained from 1:50 000-scale topographic maps of Belize, produced under the direction of the Director General of Military Survey of the UK Ministry of Defence and published in 1992. The study area consists of four maps, which represent a large portion of northwestern Belize (Figure 7.1). The resulting area measures 46 km × 43 km (north–south by east–west), covering a total of 1978 km^2. Over 50 000 points were manually digitized in the process of creating this topographic coverage.

This area of northwestern Belize is characterized by two rivers flowing southwest–northeast: the Rio Bravo to the west, and the Booth's River to the east. To the west of the Booth's River, a karstic topography dominates the landscape. To the east of the same river is a large coastal plain. The land surface is characterized by the Booth's River floodplain and an associated swamp. Elevations across the entirety of the study area range from 7 to 20 m above mean sea level (AMSL) on the coastal plain and 20 to > 300 m AMSL in the karstic uplands. The contour interval for these maps is 20 m, making the choice of DEM extremely important so as not to compromise surface accuracy or detail. This highly variable data set is used in spite of, rather

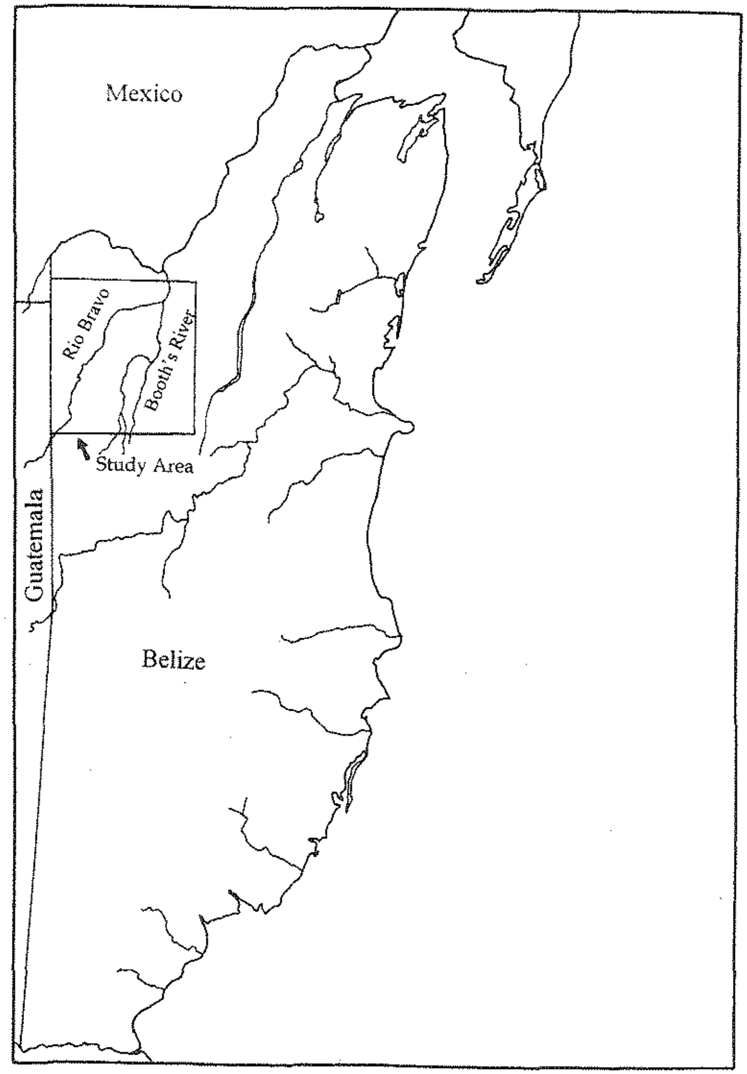

Figure 7.1 Map of Belize showing location of study area.

than in accordance with, the assumptions of the interpolators described above purely for the purpose of demonstrating qualitative and quantitative error assessment.

As mentioned above, this coverage was manually digitized from paper contour maps. The digitizing regime centered on representing contour inflections rather than capturing data about individual features or landforms. Prior to running the data set through various interpolation algorithms, a generalizing procedure was run. The effect of this procedure was to eliminate redundancy by removing points of equal elevation with virtually identical values located closely together that do not contribute to the form of the line.[3] As a result, some 15,000 points were removed from the data set.

Prior to constructing a DEM from this database, we considered the assumptions of each of the algorithms described above. The data set consists of an irregular distribution of points that are not homogeneous in their elevations. Since the digitizing method did not explicitly include break-line features, and contours rather than landforms were digitized, TINs were ruled out. At first glance, the uneven distribution of data points suggested that IDW would not be applicable here; however, the generalization procedure reduced the relatively uneven nature of this particular data set. Thus, IDW would be a consideration. Kriging, with its ability to handle unevenly distributed data, was also thought to be a favorable choice. Whether to prefer ordinary or universal kriging, however, was not obvious. Thus, both forms of kriging (with their accompanying variants) were deemed worthy of consideration.

In practice, this would suggest that a comparison of the results produced by IDW and various forms of kriging would be a productive means of identifying the best algorithm for this data set. For this study, however, all of the previously discussed algorithms were applied to the data set in an effort to illustrate the pitfalls associated with an inadequate understanding of interpolation techniques.

7.5.2 The analysis

All analyses were performed using ARC/INFO Version 7.0, operating on a Sun Sparcstation 5. Several common parameters for each algorithm were held as constant as possible in an effort to maintain comparability. For lattice-based interpolators, we used a maximum search radius of 250 m to search for the nearest 12 points. A 460×430 DEM was created to produce lattices with an individual cell size of $100 \text{ m} \times 100 \text{ m}$.

The IDW procedure took about 10 minutes to complete. Five Ordinary Kriging procedures were run, based on circular, exponential, spherical, linear, and Gaussian models. Two Universal Kriging procedures were also performed, one with a linear local interpolator and one with a quadratic local interpolator. Each of the kriging operations required about 1.5 hours of processing time. Next the TIN was created; this took about 5 minutes. From this TIN, both a linear and a quintic interpolation were run. These procedures resulted in a total of ten DEMs.

One hundred reference points were then digitized from the original paper maps. Survey benchmarks and spot heights were used as reference points. None of these points was located on a contour line. The reference points and the predicted elevations for a given DEM were compared and the resulting error was calculated. Fifteen of the reference points were eventually disregarded as they were too near the edge of the coverage to provide accurate results.

In fact, a few interpolators returned negative elevation values near the margins of the DEM. This may have been due to edge effect. Edge effect is the artificial exaggeration of certain landscape trends (such as steep slopes) by an interpolation algorithm due to a shortage of information along the edge of the coverage, resulting in unrealistically high or low elevation values (Clarke 1995). Once these points with spurious elevations were identified and discarded, the root mean square error (RMSE) for each DEM was calculated and recorded. RMSE is, essentially, standard deviation. The procedure of comparing reference and DEM values was repeated for each DEM.

7.5.3 The results

The results of this study are presented here in tabular form (Table 7.1). A low RMSE is desirable. As can be seen, no DEM perfectly matched the reference points. Some DEMs, however, are distinctly better than others. Kriging with a circular semivariogram model has the lowest RMS error at 7.99 m, and appears to best fit this data set. The TIN interpolations are extremely inaccurate; this could be due to the manner in which the contours were initially digitized (ESRI 1995). Essentially, TIN is more accurate when the data represents landforms rather than contour lines. In addition, the two methods with the most complex local interpolator, the Quintic TIN and Quadratic Universal Kriging, were also the least accurate. These algorithms seemed to be particularly inaccurate when estimating the elevation of points in close proximity to steep slopes, such as cliff edges.

Table 7.1 also verifies the rationale outlined above for selecting an algorithm. Given the nature of the Belizean data, IDW and one of the various forms of kriging were thought to be particularly suitable. TINs were considered to be inapplicable to this data set. As Table 7.1 shows, IDW and six forms of kriging have an RMSE within 3.3 m of one another.

Quantitative analysis provides only half of the picture, however.[4] While Table 7.1 shows the overall error of each DEM, it does not indicate how this error is spatially distributed. A qualitative visual analysis can be used to identify the spatial distribution

Table 7.1 Comparison of digital elevation models (DEMs) by their root mean square error (RMSE).

DEM method	RMSE
Ordinary Kriging (circular)	7.990
Inverse distance weighting (IDW)	9.240
Ordinary Kriging (exponential)	9.994
Universal Kriging (linear)	10.180
Ordinary Kriging (spherical)	10.319
Ordinary Kriging (linear)	10.509
Ordinary Kriging (Gaussian)	11.311
TIN (linear interpolator)	17.129
TIN (quintic interpolator)	18.388
Universal Kriging (quadratic)	26.375

of error (Wood and Fisher 1993). Many of the reference points used to assess RMSE came from peaks, which are notorious for being sources of error in DEMs. An examination of the reference points indicates that, for all methods described above, predicted elevations for hilltops and peaks were very low. This problem may be remedied by digitizing peaks in as points (rather than arcs) when such values are provided on the source map.

In addition, these features may be checked visually by generating a grayscale representation of the coverage and comparing it to the original source map. Potential sources of error, such as peaks, ridge lines, and streams, can be examined in this manner. Figure 7.2 shows a portion of the study area as represented by the source map, from which the digital data for this exercise was obtained. This area is characterized by uplands to the west, with a sharp drop to the Booth's River floodplain as one moves east. Figure 7.3 is a grayscale representation of the same area created by ordinary kriging with a circular model. Note how the swampy area of the floodplain is represented as alternating dark and light shades of gray. The darker the color, the lower the elevation; thus, this area appears lower than the adjacent river. These alternating bands of color are an artifact of the interpolation algorithm, and could be remedied by including several points of the same elevation as the rest of the floodplain in the zone between the cliff line and the even-colored area to the east.

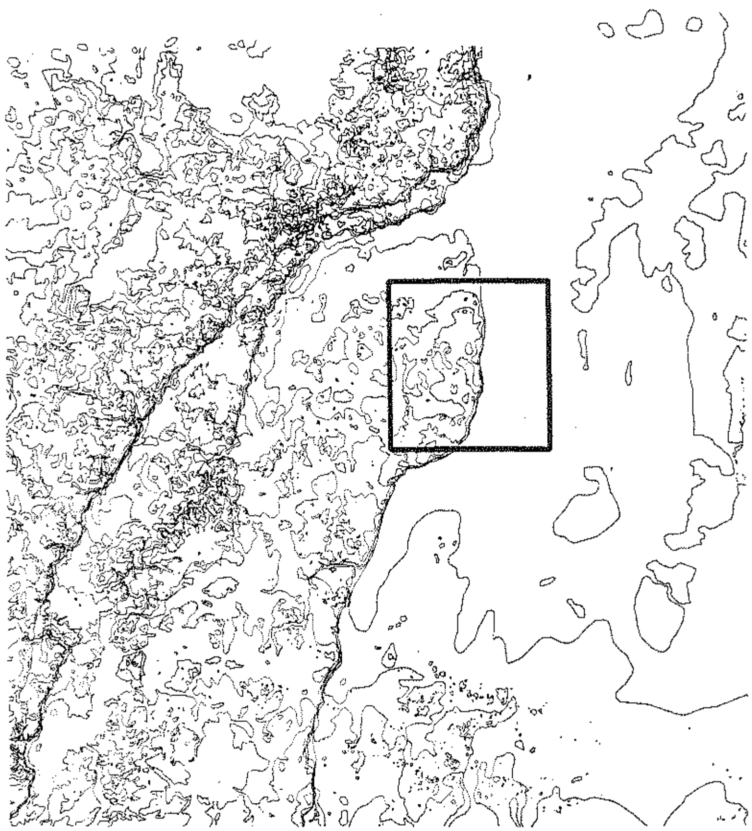

Figure 7.2 Map of study area (box delineates area represented in Figures 7.3 and 7.4).

In contrast, Figure 7.4 is the same area created by IDW. Note that the area appears to be characterized by periodic rises in the floodplain, without any trace of the low area seen in Figure 7.3. Again, this is an unintended effect of the interpolation algorithm. A solution to this problem would be similar to that mentioned for the kriging example mentioned above: to include additional points on the floodplain east of the cliff edge in order to reduce the reliance of the algorithm on points located on the cliff edge for information. As can be seen, then, the two algorithms with the lowest RMSE are not perfect. Additional work beyond the digitizing of contours is required.

As noted above, the data set used in this study was generalized to remove redundant data. After the data set had been generalized, data points were more or less regularly distributed across the landscape. Thus, we were fortunate not to encounter a problem common to users of IDW. In their evaluation of different interpolation algorithms, two geographers, Wood and Fisher (1993), experienced a terracing, or "stair-step", effect in their IDW-generated DEM. In his creation of a predictive model

Figure 7.3 Booth's River floodplain as created by Ordinary Kriging using a circular model.

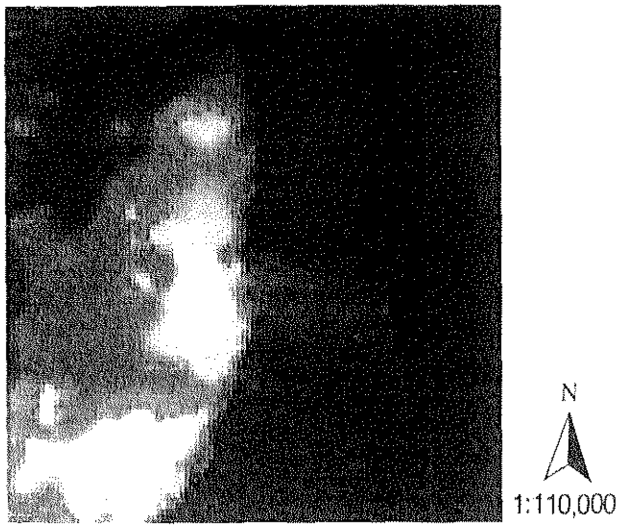

Figure 7.4 Booth's River floodplain as created by inverse distance weighting (IDW).

for southern Illinois, Robert Warren (1990: 210–11) encountered an identical problem, in that the hill slopes of the resultant DEM appeared as "step-like tiers." This is an artifact of the IDW algorithm applied to a data set composed of points that are clustered closely together. In these cases, both landscapes were represented inaccurately. In Warren's (1990) case, this was identified as the primary factor in a predictive model of archaeological site location that was not very powerful. These particular situations are illustrative of the need for qualitative as well as quantitative examination of DEMs used in archaeological analysis.

7.6 CONCLUSION

As Kvamme (1990: 123) has noted, archaeologists tend to be more concerned with archaeological data than data obtained from a computer. Warren (1990) found that an inaccurate DEM can be detrimental to the overall power of a predictive model, since coverages such as slope and aspect are ultimately derived from a DEM. This exercise, based on topographic data from northwestern Belize, has shown that the same critical eye an archaeologist casts toward a sample of artifacts can also be used to evaluate the overall quality of data manipulated within the context of a GIS. Given the fact that an archaeologist using a GIS or computer mapping program is likely at some point to encounter a situation in which interpolation is a consideration, a basic understanding of the nature of interpolation is essential. Through an awareness of the assumptions of various algorithms, as well as the combined use of quantitative

and qualitative methods, archaeologists can create more accurate representations of land surfaces and avoid the pitfalls inherent in the uncritical usage of spatial statistics. This, in turn, can lead to more powerful predictive models of archaeological site location.

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Notes

1 Throughout this chapter, the terms "lattice" and "raster" are interchangeable.
2 For a recent review of this concept see Vasiliev (1996).
3 This procedure uses the Douglas–Peucker (1973) simplification algorithm.
4 For a discussion on the limitations of RMSE as an error estimation technique, see Morad *et al.* (1996).

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