

11 Cartographic modelling in a cell-based GIS

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11.1 INTRODUCTION: AIMS & DATA

Starting in 1986, the five departments comprising the Faculty of Environmental Sciences of the University of Amsterdam (Physical Geography, Social Geography, Planning and Demography, Ecological Sciences, and Pre- and Protohistoric Archaeology), aiming to renew their research efforts, participated in a GIS working group.

Hardware was provided by IBM through a number of research contracts, and among the software acquired were two GIS packages. In 1989 the vector-based GIS *Genamap* was bought, while the cell-based GIS GRASS (available in the public domain) was up and running since 1990¹. The following paper contains the results of our first foray into the field of cartographic modelling with GRASS.

11.1.1 Aims

Applying GIS-techniques to the solution of traditional archaeological problems in effect means the formulation, building, testing, and interpretation of *cartographic models* of archaeological situations. The possibilities of cartographic modelling in a cell-based GIS have been well described by Tomlin (1990); research into its application to archaeology is not far developed yet².

The aim of this research has not been to try out ready-made GIS-tools on an ideal set of data, but to create a real-life situation in which problems

relating to the availability and quality of the data, the translation of an archaeological problem in GIS-terms, and the restrictions inherent in the GIS itself would stand out.

Sections 2, 3, and 4 of this paper will be devoted to a description of the three main archaeological problems investigated during the past year. They cover a wide range of analytical techniques and highlight some of the possibilities and restrictions of the use of a GIS. They also run parallel to three distinct levels of investigation: first, the *translation* of traditional cartographic techniques used by archaeologists into the automated form of the GIS. Second, the *extension* of traditional cartographic techniques used by archaeologists through the use of the tools provided by the GIS. And third, the *development* of cartographic techniques new to the archaeologist through exploitation of the GIS's capabilities.

The results of this research are evaluated in section 5, which contains paragraphs on the methodology of using GIS, on the bottlenecks encountered, and on the future place of GIS in education and research at our Institute.

11.1.2 Study area

The choice of the study area was dictated by our requirement that, for reasons to be discussed below, the digital terrain model (DTM) should play a prominent role in the analysis. This requirement restricted our choice of terrain to the southernmost part of the Netherlands, the area known as South Limburg (Figure 11.1). A happy coincidence proved to be that parts of this area had recently been the subject of an archaeological field survey, guaranteeing the best possible distribution maps.

11.1.3 Database

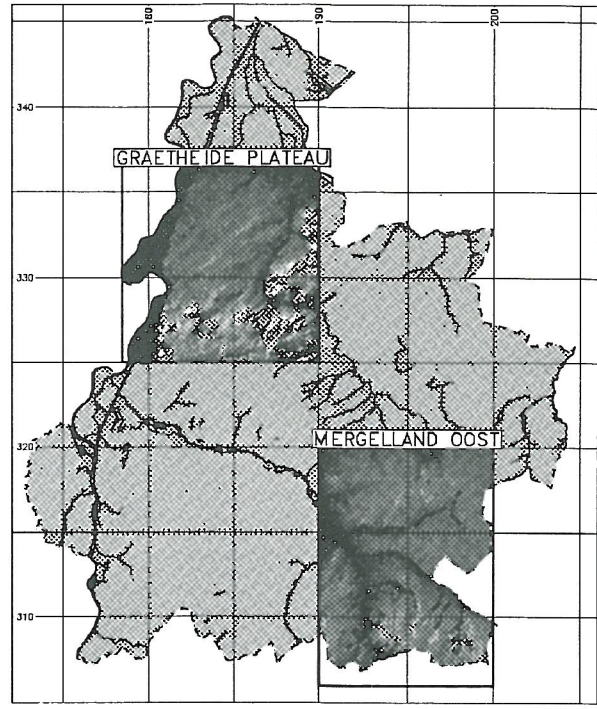
A fairly simple archaeological database, containing some 1300 records for an area total of 700 km², was assembled from the paper archives of

1 For the digitising of base maps Genamap 4.1 was used, which provides a user-friendly environment for the entering and editing of vector data. These data were then converted for use as cell-maps in GRASS, a GIS developed by the US Army Corps of Engineers, the source code of which is freely available in the public domain. As of this writing version 4.0 is in use. These programs run under IBM OS/2 version 1.2, IBM AIX/RT version 2.2.1, and AIX version 3 for RISC System/6000.

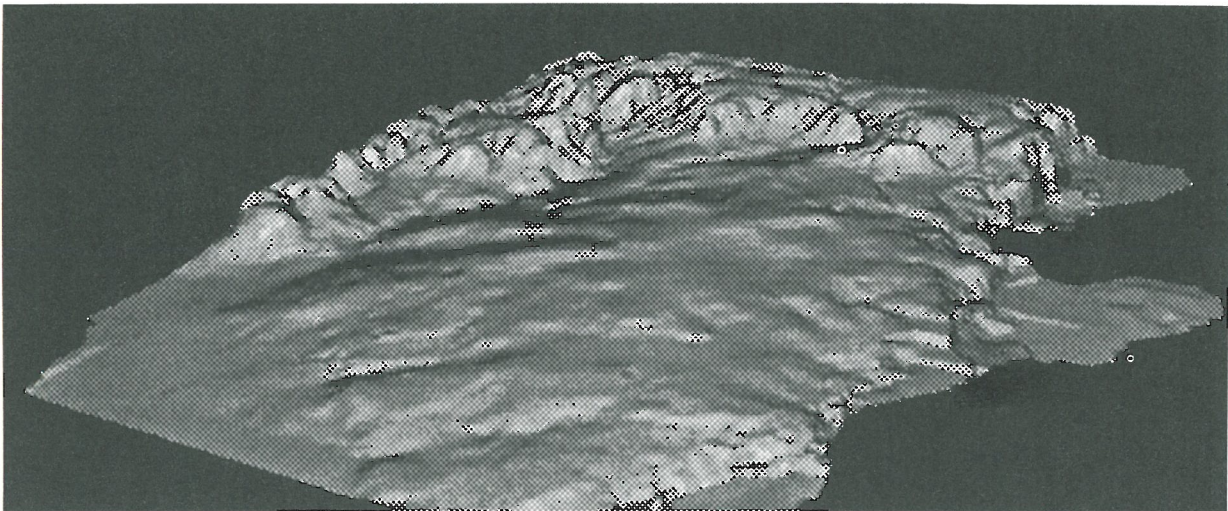
2 For a recent review of the relevant research, see Kvamme 1990.



a



b



c
 Figure 11.1: The Province of South-Limburg is part of the Dutch Pleistocene landscape. It is shaped in large measure by the river Maas and its tributaries (a). In the north of this area lie the loess-covered Graetheide Plateau, where a concentration of Linear Band Keramik sites has been found.

The chalky Mergelland East area, drained by the Geul river, lies to the south (b). A 3-d view of the Graetheide Plateau from the Northwest with a vertical exaggeration of 10 shows its position as the Middle Terrace of the river Maas (c); it now lies between 20 and 40 meters above the river.

the State Archaeological Service (ROB). Apart from its national grid co-ordinates, four fields were recorded for each site: its ROB-identification code, the find type and period, and a comment field. These data were read into GRASS's SQL-type database. The results of queries made in the database can be used directly, or be converted into GRASS raster maps.

11.1.4 Base maps

Before the actual analyses could be carried out, a number of base maps³ had to be obtained in digital form. Since these are not yet commercially available, or are much too expensive, they had to

3 "Base maps" are the maps containing the raw georeferenced data.

be digitised by hand or acquired through barter with the appropriate provincial authorities. These procedures, and the process of checking and converting the maps to a format readable by GRASS proved to be extremely time-consuming, taking about one third of the total amount of time available for the research.

Among the base maps collected are the soil, geology and geomorphology maps, a map depicting early 19th century land use, surface hydrology, mean annual rainfall and elevation contours. Where-ever possible, a scale of 1:50,000 was maintained.

11.2 TRANSLATION: MODELLING SETTLEMENT PATTERNS

11.2.1 Introduction

In the Netherlands serious attempts at cartographic modelling with the help of a GIS have been undertaken mainly by researchers at RAAP, an organisation that conducts archaeological surveys and related research for provincial and municipal authorities. Since their primary aim is to boost the efficiency of their surveys, the methods they have used reflect the importance of the relation between the sites and the landscape (Ankum & Groenewoudt 1990).

One of the aims of regional studies in archaeology is to describe and, if possible, to understand and predict settlement patterns. Explanations typically include environmental, social/cultural and statistical factors. The spatial nature of these patterns and the equally spatial nature of the factors invoked to explain them make this type of problem admirably suited for cartographic analysis. One particularly well-known example of settlement-location modelling is contained in Bakels (1978, 1982), which describes Linear Band Keramik (LBK) settlement in the Graetheide plateau area of southern Limburg. In the present section we shall duplicate her approach to model-building using GRASS instead of paper.

11.2.2 LBK-sites and their environment

To begin with, we assume with Bakels that LBK settlement location choice is determined by economic and social factors. Since the latter cannot be reliably reconstructed, settlement locations can only be related to what we know about the economic activities of the inhabitants. Among the factors of prime importance Bakels lists climate, relief, hydrology, vegetation and fauna. These are successively reduced to four factors considered both important and amenable to cartography: the

availability of loess soils, the slope of the terrain, the amount of relief, and the distance to permanent streams.

In geological terms the Graetheide plateau is the loess-covered Middle Terrace of the river Maas, bordered on the west side by the Maas valley, in the east and south by the valley of the Geleen and by steep slopes leading to the High Terrace (see Figure 11.1). In the north the edge of the plateau is less clearly marked but still visible in the terrain. The sites dating to the early Neolithic are distributed mainly along the eastern and south-western borders of the plateau.

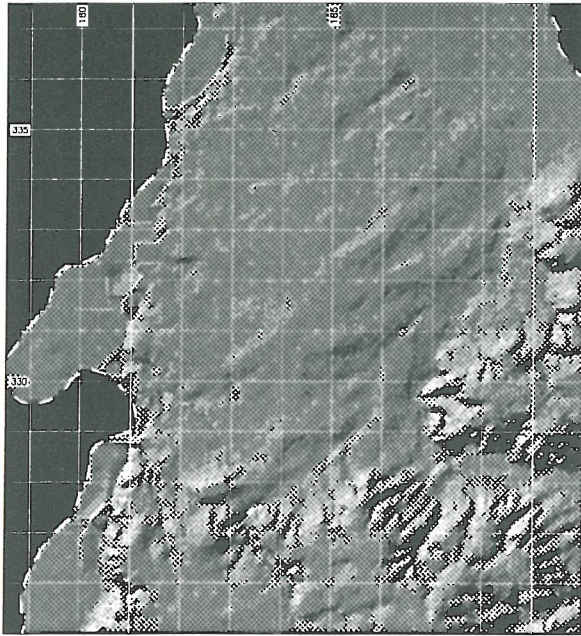
11.2.3 Region and scale

The extent of the region taken in consideration during the modelling evidently determines whether a settlement factor can be mapped in a meaningful way. Within north-western Europe the availability of loess is not obvious, nor are large flat areas present everywhere. Within the 11.5 by 12.5 km region taken into consideration by Bakels, the Graetheide plateau is the only large flat loess-covered area available to would-be settlers. This introduces an important point: once it is assumed that LBK farmers needed a large flat loess-covered *Siedlungskammer*, and chose the Graetheide plateau for their purpose, the criteria of loess availability and low relief should no longer play an important role in further modelling: other locational factors must take precedence. We shall return to this point when discussing the results of our modelling attempt.

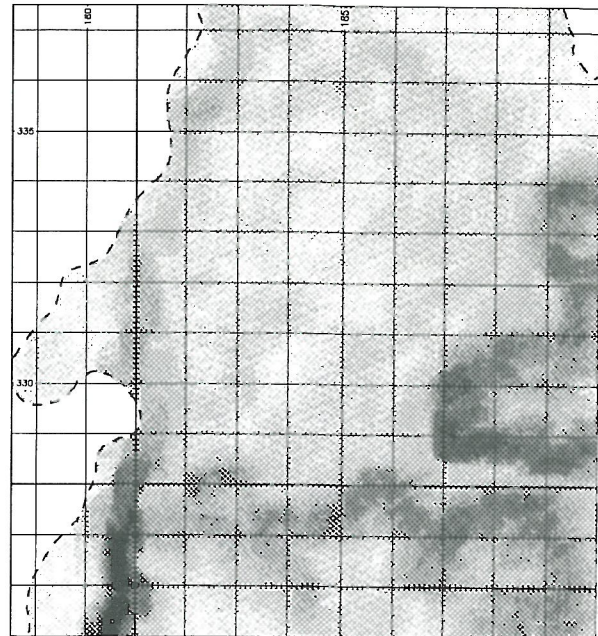
A second factor that will obviously influence our modelling attempts is the scale of the maps we use. This will determine the maximum resolution of our cartographic model. In a cell-based GIS the resolution of a map is expressed as the size of a cell along the main map axes. The choice of our map scale is to a large extent taken out of our hands, since most of the available base maps are scaled 1 in 50,000, implying a maximum resolution of ca. 25 meters, that is, points spaced 25 meters or more apart in reality can be reliably distinguished both in the paper and the digitised maps⁴.

Although restrictions of processor speed and memory capacity might only a few years ago have prompted us to lower the resolution of our maps we can now keep them at maximum resolution.

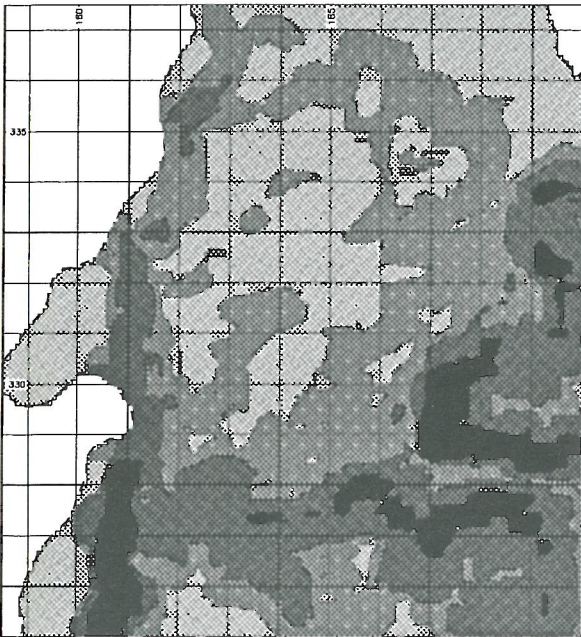
⁴ This is not to say that a larger precision cannot be attained. In fact, careful digitising of a map scaled 1 in 50,000 may result in a *de facto* mean resolution of about 12.5 meters.



a



b



c

Figure 11.2: Preparation steps for the Local Relief map. Starting from the DTM (a), the difference between the minimum and maximum elevations within a radius of 250 meters from each cell is calculated as a measure of the relief (b). In the next step, the relief map is reclassified into four categories according to the rules customary for geomorphology maps (c).

11.2.4 Definition and preparation of factor maps

Our modelling attempt starts with the preparation of map layers for each of the factors mentioned by Bakels. Here we encounter a problem right away: some of the factors determining LBK settlement location choice are defined by Bakels in a way that cannot directly be translated into rules for the preparation of map layers. For example, the description «availability of a sufficiently thick loess cover» leads to questions such as: «what is meant by “sufficient”?» In what way should we translate the legend of the soil base map so that it shows us which areas are covered

with «a sufficiently thick loess cover»? We are forced to make a decision for each of the legend entries of the soil map.

Equally, there is no clear definition of “local relief” (Figure 11.2). Should we adhere to the definition used by the State Geological Service? Where should the threshold value (if any) between «too much relief» and «not too much relief» lie? I have defined the “local relief” as the maximum difference in elevation to be found within a radius of 250 meters from each cell. Following Bakels, who sees the total surface area of adjacent “low relief” cells as the important measure of settlement fitness, these local relief values have been reclassified to the ordinal values low, medium and high relief (Bakels 1978:132–3).

As a last preparatory step the surface area of all blocks of adjoining cells with the same value was measured and the largest block of value “low relief” — corresponding, incidentally, to the Graetheide plateau — was taken to represent the area preferentially settled by LBK frontiersmen.

A second set of problems encountered during the preparation of factor maps concerns the absence of data⁵. A large part of the surface area of the soil map is man-made (mainly caused by the built-up areas of the towns of Sittard and

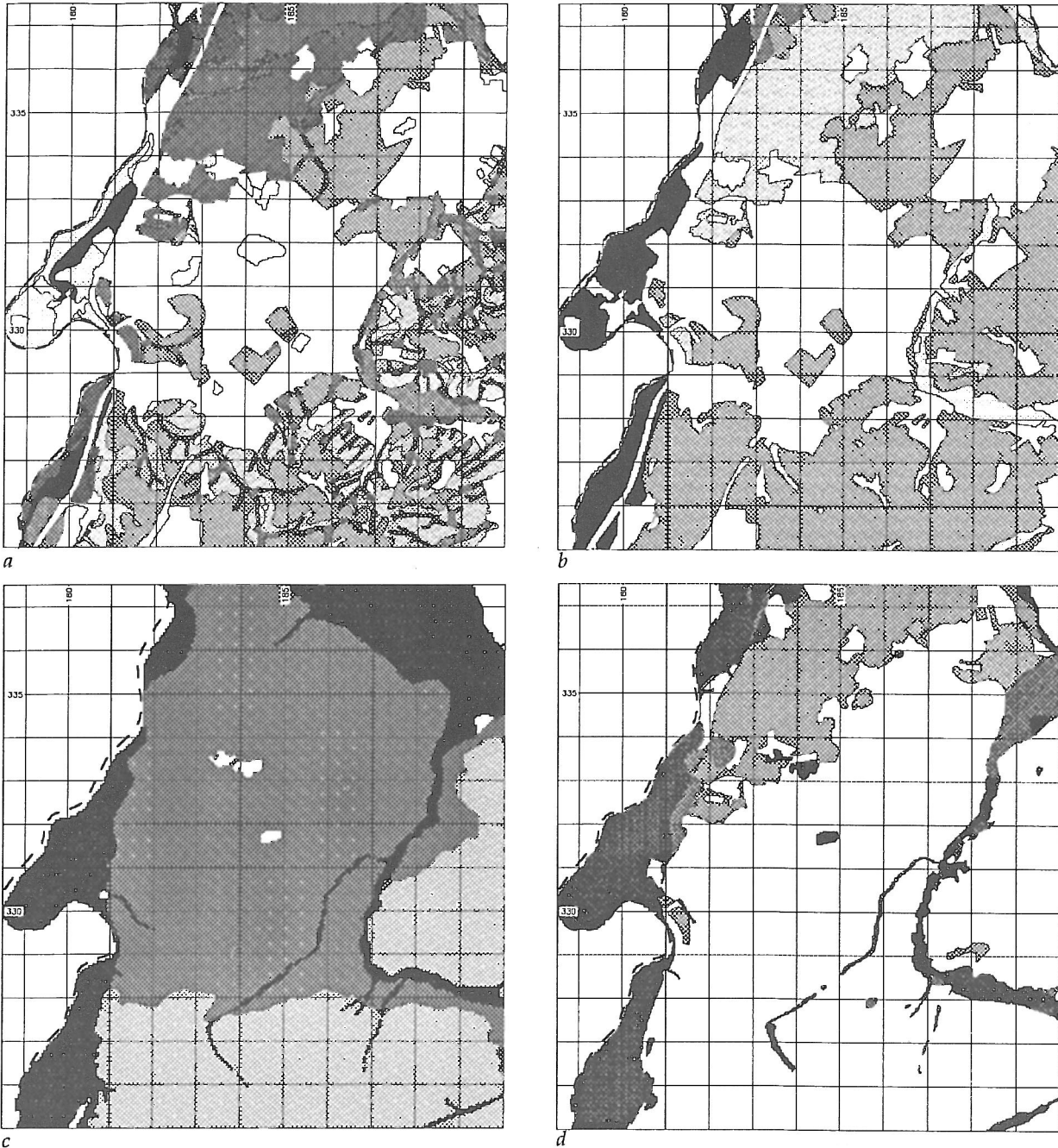


Figure 11.3: Preparation steps for the Loess map. Starting from the soil base map (a) a simplified map is created through reclassification into the main soil groups (b). The white areas in the new soil map, where a soil classification

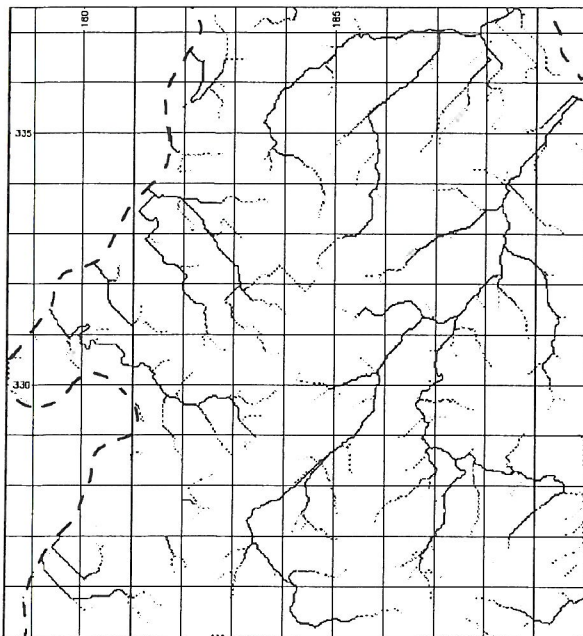
is missing, are filled with the corresponding cells of a less reliable geological map (c), and the resulting map (d) is evaluated for LBK settlement suitability according to the thickness and quality of the loess cover present (not shown).

Geleen). Should we accept these “no data” areas in our factor map or should we find a way to fill in the missing data? I have used a geological map

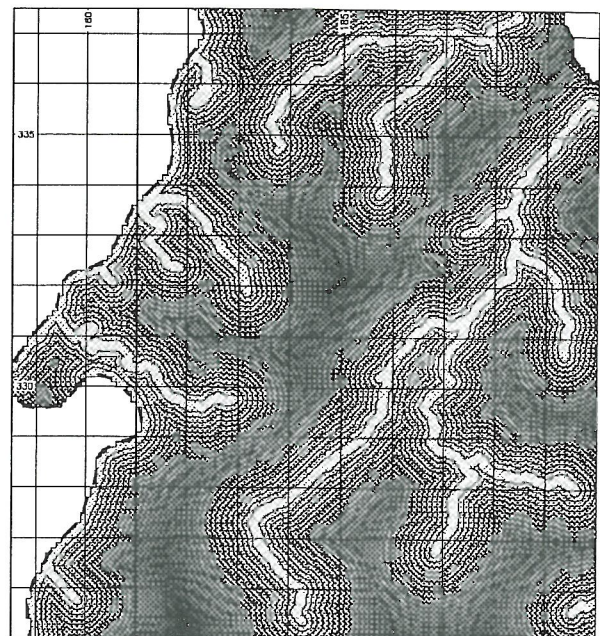
made in the 1920's to reconstruct soil types for these areas (Figure 11.3).

The same problem is encountered on a more massive scale with the “distance to water” factor (Figure 11.4). Calculating the distance to the nearest surface water is easy if the early Neolithic pattern of drainage is known. Obviously, contemporary surface hydrology cannot be used for a

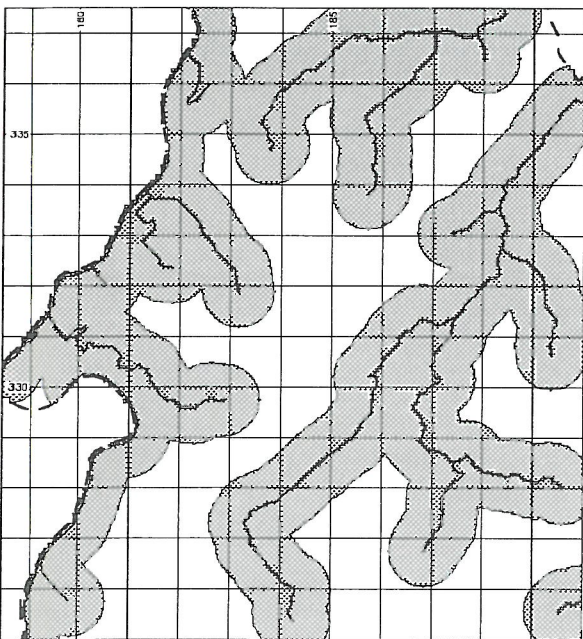
5 Map layers containing the data relevant to one of the settlement location factors will be hereafter called “factor maps”.



a



b



c

Figure 11.4: Preparation steps for the Distance-To-Water map. Since modern surface hydrology cannot be transplanted to early Neolithic conditions, water courses are simulated by calculating the theoretical amount of surface runoff on the basis of the DTM. The new map (a) contains a value for each cell; a threshold value is established and all cells with higher accumulated runoffs are selected. In the next step, distance buffers are used to establish the distance of each cell to the nearest water (b). A distance threshold value is chosen to divide the region into cells attractive and unattractive to LBK settlers (c).

number of reasons: climate in the Atlantic was somewhat wetter than it is now, rivers have changed their course, erosion and deposition have altered topography. Moreover, many streams have been moved, straightened or even filled in by man, mainly during the last century.

Therefore we have to *simulate* the Atlantic drainage pattern. This is done by first simulating a spell of rain over the elevation map and calcu-

lating the accumulated runoff for each cell⁶. Next, we pick a modern stream that we consider to be “natural” and query the accumulation map for the amount of accumulated water at its source. This value is the contemporary stream threshold value and is diminished by 10 per cent to serve as the threshold value for Atlantic streams. The cells that have accumulated more than this amount of water together form the Atlantic drainage pattern⁷.

As a last step the distance to these streams is calculated. Since Bakels does not define “near water” in a quantitative manner, but says most sites appear to be between 250 and 750 meters from water, we will take 750 meters as our outer limit.

The GIS not only forces us to be clear about our definitions and to deal with missing data; it also forces us to express map categories on some

6 The accumulated runoff is calculated on the assumption that the terrain is non-permeable. It is of course recognised that this is not a realistic assumption.

7 It is of course recognised that surface hydrological conditions are determined by other factors besides topography, among them soil characteristics. These factors have been left out of the model because their precise influence on the drainage pattern is not known.

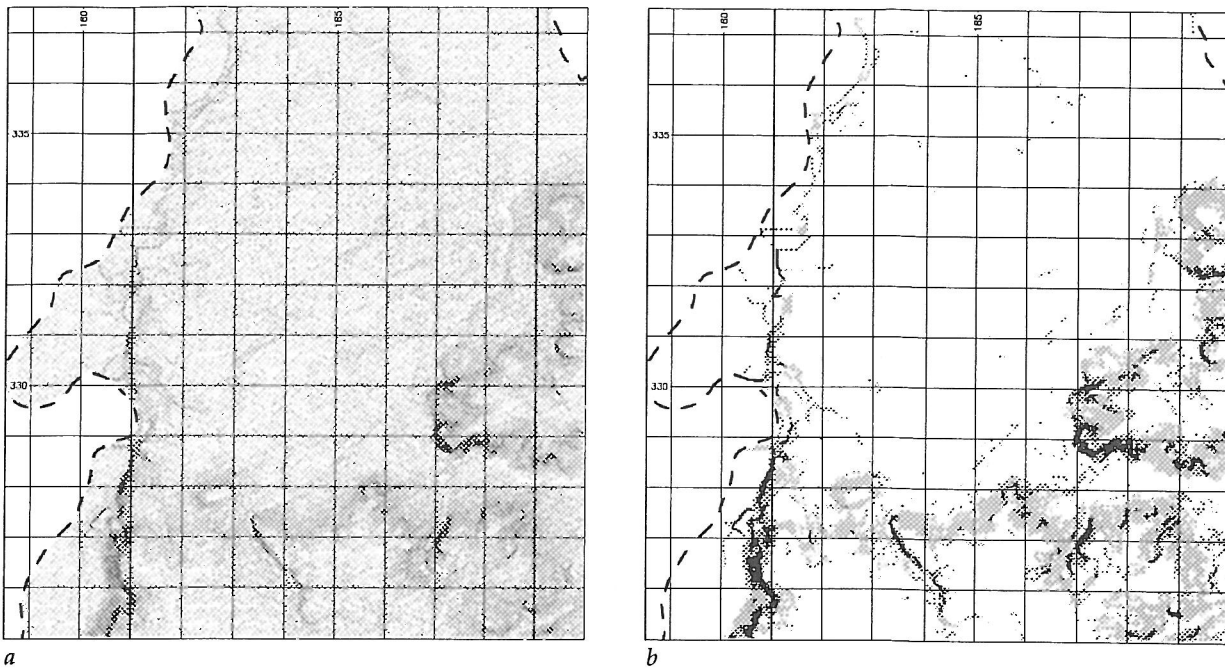


Figure 11.5: Preparation steps for the Slope map. Starting from the DTM, a routine slope calculation is performed (a). In order for the result to be reclassified into three categories that are in general use among archaeologists (b), a conversion from percentage to degrees of slope is applied.

numerical scale — either ratio, interval, ordinal, or nominal (Tomlin 1990:14). The kind of scale we choose will influence the role a factor map will play in giving shape to the eventual cartographic model.

For example, to arrive at a map layer representing slope in degrees, a slope calculation is performed on the elevation map and, since the results are expressed in percentages, a conversion to degrees is applied. The resultant range of slope values is then reclassified into three categories in general use among archaeologists: low relief from 0 to 2 degrees, medium relief between 2 and 8 degrees, and high relief where there are more than 8 degrees of slope (see Figure 11.5). Both the rounding of slope values to integers (inevitable in GRASS) and the conversion to degrees lead to unintended but considerable loss of information. The reclassification leads to an intentional loss of information, which is traded for simplicity.

It should be noted that the steps described in this section, innocently termed «preparation of map layers», take us far from the relative objectivity of the base maps that indicate soil type and terrain elevation. Generally, any attempt at cartographic modelling will involve executing many subjective operations on the base maps. The archaeologist should either be able to account for these operations, or be aware that he can not⁸.

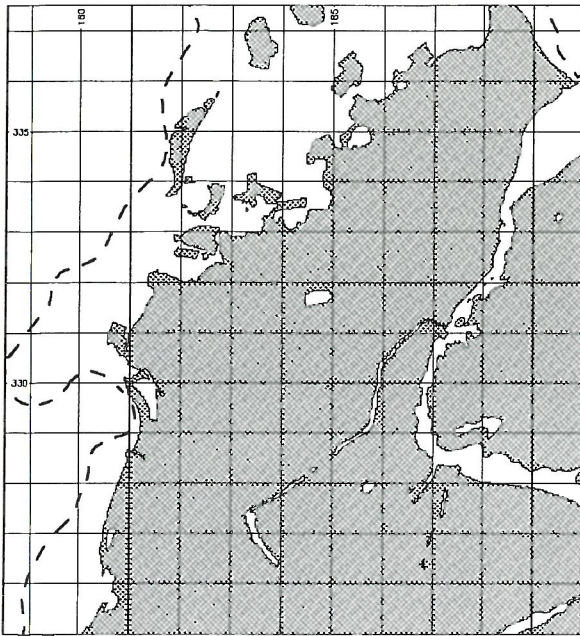
11.2.5 Combining factor maps in a settlement model

The purpose of cartographic modelling in general is *cartographic allocation*, that is, the process of selecting locations in order to satisfy stated objectives (Tomlin 1990:198).

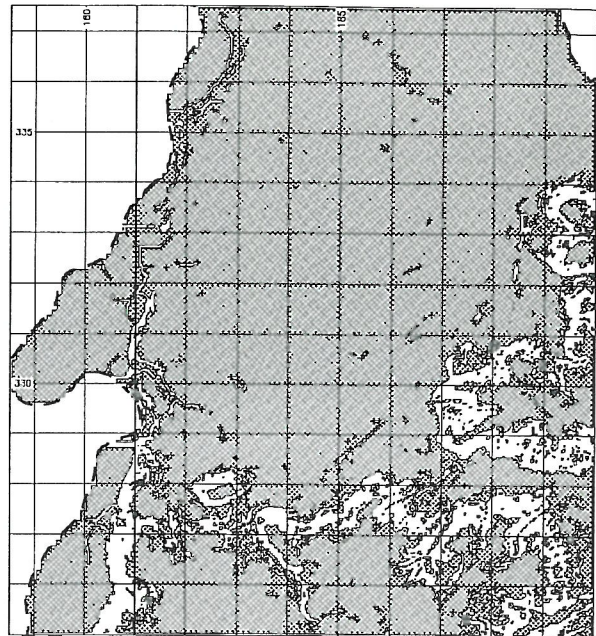
Having prepared all factor maps considered to be of importance with respect to LBK site location, the first step in this process is to develop decision rules, called *allocation criteria*, for each of the map layers representing loess cover, distance to water, slope and local relief. Allocation criteria are reclassification rules that translate the measurements contained in the factor maps into values which convey a definite meaning to the archaeologist. To clarify this with an example, the slope measurement «4 degrees» is translated to the value «medium» or even «suitable for settlement purposes by LBK farmers».

Modelling LBK settlement location choice is done in a second step that simply consists of the process of deciding for each cell whether it satisfies some predefined combination of the stated

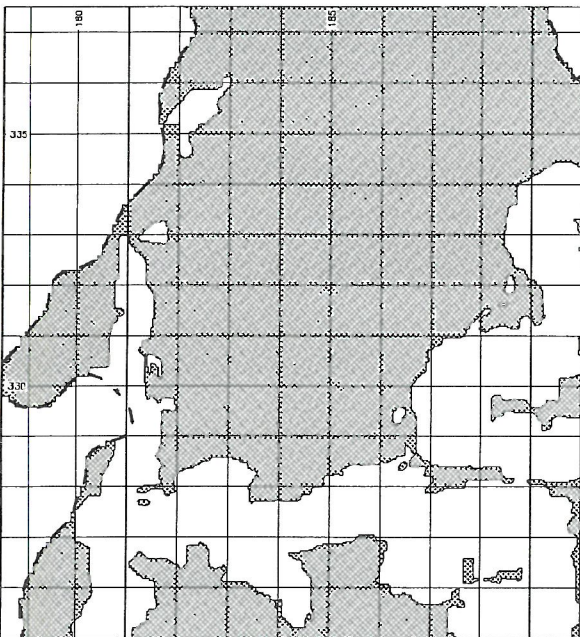
8 Not discussed in this paper is a method that largely avoids these problems. Given the locations of LBK sites in the Graetheide area, statistical methods can be applied to determine predictive geographical correlations useful in the assignment of values to map characteristics. The significance of these correlations can be used as a weighing factor for the map characteristics.



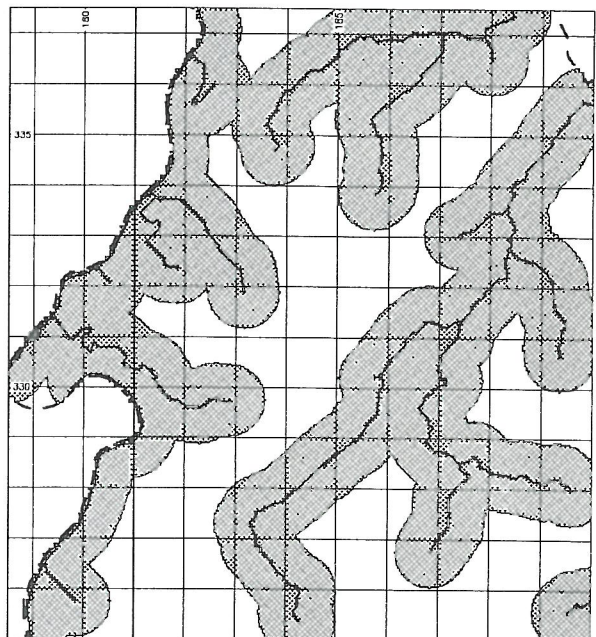
a



b



c



d

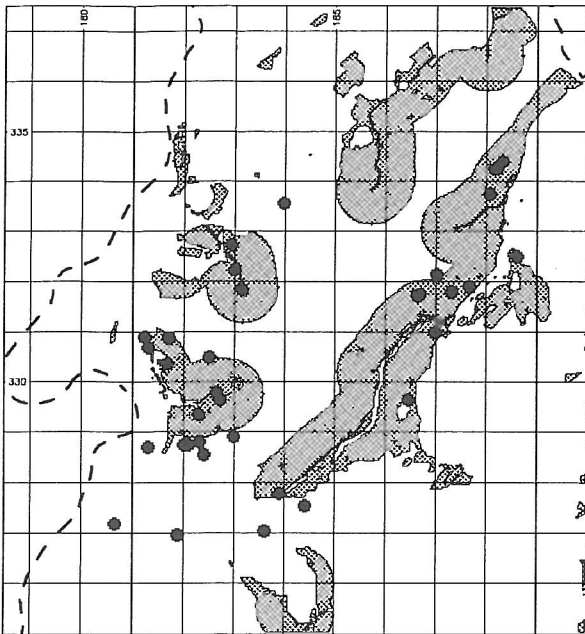
allocation criteria. The decision rule in effect expresses some desired result ("LBK") as a function of these values in one or more factor maps ("L, W, S, and R").

During the preparation of our factor maps we have in fact already applied some implicit allocation criteria. We have allocated suitable and unsuitable areas on the soil and distance-to-water maps, we have assigned ordinal values to the local relief map, and we have grouped slope values according to a rule that is non-random. We shall see that these allocations restrict the subsequent modelling possibilities.

11.2.5.1 Boolean overlays

Decision rules may be simple or complex: one possible approach (the one taken by Bakels) would be to devise allocation criteria that result in dichotomous or binary (yes/no or 1/0) maps, reclassifying each map layer into just two types of cells: those that are unsuitable for settlement and those that are suitable (see Figure 11.6)⁹. Combining these maps would then require a simple rule using Boolean operators to the effect that a cell is

⁹ Robinove (1977) reviews the use of logical overlays in GIS.



e
Figure 11.6: An "AND" or mutually exclusive intersection of the four factors assumed to play an important role in LBK settlement choice. The Loess (a), Slope (b), Relief (c), and Distance-To-Water (d) factors are represented as binary map layers. As can be seen in the resulting map (e), the correspondence with known early Neolithic sites can be improved by assuming a somewhat less restrictive role for the Distance-To-Water factor. A transparent overlay of the four factor maps yields a map containing a total of 16 (two to the fourth power) categories (f). Note the correspondence of (e) with the darkest areas in (f).

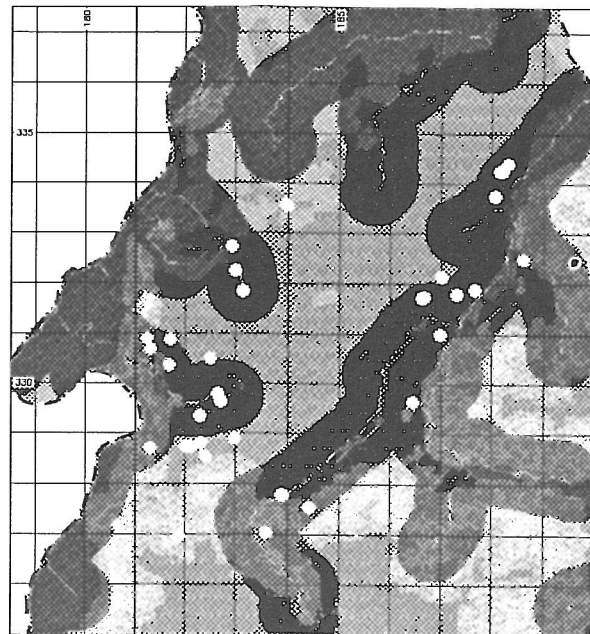
considered suitable for LBK settlement if, and only if, it is found to be suitable in all factor maps. This can be rephrased as a formula:

$LBK_{bin} = \text{if } (L=1 \text{ and } W=1 \text{ and } S=1 \text{ and } R=1)$.
The maps resulting from the application of this decision rule will be dichotomous themselves, indicating only whether a cell must be considered suitable or not.

Other logical combinations of the factor maps, such as selecting locations that satisfy at least three of the allocation criteria, are of course possible, but the result will still be a dichotomous map. Since four binary factor maps are used, a total of 2^4 such combinations is possible. Rather than map all possible combinations separately, we should perform a transparent overlay of the four factor maps, creating one map showing all combinations.

11.2.5.2 Mathematical decision rules

An important drawback to the use of decision rules based on logical combinations of allocation criteria is that it necessitates binary maps for input. Most of the information contained in the



f
original factor maps has therefore been lost through simplification. A better use of the available information could be made with a mathematical decision rule, allowing us to combine the factor maps through summation, multiplication or other methods.

Weights can now be assigned to the various categories in the factor maps, and the relative importance of the individual allocation criteria can be expressed by assigning a coefficient to the factor maps, resulting in a formula like:

$$LBK^+ = \frac{aL + bW + cS + dR}{4} \text{ or}$$

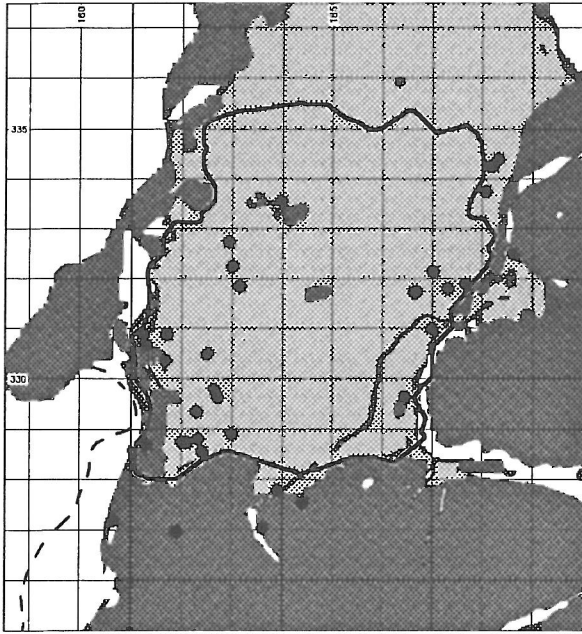
$$LBK^* = \sqrt[4]{(aL * bW * cS * dR)}$$

where L, W, S, and R are measures of suitability of the four factors, and a-d indicate the relative importance that is attached to each factor. An example of the use of such a coefficient is provided by Bakels (1978:138) when she remarks that «the desire to have loess close to the house apparently prevailed over the wish to have water at hand.»

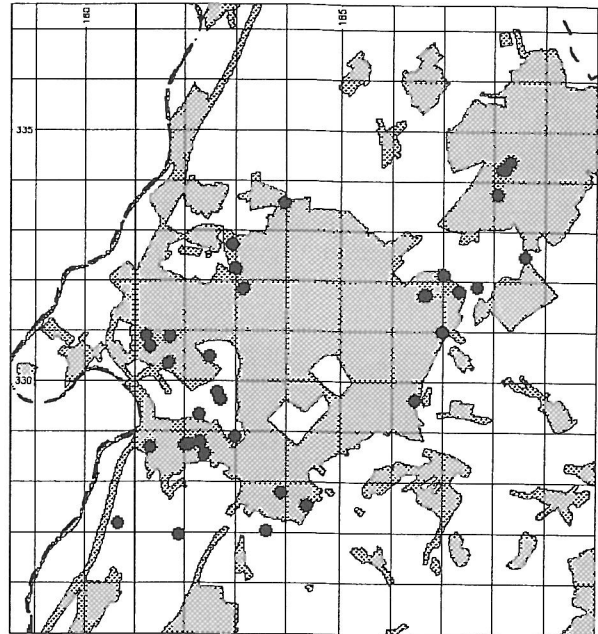
Any maps constructed from this type of decision rule will contain a continuous range of values, which can be interpreted as representing a scale from "minimally suitable" to "maximally suitable" locations¹⁰.

11.2.6 Interpretation of the results

In view of the many caveats expressed in earlier sections, it should come as no great surprise that



a
Figure 11.7: Effects of the region settings and the find circumstances on the significance of the correlation between site locations and map zones. When we look at the region as a whole, there is a strong and highly significant correlation between early Neolithic site locations and the flat



b
loess-covered area (a). If we restrict our view to the Graetheide plateau itself (indicated by the unbroken black line) the significance of this correlation disappears. In contrast, correlations with factors unrelated to settlement choice, such as recent building activity, can be quite strong (b).

the interpretation of the results obtained is not entirely straightforward either.

Firstly, the results shown in Figures 11.6e and 11.6f in effect are *predictions* of LBK site presence, based on some combination of allocation criteria. The correspondence between predicted and actual site presence can be measured by correlation/regression analysis. If the model perfectly reflects LBK settlement location choice, all the known sites should correspond with high suitability values.

The reverse is not true, however. If the allocation criteria are lax, so that a large part of the region is deemed highly suitable for settlement, the same high correspondence with known sites will be found, but in this case the predictive value of the model is very low. Methods for dealing with this problem have been described by Kvamme (1989, 1990)¹¹.

Secondly, we saw in section 11.2.3 that the choice of the boundaries of the study area may restrict the role of some factors and enlarge that of others. This role can most easily be understood

by comparing the actual number of LBK sites per category of the factor maps with the expected number of sites in a random situation (Figure 11.7a). For the relation between flat loess soil and LBK sites the Chi-square is a significant 4.96¹² when the whole region is taken into consideration, but 0.21¹³ if we restrict the region to the Graetheide plateau¹⁴. Predicting LBK settlement on the basis of these two factors alone would result in a map with high suitability values for the whole of the plateau, and therefore with little predictive value.

Thirdly, even if there is a highly significant correlation between predicted and actual sites, this is no proof of the correctness of our model; the correlation may be entirely due to factors out-

10 Multiplication of factors has the effect of maximising the differences between the values in the resultant map. In visual terms, it enhances contrast. Psychologically speaking, it probably reflects some of the processes involved in deciding which places are best for settlement.

11 Kvamme 1989:168–82, discusses some of the statistical checks applicable to regional environmental analysis and locational modelling; Kvamme 1990:260–7 and 279–80, discusses the use of prior probabilities as base-rate or chance models and the assessment of model performance.
12 Expected number of sites 19.2, actual number of sites 29. The flat loess area is 50.6% of the total area.
13 Expected number of sites 25.3, actual number of sites 23. The flat loess area is 93.8% of the total area.
14 A change in the resolution of the base maps will obviously affect the results obtained through modelling. On this subject the reader is referred to the extensive literature on map resolution effects.

side the model, such as the surveying conditions or find circumstances. It is conceivable that all or most of the known LBK sites have been discovered as a consequence of building activities. The allocation criteria will then reflect regularities in building activity rather than LBK settlement conditions. In that case the correlation between sites and built-up areas may be stronger than that between the sites and the Neolithic landscape. If we tabulate the correlation between early Neolithic sites and the soil map, the most significant correlation (Chi-square 13.6) turns out to be that between the sites and the built-up areas (Figure 11.7b).

Keeping in mind the requirement that the meaning and significance of the results obtained should always be made explicit, we seem to have the tools in hand to make some useful locational models. Alternatively, statistical techniques can be applied to existing data sets.

11.3 EXTENSION: DETERMINING TERRITORIAL BOUNDARIES USING COST-SURFACING TECHNIQUES

11.3.1 Introduction

Having reconstructed a prehistoric landscape and settlement pattern, the archaeologist would like to go further: is it perhaps possible to determine aspects of regional economic and social structure? Territoriality, in the guise of catchment areas, boundary markers, or core territories, must be brought into the cartographic model¹⁵.

Since territories often are a function of a centre or *focus* and some characteristic of the surrounding terrain, a GIS-technique known as cost-surfacing or resistance mapping can be applied (Figure 11.8). In traditional archaeological cartography horizontal distance between foci is the criterion by which a map is subdivided into territories, an essentially two-dimensional technique called Thiessen or Voronoi tessellation¹⁶.

Cost-surfacing adds a third dimension in that it allows a differentiation not only in the weight or importance of the foci but also in the value of the cells between them. Thus territorial boundaries reflect both the relative importance of their

foci and characteristics of the terrain deemed important by the archaeologist, such as slope, wetness, and the existence of natural barriers. It is even possible to change the "laws of physics" for a cost-surface by changing the rules applicable to movement over that surface.

The resulting differentiation of cell values expresses the fact that we are measuring the *perceived cost* of traversing a cell. These perceived costs can be aggregated into cost-paths or cost-areas, in which the cell value represents the total costs involved in reaching that cell.

11.3.2 Tessellation of cumulated costs

Consider a group of sites in a cost surface where all cells contain the value "1"¹⁷. If we were to travel outwards from the sites and sum the cell values encountered, the aggregated costs would rise in direct proportion to the distance travelled. If we use the accumulated costs to assign new values to the cells, the highest costs will occur in cells equidistant from two or more sites, precisely where Thiessen polygons calculated in the traditional manner would be expected to lie. We can regard the resulting map as an elevation map and the highest values as ridges in the surface. Extracting these ridges through various filtering operations leaves us with territorial boundaries that the archaeologist can use for other analyses. These steps can be performed no matter what the actual values in the cost surface are.

The archaeologist will want the calculation and subsequent tessellation of the cumulative cost surface to proceed on the basis of three cost factors: the characteristics of the terrain (terrain cost), the relative importance of the sites or foci (site cost), and the manner in which costs are accumulated (accumulation rule). Examples of all three are given below.

11.3.2.1 Terrain cost

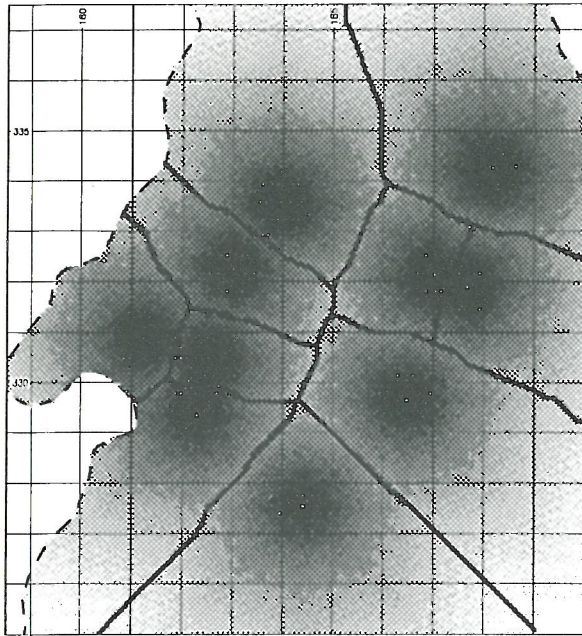
Characteristics of the terrain can influence the size and shape of a territory. Boundaries may become "attracted" to natural features such as streams and ridges. The slope of the terrain influences its accessibility: difficult terrain will be avoided. Factors like these can be encoded in a cost surface.

If we compare the accumulated costs in the Graetheide area, where the costs have been differentiated according to slope class and the presence of surface water, to the accumulated costs of the

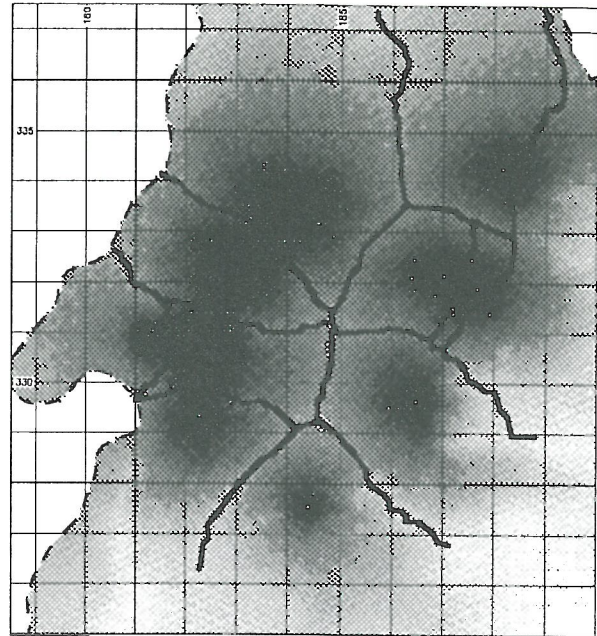
15 Haggitt 1965:48 ff. and 161 ff., discusses the concepts of territories and movement minimisation.

16 See Haggitt 1965:247 ff. for a discussion of various methods for the identification of territories through quantitative analysis, including Thiessen polygons. Also Grigg 1968, 478 ff., discusses the concepts of "cores" and "boundaries".

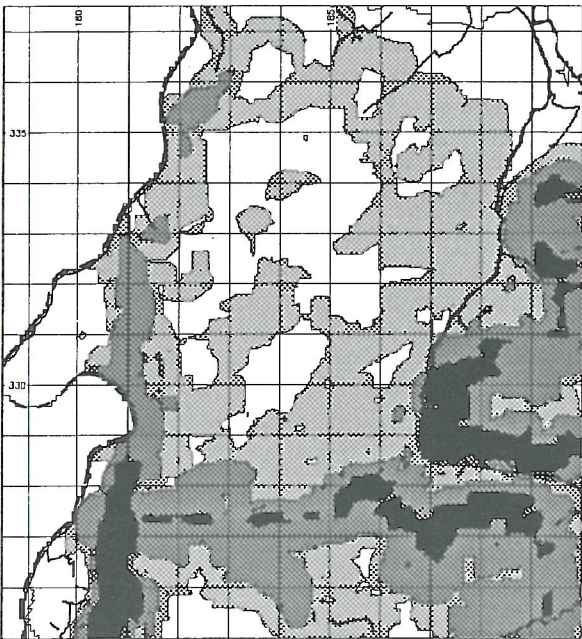
17 The value used should be multiplied by the map resolution to avoid problems with the interpretation of the resultant accumulated cost values.



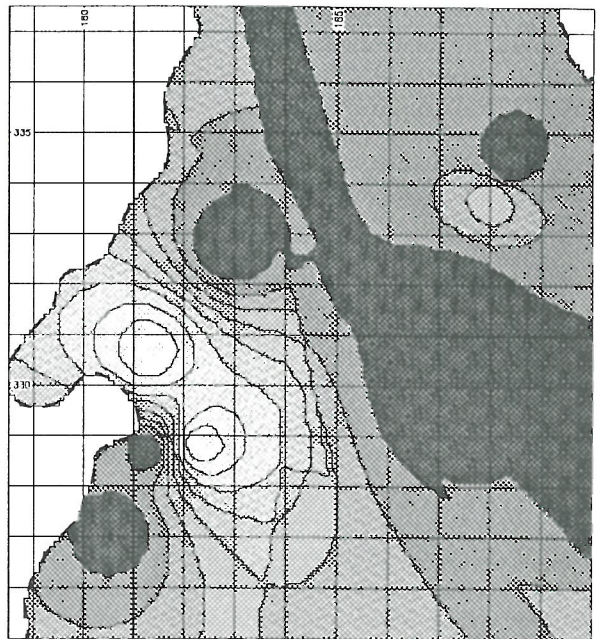
a



b



c



d

“flat” cost surface, the influence of this differentiation becomes immediately clear: the size and shape of the territories have been differentiated¹⁸.

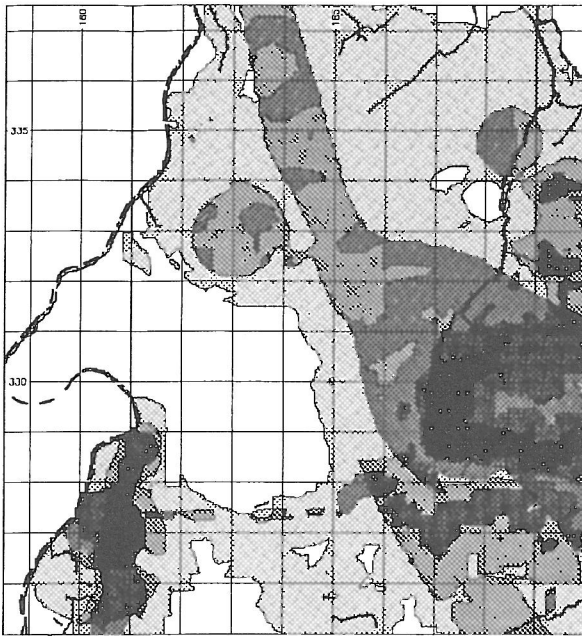
11.3.2.2 Site cost

The relative importance of the foci (determined independently through archaeological research) can be expressed as a weight. Iterative smoothing of a site-map in which sites have different weights produces a surface in which the sites are

the summits of hills of varying height and extent. Already we can regard this surface as an accumulated cost surface: the valley bottoms indicate the boundaries of site influence and the territory boundaries are where the slope of the surface is zero.

If we want to combine this type of “weighted site surface” with the cost surface discussed before, we must somehow make costs accumulate less quickly for the important sites, since this will make their territories larger. This goal is accomplished by dividing the terrain costs by the site costs, or:

¹⁸ The octagonal shape of the cost contours is an artefact of the accumulation algorithm used by GRASS.



e

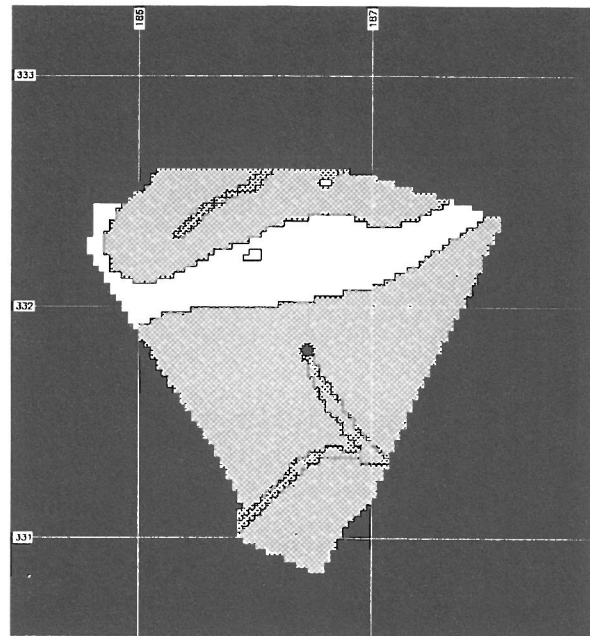
Figure 11.8: Preparation steps for a cumulative cost surface. With an undifferentiated or “flat” cost surface, the calculation of cumulative costs will have a result comparable to that of the vector-based Thiessen tessellation (a). Differentiating the costs affects the cumulative cost surface in ways that cannot be duplicated by the vector approach (b). Calculation of a cost surface proceeds on the basis of both terrain costs and site weight. The map representing terrain costs (c) is divided by the map representing weighed site costs (d) to yield a combined cost surface (e). Note that lower costs will lead to a slowdown in accumulation, hence to larger territories. The tessellation resulting from the extraction of ridges from an accumulated cost surface is used to divide other maps into territories. The characteristics of such a territory (f) may have an archaeological significance.

$S(\text{weighted costs}) = S(\text{costs})/S(\text{weighted sites})$. Higher site weight will then lead to lower weighted costs, and when accumulated weighted costs are calculated the territories of the more important sites will be larger than those of lesser sites.

11.3.2.3 Accumulation rules

The third factor that determines territory size and shape is the “physics” of the surface as expressed in the accumulation rule. Accumulation of cell values simply continues until it reaches the boundaries of the region, as if the foci had an inexhaustible supply of accumulation energy, and this leads to arbitrarily large territories for sites with an eccentric position. Clearly, this does not conform to reality; a more realistic accumulation rule must be applied.

The inverse square law implies that any influence emanating from a focus diminishes as the



f

inverse square of the distance travelled. Therefore the influence of the site weight on the cost surface diminishes with distance until it effectively reaches zero¹⁹. This can be called a “gravity” type of accumulation rule.

The accumulation rule can be changed to one calculating the natural logarithm of the accumulated costs²⁰. Further refinements might include introducing a cut-off point for the accumulation.

11.3.3 Results

Results consist of a continuous map layer containing accumulated costs, in the calculation of which terrain costs, site weights and accumulation rules have been used. Filtering for the ridges in this map will produce territory boundaries and, with a few extra steps, the territories themselves. Within the parameters set by the archaeologist the cost-surface method will result in a more realistic tessellation than is possible with vector-based methods.

For many applications these results will suffice. However, they do offer the possibility of further analysis. An obvious step would be to query the territories for their characteristics as expressed in other maps. Thus one might like to know what soil categories are present in each territory and in what amount, whether the foci each

¹⁹ At least this is so in GRASS, which allows only integers for cell values.

²⁰ Research on accumulation rules has been done by, among others, Haggett & Chorly (1968) and Hodder & Orton (1976).

have access to streams and other scarce resources, etcetera.

The cost surface offers still other possibilities. It can answer queries like: can the flint-bearing soil be reached from this site within the hour? or: What is the shortest path between two sites? This type of question is yet to be explored.

11.4 DEVELOPMENT: AN EXAMPLE OF NON-LOCAL ANALYSIS BASED ON LANDSCAPE VISIBILITY

11.4.1 Introduction

The cell map representing the terrain elevations (DTM) is one of the more important base maps. Many other characteristics of the terrain can be deduced from it, such as the slope, aspect and convexity. From an archaeological perspective the DTM represents the basic shape of the landscape in which people have always lived, farmed, hunted and gathered. The shape of the landscape together with geology and climate ultimately determine the geography of plant and animal life, humans included.

Although many tools exist in GIS that allow so-called *local* analysis, i.e. analysis of one cell or location in a number of map layers stacked vertically, the landscape should clearly be approached in a *non-local* manner. This has long been recognised by cartographers, in that they publish geomorphological and physiographic maps with legend entries which represent chunks of landscape somehow perceived by humans to be separate entities: hills, plateau's, etc. This type of subdivision of a landscape-map can also be achieved through the use of the concept of *neighbourhoods* in GIS (Tomlin 1990:25).

Turning to archaeological applications, a site or location can be analysed using non-local characteristics of its surroundings. The surroundings of a site can be defined by a combination of distance and direction (resulting in an immediate or extended neighbourhood) and/or cell values (resulting in the formation of a zone).

11.4.2 Paleo- and Mesolithic sites in the Mergelland Oost area

If the position of sites in the landscape is not random but is related somehow to the physiographic characteristics of the surroundings, we may expect sites with differing functions to occupy different positions in the landscape. If we can somehow use GIS to describe this position in a meaningful way, it may turn out that there are differences between groups of sites. These could

then be explained by assuming functional differences to exist — a hypothesis easily checked from the site inventory.

"Meaningful descriptions" might include simple locational characteristics of the type used in the LBK settlement model discussed earlier, but complex characteristics of the surrounding terrain are probably more influential.

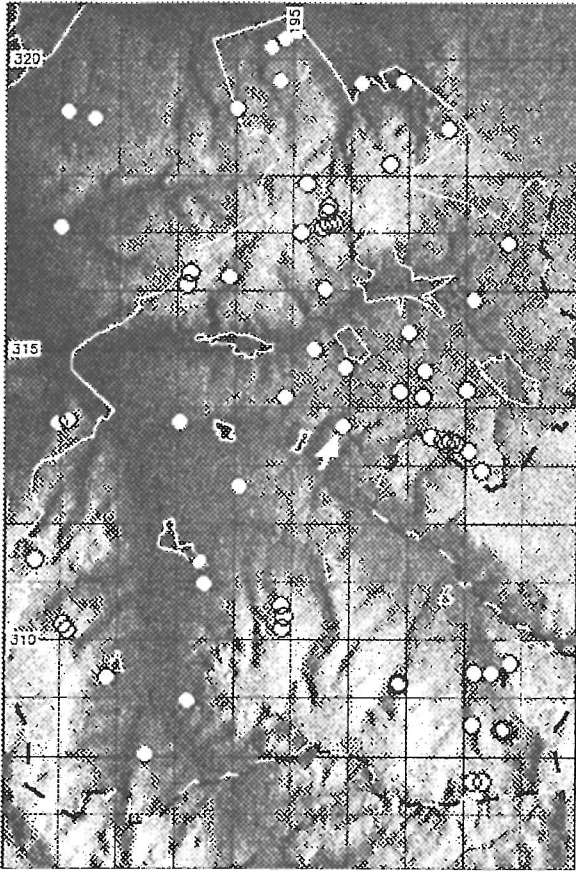
For this analysis I have chosen the Mergelland Oost (East Chalkland) area of Limburg, which is sharply divided into valleys and uplands and has recently been surveyed (Derks 1989). The group of sites to be examined are the 69 sites in the area that are dated, often tentatively, to the Paleo- and/or Mesolithic. Positional differences with respect to the landscape are expected to occur between base camps, extraction sites, and aggregation sites (Van den Broeke 1991:210). Differentiation will take place on the basis of the characteristics of the part of the landscape that is visible from the sites (see Figure 11.9).

11.4.3 The DTM and visibility

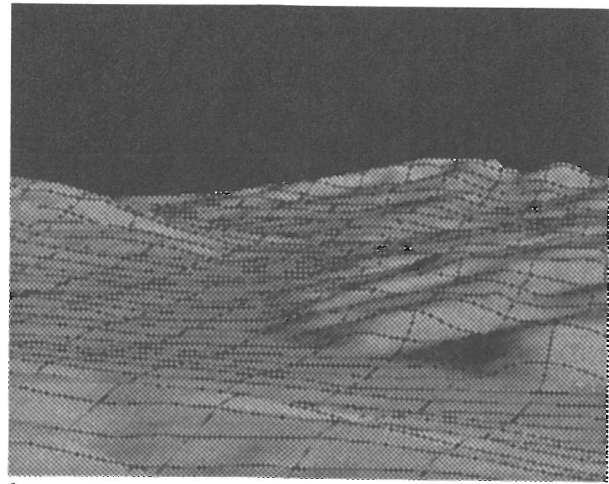
The DTM for this area is calculated by interpolation from elevation contour lines digitised from the topographic map. This means that the elevations are incorrect in three ways: the elevation contours themselves are interpolations of point measurements, they represent contemporary elevations, and the DTM is an interpolation of the contours. This point should be kept in mind, especially when elevation-derived characteristics of small areas are used in the analysis.

Physiographic units are derived from the DTM with various techniques, ranging from the determination of slope and aspect to the extraction of areas with a specific convexity index. Here the position of the sites with respect to the topography is determined by a visibility analysis. This is a procedure that determines which locations are visible from a certain point, given the height of that point above the surface, the maximum

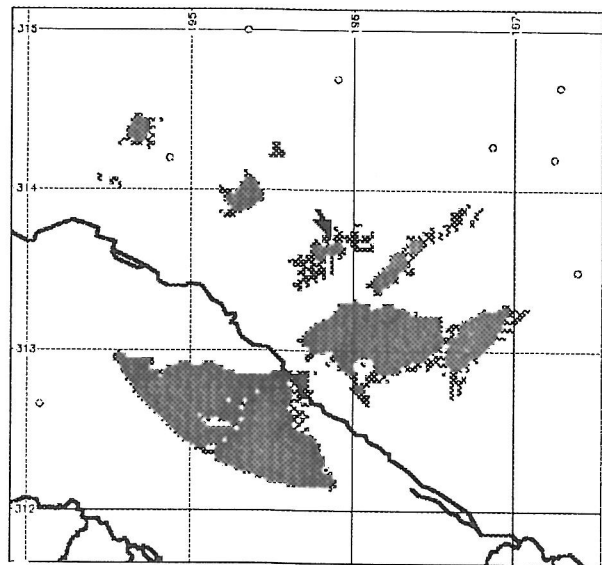
Figure 11.9: The input necessary to complete a line-of-sight analysis: a model of the landscape and list of sites, one of which (see arrows) is used as an example. The line-of-sight analysis proceeds on the basis of the DTM and the site locations (a). A meaningful division of the landscape can be obtained by using the categories of the geomorphologic base map. One of the functions of a site may be that of a lookout location (b). The area visible from each site is calculated (c), and the results are overlaid with whatever map layer is considered significant — here geomorphology (d). The results of the clustering step are depicted using black vs. white symbols for each of the main clusters (e).



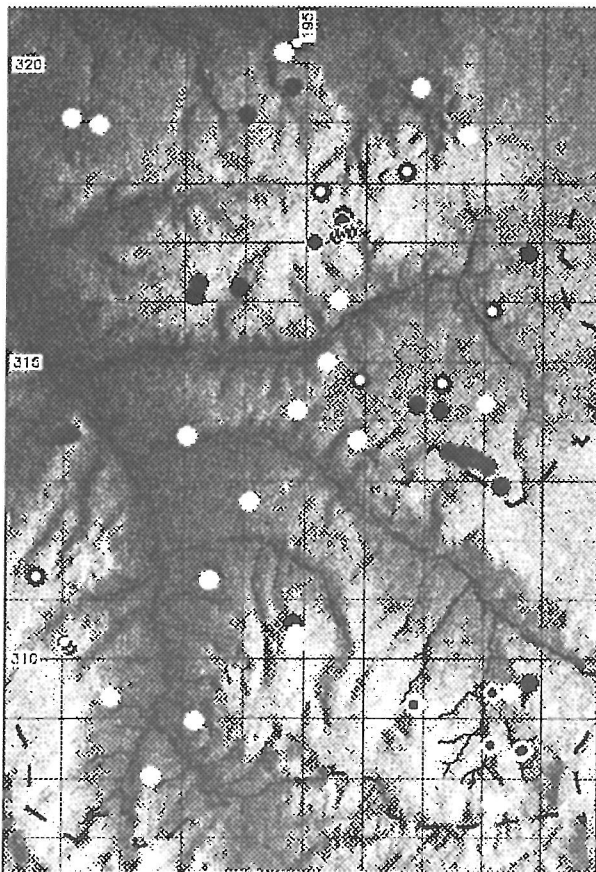
a



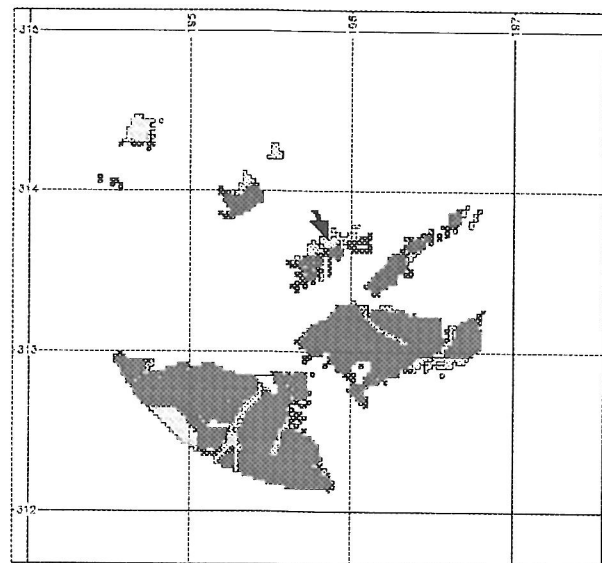
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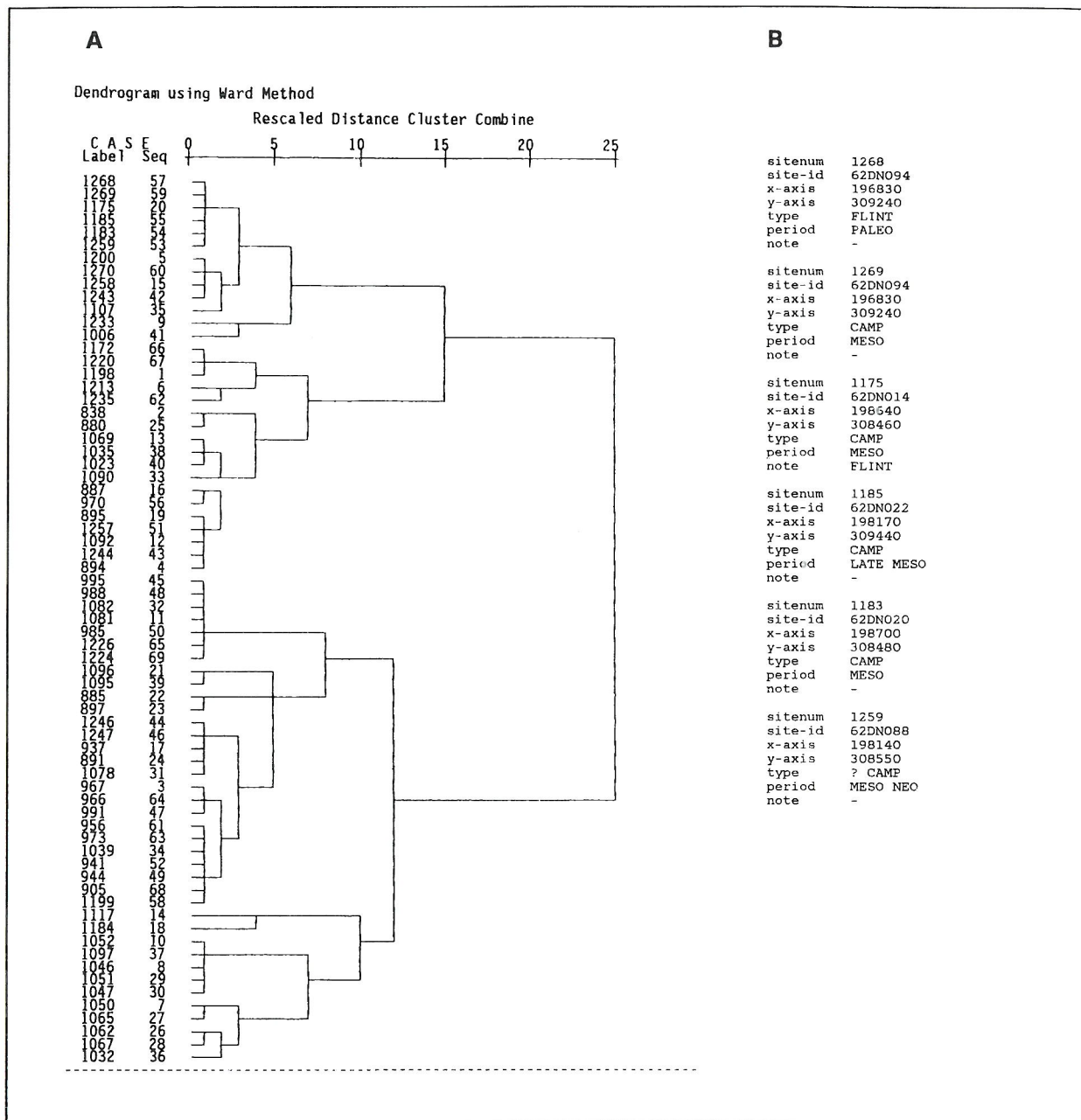


Figure 11.10: Results of the clustering step, performed on the geomorphological characteristics of each site's visible area (a). Some clear first-level clusters can be seen; the database 'signature' for the six sites in the uppermost cluster

(black-on-white symbols in Figure 11.9e) is shown (b). On the highest clustering level there is a clear separation between the two main clusters.

viewing distance and the presence or absence of obstructions in the field of view.

The resulting visible areas go through a filtering step to correct for errors in the elevation map, and are then used to query other (base or factor) maps.

11.4.4 Shell-scripting

The visibility analysis, filtering and querying steps described above have to be executed for

each of the 69 sites selected and take quite some time; processing all the sites separately would be a boring and error-prone exercise. Programming the steps of the analysis by making use of the capabilities of the operating system will generally take little time and save lots of trouble. Ease of use is heightened by having the shell script prompt the user for the required input.

The one-page script I have written for this analysis consists of the following steps:

- 1: Prompt for all necessary in- and output
- 2: Open the site list (prepared beforehand) and execute for each site the following steps:
 - 3: Do visibility analysis on elevation map
 - 4: Reclassify and filter the resulting visible area
 - 5: Overlay the filtered area with each of a list of maps, executing the following steps:
 - 6: Query for the area occupied by each category value within the visible area
 - 7: Send results to file
 - 8: end
- 9: end
- 10: end

The results of this analysis consist of a database for each map queried; the categories of this map are the fields of the database, the sites are the records. The values entered in the database are in the units prompted for by the script, in this case the number of cells in the visible area.

This database is used as the input for a clustering program (SPSS) in order to distinguish groups of sites (Figure 11.10). If such groups exist they are characterised by their "signature", expressed as group boundaries or a group mean. This signature can be used in two ways: first, it can be used to define functional differences between groups of sites, and second, it can be used to search for other locations with the same signature and therefore — presumably — the same functional aspects.

11.4.5 Interpreting results

The results of this analysis show, firstly, that analyses based on non-local characteristics of sites are now feasible and, secondly, that it is fairly easy to create output that can be read by software for statistical analysis.

Since non-local analysis has not been possible before the advent of GIS, the field is wide open to the creation of new applications.

The type of locational modelling exemplified by Bakels can now be extended with a wholly new range of non-local factors, enabling archaeologists to devise increasingly realistic models.

11.5 CONCLUSIONS

11.5.1 Results

As a consequence of the methodological aims of my research, there are no purely archaeological

results to be reported. This does not mean, however, that there are no results directly applicable to archaeology. I would summarise these direct results as leading, firstly, to proper *preparations* for a project involving GIS, secondly, to a realisation that the speed and flexibility of GIS result in a "quantum leap" forward for any but the simplest of cartographic modelling attempts, and thirdly, to the development of a library of tools open to contributions from all sides.

The analysis of the three examples of archaeological modelling described above has yielded insight into the kinds of input that will be required of an archaeologist using GIS. Most important of these are, in my view, the value judgements required for cartographic allocation and for the weighing of maps and map categories. Ultimately it is the judgement of the archaeologist about the characteristics within each factor map *and* about the relations between the factor maps that determines the outcome of the model²¹.

The speed with which models can be built and tested once the data acquisition, entry, and validation phases are over can only be fully appreciated by an archaeologist working under real-life pressures of time and money. GIS in archaeology have until now been restricted to more or less exploratory uses, and advantages like these will only become apparent with their acceptance as a research tool.

Reviewing both the nascent literature of GIS-studies in archaeology (see References) and the results of my research, it seems clear that GIS are already starting to contribute some analytical and cartographic added value to regional archaeological studies, although these are still mainly used as an aid to field surveys. It is to be hoped that continued research into the theory and practice of applying GIS-techniques to archaeological cartography will lead to a deeper understanding of the conceptual problems involved in archaeological prediction, and to an increased use by archaeologists both of customised procedures and "raw" GIS-capabilities.

11.5.2 Bottlenecks

Although it was only briefly mentioned in the introduction, the first obstacle encountered by the archaeologist using GIS will be the acquisition

21 An example of such a judgement influencing the decision rule would be the addition of some kind of threshold value or cut-off point for LBK site allocation, expressing the judgement that the low end of the range of suitability values should not represent a small chance of LBK settlement, but its absence.

and quality of the base maps. A large part of our efforts goes into the digitising, converting or otherwise acquiring of digital maps, which have to be checked for topological consistency and which bring their own set of problems with them (e.g. incompatible legends).

"Quick and easy" methods for the acquisition of large amounts of map data are beginning to become available just now: the use of high resolution colour scanners, software for the extraction of map features and image enhancing techniques, and CD-ROM will put an end to this particular bottleneck.

While we are waiting for the age of centralised automated archaeological databases to get going, the acquisition of the archaeological data may not be easy either. Checking on the quality of the site records is still a laborious process. Happily, it is partly taken out of the hands of Dutch archaeologists by the "ARCHIS" (ARCHaeological Information System) project which is automating the central archaeological archives, a project due to finish in 1995²². This should at least assure us of trustworthy data for future regional analysis.

A second bottleneck lies in the lack of (inter-) nationally recognised standards for the weighing of map layers and categories. The archaeologist may simply use the traditional legends or develop a new legend for his own purposes. For example, the geomorphological map provides a ready-made and standardised relief legend. Alternatively, we can use our own method to calculate the local relief from the DTM and classify the values in this continuous map layer into our own legend. Computerised "expert systems" attempt to embody this kind (i.e. classification rules) of institutional knowledge and analysis approach.

The GIS itself will sometimes impose restrictions on the quality and quantity of data. In GRASS, the main problem is posed by the requirement that cell values must always be integers. This necessitates the interposition of procedures to prevent loss of information through rounding of decimal values.

11.5.3 The future of GIS

GIS-education has been around for more than 10 years now in a number of archaeology departments around the world. The diminishing prices for hardware and the increasing use of networking facilities and the public domain will dramatically increase that number in the near future. In our view GIS will join word processing, database

management and statistical software as one of the tools used by archaeologists. We may expect the user to decide for him/herself how the GIS-capabilities are applied to the archaeological problem at hand. In fact, we cannot possibly anticipate every possible use of GIS in archaeology.

Our efforts should therefore be directed toward the elimination of problems relating to the acquisition of data, the exploration of new analytical tools and, in particular, toward the education of a generation of self-sufficient GIS-users.

The field of data acquisition has clearly been on the move these past years, with techniques used for decades in remote sensing percolating through to the archaeologist end-user level. The costs of quality colour scanners and hardware for the storage and processing of very large amounts of data are dropping fast and are starting to come within reach of insolvent archaeology departments. We should speed up this development by acquainting ourselves with these new data acquisition techniques.

A particularly urgent task lies ahead in the exploration of methods of dealing with the absence, incompleteness, or uncertainty of archaeologically relevant data. Simulation techniques and probabilistic reasoning ("fuzzy logic") may be two of many possibilities in this area.

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22 This is a development taking place in many European countries. See Larsen 1992.

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