Extracting "Natural Pathways" from a Digital Elevation Model

Applications to Landscape Archaeological Studies.

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Abstract: The relationship between the distribution of archaeological sites and "natural pathways" through the landscape forms the first stage of a research programme into the relationships between prehistoric "ritual" sites in the UK and their landscape environment.

A technique has been devised to extract "natural" pathways, from a landscape Digital Elevation Model. The method is derived from GIS based hydrological modelling techniques and identifies potential multi-scale pathways across a landscape.

The "natural pathways" modelling process has been used on several areas in the UK to test the validity of the approach. Initial tests have produced promising results and indicates the usefulness and validity of the methodology. Further analysis on an area around the prehistoric site of Stonehenge hint at several possible relationships between burial monuments and "natural pathways" in the landscape.

Key words: Natural Pathways, Digital Elevation Models, Cost Surfaces, Prehistoric routes, Ritual sites.

Introduction

Overall, archaeological landscape studies have focussed on the potential relationships between sites and their landscape environment on a site by site basis, or by small-scale regional studies. While these studies may enhance the interpretation of these sites and perhaps regional patterns, they do not provide a higher level view of site characteristics. For our research, newly available data sources were to be used to facilitate a landscape analysis at the macro level. Specifically, the investigation aims to look at generalised patterns for the whole of the UK.

Initial researches into the patterns of site location focussed on relatively simple, 2-dimensional distribution analyses. These early studies generally treated the landscape as a flat plane. Recently, Digital Elevation Models (DEM) have facilitated 3-dimensional analyses. The most commonly analytically studied aspects of the landscape and sites have been intervisibility and viewshed type analyses. These techniques aim to provide an insight into site distribution and form, but may fail to take account of other, formalised aspects of the landscape, such as pathways.

It has been stated that settlements are often located at natural crossroads or thoroughfares, suggesting that before intensive road building schemes took place, sites were situated close to natural pathways through the landscape.

The formation of tracks and pathways, at any period, on a landscape, is an inevitable result of human and animal movements over time. These paths may permeate the landscape for long periods, waxing and waning in their use and significance. These pathways also provide a human structure to the landscape and allow a direct connection to the landscape and its elements. Their existence and nature should be an important element in archaeological interpretation. As Ingold (1993) states, "In short, the landscape is the world as it is known to those who dwell therein, who inhabit its places and journey along the paths connecting them".

Potential relationships between prehistoric sites and pathways have been mentioned by many authors, however the locations of these pathways are often subjectively defined. In (Llobera, 1996; ParceroOubina et al. 1998) the authors suggest that rock art and megalithic barrow sites in Iberia, are related to probable pathways. (BRADLEY et al. 1994) have looked at the relationship between potential pathways and rock art sites, however the notion of "paths" is again, subjective. Bodmin Moor and its cairns, are suggested by (Tilley, 1996), to be accessed by pathways along the main river courses and their tributaries.

(Loveday, 1998) calculated a correlation, greater than 54%, between the alignments of Roman roads and nearby double entrance henges. The author comments on the possible reasons for this correlation, which in some cases may relate to the natural topography, indicating probable pathways through the henge openings. In this scenario, the Roman roads simply follow the same terrain, as might a modern pathway. Although the alignments also occur in relatively flat terrain, which is difficult to interpret, the data set is sufficient to hint at a potential relationship between the alignments of the road and double entrance henges.

The locations of road networks are generally understood during the Roman period. Whilst a recent study[1] on the Ridgeway path in England postulates a prehistoric date for that pathway, many studies of prehistoric pathways suffer from a dearth of independent evidence. Furthermore, their dating is often concluded from the prevalence of nearby prehistoric sites.

In order to ascertain any correlation between sites and "natural pathways", a formal methodology to extract potential "natural pathways" independently from site location had to be developed.

At the scale of the analysis, discussed later, the natural topography of the UK is assumed not to have significantly changed since the prehistoric period. Therefore a modern landscape Digital Elevation Model forms the basic data set for deriving these "natural pathways".

The "natural pathways" are defined by the natural constraints of traversal across a landscape, and in general, will be routes of minimum constraint. It is important to note that the concept of natural pathways does not explicitly imply their human use as a path, but only their potential to be used as such.

Review of Path Finding Techniques

Almost all studies on the extraction of paths from a landscape relate to finding optimal least cost paths between known points across a landscape. These techniques do not possess the non-a-priori knowledge characteristics to extract natural pathways.

In (Kweon In So and Kanade Takeo, 1994) the author described a methodology using contour trees, to extract topographical features such as ridges, peaks, valleys from a contoured DEM. However, in order to extract natural pathways using this technique, we would still need to define pathways in terms of particular topographical structures. This may be relatively easy for a mountain pass, but rather more complex for a pathway that may comprise of several topographical elements such as rivers, rolling hills, and ridges.

A variety of image analysis algorithms, such as skeletization, aim to extract structure from images. These could be applied to DEMs to extract valleys and ridges, but these suffer from similar limitations to topographical feature extraction.

By far the majority of formal methods in landscape studies using GIS, have been applied to hydrology and geology. It was while studying the online documentation within Arcview GIS, relating to hydrological modelling, that a natural pathway finding methodology began to be formulated.

Description of "Natural Pathway" Algorithm

The path finding process comprises several distinct stages and is an attempt to form a drainage network of a constraint or cost surface. The complete process is illustrated by a flow diagram (figure 1). The procedure and algorithms are identical to the extraction of surface runoff characteristics used in hydrological modelling. The essential difference is the nature of the input data. Whilst hydrological analysis uses a raw DEM to produce a stream model, the extraction of "natural pathways" uses a constraint surface model as input. All of the analytical stages are cell based, as the terrain models used in this research are grid-based.

Further information on the separate stages can be found in Arcview 3.2 GIS (spatial analyst & hydrological analysis v1 extensions). These discuss a notion of flow as they relate to hydrology. This nomenclature is used here but it is useful to think of flow, in relation to "natural pathways", as equivalent to potential movements of people.

The Generation of a Constraint or Cost Surface Grid

The input to the path network algorithm is a cost grid defining the relative frictions of human traversal through each grid cell that depends on the type of landscape component in that cell.

The desired constraint surface may comprise a number of landscape and/or perceptive elements such as;

- Rivers
  - Navigable rivers
  - Rocky mountain streams
- Lakes
- Open land (default factor)
- Dense woodland
- Boggy land
- Sea
- Visual quality from a point.

The quality of the constraint surface model depends on the weighting, attributed to each of these landscape features. The model could be tailored to suit certain modes of mobility. For example, if we assume the availability of boats and ferries for river movement then this may be built into the model. A sedentary farming society may impose different constraints on the landscape which may include territorial boundaries that confine movement. The constraint surface could also be generalised to use subjective attributes such as sacred spaces, forbidden areas or landscape attractors.

The generation of a good constraint surface is the most important step in the process. The subsequent stages of the algorithm are deterministic. It should be noted that the technique relies on the relative costs between areas and so absolute measures of cost are not needed.

The cost model used in the analyses presented in this paper, uses relative terrain values, or weightings given to each landscape attribute. The effort based cost equation as outlined in (Pandolf K B et al. 1977) is not needed, however the relation of cost to slope is still deemed valid for most types of terrain. Some work by Bell, T & Wilson A (submitted for pub[2]) suggests that the tangent of the slope is a more accurate measure of traversal cost, than slope. However, the natural pathway extraction process utilises relative costs and so the form of the cost function is not crucial. This allows us to derive a simple equation. As the analysis uses a grid based DEM, the equation is described using grid nomenclature.

The grid based cost equation used to generate the cost surfaces used in the subsequent analyses, is shown below.

$$[C] = \left(\sum_t ([G]N_t[t]+ N_t[t])\right) + \left((1-\Sigma[t])N_l(G+1)\right)$$

Where:

- $[C]$ is a grid of relative cost values.
- $[t]$ is a binary grid. Value 1 depicting areas of terrain t.
- N_t is a terrain value for terrain t.
- N_l is the default terrain value for open land based on the DEM model.
- $[G]$ is slope for each cell in the [DEM].
- $\Sigma[t]$ is the sum of all the terrain binary grids.

This particular equation is linear for each terrain factor with a gradient of G. The relative values of N_t and N_l, are important, not their absolute values. If no other constraints are used, the equation reduces to: $[C]=GN_l+N_l$

It should be noted that further work may be needed to develop better constraint models perhaps incorporating perceptive landscape attributessuch as topographic prominence (Llobera M, 2001).

The Depressionless Cost Surface Grid

This is an iterative process and involves the filling of data sinks. A sink is a cell or set of spatially connected cells whose flow direction cannot be assigned one of the eight valid values in a flow direction grid (see below). This can occur when all neighbouring cells are higher than the processing cell, or when two cells flow into each other creating a two-cell loop. As the cell size of the data increases, the number of sinks in a data set often also increases.

To create an accurate representation of flow direction and therefore accumulated flow, it is best to use a data set that is free of sinks. This ensures that sinks created by sampling errors are filled, and paths do not drain into artificial sinks. Naturally occurring cost sinks may also occur. For example, a steep circular conical hill with a flat top would be a morphological sink which if filled would result in a circular pathway at its bottom but none on its top, which could be a valid pathway. Sinks are filled to the lowest cost "pour point".

The Path Direction Grid

One of the keys to deriving the path network is the ability to determine the direction of flow from every cell in the grid. This is calculated using a flow direction algorithm (Jenson S K and J O Domingue, 1988) which outputs a grid showing the direction of flow out of each cell. The direction of flow is determined by finding the direction of best gain, that is, to the lowest cost value. If the gradient is the same to all the cells then the neighbourhood is enlarged until the steepest gradient is found. If a cell has the same change in cost value in multiple directions and is not part of a sink, the flow direction is assigned with a lookup table defining the most likely direction (Greenlee D D, 1987). The behaviour of the flow direction algorithm, at the edges of the analysis area may be chosen. Cells at the analysis boundary may de deemed to flow inwards rather than to possibly undefined cells outside the area. (See Arcview Help discussion).

This flow direction function is also used as part of the process to create the depressionless surface.

The Path Accumulation Grid

This stage creates a grid of accumulated flow each cell, by accumulating the flow from upstream cells using the method described in (Jenson S K and J O Domingue, 1988). This is determined from the flow direction. Output cells with a higher flow accumulation represent areas of the landscape that have a higher probability of being potential pathways.

The Path Network

The results of flow accumulation are used to create a path network by applying a threshold value to the path accumulation grid.

The resulting, dendritic path networks can be further processed by ordering, identical to stream ordering, using any of the published algorithms (Shreve R L, 1966; Strahler A N, 2001).

Initial Test Results

Initial tests were applied to a series of synthetic cost surfaces to test the behaviour of the technique. These clearly showed the validity of the methodology and its limitations.

In order to provide a real test of the "natural pathway" extraction process, a digital terrain model of an area of approximately 430km^2, including sections of the Chiltern Hills, was analysed. The DEM was extracted from the UK Land-Form PANORAMA data set, and consists of height values at each intersection of a 50m horizontal grid, the values have been mathematically interpolated from the contours on 1:50000 maps. DEM height accuracy is no greater than one half of the vertical interval of the source contour data, (10m). The water features were extracted from the UK STRATEGI dataset, these are at a scale of 1:250000.

The area is also crossed by a long distance footpath, the Ridgeway.

The results of the tests are illustrated in figs 2-3.

Fig. 2 is a coloured representation of a DEM for an area that covers part of the Ridgeway long distance footpath. The graticule shows the National Grid Co-ordinates. The modern route is highlighted in black. The path network, in yellow, was created from thresholding the path accumulation grid to 1000 cells. A terrain value of 10 and 1 was used for water and land respectively.

A purely visual inspection shows that the approach is reasonable. It can be seen that paths in hilly terrain generally follow ridges. It can also be seen that the methodology produces many potential path networks in relatively flat plains. This is to be expected in the absence of any constraining terrain. It is probable that in prehistory, swathes of dense woodland or wetlands existed in these flat plains near to rivers. These terrain types would be areas of high cost. An estimation of the extent and nature of woodland and any other constraints would therefore be important in order to gain a better understanding of natural pathways in otherwise flat unconstrained areas.

The very high cost attributed to water produces paths that avoid crossing rivers. This model is therefore too simplistic as some of the rivers are slow moving lower sections, (usually navigable), but serves to test the behaviour of the technique and cost surface equation.

No account of other terrain costs has been taken. The modern Ridgeway path will also follow routes of low cost and deviate from areas of high cost, which became high in modern times, such as defined rights of way, agricultural land. The modern paths cross modern river bridges, which are low cost, artificial elements of the landscape.

Fig. 3 shows the same area as fig. 2, but in this case, a terrain value of zero for water was used to produce pathways that ignore the river constraints. Note that this produces different results for paths in the relatively flat areas, as these have numerous rivers. These paths frequently cross the rivers as expected.

Discussion on Methodology

There are several factors limiting the accuracy of the paths, created by using the "natural pathway" derivation technique.

The resolution of the DEM and the accuracy of the elevation data are a major limiting factor. Coarse cells can provide only average height data, and so may hide small areas of high cost which would affect path location. This will effect the minor paths in a network more than the high thresholded segments. The effect of cell size is lessened in areas of gentle topography.

The path finding method is very sensitive to the input constraints. The accuracy of the path networks depends on a realistic model of terrain costs. This cost model could be subjective, and limited by a lack of appropriate data. As mentioned previously, in the absence of other constraints, the method is robust to the slope function used for cost.

In areas of land with visible topography, the technique will locate natural pathways as defined by the absence of any other unknown constraints. However, in flat terrain other constraints would be needed in order to provide more meaningful pathways.

The river features need to be converted to a grid with a cell size equal to the DEM cell size. The PANORAMA data used in the previous analysis has a cell size of 50m, producing, in many UK cases, an unrealistically large river. If 2 river grid cells, join at the corners, the river grid may be incorrectly crossed by pathways across the data gap. This is an unavoidable consequence of grid based schemes, which can be improved by artificially thickening the rivers. This limitation should only affect the accuracy close to rivers.

The path direction grid has only eight possible values, which is simplistic, although the digital grid based nature of the DEM defines this limitation. A possible approach to improve this is by incorporating the parsimonious techniques described in (Douglas David, 1994) as a refinement to the flow direction algorithm.

The technique does not attempt to connect natural pathways together. The located paths will generally avoid high cost areas. A long distance path may comprise segments of natural pathways combined by the crossing of relatively small, high cost areas.

The accuracy of paths close to the edges of the area being analysed depends on typical boundary effects. For the tests described in this paper, the analysis area was a subset of a larger DEM. For DEMs that include sections of coastline, the sea needs to be correctly cost modelled, or the coastline must be defined as a boundary, otherwise the sea may act as a pathway drain.

The cost grid is currently isotropic and this characteristic may need further investigation.

Natural Pathways around Stonehenge: An Initial investigation into their Relationship to Prehistoric Ritual Sites

With due consideration to the limitations of the natural pathway extraction technique, an attempt was made to investigate potential patterns and relationships between the natural pathways around Stonehenge, and the surrounding ritual monuments.

An area of approximately 30km^2 around the site of Stonehenge was analysed using the path finding method. The DEM used was the Land-Form PANORAMA data from the Ordnance Survey, as described previously. This was the only constraint data utilised in this analysis due to the lack of appropriate resolution river data. The available river data set at 1:250,000, had evident misregistration with the DEM data. It was considered reasonable to leave out the river constraints in this area as there are virtually no minor rivers around Stonehenge. Instead, the larger area is notable by the presence of a few navigable rivers including the Avon.

An archaeological site database, provided by English Heritage, was used to investigate potential relationships. The archaeological data included information on; Long Barrows, Round Barrows, Henges, Causewayed Enclosures and Ring Ditches. Basic data on the cursus monuments and the Stonehenge Palisade was also included.

The results of the analysis are shown in figs 4 and 5.

Fig. 4 shows a coloured representation of a DEM for an area centred on Stonehenge. The path network denoted by a thick yellow line, was created from thresholding the path accumulation grid to 1000 cells. This is overlaid by a thin yellow line, which is the result of thresholding the path grid to 100 cells. A terrain value of one was used for land.

As discussed previously, It is possible that in prehistory, swathes of dense woodland existed in the valleys.

Fig. 4 shows a small section of the analysis area centred on Stonehenge. The path network, denoted by a thick yellow line, was created from thresholding the path accumulation grid to 1000 cells. This is overlaid by two other yellow lines, which are the result of thresholding the path grid to 100 and 20 cells.

Discussion of Results

Some possible relationships between the prehistoric ritual sites and the natural pathways can be speculated from a purely visual analysis of the images. One of these is the possible correlation of round barrows near the paths. To test if this potential relationship was non-random, a Kolmogorov-Smirnov analysis was performed.

For the 874 round barrows in the analysis area, the difference between the cumulative area distribution and the cumulative site frequencies at several distances from the pathways was calculated. The results are shown in Table 1. The figures are based upon pathways which have a been thresholded at 20 cells.

The difference between the two distributions was found to be significant at below the 5% level. Although this result provides evidence of some relationship, it does not provide causal information. In addition the test does not allow for any information on the structural distribution of the round barrows. For example, from a purely visual analysis, some of the round barrow clusters seem to be congregated at pathway cul-de-sacs.

It could be conjectured that many of the long barrows seem to have a similar alignment to major paths. However it has been suggested that many long barrows are aligned along ridges and so this may be the cause of the visual pattern. Since slope was the only constraint used for this analysis, the natural pathway technique will locate ridges and valleys.

An initial look at the results might suggest that the henge monuments seem to be closer to the major pathways. A major pathway heads off to the Northwest from the Stonehenge area in the direction of Robin Hoods Ball, another major prehistoric site. At Stonehenge, a spur off the major pathway to the Northwest, seems to lead to Stonehenge going through the palisade. It is known that a gap exists in the palisade structure, perhaps a gateway for the pathway?

The Stonehenge Avenue, interestingly has only a vague relationship to the paths, but its changes of direction are echoed in the major path some 300m to the North.

It is interesting to note that a small path starts at Durrington Walls, leaving near the known SE entrance, and goes to Woodhenge and just beyond, joining the round barrows nearby. Some of these initial observations will form the basis of a further, in depth study, of the Stonehenge area. Further analyses will utilise the temporal dimension to investigate the existence and nature of any chronological patterns.

Future Work

As mentioned previously, one of the main limitations to the accuracy of the path network is the quality of the constraint model. Therefore, more research will be directed to improve the model with the addition of other landscape and perceptive components. These are to include;-

- Dense woodland
- River flow direction
- River type (navigable-low cost) mountain river (high cost)
- Wetlands or Bogs.
- Sea
- Visual quality: low cost attributed to cells with rich visual affordances.

The path accumulation stage can also be combined with a weighting grid. Knowledge of settlement sites could be used to produce a weighting grid to enhance the path network, although this information is scant for prehistoric Britain.

The relationship between threshold level and Kolmogorov-Smirnov test results will be investigated in more detail.

The pathway approach will be attempted with a much larger DEM of the whole UK. Potential relationships between these pathways and an archaeological database of over 20000 ritual Neolithic and Bronze age sites, will be explored.

Conclusions

From the outset, it has been our intention to be able to study the potential correlation between natural pathways through a landscape, and prehistoric ritual sites in the UK. This led to a need to develop a technique to find such pathways, independently of site location. A method to extract "natural pathways" was formulated. The nature of the techniques, based on terrain cost, produces a network of potential natural pathways. These path networks do not exclude the possibility of other, perhaps minor paths, existing between path networks or across short stretches of high cost terrain. The higher order pathways are probably more reliable as indicators of major potential thoroughfares.

The results of the initial applications suggest that research into the relationships between archaeological sites and "natural pathways" is worth developing further.

The natural pathways process, provides archaeologists with a useful tool to investigate the landscape, that may improve the interpretation of site or artifact distributions. It may also allow archaeologists to provide structural meaning to inter-site landscape studies.

Furthermore, the approach is generic and could be used for exploring any constraint surface model.

Acknowledgements

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End notes

[1]Bell, T. and Lock, G. Information discussed by private communications with the author.
[2]Bell, T. and Wilson, A (submitted for pub) "Tracking the Samnites: landscape and communications routes in the Sangro Valley, Italy". Extract received by private communication from Bell, T.
[3]A recent paper by Marcos Llobera in "Beyond the Map, 2000" edited by Lock, G explained to the author by Lock, G by private communication at CAA2001.

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Tables

distance range to pathway (m)	cumulative area of land (m2)	area (percentage of total)	cumulative number of round barrows	round barrows (percentage of total)	difference between cumulative distributions
0-50	358369984	0.416974	354	0.405034	-0.01194
50-100	526497488	0.612595	579	0.662471	0.049877
100-150	699492496	0.813879	745	0.852403	0.038524
150-200	792272496	0.921831	828	0.947368	0.025537
Total	859455000		874		

D_{max} is Greatest cumulative difference = 0.049877

Critical value for 5% level is $1.36/\sqrt{874}$ = 0.046003

Critical value for 1% level is $1.63/\sqrt{874}$ = 0.055136

Table 1.

Figures

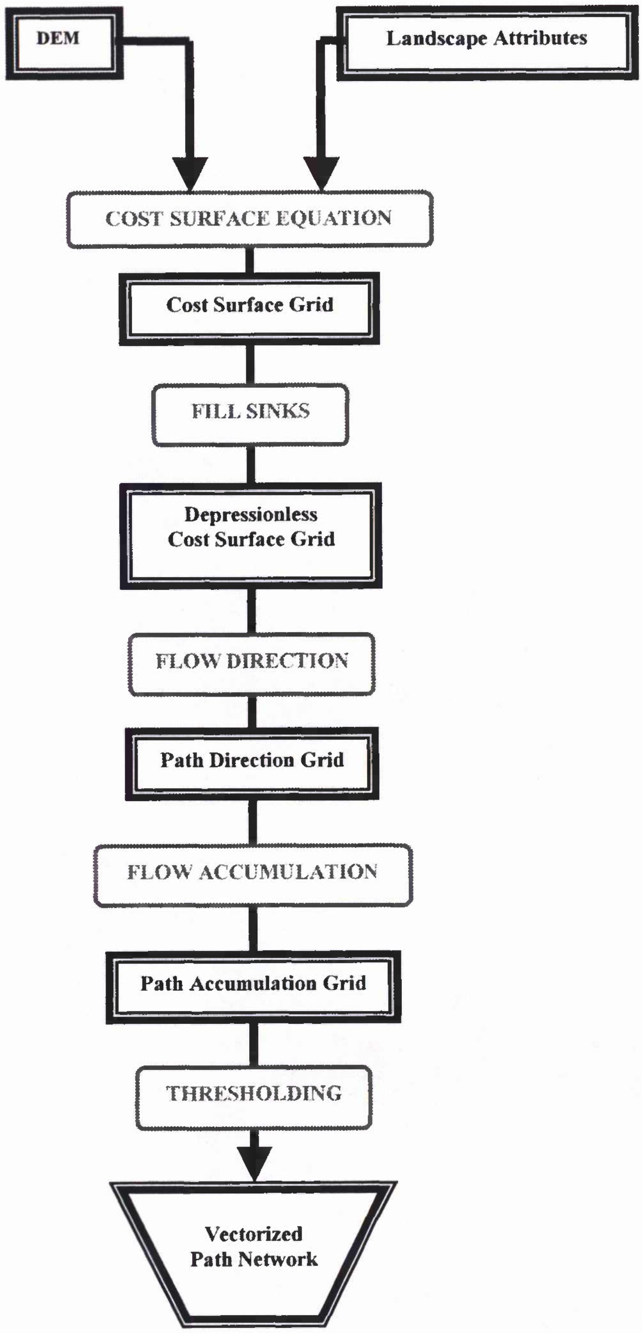

Figure 1. flow diagram of the "natural pathway" process

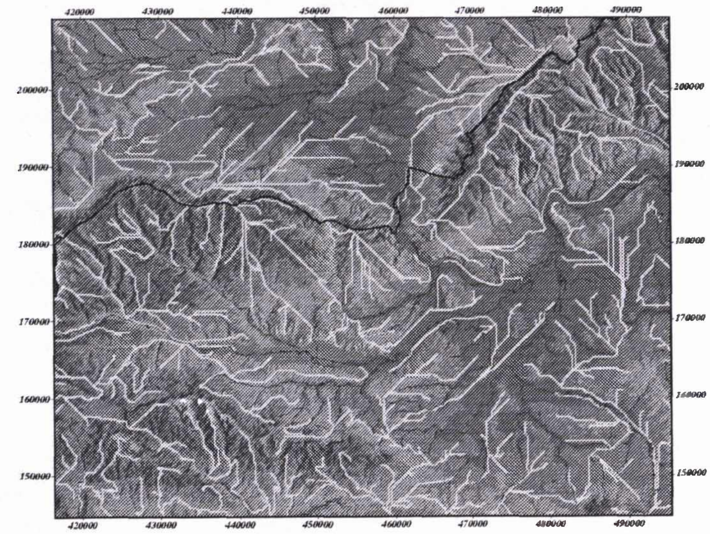

Figure 2: Natural Pathways in the Ridgeway area with river constraints

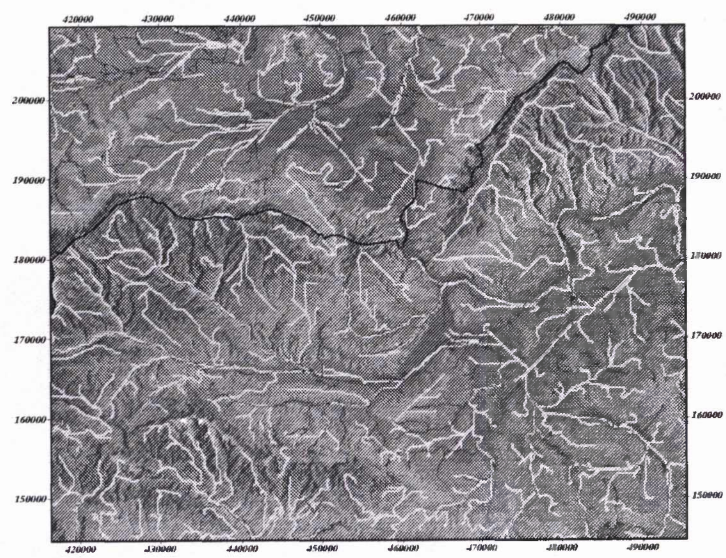

Figure 3: Natural Pathways in Rideway area, ignoring water constraints

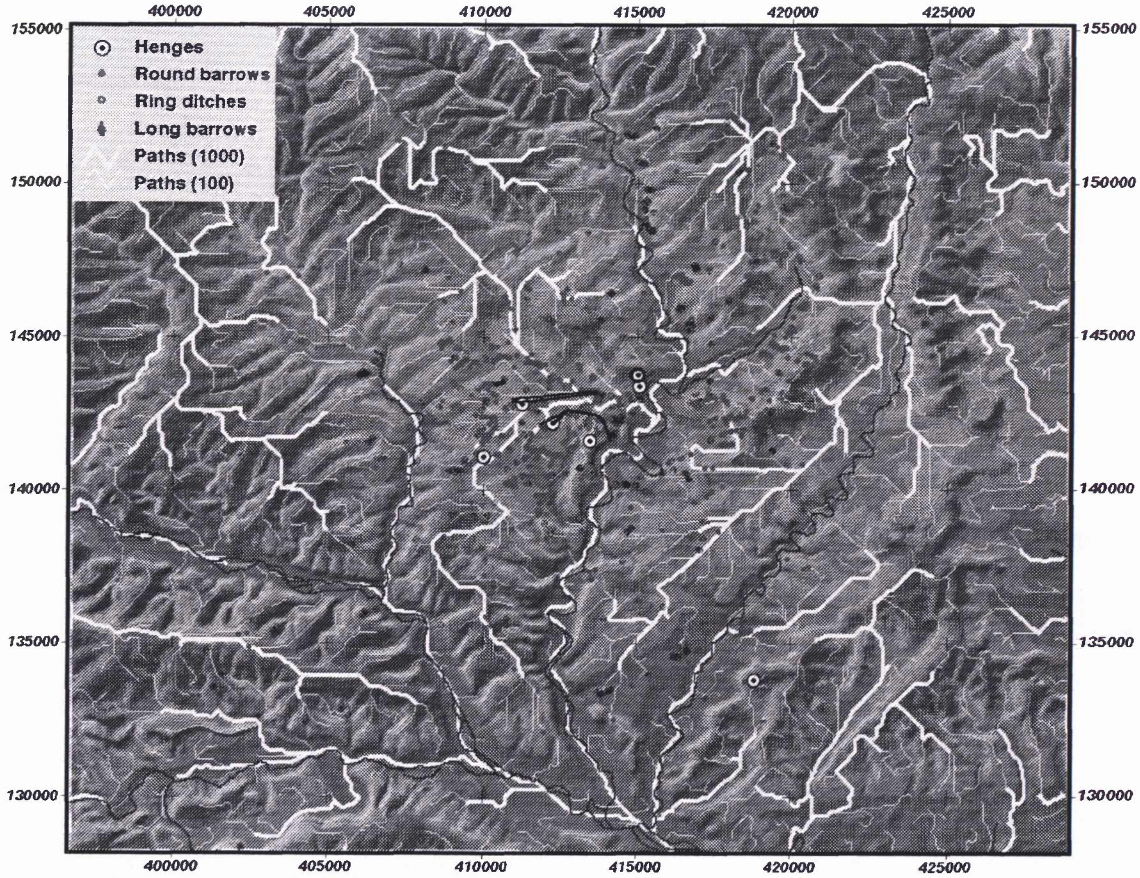

Figure 4: Natural Pathways in the larger Stonehenge area

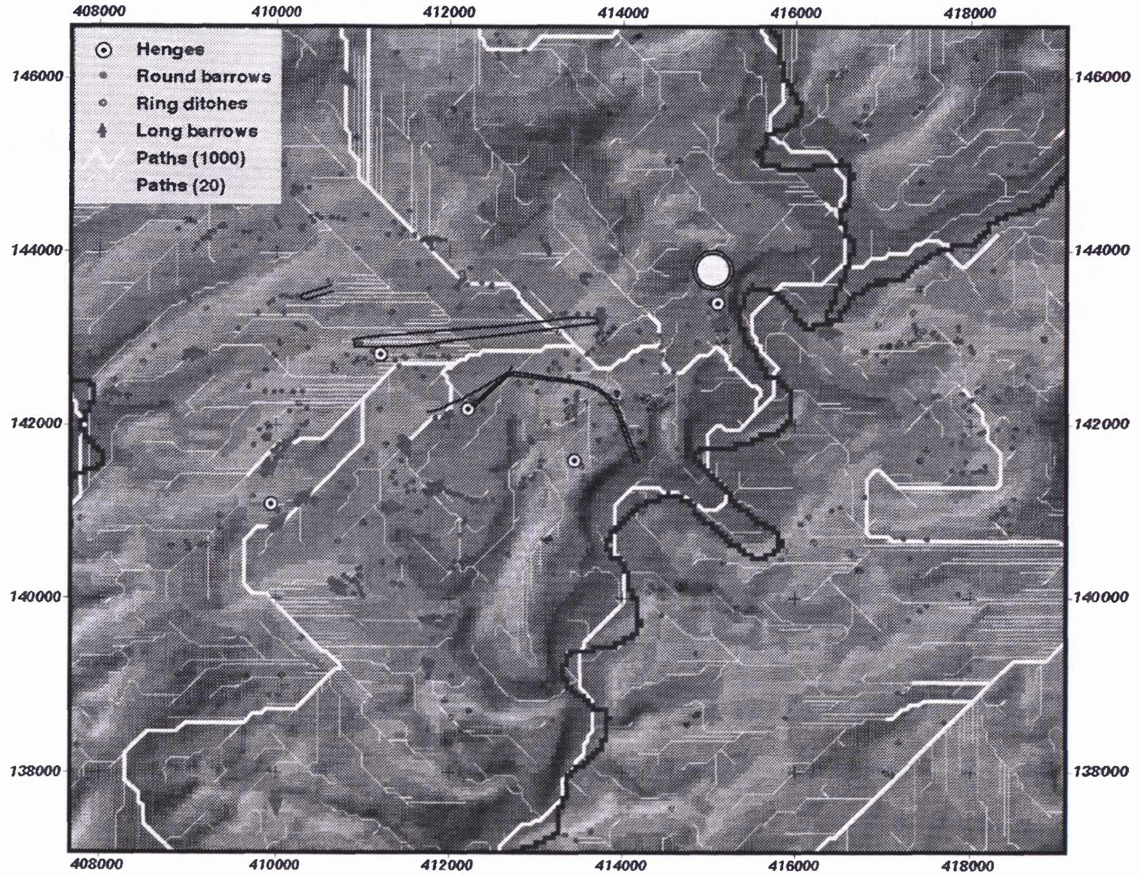

Figure 5: Natural Pathways in the Stonehenge area