A GIS-BASED APPROACH TO ESTIMATING THE HUMAN EFFORT INVOLVED IN MOVEMENT OVER NATURAL TERRAIN

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Abstract

Although it is often perceived as a simple activity, walking represents an important aspect of the relationship between humans and the physical environment within which they live. Our ability to move ourselves and our goods from place to place under various environmental conditions is a fundamental factor conditioning the human use and structuring of space. Measures of our relative ability to move between different locations are called accessibility, and these measures are dependent upon both spatial and aspatial variables. In walking, these include the location of the origin and destination of the proposed trip, the relevant characteristics of the individual undertaking the movement (physical condition, etc.), and those environmental factors (terrain, vegetation cover, etc.) that directly influences our ease of movement or our perception of the difficulty of movement.

Research in human physiology over the last several decades has led to several quantitative estimates of the human energy expended in walking under a variety of conditions. The difficulty in archaeological research has been effectively to apply these effort equations within the context of specific landscape situations. By evaluating these equations within the context of geographic information system (GIS) technology we can easily create 'energy views' of the landscape as viewed from any desired location. This paper reviews the walking energy equations developed elsewhere and provides an illustration of their practical use within the context of the GRID module of Arc/Info. Some suggestions for additional research are also presented.

Introduction

Walking represents an important aspect of the relationship between humans and the physical environment within which they live. Our ability to move both ourselves and our possessions from place to place under sometimes demanding environmental conditions is a fundamental element conditioning human use and structuring of space. Measures of our relative ability to move among different locations have been developed and these measures are associated with what geographers often call *accessibility*. Some of these accessibility measures involve only physical distance, while others are based upon the cost of movement, or the time consumed in travel.

Accessability of one location relative to another based upon walking reflects, of course, the interplay of many spatial and aspatial factors. These may include characteristics of the individual (age, health, physical condition, etc.), the load to be carried

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A paper prepared for presentation at the *VII Nordic Conference on the Applications of Scientific Methods in Archaeology*, Savonlinna, Finland, September 1996. The partial financial support provided by the U.S. National Park Service through contract 6115-4-8031 is gratefully acknowledged.

(including clothing, etc.) from one location to another, the terrain that must be traversed (slope, etc.), surface conditions (sand, snow, etc.), vegetation (dense, sparse, etc.) and the simple physical distance to be covered. The question of human perception should not be neglected since behavior often reflects what we believe rather than what is actually there. For example, the problem of movement over a distance of 500 meters of natural terrain is not going to be viewed in the same fashion by, say, an active ten year old child and a woman 70 years of age who is experiencing significant gait difficulties.

Questions relating to walking-based human mobility have been addressed in many fields where the focus of the questions has ranged from mechanics of the operation of the human foot and ankle (e.g., questions of kinematics and kinetics), to how long it will take a firefighter to reach a fire at a specific location in a large forest (forestry). This paper reviews some interesting research and demonstrates how it may be applied in archaeology, by using GIS technology, to the generation of landscape-explicit estimates of the difficulty of human movement based on walking.

Landscape Utilization Concerns in Archaeology

Archaeologists, like geographers, are concerned with the way in which individuals and societal groups use space. Although geographers generally have a different temporal orientation, few of them would encounter any difficulty in working with the site catchment analysis objectives as set forth by Bailey and Davidson (1983). For instance, these objectives could just as easily been stated by a geographer working, say, in eastern Ecuador or parts of Africa:

- To define the area habitually used by the occupants of a site for their daily subsistence.
- To trace to their points of origin in the surrounding landscape materials and resources (whose archaeological remains are) present on-site.
- To reconstruct the food resources potentially available to the occupants of a site.
- To reconstruct the function of sites.
- To reconstruct the social and economic relationships between sites as member of regional settlement systems.

A problem that has interested geographers, as well as marketing analysts and others interested in spatial behavior, is how to explicitly deal with the influence of distance from a site upon individual or group behavior. Decades ago, a common approach was to draw a series of concentric circles based upon the site. The radius of these *magic circles*, as the marketing people liked to call them, was supposed to reflect major changes in behavior. For example, a distance of ten kilometers or two hours travel time would be assumed to mark either the limit of a service area or the point at which contact probabilities changed significantly. The derivation of the specific radii was often dubious and, in any case, simplistic since yesterday's circles effectively treat a two-dimensional spatial situation as one-dimensional (direction is ignored).

This simplistic reduction in dimensionality was attractive since it was, aside from deciding upon the radii, easy. The alternate was to deal with a very much more complex situation: the heterogeneous two-dimensional case. The step is a substantial one and many researchers, while realizing the necessity of explicitly confronting the more realistic situation, have been frustrated in their attempts to do so. Bailey and Davidson (1983) discuss these frustrations in some detail and propose several 'make do' solutions. Gorenflo and Gale (1990) utilize a function that relates travel time in the southern Basin of Mexico to terrain factors, but were forced to work with data at a scale far removed from that of the human traveler (five km cells and 50 m contours). Savage (1990) also used GIS technology to estimate travel difficulty, but again the analysis scale was inappropriate (1:100K) and no explicit equations for difficulty of movement were utilized.

The work by Jones and Madsen (1989) on the costs of resource transportation in the Great Basin explicitly dealt with the energy expenditure basis for human movement but was again forced to fall back upon simplistic assumptions to create their examples. Brannan (1992) in his subsequent critique of their work pointed out the shortcomings induced by these assumptions and made several excellent suggestions on how the energy expenditure approach could be strengthened and the analysis improved.

However the problem of implementation within the context of a real landscape of some complexity still remains. If energy expenditure is a valid approach to the analysis of unaided human movement over natural terrain, and we strongly suggest that it is, how is it to be implemented by archaeologists on a routine basis? The remainder of this paper briefly reviews some of the relevant research on human energy expenditure while walking and demonstrates how the application of GIS technology can lead to significantly improved views of what we might call the *energy landscape*.

Energy Expenditure in Walking

Perhaps the most comprehensive summary of the physiological research undertaken on all aspects of human walking is found in Rose and Gamble (1994). While only one chapter is devoted to the energetics of human walking, nevertheless it is an effective summary of the relevant physiological research. Briefly, aside from the classic work undertaken in the early part of this century, some of the more useful work on walking appears to have been undertaken by researchers such as McDonald (1961), Pandolf, et al (1977), and Duggan and Haisman (1992). From a geographical standpoint, few investigations exist aside from that of Imhof (1968). Imhof's work was based upon empirical observations of Swiss soldiers and his tabular observations were subsequently reduced to formula form by Tobler (1993). Imhof's work does not appear to have been known to the various physiological researchers. The research results reported by McDonald, Pandolf and other researchers were based on laboratory experiments as were the subsequent validation tests of alternate formulations carried out by Duggan and Haisman.

Apart from the establishment of a norm to which disability-derived deviations could be compared, a concern of the physiological researchers was with what they felt to be a fundamental feature of human motor behavior: *energy efficient behavior*. Rose and Gamble (1994) note that:

> In a freely chosen rate of activity, a rate is chosen that represents minimal energy expenditure per unit task. In the case of natural walking, the unit task is traversing one meter of ground. A speed is adopted such that each meter is covered as efficiently, from the energy standpoint, as possible. (p. 59)

Persons walking in a natural, self-selected manner usually adopt a speed close to the optimal (about 80 meters/minute or 4.8 km/hour). Many attempts have been made to quantitatively measure both relative and total energy expenditure under different walking conditions.

Duggan and Haisman noted (1992) that Pandolf's formulation provided the best match to their laboratory observations. The modified Pandolf equation for energy expenditure associated with movement over a unit distance is given as follows:

$$M=1.5W + 2.0(W+L)\left(\frac{L}{W}\right)^2 + n(W+L)(1.5\,V^2+0.35\,VG)$$

where:
- M = metabolic rate in watts
- W = weight of the unclothed person in kg
- L = load carried by the person (including clothing) in kg
- n = terrain factor (n = 1 for treadmill)
- V = speed of walking (e.g., 4.8 km/hour)
- G = grade (%)

In the context of this model, we should note that Rose, et al (1994) reached two interesting conclusions following their review of the physiological literature on walking energetics:

- It is the total weight moved (body weight plus load) that correlates most highly with human energy expenditure while walking.
- Most studies have found no consistent differences in *energy expenditure per kilogram* while walking in adults of different age, weight, and gender, whereas for children and adolescents some differences are seen to occur with age and possibly gender.

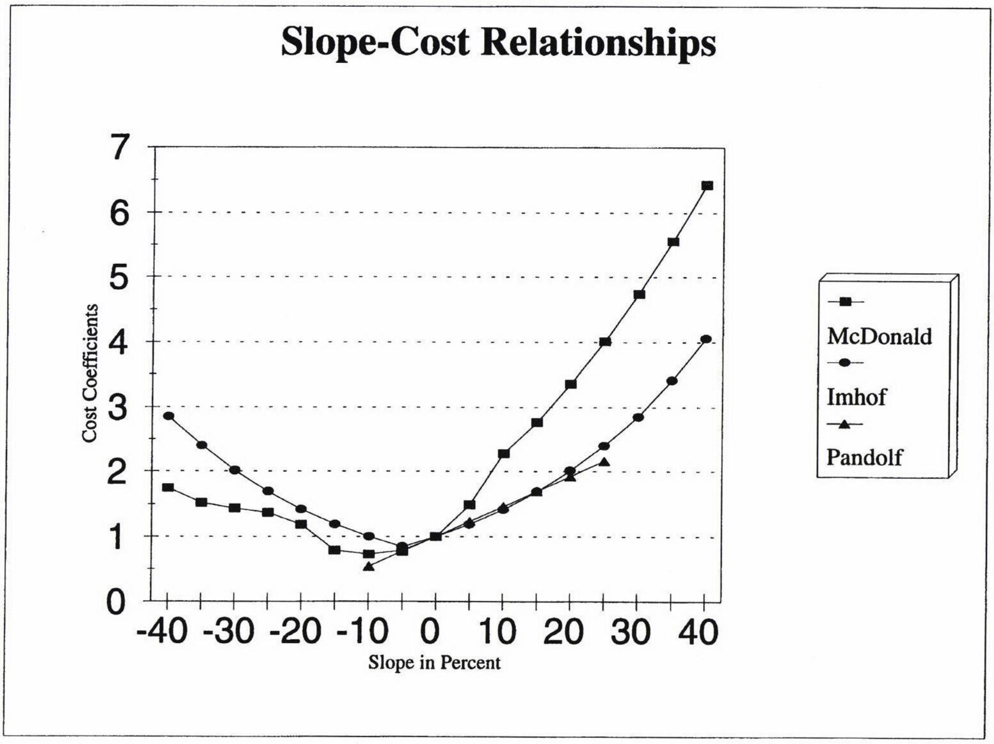

Fig. 1. Different Slope-Cost Relationships. Source: Machovina (1996).

The two factors that vary spatially in the Pandolf and similar models are the terrain factor (n) and the grade (G). Figure 1 compares the slope (grade) factors derived from Imhof's empirical work with those put forth by two of the major physiological researchers. Table 1 provides one view of the possible variations in the terrain coefficients encountered. The numeric values represent the impact of different walking surfaces (dirt, sand, etc.) upon movement effort.

Table 1 Terrain Coefficients

Terrain Type	Coefficient (n)
Treadmill	1.0
Blacktop Surface	1.0
Dirt Road	1.1
Light Brush	1.2
Heavy Brush	1.5
Swampy Bog	1.8
Loose Sand	2.1

Source: Givoni and Goldman (1971)

The physiological research work on walking has been known to archaeologists (e.g., Jones and Madsen, 1989; and Brannan, 1992), but there has been no realistic method of applying it to specific landscape situations. The use of GIS technology provides the archaeologist with an effective way of doing so.

A Sample Application Using GIS Technology

Real landscapes are complex, especially when viewed at a scale that reflects the factors that influence human route choice decisions. GIS technology permits us to evaluate many paths in the landscape with respect to a specified point. This evaluation can reflect complex local differentials in the effort, cost or time involved in human movement. Recently the authors provided a demonstration of how this can be accomplished in a proof of concept investigation involving a 15' x 15' area west of the Mound City site in southern Ohio. The study area was subdivided into many 12 meter square cells (about four million of them) and a composite effort level was defined associated with the crossing of each 12 meter cell. This factor reflected such factors as slope, land cover, etc., while other factors such as weight, walking speed, etc., were held constant. Effects of hydrography and vegetative cover were also included.

Grid cells were used since the map algebra incorporated into the GRID module of ESRI's Arc/Info GIS provides a most useful tool for data manipulation in problems of this type. The *pathdistance* function was used to compute the weighted distance from each grid cell to the selected destination site (here the Mound City group). As Brannan (1992) points out, the return journey should also be incorporated in the analysis. However since our purpose was directed toward demonstration of the methodology rather than analysis, it was ignored here. The analysis was repeated three times reflecting the models and parameters suggested by Imhof, McDonald and Pandolf. The work was carried out on an older Unix–based workstation and the direct computations involved about seven hours for each separate test. The use of more modern workstations would drastically reduce the time required.

The path that is computed is not the airline distance but rather the minimum cost path (in this case minimum energy expenditure path) between the grid cell and the

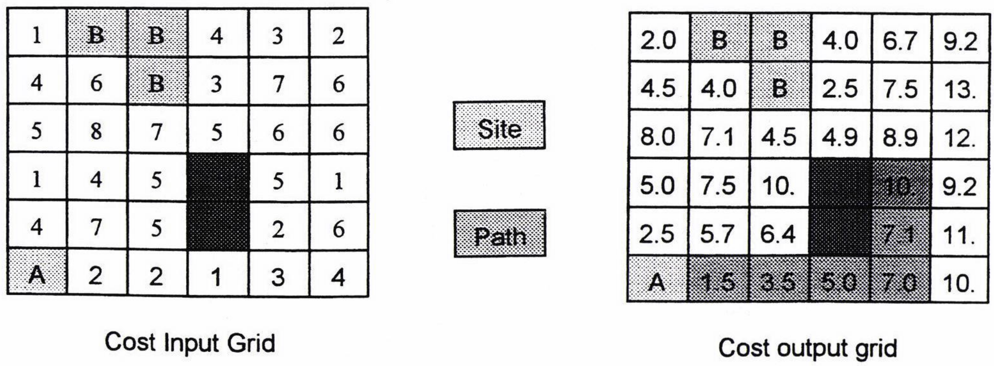

Fig. 2. Path Identification by the GIS.

destination site. The GIS returns not only the total cost of the journey, but also identifies the specific grid cells that compose the energy efficient path between the two locations. If more than one site is involved, the site that is 'closest' to each cell is identified so that potential competition between sites can also be identified (see Figure 2).

Figures 3 shows a shaded relief map of the study area. This should be compared to Figure 4 showing, jointly, the results obtained from one of the model/parameter combinations as well as the isotropic (unweighted distance) case. The black areas on the shaded relief map represent slopes too steep, according to the model, to be traversed. The isotropic distance (appears as regular half circles in Figure 4) has been divided into categories ranging from nearest to most distant. This will always over predict when compared to the energy equation result. The energy equation result was also 'sliced' and the figures given illustrate the differences, e.g., an entry of -2 indicates that, for example, the isotropic model was showing distance class 2 while the energy model was showing class 4 at that location.

Table 2 provides a percentage comparison between the four accessability cases that we examined. The figures were calculated on a cell by cell basis by subtracting each case from one another and dividing the absolute difference by the total number of cells in the grid.

Table 2 Percentage Differences Between Four Accessability Cases

	Pandolf	McDonald	Imhof	Isotropic
Pandolf	0%	71%	65%	44%
McDonal	71%	0%	14%	94%
Imhof	65%	14%	0%	73%
Isotropic	44%	94%	73%	0%

The Pandolf results are not really directly comparable to the other three cases since his model included parameters for only a restricted range of slopes (see Figure 1). This effectively excluded steeper portions of the study area from the analysis. The McDonald and Imhoff formulations, with a much greater range of slope coefficients available, provide results that differ only 14% from each other over the study area.

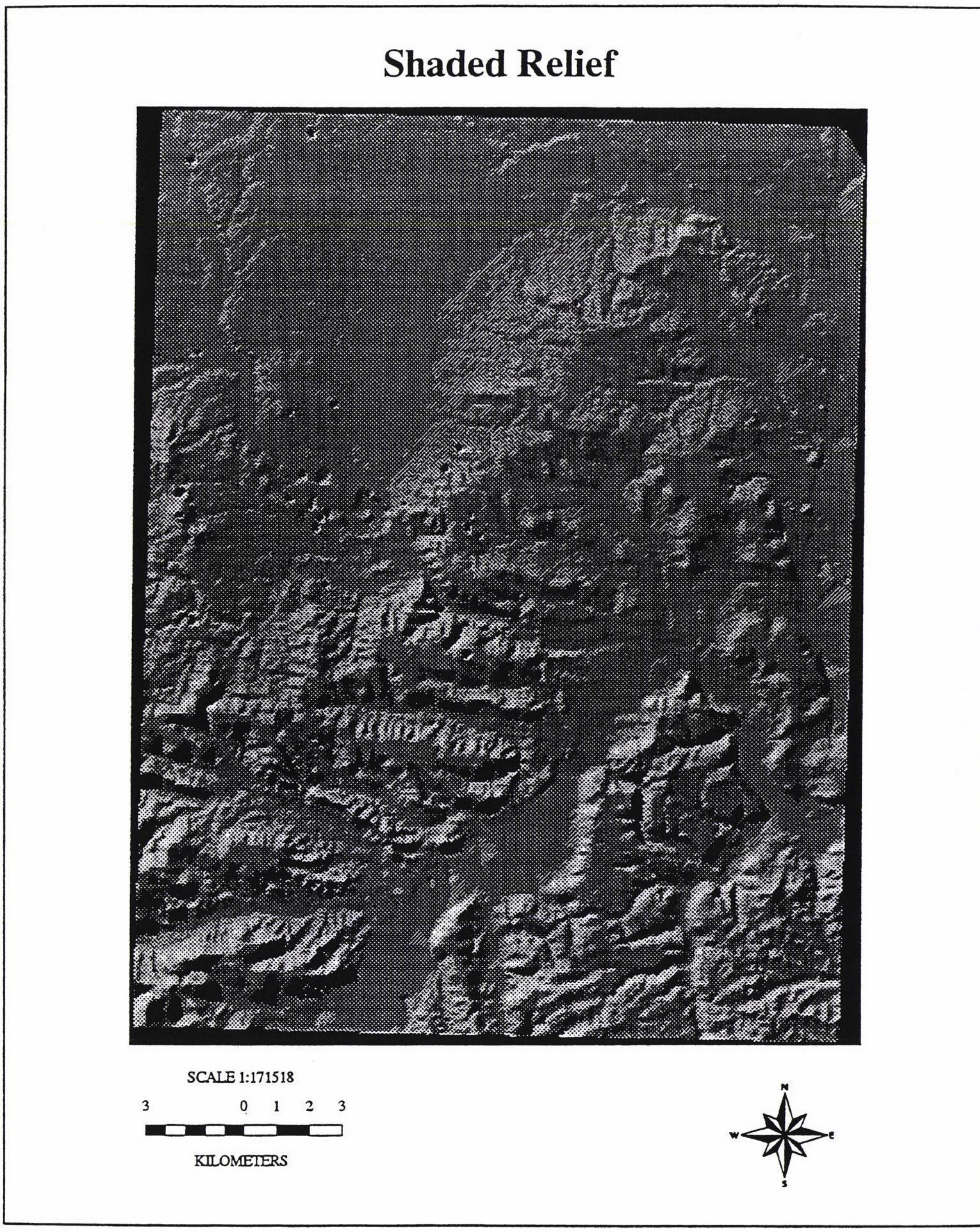

Fig. 3. Study Area Shaded Relief.

The most interesting result, although not an unexpected one, is the substantial differences seen between both the McDonald and Imhoff cases on the one hand and the baseline isotropic case on the other. Clearly, significant differences in accessability and, most likely, landscape utilization can be identified when these models are applied within the context of modern GIS technology. A more extended discussion of these investigations may be found in Machovina, 1996.

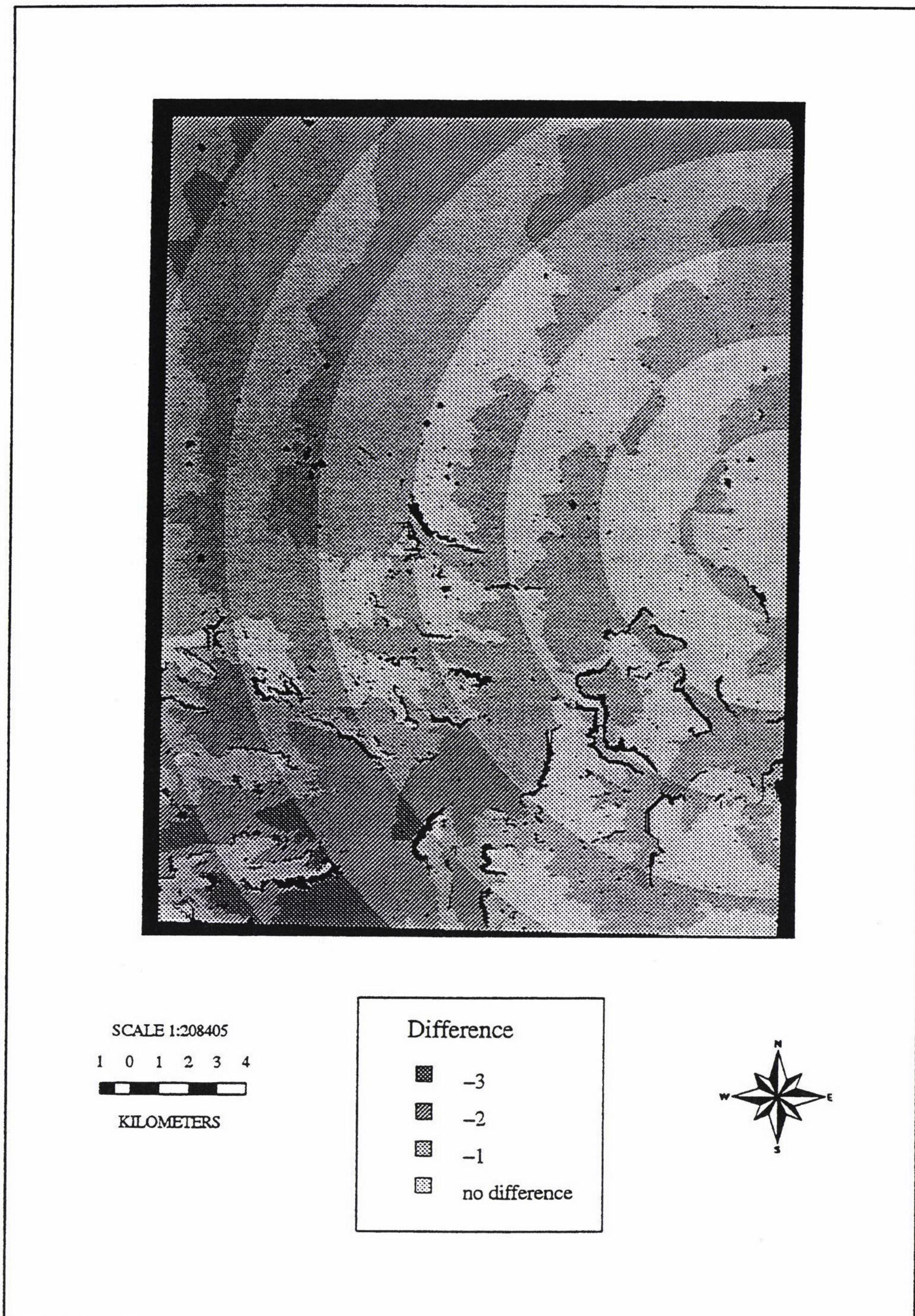

Fig. 4. Comparison of Results from the Isotropic and McDonald Cases.

Next Steps

Space limitations prevent an extended discussion of what we feel should come next. Clearly the application of GIS technology has been successful, but from the standpoint of the archaeologists its long term utility depends upon (a) the specific model and the parameters that are provided to it, and (b) the availability of fairly large scale spatial databases. Brannan's discussion (1992) provides several useful suggestions with respect to the role of trails, the use of Western parameters for non-Western people, the need to deal with the round-trip nature of journeys, etc. While these clearly should be pursued, we would also like to suggest some ways that this new technology could be applied within the context of archaeological investigations:

- Given a computed 'energy landscape,' it is possible to examine the optimal paths from a number of dispersed locations to our site and to determine how these overlap. This could provide estimates of potential trail locations as well as identifying those areas near the site that are more likely to have been heavily used by the occupants. The dispersed locations identified might involve, for example, those areas where gathering is expected to be particularly fruitful or where the probability of locating game is high.
- Building other data layers into the GIS (soils, etc.) should make it possible to identify the most likely areas near the site for agricultural and hunting activities. Some work is available on large animal energetics (see entries in Marble, 1996) and this could also lead to GIS-based definition of the best hunting areas, etc., near the site. The recent work by Van West (1994) would certainly form a good starting point.
- Given a number of sites located in a general area, these computations could be used to estimate energy boundaries or break points between them. These energy break points could prove to be correlated with patterns of landscape utilization associated with the individual sites.

Quite often the application of new technology permits the reexamination of questions that have been set aside as well as suggesting a number of new ones (Marble, 1990). There appears to be very little in the anthropological or archaeological literature on trail formation or upon the trade–offs between travel on trails vs available waterways. Studies of present day travel indicate that individual perceptions of the environment, together with the level of information available to the traveler, have a significant impact upon destination and route selection. We have models of how people search for modern destinations (Miller, 1993), but how did they search the primitive environment? These and many other interesting questions arise out of this attempt to address an archaeological problem using modern geographic tools.

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[1] The limited length of this paper does not permit the inclusion of an extensive list of references. While some are provided here, the text of Marble (1996) with many entries including an abstract may be found on the Internet at *http://geography.ohio-state.edu/faculty/marble*. Additional GIS materials are also available at that site in the GIS Master Bibliography.

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