

MODELING OF PEDESTRIAN MOBILITY ACROSS
A NATURAL LANDSCAPE USING A GEOGRAPHIC
INFORMATION SYSTEM

A Thesis

Presented in Partial Fulfillment of the Requirements for
the degree Master of Arts in the
Graduate School of The Ohio State University

by

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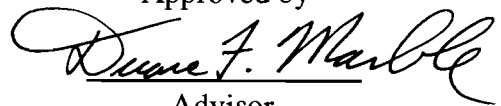
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CHAPTER I

INTRODUCTION

There exists a great deal more to walking than being able to put one foot in front of the other. Although it may be perceived as a simple and mundane activity, superior on the complication scale to only breathing, walking represents an important aspect of the relationship of humans to the physical environment in which they live. This project presents an analysis of walking with respect to geographic factors with the goal of extracting information about human existence and some of the restrictions the environment has laid upon us. Our ability to move from place to place under various environmental conditions is an important feature of human use of space. This ability to move between locations is generally called accessibility, and is dependent upon a number of spatial variables. The particular problem addressed here concerns the quantitative representation of human accessibility to a single location on foot. Prior quantitative physiological research on walking is combined with the spatial analytical capabilities of the GIS to cartographically model the ability of a human to travel by foot across natural terrain in central Ross County, Ohio. By doing so, it is hoped to provide a working approximation of how the accessibility of a select location appeared to the native inhabitants of the area.

Justification

The inspiration for this work addressing human accessibility on foot stemmed from inadequate applications of existing knowledge on pedestrian travel to the field of archaeology. Existing research concerning man-environment relationships in site catchment and site exploitation territories, which involve transportation by human foot, are limited by the fact that they do not normally include an appropriate method for the prediction and delimitation of the boundaries of these territories. Site catchment and exploitation territory analysis deals with examining the relationship between human behavior and the immediate environmental surroundings of particular archeological sites. This neighborhood-type analysis has been used and developed in a variety of contexts including areas such as subsistence, defense, politics, economics, and inter-site interaction.

The most common, and least satisfactory, approach to constructing these site territories has been to simply draw circles of 5 km or 10 km radius around sites on a commercial map projection. This isotropic method naively assumes straight-line Euclidian distances and fails to account for variations in terrain and other impedances to foot travel such as thick vegetation or standing water. The researchers in these studies implicitly assumed that the inhabitants were walking across a perfectly flat and unobstructed landscape, much like an empty parking lot.

Yet another method that uses isochronic distance was developed by Higgs (1975) that involves the investigator walking a minimum of four arbitrarily defined, orthogonal transects in an attempt to account for the differential effects of terrain. The outer limit of the transects, usually 2-hours, is set by empirically derived, economic distance thresholds that reflect the

trade-off between the amount of energy the pedestrian acquires as food and the amount of energy he or she expends in travel and exploitation. The boundary connecting the four end points of the transects is then visually interpolated from maps. This isochronic method, although constituting an improvement over the isotropic circle technique, is obviously crude, especially where the interpolated boundary runs over difficult terrain. This is often the case due to the fact the persons walking the transects appear to avoid areas of rough landscape. Furthermore, the approach is time consuming to implement, absorbs valuable professional time, and necessarily involves substantial interpolation to delimit the assumed boundary.

Bailey and Davidson (1983), in their review of the published methodology, highlight the limitations of existing techniques in the delimitation of territory size. They urge the development of a new method which would be “independent of the knowledge of the terrain, the energies of the individual researcher, and of the time available for the fieldwork” (Bailey and Davidson 1983). Their proposed method involves using detailed topographic maps, manual cartographic measurements with a drafting compass, and the application of a crude hiker’s calculation based on altitude change. They recognize that taking slope changes into account is desirable, but discard this refinement due to the “complex nature of the calculations.” While they acknowledge the existence of other impediments to human movement such as the nature of the ground surface and vegetation characteristics, these are ruled out of consideration because non-topographic impediments to travel are regarded as too difficult to access in a comprehensive fashion. These complex spatial queries simply can not be processed easily and quickly by the user even with the aid of simple manual tools such as the ruler, the compass and the planimeter. The approach devised by Bailey and Davidson

suggests an obvious opportunity for the application of GIS technology to the problem. A GIS system is capable of handling the full range of factors proposed by Bailey and Davidson, including those factors, such as slope angles and non-topographic impediments, that they deemed too complex and difficult to incorporate.

Purpose

Although the inspiration for this particular study was prompted by deficiencies existing in archaeological studies, the methods developed could be extended and applied to a myriad of topics beyond those associated with archaeology. The aim of this project is to develop a new and improved technique for modeling pedestrian locomotion and illustrate its effectiveness by applying it to a sample region in central Ross County, Ohio. The present application involves the creation of maps showing human accessibility on foot to an Indian burial mound site in this sample region. The scope of the project is limited to the production of a general pedestrian movement model that is not tailored to a specific discipline or field, but that can be custom fit to any particular study area and time period. The primary objective in this study is to implement, within a GIS context, an accessibility model based upon pre-existing research in order to facilitate research involving pedestrian locomotion across a natural, as opposed to man-altered, terrain.

The thesis is divided into five chapters. The first is an introduction covering the justification, aim, scope, and objective of the paper. The second chapter reviews and examines previous attempts at combining walking research with a GIS and summarizes prior research on the subject of human pedestrian locomotion. The third and fourth chapters deal

with the data and procedures employed in the project while the final chapter concludes the paper with a summary, a detailed discussion on the limitations of the model, and suggestions for extending the work done in the present project.

CHAPTER II

PRIOR RESEARCH

Introduction

Walking is effected by a myriad of variables, spatial and aspatial. For example, the ability of an infantry soldier to walk through a certain landscape may be influenced by spatial variables such as differing slopes along the traverse, the wind direction and speed, and the vegetation characteristics of the region. Aspatial components such as body weight, cardiovascular condition, how much equipment is being carrying, nutritional condition, and daytime or nighttime conditions may also be influential. This is obviously only a sampling of the multitude of variables that can effect walking; others can be easily suggested in the context of specific situations. It would be futile to specify, let alone model every conceivable factor, therefore this project focuses upon only a limited number of variables felt to be among the most influential geographic variables while also incorporating some critical aspatial components. The designation of “most influential” and “critical” was determined by examination of prior research focusing upon the modeling of pedestrian travel impedances.

Past research has either calculated walking impedance with simple travel time estimations based on the mental travel logs of experienced hikers, or by comprehensive physiological methods, largely laboratory-based, that specifically analyze energy costs and

expenditure in terms of oxygen consumption and caloric loss. The travel time methods are the type employed by the archaeology studies discussed previously, and are relatively crude when compared to those based upon physiological methods. This chapter begins by discussing the small number of archaeological studies that involved pedestrian travel and GIS. Disadvantages associated with the travel time techniques used to measure energy costs in these studies are highlighted, as well as the disregard of other elements that should be considered equally vital to an accurate model. These elements include the use of an appropriate scale and the consideration of non-topographic impediments to travel. The chapter continues with a section on the history and development of the energy cost derivation methods pursued by the physiological researchers and concludes with an introduction to the primary energy cost equation selected for use in this thesis. A full examination of prior research can help lead us to an improved pedestrian accessibility model that uses the more accurate, quantitative-based physiological research, an appropriate scale, and considers non-topographic impediments to travel.

Archaeological Studies That Involve Pedestrian Travel and GIS

Two recent archaeology projects have attempted to blend walking research with the spatial analytical capabilities of a GIS, however both prove to be significantly deficient in some respect. Gaffney and Stancic (1991) implement a GIS in order to construct site catchments on the island of Hvar which lies off the coast of Dalmatia, Yugoslavia. The principal deficiencies of their application are that it does not utilize the more accurate and precise physiological methods for determining the energy cost of walking, it uses too coarse

a resolution for the Digital Elevation Model (DEM) (20 m x 20 m), and it does not specifically include non-topographic impediments to travel. A second study, conducted by Gorenflo and Gale (1990), attempts to determine patterns of settlement interaction between sites in the southern Basin of Mexico in terms of their accessibility to one another. Accessibility is calculated by systematically estimating travel times. Inadequacies in their study are similar to those noted above: an ill-supported method for determining the energy cost of walking is used, the resolution of the contour lines is too aggregated at 50 m, and non-topographic impediments to travel are not included. The deficiencies of these studies are addressed here by organizing them into three distinct problem areas which are common to both projects. Deficiencies are discussed in detail in the following sections along with reasoning behind why they are considered so. These areas include:

- 1) the use of poor energy cost estimating equations;
- 2) problems with scale and spatial aggregation; and
- 3) the exclusion of non-topographic impediments to travel.

The Use of Poor Energy Cost Estimating Equations

Procedures that were used in both the Gaffney and Stancic (1991) and Gorenflo and Gale (1990) studies for estimating pedestrian travel times were relatively crude and inadequate. Only one employs a walking equation calibrated from empirical data, while the other appears to use a simple hiker's equation proposed by Bailey and Davidson (1983), although it is not specified. Both equations should be considered substandard and less than

reliable because they are rarely supported or even mentioned by other researchers and were fabricated by individuals who are not considered experts in human physiology.

Gorenflo and Gale (1991) estimate pedestrian travel times between a set of 25 separate locations in the southern Basin of Mexico in an attempt to transform the geographic space of the southern basin into a space that is based upon travel time between places. They generated travel time estimates between each point and all 24 others using topographic maps and a formula developed by a geographer, Imhof (1968). Since they assume that settlement interaction would involve movement to and from a location, two estimates for each pair of points were averaged to provide a single travel time value. Travel times were calculated for 1 km intervals and then summed as appropriate to connect the 25 sample points. Imhof's (1968) formula was calibrated from empirical data on soldiers hiking in various types of topography and is shown below in its original form:

$$v = 6 e^{-3.5|s + 0.05|} \quad (1)$$

where

v = walking speed

s = the slope of terrain (calculated as vertical change divided by horizontal change)

e = the base for natural logarithms

The function is somewhat similar to equations supplied by physiological researchers in that it is symmetric and slightly offset from a slope of zero. Estimated velocities are greatest when walking down a slight decline and decrease for changes in slope above and below the threshold (see Figure 12). Although this equation is empirically based, it remains questionable

because it has never been investigated by other persons nor is it even mentioned in the physiological literature.

Gaffney and Stancic (1990) construct catchments for five major hillfort sites on the island of Hvar by performing a cost surface analysis designed to determine the energy expended when an individual crosses from one point to another. They appear to calculate energy expenditure by using a combination of the transect method devised by Higgs (1975) and the measurement technique proposed by Bailey and Davidson (1983), although it is not clearly stated in their study. They measured the time for walking across a portion of their study area and used it as a template to modify the individual catchments. Although it is noted that the modifications were calculated according to topography, the exact method is not mentioned in their meager discussion. They simply explain that steep land resulted in greater energy use and shorter catchment distances, while relatively flatter land resulted in less energy use and longer distances to the catchment boundary. Although the practice of on-site walking is similar to Higgs's transect method, using a template and modifying the catchments according to topography is more characteristic of the technique developed by Bailey and Davidson (1983). Even the derived catchment boundaries are presented in the same temporal basis as those proposed by Bailey and Davidson (1983): walking times. Because of these similarities it is assumed that Gaffney and Stancic (1990) use the Bailey and Davidson technique for deriving site catchments. It is founded upon Naismith's rule, which is shown below as it was presented by Westacott (1979).

Allow one hour for every three miles measured on the map, plus an additional hour for every 2,000 ft climbed. The distance climbed is not the highest point reached but the sum total of all the ascents.

This rule was intended for hikers who required a rough estimate of travel times, and was certainly not designed for scientifically based archaeological research. Although the formula is frequently mentioned in simple hiking books and manuals it is rarely mentioned in any research publications. It is clearly evident that the formula was developed by a hiker for the sole purpose of quickly and easily calculating walking time while in the field, which is obviously far from what is required for an archaeological site catchment analysis. Bailey and Davidson (1983) have therefore advocated an inappropriate formula for the derivation of site catchments. Any quantitative study that utilizes Naismith's formula is of questionable validity.

Problems with Scale and Spatial Aggregation

Both the Gaffney and Stancic (1991) and Gorenflo and Gale (1990) studies use spatial data on a scale that is unsatisfactory. They inappropriately utilize small scale and highly generalized maps in order to study large scale, complex human activity ignoring the axiom that disaggregate spatial analysis requires disaggregate spatial data. Even Modderman (1988), an archaeologist, explains that investigating human activity at particular scales can only be accomplished by mapping them at those scales. Gaffney and Stancic (1991) used a 1:50,000 topographic map in order to create the DEM for their study, eventually producing

a cell size of 20 X 20 m. Although they do not discuss the contour interval on the original map that eventually produced the DEM, it can be assumed that it was far too coarse for an analysis of this nature due to the small scale of the original map. A 1:50,000 scale map is too generalized to support an analysis on the detailed level of human foot travel. Gorenflo and Gale (1990) specify the use of a 50 m contour map and a 1 km x 1 km cell resolution in order to calculate accessibility and estimate travel times, which is also far too great an aggregation.

Although many applications using physical geographic data can make use of aggregated forms of spatial data, projects concerned with analysis on the level of individual human behavior require more detailed data presented on a spatially much more disaggregate level. The use of small area, aggregate figures as a substitute for information on the actual behavioral units leads to what is termed the ecological fallacy. Similarly, relationships observed for a heterogeneous aggregated group are often misleading when applied to individual units. Since the eradication of the effects of aggregation is not an option, reducing its effect is a primary objective. This is accomplished by using a level of aggregation appropriate to the specific study being conducted. In these studies, it is understood that pedestrian travelers are likely to be effected by small geographic features. Ultimately, each step has the potential to effect the outcome. The difficulty is that most physical geographic databases do not contain data that is this highly spatially disaggregate. Thus, the Gaffney and Stancic (1991) and Gorenflo and Gale (1990) studies, which pragmatically employ the readily available, aggregated physical data, may be held to lack validity.

Aggregation problems encountered by archaeologists using these typical topographical databases begin with the sampling methods utilized to create the original database. Not every location on the earth's continuous surface can be measured in terms of its elevation, therefore only certain discrete sample locations are considered in constructing the database. These locations often represent significant features, such as valleys, ridges, summits, pits, passes, and pales or locations taken at regularly spaced intervals. This discrete point data, representing the continuous topographical surface of the earth, is then transformed back into terrain models that, in turn, simulate the actual earth surface. Martin (1991) cautions that the full detail of the surface can never be recovered when it is recorded as a series of points.

Conventional data structures for surface models include the digital elevation model (DEM) and the Triangulated Irregular Network (TIN). DEM data structures make use of regular arrays and constant sampling intervals while TIN structures use significant feature sample points connected into networks of irregular triangles. Besides using significant feature points, like peaks, TINs often use line features like streams and ridges as break lines in the construction of networks. A major problem with both models lies in their interpolation algorithms. These smooth over those locations that were not sampled, specifically the areas in between the sampled points. This ultimately results in the elimination and misrepresentation of many real world features.

Small area analyses, such as those addressed here, are intimately concerned with landscape features that are smoothed over in small-scale terrain models. Kvamme (1990) assesses this spatial aggregation problem by examining a map with 40 ft contour intervals. At this scale he complains that many small ridges and hills are absent, many small drainage

features are missing and the larger features are greatly smoothed. He notes that, for archaeological research purposes, it is just this kind of data, small ridges, hills, and drainages, that are usually the most important in regional studies. Any regional site study that ignores these small landscape variables is "an error prone exercise of questionable worth" (Kvamme 1990).

Aggregate topological spatial databases in physical geography not only adversely effect the direct elevation information presented by the model, but may compound problems associated with indirect information calculated from the model. This indirect information includes such things as slope and aspect transformations of the terrain model. This type of information is derived from the original model; therefore any aggregation problems are transferred to the new information. Any problems with the original aggregated terrain model are generally compounded in the subsequent slope and aspect calculations.

Modderman (1988) also addresses the difficulties associated with linking aggregated physical data mapped at small scales with data provided by regional and small area studies mapped at large scales. He notes that in archaeology, topographical, soil, and geological maps are often inappropriately applied in support of research on archaeological sites. He highlights the tremendous gap existing between the scale of 1:50 used in excavations and that of 1:50,000 soil and geological maps, and notes that the latter certainly were not made to serve the needs of archaeologists.

The generalized data that was used in these previous archaeological studies was not appropriate. It was far too aggregated for an analysis supposedly concerned with the larger scale phenomenon involved with individual human travel on foot. Studies focusing upon this

type of human activity should be very concerned with obtaining and using appropriate, non-aggregate spatial data. Every human activity has its own appropriate level of scale and aggregation, and thus any spatial analysis that involves large scales and disaggregation should implement data that is appropriate.

Exclusion of Non-Topographic Impediments to Travel

Both the Gaffney and Stancic (1991) and Gorenflo and Gale (1990) projects ignored the possible influence of non-topographic impediments to travel. Gaffney and Stancic (1991) fail to mention or consider any factor except slope and Gorenflo and Gale (1990) simply state, “the speed with which people travel by foot over land tends to be a function of the slope of the terrain.” This is obviously not the case as evidenced by the extensive physiological research that has been conducted concerning the energy expenditure of walking, as well as the simple observations of those who are intimately familiar with walking and hiking across natural terrain. The effects of surface water, vegetation, and ground surface composition can be equal or even much more significant than the effects of topography.

Bridge (1981) discusses the importance of water to hikers: “It may present impassable obstacles like large fast-falling rivers or it may provide the easiest means of access, as stream beds in densely forested areas often do.” The effects of water are therefore uniquely dependent upon the region of travel. Vegetation may likewise impose certain restrictions that are just as influential as topography. Bridge (1981) continues with a statement concerning vegetation: “the vegetable cover is of particular interest for still another reason; it effects a hiker’s mobility as much as the terrain does.” Moorers (1972) likewise has advice concerning

vegetation cover: “Many miles of trail are preferable to hours of futile lunging, hacking and tight-rope walking.” Besides water and vegetation the specific ground surface composition can be extremely influential. Westacott (1979) qualitatively describes the qualities and effects of different path surfaces under the assumption that “hard moulded rubber soles are worn.”

The original account (p. 45-46) is reproduced below:

ROCK	Dry rock of all kinds, from sandstone to granite, provides a good surface on which the boots will not slip. Rubber soles grip reasonably well on clean (i.e. lichen- or mud free) rock but when the rock is covered with lichen or mud (usually known as greasy rock) great care is necessary as it is easy to slip. Ice-covered rock is lethal.
SCREE	Scree is loose pieces of rock, about the size of large pebbles, on a steep mountain slope. It is very fatiguing to climb because when advancing one step you slip back half a step, rather like climbing steep shingle on the beach. However, scree can be fun to descend. Run down the slope boldly, digging in the heels at each step. The loose rock will move under your feet, as shingle would, but it is very bad for the boots.
CLAY	Clay is dreadful stuff. If frozen or baked hard, it becomes rutted and one fears for one's ankles at every step. When waterlogged, it is as slippery as a skating rink. Clay, when ploughed, clings tenaciously to the boots in great lumps, increasing the weight on the feet severalfold. It is very difficult to remove, but the worst can be got off with the aid of a stick and plenty of wet thick grass. It is often helpful to kick an imaginary football as this will loosen the largest lumps.
CHALK	The finest and most springy turf grows on chalk. With heavy use the grass is worn away exposing the chalk which can erode badly. It provides a good firm surface when dry, although it marks the boots distinctively, but it is treacherous when wet as it becomes very slippery. Wet escarpments should be avoided whenever possible.

PEAT	Peat is formed by decomposing vegetation, usually heather and bracken, and is a dark chocolate colour. Dry peat provides a good surface, pleasantly springy underfoot. Wet peat is slightly slippery, but as it tends to be covered with heather it causes difficulties only when deep and free from vegetation. In wet weather on some fells it is possible to sink to one's knees in peat bogs. With a little experience it is possible to see firmer footing provided by clumps of sphagnum grass and bog cotton which will help to keep you from sinking too deeply into the bog.
GRASS	Grass provides pleasant walking though it is slippery on slopes when it is wet.

Obviously, this excerpt addresses only a handful of different ground surfaces, mostly those encountered in England, but it clearly demonstrates the significant variability associated with factors other than slope. Bridge (1981) also identifies this location dependent variability and directly contrasts it to topographic effects. He explains: "A steep ravine of identical contour will have an altogether different meaning in two different places: in one it may provide a highway of talus blocks from top to bottom, while in another it may present difficult slabs of smooth granite or treacherous heaps of crumbling rubble." These accounts are a testimony to the importance of non-topographic impediments to pedestrian travel as well as to their highly variable effects. These effects are as important and worthy of consideration as those of topography.

Physiological Research

Physiologically-based studies of pedestrian locomotion, specifically focusing on the role that body dimensions play in determining the energy required for walking, began as early

as 1899 (Fisher 1899), while less scientific conclusions were most likely devised shortly after man's first steps were taken. Work on the metabolic cost and rate of energy expenditure of walking dates back to Cathcart, et al. (1920), where indirect calorimetry was first employed in order to determine the metabolic cost of walking. This standard physiological procedure involves analyzing the oxygen and carbon dioxide concentrations in inspired and expired air and calculating the metabolic rate based upon these variables. Recent work has expanded upon the foundations laid at the beginning of the century and has developed guidelines that more accurately describe the process of walking. An early tendency to undertake extensive studies involving only one or two subjects has progressed to approaches that involve larger numbers of subjects. This change has led to more empirically-based data and ultimately a better understanding of the energy costs associated with walking.

Initially Cathcart, et al. (1920) conducted a study on the rate of marching and energy expenditure using indirect calorimetry in order to determine the optimal rate of marching. They represented the relation between energy cost per unit of time and speed by a parabola:

$$y = ax^2 + bx + c \quad (2)$$

where y is the energy cost per unit time and x the distance covered per unit time. The equation implies that the cost of work is at first great, diminishes to an optimal value, and again increases. Cathcart, et al. (1923) extended their previous work on energy expenditures by including the load carried by the soldier as an additional variable in the estimating function. Since this pioneering work, subsequent research has been largely directed toward developing a more accurate equation for predicting the energy expenditure of walking. The equations

developed have generally introduced factors such as the speed of walking, the weight of the body and the load, and the gradient traversed, although other research has shown that additional factors are also important. Body weight (Cotes 1969), overfeeding (Durnin and Norgan 1969), distribution of load carried (Soule and Goldman 1969), wind resistance (Pugh 1970), weight of footwear (Jones et al. 1984), age (Durnin and Mikulicic 1956), and level of physical training (Knehr et al. 1942, Cotes and Meade 1955, Levine et al. 1982) all show their respective factors to be influential. On the other hand, research indicates there exists rather little variation in energy expenditure attributable to time of day (Durnin and Namyslowski 1958), sleep loss (Martin 1981), and gender, when results are adjusted for body weight (Evans et al. 1980).

A large number of researchers have focused on the development of an equation designed to predict the energy cost of walking. Some studies include Redfearn, et al. (1956), Ralston (1958), Cotes and Meade (1960), McDonald (1961), Grimby and Soderholm (1962), Goldman and Iampietro (1962), Workman and Armstrong (1963), Durnin and Passmore (1967), Giovoni and Goldman (1971), and van der Walt and Wyndham (1973). Giovoni and Goldman (1971) appear to have developed an equation with the lowest mean standard error of estimate: ± 29 kcal/h. Because this equation is the predecessor of the majority of research conducted after its publication, it is discussed here in detail. The original form of this equation is shown below.

$$M = n(W + L)[2.3 + 0.32(V - 2.5)^{1.65} + G(0.2 + 0.07(V - 2.5))] \quad (3)$$

where

M = metabolic rate, kcal/hr

n = a terrain factor, defined as 1.0 for treadmill walking

W = body weight, kg

L = external load, kg

V = walking speed, km/hr

G = slope (grade), %

Soule and Goldman (1972) modified this equation by including additional coefficients reflecting different types of terrain. They measured the energy cost of traversing level terrain covered with heavy brush, swampy bog, loose sand, blacktop road, dirt road, and light brush. These were compared to the predicted treadmill costs based upon the Giovoni and Goldman (1971) equation for the same loads and speeds. Their results are summarized in Table 1.

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, B., and R. F. Goldman. 1971. Predicting metabolic energy cost. *Journal of Applied Physiology* 30, 429-433.

These coefficients were felt by the authors to indicate the relative energy cost of walking across difficult terrain with reasonable precision. The only problem area mentioned by the authors concerns travel in swampy terrain. They note that their standard swamp coefficient can not precisely account for the highly variable conditions normally found in swampy environments. Further modifications were made to the Giovoni and Goldman (1972) equation including the addition of an additional terrain category for snow (Pandolf, et al. 1976) and an adjustment to include walking speeds down to a zero (Pandolf, et al. 1977). Inspiration for this final adjustment originated from problems found in the Pandolf, et al. (1976) study. Subjects in that study became exhausted and stopped walking altogether in deep snow conditions. An ensuing investigation concluded that the zero intercept of the Giovoni and Goldman (1972) equation was not a simple extension of the prediction curve for walking at normal speeds but that it had to be adjusted for standing still. The Pandolf, et al. (1977) equation, adjusted for the total range of walking speeds, is shown below in its original form.

$$M = 1.5W + 2.0(W + L)(L/W)^2 + n(W+L)[1.5V^2 + 0.35VG] \quad (4)$$

M = metabolic rate, watts

W = subject weight, kg

L = load carried, kg

n = terrain factor ($n = 1$ for treadmill)

V = speed of walking, $m \cdot s^{-1}$

G = grade, %

The weight term is the weight of the pedestrian naked, the load term is the load carried by the pedestrian in the form of clothes and backpack, while the other terms are self evident.

Specific criticisms of the final Pandolf, et al. (1977) equation are extensive. Pimental and Pandolf (1979) complain that it predicts slightly high for standing when carrying a load and low for walking at a slow speed (0.5 ms^{-1}) on a 10% grade. Pimental, et al. (1982) did further comparisons and concluded that the equation underestimated by up to 33% for level walking. Likewise, Pierrynowski, et al. (1981) found that the predicted values diverged from observed values as the load carried increased up to 34 kg.

Recently, Duggan and Haisman (1992) concluded that the equation devised by Pandolf, et al. (1977) is superior to the other equations and acceptable for most practical purposes. They reached this conclusion by comparing how well all the equations worked on their group of 18 subjects under a wide range of conditions and work rates. Their critique shows only relatively small and statistically insignificant errors as well as a high overall correlation between the actual values and the values predicted by the Pandolf, et al. (1977) equation. The mean prediction error was -7 W (-0.5% of actual metabolic rate) with a standard deviation of 47 W (7.9% of actual metabolic rate). Linear regression showed an r value of 0.94. The largest absolute mean prediction error was 25 W or 6.3% of the actual metabolic rate, but none of the prediction errors were statistically significant using a t -test with $p > 0.05$. The highest standard deviation about a prediction error was 62 W (11.5% of actual metabolic rate). Duggan and Haisman (1992) conclude their critique by noting that: "The Pandolf, et al. (1977) equation has given good results in comparison with observed data from typical studies using soldiers in our laboratory, and the observed errors are acceptable for most practical purposes." (Duggan and Haisman 1992)

The existing quantitatively-based, physiological research on walking and the resulting equations has been quite comprehensive in relation to the simple measurement techniques currently in use by archaeologists. A GIS-based application of this proven research added to the use of an appropriately scaled spatial database and the incorporation of non-topographic impediments to travel would result in a highly improved accessibility model. A model of this nature is developed in the remainder of this thesis. It is also customized for a portion of Ross County, Ohio and is run based on the accessibility to a specific prehistoric Indian mound site.

CHAPTER IV

A ROSS COUNTY IMPLEMENTATION

Introduction

The accessibility model developed in this thesis is applied from a portion Ross County, Ohio to the Mound City unit of the Hopewell Culture National Historic Park. The goal of these calculations is to provide a working approximation of how the accessibility of Mound City appeared to the native Hopewell living in the selected study area. This chapter provides a brief description of Mound City and a short discussion concerning the Hopewell culture. This is followed by a detailed description of the physical character of the study area and a comprehensive overview of the spatial data required for the model. These data include information on topography and terrain types, namely those variables in the energy cost equation that are associated with geographic themes.

Mound City and the Hopewell

Mound City was an ancient gathering place and burial site for Hopewell Indians living along the Scioto River during the first two centuries A.D. Within the 13 acre necropolis is one of the most remarkable and greatest concentrations of Hopewell mounds known. There

are a total of 23 burial mounds within a rounded-square enclosure that is 3 to 4 ft high and 2,050 ft long (Woodward and McDonald, 1986) (see Figure 1).

Despite construction of numerous large ceremonial centers involving vast amounts of manpower and organization, the Ohio Hopewell people lived in scattered small settlements throughout the southwest quarter of the state. People came to the ceremonial centers to work, trade, and participate in rituals, otherwise the centers remained vacant. The small Hopewell villages occupied lowland sites along major streams with broad bottomlands. Primary concentration was along the Scioto River, although important settlements were also developed along other drainages. Settlements were generally situated on the second and third terraces of the rivers, well above normal flood danger, yet still near the water which provided food, water, and transportation. Isolated settlements have also been found on hilltops away from the rivers. An understanding of the ability of the Hopewell people to travel to Mound City from these detached settlements in the study area will be enhanced by construction of an accessibility model based on the natural landscape of the region.

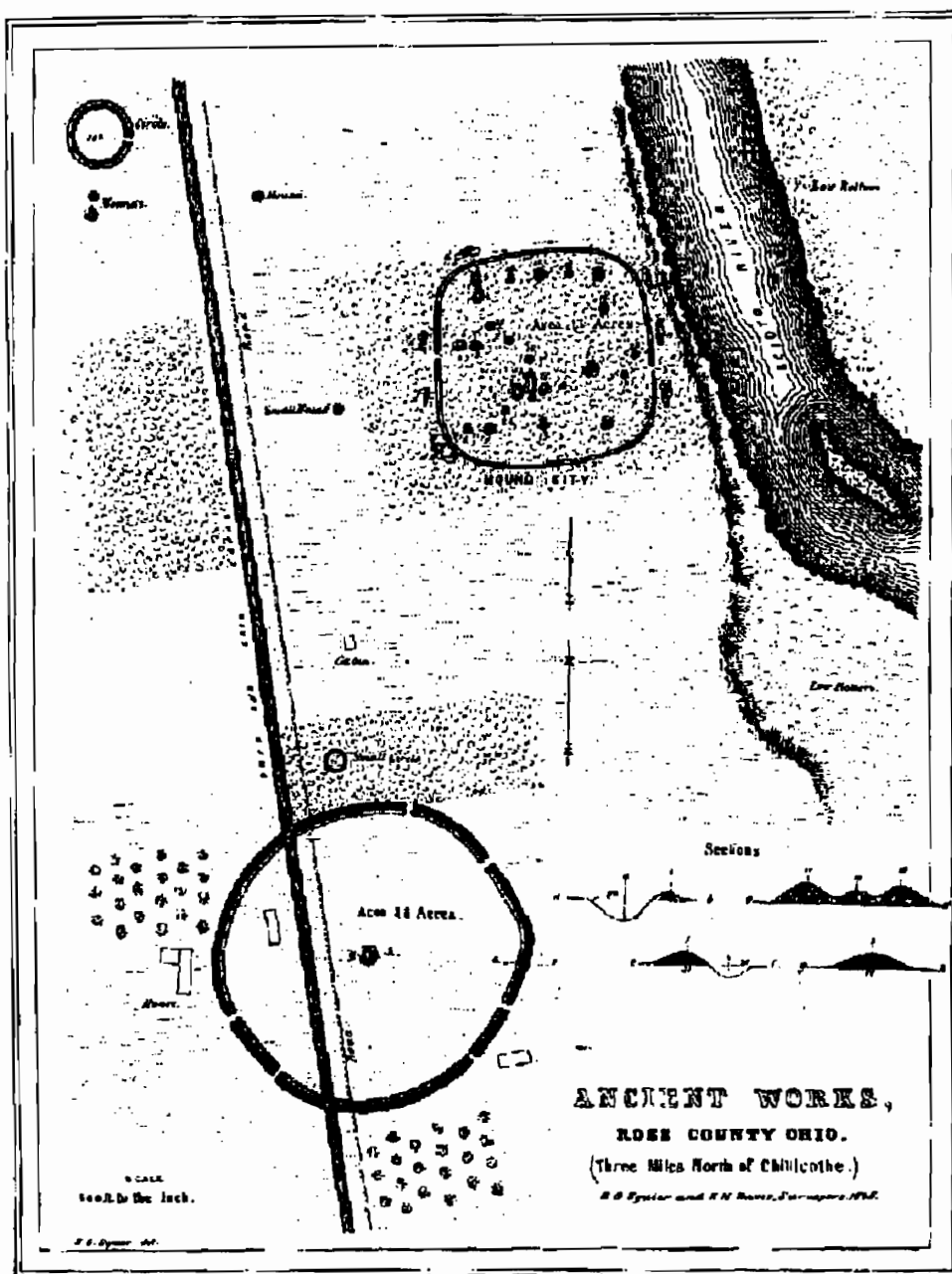


Figure 1. A map of Mound City. Source: Squier, A. M., and E. H. Davis. 1992. "Mound City," Ross County, Ohio. Map. *Ancient Monuments of the Mississippi Valley*, 1848. As reproduced in Arthur W. McGraw *Ancient Monuments of the Mississippi Valley*. Privately printed. Plate XIX.

Physical Geography of the Study Area

Ross County is located in the south central portion of the state lying astride the Scioto River (see Figure 2). The specific area chosen for the investigation is located west of the city of Chillicothe. It is rectangular in shape with an east-west width of 21.12 km and a north-south length of 27.36 km for a total of 577.8 km² (see Figure 3). It was chosen as the study area because it is presumed that numerous detached Hopewell settlements were located within its borders (Dancey 1995). The area encompasses a varied terrain, primarily reflecting the effects of the ice ages in that it actually straddles the southernmost extent of the glacier advance. The northwestern portion of the study area is relatively flat while the remaining three-fourths of the area is covered with rugged hills, which often experience elevation differences of over 600 ft. between valley and hilltop. The distinct division between the level areas in the northwest and the hilly topography in the south is clearly evidenced in a three dimensional view of the terrain (see Figure 4).

Preceding the ice ages, all of Ross County and the surrounding region had been reduced to base level and was part of the widespread Lexington peneplain. The area was subsequently uplifted and eroded so intensely that the only remnants of the original Lexington plain are found on the hilltops in the unglaciated part of the county (some of these rise to 1200 ft). The area of hills and valleys, portions of which are found in the southern part of the study area, lies within and on the western boundary of the Appalachian Physiographic Province. The preglacial drainage of this region was north through the Teays River system, whose main tributaries were the Portsmouth and Marietta rivers. In essence, the Scioto River flowed in reverse with its main stream headwaters located in southern West Virginia, Virginia,

and North Carolina. The flow of these north flowing streams was reversed with the arrival of the glaciers. The initial advancing ice dammed the northern drainage outlets and subsequently formed lakes and ponds between the ice front and the southern divides.

These valley lakes, which were likewise inundated by glacial meltwater, became settling basins for weathering and erosion material. They eventually rose, overflowed the lateral divides to the south, and initiated a downcutting process that has lead to the present southward drainage into the Ohio River. The initial reversal of flow was labeled “static rejuvenation.” Erosional processes and waterfall recession during this period led to the carving of a 150 ft. gorge below the valley of the Teays, called the “deep stage.” The formation of the gorge left a shoulder or huge terrace adjoining the surrounding hills. This terrace was formerly the bottom of the preglacial valley and is known as the “Parker Strath”. Eventually the southern drainage was raised and/or lengthened and subsequent aggradation filled the “deep stage” with depositional material. The source of this material came mainly from another advancing ice sheet, the Wisconsin continental glacier, that retreated about 25,000 years ago. Postglacial erosion by the Scioto and its tributaries has removed much of the fill material and meander scars in the study region have constructed valley terraces of clay and gravel along the stream banks.

Certain unconformable physiographic relationships can be explained by the Pleistocene geological history. The Paint Valley, running from the southwest to the east central portion of the study area, is made up of a portion of the old Teays valley and a new cut. Near its mouth, the Paint is very narrow and steep, characteristic of a youthful valley or water gap, while the upper portions are characterized by wide, flat expanses. Sometimes abandoned

portions of preglacial valleys are left with little or no stream action in proportion to their size (Bownocker 1923).

Under the conviction that regional site studies require disaggregate geographic data, an earnest attempt was made to obtain the most detailed data available on the study area in the form of large scale maps. The ensuing sections in this chapter describe the topographic, hydrologic, and vegetation data in detail, and discuss the efforts to manifest this data in a historical context.

Topography

Topographic data was acquired in the form of four digital line graphs (DLG) from The OSU Center for Mapping. The initial DLGs contained hypsographic data in contour line format. Essentially the DLGs were digitized 1:24,000 scale United States Geological Survey 7.5' quadrangle topographic maps. The base quadrangle maps included were: Andersonville, Chillicothe West, Bourneville, and Frankfort. All were compiled in 1961 and three were revised from aerial photography in 1981 (the Bourneville quad was not updated). Both of the northern quads, Frankfort and Andersonville, had contour intervals of 10 ft, while the two southern quads, Bourneville and Chillicothe West, had intervals of 20 ft (see Figure 5).

All four quads were joined into one coverage and converted into a TIN with a proximal tolerance set at 50 m. This eliminated elevation points from the network that fell within 50 m of other points and produced nearly 350,000 triangles. The lakes and streams data were also employed as hard break line features (see Figure 6).



Figure 2. A map of Ohio showing the location of Ross County

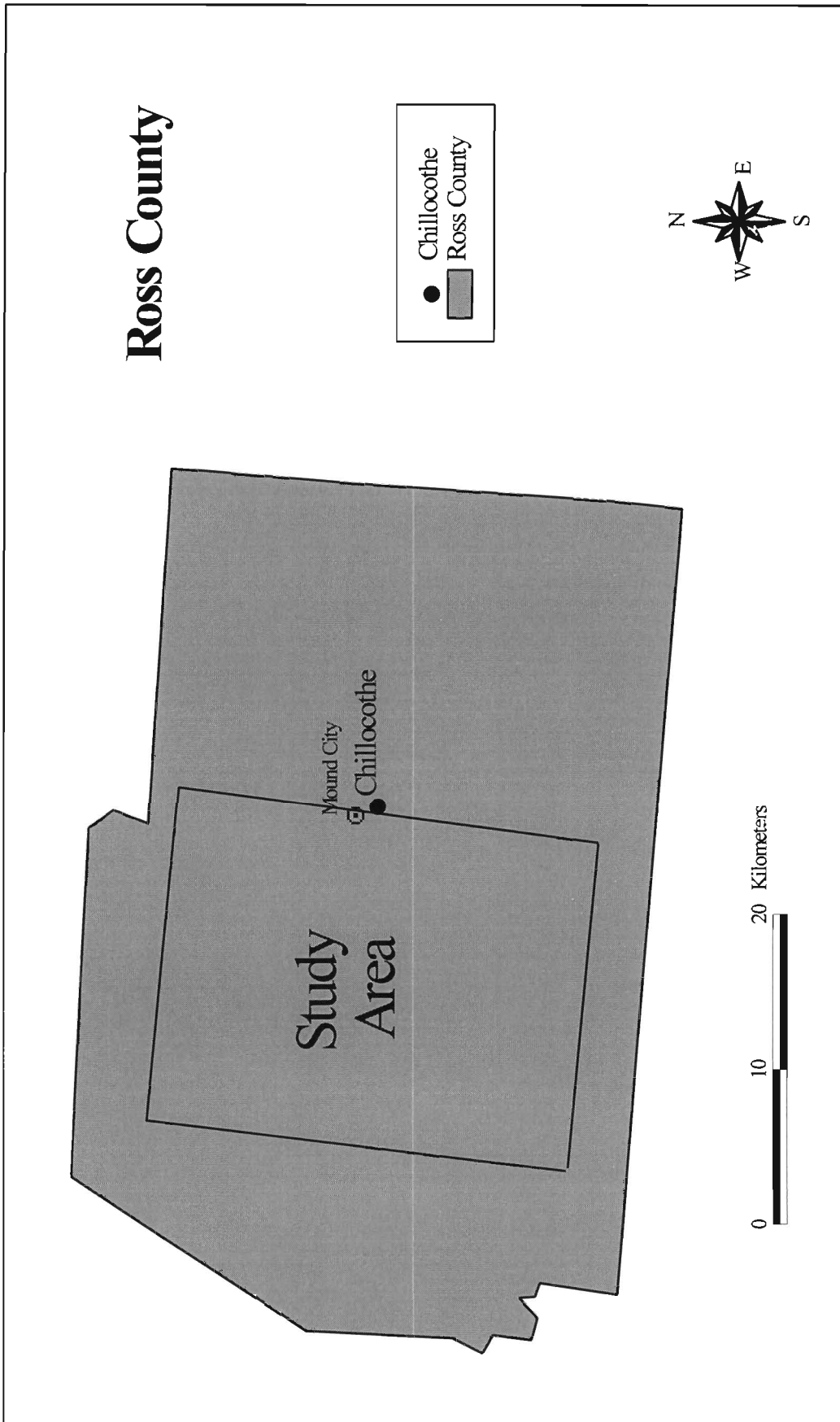
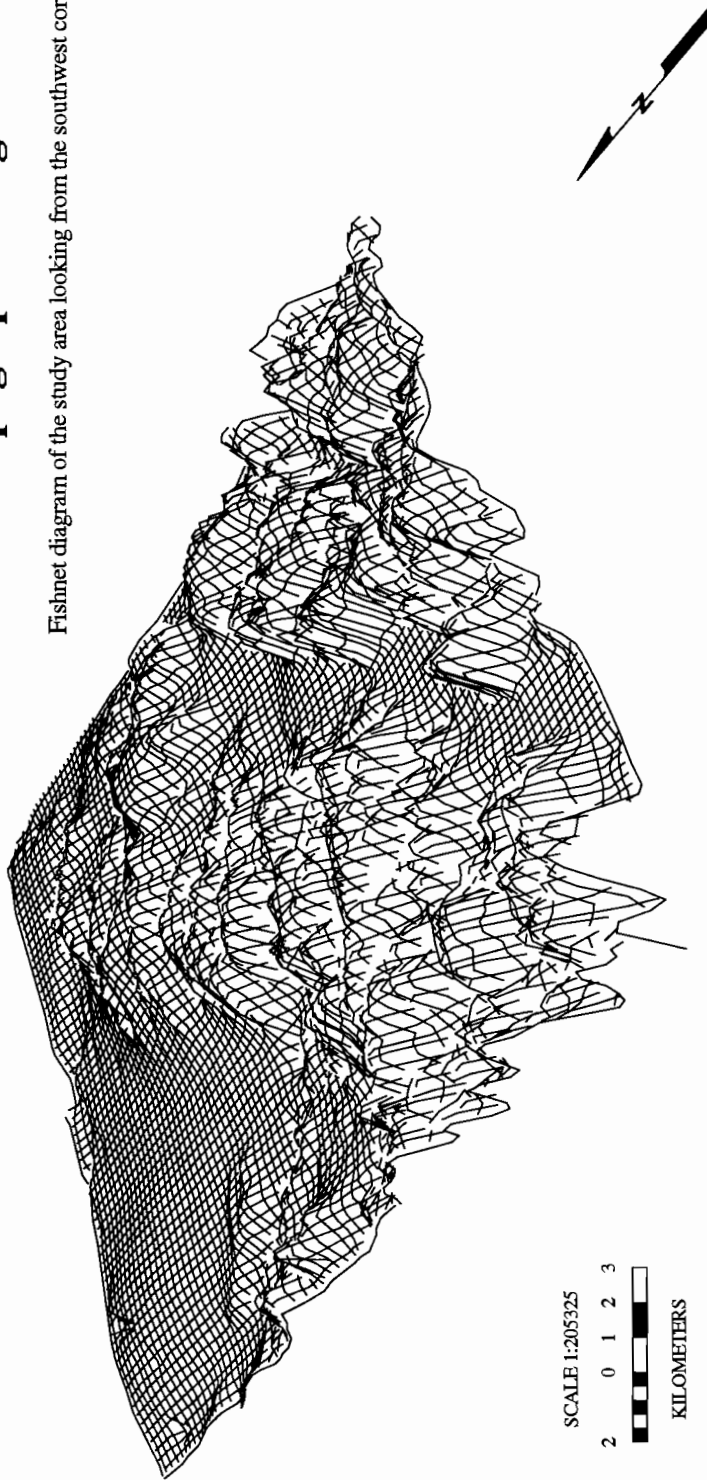


Figure 3. A map of Ross County, Ohio showing the location of the study area

Topographic Diagram

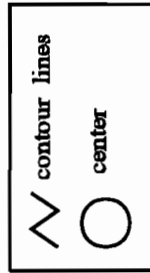
Fishnet diagram of the study area looking from the southwest corner



Note: The vertical scale is increased by a factor of 3.

Figure 4. A 3-D diagram showing the topography of the study area.

Topography



1:12000

Figure 5. A topographic map of the region where the four USGS quads meet clearly shows the mismatch between the 10 ft and 20 ft contour intervals.

Elevation



SCALE 1:208316
1 0 1 2 3 4
KILOMETERS

Elevation in feet

■	611 to 715
■	715 to 818
■	818 to 922
■	922 to 1026
■	1026 to 1129
■	1129 to 1233
■	1233 to 1337



Figure 6. A map showing topography using hypsographic tinting.

The topographic character of the study area is assumed to be essentially unchanged from the time of construction of the Indian mounds to the present since erosional processes have been relatively minor during this period. If it is assumed that erosional processes are generally attributable to variations in climatic factors, and that these variations have not changed dramatically in the past thousand years, it can be concluded that the topography is similar to when the American Indians belonging to the Hopewell culture built their well-known burial mounds, effigy mounds, and fortifications (Gordon 1973), although a completely unchanging landscape is a bold assumption. Man has undoubtedly altered the surface of the terrain in some respects, mostly within the past two centuries. Earth has been removed and added with the construction of roads, buildings, and drainage projects, while other human activities have lead to indirect changes. Crawl (1937) describes the changes in Ross County by first commenting on the lowlands and then the uplands. He explains that swamps have been drained, wet places tiled, small streams straightened, and county ditches dug. These modifications not only change the topography, but also alter the hydrography of the area (see below). Crawl (1937) also notes that thin soils have been severely eroded on the steep hills due to lumbering and clearing for grazing. Because human induced topographical changes have been minor in relation to the overall character of the region, and because there is no concrete source for information on these changes, the terrain alterations are assumed to be insignificant.

Hydrography

Hydrographic data was also obtained from the four original DLGs. The data included information on the location of lakes and streams (see Figure 7), and detailed information on their characteristics. Because of this detailed information, some man-made and human-altered hydrography could be removed from the model in order to more accurately simulate the original lakes and streams. For example, the Ohio and Erie Canal in the northeastern portion of the study area was removed from the model (see Figure 8).

Two coefficients were attached to the hydrographic data. Ponds were determined to be absolute barriers to travel while all other streams, including those categorized as permanent and intermittent, were assigned a coefficient of 1.8, which is the published coefficient for swampy bog (Gioveni and Goldman 1971). Ponds are obviously impossible to walk across and deserve the absolute barrier classification, while streams, on the other hand, can often be crossed by the pedestrian traveler. Since it was determined by direct investigation that most streams in the study area, except the Scioto River and a few sections of Paint Creek, are relatively shallow, a coefficient equal to that of swampy bog was assigned to all of them. It was felt that this was the most appropriate coefficient since it reflects the cost of traversing a terrain most similar to that of a shallow stream. Although water levels appeared at the time of investigation to be at a depth that would allow an average-sized adult to wade across, conditions may easily change. Heavy rains may cause the streams to swell and become impossible to cross on foot. It is assumed that the streams in the study area are all under normal conditions and are therefore crossable by an average pedestrian.

Hydrography in the Study Area



1:200,000

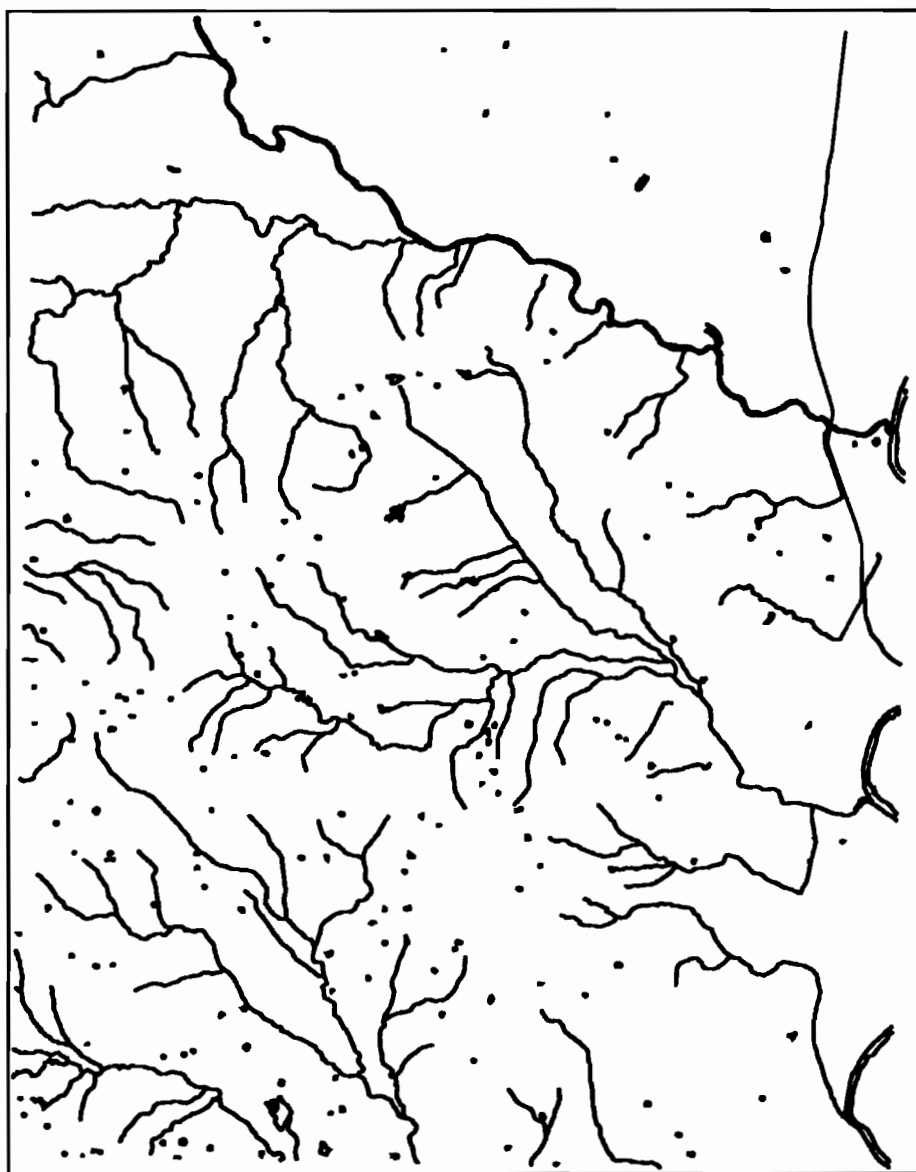


Lakes and Streams



Figure 7. A hydrologic map of the study area

Hydrography in the Andersonville Quad



1:24,000

 Ohio and Erie Canal
 Lakes and Streams



Figure 8. A map showing the removal of man-made hydrographic features in the Andersonville quadrangle

Vegetation

Vegetation data was provided by The Public Utilities Commission of Ohio (PUCO) in the form of a digital map of the natural vegetation of Ohio in pioneer days. The original map was constructed by Gordon (1973) (see Figure 9), while additional data was derived from observations made by Crowl (1937). The vegetation cover of the study region was organized into primary plant associations that were somewhat arbitrarily generalized. These generalizations were necessary because it is impossible to precisely estimate original vegetation and map the area in implicit detail. Rapid changes in topography, exposure, and drainage, would have allowed various vegetation types to interlock in complicated and intricate patterns (Crowl 1937). Vegetation cover was more easily delimited by combining similar types into organized associations. An association was named according to its dominant tree type and was assigned to an area if it was the most common.

The study area in Ross County contains seven of the major associations from the Gordon (1973) map (see Figure 10). These include beech forests, mixed mesophytic forests, oak-sugar maple forests, mixed oak forests, elm-ash swamp forests, bottomland hardwoods, and prairie grasslands. Gordon adopted these major plant associations from more detailed examinations made by Crowl (1937) in "A Vegetation Survey of Ross County". Crowl developed plant classifications for Ross County that were more specific and precise than Gordon's, although locations for the associations were similar. A comparison between both Gordon's and Crowl's categories is given in Table 2.

Ohio Vegetation

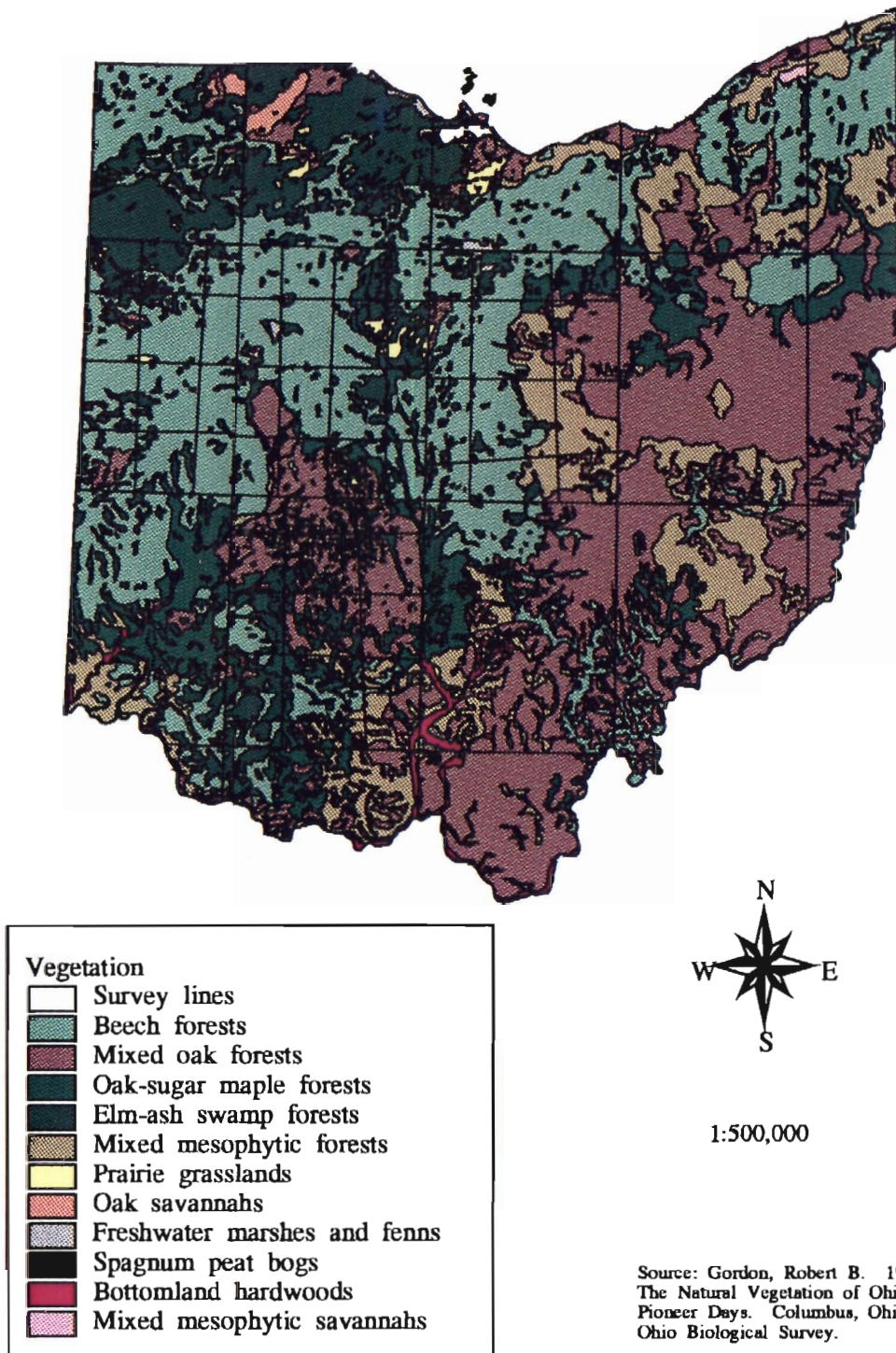
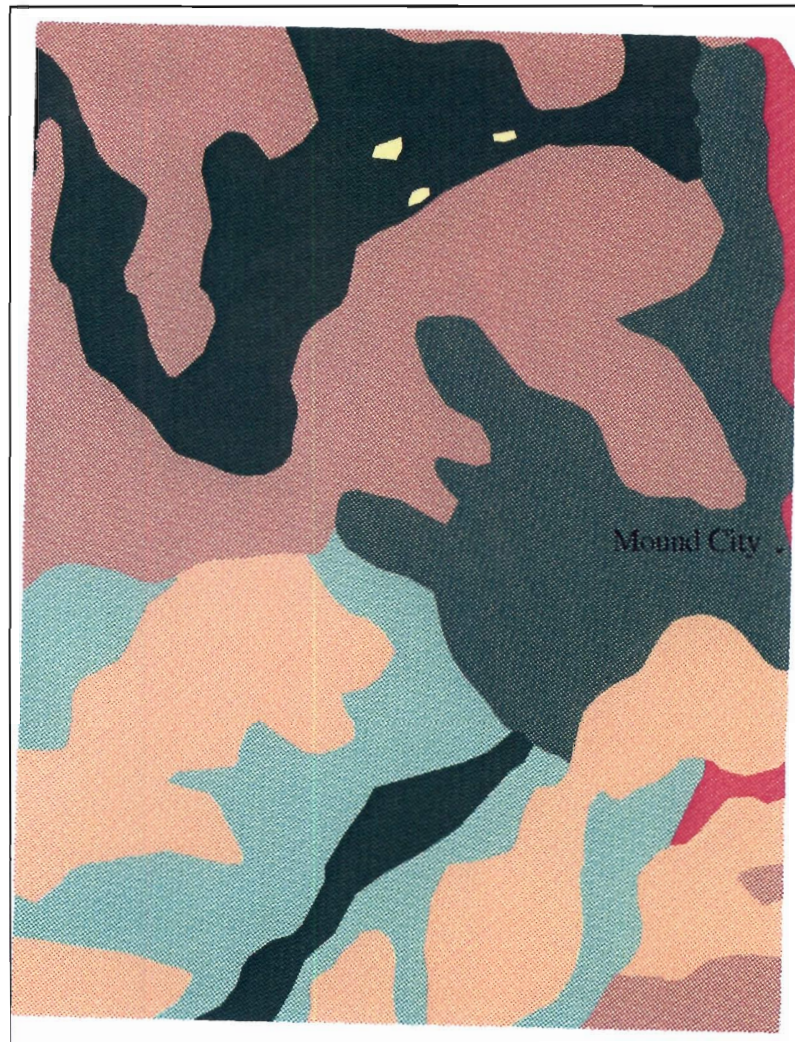


Figure 9. A map showing the natural vegetation of Ohio

Vegetation in the Study Area



SCALE 1:212777
1 0 1 2 3 4
KILOMETERS

- Vegetation**
-  Beech forests
 -  Mixed oak forests
 -  Oak-sugar maple forests
 -  Elm-ash swamp forests
 -  Mixed mesophytic forests
 -  Prairie grasslands
 -  Bottomland hardwoods



Figure 10. A map showing the natural vegetation of the study area.

TABLE 2

A COMPARISON BETWEEN THE GORDON (1973) STATE VEGETATION CATEGORIES AND THE CROWL (1937) ROSS COUNTY CLASSIFICATIONS

Statewide Generalized Categories from Gordon (1973)	Ross County Classifications from Crowl (1937)
Beech Forests	Beech - Maple Association
Mixed Oak Forests	Mixed Oak Association, Oak - Hickory Association, Mixed Oak - Pine Subtype, Oak - Chestnut Associations
Oak - Sugar Maple Forests	Oak - Maple Association, Oak - Maple - Tulip Association
Elm - Ash Swamp Forests	Swamp Forest Association
Mixed Mesophytic Forests	Mixed Mesophytic Association
Prairie Grasslands	Prairie Openings
Bottomland Hardwoods	Flood Plain Subtype of the Swamp Forest Association

The classification rules used to delimit the major vegetation associations specifies that the dominants determine the individual categories. This does not conform with what is required for this project, which is information on vegetation that has the potential to impede pedestrian travel. Large, dominant trees would tend to be quite similar in their capacity to slow down a pedestrian despite their particular species. For example, the difference with respect to impedance between an Oak tree with a 4 ft circumference and an Elm tree with the same dimensions is negligible. The above data concerning dominants therefore appears meaningless with respect to pedestrian impedance. Fortunately, dominants have a direct relationship with the vegetation below, which does have the potential to impede pedestrian

travel. Crowl (1937) attaches a coordinating understory and herbaceous groundcover with the respective dominants. A summary of his associations is shown in Table 3.

TABLE 3
UNDERSTORY AND HERBS ASSOCIATED WITH THE MAJOR VEGETATION CATEGORIES

Associations (Dominants)	Understory	Herbs
Beech - Maple Association	<i>Carpinus caroliniana</i> , <i>Ostrya virginiana</i> , <i>Cynoxylon floridum</i> , <i>Crataegus</i> spp.	<i>Sanguinaria canadensis</i> , <i>Bicuculla cucularia</i> , <i>Podophyllum peltatum</i> , <i>Phlox divaricata</i> , <i>Dryopteris marginalis</i> , <i>Polystichum acrostichoides</i> , <i>Geranium maculatum</i> , <i>Heuchera americana</i> , <i>Hydrophyllum macrophyllum</i> , <i>Aralia racemosa</i> , <i>Pilea pumila</i> , <i>Aster</i> spp.
Mixed Oak Association, Oak - Hickory Association, Mixed Oak - Pine Subtype, Oak - Chestnut Associations	<i>Cynoxylon floridum</i> , <i>Viburnum acerifolium</i> , <i>Ostrya virginiana</i> , <i>Amelanchier canadensis</i> / <i>Carpinus caroliniana</i> , <i>Cercis canadensis</i> , <i>Rhus glabra</i> / scrub pine / <i>Vaccinium vacillans</i> , <i>Gaylussacia baccata</i> , <i>Polycodium stamineum</i>	<i>Smilax rotundifolia</i> , <i>Eupatorium urticaefolium</i> , <i>Helianthus microcephalus</i> , <i>Asclepias quadrifolia</i> , <i>Polystichum acrostichoides</i> , <i>Uvularia sessilifolia</i> , <i>Desmodium nudiflorum</i> , <i>Vagnera racemosa</i> , <i>Hystrix hystrix</i> , <i>Solidago nemoralis</i> / <i>Rubus allegheniensis</i> , <i>Asarum canadensis</i> , <i>Desmodium</i> spp., <i>Adiantum pedatum</i> , <i>Viola</i> spp., <i>Geranium maculatum</i> , <i>Antennaria plantaginifolia</i> , <i>Senecio obovatus</i> / <i>Mitchella repens</i> , <i>Gaultheria procumbens</i> , <i>Polypodium virginianum</i>
Oak - Maple Association, Oak - Maple - Tulip Association	<i>Carpinus caroliniana</i> , <i>Viburnum prunifolium</i> , <i>Cynoxylon floridum</i> , <i>Hamamelis virginiana</i>	<i>Sanicula canadensis</i> , <i>Washingtonia claytoni</i> , <i>Urticastrum divaricatum</i> , <i>Adiantum pedatum</i> , <i>Rubus</i> spp., <i>Potentilla canadensis</i> , <i>Podophyllum peltatum</i> , <i>Aster divaricatus</i>
Swamp Forest Association	<i>dry phase</i> : <i>Ostrya virginiana</i> , <i>Corylus americana</i> , <i>Benzoin aestivale</i> , <i>Sambucus canadensis</i> <i>wet phase</i> : <i>Carpinus caroliniana</i> , <i>Cephalanthus occidentalis</i> , <i>Cornus stolonifera</i> , <i>Alnus rugosa</i>	<i>dry phase</i> : <i>Ambrosia trifida</i> , <i>Cirsium altissimum</i> , <i>Ipomoea pandurata</i> , <i>Phytolacca decandra</i> , <i>Erythronium americanum</i> , <i>Dryopteris thelypteris</i> , <i>Rudbeckia lacinata</i> , <i>Asclepias syriaca</i> , <i>Thalictrum polygamum</i> , <i>Ranunculus recurvatus</i> , <i>Rubus occidentalis</i> , <i>Viola striata</i> <i>wet phase</i> : <i>Lobelia syphilitica</i> , <i>Helianthus tuberosus</i> , <i>Bidens</i> spp., <i>Carex</i> spp., <i>Ranunculus septentrionalis</i> , <i>Caltha palustris</i> , <i>Eupatorium maculatum</i> , <i>Spathyema foetida</i> , <i>Onoclea sensibilis</i> , <i>Impatiens</i> spp.
Mixed Mesophytic Association	same as beech - maple association, but generally richer in the number of species present	same as beech - maple association, but generally richer in the number of species present
Prarie Openings	Non - existent	<i>Sorghastrum nutans</i> , <i>Acerates floridada</i> , <i>Asclepias verticillata</i> , <i>Rudbeckia hirta</i> , <i>Heliopsis scabra</i> , <i>Solidago canadensis</i> , <i>Ratibida pinnata</i> , <i>Kuhnia eupatorioides</i> , <i>Lacinaria scariosa</i> , <i>Euthamia graminifolia</i> , <i>Tithymalopsis corollata</i> , <i>Cassia medsgeri</i> , <i>Koellia flexuosa</i>
Flood Plain Subtype of the Swamp Forest Association	Not Provided	Not Provided

Source: Crowl, Gordon Sherman. 1937. A vegetation Survey of Ross County. M.S. Thesis, The Ohio State University.

Although the location of vegetation with the potential to affect the pedestrian traveler is now known, it must be classified according to the known terrain coefficients.

Known terrain coefficients for vegetation are based upon the thickness of the understory and herbaceous groundcover. Because thickness of groundcover is not dependent upon species, an assignment of terrain coefficients based only upon the associations found in Table 3 would be invalid. Since the type of species has little to do with the potential to impede pedestrian travel, a more accurate assignment would reflect the different vegetation densities associated with the different categories. Unfortunately, thickness of groundcover is not dependent upon the different associations but rather upon the age of the canopy dominants. Climax or mature dominants tend to inhibit groundcover and result in a relatively open forest floor, while young trees promote heavy groundcover and a thickly vegetated forest floor. Age is furthermore dependent upon the occurrence and extent of forest fires, tornadoes, ice storms, and high wind thunderstorms. Since this information is impossible to obtain for the time period under investigation it was assumed that the entire region at that period was characterized by mature dominants. In this context, all vegetation having a canopy is assigned a terrain coefficient of 1.2 (light brush), while that without a canopy, namely prairie openings, is assigned a terrain coefficient of 1.5 (heavy brush) (Boerner 1995).

CHAPTER V

A GIS BASED APPROACH

Introduction

Since physiological research has obviously been far more extensive and precise, and has included a larger number of geographic and aspatial variables than the simple travel time methods, it is applied in this project mainly through the use of the Pandolf, et al. (1977) equation implemented within a workstation-based GIS (Arc-Info). Determination of the energy cost of walking from this equation is seen as being influenced by five variables. Since two of these variables specifically deal with geographic factors: gradient and the terrain coefficient, it appears that GIS technology would be a useful tool for implementing the walking equation in a practical situation. This chapter begins by discussing the general methodology employed in the project, continues with a section on data and equation manipulations, presents the main analyses performed, and concludes with a discussion of the results.

Methodology

The ultimate goal of this project was to define a surface representing human accessibility on foot to a selected Indian burial mound site in Ross County, Ohio. There is

is not to provide new insights into the early cultures of the area, but to illustrate the potential of this fledgling operational analysis system. Accessibility is generally defined as a quantitative measure of a person's ability to move from one destination to another. The cost of pedestrian movement is most accurately measured in terms of energy consumption and this, in turn, has been determined to be highly influenced by five specific variables: pedestrian weight, load weight, terrain, walking speed, and slope (Pandolf, et al. 1977). Only two of these variables vary across space: the geographic components of gradient and terrain. These two fundamental components can be dealt with in the GIS, while the aspatial components can be dealt with in a traditional fashion. The general methodology followed here is based on the cartographic modeling and map algebra techniques devised by Tomlin (1990). The Grid module within Arc-Info complies with Tomlin's concepts and also contains tools that are specifically designed for modeling accessibility. Specifically these tools include the cost distance functions of *Costdistance*, and *Pathdistance*.

These cost distance functions are similar to simple Euclidean distance functions, but instead of calculating actual distance from one point to another they determine the accumulated travel cost from each cell to the source cell. Weighted distance functions apply distance in cost units, not geographic units. The cost grid assigns an impedance in some uniform measurement form that depicts the cost of moving through any particular cell. The value of each cell in the cost grid represents the cost-per-unit distance of passing through the cell, where a unit distance corresponds to the cell width. These costs may be stated in travel time, dollars, preference, or in this case metabolic cost. The *Costdistance* function creates an output grid in which each cell is assigned the accumulative cost to the source cell. This

function is rudimentary when compared to the calculations made in *Pathdistance*. It calculates the accumulative cost while compensating for the actual surface distance traveled and the horizontal and vertical factors influencing the cost of travel. The compensating characteristics of the *Pathdistance* function make it an ideal tool for the mobility model developed in this thesis.

The general procedure for implementing the model involved two main steps, data manipulation and analysis. The intent of the data manipulation step was to create a terrain layer in order to satisfy the terrain variable and to accurately account for gradient. The analysis step focused upon processing the data so as to create a layer which indicated relative energy consumption for movement from all points in the study area to the site. All of this was based upon initially placing the data into a cell-based, raster environment, which first required that an important decision be made concerning cell resolution.

The decision on cell size is based on accepted guidelines and on following the fundamental principle that a fine resolution is required for a detailed archaeological study. General guidelines concerning cell size state that the resolution of a resultant grid should be the same or coarser than the input data. If only this rule is followed, cell size would be set at 3 m due to the fact that 0.125 mm is the resolution of the original DLG 1:24,000 scale maps. A 3 m cell size was calculated from simple scale transformations of these maps. A 1:24,000 scale simply means that 1 m on the map means 24,000 m in the real world. A transformation of these figures indicates that 1 mm on the map equals 24 m in the real world, or 0.125 mm on the map equals 3 m in the real world. Since the accuracy of the digitizer used to make the DLGs was around 0.125 mm (U. S. Department of the Interior, 1990), the

resolution of the grid should not fall below this threshold according to the guideline stated above. Unfortunately cell size decisions are not always made according to simple rules. An inverse relationship between processing speed and precision more often dictates the outcome of decisions made concerning cell size. Greater precision and larger numbers of cells results in slower processing speeds. The size chosen for this thesis is therefore 12 m x 12 m, which results in a matrix of 2280 rows and 1760 columns for the entire study area. The total size of the grid utilized is just over four million cells. This size is large enough to be processed relatively fast (7.5 hours) and small enough to satisfy the requirement for a fine resolution.

After establishing the cell size, the original data were transformed from a vector based format to the grid format in Arc-Info. Polygon and line coverages were directly converted while the TIN was transformed into a lattice. The original coverages, the items chosen for conversion in the attribute tables, the original data type, and the grid coverage names for the study area in Ross County are listed in Table 4.

TABLE 4

TRANSFORMATION OF DATA INTO THE GRID MODULE

Data Category (Item)	Original Data Type	Grid Coverage Name
Vegetation (Lcov)	Polygon	ROSSVEGE
Lakes (Minor 1)	Polygon	ROSSLAKE
Streams (Minor 1)	Line	ROSSHYD1
Streams (Minor 2)	Line	ROSSHYD2
Elevation	TIN	ROSSELEV

Manipulations

Simple map algebra operations were performed in order to calculate the terrain coefficient layer, resulting in a single grid containing all the terrain coefficients across the study region. Each cell in this layer, called ROSSCOST, had a specific value of impedance related to whether the surface was swampy bog, light brush, heavy brush, and so forth. This step involved a multitude of reclassifications and additions, which required a series of 12 individual steps. Due to the fact that values within grid cells must be integers, impedance values were increased tenfold. This allowed for them to be input into the model while retaining their accurate metabolic cost relationships. For example, an impedance of 1.8 was altered to 18. The 12 step process is summarized below, while the resulting grid is depicted in Figure 11.

Step 1: ROSSVEGE was reclassified assigning 12 to 1, 2, 3, 4, 5, and 10 while assigning 15 to 6 (1 was the PUCO coding for beech forests, 2 was for mixed oak, 3 was for oak-sugar maple, 4 was for elm-ash swamp forests, 5 was for mixed mesophytic, 6 was for prairie grasslands, and 10 was coding for bottomland hardwoods). This step assigned an impedance of 12 to all vegetation except prairie grasslands which was allocated an impedance of 15. The new grid, called ROSSVEGE2, contained values of 12 and 15.

Step 2: ROSSLAKE was reclassified assigning 421 to 100, which was the original coding for lakes, while assigning 200 to 0 (0 was the DLG coding for an island). The new grid was called ROSSLAKE2 and it contained values of 100, 200, and NODATA.

Step 3: Cells with values of NODATA in ROSSLAKE2 were assigned a value of 0 and the new grid was called ROSSLAKE3. It contained values of 0, 100, and 200.

Step 4: ROSSVEGE2 was added to ROSSLAKE3 and the new grid was called ROSSIMPEDE1. Values in this layer were 112, 212, 12, and 15.

Step 5: ROSSIMPEDE1 was reclassified assigning 12 to 212 and 1000 to 112, resulting in a new grid called ROSSIMPEDE2 with values of 12, 15, and 1000.

Step 6: ROSSHYD1 was reclassified assigning 0 to 0, 200 to 0 (200 was the DLG coding for shoreline), 204 to 0 (204 was the DLG coding for apparent limit), 412 to 18 (412 was the DLG coding for stream), 414 to 0 (414 was the DLG coding for ditch or canal), 605 to 18 (605 was the DLG coding for right bank), and 606 to 18 (606 was the DLG coding for left bank). The new grid, called ROSSHYD1A, contained values of 0 and 18.

Step 7: ROSSHYD2 was reclassified assigning -9999 to 0, 0 to 0, 200 to 0, 202 to 0 (202 was the DLG coding for closure line), 412 to 18, 1107 to 0, 605 to 18, 606 to 18, and 610 to 18 (610 was the DLG coding for intermittent stream). The new grid was called ROSSHYD2A and it contained values of 0 and 18.

Step 8: ROSSHYD1A and ROSSHYD2A were added to form the new layer ROSSHYD3. This layer housed values of 0, 18 and 36.

Step 9: ROSSHYD3 was reclassified assigning 36 to 18. The new layer was called ROSSHYD4.

Step 10: ROSSIMPEDE2 and ROSSHYD4 were added to form ROSSIMPEDE3 which contained the values 12, 15, 30, 33, 1000, and 1012.

Step 11: ROSSIMPEDE3 was reclassified assigning 12 to 12, 15 to 15, 30 to 18, 33 to 18, 1000 to 1000, and 1018 to 1000. The new layer was called ROSSIMPEDE4.

Step 12: The final step involved assigning NODATA to values of 1000 in ROSSIMPEDE4. This transformed impedences of 1000 into absolute barriers. The final layer was entitled ROSSCOST (see Figure 11).

The second portion of the data manipulation involved accounting for gradient. This was approached by first operationally defining gradient. The Pandolf (1977) equation defines gradient as a percentage, which is incompatible with the manner in which the *Pathdistance* function in the Grid module portrays gradient. It uses degrees for the calculations. It is therefore apparent that gradient as defined by Pandolf (1977) must be converted into a format that is acceptable to Arc-Info. This was accomplished by altering Pandolf's original equation, solving for M, computing coefficients, and converting from percentages to degrees. All elements of the original equation were held constant by initializing the terrain coefficient at 1, using an average weight of 78.2 kilograms, adding no load, and setting the walking speed at 4.83 kilometers per hour. This is the United States Army pace for long hikes (Sussman and Goode 1980). The new form of the equation is thus:

$$M = 1.5(78.2) + 2.0(78.2)(0/78.2)^2 + 1(78.2 + 0)[1.5(4.83)^2 + 0.35(4.83)G] \quad (5)$$

$$M = 117.3 + 0 + 78.2[34.99 + 1.6905G] \quad (6)$$

$$M = 117.3 + 2736.218 + 132.1971G \quad (7)$$

$$M = 2853.518 + 132.1971G \quad (8)$$

The equation was then solved for M using percentage gradients that ranged from -10% to +25%. The Pandolf equation was not designed for extremes in gradient data and has only been proven effective within the above range. M values for the different gradients were then divided by the M value associated with a 0% slope in order to compute vertical factors for each gradient percentage so that they could be utilized in a vertical factor table. The percentage gradients were then converted into degrees so that they would also be compatible with the *Pathdistance* function. The formula used to convert from percentages to degrees is shown below, while the percentages, degrees, and coefficients are shown in table 5.

$$\text{Degrees} = \tan^{-1} (\text{Percentage}/100) \quad (9)$$

TABLE 5
PANDOLF (1977) SLOPE COEFFICIENTS

Percent grade	Degrees	Watts	Coefficients
-10	-5.7106	1531.547	0.536722
-9	-5.1428	1663.744	0.58305
-8	-4.5739	1795.941	0.629378
-7	-4.0042	1928.138	0.675706
-6	-3.4336	2060.335	0.722033
-5	-2.8624	2192.533	0.768361
-4	-2.2906	2324.73	0.814689
-3	-1.7184	2456.927	0.861017
-2	-1.1458	2589.124	0.907344
-1	-0.5729	2721.321	0.953672
0	0	2853.518	1

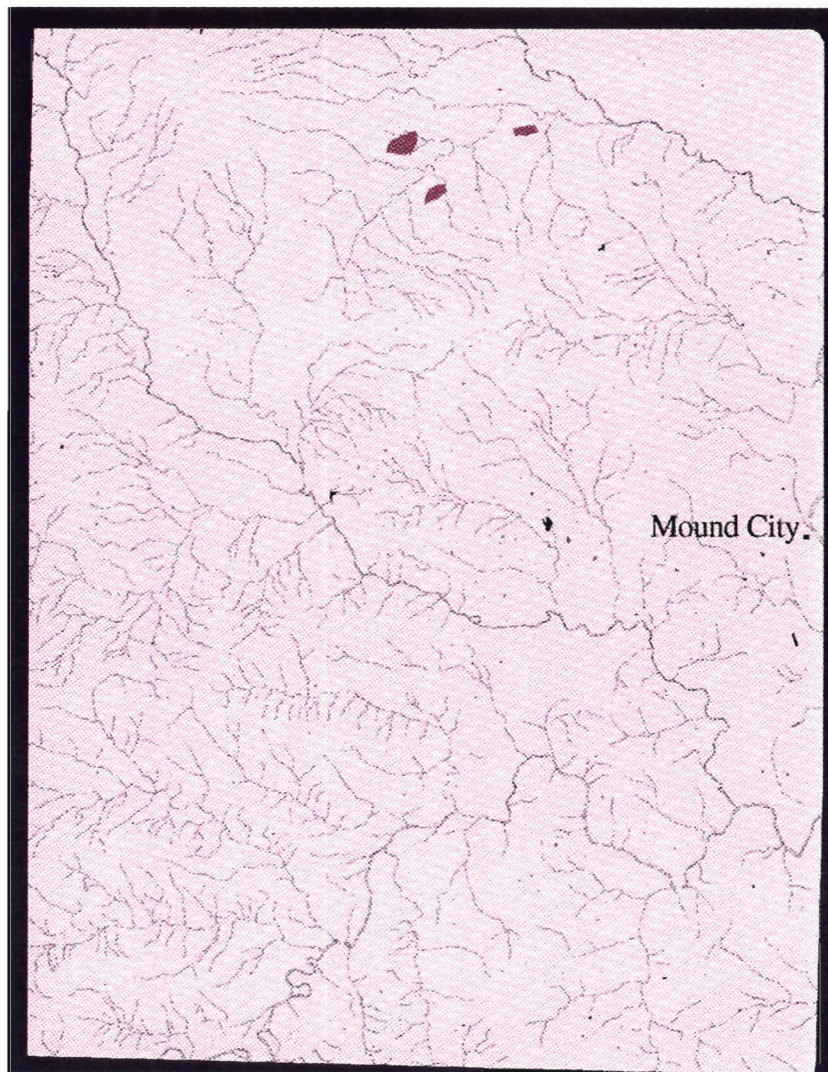
TABLE 5 - *CONTINUED*

Percent grade	Degrees	Watts	Coefficients
1	0.5729	2985.715	1.046328
2	1.1458	3117.912	1.092656
3	1.7184	3250.109	1.138983
4	2.2906	3382.306	1.185311
5	2.8624	3514.504	1.231639
6	3.4336	3646.701	1.277967
7	4.0042	3778.898	1.324294
8	4.5739	3911.095	1.370622
9	5.1428	4043.292	1.41695
10	5.7106	4175.489	1.463278
11	6.2773	4307.686	1.509605
12	6.8428	4439.883	1.555933
13	7.4069	4572.08	1.602261
14	7.9696	4704.277	1.648589
15	8.5308	4836.475	1.694916
16	9.0903	4968.672	1.741244
17	9.6480	5100.869	1.787572
18	10.2040	5233.066	1.8339
19	10.7580	5365.263	1.880227
20	11.3100	5497.46	1.926555
21	11.8598	5629.657	1.972883
22	12.4074	5761.854	2.019211
23	12.9528	5894.051	2.065539
24	13.4957	6026.248	2.111866
25	14.0362	6158.446	2.158194

Additional alterations, which proved to be extensive, were necessary because some of the gradient data in the study area substantially exceeded the threshold limits of Pandolf's (1977) equation. Gradient data in Ross County ranged from 0 to 743.196%, therefore any values

that were beyond those studied by Pandolf were considered absolute barriers to normal travel. Fortunately other researchers have pursued the effects of extremes in gradient data on the metabolic cost of walking. Brannan (1992) presents an excellent overview of the relationship between slope and energy expenditure. In summary of his work, expenditure is lowest at around a gradient of -10%, while it increases in both the negative and positive directions from this origin, more so in the positive direction. The studies he reviews are also limited by certain thresholds, but these are larger than those set by Pandolf (1977). The most extensive range is provided by McDonald (1961) where energy expenditure in calories per kilometer are given from -40% to +40% in 5% increments (Brannan 1992). A copy of this table and associated coefficients is shown in Table 6. Iterations are calculated in order to provide energy expenditure values for slopes that are in between the increments.

Friction Values in the Study Area



SCALE 1:201959
1 0 1 2 3 4
KILOMETERS

Friction Categories

-  Light Brush
-  Heavy Brush
-  Swampy Bog

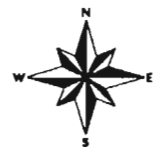


Figure 11. A map showing friction values based on terrain coefficients from Giovoni and Goldman (1971).

TABLE 6

McDONALD (1961) SLOPE COEFFICIENTS

Percent grade	Degrees	Calories per Kilometer	Coefficients
-40	-21.8014	88.4	1.7470
-35	-19.2900	76.8	1.5178
-30	-16.6992	72.6	1.4348
-25	-14.0362	69.2	1.3676
-20	-11.3099	60	1.1858
-15	-8.5308	39.6	0.7826
-10	-5.7106	36.6	0.7233
-9	-5.1428	37.2	0.7352
-8	-4.5739	37.9	0.7490
-7	-4.0042	38.5	0.7609
-6	-3.4336	39.2	0.7747
-5	-2.8624	39.8	0.7866
-4	-2.2906	42	0.8300
-3	-1.7184	44.1	0.8715
-2	-1.1458	46.3	0.9150
-1	-0.5729	48.4	0.9565
0	0	50.6	1
1	0.5729	55.6	1.0988
2	1.1458	60.5	1.1957
3	1.7184	65.5	1.2945
4	2.2906	70.4	1.3913
5	2.8624	75.4	1.4901
6	3.4336	83.4	1.6482
7	4.0042	91.3	1.8043
8	4.5739	99.3	1.9625
9	5.1428	107.2	2.1186
10	5.7106	115.2	2.2767
11	6.2773	120.2	2.3755
12	6.8428	125.2	2.4743

TABLE 6 - CONTINUED

Percent grade	Degrees	Calories per Kilometer	Coefficients
13	7.4069	130.2	2.5731
14	7.9696	135.2	2.6719
15	8.5308	140.2	2.7708
16	9.0903	146	2.8854
17	9.6480	151.9	3.0020
18	10.2040	157.7	3.1166
19	10.7580	163.6	3.2332
20	11.3100	169.4	3.3478
21	11.8598	176.1	3.4802
22	12.4074	182.8	3.6126
23	12.9528	189.4	3.7431
24	13.4957	196.1	3.8755
25	14.0362	202.8	4.0079
30	16.6992	239.8	4.7391
35	19.2900	281.2	5.5573
40	21.8014	325.2	6.4269

A comparison between the coefficients calculated for Pandolf (1977) and those calculated for McDonald (1961) indicates distinct contrasts between coefficients provided for the same gradient. The figures shown in Table 7 illustrate this contrast more clearly. Also within Table 7 is a column for coefficients calculated from Imhof's (1968) travel time equation. A graph of the resulting slope-cost relationships is shown in Figure 12. Because of this incongruence between coefficients computed for the same gradient three separate accessibility cases are pursued in the analysis step. One case is calculated that follows the gradient coefficients computed for Pandolf's (1977) equation, another that follows the gradient coefficients computed for McDonald's (1961) equation, and a final that follows the Imhof (1968)

coefficients. Three maps are eventually produced, each depicting a slightly different accessibility based on each researcher's own equation.

TABLE 7
COMPARISON BETWEEN DIFFERENT SLOPE COEFFICIENTS

Gradient in percent	Pandolf (1977)	McDonald (1961)	Imhof (1968)
-40	NA	1.747036	2.857702
-35	NA	1.517787	2.398886
-30	NA	1.434783	2.013713
-25	NA	1.367589	1.690451
-20	NA	1.185771	1.419069
-15	NA	0.782609	1.191244
-10	0.536722	0.72332	1
-5	0.768361	0.786561	0.83945
0	1	1	1
5	1.231639	1.490119	1.191244
10	1.463278	2.27668	1.419069
15	1.694916	2.770751	1.690451
20	1.926555	3.347826	2.013713
25	2.158194	4.007905	2.398886
30	NA	4.73913	2.857702
35	NA	5.557312	3.404096
40	NA	6.426877	4.055314

Slope-Cost Relationships

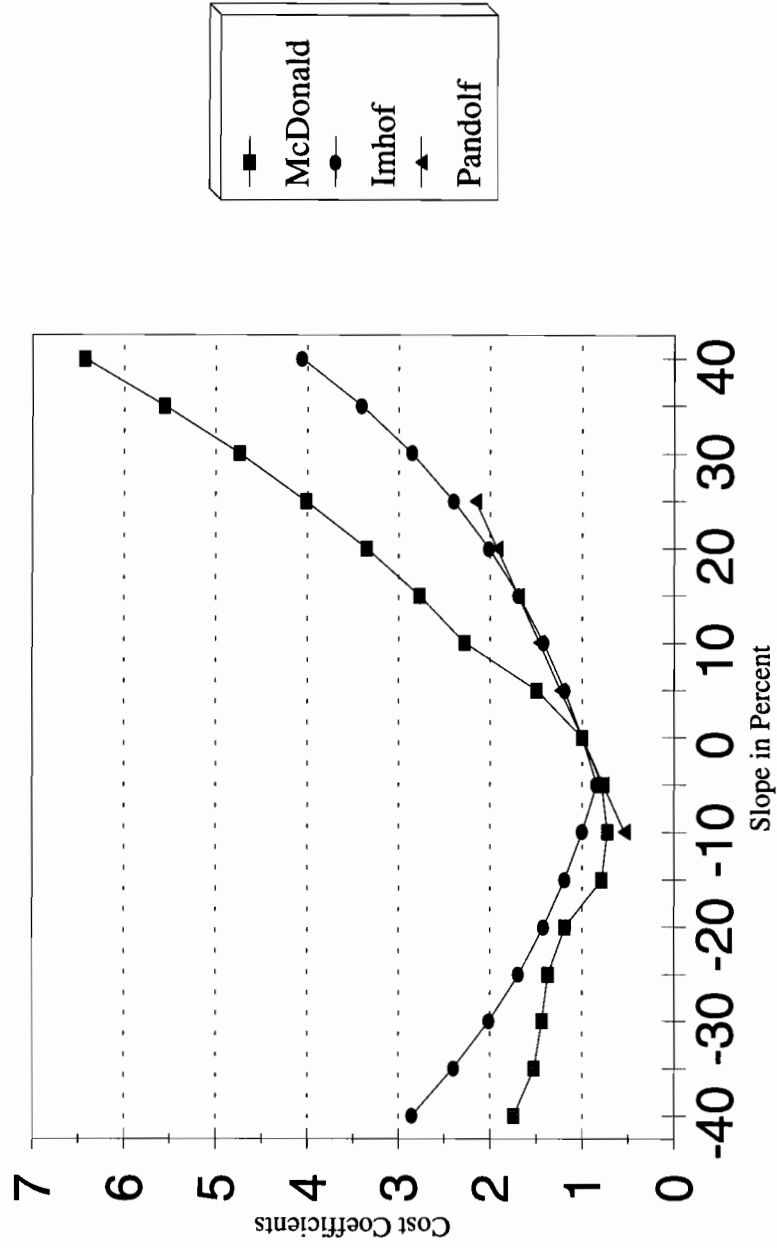


Figure 12. A graph showing the slope-cost relationships between different researcher's equations

Analysis

As an analysis, the *Pathdistance* function was used in order to discover the most difficult and least difficult regions to travel across to the Mound City National Monument from all other locations in the study area. *Pathdistance* determines the minimum accumulative-travel cost to a source from each cell location on a grid while compensating for non-topographical impedences, the actual surface distance that must be traveled, and the topographical factors influencing the total cost of moving from one location to another. The analysis process involved defining the location of the source Mound City site and then calculating accessibility according to the ROSSCOST friction layer and the vertical factor tables associated with each researcher.

The location of the Mound City site was defined by investigating Indian mound research and a hardcopy USGS 1:24,000 topographic quadrangle map. The center of the Mound City Group was used as the origin for the analysis and a grid, called MOUNDS, was constructed showing this location. Its Universal Transverse Mercator (UTM) coordinates and grid coding are shown in Table 8.

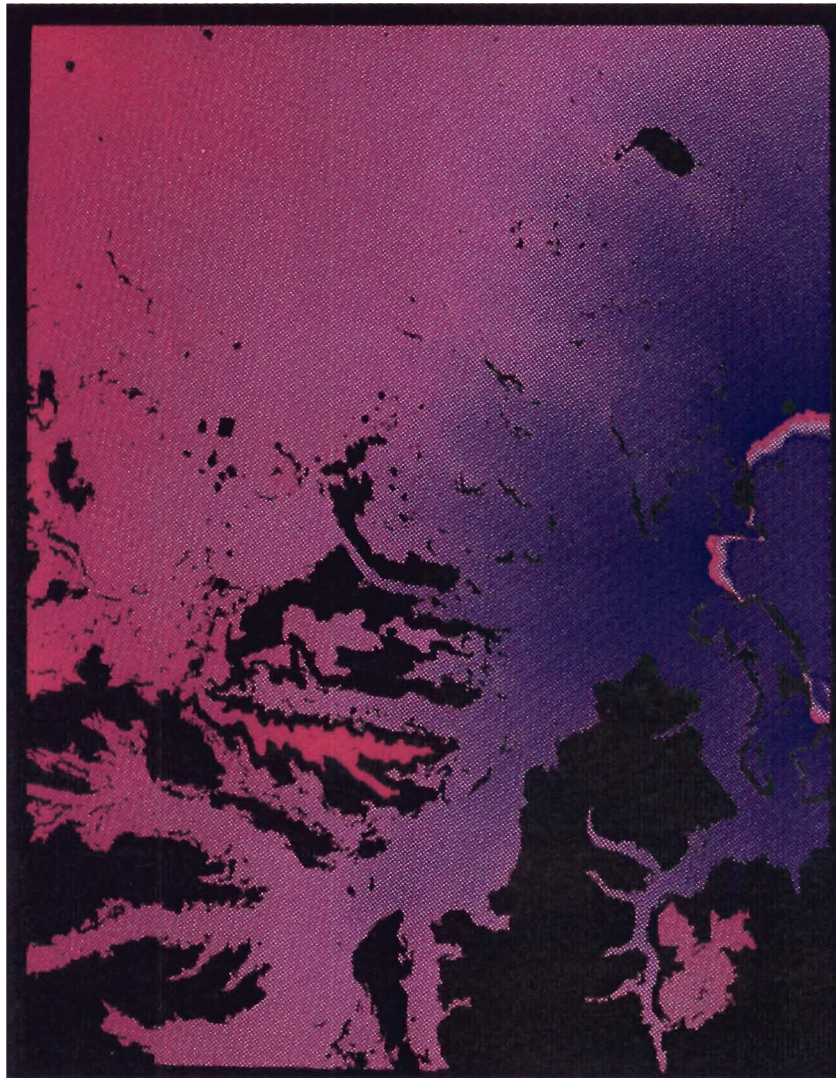
TABLE 8
COORDINATES FOR THE MOUND CITY CENTROID

Site Name	Coordinates (UTM zone 17)	Coding
Mound City	327500 4360250	3

Mobility to the site was calculated using the *Pathdistance* function in Arc-Info. The source grid used was MOUNDS, the cost grid used was ROSSCOST, the surface grid and the vertical factor grid used was ROSSELE, while the vertical factor parameters used were the Pandolf coefficients table, the McDonald coefficients table, and the Imhof coefficients table. The resulting grids were called ROSSPATH1, ROSSPATH2, and ROSSPATH3 (see Figures 13, 14, 15).

As a concluding final manipulation, ROSSPATH1, ROSSPATH2, and ROSSPATH3 were sliced into 8 categories for a better visualization. The new layers, called ACCESS1, ACCESS2, and ACCESS3 respectively, can ultimately be compared to a case calculated across an isotropic surface where there are essentially no impedances (see Figures 17, 18, 19). ISOTROPIC represents this layer (see Figure 16).

Metabolic Costs from Pandolf (1977)



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KILOMETERS

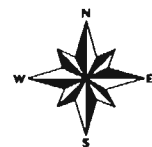
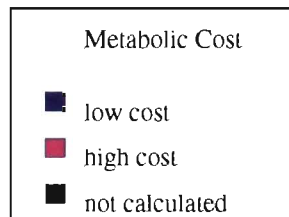
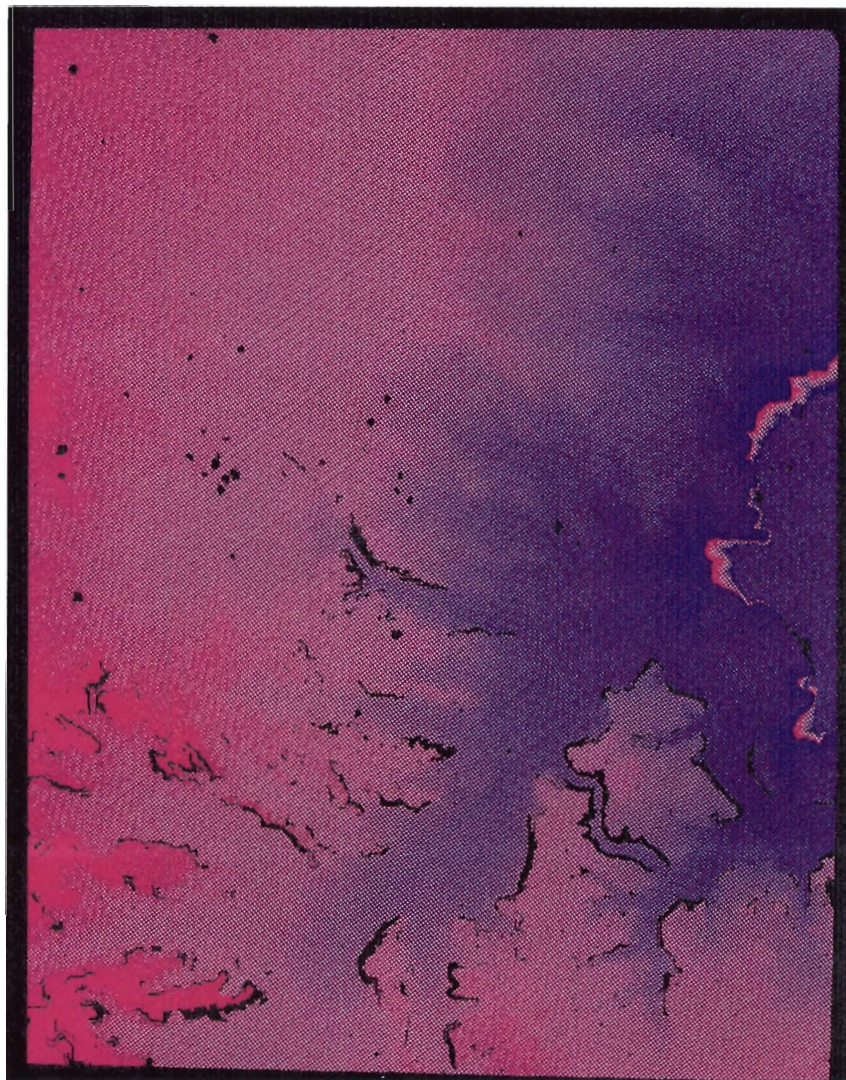


Figure 13. A map showing metabolic costs of walking based on the Pandolf (1977) case.

Metabolic Costs from McDonald (1961)



SCALE 1:199898
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KILOMETERS

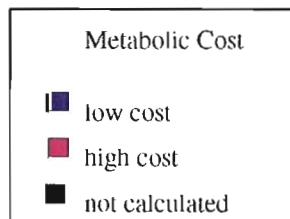


Figure 14. A map showing metabolic costs of walking based on the McDonald (1961) case.

Metabolic Costs from Imhof (1968)



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KILOMETERS

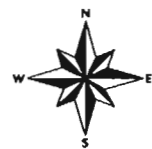
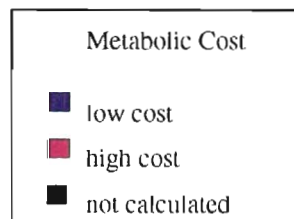
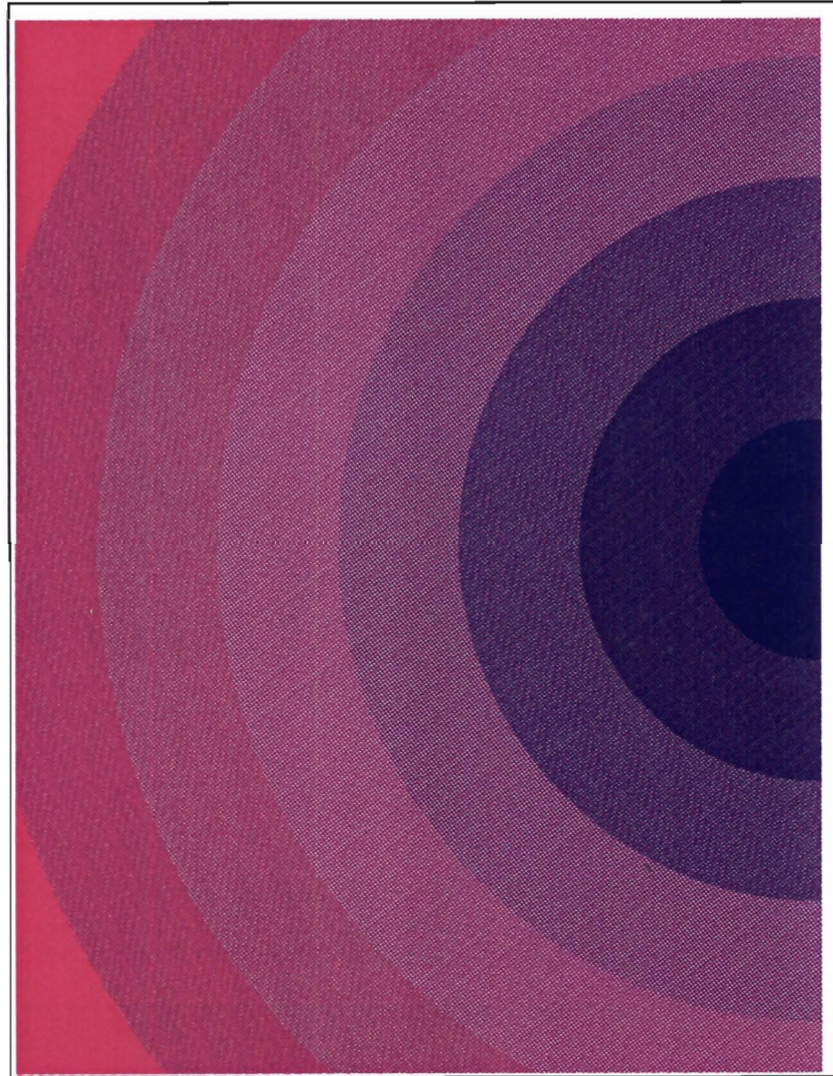


Figure 15. A map showing metabolic costs of walking based on the Imhof (1968) case.

Isotropic Accessibility



SCALE 1:199472
0 1 2 3 4
KILOMETERS

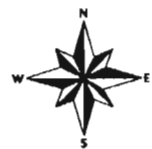
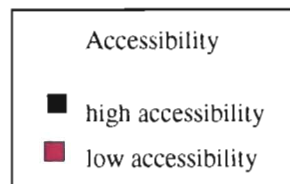


Figure 16. A map showing walking accessibility based on an isotropic surface.

Pandolf Accessibility



SCALE 1:199898
1 0 1 2 3 4
KILOMETERS

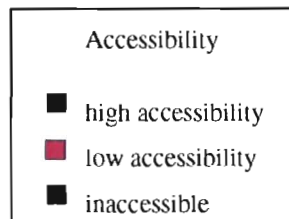


Figure 17. A map showing walking accessibility based on the Pandolf (1977) case.

McDonald Accessibility



SCALE 1:201959
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KILOMETERS

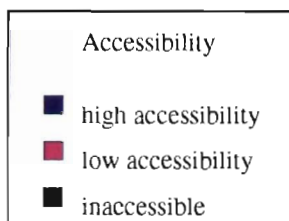


Figure 18. A map showing walking accessibility based on the McDonald (1961) case.

Imhof Accessibility



SCALE 1:199898
1 0 1 2 3 4
KILOMETERS

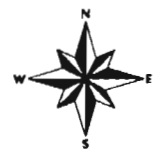
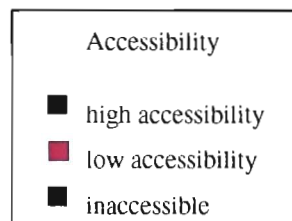


Figure 19. A map showing walking accessibility based on the Imhof (1968) case.

Discussion of the Results

The results of the analysis for all three cases of the model clearly indicate that accessibility is highly dependent upon topography and other impediments to travel. Less accessible areas, as shown on the maps, are lakes, ponds, and areas of steep topography. Easily traveled corridors are also as expected: flat lands along the major drainage networks. All three models are subject to the general topography and the non-topographic impediments in the study area, unlike the isotropic model. A visual comparison can be made by contrasting each model's output with the slope, aspect, and elevation maps (see Figures 20, 21, and 22).

It is also apparent that the competing models, although similar, are far from congruent. A subtraction of the mobility layers associated with each form of the equation from each other illustrates the similarities and differences between each form of the model (see Figures 23, 24, 25, 26, 27, and 28). The percentage differences noted between the cases are summarized in Table 9. The figures in the table are calculated by subtracting each case from one another and dividing the absolute difference by the total number of cells in the grid.

TABLE 9

PERCENTAGE DIFFERENCES BETWEEN COMPETING ACCESSIBILITY CASES

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

Slope



SCALE 1:183443
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KILOMETERS

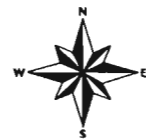
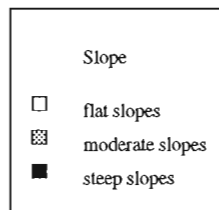
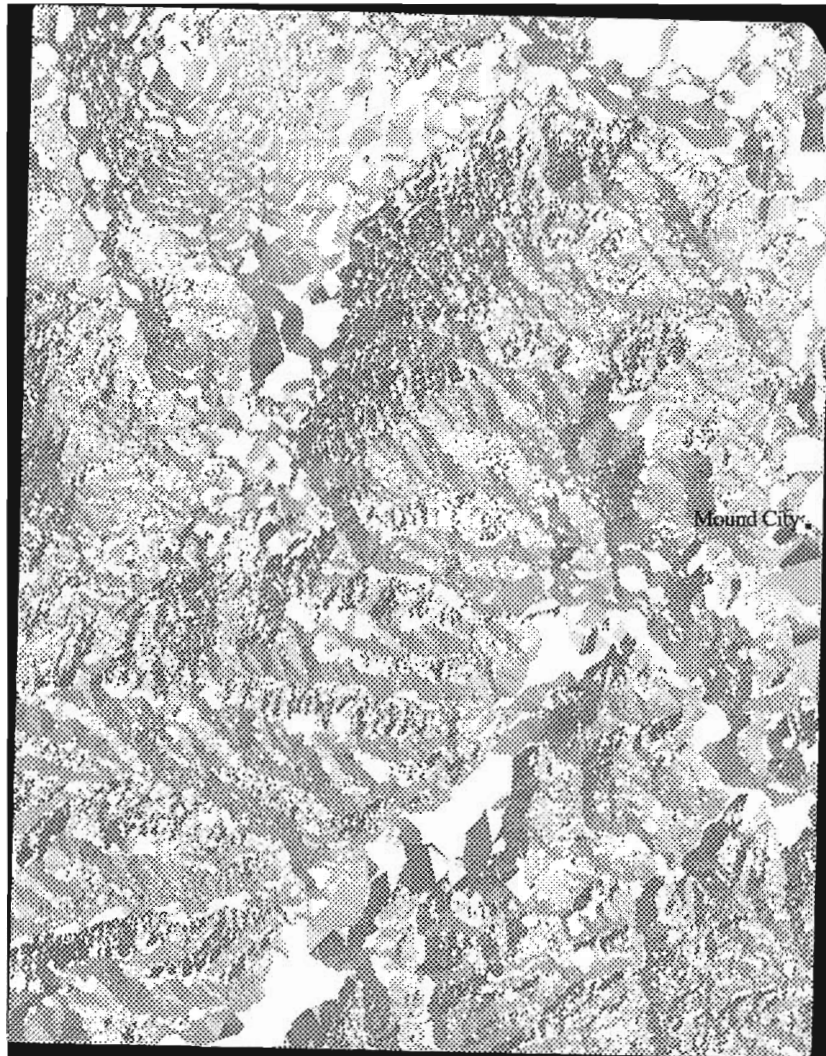


Figure 20. A map showing slope values in the study area.

Aspect



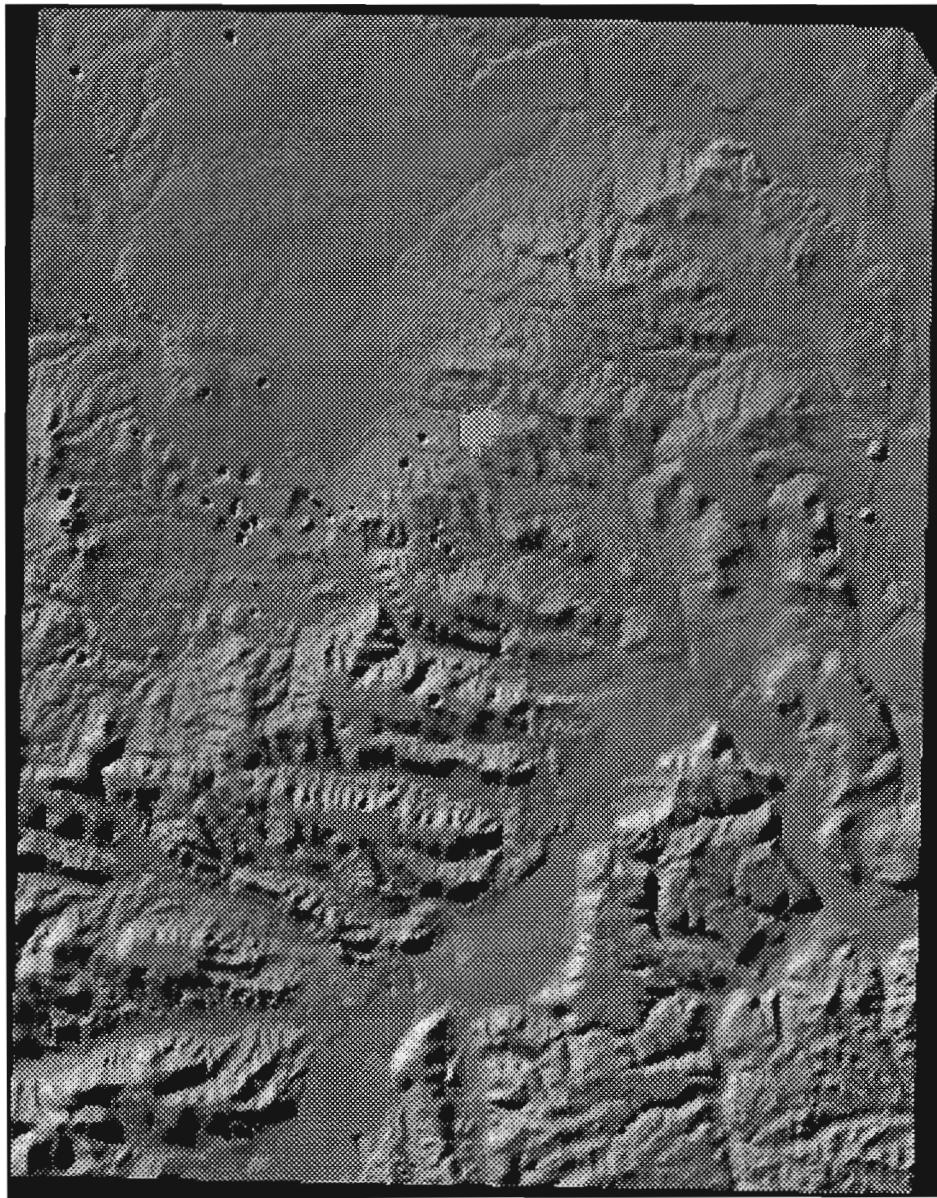
SCALE 1:193879
1 0 1 2 3 4
KILOMETERS

- Direction
- ☐ Northeast to East
 - ☐ East to Southeast
 - ☐ Southeast to South
 - ☐ South to Southwest
 - ☐ Southwest to West
 - ☐ West to Northwest
 - ☐ Northwest to North
 - ☐ North to Northeast



Figure 21. A map showing aspect in the study area.

Shaded Relief



SCALE 1:171518

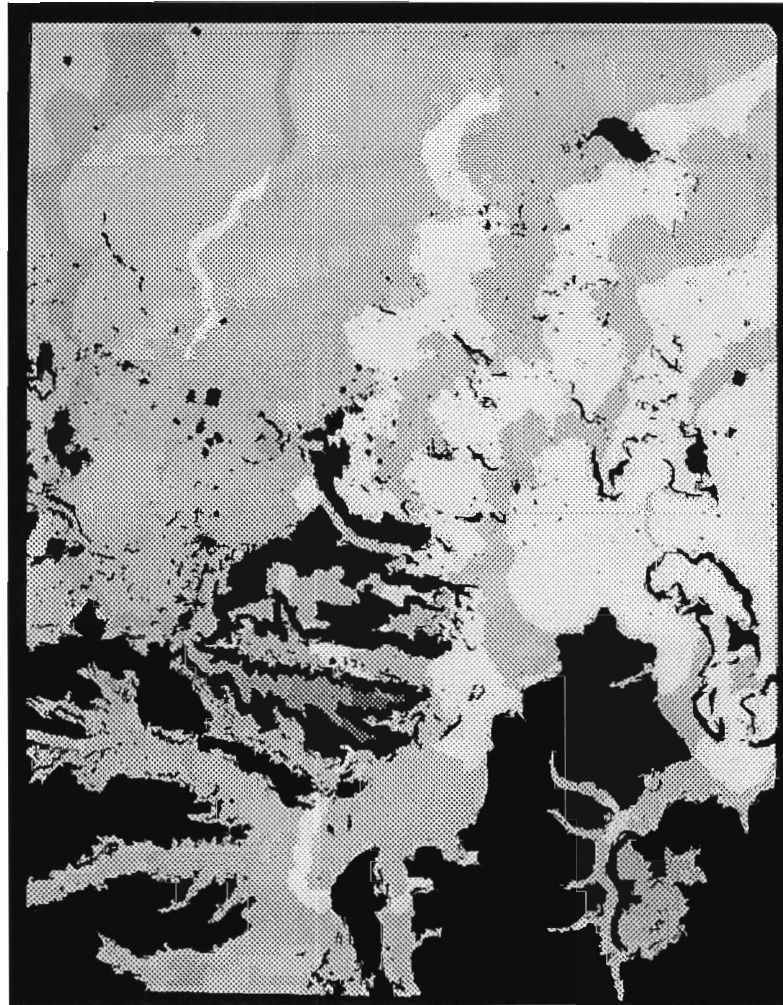
3 0 1 2 3



KILOMETERS



Figure 22. A map showing topography using shaded relief.

Figure 18 –Figure 17

SCALE 1:204063
1 0 1 2 3 4
KILOMETERS

Difference

-  -1
-  no difference
-  2
-  3
-  4

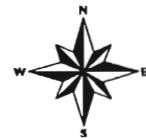


Figure 23. A map showing the difference between the Pandolf and McDonald cases.

Figure 19 –Figure 17



SCALE 1:206211
1 0 1 2 3 4
KILOMETERS

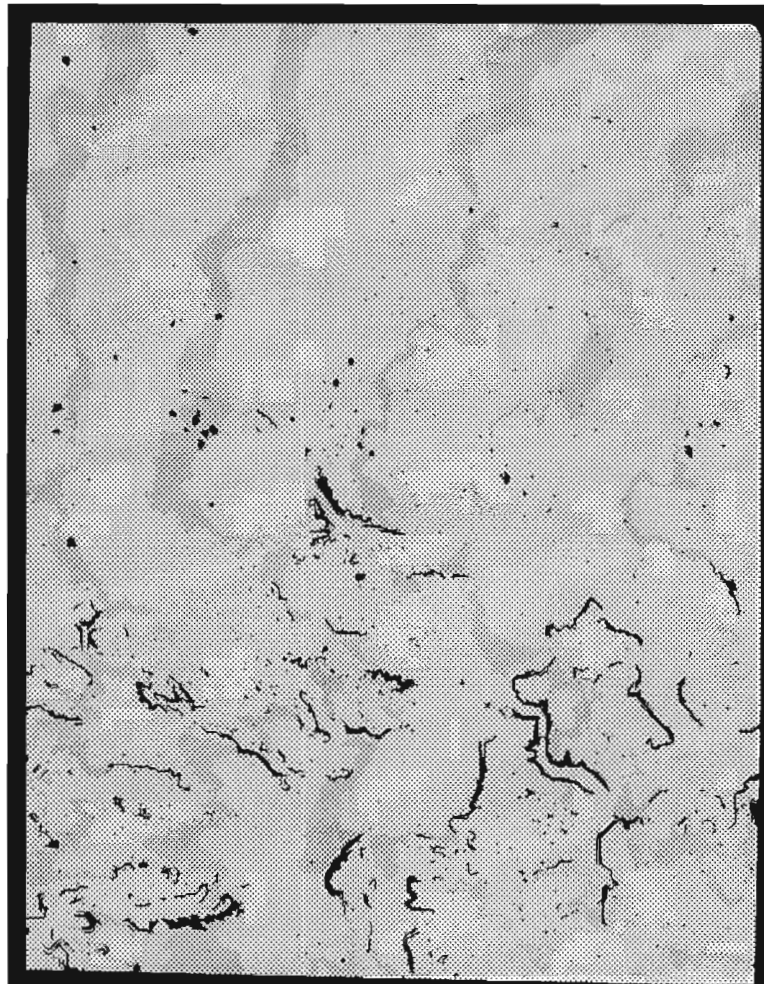
Difference

□	no difference
▤	1
▥	2
▦	3
▧	4



Figure 24. A map showing the difference between the Pandolf and Imhof cases.

Figure 18 –Figure 19



SCALE 1:208405
1 0 1 2 3 4
KILOMETERS

Difference
-1
no difference



Figure 25. A map showing the difference between the McDonald and Imhof cases.

Figure 17 –Figure 16

SCALE 1:206211
1 0 1 2 3 4
KILOMETERS

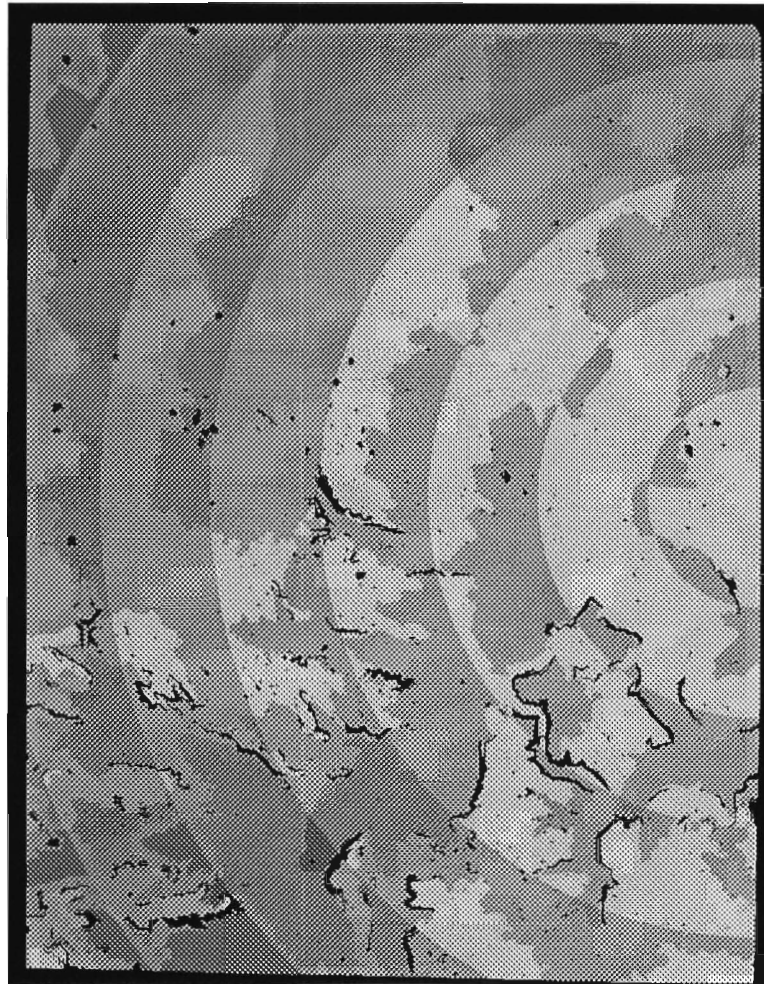
Difference

■	-2
■	-1
■	no difference
■	3
■	4



Figure 26. A map showing the difference between the Pandolf and isotropic cases.

Figure 18 –Figure 16



SCALE 1:208405
1 0 1 2 3 4
KILOMETERS

Difference

- -3
- -2
- -1
- no difference



Figure 27. A map showing the difference between the McDonald and isotropic cases.

Figure 19 –Figure 16

SCALE 1:206211
1 0 1 2 3 4
KILOMETERS

Difference

- -3
- -2
- -1
- no difference

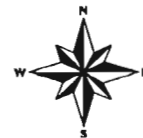


Figure 28. A map showing the difference between the Imhof and isotropic cases.

The largest anomaly between cases is shown by the Pandolf, et al. (1977) based case because it required treating large areas as inaccessible. Although this is expected because his form of the equation covers a smaller range of gradient values than the other two cases, the disparity between the models causes a dilemma. Which physiologically based set of coefficients should be used for a particular analysis? (Since it is already assumed that the time-based metabolic cost derivation methods developed by Imhof (1968) are substandard, only the Pandolf, et al. (1977) and McDonald (1961) based models are considered in this decision.) The answer lies in the character of the study area under investigation. The study region in this thesis is characterized by many areas with slopes that exceed the Pandolf, et al. (1977) limits, therefore the McDonald (1961) based model, which has a higher gradient threshold, is used. If a different study area has relatively flat topography (between - 10% and + 25%) then the Pandolf, et al. (1977) based model should be used because it has proven to be more accurate in that lower range.

CHAPTER VI

SUMMARY, LIMITATIONS, AND EXTENSIONS

Summary

This thesis has described a pilot project that was successful in quantitatively representing and mapping human accessibility on foot with a GIS. The general system developed and used in the project is a substantial improvement over previous techniques used to calculate pedestrian mobility. Prior physiological research on the metabolic costs of walking were combined with the spatial analytical functions of a GIS in order to analyze walking with respect to geography. A proven walking prediction equation developed by Pandolf, et al. (1977) was transformed into an appropriate form and applied using the Arc-Info GIS. Pedestrian accessibility to a prehistoric Hopewell Indian burial complex was calculated for locations within a predetermined study area. The model was customized according to topography, vegetation, surface water, walking speed, pedestrian body weight, the load carried by the pedestrian, and the time period under investigation. Possible uses of this general accessibility model are extensive. Beyond use by archaeologists to create improved site catchments; historical, cultural, and human geographers could use the model to assist their study of humans and our relationship with the physical environment. Patterns of transportation, cultural and technological diffusion, and human development could be more

accurately investigated with customized applications of this general movement model. The limitations of the model essentially originated from either the physiological research on walking, the input data, or the capability of the GIS. Possibilities for extending this research is restricted by the existing physiological research, the current limitations of GIS technology, and the imagination of the researcher.

Limitations

The fundamental limitations encountered in this research can be divided into three categories. They are as follows in descending order of difficulty:

- 1) There are problems associated with the physiological research.
- 2) Difficulties arise with the available data.
- 3) There remain fundamental problems with the capabilities of GIS technology.

These limitations are discussed separately below. Problems with the applied research appear to compose the most critical of the limitations, and are also the only ones that can not be solved within the context of GIS research.

Incomplete Physiological Research

This problem is generally out of the hands of GIS research. Since the GIS is only a platform for the application of the physiological walking research any application is dependent upon the strength of that work. The physiological research on walking is limited and has not been fully explored because of the controlled nature of quantitative research, the cost of physiological researching methods, and shortsighted researchers. Many questions remain

unanswered which cause problems in the ensuing cartographic modeling applications. Although these problems may be considered minor in relation to the overall capability of the model they still present some formidable obstacles. The foundation ultimately determines the vitality of the model.

There is a major difficulty with correctly classifying terrain type and assumptions made about the data. For example: what actually constitutes "Swampy bog" or "Heavy brush"? There are literally different types for each bog or brush covered area that exists on the earth. Furthermore, what happens if we have two spatially coincident impedances such as light brush on loose sand, is there a compound impedance? There are also many terrain types that have not been investigated. Race of the subjects has likewise not been taken into account. For example, it would seem obvious that native inhabitants were much more suited to pedestrian travel than modern Caucasians. Difficulties with the existing research on slope is also a problem. Research in this realm needs to be extended in order to somehow account for extremes because humans can certainly move across gradients greater than those previously studied.

Besides the above restrictions, physiological researchers also have a myopic view on the metabolic costs of walking. An exhausted traveler would most definitely have more difficulty walking than a fresh traveler. In other terms, the equation also does not account for the effect of distance traveled on the metabolic cost of walking. For example, a 10 ft ridge after 20 km of walking would be a more formidable obstacle than the same hill encountered at the onset. On a similar note, the perceptions of the traveler are not considered. A long hill may pose more of an impedance in the mind of the traveler than it actually does quantitatively.

The problems with the applied research should eventually be overcome when existing studies expand to include more parameters.

Inherent Problems With Data

Data has been noted as the most important element in a GIS. No matter how accurate and appropriate the data is for a particular study, problems with it can always be discovered because of the basic nature of geographic study. Representation of real world phenomenon on a map and the study of spatial entities inherently involves reduction transformations and the loss of data. This procedure is essential to the efficient analysis of spatial data. The key to this representation of actual features, entities, and characteristics is to maintain these data that are important and discard those elements that are not. Difficulties arise when decisions are made to determine what is significant and what is not. How much aggregation can be permitted while retaining the necessary information to solve the problem at hand? This fundamental dilemma, concerning the use of areal aggregates instead of the actual observational unit, is confronted in all facets of geographic study. Concerning this thesis and physical geography, continuous spatial data is frequently converted into discrete, aggregate forms to simply allow for its collection. Difficulties arise in transformations of the point data into a continuous model of the surface. These subsequent transformations compound later problems associated with analytical studies performed on the model. The problems associated with the use of areal aggregates in the sphere of archaeology are immense, although often insignificant for other applications. To solve the problem by simply using the actual observational unit is illogical, although new advances in technology have largely removed the

roadblock that has hindered attempts to conduct empirical observations at a high degree of spatial disaggregation.

Small, inexpensive Global Positioning System (GPS) units have removed part of the barrier that has hindered empirical investigations at high levels of disaggregation. GPS units allow for the easy collection of accurate spatial data in all three dimensions. With computer links this collection is an extremely efficient method as opposed to previous techniques. If existing physical geographic data is aggregated, which is normally the case with topographic maps, it could be supplemented and enhanced by collecting additional GPS primary data points in the field.

A second problem with the data in this thesis was placing it in the proper historical context. This was only possible by making many bold assumptions and simplifications. The existence of long-standing patterns of overland trade and the subsequent presence of trails was not even considered. It is well known that many Ohio trails were in use during Hopewell times and earlier that connected with other trails spanning the continent (Wilcox 1933). Data problems of this nature are specific to the particular area or time period under investigation and can only be discussed in the context of these considerations.

Technology Limitations

Limitations concerning GIS technology are confined to difficulties in dealing with the large amount of data associated with a detailed analysis, the unavoidable generalizations of raster-based GIS, and underdeveloped software.

Due to the large number of cells, processing time for the model in this thesis was over seven hours. This is extremely slow, even though Grid in Arc-Info stores data using adaptive run-length compression. It is still generally true that the more cells in a grid, the slower analysis operators will be, although inevitable improvements in computer hardware technology should help alleviate this problem. New methods of data storage within GIS are also being investigated to more effectively deal with the large spatial data volumes involved with storing geographic data.

Fundamental problems with the representation of this data in raster format must also be acknowledged as a limitation. The real world is not divided into blocks as it is within the Grid module of Arc-Info. Cell size is therefore of primary concern, especially when there is widespread overlap of data in the cells. Cell size needs to be as detailed as the analysis will allow, although a certain degree of error is always present. It often can not be determined what really occupies a cell in question no matter what the cell size. For example, under a majority rule, a cell that is 51% flat will be classified as 100% flat, although 49% may be as rugged as the Himalayas.

Arc-Info, although considered by many to be a leader in the GIS software industry, remains underdeveloped in certain respects. The current cost distance functions in Arc-Info are limited and could be expanded in order to more accurately compute accessibility. *Pathdistance* calculates accessibility in only one direction: from the study area to the source location. This results in an inaccurate representation of accessibility because computations ignore the return trip. The ability to move between locations inherently includes both going and returning. Although this limitation can be overcome by the user creating a custom Arc

Macro Language program, it should be fixed by ESRI creating a direct function. Considering the return trip would not have altered the results in the present study, but could greatly alter the results of other accessibility studies. The return trip is a fundamental consideration when attempting to calculate accessibility.

Extensions

The metabolic cost of traveling across a portion of the natural landscape by foot to a specified location has been calculated and portrayed in cartographic form with the use of a GIS in the most basic manner possible. The scope of this thesis is limited to the production of a general prototype movement model, although it has the potential to be expanded in a number of dimensions. The model can be calculated differently, tailored to specific settings, or portrayed in alternative cartographic forms.

Manipulations of the original walking equation can open the door to different information. For example, metabolic costs could be transformed into travel times and distances. Although this project focuses solely on employing metabolic cost as the unit to portray impedance there exist the potential for alternatives.

Other avenues can also be explored by considering different types of surfaces. This project is concerned with a natural landscape in south-central Ohio. Future studies could explore natural landscapes in desert environments, high-altitude regions, or snow-covered landscapes. Various man-altered landscapes with features such as roads and fences could likewise be studied or a comparison between different landscapes, temporally or locationally dissimilar, could be pursued.

Different forms of cartographic representation and comparisons between the different forms is a another possible extension. Settlement pattern maps developed in travel time space could be constructed and used to determine patterns of settlement interaction and cultural diffusion. These maps could in turn be compared to the original maps, based on geographic distance, in order to better understand site locations. The avenues for extending the model developed in this thesis are considerable.

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