DERIVING TRAVERSE PATHS FOR SCIENTIFIC FIELDWORK WITH MULTICRITERIA EVALUATION AND PATH MODELING IN A GEOGRAPHIC INFORMATION SYSTEM

by

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ABSTRACT

Field research is a necessary component of many realms of ecological and geoscientific practice since it provides the primary data crucial to understand the characteristics of an object, phenomenon, or process. Unlike work in an office or laboratory, fieldwork has additional cost related to travel, lodging, and per diem expenses. Field scientists must therefore ensure they make efficient and effective field navigational decisions that result in expedient execution of field campaign objectives.

Technologies and analytical approaches such as decision analysis, path modeling, and geographic information systems offer assistance to navigational decision making while in the field as do the analytical techniques of weighted linear combination and analytical hierarchy process. These tools are often underutilized, however. This thesis describes a methodology by which these technologies and analytical procedures may assist field scientists with navigational decision making. Specifically, the thesis documents development of a model that uses a spatial multicriteria decision evaluation to derive favorability values. These values are then used to determine the placement of traverse paths that are suggested routes to be taken by field researchers. The thesis includes a description of concepts behind the methodology, a demonstration of the methodology for a hypothetical geologic campaign, and an analysis of resulting traverse paths.

CHAPTER ONE: INTRODUCTION

Field research is a necessary component of many realms of ecological and geoscientific practice since it provides the primary data crucial to understand the characteristics of an object, phenomenon, or process. While data may be acquired from existing maps and other publications and through various remote sensing techniques, scientists still need to work in the field, interacting directly with the entity in which they are interested.

An inherent component of this fieldwork is the need to navigate across a study area in order to make observations or attain measurements and samples, a process referred to in some domains as making a traverse. Scientists carefully record descriptions of the observations and measurements they make while on a traverse and often use global navigation satellite systems (GNSS) to record precise coordinates of where these data were collected. Scientists use these primary data, and information derived from them, as evidence to explore a set of existing hypotheses or to discover patterns. This information then allows scientists to constrain the set of plausible hypotheses about the origin and distribution of features within the study area. This knowledge may then be used to better understand a region's likelihood for the presence of a hazard, species habitat, or resource, for its suitability for a human-made structure, and so on.

While in the field, scientists are faced with scientific and logistical objectives. The primary scientific objective is to achieve a high scientific return. This is considered to occur when efforts made result in substantial progress related to expanding the knowledge regarding an object, phenomenon, or process. A high scientific return is often attained at sites that provide opportunities for direct observation and measurement of materials that help test current working hypotheses, exceptional views of features of interest, or broad views of the study area or entity of interest.

The logistical objectives of fieldwork relate to issues of access, preparation, and time. Issues of access may include constraints such as property ownership, waterways, slope of the terrain, lack of access trails, and hazardous topography. Preparatory issues relate to such aspects as weather, lodging, equipment, and so on.

Unlike work in an office or laboratory, fieldwork has costs related to travel, lodging, and sometimes per diem allowances. These costs, both in time and in money, make it necessary to conduct fieldwork in an efficient and effective manner. To do so, scientists are required to strategically consider how they may fulfill their particular field campaign objectives. One way to do this is to plan a cost- and time-effective traverse.

Technologies and analytical approaches such as decision analysis, path modeling, and geographic information systems offer assistance to navigational decision making while in the field as do the analytical techniques of weighted linear combination and analytical hierarchy process. These tools are often underutilized, however, in these contexts. This thesis describes a methodology by which these technologies and analytical procedures may assist scientists with navigational decision making.

1.1 A Methodology to Explicitly Define Traverse Paths

Field scientists have long used published maps and remotely sensed imagery to understand the scientific value and difficulty of traversing through particular terrain. Often these tools are used in an informal manner, with decisions being made implicitly, without the use of formally defined analytical models.

As this thesis shows, however, a supplemental approach is to make navigational decisions more explicitly by using analytical techniques from decision analysis, path modeling, and geographic information science. Such explicit navigational models are needed and have been developed for geologic fieldwork in planetary science where all work is supervised remotely (e.g., Carr et al. 2003, Hörz et al. 2010, Johnson 2010, Skinner and Fortezzo 2013). Examples are also found outside the realm of geologic science. Store and Antikainen (2010) is a good example from the domain of forestry.

Building on tools used in other domains, this thesis presents a methodology that makes explicit the often ad hoc and implicit process of field navigation for scientific fieldwork. This methodology is intended to provide scientists with a set of traverse paths that have been derived using explicit tools and processes that can be used to supplement traditional traverse planning. As will be demonstrated later, these traverse paths are designed to place scientists close to locations where they may attain a high scientific return, using as much as possible existing routes with low slope that provide increased accessibility.

This methodology collectively considers many of the criteria, objectives, and constraints associated with fieldwork, while accounting for their relative importance, to suggest strategic traverse paths to be used by field scientists. This methodology is first presented in a generic sense, outlining the sequence of steps needed to derive the traverse paths. Then, it is implemented for a hypothetical geologic field campaign in Hildago County, New Mexico. This demonstration shows how the methodology might be applied using Esri ArcGIS version 10.2.2 to create and overlay the criteria layers and develop the traverse paths for this example field campaign. All GIS work performed for this thesis was administered using Esri ArcGIS version 10.2.2. Lastly, an initial assessment of the validity of results from this methodology is performed through analyses of the resulting traverse paths.

1.2 Thesis Organization

Chapter One has introduced the nature of fieldwork and outlined the objectives of the present thesis. Chapter Two offers a background to the relevant aspects surrounding fieldwork, multicriteria evaluation, and path modeling and describes other works related to deriving traverse paths in the fields of planetary science, geological science, and forestry. Chapter Three outlines the concepts underlying the traverse generating methodology. Chapter Four provides a demonstration of its employment and examines the traverse paths generated from the methodology. Chapter Five discusses the advantages and limitations of the methodology and considers its usability and suggest potential improvements and future work.

CHAPTER TWO: BACKGROUND

This chapter provides background regarding the process of planning fieldwork as well as some of the data and technologies that are available for its practice. Also, this chapter provides an introduction to the decision analysis technique termed multicriteria evaluation (MCE), including a brief description of its components of standardizing, weighting, and combining criteria, and the technique of path modeling.

2.1 Fieldwork Planning and Technology

Scientists often use archival data such as government records, maps, and remotely sensed imagery to inform fieldwork planning. For example, a team of soil scientists and plant ecologists conducting a soil survey within Denali National Park and Preserve, Alaska used aerial photography and satellite imagery to interpret landform and vegetative characteristics and distribution (Clark and Duffy 2006). These interpretations allowed them to delineate representative sites of the various physiographic regions within the park and thus identify the locations where fieldwork should occur.

Geologists, too, use archival data to conduct preliminary inspections of study areas prior to visitation (Compton 1985, Coe 2012). This may involve digital processing of satellite imagery to characterize and distinguish varying rock types (e.g. Mars 2013), study of existing geologic maps and reports, or personal communiqué from other field scientists. Scientists are able to use this archival data prior to conducting their fieldwork to reduce the size of the sampling area necessary to fully describe a study area.

The tools that may be used to plan a traverse and augment it while in the field are quickly advancing. House et al. (2013) describe how technological advancements regarding geographic information systems, light detection and ranging (LiDAR), virtual globes, mobile hardware and software, and geocoded field data are changing the practice of geologic mapping. Nevertheless, fieldwork is still an essential and costly activity, so the incorporation of such advanced technology to improve the process of traverse planning is important.

2.2 Traverse Planning and Related Work

A few researchers have attempted to strategically define the traverse planning process. Examples of some of these efforts can be found in the fields of planetary science (Carr et al. 2003, Johnson 2010, Hörz et al. 2013, Skinner and Fortezzo 2013) and forestry (Store and Antikainen 2010). These are discussed in the following sections.

2.2.1 Traverse Planning in Forestry

To advance the effectiveness of field inventorying in Finnish forests, Store and Antikainen (2010) demonstrate how to determine visitation sites and design optimal routes to reach those sites. They combine decision analysis and path modeling techniques using a GIS platform. Sites deemed most important for forest inventorying endeavors and areas that affect traversability are selected through a multicriteria evaluation (MCE) process involving expert knowledge modeling and the analytical hierarchy process (AHP). A custom path modeling tool was developed to derive paths among a series of selected forest stands. This tool uses greedy heuristics and a variation of the traveling salesmen problem to establish the optimal solution for their traverse path, which they view as an orienteering problem, .

Store and Antikainen note that existing tools that may be used to determine optimal traverse paths using least-cost path analysis were too inaccurate for their needs. The technique they use relies on nodes at a raster's cell boundary as opposed to its center, noting that this enables "a more accurate calculation of traverse path" (Store and Antikainen 2010, 156). In an effort to mitigate elongation and deviation errors caused by the raster data model, as presented by

Goodchild (1977), their technique also uses a rectification procedure to give priority to bent-line over straight-line segments.

The MCE process allows decision makers to assign weights to the various criteria and objectives relevant to fulfilling a particular goal. These weights indicate the relative importance of each criterion and objective. Store and Antikainen note that their work lacks a sensitivity analysis step to determine the effects of variations in the values of these weights. Such an analysis will determine if small adjustments to the input of a MCE results in significant changes in its output. If significant changes do occur, it often means that the model is overly sensitive and adjustments that mitigate these affects need to be performed.

2.2.2 Traverse Planning in Geological Science

Despite numerous advancements in remote sensing technologies (e.g., digital image processing and geophysical analysis), there continues to be a need for geologists to visit the field. These technologies may actually support the need for further surveys, as they often reveal gaps and potential error in current knowledge. Compton (1985) explains that while the geologic makeup of many areas has been mapped (e.g., the contiguous United States at a scale of 1:24000), advancements in geologic theory and techniques related to new remote imagery, field techniques, and analysis create the need for these surveys to continue. Passchier and Exner (2010) describe that many areas lack geologic information with sufficient detail and that new understanding of many geologic phenomenon renders many older geologic maps obsolete. Ernst (2006) describes how he simply uses geologic field mapping to acquire answers to specific geologic questions.

Prior to arriving in the field, geologists may have outlined areas they intend to go and perhaps even plan what appears to be the best way to get there. However, based upon new observations made while in the field, the initial plans often change. As observations are made, a geologist gradually becomes more aware of the geologic makeup of the study area, as well as discovers its imposing obstacles. Also, geologists will often operate under multiple working hypotheses (Chamberlin 1890) in contrast to the ruling hypothesis mentality dominating many other facets of science. New observations may confirm or refute these hypotheses and thus change where the geologist chooses to go.

This does not, however, undermine the advantages wrought through careful consideration of the available archival data. Field geologists will often bring this archival data along with them into the field and use it to supplement the primary data they collect there. Field geologists have long used geologic maps, topographic maps, and remotely sensed imagery to understand the scientific value and difficulty of traversing through particular terrain. Traditionally, these tools have been used in an informal manner, with decisions being made implicitly, without the use of formally defined analytical models (Riggs et al. 2009).

2.2.3 Traverse Planning in Planetary Science

A predicted increase in the amount of surface travel that will be conducted during future planetary missions has led researchers to develop means by which the space crew may plan and conduct traverses in an efficient and effective manner (Johnson et al. 2010). Many of the factors affecting planetary fieldwork, such as concerns regarding thermoregulation, oxygen support, depth perception, are not applicable to fieldwork on Earth. Like fieldwork on Earth, however, planetary fieldwork contains many expenses not relevant to work in an office or laboratory. It is therefore sensible that those concerned with extraterrestrial geologic fieldwork would be concerned with matters affecting its efficiency and effectiveness.

Desert Research and Technologies Studies (DRATS) are analog planetary endeavors carried out in northern Arizona to test various hardware and operations (Ross et al. 2013). Skinner and Fortezzo (2013), in their work to assist the 2010 DRATS team, used photogeologic mapping to gain an initial understanding of their study area and to identify key locations where remaining research questions could be addressed. Their work involved first identifying the study area's various geologic materials based on imagery characteristics. Then, a geologic map was constructed based upon these distinctions. Upon completion of the map, numerous questions remained. Sites interpreted as locations where these questions could be deciphered became visitation sites recommended for the DRATS team.

Horz et al. (2013), in similar work aimed at assisting the same 2010 DRATS team in their analog mission, made a series of traverse paths intended to account for a series of technical and operational constraints associated with planetary geologic campaigns. The work described in their article was supported by the earlier work of Skinner and Fortezzo (2013). Sites given visitation preference were determined based upon scientific return and logistical considerations such as slope trafficable by rovers, road conditions, and fence and gate locations. The best traverse paths were determined manually via group consensus as the result of an on-site reconnaissance trip and workshop.

This work by Skinner and Fortezzo and Horz et al. demonstrates the process of discerning what may be seen within satellite imagery and using these observations to derive and test hypotheses remotely. These hypotheses may then be used to select key locations within a study area where geologists are likely to attain a high scientific return.

Carr et al. (2003) and Johnson et al. (2010) used similar approaches to generate traverses to be used for planetary extravehicular activities. Both developed MATLAB based tools and assessed what effect factors such distance, time, energy, slope, and visibility have on potential traverse paths. These tools provide geologists with information regarding metabolic cost, visibility, mission compliance, and hazards once they have identified a series of waypoints.

2.3 Multicriteria Evaluation

MCE is set of analytical procedures that may be thought of as a sub-discipline of multicriteria decision analysis (MCDA) or multicriteria decision making (MCDM) (Carver 2008). Many of the methods applied in MCE originated from the field of operations research in the 1960s and 1970s (Carver 2008). They arose in response to critiques of early techniques in decision making and site location analysis (Carver 1991). The MCE approach combines multiple datasets representing various criteria and/or objectives, assigns them with a weight indicating their relative importance, and produces a multi-valued output (e.g. a raster data model with a grid of georeferenced cells with different values) indicating the degree to which an objective(s) has been met.

The term *criteria* is often used generically to refer to concepts of both criterion attributes and objectives. It is used here to refer to attributes of entities or phenomena that may be used to measure the fulfillment of a certain objective, or various objectives. This process may be done for geographic space by designing such an evaluation around spatial data. A GIS is often used for this due to its ability to store, display, and analyze this data relevant to many decision problems (Carver 1991).

Geographic information systems alone, while advantageous for working with various types of spatial data in a wide variety of applications, were originally not designed to handle an analysis involving a complex value structure consisting of conflicting objectives and varying priorities (Malczewski 1999). In 1991, Carver described a GIS as a data management framework for the spatial data used in a MCE. He noted that a MCE provides a GIS with the ability to handle conflicting objectives that encompass multiple criteria and multiple decision makers. Now, two decades later, most GIS do provide a means by which at least some MCE techniques may be implemented directly within the GIS framework. By incorporating the technologies associated with MCE and GIS, decision makers are able to confront spatial problems containing multiple criteria, objectives, and decision makers.

Carver (2008) outlines the main steps involved in a multicriteria evaluation. These are problem definition, criterion selection, standardization of criterion scores, allocation of weights, and implementation of an aggregation algorithm. Additional steps such as a sensitivity analysis and making decisions with the processed information may also be included. Problem definition involves identifying the difference between existing and desired states of a system (Malczewski 1999). Once the problem has been identified, it can be determined that the achievement of a certain objective(s) may bring the system closer to the desired state. Once the attribute values of multiple criteria have been standardized, weighted, and aggregated, they may then be used to determine the degree to which an objective(s) has been met. A sensitivity analysis is performed to discover error or uncertainty that may be contained within the derived values. Once confident that the values attained are of sufficient quality, they may be used to make decisions (Figure 3).

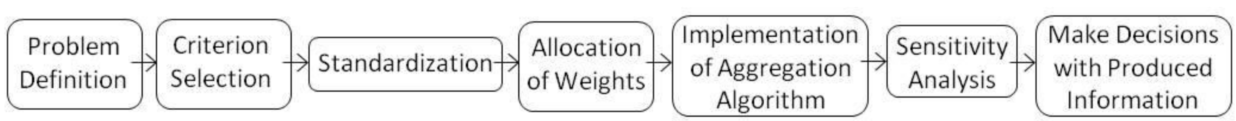

Figure 1 - Multicriteria Evaluation Flowchart: Typical flowchart of multicriteria evaluation procedures.

2.3.1 Problem Definition

When defining a problem for the MCE process, considerations must be made as to whether there are groups of people with different vested interests in the decision problem.

Groups, as opposed to individuals, are of concern as the decision making process will be affected more by the amount of conflicting goals, preferences, and beliefs than by the number of those involved (Malczewski 1999).

2.3.2 Criterion Selection

Criteria are selected based upon their ability to measure the degree to which an objective(s) has been met. Criteria are often defined as either factors or constraints. Factors describe criteria attributes that promote fulfillment of a given objective, while constraints describe criteria attributes containing hard limitations to objective fulfillment. There are several ways to select criteria including a survey of relevant literature, analytical studies, and an opinion survey (Malczewski 1999).

2.3.3 Standardization

Data used as input to derive criteria layers are likely to contain varying value scales. Input data may use nominal scales such as soil and rock types, or quantitative scales such as slope and distance to a feature. They may also be based upon natural or constructed scales (Keeney and Raiffa 1976). A natural scale is often considered objective meaning that it is standard and may be measured, whereas a constructed scale is considered to be subjective in that it is based on opinion.

Given the variety of scales used, data for each criterion must be standardized prior to being compared. Any mathematical or logical function may be used to describe the relationship between input data and the developed criterion layer. This relationship, however, should be based on a defensible association (Bolstad 2012). The standardized values may also be seen as having a direction (Voogd 1983). For instance, as explained by Malczewski (1999), when using a floating point scale from zero to one, the criteria are seen as benefit criteria when favorable characteristics are given a high score (e.g., one) and detrimental characteristics are given a low score (e.g., zero). The criteria are seen as cost criteria when favorable characteristics are given a low score (e.g., zero) and detrimental characteristics are given a high score (e.g., one). There are numerous standardization techniques available, four of which have been summarized in Table 1.

Table 1 - Summary of Standardization Techniques: Summary of four common standardization techniques (after Malczewski 1999)

Standardization Technique	Description
Linear scale transformation	Divides the raw attribute values within a given criterion layer by the layer's maximum value for this same attribute.
Value/Utility function approach	Uses input from decision makers to assist in defining a function that identifies the relationship between a non-standardized criterion layer and a standardized criterion layer.
Probability	Uses probability theory to determine the likelihood of a given outcome, which is then used to determine standardized values.
Fuzzy set membership	Process of assigning standardized values based on a membership function.

Two forms (Equations 1 and 2) of a linear scale transformation technique, the score range procedure (Malczewski 1999), are explained in more detail below. This is followed by an explanation of the value/utility function approach.

A linear scale transformation technique, termed the score range procedure, assumes a linear relationship between non-standardized and standardized criterion attribute values. If the criteria layer to be standardized is of the benefit-criteria variety, then the following equation may be used to transform each value x into the standardized value x':

$$x'_{ab} = \frac{x_{ab} - x_b^{min}}{x_b^{max} - x_b^{min}} \qquad (1)$$

where x is a raw value of the non-standardized criterion layer a for the attribute b, x_b^{min} is the minimum value contained within layer a for the attribute b, and x_b^{max} is the maximum value contained within all criteria layers containing attribute b. If the criteria layer to be standardized is of the cost-criteria variety, then the following equation may be used to transform each value x into the standardized value x':

$$x'_{ab} = \frac{x_b^{max} - x_{ab}}{x_b^{max} - x_b^{min}} \qquad (2)$$

where x is a raw value of the input layer a for the attribute b, x_b^{min} is the minimum value contained within input layer a for the attribute b, and x_b^{max} is the maximum value contained within all criteria layers containing attribute b. This standardization procedure, implemented with the use one of these two equations, assumes that the raw input values contain a high value when the criterion is favorable and low raw input values when the criterion is unfavorable. Thus, when the reverse is true, the nomenclature defining the variety of criteria to be standardized is switched making Equation 1 suitable for cost-criteria and Equation 2 suitable for benefit-criteria.

The value function approach to standardization defines the relationship between a non-standardized criterion layer and a standardized criterion layer based upon the decision makers' preference of worth (i.e. its value or utility). An example of this is the mid-value method. This technique requires decision makers to define the value they think best describes the middle value between two endpoints, where the endpoints are the maximum and minimum values of the non-standardized criteria layer. Once this value is chosen, it becomes the abscissa of a point in a curve. The ordinate of this same point is the median value of the desired standardized criterion layer.

When creating a benefit-criterion layer, the maximum non-standardized criterion layer value would be paired with the desired maximum standardized criterion layer value and the minimum non-standardized criterion layer value would be paired with the desired minimum standardized criterion layer value. The opposite is the case for a cost-criterion layer where the maximum non-standardized criteria layer value would be paired with the desired minimum standardized criterion layer value and the minimum non-standardized criteria layer value would be paired with the desired maximum standardized criterion layer value. This work results in three ordered pairs of numbers. The equation that simultaneously fits each of these points defined by these pairs is the value function and may be used to standardize the remaining values of the applicable non-standardized layers.

Standardization algorithms, such as those described above, may be applied to non-standardized attribute values within a GIS by way of applying the appropriate algorithm to the non-standardized attribute field within a criterion layer's attribute table (e.g., with the Field Calculator function of ArcGIS). The ArcGIS Fuzzy Membership tool may also be used to define the function describing the relationship between the non-standardized and standardized criterion attribute values. This tool provides various options to describe membership types. One option, termed fuzzy linear, transforms attribute values using a linear function, yet gives decision makers the opportunity to define minimum and maximum threshold values. These threshold values may be used to transform criterion attribute values beyond a certain range to either definitely a member of an entity group or definitely not a member of an entity group.

2.3.4 Allocation of Weights

Following standardization, weights or priorities are derived to indicate the relative importance of each criterion and/or objective. Voogd (1983) identifies weights as quantitative values indicating the relative importance of given criterion layers and priorities as ordinal expressions of their importance. The term weights is used to describe the importance of criteria and objectives discussed here when ratio attribute values are used to make these comparisons. There are numerous weighting techniques available (see Table 2). Malczewski (1999) identifies pair-wise comparison (i.e. AHP) as more appropriate for analysis where accuracy and theoretical foundations are a concern, whereas ranking and rating systems are appropriate where cost, ease, and time are a concern.

Table 2 - Summary of Weighting Techniques: Summary of four common weighting techniques (after Malczewski 1999)

Weighting Technique	Description
Ranking	The weighting process of ranking requires the decision maker to use their preference to place the set of chosen criteria in order based on their relative importance. Then, numerical weights may be derived by inserting these ordinal values into a mathematical formula.
Rating	The weighting process of rating involves the decision maker's estimate of criteria weights as they relate to a predetermined scale. Then each criterion is allocated a number of points across a predetermined scale with a set range, where the collective points allocated equate to a set number.
Analytical Hierarchy Process (AHP)	Use of pair-wise comparison to create a matrix, which is then subject to calculations to derive the right eigenvector of the largest eigenvalue of this matrix. It is the derived eigenvectors that become the criterion and objective weights.
Trade-off analysis	Assess trade-offs between pairs of alternatives.

The AHP begins by developing a matrix that records the relative importance of each criterion for each objective. This pair-wise comparison is performed by using an intensity of importance scale such as that developed by Saaty (1980) (Table 3). Every possible pair of criteria is compared using such a scale to determine relative importance when considering each objective individually.

Table 3 - Intensity of Importance: Reference used when determining the relative importance of criteria during pair-wise comparison (after Saaty 1980)

Intensity of Importance	Definition
1	Equal importance
2	Equal to moderate importance
3	Moderate importance
4	Moderate to strong importance
5	Strong importance
6	Strong to very strong importance
7	Very strong importance
8	Very to extremely strong importance
9	Extreme importance

The results of these comparisons may be recorded within a table for documentation or inserted directly into the matrix M shown below.

$$\begin{array}{lccccc} & \textbf{Criterion}_1 & \textbf{Criterion}_2 & \cdots & \textbf{Criterion}_n & \\ \textbf{Criterion}_1 & c_1/c_1 & c_1/c_2 & \cdots & c_1/c_n & \\ \textbf{Criterion}_2 & c_2/c_1 & c_2/c_2 & \cdots & c_2/c_n & = M \\ \cdots & \cdots & \cdots & \cdots & \cdots & \\ \textbf{Criterion}_n & c_n/c_1 & c_n/c_2 & \cdots & c_n/c_n & \end{array}$$

where c represents the intensity of importance given to the corresponding criterion 1 through n. For example, if a criterion, C_1, is compared to another criterion, C_2, where C_1 is moderately important when compared to C_2, then the following table may be constructed:

Table 4 - Pair-Wise Comparison Example

Criteria	Intensity of Importance	Criteria	Intensity of Importance
C_1	3	C_2	1

Inserting these values into matrix M results in the value $3/1$ for row one, column two (i.e. C_1/C_2) and $1/3$ for row two, column one (i.e. C_2/C_1).

Once a matrix is created for each objective, it is necessary to square the eigenvalues (i.e. the matrix) until the eigenvectors begin to approach unity. The eigenvectors are the values resulting from the normalization of the product of matrix multiplication. The approach towards unity will be reflected in the decimal values of the eigenvectors. Decimal places of decreasing value will begin to match the previously derived eigenvector. In order to derive weights accurate to the second decimal place, the matrices must continue to be squared and normalized until the second decimal place of the normalized eigenvectors remains unchanged. Unless one is using a GIS that has built in AHP functionality, these steps must be performed outside of the GIS environment (e.g., within Microsoft Excel) and the results reinserted. An example implementation of this technique is demonstrated in section 4.6.

2.3.5 Implementation of Aggregation Algorithm

One of the most important components of a GIS is its ability to combine spatial data from a variety of sources (O'Sullivan and Unwin 2010). The process of aggregation, within the context of a MCE, produces a layer representing the degree to which the objective(s) has been met. Several options are available to aggregate various layers. One common and deterministic approach is a Boolean overlay, which utilizes binary true/false logic. This technique, formalized by McHarg (1969), involves aggregating multiple layers, each containing values indicating whether or not a particular characteristic is met, to determine what locations meet a set of desired characteristics.

An alternative to the Boolean overlay, formalized by Malczewski (2000), is termed a weighted linear combination. This technique differs from the binary logic imposed in the Boolean overlay. The output values produced from this process indicate, on a graduated scale, the degree to which a particular objective has been met. This approach is advantageous, as it retains the metric information contained within the layers being overlain and avoids the oftentimes illogical assumption that a given criterion no longer has an effect on an objective once it boundaries have been crossed (O'Sullivan and Unwin 2010).

After all the relevant criteria factoring into a decision making process have been standardized and once weights for these layers have been determined, these layers may then be aggregated. There are numerous weighting techniques available, three of which are summarized in Table 5.

Table 5 - Summary of Aggregation Techniques: Summary of three common aggregation techniques (after Malczewski 1999)

Aggregation Technique	Description
Weighted linear combination	Takes predetermined weights and multiplies them by normalized values given to criterion attributes and then sums the products over all criteria.
Ideal Point methods	Derives values that represent amount of separation from an ideal value.
Concordance methods	Based on a pair-wise comparison of alternatives and a mathematical function applied to a matrix derived from these comparisons. Differs from AHP in that criteria may only be compared as having preference over another criteria, but without indication of how much.

The weighted linear combination technique is represented by the following formula:

$$A = \sum_j W_j X_{ij} \qquad (3)$$

where A is the aggregated layer, W_j is the weight given to criteria layer j, and x_{ij} is the normalized value for the criteria layer j for attribute i. This process multiplies each criterion value by its corresponding weight and then sums these new values.

For benefit criteria, the highest values in the aggregated layer represent the most favorable conditions. When concerned with cost criteria, one may develop cost criteria during the standardization process or they may subtract the product from the above equation from 1. This is represented in the following formula:

$$A = 1 - (\sum_j W_j X_{ij}) \qquad (4)$$

Cost criteria values may have already been incorporated into the criteria layers during the standardization step. Therefore care should be taken to ensure these values are not reversed unnecessarily.

2.3.6 Sensitivity Analysis and Analysis of Outcome

The penultimate step of a MCE is an analysis of the outcome from the aggregation step and/or sensitivity analysis. Such analyses are necessary to determine if errors contained in raw input data or created during any of the MCE steps have been propagated into the outputs from the evaluation. Errors may be derived from inaccuracies related to data collection or manipulation strategies, misrepresentation of real world features, spatial autocorrelation, modifiable aerial unit problem, scale, edge effects, or other factors.

The most basic approach is to analyze the range of output values from the aggregation step to explore the reason they contain particular values. This will help build an understanding of what factors are most important in determining the outcomes. An assessment of errors of omission and commission (e.g., an error matrix) may be conducted if the error present can be quantified. Also, one may make small changes to the analysis boundaries or input values and determine if these changes have significant effects on the aggregation output (i.e., the weighted surface). Additional sensitivity analysis methods are the Monte Carlo simulation and the analytical error propagation method, which involve changing two or more criteria simultaneously to assess the effect. If significant effects do occur, a more detailed analysis would need to be conducted to determine the underlying issue and whether the results are sufficiently stable to be meaningful.

2.3.7 Using MCE Results to Make Decisions

The end result of the MCE process is an assemblage of choice alternatives. As is the case with a spatial MCE, these alternatives define locations that are preferred, that should be avoided, or that act as hard constraints. In the case of a raster GIS environment, each alternative would be represented as an individual raster cell. One must keep in mind, however, that there is no "correct" or "best" alternative. As O'Sullivan and Unwin (2010) explain, the results provide one or more solutions given the standardization, weighting, and aggregation techniques chosen. They note that this process helps reveal the effects of the various criteria involved and may assist in reducing the size of the area under investigation.

2.4 Path Modeling

Paths may be modeled to suggest the best way to move between locations (Mitchell 2012). There are two common types of paths that are generated. This includes those that follow a predetermined network (e.g. transportation network), termed network paths, and those that model a path between two points, termed overland paths. The former is performed in a vector GIS environment while the later is performed in a raster GIS environment. The placements of paths are often determined by associated costs. These costs may be expressed as money, time, distance, and so on. Network costs are associated with edges, intersections, and turns, while overland costs are associated with raster cells values (Mitchell 2012).

A cost-path analysis may be performed within ArcGIS using a raster to determine the cost values associated with traveling across particular cells. Using an evaluation process such as MCE is an example of how such a cost surface, or weighted surface, may be created. The accumulative cost is calculated on a cell by cell basis by starting at the origin cell and traveling towards a destination cell, sampling all of its adjacent cells, and recording the value associated with each edge. Once the cost distance rasters have been generated, they may be used as inputs to derive a path.

CHAPTER THREE: METHODOLOGY

The methodology described here derives traverse paths for fieldwork in a nine-step process. Most of these steps follow the workflow of a MCE described in the previous chapter. Additional steps cover the processes of data assembly and construction of evaluation criteria layers. The final step involves the derivation of the origin and destination points and the traverse paths that cross these points. The location of the origin and destination points and the traverse paths are determined by the values contained within the final weighted surface derived by the MCE. These steps, along with a summary of the work they require and the GIS layer relevant to each of them for a typical scientific field campaign, are shown below in Table 6. There are many options available with regard to the specific techniques that may be employed at each step during this methodology. While a generic framework is presented in this chapter, one must determine which of these techniques is best suited to the decision problem of a particular field campaign. Chapter Four provides a demonstration of how this methodology may be performed for a specific, yet hypothetical, geologic field campaign representing an attempt to develop a traverse for fieldwork intended to determine whether an area contains ore.

Table 6 - Methodology Steps, Required Work, and the Related Layers

Steps	Required Work	Relevant Layers
1. Identify objectives and criteria — *Problem definition* and *criteria selection* steps of MCE	Literature examination, analytical study, or attainment of expert opinions	not applicable
2. Assemble relevant data	Acquire data that may be used to create criteria layers for measure of objective(s) fulfillment	e.g., remotely derived imagery, digital elevation model, topographic map, and special-purpose map — Termed *raw data*
3. Sketch and derive features of interest relevant to meeting objective(s)	Delineate and/or create criteria layers and ensure they share a common coordinate system and extent	Points, lines, polygons, or continuous data delineating features of interest — Termed *features of interest*
4. Apply necessary manipulations or analysis to derived features of interest	For example, apply distance calculations	Layers containing manipulation or analysis results — Termed *non-standardized criteria layer*
5. Standardize the non-standardized criteria layers — *Standardization* step of MCE.	Transform non-standardized criteria layer values to a common scale	Termed *standardized criteria layers*
6. Establish field campaign priorities — *Weighting* step of MCE.	Derive and assign weights to each criteria and objective	not applicable
7. Produce weighted surface layers of study area — *Aggregation* step of MCE	Perform map overlay (aggregation)	Termed *weighted surface*
8. Review results of MCE — *Sensitivity analysis* step of MCE	Perform sensitivity analyses and/or analysis of results	not applicable
9. Define traverse paths on basis of time availability	Derive origin and destination points and traverse paths	Termed *destination points*, and *traverse paths*

3.1 Identify Objectives and Criteria

This step of the methodology relates to the problem definition and criteria selection steps of a MCE. As field research will often be conducted to attain data that is unavailable via remote means, the problem facing scientists preparing to go in the field will often be determining what data should be acquired and how. This problem should be divided into multiple objectives. These objectives may be, for example, to attain a scientific return and to avoid obstacles that impede travel across the study area. A group consensus, or individual decision, establishing the overall decision problem and separating this problem into applicable objectives is required to proceed to the subsequent steps.

This step also involves deciding which criteria may be used to measure the fulfillment of the determined objectives. Research may be needed to determine which criteria affect a given objective in order to establish a scientific foundation for the remaining steps. Analytical studies or an opinion survey are additional options that may be used to make this decision regarding appropriate criteria.

Once the set of criteria is determined, they should be separated into factors or constraints. If a criterion is considered a constraint, the constraining attribute values should be noted. For example, a criterion layer containing slope values may be considered a constraint where all values are greater than some threshold, for example, slope values greater than fifty degrees. It also should be determined whether a given criterion's attribute values will have a favorable or unfavorable influence on meeting the objective to which it is applicable. This will assist in determining an appropriate algorithm to use during standardization. While a criterion may contain attribute values that are not favorable with regards to meeting a particular objective, they may not necessarily act as a constraint (i.e., a hard limitation).

3.2 Assemble Relevant Data

Once it has been determined which criteria may be used to measure the degree to which a particular objective(s) is being met, data are sought that may be used to represent these criteria.

Each data set used must share a common coordinate system and have positional accuracy sufficient for the research at hand.

3.3 Sketch and Derive Features of Interest Relevant to Meeting Objective(s)

Raw data that provide information on criteria influencing the degree to which a given objective(s) is being met will often not be suitable for the remaining steps of this methodology in its raw form. That is, it may not provide a suitable representation of the criteria or objectives being evaluated. Such data should be brought into a suitable form through various manipulations or analyses. Such techniques may include the derivation of slope or visibility from a DEM, or buffering of features. It may also include the manual delineation of various features of interest based upon image or map interpretations.

3.4 Apply Necessary Manipulations or Analysis to Derived Features of Interest

The delineated features of interest may be further analyzed so that they contain information more directly related to measuring the degree to which a particular objective(s) has been met. An example of this is determining the distance from these delineated features of interest to all other locations within the study area. This would be relevant to situations where a scientist's proximity to various features of interest relate to the ability to attain a scientific return from the features.

3.5 Standardization

This step relates to the standardization step of a MCE. Criteria layers that do not share a common scale must be converted to a common scale before they may be aggregated. This is done through the process of standardization. Various standardization techniques are shown in section 2.4.3. During this process, each layer is transformed into a common scale containing floating point values ranging from zero to one. The aim of this methodology is to create traverse paths derived from a cost surface, based on cost-criteria. It is fitting therefore, to represent favorable characteristics with a low value and unfavorable characteristics with a high value. Care should be taken to ensure these values are not reversed erroneously in the subsequent steps.

3.6 Allocation of Weights

This step relates to the weighting step of a MCE. It must be determined which weight assessment technique is appropriate for the given decision problem. Various weighting techniques are shown in section 2.4.4.

3.7 Implementation of Aggregation Algorithm

This step relates to the aggregation step of a MCE. After all the relevant criteria factoring into the navigational decision making process had been standardized and once weights for these layers had been determined, these layers may then be aggregated. Various aggregation techniques are shown in section 2.4.5. If more than one objective is necessary to assess the decision problem, then multiple weighted surfaces will be created. These surfaces may be combined to create one final weighted surface to be used during the subsequent steps.

3.8 Review Results of Multicriteria Evaluation

This step relates to the sensitivity analysis and analysis of outcome steps of a MCE. If appropriate, an error propagation analysis or the construction of an error matrix may be performed. Otherwise, one should inspect the values contained within the weighted surface to ensure its values contain the desired meaning. Once confident that these values are reliable, one may proceed to the subsequent steps.

3.9 Define Traverse Paths on Basis of Time Availability

This step involves deriving the set of points that the traverse path must visit during the field campaign and the path to be followed between them. Note that this methodology does not describe how to determine visitation sites, but produces suggested traverse paths that position field scientists within close proximity to features they have deemed to be of interest. The description below explains how this step may be performed within ArcGIS. In order to derive a traverse path using this software, users must possess origin and destination points and a weighted surface. These are used as inputs to the ArcGIS Cost Distance and Cost Path tools. The tools are run once for each segment of the traverse path. Each iteration of these tools requires the weighted surface, one origin point, and one destination point. All origin points also act as destination points and will thus be referred to hereafter as destination points.

Since the lowest values in the weighted surface (i.e. the cost layer) indicate favorability with regard to meeting a particular objective, this layer is used to determine the destination points. If time is limited for a particular field campaign, a traverse path may be prioritized by delineating only the most favorable locations (i.e. those with the lowest values on the weighted surface). For example, only locations with the top five percent most favorable values of the weighted layer may be used when a short time duration is available for fieldwork. Once it is determined which percent to use, the weighted layer is reclassified so that these most favorable values are represented as some value (e.g., one) while all greater values (i.e., less favorable) are represented as NoData. This reclassified layer is then converted to a polygon feature class. The centroids of these polygons are then derived and serve as the destination points. Derived points that are in close proximity should be manually deleted to avoid excessive calculations that will not greatly alter the location of the derived traverse path.

In order to use these derived points as individual destination points in the multiple iterations of the Cost Distance and Cost Path tools, all points in the feature class created above must be separated into separate feature classes. The sequence in which these points are used in the iterations of the Cost Distance and Cost Path tools will determine the connectivity of the destination points of the derived traverse path. Thus, these points should be manually ordered such that the resulting path will contain a logical sequence. For example, in Figure 2, the destination points have been arranged so that no segments of the traverse path cross. Rather, the traverse path makes a loop around this portion of the study area. Figure 2 also illustrates that each point acts as both an origin and destination point. These locations can either contain one point feature class that acts as both and origin and destination point or contain two point feature classes with one representing an origin and the other, a destination.

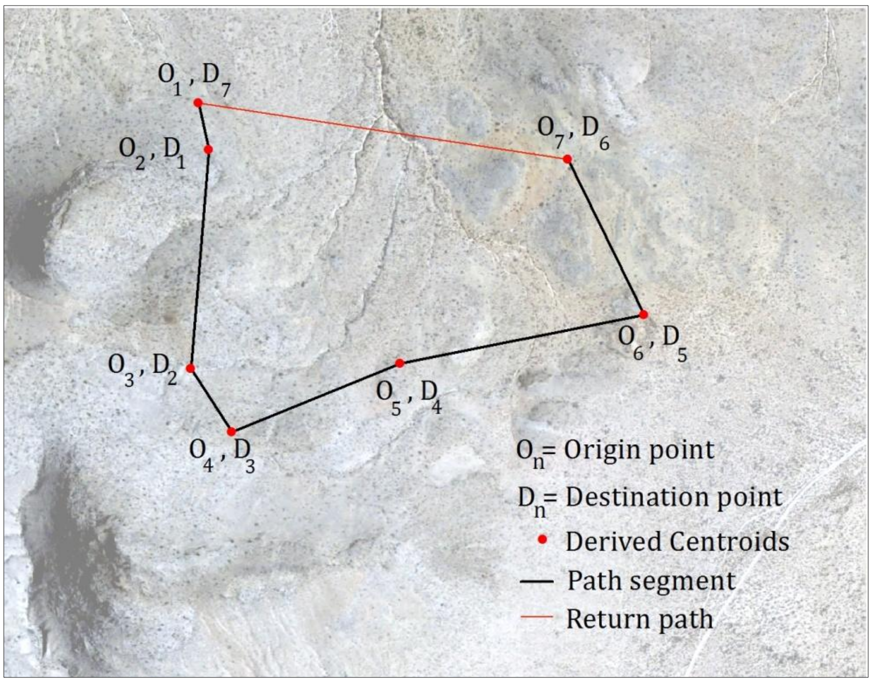

Figure 2 - Example Derivation of Traverse Paths: Example of how the origin and destination points factor in to the derivation of the traverse paths. Note that the segments between points are drawn here as simple straight lines, not as final derived traverse paths.

Once the destination points have been derived they may be used in combination with the weighted surface to complete the traverse path derivation process using the ArcGIS tools mentioned above. Finally, the ArcGIS Raster to Polyline tool is used to convert the raster output of the Cost Path tool to a polyline feature class. This will reduce the size of the files representing the traverse path and will convert it to a format that may be easier for use in the field. The former will assist with bringing the traverse files into the field on a mobile computer. The latter will enable the traverse paths to be seen more easily seen in combination with a raster (e.g., it may be overlain on imagery or a topographic map).

Shown in Figure 3 is a portion of a model, built using ArcGIS ModelBuilder, that is used to derive one segment of the traverse path. In order to make a traverse path with multiple segments this series of tools will need to be run multiple times. Conducting this work within ModelBuilder expedites this process.

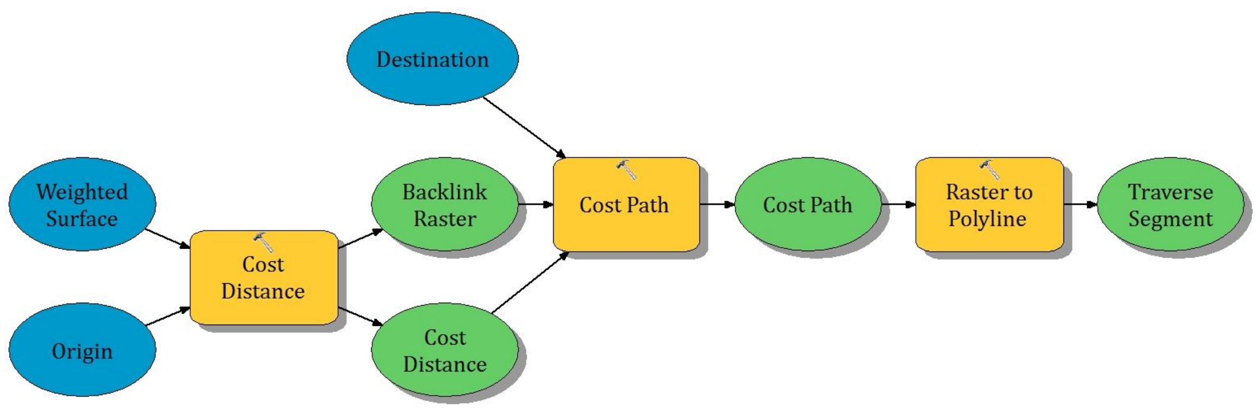

Figure 3 - Workflow to Create Traverse Path Segment: ArcGIS ModelBuilder steps used to derive traverse path segment.

In summary, this chapter has outlined a straightforward, generic methodology that may be used by a field scientist to determine a traverse path in unfamiliar territory. The next chapter demonstrates the use of the methodology to plan a simple hypothetical geologic field campaign.

CHAPTER FOUR: DEMONSTRATION OF METHODOLOGY

The hypothetical field campaign used to demonstrate the traverse generating methodology is designed to depict preparatory efforts of an exploration geologist (who is arbitrarily considered to be a woman) who is about to embark on a geologic field survey. Exploration geologists identify and assess the landscape to determine the likelihood of economically extracting minerals from a particular area. The geologist here has become aware of a new, more detailed geologic map for a small area within Hildago County, New Mexico. (This “new map” has been created for the purpose of demonstrating the methodology described here and does not necessarily represent the true geology of the area (see Figure 4).) This map depicts an abundance of dikes and sills (sheet like bodies of rock that cut or follow surrounding rock features) that share characteristics with other dikes and sills within Hildago County that have been known to contain elevated amounts of gold. This geologist has been allocated one day to carry out a survey to determine if a 4.5 km^2 portion of this new map area contains evidence that suggests the need for further exploration (see Figure 5). Her work will consist of documenting the location and a description of gold bearing rocks or any other potentially economic materials within the study area. In addition, she will try to record the overall history and distribution of rocks in the study area in order to supplement the information provided by the geologic map.

As the existence or precise distribution of the gold and its relation to the dikes and sills are not known for this area, the geologist will attempt to better understand the nature of any gold deposits and allow this to determine the exact locations she visits. Nevertheless, she must also attempt to cover a significant portion of the study area in a short time and wants to take a more analytical and systematic approach in determining how to do so. She has chosen to perform a MCE in an attempt to place herself near the most advantageous and accessible regions within the defined study area. The goal is to develop a traverse path using the aforementioned methodology for an approximate ten hour day. This path will place her in close proximity to locations containing a high scientific return and that are most accessible to foot travel. Described below is the methodology used to develop this path.

4.1 Identify Objectives and Criteria

There are geologic and logistical objectives that have been determined to be applicable to the hypothetical field campaign (Table 7). These have been categorized into their suitability to measure the fulfillment of meeting these objectives through a MCE or path model. A category of procedural assumptions has also been included, but no attempt is made here to measure their effect on the target objectives. All of the criteria listed have been derived from a review of Compton (1985) and Coe (2010).

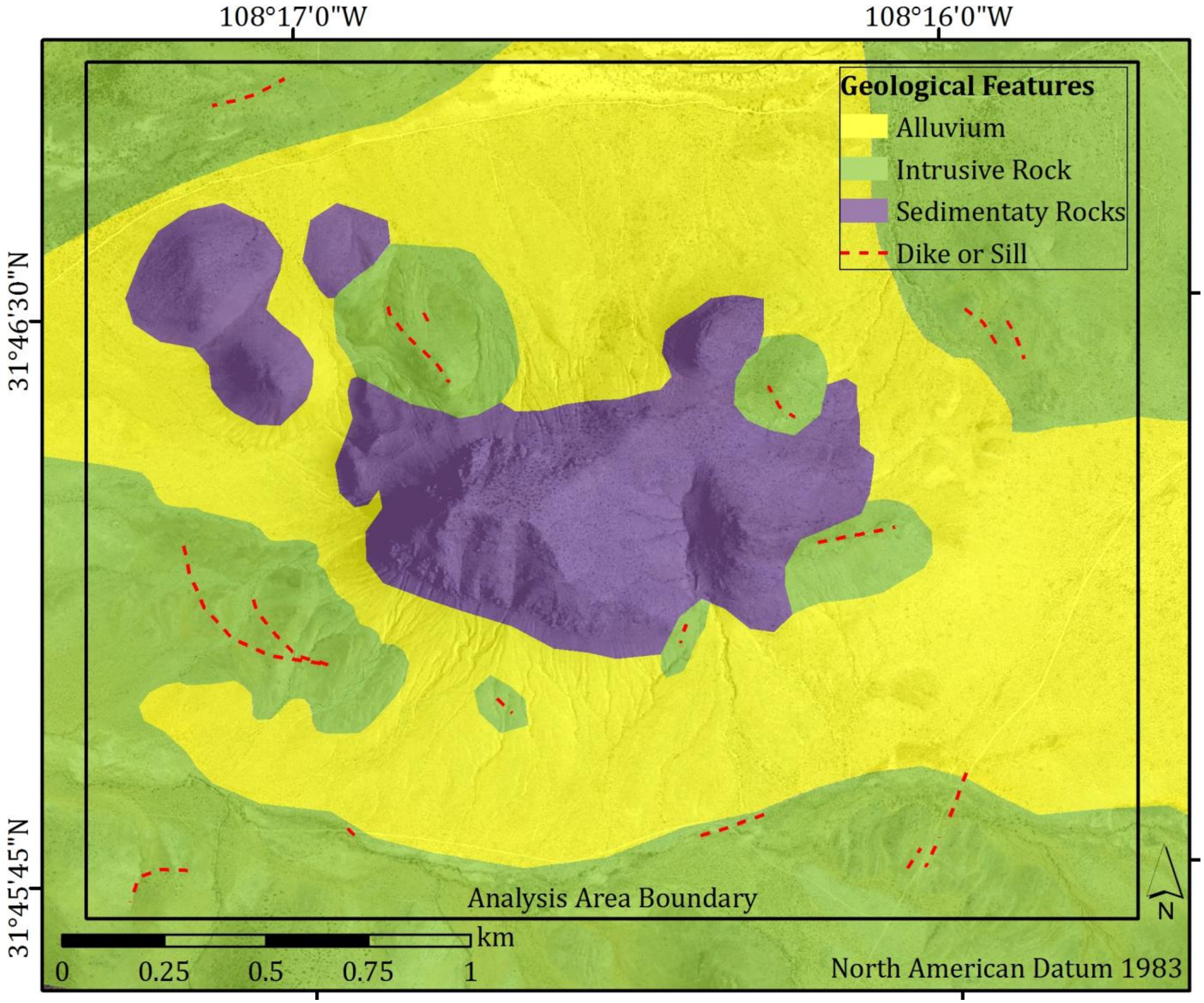

Figure 4 - Hypothetical Geologic Map: Hypothetical geologic map identifying the geologic features that exist within the study area.

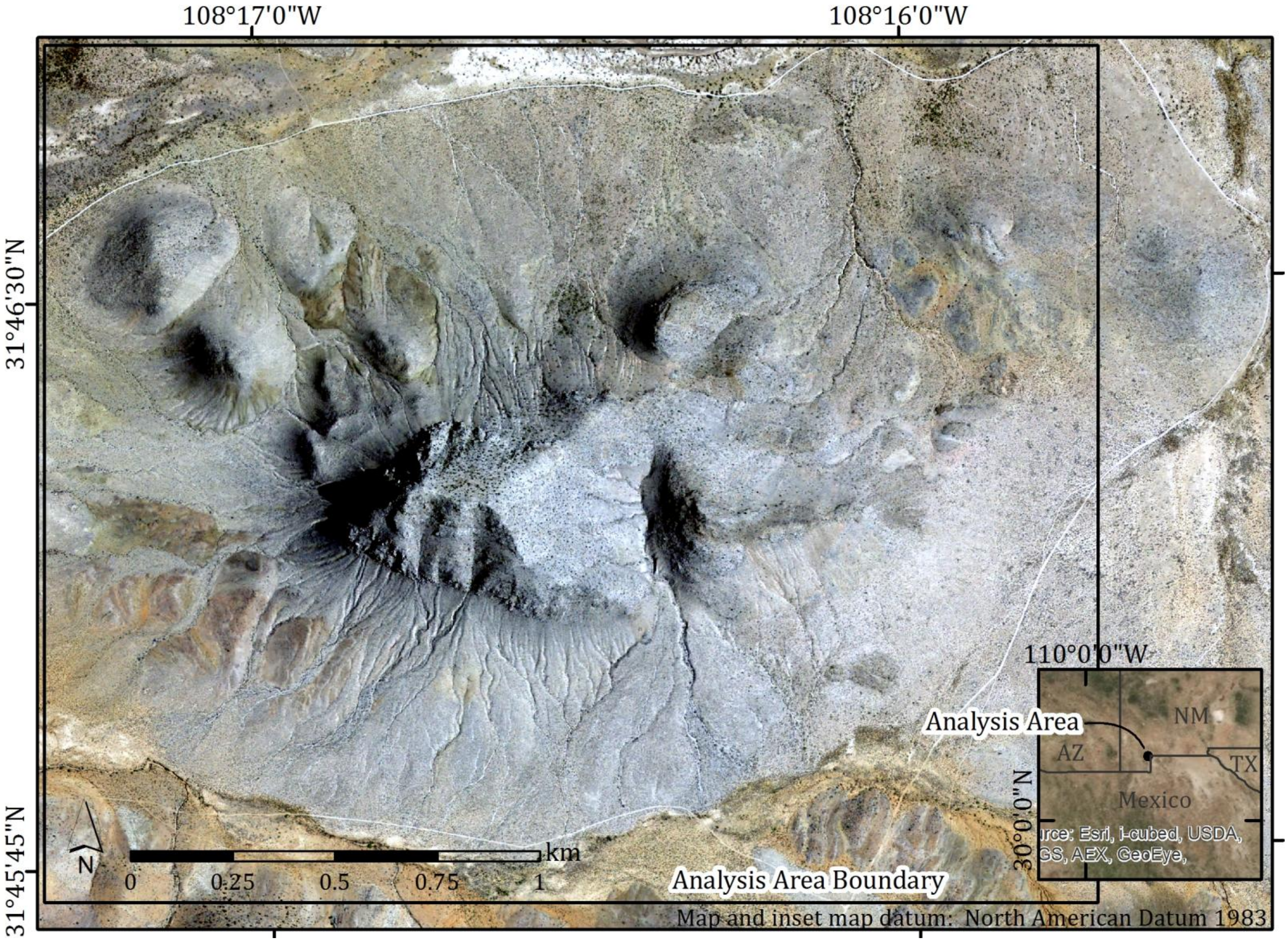

Figure 5 - Location Map for Demonstration: Location map illustrating the analysis area used for the demonstration of the developed methodology. This area includes a buffer around the actual study area and is approximately 5.4 km^2.

Table 7 - Criteria and Procedural Assumptions Relevant to Geologic Fieldwork

Criteria Appropriate for a Multicriteria Evaluation
1. *Regions*: Regions of interest where opportunities for direct observation and measurements exist. This criterion differs from Exposures in that these areas correspond with testing existing hypotheses.
2. *Exposures:* Areas where geologic materials are exceptionally exposed due to mines, road cuts, wash cuts, etc. This criterion differs from Regions in that this layer only represents locations where relatively exceptional opportunities for direct observation, measurement, or sampling exist, but not locations where hypotheses may necessarily be tested.
3. *Visibility:* Areas where exceptional distant observation opportunities exist.
4. *Access:* Areas containing roads and trails.
5. *Slope:* Change in elevation per change in distance.
Criteria Appropriate for Path Modeling
6. Time to conduct survey
7. Utility cost of travel across the surface
8. Distance
9. Survey scale
Procedural Assumptions
10. Data availability
11. Property ownership
12. Vegetation
13. Soil cover
14. Weather
15. Equipment
16. Lodging/Camping locations

Criteria one through three are used to measure scientific return, while criteria four and five are used to measure accessibility. Scientific return, with regards to exploration geology, is the likelihood of locating and defining potential economically mineable geologic materials. Criteria one and two are often related, but have been separated here to distinguish the anticipated amount of scientific return associated with each criterion. Time is incorporated because it will control the number of way points through which the traverse paths will cross. Cost is incorporated, in that the traverse paths between the selected points will travel across a weighted cost surface. Of the remaining two criteria, distance is implicitly considered, in that it is related to cost and scale is incorporated by conducting all GIS work at a particular scale.

4.2 Assemble Relevant Data

The hypothetical case study presented here uses four authentic data sets and one hypothetical data set. The process of using these data to derive and sketch the features relevant to meeting the campaign objectives is described in the next section. These data sets include a New Mexico Bureau of Geology and Mineral Resources (NMBGMR) state geologic map, aerial imagery provided by the U.S. National Agriculture Imagery Program, a digital elevation model from the USGS National Elevation Dataset, and a USGS topographic map. The hypothetical geologic map was derived to depict a scenario in which a new, more detailed map has peaked the interest of an exploration geologist.

The NMBGMR state geologic map was acquired from the USGS National Geological Map Database website. This map was published by the New Mexico Bureau of Geology and Mineral Resources in 2003 at a scale of 1:500,000. This map was not available for download directly from the USGS website, but was available only by mail order from NMBGMR offices. Rather than order this map, with realization that the scale was far more generalized than what was needed for the case study, a screen shot was taken and then georeferenced using as control points, state boundaries and roadways contained in the USGS aerial imagery. The total root mean square error for the georeferencing process was approximately 0.84 meters, using an affine coordinate transformation.

The National Agriculture Imagery Program aerial imagery was acquired from The National Map Viewer and Download Platform website on 11 October 2014. This imagery has a spatial resolution of 1.0 meter and was captured between 2011 and 2013.

The USGS National Elevation Dataset (NED) digital elevation model (DEM) was acquired as a single 10,500 km^2 tile from the USGS National Map Viewer website. It has a horizontal resolution of 1/3 arc second (which is approximately nine meters at this latitude). The overall absolute vertical accuracy of the NED within the conterminous US is 1.55 meters and while this value varies greatly across the US, it does not exceed twenty five meters when compared to National Geodetic Survey benchmark elevations (Gesch et al. 2014). The various light detection and ranging (LiDAR), radar, photogrammetric, and topographic data sources used to create this DEM tile were acquired between 1 February 1999 and 1 November 2013. This DEM tile was published in 2013.

The Doyle Peak, New Mexico topographic map was acquired from the The National Map Viewer and Download Platform website on 20 August 2014. It was compiled from aerial imagery taken in 1976, field checked in 1977, and contains a map scale of 1:24,000. This map was published in 1982 as a provisional edition map.

Of these datasets, the aerial imagery was used to delineate features of interest pertaining to Regions, Exposures, and Access. The DEM was used to delineate features of interest pertaining to Visibility and Slope. The topographic map was used to provide additional support for the delineation of features of interest pertaining to Exposures and Access. The geologic map was used to support interpretations made from the aerial imagery regarding the delineation of features pertaining to Regions.

4.3 Sketch and Derive Features Relevant to Meeting Objectives

The hypothetical case study presented here required both delineation of various features of interest and additional analyses relevant to these features such as distance. These processes are further described below. Prior to such analyses, however, it was necessary to ensure all raw data were projected to a common coordinate system, North American Datum 1983 Universal Transverse Mercator Zone 12. It was also necessary to ensure this data extended across all portions of the study area. All analyses performed on the data were done for a buffer of approximately 200 meters beyond the actual study area to mitigate any possible edge effects (a nonuniformity problem). This area is termed the analysis area and is the rectangular boundary bounding most figures shown in this thesis. The derivation of slope is the only process that incorporates neighboring cells into its computation (i.e. bilinear interpolation) and likely the only layer that may be affected by such a non-uniformity problem. It is assumed that by running each analysis in this methodology for the extent of the analysis area, and not the study area, any possible edge effects that may have occurred have been prevented.

This methodology also required that each criteria layer have the same spatial resolution. With the exception of the NMBGMR geologic map, the elevation data required for the Visibility and Slope criterion layers had the coarsest resolution at approximately 9.26 meters. The NMBGMR map, published at a scale of 1:500,000, was only used to gain a broad understanding of the study area's geology and was only subjected to a brief and visual analysis. Thus, it was not used to determine the resolution for the subsequent work. A resolution of ten meters was selected for these analyses due to its similarity to the DEM resolution, its applicability to a 4.5 km^2

survey, and for the computer processing requirements involved. Provided below is a description of how each criterion layer was created.

4.3.1 Derivation of Criterion Layers Representing Scientific Return

The criteria chosen to measure scientific return are Regions, Exposures, and Visibility. The layers used to represent these criteria not only delineate features of interest, but also the Euclidean distance, measured in meters, from these features to all other locations within the analysis area. Where the cells are coincident with the layer's feature of interest, this value is zero. As the distance away from these features increases, its value increases linearly. This design was used in order to account for the advantage of being close to these features of interest considered to be aids to achieving high scientific return. This is an example of some functionality that would be unavailable when using the Boolean logic of sieve mapping.

The Regions non-standardized criterion layer represents the distance to areas where the geologist may test one or more of her current working hypotheses (i.e., those related to understanding of the distribution and history of the geologic materials within the study area, with emphasis placed on those materials containing economic interest). The features of interest from which a measure of distance was calculated were manually delineated based upon information provided by the aerial imagery and the geologic maps. While sophisticated digital image analysis is possible and would produce much more precise results, for the purposes of this demonstration, it was decided that a classic manual interpretation approach was sufficient. Characteristics of tone, texture, pattern, and shape within the aerial imagery were used to interpret where changing rock units were likely to occur, what types of rocks were contained in these units, and to determine structural aspects of the study area. Also, the geologic maps provided a further explanation of what rock types could be expected to exist in certain portions of the analysis area.

This information provided context for determining which locations might provide opportunity to test hypotheses.

Once the Region's features of interest had been delineated, the Euclidean distance from these features was derived. This was done using the ArcGIS Euclidean Distance tool. The input for this tool was the Regions polygon feature class and the output was a raster with the resolution set to ten meters. This output raster was used later as an input during the standardization process.

The Exposures criterion represents areas containing features that provide an exceptional view of the study area rocks. These features include locations such as road cuts, mines, deep canyons, and perhaps, in non-arid lands where intact rocks are limited, rock outcrops. The only mines discovered around the study area were approximately 150 meters beyond the analysis area boundary. Also, no road cuts or deep canyons were found within the study area. To demonstrate the effect of Exposures on the traverse paths generated, however, three Exposures point features have been manually added. Once these Exposure's feature of interest had been delineated, the Euclidean distance from these features was derived. This was done using the ArcGIS Euclidean Distance tool. The input for this tool was the Exposures point feature class and the output was a raster with the resolution set to ten meters. This output raster was used later as an input during the standardization process.

The Visibility criterion represents areas that provide opportunities to view large portions of the study area. Visibility was determined using the ArcGIS Visibility tool. This tool derives visibility by calculating the elevation change between an observation point and the local horizon. If a center of a raster cell making up a portion of the local horizon is positioned so that there are no obstructions, or cells with higher elevation values, between it and an observation cell, it is considered to be visible by that specific observation point. Each cell within the input raster is considered when determining its relation to the observation points. The output from this analysis is a raster layer representing either the number of times that each cell of the input raster can be seen by an observer point (the frequency analysis type) or the number of observation points that can be seen by each cell in the input raster (observation analysis type).

The Visibility analysis used for the methodology described here was of the frequency analysis type. However, the geologist's concern was not to determine visibility for just a few observation points, but from every point across the entire study area. Thus, the centroids for each raster cell making up the study area were derived and these centroids then became the observation points used within the visibility analysis. The resulting output raster contained a value field defining how many cells within the study area could be seen from each observation point, or from every cell, within the study area. The observation points containing the top thirty percent of the value results was considered the high visibility area and delineated as such. A layer containing only the cells with these top values was created by reclassifying the layer. Those cells with values in the top thirty percent were reclassified to a value of one and the remaining cells were reclassified to NoData. The Euclidean distance from the visibility features making up this new reclassified layer was then calculated. This output raster was used later as an input during the standardization process. Figure 6 depicts these features that were delineated as Scientific Return criteria in this analysis. An inset in this figure shows the raw values derived from the Visibility tool.

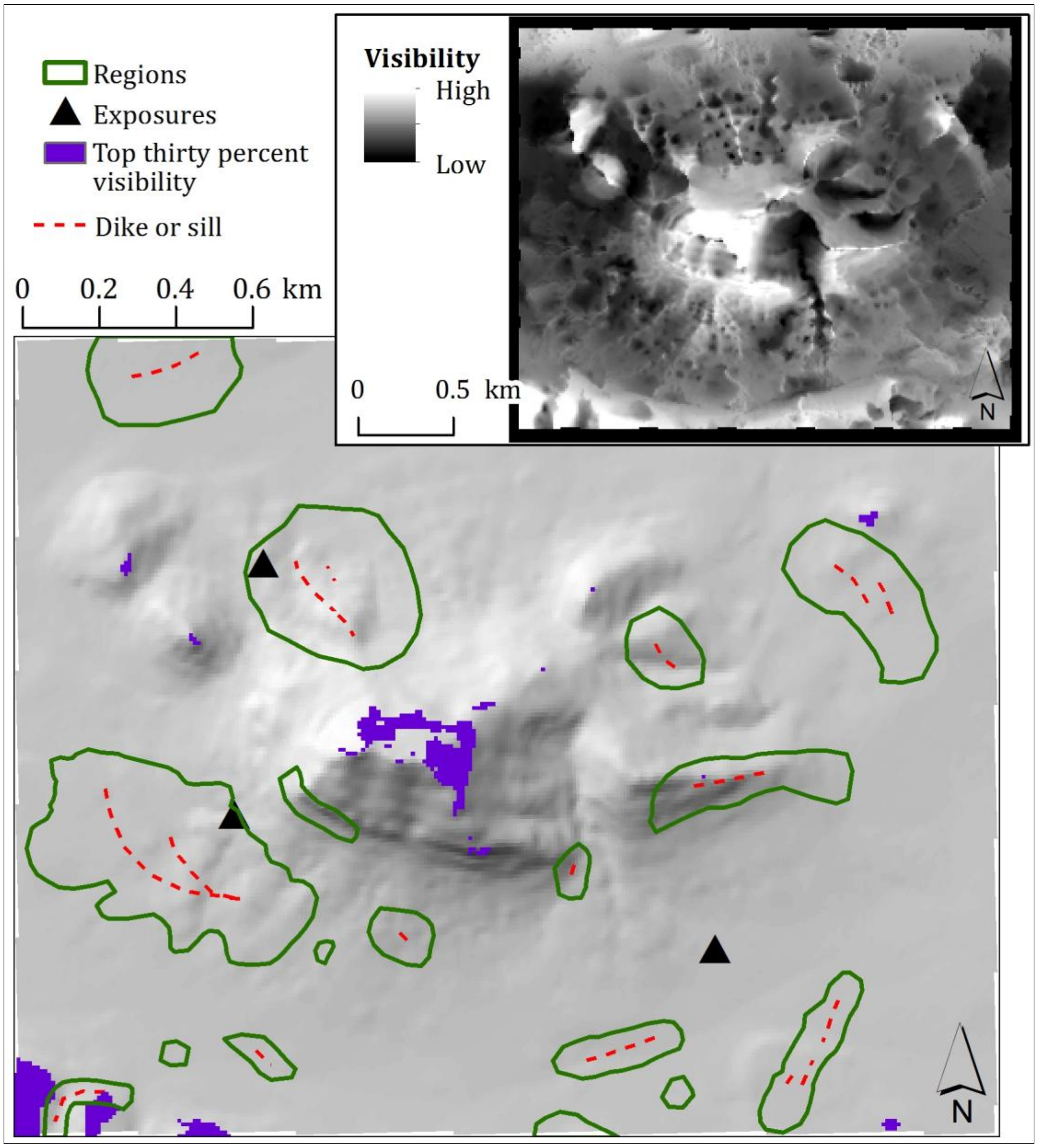

Figure 6 - Features of Interest Relevant to Scientific Return Objective

4.3.2 Derivation of Criterion Layers Representing Accessibility

The criteria chosen to measure impedance to foot travel are Access and Slope. The layer used to represent the Access criterion not only represents the access to features of interest (i.e. roads and trails), but also values derived from a distance function indicating a decreasing favorability value as the distance away from these features increases. The layer used to represent the Slope criterion contains values of slope in degrees.

Aerial imagery and USGS topography maps have been used to identify access routes. Roads were discovered on the northern and southern edges of the analysis area. The same roads were identified in both the topographic map and aerial imagery. No trails of significant size were found within the analysis area. Figure 7 shows the routes identified in this step. Once the Access features of interest had been delineated, the Euclidean distance from these features was derived. The input for this tool was the Access polyline feature class and the output was a raster with the resolution set to ten meters. This output raster was used as an input during the standardization process.

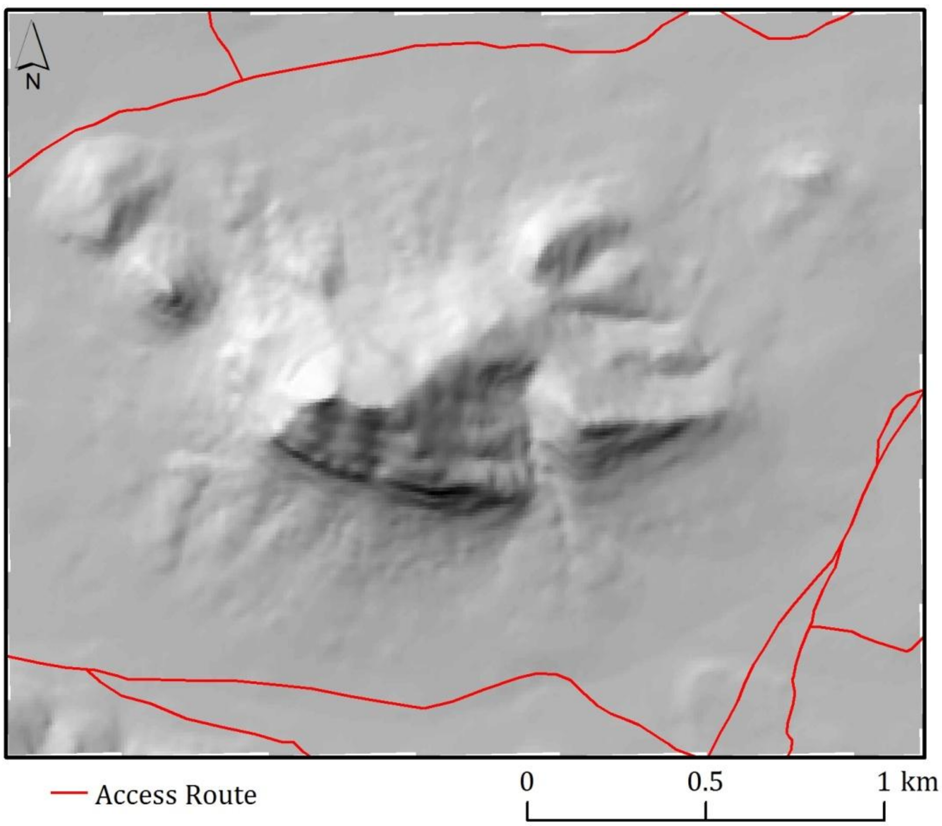

Figure 7 - Access Features of Interest: Access features of interest relevant to the Accessibility objective

The Slope criterion represents the slope across the analysis area. The slope within the analysis area was derived by running the ArcGIS Slope tool. Unlike the other four criteria, Euclidean distance was not involved, as a value of slope was derived for each cell. Slope values greater than forty nine degrees were consider a constraint. Thus, the slope layer representing this criterion was reclassified so that all values greater than forty nine degrees were converted to a value of NoData. This process ensured that the traverse paths generated would not intersect these areas. This reclassified raster containing the slope and NoData values was used as input during the standardization process. This layer is shown in Figure 8 below.

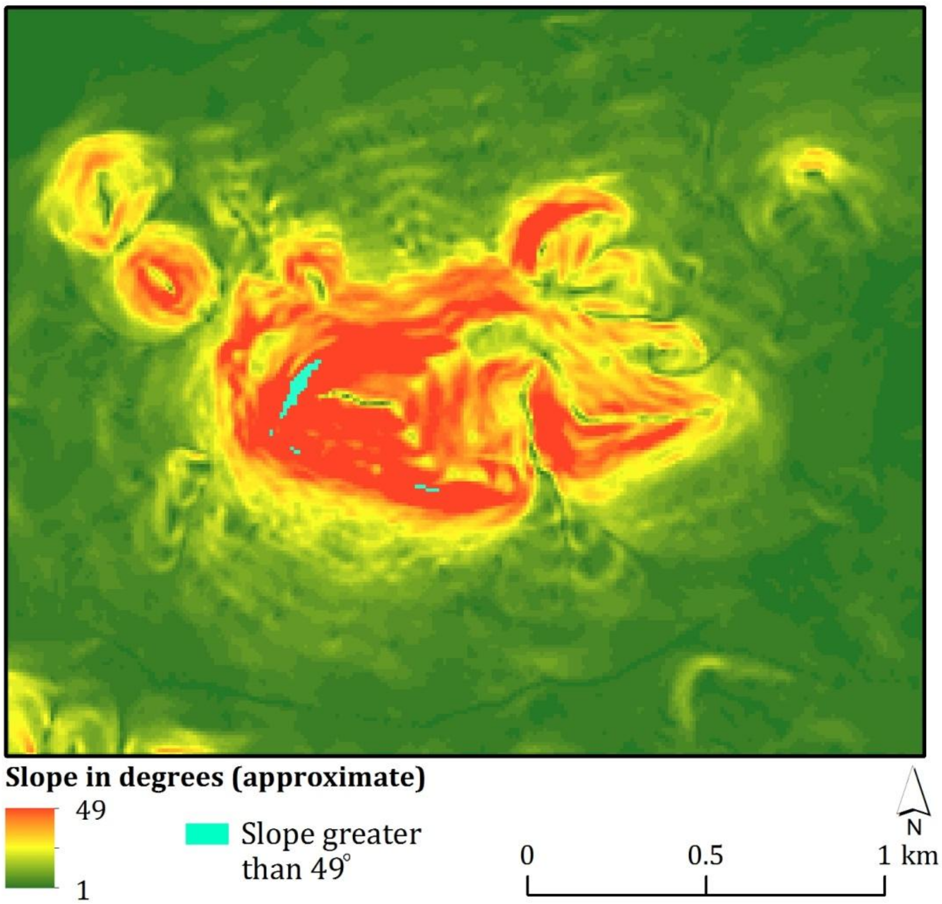

Figure 8 - Slope Criterion: Slope values relevant to the Accessibility objective

4.4 Standardization

The non-standardized criteria layers must be converted to a common scale (i.e., standardized) before they may be aggregated. The attribute values defining the five non-standardized criteria layers contain measures of distance and slope. In the standardization step, these layers are transformed into a common scale containing floating point values in a range from zero to one. The aim of this methodology is to create traverse paths derived from a cost surface, based on cost-criteria. It is fitting therefore, to represent favorable characteristics with a low value and unfavorable characteristics with a high value.

The Regions, Exposures, and Visibility non-standardized criteria layers are entirely composed of distance values. These non-standardized criterion layers are named after the delineated feature of interest they represent. The distance value within the boundary of these delineated features of interest is zero. The values of the remaining cells within the non-standardized criterion layers represent its distance from the given feature of interest within that layer.

Because these three layers must be compared to layers representing very different values (i.e. utility for the Access criteria and slope for the Slope criteria), they must be standardized. There is no information available that quantifies the relationship between the values defined here for proximity to Regions, Exposures, and Visibility and their ability to assist in meeting the objective of attaining a high scientific return. Thus, choosing a simple, straightforward approach, it is assumed here that there is a negative linear relationship between distance from the given feature of interest contained within these layers and likelihood of attaining a high scientific return from these features. As the distance from the given layer’s feature of interest increases, its favorability, or value representing its ability to help meet the objective of scientific return, decreases.

Equation 1 (Chapter Two) was used to standardize the non-standardized criteria layers of Regions, Exposures, and Visibility. This equation was run separately for each of these three layers and calculated for each ten square meter cell within each layer. This function is shown graphically in Figure 9. The minimum distance value (i.e. zero) within these layers was assigned a standardized value of zero. The greatest possible distance value given the defined analysis area (i.e. approximately 3319 meters) was assigned a standardized value of one. The intermediate distance values increased linearly between these two endpoints.

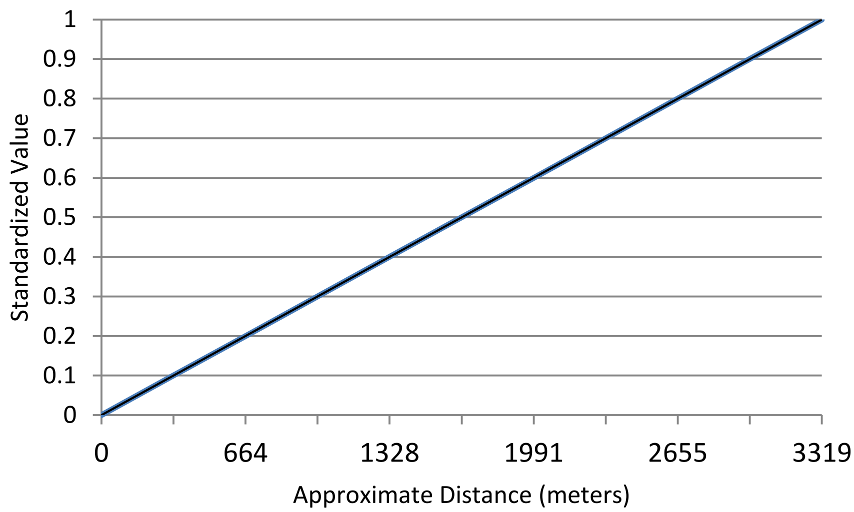

Figure 9 - Standardization Function for Regions, Access, and Visibility Criteria: Graphical form of the function used to describe the relationship between distance to Regions, Exposures, and Visibility features of interest and their anticipated contribution to meeting the Scientific Return Objective.

The Access criterion has been standardized using the value function approach described in Section 2.3.3. This differs from the simple linear scale transformation in that it is not based entirely upon a linear relationship between the non-standardized and standardized criteria layers. No research quantifies the relationship between distance to access routes and its ability to support accessibility. Thus, consideration of time it would take to travel to a delineated access route was used to determine the linear function used to standardize this layer. At 3.2 kilometers per hour it would take five minutes to walk approximately 268 meters. This was assumed to be the distance at which it no longer makes sense to travel to an access route rather than directly to the next destination. A decay function is used to represent this relationship. This function is shown graphically in Figure 10. Similar to the value function for the Regions, Exposures, and Visibility layers, the minimum distance value (i.e. zero meters) within the Access layer was assigned a standardized value of zero. The standardized values increased linearly as distance values increased, until a distance value of 268 meters was reached. All distance values between 268 meters and the maximum possible distance value (i.e. 3319 meters) were assigned a standardized value of one. The maximum value, however, was set to 268 meters rather than 3319 meters. This resulted in all values above this maximum to receive a standardized value of one. It is important to note that since locations beyond the 268 m distance may still be incorporated into the path if other criteria make it worthwhile to go there, they have not been set to NoData as is described below for slope.

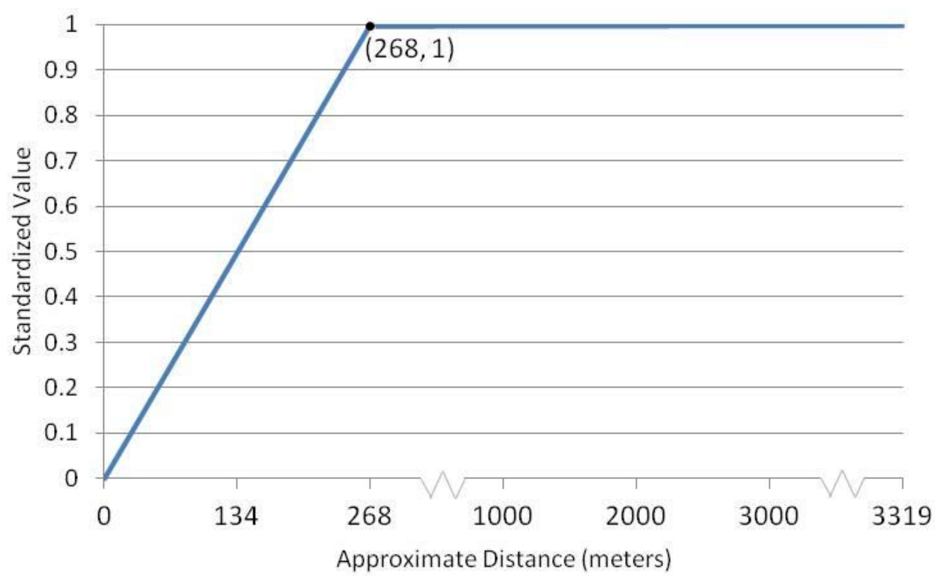

Figure 10 - Standardization Function for Access Criterion: Graphical form of the function used to describe the relationship between the location of Access features of interest and their anticipated contribution to meeting the Accessibility Objective.

There is no information available that quantifies the relationship between slope and its detriment to accessibility. Thus, once again, it is assumed that there is a negative linear relationship between an increase in slope and accessibility for foot travel. This occurs until a value of fifty degrees is reached, at which point all higher slope values are represented as NoData. As the slope increases, its value representing its ability to help meet the objective of accessibility decreases. Equation 1 defines this relationship and was used to derive the standardized criterion layer for Slope. Figure 11 shows the standardized layers for each of the five criteria.

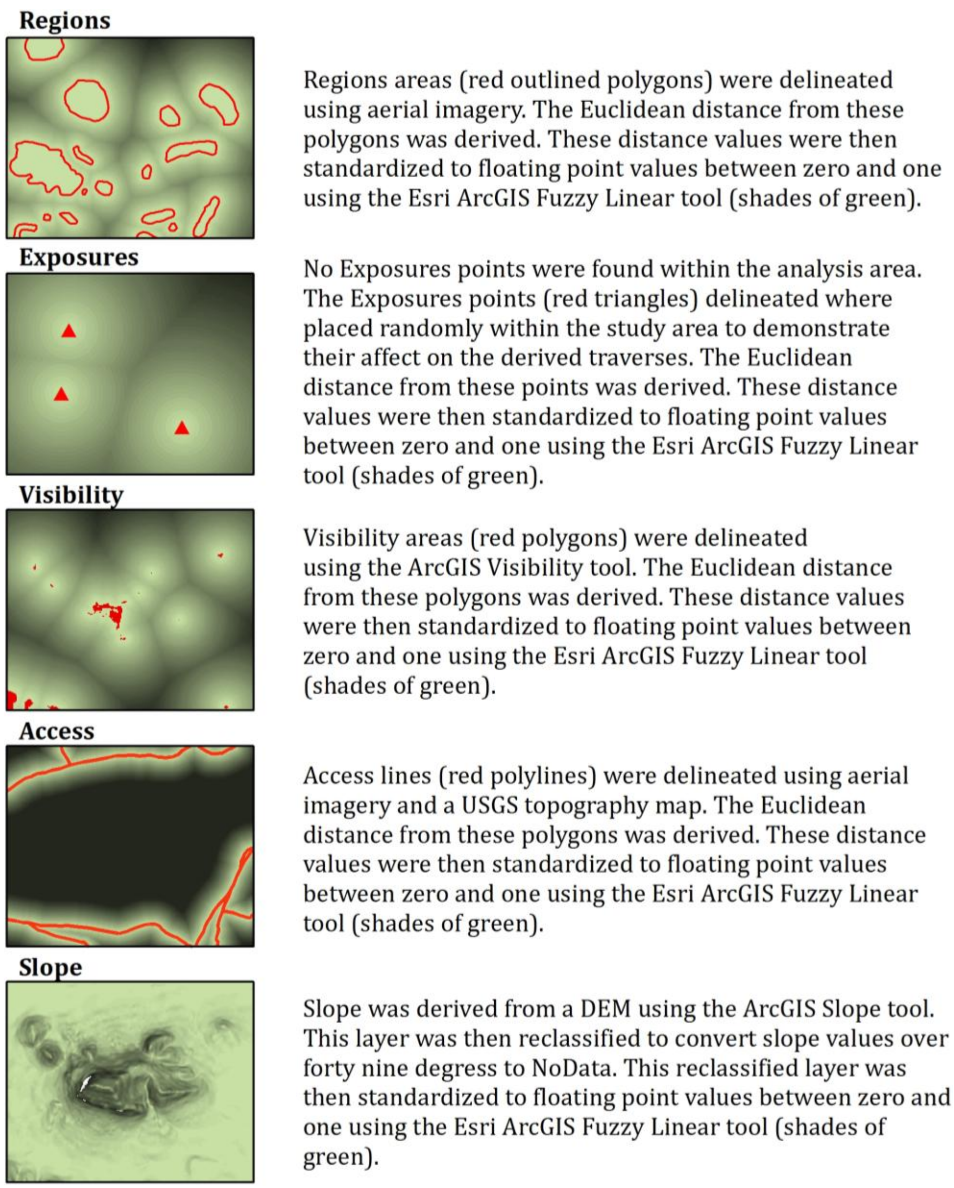

Figure 11 - Derivation of Five Criteria: Illustration and description of the formation of the standardized criteria layers where lighter shades of green indicate a greater favorability with regard to meeting the objective of either attaining a high scientific return or increasing accessibility

4.5 Establish Field Campaign Weights

The analytical hierarchy process was chosen to determine the weights for the hypothetical field campaign. As described in Section 2.3.4, pair-wise comparisons may be made among all criteria affecting a given objective and between objectives. For the purposes of this demonstration, three illustrative pair-wise comparisons were proposed using the intensity of importance scale shown in Table 3 above. Results of this comparison are shown in Table 8 below. To assign these values, the less important item in each pair is given a weight of one and the other is assigned a relative importance value determined by assessing the level of greater importance.

Table 8 - Pair-Wise Comparison Results: Results of the pair-wise comparison for each criteria using the intensity of importance definitions outlined in Table 2. Truncated intensity of importance definitions are 1 = Equal Importance, 3 = Moderate importance, 5 = Strong Importance, 7 = Very strong importance, and 9 = Extreme Importance

Comparison of Criteria Affecting Scientific Return				
6	Regions	over	Exposures	1
7	Regions	over	Visibility	1
4	Exposures	over	Visibility	1
Comparison of Criteria Affecting Accessibility				
4	Slope	over	Access	1
Comparison of Objectives				
8	Scientific Return	over	Accessibility	1

As shown in Table 8, Regions is considered to have a strong to very strong importance when compared to Exposures. Regions is considered to have a very strong importance when compared to Visibility, and so on. Once all comparisons had been made, their values were inserted into matrix M, which, for example, led to the derivation of the following matrix for the Scientific Return objective shown in Table 9.

Table 9 - Example AHP Matrix

	Regions	Exposure	Visibility
Regions	$^1/_1$	$^6/_1$	$^7/_1$
Exposures	$^1/_6$	$^1/_1$	$^4/_1$
Visibility	$^1/_7$	$^1/_4$	$^1/_1$

Once the matrices had been created, it was necessary to derive the eigenvectors of the largest eigenvalues. This was done by squaring each of the three matrices until the second significant decimal point of the normalized eigenvectors remained unchanged. This allowed for the derivation of a weighted value accurate up to two decimal points. For example, the work used to derive the right eigenvector of the largest eigenvalue for the Scientific Return objective is as follows:

$$\begin{pmatrix} 1 & 6 & 7 \\ 1/6 & 1 & 4 \\ 1/7 & 1/4 & 1 \end{pmatrix}^2 = \begin{pmatrix} 3.00 & 13.75 & 38.00 \\ 0.90 & 3.00 & 9.17 \\ 0.33 & 1.36 & 3.00 \end{pmatrix}$$

Adding the sums of each of the product rows and normalizing produces the approximate eigenvector of:

$$\begin{pmatrix} 0.7551 \\ 0.1803 \\ 0.06460 \end{pmatrix}$$

The new eigenvalues are squared again and produce the approximate values shown below:

$$\begin{pmatrix} 3.00 & 13.75 & 38.00 \\ 0.90 & 3.00 & 9.17 \\ 0.33 & 1.36 & 3.00 \end{pmatrix}^2 = \begin{pmatrix} 33.8809 & 134.0714 & 354.0417 \\ 8.4295 & 33.8809 & 89.3809 \\ 3.1921 & 12.6443 & 33.8809 \end{pmatrix}$$

Adding the sum of each of the new product rows and normalizing produces the approximate eigenvector of:

$$\begin{pmatrix} 0.7420 \\ 0.1872 \\ 0.07068 \end{pmatrix}$$

Note the values of this eigenvector differs slightly from that shown in the first eigenvector (i.e. the second decimal place in top and bottom rows and the third decimal place in the middle row). The eigenvectors will approach unity as their eigenvalues continue to be squared. Again, the newest eigenvalues are squared and produce the approximate values shown below:

$$\begin{pmatrix} 33.8809 & 134.07143 & 354.04167 \\ 8.4295 & 33.8809 & 89.3809 \\ 3.1921 & 12.6443 & 33.8809 \end{pmatrix}^2 = \begin{pmatrix} 3408.2461 & 13561.5604 & 35973.9696 \\ 856.5230 & 3408.2461 & 9041.04029 \\ 322.8943 & 1284.7846 & 3408.2461 \end{pmatrix}$$

Adding the sum of each of the new product rows and normalizing produces the approximate eigenvector of:

$$\begin{pmatrix} 0.7429 \\ 0.1867 \\ 0.07038 \end{pmatrix}$$

It can be seen that the second decimal place in this last eigenvector remains unchanged. A weight, up to two decimal places, may now be used. The first row of the original matrix represents the Regions layer, the second represents the Exposures layers, and the third the Visibility layer. Thus, the values extracted from this process is 0.74 for the Regions layer, 0.19 for the Exposures layer (rounded up), and 0.07 for the Visibility layer. This same process was performed for the Accessibility and Combination objectives. These results are shown in Table 10.

Table 10 - Derived Weights: Weights for each criterion and objective resulting from the analytical hierarchy process.

Criteria for Scientific Return	Weight
Region	0.74
Exposures	0.19
Visibility	0.070
Criteria for Accessibility	**Weight**
Slope	0.80
Access	0.20
Objective	**Weight**
Scientific Return	0.89
Accessibility	0.11

Unless one is using a GIS that has built in AHP functionality, these steps must be performed outside of the GIS environment and the results reinserted. The AHP work conducted to derive the weights for the hypothetical field campaign criteria and objectives was performed using Microsoft Excel.

4.6 Production of Weighted Overlay Layers

After all the relevant criteria factoring into the navigational decision making process had been standardized and once weights for these layers had been determined, these layers were then aggregated. As the cost criteria values were incorporated into the criteria layers during the standardization step, Equation 5 has been used for the analysis presented here. Had the cost not been incorporated up to this point, Equation 6 could be used to do so. Care should be taken, however, to ensure these values are not reversed unnecessarily.

Three weighted overlay layers were created to represent: the Scientific Return objective, the Accessibility objective, and the Combination objective that represents the combination of these two objectives, or the ultimate goal of the field campaign. The two former maps were created by aggregating the appropriate criteria and the later by aggregating the appropriate objectives. A weighted linear combination was used to aggregate these layers with the weights determined through the AHP. These results are shown in Figure 12.

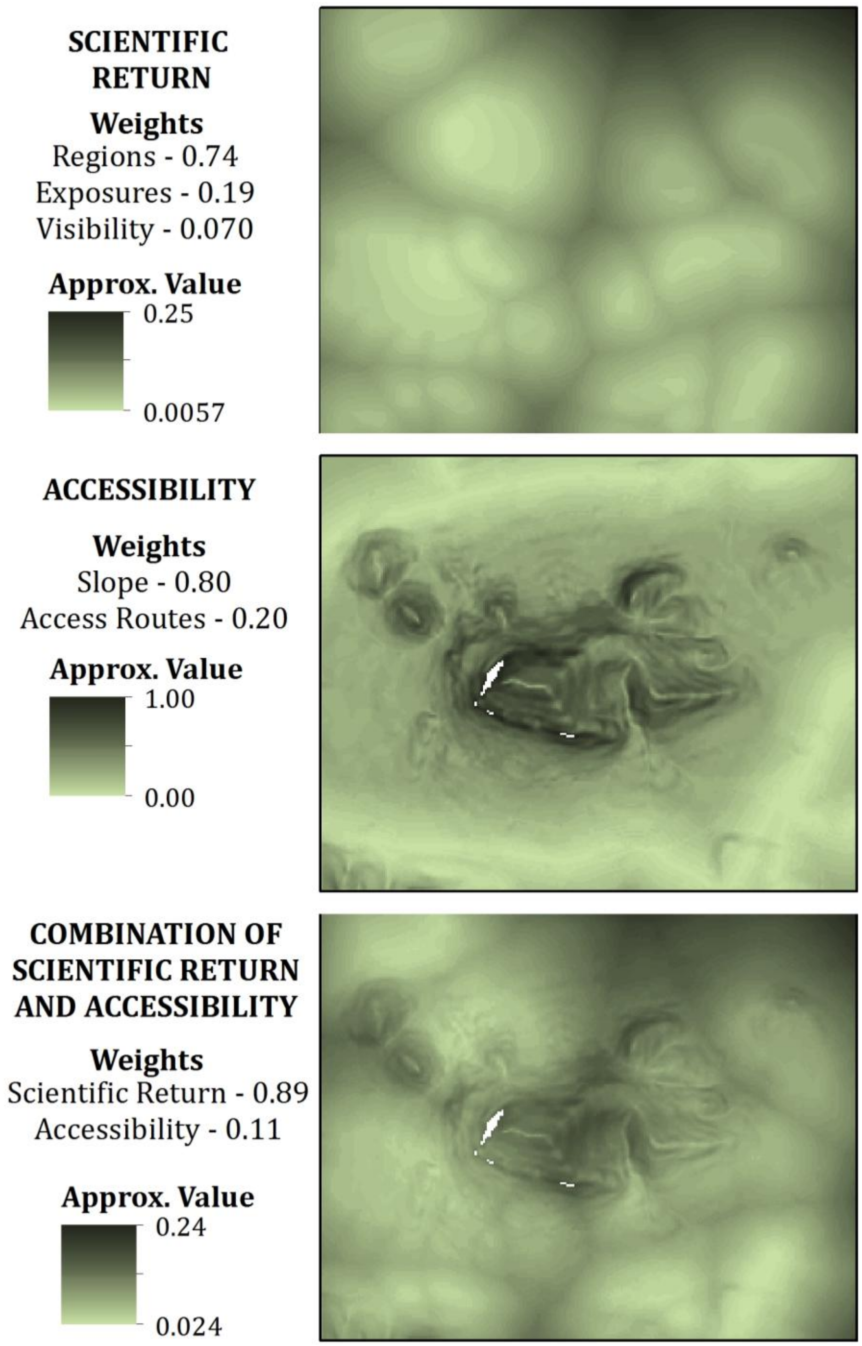

Figure 12 - Outputs from Aggregation Steps: The outputs from the three aggregation steps. Notice the NoData cells contained within the Accessibility objective layer carried through to the Combination layer and that the Combination layer has characteristics of both the Scientific Return and Accessibility layers. Also, note that lightest shaded of green represent the most favorable locations for a traverse path.

4.7 Prioritize Target Paths for Fieldwork on Basis of Time Available

For the hypothetical case study, those cells from the aggregation step of the MCE with the most favorable ten percent value were used to determine the origin and destination points for the day's traverse. As described in section 3.9, these points, along with a weighted surface, determine the placement of traverse paths.

These points were created by reclassifying the MCE output so that all but the most favorable ten percent values contained a value of NoData. This reclassified raster was then converted to a polygon feature class, thus making polygons in those areas containing the top ten percent favorability values. From this new layer, the polygon centroids were derived. In order to avoid the extra work of creating more origin and destination points and small traverse path segments, centroids that were clumped within groups less than seventy five meters apart had all but one centroid manually deleted, a task that was relatively simple and did not require the use of an automated tool. Lastly, new point feature classes were created to act as origins and destinations from these centroid locations. Each centroid is both an origin and destination feature class, as each of these points acts as an origin and destination point for multiple traverse path segments. Determining the order in which these segments connected was done manually with an attempt create segments that would decrease the overall length of the traverse.

Once all of the origin and destination points were derived, they were used as inputs to the ArcGIS Cost Distance and Cost Path tools. As the output of the Cost Path tool is a raster, the Raster to Polyline tool was used to create a polyline feature class. This series of tools was run fourteen times within ModelBuilder. One for each segment within the traverse path and while using different origin and destination points.

A flowchart of the entire process is shown in Figure 13. By following the paths derived from the output of the aggregation step of the MCE, geologists will be positioned in locations where they are close to features containing a high scientific return while avoiding locations that contain impedance to foot travel. The decisions made at each step up to this point determine the derived traverse paths. These include the decisions made with regard to criteria selection, standardization technique, weighting method, aggregation algorithm, and point derivation.

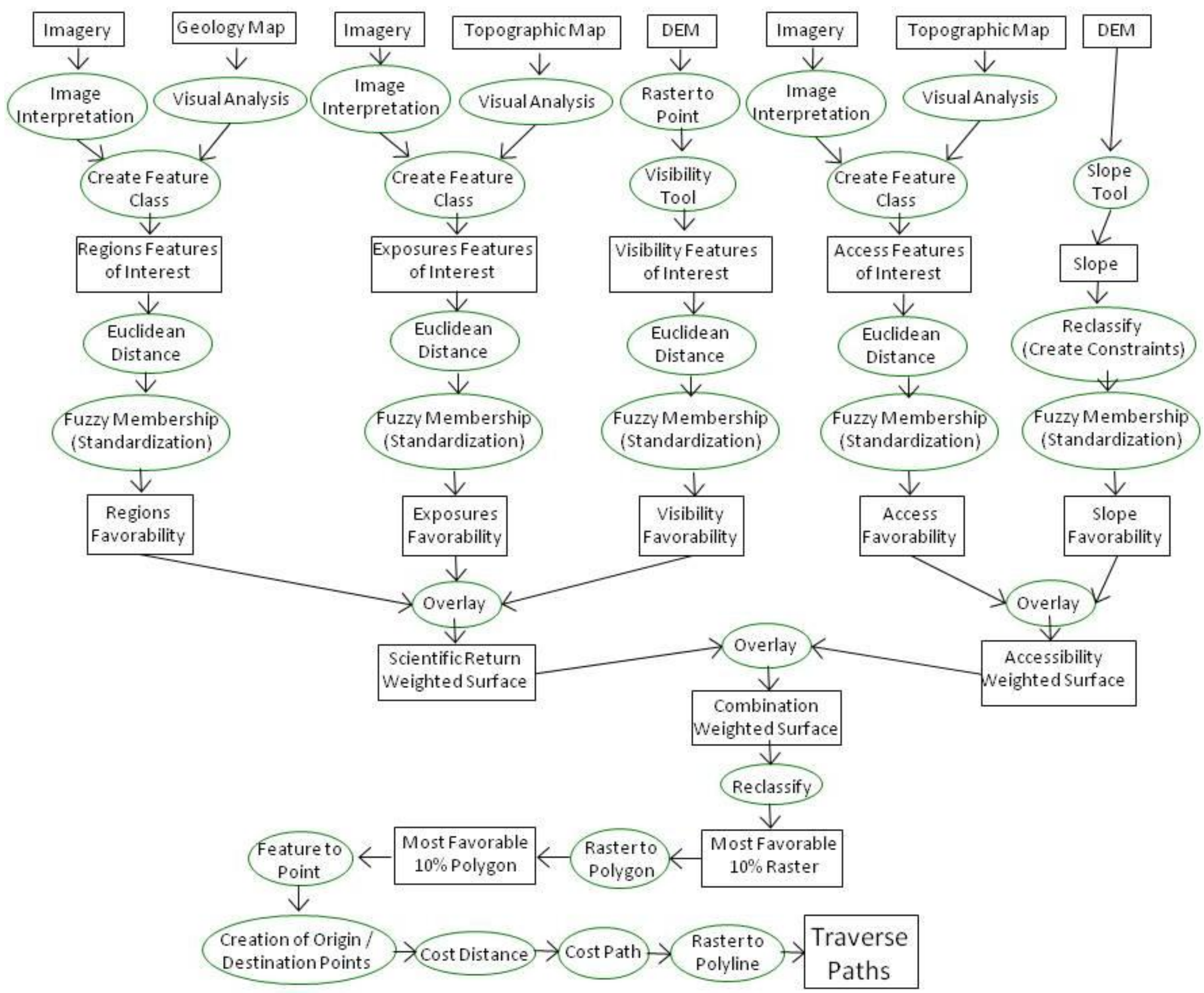

Figure 13 - Flowchart of GIS Work: Shown here is a complete flowchart of the implemented methodology. Layers are represented by rectangles, GIS operations by green ellipses, and order of operations by arrows.

4.8 Derived traverse paths

There are four controls determining the placement of the generated traverse paths. These include the cell values contained within the Combination weighted surface resulting from the MCE, the origin and destination points that have been derived based upon the areas containing the ten percent most favorable values, the order in which the origin and destination points are created, and the determination the point at which the traverse path begins. A flow chart summarizing the development of the traverse paths is shown in Figure 14. The resulting traverse paths for the hypothetical field campaign are shown in Figure 15. A statistical summary of the traverse path is provided in Table 11.

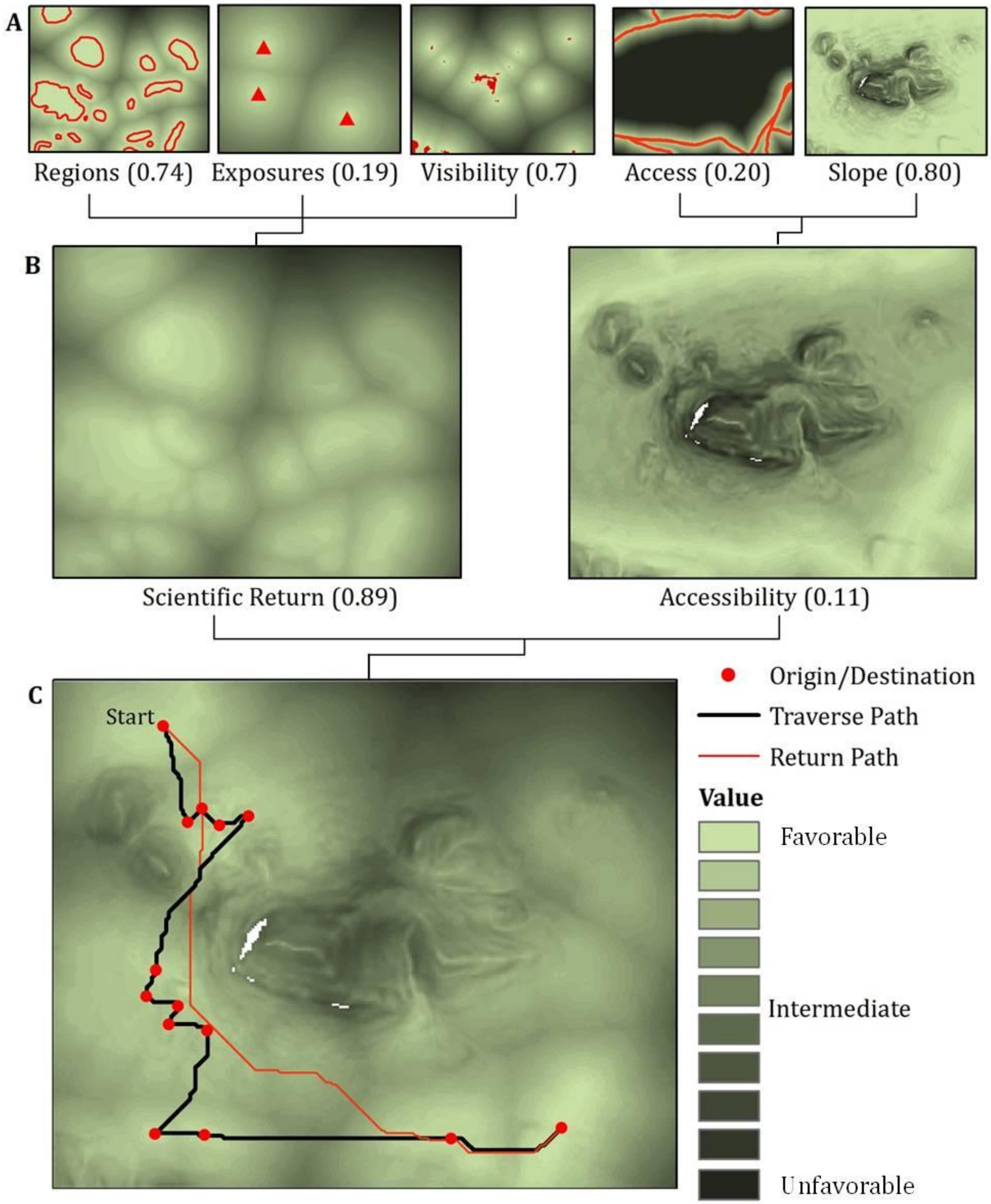

Figure 14 - Flowchart of Aggregation Steps: Illustrated flowchart of the aggregation steps involved in the developed methodology. Equation 4 is used to aggregate the three criteria representing the Scientific Return objective and to aggregate the two objectives representing the Accessibility objective. These two objectives are then aggregated using the same equation to derive the final weighted surface used to derive the traverse paths.

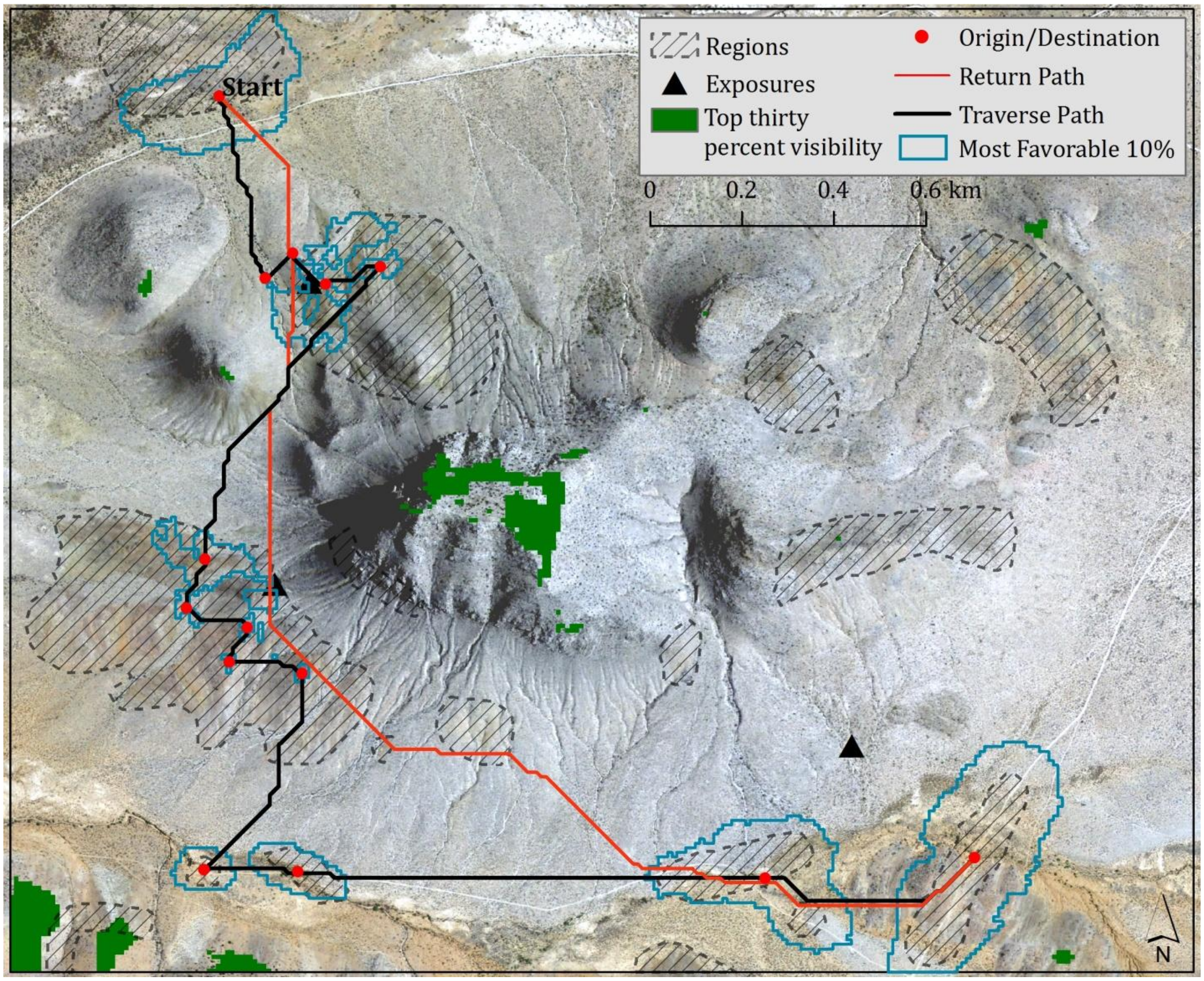

Figure 15 - Final Traverse Path: Final traverse path overlain on aerial imagery, criteria affecting the Scientific Return objective, and destination points, and the polygons making up the areas containing the top most favorable ten percent values of the Combination weighted surface.

Table 11 - Statistical Summary of Traverse Path

Traverse Path and Return Path combined	
Distance	7.39 kilometers
Maximum slope	23.8 degrees
Average slope	2.70 degrees

4.9 Analysis of Results and Sensitivity Analysis

As outlined in the background chapter, a sensitivity analysis may involve making small adjustments to the values of the MCE input data and analyzing what effects it has on the derived output. A sensitivity analysis may also involve an analysis of the output data without making any adjustments. Both of these analyses have been performed here to assess what effect the MCE based methodology employed here has had on the final recommended traverse paths.

4.9.1 Analysis of Result from Aggregation

To assess what determines the cell values of the Combination weighted surface, its values at four point locations have been analyzed. The locations of these four sample points were chosen to include some of the highest and lowest values contained within the Combination weighted surface. An assessment of these values reveals why the Combination weighted surface contains the values it contains. This, in turn, demonstrates what has determined the placement of the traverse path. The cell values of the Combination weighted surface have a maximum of 0.24, minimum of 0.024, mean of 0.095, and median of 0.13. Figure 16 shows the locations of theses sample points within the analysis area.

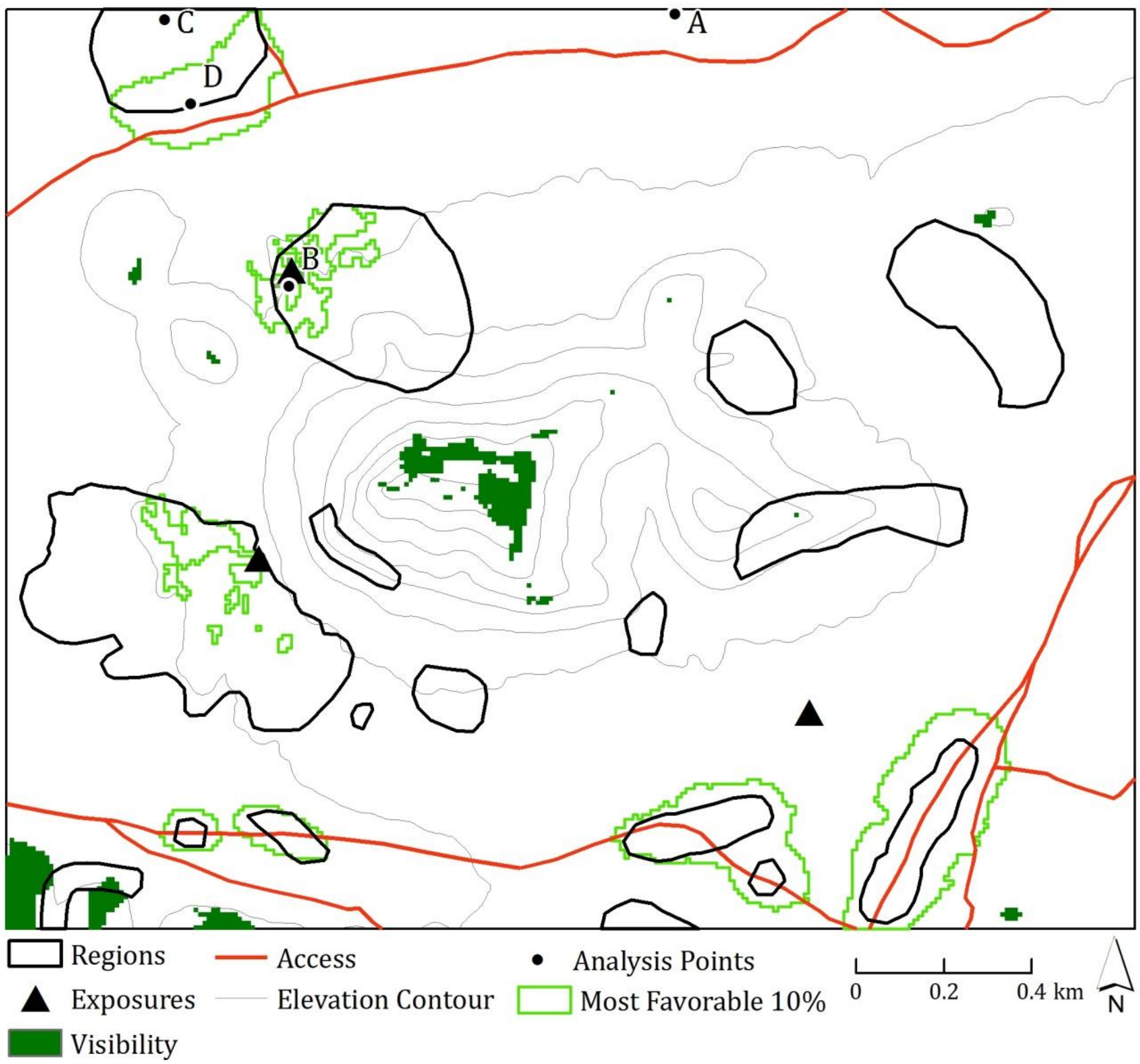

Figure 16 - Sample Point Analysis: Shown here are the sample analysis points in relation to the five criteria features of interest that are the most favorable ten percent areas from the Combination weighted surface that have been selected to derive the destination points. Elevation contours have been shown in replacement of the slope raster data model.

Location A is within a location where the weighted surface contained some of the least favorable values (i.e., approximately 0.22). Location B is within a location that contained some of the most favorable values (i.e., around approximately 0.039). While location A is located in an area with almost no slope, it is distant from Regions, Exposures, and Visibility features of interest. Location B is within a Regions feature of interest, less than 350 meters from two Visibility features of interest, and within an area of approximately three degrees slope. The generated traverse path, if followed, would put geologists within close proximity to locations such as Location B. Thus, putting them in close proximity to areas interpreted as providing a high scientific return and that contain increased accessibility.

A comparison can also be made between locations C and D. Location C has a score of approximately 0.062 and D of approximately 0.036. They both are within a Regions boundary and have a Slope value of one degree, yet the distances to Exposures, Visibility, and Access features are all less for D than they are for C. This is the reason D is within the top five percent and C is not. The reveals that the placement of the traverse path will be closer to locations such as Location C, rather Location D.

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4.9.2 Change in Weights for Scientific Return and Accessibility

Figure 17 and Figure 18 show the variation resulting from altering the weights between the Scientific Return and Accessibility objectives. Figure 17 shows a contour map of the weighted surface given three different relative weightings. The weights for the two objectives have been altered up and down by two percent around the weights determined for these objectives by the AHP. It can be seen that this weight change results in a change in the cell value distribution, although less so around the perimeter of the analysis area. Figure 18 shows the various origin and destination points derived from the point extraction process with the same slightly altered weights. The positioning of these points change due to change in the location of the centroids when the boundaries of the polygons with the top ten percent favorability values are delineated.

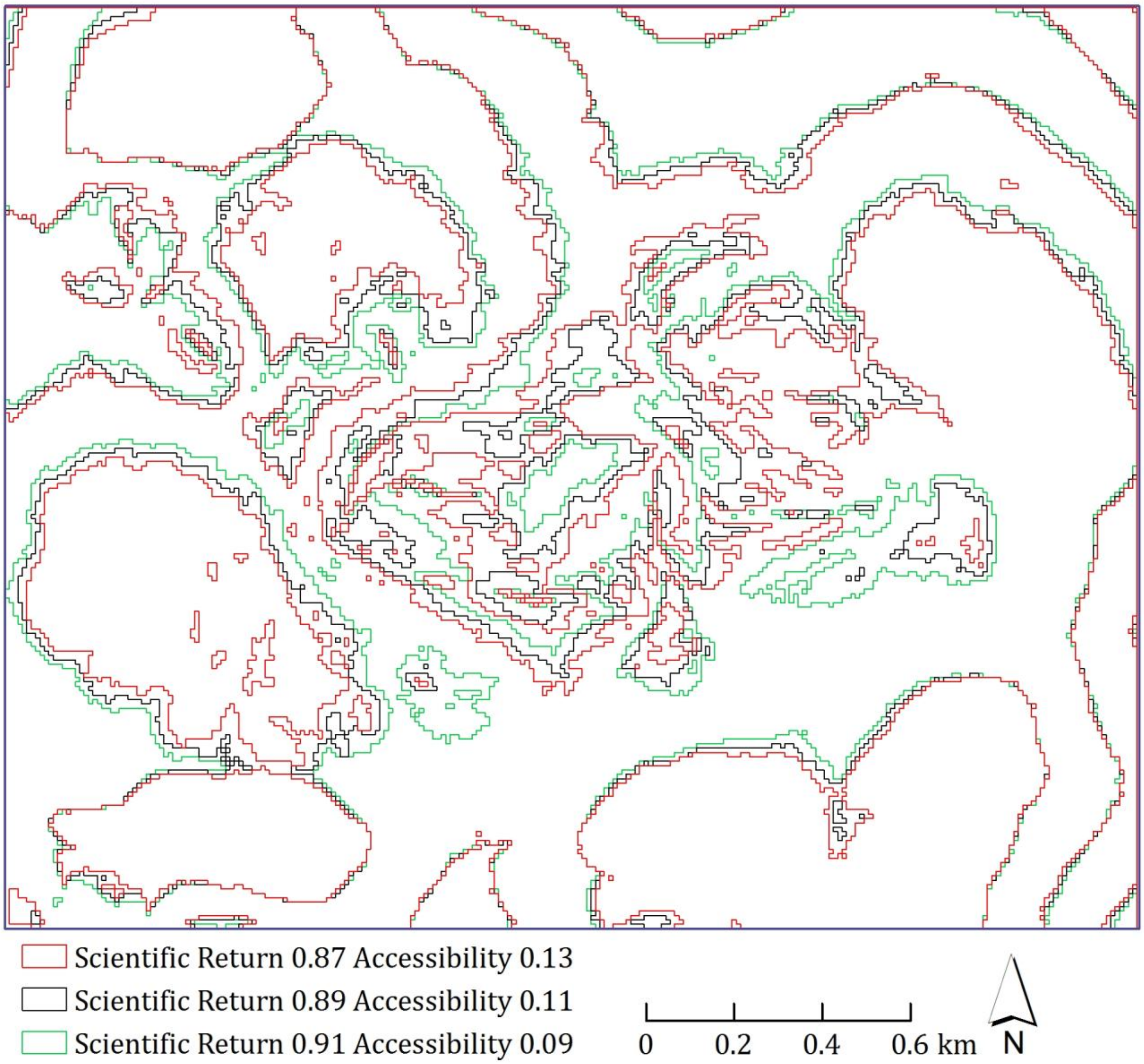

Figure 17 - Change in Weights of Influence: Variation resulting from changing the weights above and below that derived by the analytical hierarchy process (i.e. 0.89 for Scientific Return and 0.11 for Accessibility). Each weighted surface was classified into five identical classes and the boundaries of these classified areas (which are similar to contour lines) were overlain.

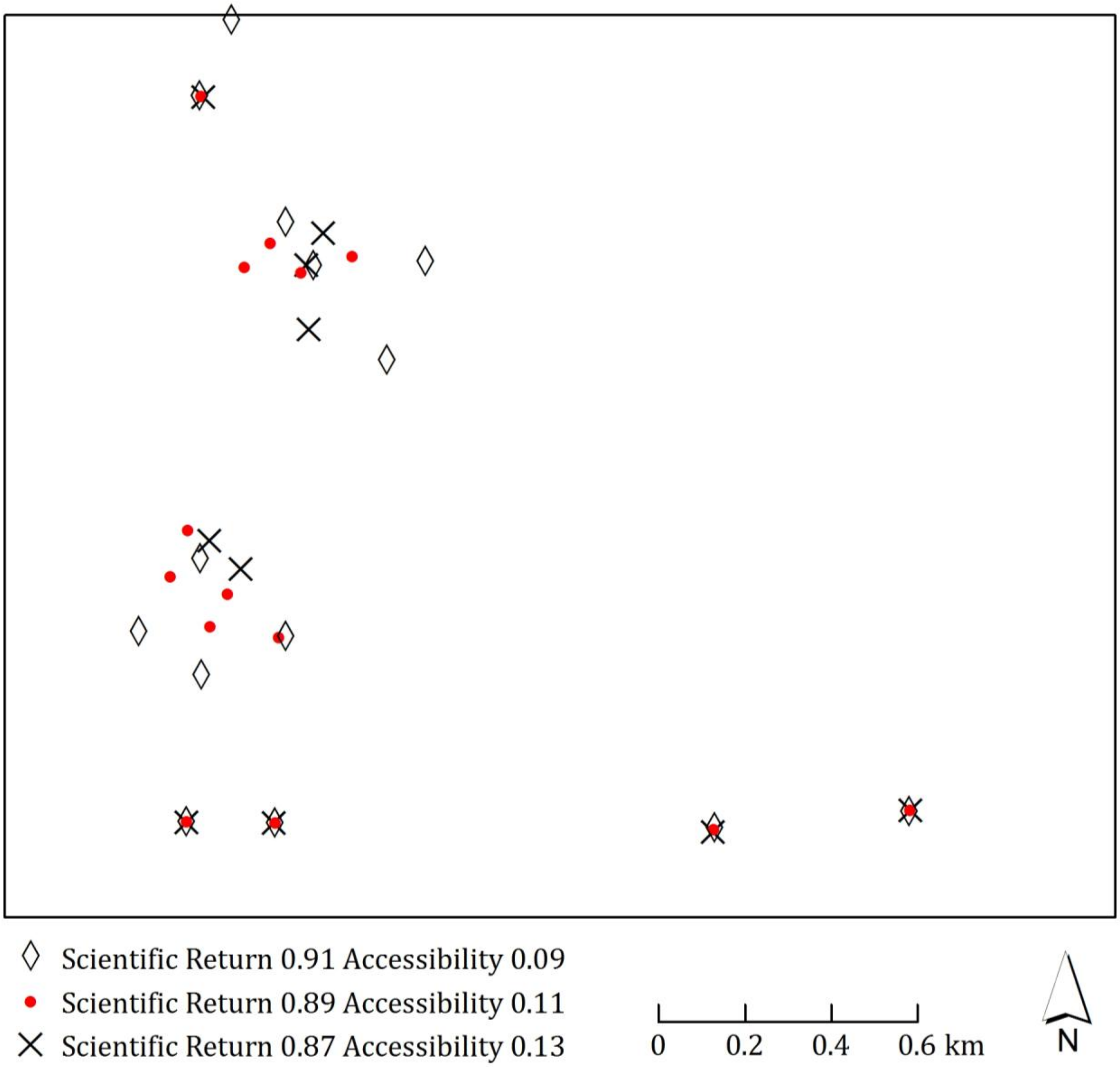

Figure 18 - Variation in Centroids Due to Change in Weights of Influence: Variation in centroids used to determine origin and destination points derived from the same weighted surfaces described in Figure 17.

4.9.3 Change in Percent used to Derive Origin and Destination Points

The traverse paths outlined above travel among points defined by the most favorable *10* percent cell values of the weighted overlay produced by the MCE. These points are the centroids of the polygons formed by the areas with these most favorable values. To assess the affects of changing the value used to derive the centroids, the most favorable *15* percent cell values have been used to derive centroids. This allows comparison of the origin and destination points that would be derived based upon a variation in the percent of favorability values used to derive polygons and their centroids. Figure 19 shows the results of this comparison. The cutoff value for the top ten percent is approximately 0.046. Examined here, is the affect of changing this cutoff value to the most favorable fifteen percent, which is approximately 0.056.

It can be seen that this five percent change produces a different number of centroids and positions them at different locations. There are fourteen centroids created when using the ten percent most favorable values and sixteen created when this value is raised to fifteen percent. Increasing the amount of favorability values used to derive origin and destination points extends the reach of the traverse path. The percent favorability values used to derive origin and destination points are based on time. This enables the length of the generated traverse to accommodate for the time available for a geologic survey. However, the number of polygons will not necessarily continue to increase as the percent of favorable cell values from the weighted surface is increased. Eventually large polygons are created and the number of centroids actually decreases. This will occur to the point where only one centroid is created and thus no traverse paths may be derived. Applying a limit on to the percent favorability values used may mitigate this occurrence.

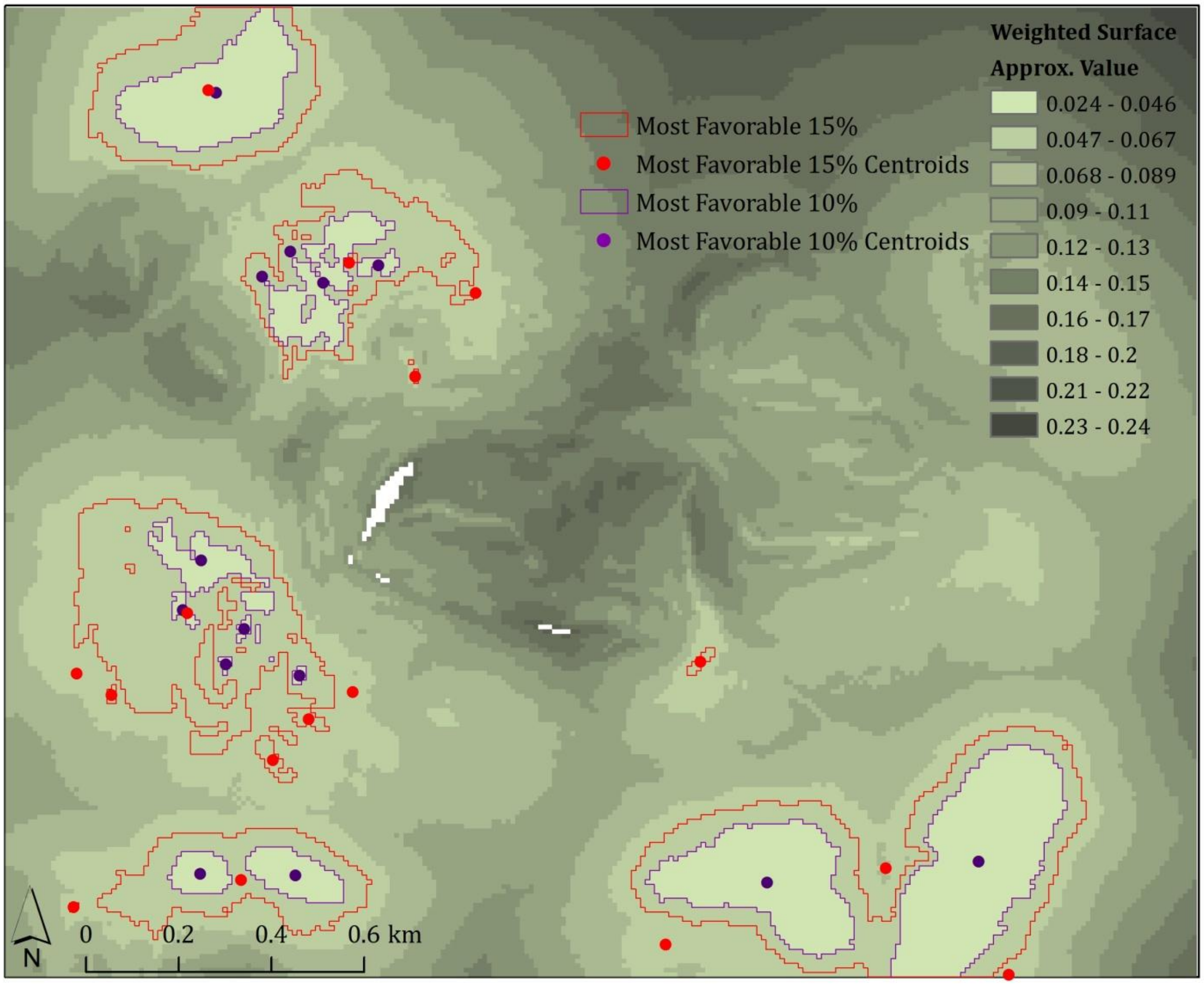

Figure 19 - Change in Destination Location Resulting from Percent Favorability Used: Areas representing the most favorable ten and fifteen percent values from the Combination weighted surface, along with centroids to be used for the origin and destination points. Note that all polygons do not contain centroids, as some may have been deleted due to their proximity to other centroids. Also, the representative center of a polygon feature may lie outside the polygon perimeter.

In summary, this chapter has demonstrated the steps involved in developing a traverse path for a mineral exploration field campaign using the methodology described in Chapter Three. This chapter has also presented a traverse path that has been produced as the result of following these steps. Lastly, aspects of the methodology determining the location of the destination points and the traverse path segments between these points has been analyzed.

CHAPTER FIVE: DISCUSSION AND CONCLUSION

This chapter discusses some of this methodology's benefits, limitations, and suggestions for its improvement. It then concludes with a summary of this work.

5.1 Benefits Gained by Using this Methodology

The methodology described in this thesis allows field scientists to obtain benefits of the MCE and path modeling processes. It also utilizes a GIS's ability to manage, manipulate, and analyze spatial data. Of these three, a GIS is the only tool that has been extensively adopted by the field research community.

Voogd (1983) explains that a MCE provides an opportunity to classify a problem and allows an examination of the form, controls, and cost of a decision making process. Field scientists are driven by a variety of objectives, but all are faced with the problem of determining where to go in the field. The MCE process divides this problem into its various components. These components are then assessed to determine their form and control on the decision making process. Classifying the problem has been the first component of the MCE process demonstrated here. For the hypothetical field campaign, the decision problem was to determine where to go while in the field in order to fulfill the objectives of attaining a high scientific return while avoiding obstacles. Five criteria were used to measure how well these objectives were being met. The process of characterizing these criteria required each to be considered both individually (i.e. with the analysis of digital data and derivation of criteria layers) and collectively (i.e. with the pair-wise comparison and aggregation step). The developed methodology also made possible an examination of form, control, and cost of the decision making process by explicitly defining each criteria and objective, considering their relative importance, and assessing their overall contribution to meeting the campaign objectives.

The advantages of using path modeling include its suitability to analytically address the problem of field navigation. The final weighted surface produced by the MCE process explicitly indicates which areas within the analysis area will best account for a campaign's objectives. The traditional fieldwork approach would involve a more intuitive and iterative determination of these areas. Path modeling has also provided a means to incorporate considerations of distance and time into the field navigational decision making process. The largest control on the traverse path placement are the values within the final weighted surface produced during the MCE. Also, the path modeling process accounts for distance and, by proxy, time by determining direct routes in between origin and destination points.

Lastly, this methodology requires scientists to thoroughly investigate a study area prior to its visitation. The steps required to complete this methodology leads scientists through work that has the potential to elicit valuable new information. This information may then be used as an advantage when the actual fieldwork begins.

5.2 Limitations of Methodology and Suggestions for Improvement

While there are many advantages to the methodology described here, there are several limitations that may impede its usefulness. Many of the disadvantages of the MCE process relate to its complexity and the lack of a simplified framework for its implementation. While the process of deriving destination points and traverse paths is quite simple, it too lacks a framework that allows a quick and easy implementation. ArcGIS ModelBuilder was used to expedite many of the techniques performed while developing the traverse paths. The development of a program to automate the entire process, however, would make this methodology better suited to widespread use. This methodology also requires the repetition of many of its components once new parameters are introduced. For example, introducing new objectives, changing feature boundaries, or changing weights would all result in the need to repeat many steps.

This methodology also lacks the ability to quickly incorporate the information provided by new observations made while in the field. An ultimate goal is the development of this methodology so that it may be employed while in the field to quickly generate new traverses once new observations related to a campaign's objectives have been made. Thus, the traverse would continually adapt to a scientist's understanding of a study area. This, of course, would require the development of a streamlined program that would allow the quick and easy incorporation of new information into this model. The methodology developed here provides an example of a workflow that may be developed into such a model or into a mobile application.

During the standardization steps of the methodology demonstration, many assumptions were made regarding the relationship between the non-standardized and standardized attributes values of these criteria. While quantification of these relationships may be impractical and expert opinion may prove to define an accurate association, misinterpretations made during this step will be carried through the subsequent steps. This may result in the development of an inferior traverse path. Research that quantifies the impact various criteria have on meeting a field campaign's objectives will likely increase the chances that a useful traverse path is generated.

An additional limitation relates to the assumptions made when using the Visibility criterion during the hypothetical demonstration. While the amount of study area observable from any given location has been determined, this view may not have provided much geologic insight. Also, the ArcGIS Visibility tool assumes that the observer will be able to see the landscape being viewed even if some portions of the study area are so distant from the observer that a beneficial view cannot be obtained. Improvements to this component may be made by developing a means to quantify the distance threshold from which beneficial observations may be made and determine whether a particular view displays science rich or monotonous scenes of a landscape.

The methodology described here only accounts for travel on foot. Many field scientists will carry out their work using a combination of foot and vehicular travel. As these differing modes of transportation will have differing criteria providing a measure of their effect on accessibility, using other forms of transportation will require a modified methodology. Thus, modifications to this methodology may involve devising a traverse-generating technique that compensates for a combination of foot and vehicular travel.

During the hypothetical demonstration another assumption was made regarding the selection of the top ten percent most favorable cell values to determine the destination points. Determining what this value should be, given the time available for a particular field campaign, will require further research. Also, an inherent characteristic of increasing the percent of favorable cell values used is that eventually the polygons representing these areas will coalesce into one large polygon. The next step of deriving the centroid of this polygon will result in one destination point. This will not suffice in allowing the derivation of traverse paths. Further development is needed regarding the means by which destination points are derived. One potential solution is to use a MCE-derived weighted surface to suggest a traverse path between a series of predetermined visitation sites. These sites could be manually determined by geologists and chosen based on their anticipated ability to assist meeting the given campaign objectives.

5.3 Conclusion and Opportunities for Future Work

This thesis has demonstrated how technologies and analytical approaches such as decision analysis, path modeling, and geographic information systems may offer assistance to navigational decision making while conducting scientific fieldwork. It demonstrates an alternative approach to planning traditional fieldwork and makes explicit key aspects of the navigational decision making process. While the intuitive and artistic aspect of field research will likely always remain, this work demonstrates the value of utilizing technologies that can provide meaningful assistance to its practice.

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