Modeling geopolitics in Tikal through least cost paths

by

Matthieu Munoz

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To my Mom and Dad, who have always supported me. Also to my sister, who has always been there for me, no matter what.

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List of Abbreviations

BCE	Before the Common Era
CE	Common Era
GIS	Geographic information system
GISci	Geographic information science
GIST	Geographic information science and technology
SSI	Spatial Sciences Institute
USC	University of Southern California
USGS	United States Geological Survey

Abstract

Since the 19th century, excavations at the Maya site of Tikal have continually provided intriguing archaeological insights into the Maya world. Tikal was one of the most influential powers in the Southern Maya Lowlands, and maintained wide-ranging relationships with neighboring sites throughout the Maya area. These inter-site relationships are described extensively in the epigraphic record of Tikal and its neighbors. As one of the major powers in the Maya region, Tikal was engaged in frequent warfare with rival cities in the Lowlands. The objective of this thesis project was to model probable paths for Tikal's warfare interactions in the region through the use of least cost path analysis. The study generated three separate sets of points, to the Maya sites of Caracol, Calakmul, and Naranjo using the Path Distance tool in ArcGIS. Least cost path analysis expresses the efficiency of each route as a function of time and distance. The study generated these least cost paths through the use of Tobler's Hiking function in order to express how the inhabitants of Tikal would have traveled through the unique terrain of the Maya Lowlands. This thesis also used sensitivity analysis to test the location sensitivity of the modeled paths. These analyses determined that the least cost paths diverge significantly if input data is altered. The least cost path analysis indicated that the modeled routes represented a set of probable paths from Tikal to its neighboring rival sites.

Chapter 1 Introduction

GIS has been an invaluable asset for archaeological research since the 1990s (Connolly and Lake 2006, 7). GIS is able to visualize the spatial landscape in a unique fashion that complements the work performed in archaeology. Least cost path methodology is perhaps one of the best examples of GIS applications that can be applied to archaeological analysis. Least cost path methodology operates based on the assumption that people familiar with a landscape will optimize the costs of travel for frequently used routes. (Herzog 2013, 180). This thesis project aims to show how least cost path methodology can illustrate human movement between archaeological sites in the distant past.

This thesis examines the spatial interactions of the Mesoamerican archaeological site of Tikal. Tikal was one of the most significant Maya cities, which was at the epicenter of a complex network of relationships during its peak between 200-900 CE. The geopolitical complexity of the Maya world opened up avenues for a wide range of interactions, chief among them conflict (Martin and Grube 2008, 21-25). This analysis aims to model the spatial movement of the inhabitants of Tikal to rival sites which it came into conflict with when Tikal was the dominant city in the region.

1.1. Motivation

As this thesis was first articulated, it was determined that the focus of this project should be based on Mesoamerican archaeology, specifically studying the Maya civilization. Inspection of the existing GIST literature revealed that there had been several spatial analyses within Mesoamerican archaeology, which could be used as a model for further investigative studies in the region. GIST would best be able to visualize inter-site relationships among the major archaeological sites of the Maya area.

The main motivation for undertaking the research project was to better understand the complexity of the geo-political relationships of the sites in the Maya Lowlands. These sites possessed a very high degree of spatial interaction. Analysis of these inter-site relationships through the use of least cost paths is vital in order to visualize how the inhabitants of these sites may have moved throughout the spatial landscape. This project was designed to determine if there was a means by which these least cost paths might be expressed in order to quantify the cost effort required to travel between sites. This project's goal was to model travel paths between Maya sites in GIS software in order to visualize how the inhabitants of these sites may have traveled in the distant past. Although archaeological confirmation of these modeled paths may be unlikely, they would serve as a comparative model for geopolitical movement throughout the Maya area.

There have been several archaeological studies in the Maya area that have used geospatial analysis as part of their research. This project was based on those archaeological studies in particular that used least cost paths in their analysis. Carballo and Pluckhahn used least-cost paths to model political interactions between Mesoamerican sites (Carballo and Pluckhahn 2007 612-615). Analysis of these paths would be integral to understanding spatial movement between sites. Doyle et al.'s analysis featured least cost path analysis to describe the possible travel corridors between the site of Tikal and other major polities in the region (Doyle et al. 2012, 796-797). These studies used epigraphic evidence to describe geopolitical relationships between the sites, and then used the results of this research in geospatial analysis.

As research on this project continued, it gradually focused on the Maya archaeological site of Tikal as the central origin site for the least cost path analysis. Tikal was chosen due to its strategic position as the epicenter of Mesoamerican politics during its peak. It was decided that this project could advance archaeological study by specifically focusing on conflicts as a means of analyzing the geopolitical relationships of Tikal through least cost path analysis.

1.2 Description of Study Area

The general area of interest for this project falls on the Yucatan Peninsula, specifically in the Maya Lowlands of Guatemala, Belize, and southern Mexico as seen in Figure 1 (Criscenzo 2017). The study area is largely within the Guatemalan Department of Petén. The history of Maya habitation in the Lowlands can be traced through archaeological documentation back to 2600 BCE (Hammond et al. 1976, 579-581). The climate of the study area is semi-tropical with seasons divided into wet and dry, although this is not constant throughout the entire region. The study further focuses on the region of the Petén situated on a densely forested limestone plateau with numerous swamps known as *Bajos*.

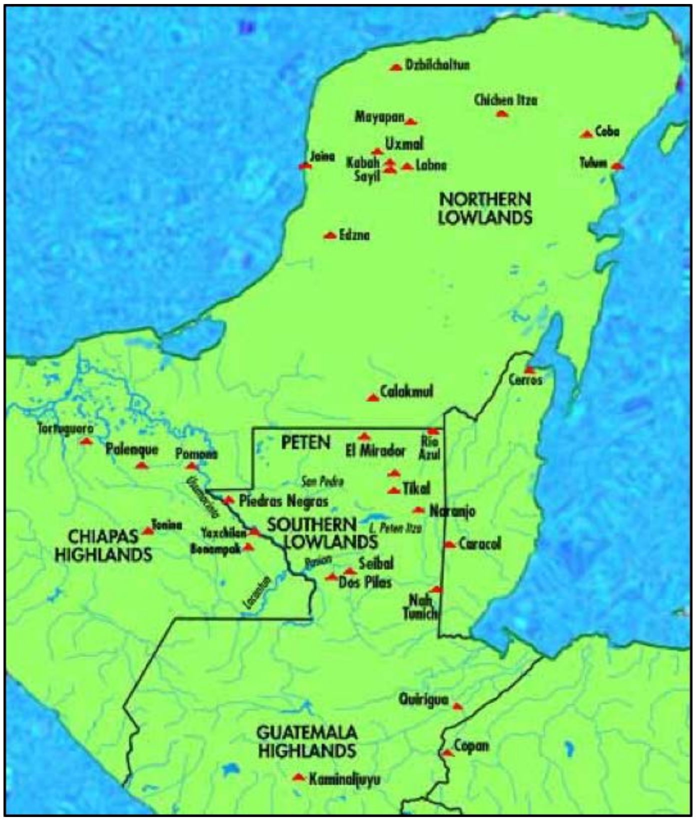

Figure 1 The Maya Region. Source: Criscenzo 2017.

This project focuses on the Maya archaeological site of Tikal, which reached its political peak during the Classic Period, c. 200-900 CE (Martin and Grube 2008). The site of Tikal was one of the most powerful Maya sites in the Petén Basin. Tikal's influence reached across most of Mesoamerica with many other Maya sites having archaeological evidence of contacts with Tikal. Scholars have compiled a body of evidence from the hieroglyphic record of wide-ranging political interactions taking place between these sites. Martin and Grube describe Tikal as having a central place in the geopolitical interactions between the majority of the sites in the Maya lowlands. Tikal's geopolitical connections with its surrounding sites were expressed in the epigraphic record in the form of alliances, trade and conflict. More warfare interactions between Tikal and its neighbors have been recorded than between any other comparable Maya site. These interactions solidified Tikal's place as a major power in the Maya region. Tikal was a dominant power that maintained that dominance through its military prowess.

1.3 Methodology

This thesis project generated least cost paths to visualize inter-site contact between Maya sites. Multiple least cost paths were calculated to show travel between the Maya site of Tikal and three other sites in the region, namely Calakmul, Caracol, and Naranjo. This least cost path analysis was based on an anisotropic cost model and used Tobler's hiking function to describe distance as a function of time. Anisotropic cost models are directionally dependent due to the different costs involved with travel based on the direction and steepness of the slope. These costs are calculated depending on the path direction from the point of origin, as more effort may be required for traversal of steep uphill versus downhill slopes. This model is more representative of the way that people travel through the landscape than an isotropic model as an isotropic model calculates costs without consideration of slope or direction of travel.

This project also created isochrones (lines drawn on a map connecting points at which something occurs or arrives at the same time.) in conjunction with the least cost path models in order to create an additional perspective. Both the isochrones and the least cost path models were constructed through the use of anisotropic cost models to ensure that they were complementary in regards to the distance modeled in each operation. Through the combination of least cost path methodology and isochrones, this thesis project aimed to show the cost effort required to travel from the origin point of Tikal to the various endpoints that were selected. The Methods chapter describes in more detail how the methodology of the project was performed.

The anisotropic cost model was also selected for inclusion in this analysis due to its frequent use in other archaeological geospatial studies. Anisotropic costs are often used in archaeological contexts due to the diverse topography often encountered in archaeological landscapes. An isotropic model would be unsuitable for an archaeological analysis as it imposes equal costs on the cell regardless of direction of travel (Anaya Hernandez 1999, 78-79; Connolly and Lake 2006, 316-317). The anisotropic cost model's use in other archaeological studies allowed this project to compare its use as a similar isochrones model was prepared. The Related Work Chapter describes in more detail why anisotropic costs were used in this project over isotropic costs.

This research project is also making use of an anisotropic cost model which can illustrate distance as a function of time traveled. Tobler's hiking function was used as the primary anisotropic cost model. This function may be able to accurately assess the range of human motion and provide a more accurate model than simpler isotropic models for the least cost paths visualized here (Doyle et al. 2012, 794; Katner 2004,5-6). This cost model allows for the creation of visualization of the movement between sites as a function of time traveled. This function allowed this project to determine the length of time required to travel, in order to compare how the travel times may have differed from the origin to each destination point in the least cost path analysis.

1.4 Research Goals

In modeling these least cost paths to represent interaction, the project does not aim to describe paths that are accurate to past spatial movement in the region. The research goal of this project is to model the most cost-efficient routes between Tikal and its neighboring sites. In the absence of archaeological documentation of Maya paths, it is impossible to determine how closely inter-site movement would have resembled the modeled least cost paths. The aim of this thesis is to use the least cost paths similar to Newhard's study of inter-regional interaction; to produce paths that provide a visualization of the relationships between the central sites in the region (Newhard et al. 2008). This thesis project modeled the least cost paths in order to attempt to replicate how the inhabitants of Tikal may have moved across the landscape in warfare events. This model may provide a close approximation of the specific routes that the Maya have taken, with the idea that the Maya may have chosen paths that required the least effort.

1.5 Thesis Organization

The remainder of the thesis is organized as follows. Chapter 2 covers the necessary background on the methodology that was used and it describes the use of least cost path models in other archaeological studies as well. Chapter 3 details the complete methodology for the current thesis project, so that other users may be able to reproduce the study if given similar data. In addition, it describes the assessment of results that was performed to ensure the quality of the results. Chapter 4 details the results from the completion of the least cost path analysis using visual aids and tabular data to support the textual descriptions of the outcomes. The chapter also shows the results of the validity assessments. Chapter 5 provides conclusions and also briefly describes possible future analyses that may be derived from the results of this research.

Chapter 2 Related Work

The subject of Mesoamerican inter-site interaction has been discussed at length in the scholarly literature. This thesis uses GIS analysis to analyze the project's subject. This literature review examines literature in this area in order to determine the methods generally used in related academic research. The majority of this chapter focuses on the literature and theory of least cost paths. This review is of use as background for the thesis project in order to ensure it expands upon previous research involving least cost paths, cost models, and previous archaeological studies.

Previous archaeological least cost path studies were examined to determine similarities between these studies and this project. This comparative analysis was done in order to obtain insight from the methodology applied in these projects. It was also important to compare the cost models used in the different studies. The analysis of these cost models is integral to the current thesis project, as is determining how these other studies assigned weights and how this impacted their calculations of a least cost path model.

2.1 Epigraphic Analysis of Interactions Between Sites

Epigraphy is the study of texts. In archaeology, examples of epigraphic evidence may be characterized as textual evidence such as hieroglyphs or engravings. Epigraphic evidence has been used in archaeological studies to indicate relations between two or more sites. Tobler and Wineberg (1971, 40-41) detail the results of an archaeological study in which an Assyrian cuneiform tablet describing a complex exchange network was used to estimate the geographical position of the 119 towns listed on the artifact. They describe the mention of two site names on the same artifact as evidence of a relationship between these sites. The authors also speculate that places mentioned together frequently are closer together or may have a higher degree of contact.

Tikal was a major Maya center, and contacts between Tikal and other major sites in the region were recorded in the epigraphic record (Martin and Grube 2008, 21,25). Martin and Grube visualize the interactions between Tikal and the other major archaeological sites in the Maya area in Figure 2. As shown in Figure 2, Tikal had familial, diplomatic, and political contacts with other sites in addition to warfare interactions. Conflict between sites is symbolized by a bright red line, diplomatic contacts by a thin black line, political contacts were defined by a bold line, and familial ties by a closely spaced dashed line in Figure 2. The schematic includes several archaeological sites, however, several of these sites only have a tangential connection with Tikal.

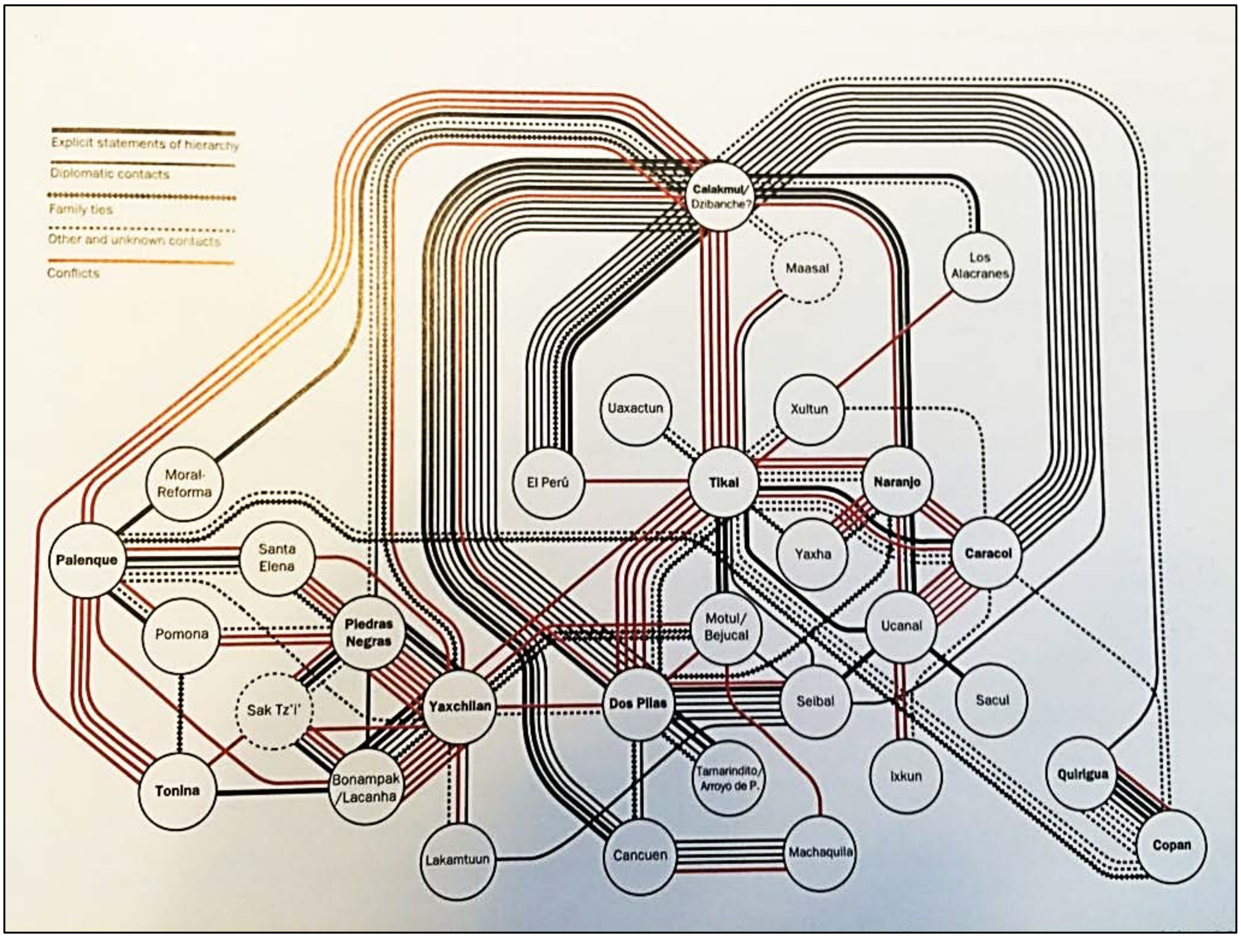

Figure 2 Diagram of Tikal’s interactions with other Maya sites. Source: Martin and Grube 2008.

This thesis focuses on archaeological sites that possess a high level of evidence for a conflict interaction, as shown on the Martin and Grube diagram. Tikal has recorded evidence of warfare interactions with its surrounding sites in the archaeological record. Many of its conflict interactions were the result of long-term hostilities involving power struggles with neighboring polities such as Calakmul, Caracol and Naranjo. These wars were fought over territory or political control of the region (Webster 2000, 86-96). Warfare was a means through which Tikal exerted its power and influence throughout the Maya area.

Nolan and Cook (2012, 75-76) describe a least cost path model in their spatial analysis of prehistoric catchment sites in which the endpoints were chosen via archaeological criteria. The criteria for the selection of the endpoints was an archaeological site index which recorded known prehistoric sites in the region. This is applicable to the current project because it also uses a sites placement in the archaeological record as a criterion for endpoint selection. Although the current project did not utilize an archaeological site index, it did utilize archaeological evidence to help further refine possible endpoints. The selection of specific sites included in this research is further discussed in Chapter 3.

2.2 Least Cost Analysis in Archaeological Contexts

Least cost paths are often used in the context of archaeological research to determine possible routes between sites. Least cost paths are defined as the most efficient route between two locations across a landscape in regard to energy or time (Conolly and Lake 2006, 2). These paths are often used in archaeology due to their ability to demonstrate the quickest route between two sites or areas. Schild (2016) used least cost paths to evaluate historical trade routes in Turkey against the known trade routes in the region. He argued that in navigating a landscape, people typically utilize the path of least-resistance in terms of energy expenditure. According to Schild, the inhabitants of a given region generally utilize their specialized knowledge of the region and are aware of the easiest routes to traverse the area. This tendency to reduce the cost of mobility results in patterned behaviors of interaction (Schild 2016, 14; White and Surface-Evans 2012, 2). Schild's conclusions indicate that archaeological sites that are far away may have significantly less interaction then those that are closer to the point of origin in the landscape.

Carballo and Pluckhahn (2007, 612) also performed a least cost path analysis in Mesoamerica using multiple endpoints and one origin point. The study identified the least cost routes in terms of travel time. To measure this, the study used a hiking function developed by Tobler (1993, 3) that could create an anisotropic surface which indicated the most efficient path of travel. This hiking function calculates effort in hours of foot travel across the terrain.

Another example of least cost path modeling was seen in an archaeological study of inter-regional interaction in the Goksu Valley of Turkey (Newhard et al. 2008, 92-98). The stated purpose of the least cost path model was to provide a rough understanding of relationships between sites in the area, not to produce definitive paths that would describe accurately how people may have traversed the region. The least cost path was performed using a constraint that the cost of climbing a slope was not proportional to the degree of the slope; this was done to account for the costs expended while traversing steep terrain. Similar to Newhard's model, the least cost paths in this thesis project are not meant to visualize accurate paths, but instead, visualize a probable path for interactions involving conflicts between the archaeological sites.

Doyle et al. (2012, 795-797) record a least cost analysis in their study of inter-site Maya exchange route travel that also used Tikal as an origin point. Doyle et al. noted that most Maya travel in the region was achieved by utilization of footpaths which were created by clearing vegetation. This suggests that ancient Maya exchange routes were susceptible to land cover alterations made by the inhabitants of the region. Their least cost routes were not modeled to attempt to describe the actual exchange routes of the Maya people, but were instead used to show how the exchange corridors may have affected settlement in the region. The analysis assigned weights to the landscape depending on what season of the year it was. These weights were integral to Doyle et al.’s analysis as some areas of the landscape were impassable depending on the season. This allowed the cost path to more accurately reflect the actual exchange corridors in the region. In addition, the study assigned partially anisotropic costs such that it adjusted for increased difficulty of foot travel through the corridor from the direction of the original origin point. Similar to Doyle’s project, this thesis used least cost analysis to attempt to model corridors for potential conflicts between Tikal and these sites.

2.3 Modeling Cost Surfaces

Least cost path models utilize a cost surface that models the energy expenditure that is necessary to travel between two separate points. Connolly and Lake (2006, 215) define costs as being separated into either isotropic or anisotropic paths. Isotropic costs are independent of direction of travel, whereas anisotropic costs are direction specific. Isotropic costs may include terrain features such as vegetation, land cover, and water. Isotropic cost models assume the cost would be equal for all directions a path may go in the landscape. Isotropic cost models are more suitable for areas with little variation in elevation.

Anisotropic models calculate costs that differ based on their initial direction from the point of origin. This cost model is generally used for archaeological geospatial studies due to its focus on direction-specific cost modeling. The anisotropic cost model is a suitable model to accurately estimate the costs that may be incurred during a least cost path analysis of the Maya area.

A case study by Anaya Hernandez (1999, 78-79, 81, 82-83) of spatial movement between sites in the Maya area focused on assessing both isotropic and anisotropic cost functions. This spatial analysis focused on movement as a function of not only distance, but also of time and energy expenditure and incorporated the isotropic costs as a fixed unit of resistance on the cost surface. Anisotropic costs are described by Anaya Hernandez as being cumulative as well as direction specific, with different friction values derived. He hypothesized that to accurately identify spatial movement over a natural setting, both anisotropic and isotropic cost models might be necessary. He also detailed the necessity of combining three different raster images in order to create a workable cost surface image that would incorporate his mixed cost model. These images were the source image, the friction cost, and a directional image. The DEM was derived from digitization of several topographic maps which were isotropic source images as slope was not incorporated into these maps. The DEM was used to generate the slope and aspect images. Slope and aspect were used together to create an anisotropic directional image, as slope measures the angle of the terrain and aspect gives the direction of the slope. The anisotropic friction cost was derived from the slope and aspect. The friction cost increases exponentially relative to slope.

Least cost paths typically utilize a spreading algorithm across the cost surface in order to create the accumulated cost surface. This spreading algorithm tallies the total cost of the travel between the original point and the endpoint in the least cost path analysis (Schild 2016). Therefore, the selection of this algorithm is crucial for any least cost study. The least cost path analysis often uses Dijikstra’s algorithm. This algorithm is mathematically based, and focuses on the determination of the total minimum cost between two points. This calculation uses a graph-based weighting solution in order to determine the total cost (Dijikstra 1959, 269-271). This algorithm is ideal for utilization in the current research project, however, Dijikstra's algorithm does not include other factors of measurement besides distance.

A least cost path study by Bell et al. (2002, 106-107) describes several techniques for calculating the final cost surface. Their study derived the cost surfaces from the slope values and accounted for movements across the sloped surface through the utilization of an anisotropic cost computation. The study focused on the magnitude of the slope as well as the direction of the slope. This model used a strategy that the best way to solve the problem of an excessive slope is to traverse across the angle of the slope rather than attempting to go against it. In a least cost path model, a path going around a high elevation area may be faster than one going through it. By using such cost functions, it ensured that the modeled path was as efficient as possible even in an area where there are complex slope changes across the landscape.

Tobler's hiking function is able to model cost paths in a way that minimizes both the time and energy expenditure required to reach the target destination. Tobler's hiking function is useful because it manages to utilize slope in its cost. The function is most efficient when going downhill at a slope of five to seven degrees, steeper slopes may force a walker to slow down. (Katner 2004, 6). This would indicate that Tobler's hiking function is more suitable for least cost path based analysis in studies where there are significant differences in slope. It is also extremely useful for indicating the exact time it takes to traverse a path as it will calculate the time cost per degree of slope in the final cost raster.

Tobler's hiking function is not the only algorithm that may be used to calculate a cost surface to determine time and distance in a least cost path analysis. Other methods such as the one used in Pandolf's report for the Army, place constraints upon the walker and utilize assumptions about the starting speed and pace of the individual (Pandolf et al. 1977, 5-10). The cost model also imposed load costs which may be only viable in studies where these load costs can be measured. These studies also may not accurately reflect the full range of human motion, as an individual’s speed may vary depending on their range of mobility. In an archaeological context such as this research project, determination of an average load cost is not possible given the lack of available information regarding individual human movement in the Maya region.

Tobler’s hiking function has been determined to be consistent with independent assessments of human motion. It was assessed in an anthropological mobility study in South America and was determined to be a valid indicator of travel times in rough terrain, although factors such as path condition could affect its accuracy (Aldenderfer 1998,12-13; Katner 2004, 6). The terrain that was assessed in this least cost model study requires a model that realistically depict human motion through the landscape. In addition, Tobler’s hiking function demonstrated that it was able to model more accurate paths as it assigns its costs through the landscape.

2.4 Assessment of Results

It is important to assess the results of least cost analysis to prevent errors when modeling in a GIS. There are several means by which an accuracy assessment may be conducted in a spatial analysis. Rothley stated that in order for least cost paths to be reliable, the validity of the data must be demonstrated (Rothley 2005, 2). It is critical to check the input raster data for errors to ensure that the model is accurate. Second, if there is a mistake in the cost raster, the output will likewise be erroneous as well. According to Rothley, raster-based spatial data may have technical issues which may nullify the original results. Therefore, when doing a cost path analysis, it is necessary to review the cost raster data before generating the final results. It may also be necessary to do a thorough review of all input and output data to ensure that there are no mistakes being created through the use of the wrong input for an operation.

Evaluation of the cost function is integral to the operation of a least cost path analysis. Herzog suggested that archaeological least cost path analysis should not be stopped after the initial paths were modeled, and that the paths be tested to determine how they may reflect reality. (Herzog 2013, 181-182). Herzog stated that the validity assessment of the least cost analysis may also be performed via alteration of the initial parameters in the cost model. This may be achieved by introducing different cost components into the model in order to determine the sensitivity of the final result. Other examples may include alteration of the endpoint or origin to determine if the cost function is operating correctly. Herzog argued that such minor deviations in the model parameters could result in a very different least cost path. However, alteration of cost parameters such as substituting a lower resolution DEM could result in an even more divergent least cost path from the original.

In the thesis project, one origin-destination pair underwent a sensitivity assessment in order to determine the potential accuracy of the least cost path. This evaluation took the form of slightly altering the locations of the original destination and origin points in order to test the sensitivity of the least cost path.

Chapter 3 Methods

This chapter describes the methodology used in the creation of the least cost paths for this project. The least cost paths developed for this thesis focus on paths between prominent Maya sites in the Maya Lowlands: Tikal, Caracol, Calakmul and Naranjo (Figure 1). This methodology uses Tobler's hiking function when determining the least cost paths in order to model the paths in the most time and cost-efficient manner. Least cost paths were implemented from Tikal to each destination site as well as vice versa. Isochrones were modeled for this project to represent travel time between Tikal and the destination sites. Sensitivity analysis was conducted on the least cost paths in order to determine the sensitivity of the results to variations in the input data. This was performed using DEM and site placement sensitivity analysis.

This chapter is divided into several sections. The first section briefly discusses the selection of the origin and destination points. The following section covers the data acquisition process. The third section describes the process by which the least cost path was executed. The fourth section describes the processes by which isochrones were created for this analysis. The last section of this chapter outlines how the sensitivity of the model results was assessed by alteration of input variables.

3.1 Study Sites

The sites used in this project were all located in the Maya Lowlands as seen in Figure 1. A vital step in this project was choosing the origin and destination points that would be modeled in the least cost path analysis. The selection of these sites was based on published epigraphic evidence without the use of GIS. This study used textual evidence given in *Chronicle of the Maya Kings and Queens: Deciphering the Dynasties of the Ancient Maya* (Martin and Grube 2008). A reading of this book led to the conclusion that Tikal was the most viable origin for the least cost path analysis due to its wide range of interactions with other archaeological sites in the Maya region as can be seen in Figure 2.

The decision was made for this analysis to focus on conflict-based spatial interactions between Tikal and its neighbors. In Figure 2, red lines indicate each spatial interaction signifying conflicts between Tikal and neighboring sites recorded in the epigraphic record. Multiple lines of the same interaction type in the diagram signify that there are multiple forms of this contact between the two sites. For the purposes of this analysis, three destination sites were selected to showcase the spatial interactions of Tikal. Naranjo, Calakmul, and Caracol were selected because they each possess evidence for conflict-based spatial interactions with Tikal.

The coordinates for Tikal, Naranjo, Calakmul, and Caracol were discovered by searching for these sites in Google Earth. These site locations were recorded in UTM coordinates. Table 1 shows these values. An Excel spreadsheet was created to record these site locations. This Excel sheet had to be rendered spatially compatible, and so it had four columns: ID, Description, Northing and Easting. This spreadsheet was then saved as a comma separated values file in order to make it compatible with ArcGIS.

Table 1 Location of the sites in UTM Zone 16N coordinates

ID	Name	Northing (m)	Easting (m)
1	Tikal	1906017	220984
2	Caracol	1854642	274016
3	Naranjo	1895735	259427
4	Calakmul	2004115	202519

3.2 Preparation of Project Geodatabase

This project required a surface model of the region surrounding the site of Tikal. This digital elevation model (DEM) was obtained from the United States Geological Survey (USGS) through one of its tools called the Global Data Explorer. This allowed me to visualize the entire world in the Data Explorer viewer, and narrow down my study area for the project. By selecting an appropriate box around these sites of interest, an ASTER Global DEM V2 and an SRTM DEM in GEOTIFF format were downloaded.

The ASTER DEM was produced in part by NASA using data gathered from the ASTER remote sensing program. The ASTER DEM has a vertical accuracy of 7-14 m. The horizontal resolution of the ASTER DEM is approximately 30 m. The SRTM data was collected by the Shuttle Radar Topography Mission. There are two SRTM products available, one with a 30 m and one with a 90 m resolution, the second of which was used for this project. The vertical accuracy of the SRTM is 10-16 m (Ramirez 2017). The ASTER DEM was selected as the primary digital elevation model for this project and the 90 m SRTM was used for the sensitivity assessment at the end of the process.

The ASTER and SRTM DEMs were imported into ArcMap via ArcCatalog. The ASTER DEM was originally obtained in a geographic coordinate system of GCS WGS 1984. The SRTM was also available in the GCS WGS 1984 coordinate system. It was later projected into a projected coordinate system of WGS 1984 UTM Zone 16N. I projected both the ASTER and SRTM DEMs from a GCS to a UTM projected system due to my decision to implement my site coordinate data in UTM coordinates.

The .CSV file containing the site data was uploaded into ArcGIS via ArcCatalog. Once the file was opened in ArcMap, the tool Display XY data allowed an events layer for the point file to be created. The events layer was then exported into a shapefile so that the points could be used in the least cost path analysis. Figure 4 shows the location of the sites in the context of the Maya area.

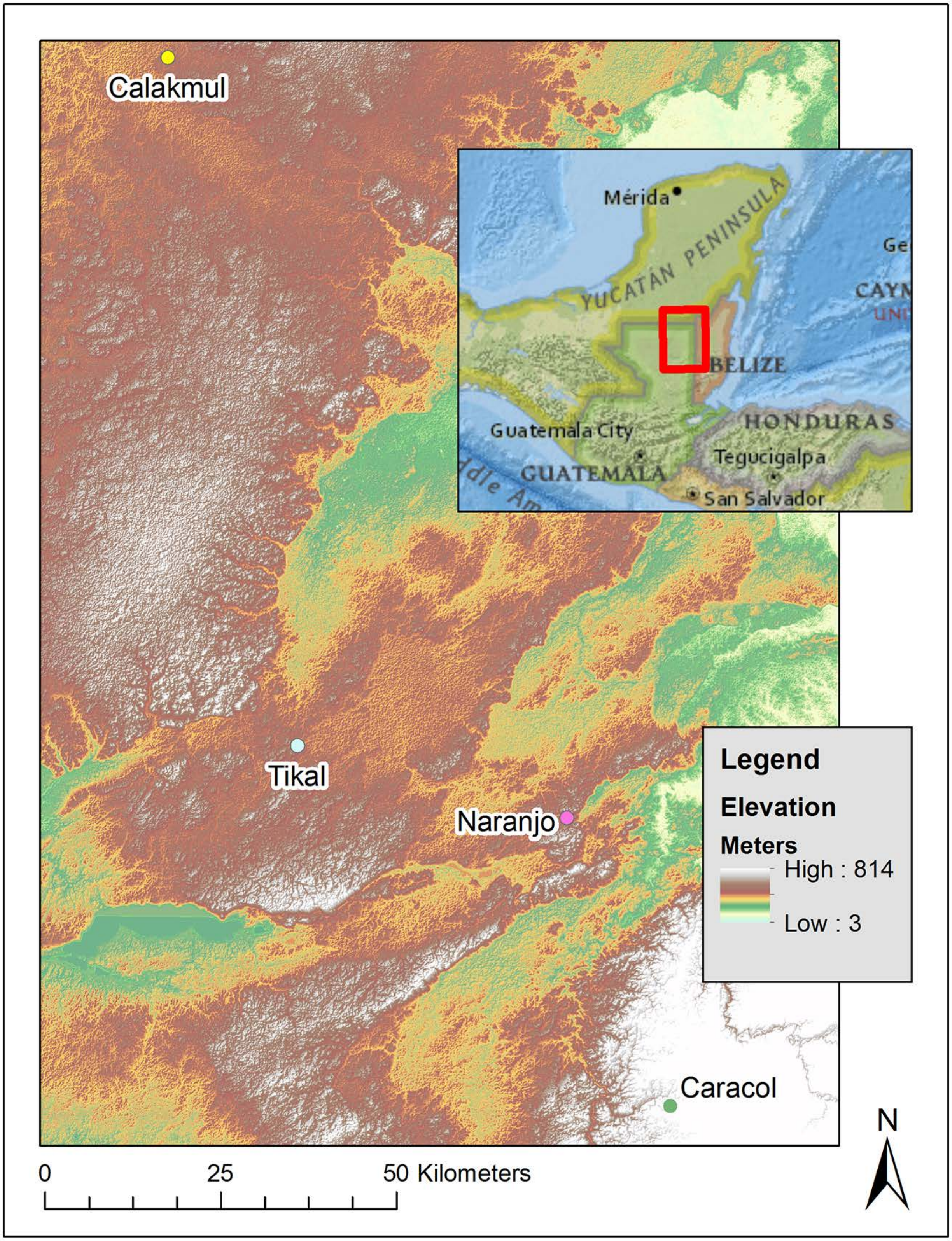

Figure 3 Four sites overlaid on the 30 m ASTER DEM

3.3 Preparing the Data for the Least Cost Path Operations

Use of the Tobler's hiking function is key in this analysis since it allows for both the determination of anisotropic paths and the calculation of path time. A vertical factor table was used in the path-distance tool to operationalize the Tobler's hiking function. It is calculated via the following equation:

$$\text{Time (hours) to cross 1 meter} = 0.000166666*(\exp(3.5*(\text{abs}(\tan(\text{radians}(slope\_deg)) + 0.05)))) \quad (1)$$

For use in the Path Distance tool, a discretized version of this equation is necessary. Table 2 shows a range of possible results from the equation, for values with slope degrees between -40 and 40. An extended version of this table, called "ToblerAway", with values for all degrees between -70 and 70, plus +/-80 and +/-90 was used in the Path Distance tool as the vertical factor table.

Table 2 Example results of Tobler's hiking function for different slopes

Slope (degrees)	Vertical Factor
-40	0.001610753
-30	0.000822629
-20	0.000474721
-10	0.000257717
0	0.000198541
10	0.000365717
20	0.000673661
30	0.001240899
40	0.002285767

The origin and destination feature classes were transformed into individual feature classes for the least cost path analysis. This was accomplished by means of the Feature Class to Feature Class tool for each of the sites. As this analysis used three paths that were analyzed separately, three path specific feature geodatabases were created to store the data. The Path

Distance and the Cost Path tool requires data from both the origin and the destination for the main input in the least cost path operations. The first path point pair to be modeled in this manner is Tikal to Naranjo, then Tikal to Calakmul, and finally, Tikal to Caracol.

Prior to the start of least cost path operations, I created buffers around each one of the sites. The buffers are used to represent an area of origin because the actual physical origin would not be a zero-dimensional point on the landscape. The area of central Tikal, for example, was approximately 4x4 km (Thomas Garrison, personal communication, May 8, 2017). Using the Buffer tool, I created a buffer for each site point of 1000 m diameter, saving each output as a separate file. Then this vector buffer was transformed into a collection of contiguous raster cells by using the Polygon to Raster tool in ArcToolbox since the Cost Distance tool requires one or more raster cells as origin and destination points. I used both of these buffers in the analysis and mapping steps so that there was a total of eight buffers created. The naming convention for the buffers follows this form: 'TikalBuffer' for the polygons and 'Buffer Tikal' for the raster versions of these buffers.

3.4 Least Cost Path Operations

The least cost path operation uses a combination of the Path Distance and Cost Path tools in ArcToolbox. The least cost path operations were performed not only to each destination site from Tikal, but also from each destination site to Tikal. This resulted in a total of six paths, with the objective to determine how the paths may have been altered depending on their point of origin. These paths were performed in both directions in order to better model a conflict interaction path for Tikal invading a site as well as being attacked by rival sites.

Figure 4 shows these input, tools and output for one destination through a flowchart to illustrate how the least cost path process would work for each path. Tikal's buffer and the destination buffer are switched for each reversed path. Tables 3 through 5 show the inputs and outputs for the Path Distance, Cost Path and Raster to Polyline operations. The Vertical Factor input shown in Figure 4 for the Path Distance tool is how Tobler's hiking function is implemented in the least cost path operation. The DEM provides the elevation extent over which the cost surface is calculated for that path.

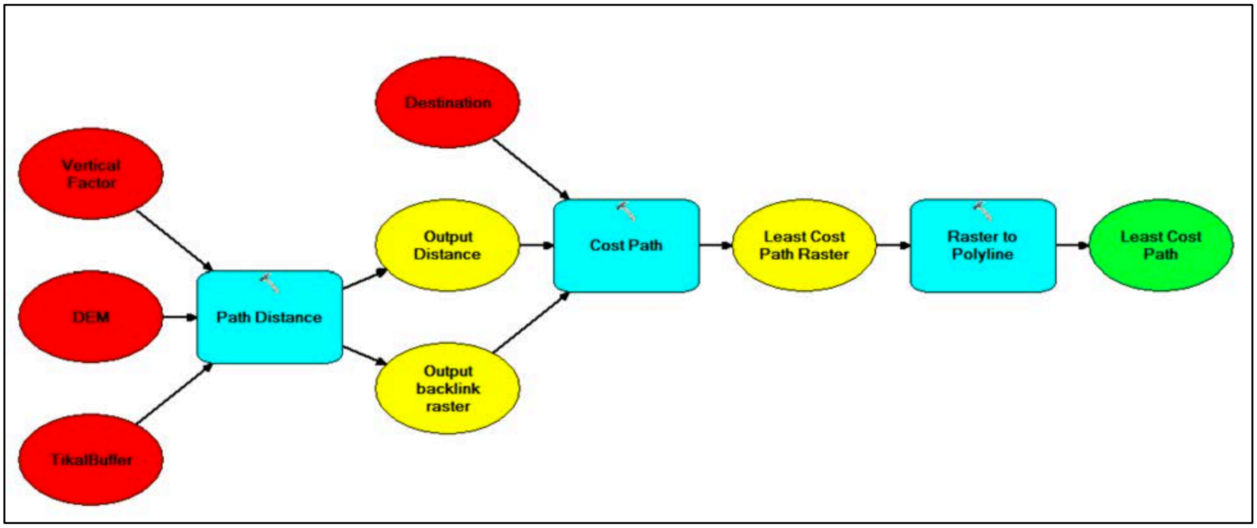

Figure 4 Flowchart showing procedures used to calculate least cost path

Table 3 Path Distance Tool inputs

Path #	Input	Vertical Factor
1 (Tikal to Calakmul)	BufferTikal	CalakmulTikal
2 (Calakmul to Tikal)	BufferCalakmul	CalakmulTikal
3 (Tikal to Caracol)	BufferTikal	CaracolTikal
4 (Caracol to Tikal)	BufferCaracol	CaracolTikal
5 (Tikal to Naranjo)	BufferTikal	CaracolTikal
6 (Naranjo to Tikal)	BufferNaranjo	CaracolTikal

Table 4 Cost Path Tool inputs

Path #	Input	Output
1 (Tikal to Calakmul)	CalakmulBuffer	Path1
2 (Calakmul to Tikal)	TikalBuffer	ReversePath1
3 (Tikal to Caracol)	CaracolBuffer	Path 2
4 (Caracol to Tikal)	TikalBuffer	ReversePath2
5 (Tikal to Naranjo)	NaranjoBuffer	Path3
6 (Naranjo to Tikal)	BufferTikal	ReversePath3

Table 5 Raster to Polyline Tool inputs

Path#	Input	Output
1 (Tikal to Calakmul)	Path1	LeastCostPath1
2 (Calakmul to Tikal)	ReversePath1	ReverseLCP1
3 (Tikal to Caracol)	Path2	LeastCostPath2
4 (Caracol to Tikal)	ReversePath2	ReverseLCP2
5 (Tikal to Naranjo)	Path3	LeastCostPath3
6 (Naranjo to Tikal)	ReversePath3	ReverseLCP3

3.5 Creating Isochrones

Isochrones are lines of equal time. Isochrones were created to determine how far an individual could travel in a set interval of time. Three sets of isochrones were created, one set from each of the three non-Tikal sites. For this operation, I used the path distance output for the calculation, using the output backlink from the Path Distance tool. Then the Contour tool from the surface analysis section of ArcToolbox was employed. From the Contour tool, the ‘output backlink’ was used as the input surface. Figure 5 shows the input, tools and outputs for one site. In this analysis, this process was repeated only twice, as the output backlink for Tikal to Caracol overlaps with that for Tikal to Naranjo.

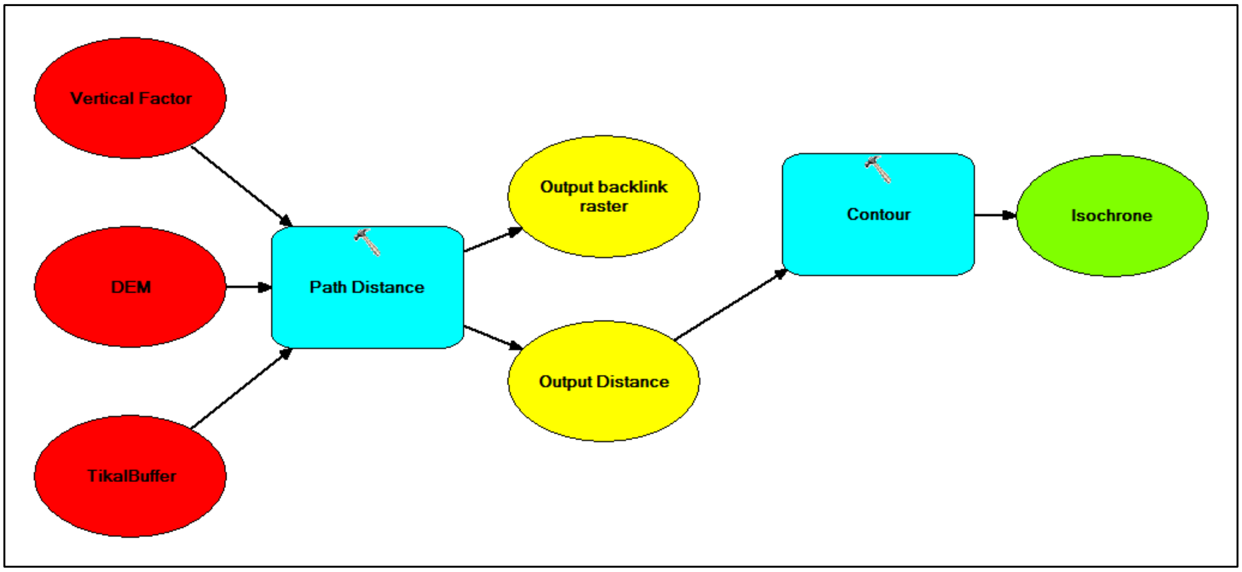

Figure 5 Flowchart showing procedures to create isochrones

As the isochrones are created, it was necessary to set the interval between them. After some trial and error, the interval was set to four hours from Tikal, an interval that would show sufficient time resolution for visualization purposes. The isochrones are meant to be used in conjunction with the least cost modeled paths and not as an exclusive means of determining the time required to travel the given distances. Thus, overlaying the isochrones with the line features that are created in the final step of the least cost path analysis allows visualization of these isochrones in comparison to the least cost paths. A slope map was created from the Aster DEM for this project to be used as the background for the isochrones. Since the path distance surface was calculated using the Tobler Hiking Function table, the isochrones represent the distance traveled as an anisotropic time-distance, allowing a visualization of the approximate cost effort required to travel away from each site. This helps to demonstrate the possible range of motion for an individual in the given time frame that is expressed in the result of the original least cost path model.

3.6 Sensitivity Analysis

In order to determine the validity of the least cost path, it was necessary to perform a sensitivity analysis. The sensitivity analysis was performed using two methods: an origin and destination location sensitivity analysis and a DEM resolution sensitivity analysis. The origin and destination location sensitivity analysis used a new pair of origin and destination points. The new origin point is near the site of Tikal, but moved 1500 meters east. The destination point selected for this sensitivity analysis is Calakmul. It was repositioned 1500 meters east. For this assessment, new buffered points were created using the repositioned site features. Least cost paths were generated from these points and these were compared to those modeled in the original methodology.

The DEM resolution analysis was completed by using the original methodology, but substituting the SRTM DEM instead of the ASTER DEM as the base digital elevation model in all procedures. This check helped to determine if there were discrepancies between the modeled paths when performed with the SRTM DEM as the base instead of the ASTER DEM. For this comparative analysis, the SRTM replaced the ASTER DEM specifically for the extent of the path between Calakmul and Tikal.

Chapter 4 Results

This chapter presents the results of applying the methodology outlined in the preceding chapter. Results include an inspection of each pair of paths and the isochrones, and a discussion of the results of sensitivity testing.

4.1 Least Cost Path Corridors

Figure 6 shows the multiple paths generated between Tikal and Calakmul. The Tikal to Calakmul path merges with the Calakmul to Tikal path throughout the majority of its path except at the ends. As noted earlier in Chapter 3, origin and destinations were modeled as 1000 m buffers to allow the least cost paths to begin in raster cells over a larger area than a zero-dimensional point which causes all of the paths to split into multiple branches as they approach the destination.

The Tikal to Calakmul path initially descends to a lower elevation then travels across this low elevation until starting a climb up to a higher elevation, eventually declining on its way to Calakmul, ending with a short uphill slope. The reverse path begins on a downward slope to a slightly lower elevation before the path treads upwards again, wherein it stays on the higher elevation until it reaches the green lower elevation point. There, the reverse path splits off into two branches, both of which stick close together.

In Figure 6 the buffers create multiple destination points for both the Tikal to Calakmul path and the reverse path. Both paths split as the path travels downhill into a lower elevation area. The Tikal to Calakmul path overlaps with the reverse path throughout the majority of its course. The maximum distance that the paths deviate from each other as they travel in opposite directions is 1 kilometer as the Tikal to Calakmul path initially descends downhill into the lower elevation region.

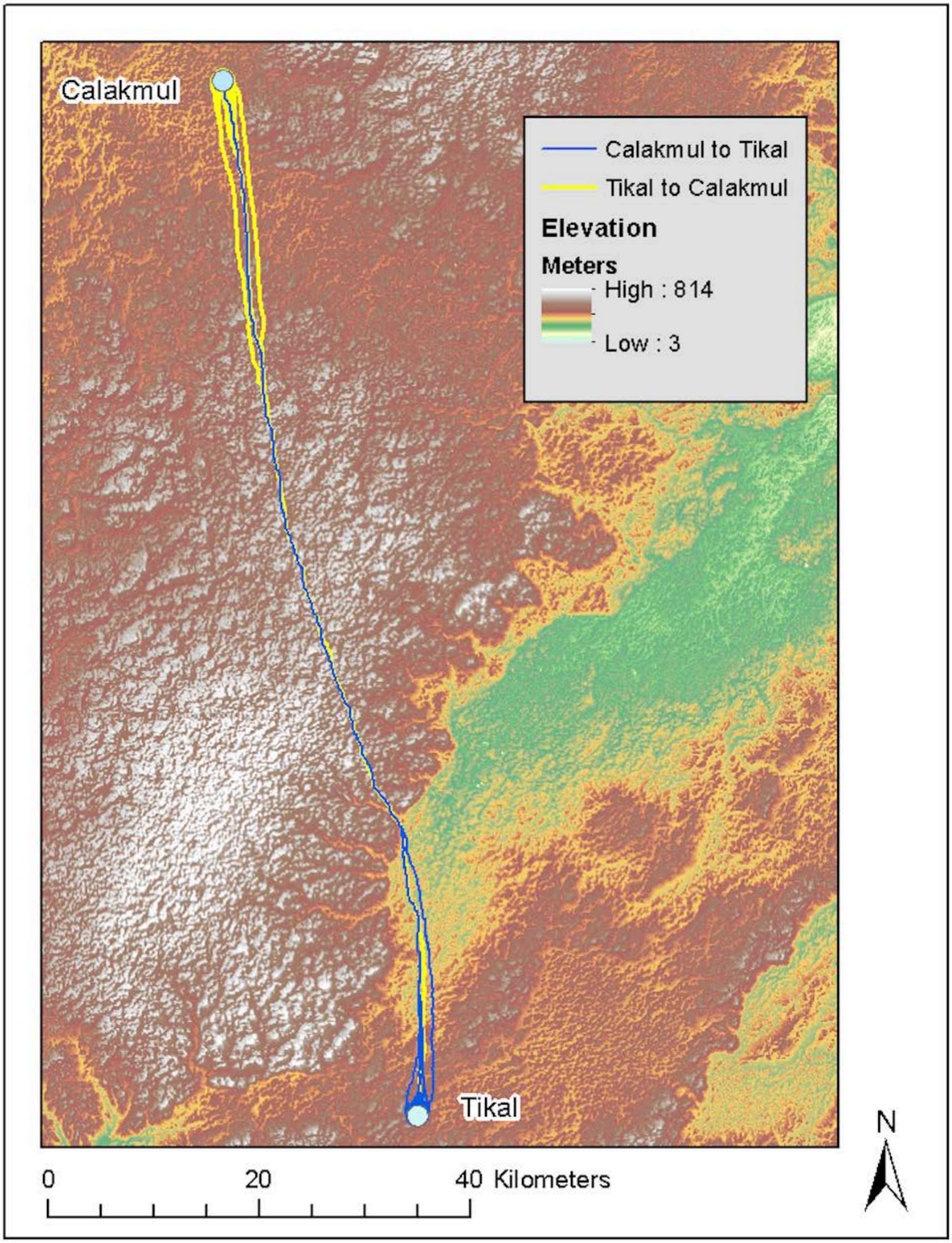

Figure 6 Least cost paths between Tikal and Calakmul

The Tikal to Naranjo path, shown in Figure 7, has several different routes, some of which merge with the reverse route at various points along the paths. The single path from Tikal merges with one of the reverse paths near the beginning then bifurcates and begins to deviate as the path heads towards a downhill slope in the yellow lower elevation area. The Naranjo to Tikal path flows an original path until a lower elevation area is reached, wherein it deviates to the south until the path goes uphill as it returns to the higher elevation area and rejoins one of the Tikal to Naranjo routes.

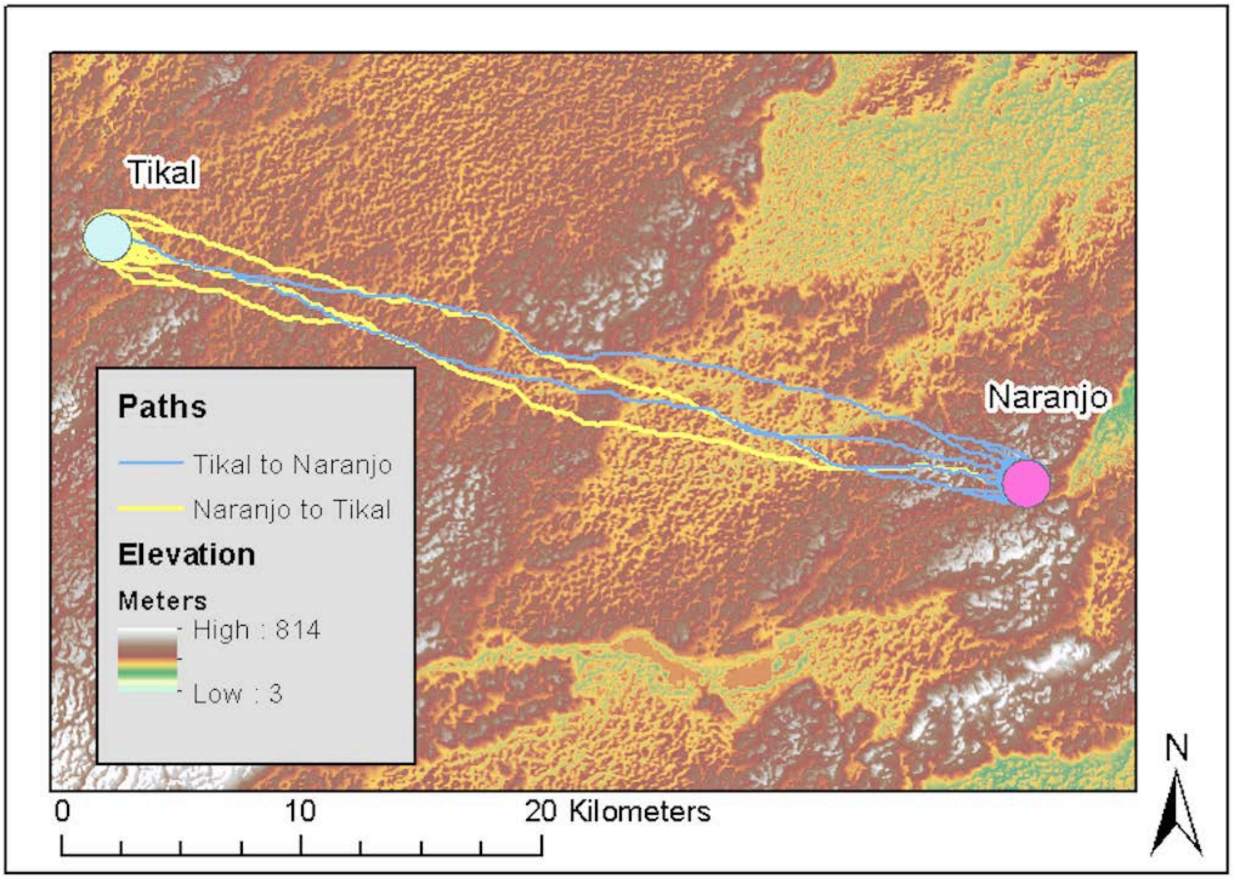

Figure 7 Least cost paths between Tikal and Naranjo

In Figure 7, the buffers create multiple routes at the destinations for both the Tikal to Naranjo path and the reverse path. In both paths, the routes split into two separate branches. The maximum distance that the original and reverse paths deviate from each other is in the yellow lower elevation region; the separation between the paths going in opposite directions is 2.3 kilometers.

The Tikal to Caracol Path and its reverse path, shown in Figure 8, both split into two branches as the paths go downhill towards lower elevation regions. The buffers create multiple destination points for both paths. The maximum distance that the paths in opposite directions deviate from each other is 3.7 kilometers in the white higher elevation area where the Tikal to Caracol path heads downhill as the reverse path makes its way uphill.

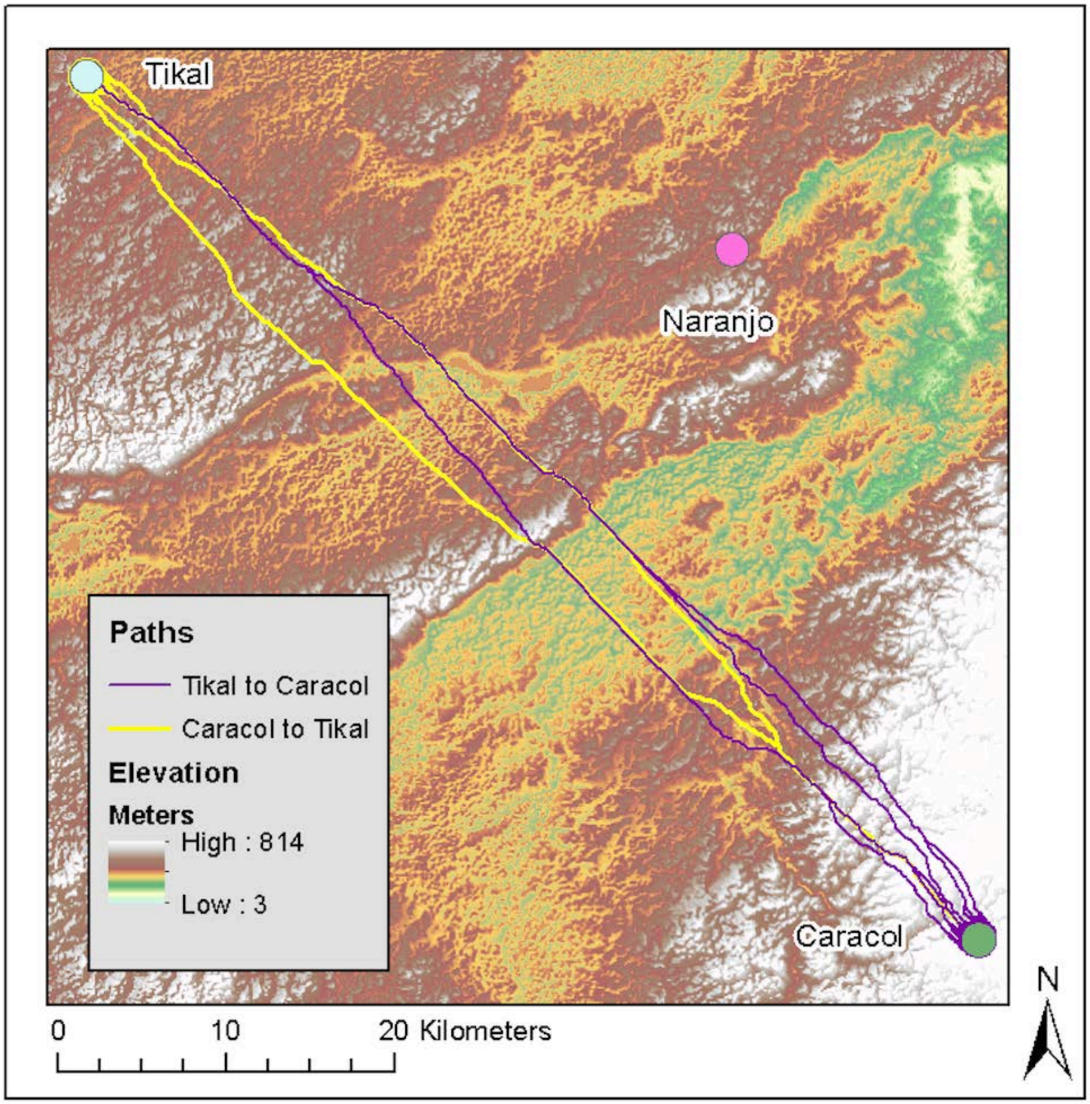

Figure 8 Least cost paths between Tikal and Caracol

4.2 Isochrones

Figure 9 displays isochrones of walking time from Tikal calculated for both the northern and southern extents of the study area. They are shown over the slope raster instead of elevation in order to better represent the costs involved in travel. Visualizing slope in this map provides a clearer picture of the cost-effort required to travel than simple elevation. The time to walk from Tikal to Calakmul was estimated to be over 20 hours, Tikal to Naranjo at 8 hours, and Tikal to Caracol at 16 hours.

The four-hour intervals used here are intended to represent an average continuous walking period between rest stops. This interval is integral as this project models conflict interactions between sites, these routes would be traversed by large groups of people carrying heavy equipment. This would necessitate multiple rest stops, most likely more than an individual would require for the same distance. The approximate distance between each four-hour interval is 17.5 kilometers.

The intent of creating the isochrone map was to illustrate the travel time from Tikal to the destination sites. In this analysis, the isochrone lines are not consistently smooth across the entire area, with the lines showing the most irregularities in areas of higher slope. These irregularities typically occur in regions where there is a sudden change between higher and lower slope. This shows how the actual horizontal distance covered will vary between individuals who approach the location of a particular isochrone at a different point. The isochrone lines are smoother in the green areas as these represent lower slope, indicating decreased cost effort required to travel through the region. Although the majority of the region has low slope, there are some red higher slope areas throughout the region, which is the ultimate cause of the isochrone lines not forming perfect concentric circles moving outward from the point of origin.

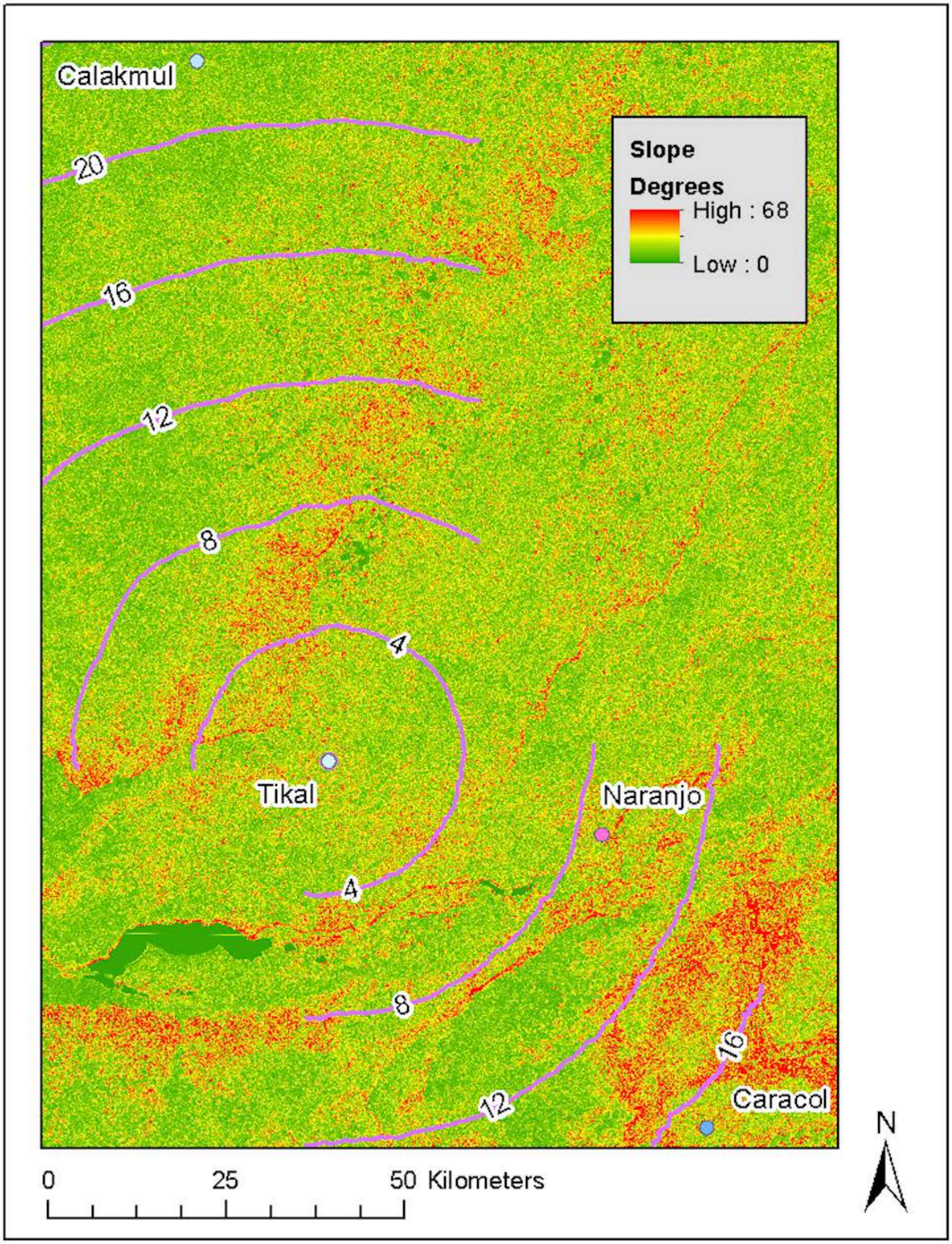

Figure 9 Isochrones from Tikal to three sites

4.3 Sensitivity Analysis

The following section presents the results of the origin and destination location sensitivity analysis as well as the DEM sensitivity analysis that used the SRTM DEM instead of the ASTER DEM. The first sensitivity analysis was conducted by comparing the original Tikal to Calakmul paths against paths performed using modified origin and destination points. This was done to determine if the results were sensitive to repositioning of the original points. The DEM sensitivity analysis uses the extent between Calakmul and Tikal, substituting the SRTM DEM for the ASTER DEM. The objective of this DEM analysis was to determine whether the lower spatial resolution of the SRTM DEM would lead to significantly different paths.

4.3.1. Origin and Destination Location Sensitivity Analysis

This sensitivity analysis was performed by moving both Tikal and Calakmul points 1500 meters to the east. The least cost path methodology for the original paths was repeated using the new placement of the points. As the distance between the original and shifted points is significant, and crosses a higher elevation, it was expected that this path might diverge significantly and cause the path to shift as it reaches a lower elevation area.

Figure 10 shows how the sensitivity path behaves when compared to the originally modeled least cost path. The new placement of Tikal and Calakmul buffered points, shown in yellow, resulted in a path that is similar to the original, but deviates at key points. The paths initially follow simple separate paths, going relatively straight north from the origins until they merge at the same canyon at the north side of the green low elevation area. From this point, they overlap until they deviate again as they gradually head downhill on their final approaches to Calakmul. The maximum distance that the paths deviate from each other in the same direction is 5.0 kilometers as the paths began to head downhill in the central region of the map.

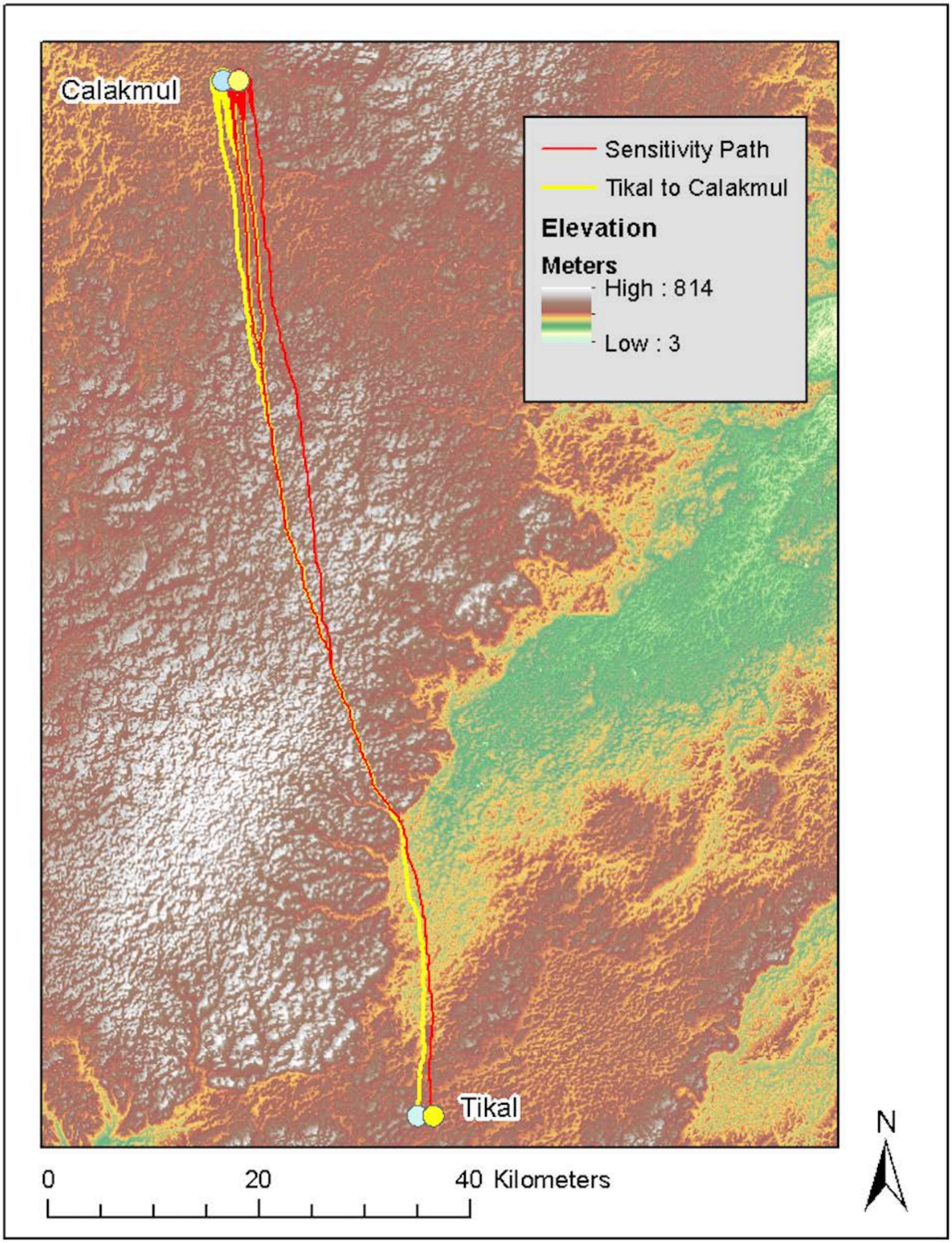

Figure 10 Results of origin and destination location sensitivity analysis for Tikal to Calakmul path

4.3.2. DEM Resolution Sensitivity Analysis

Using the SRTM DEM, the least cost path methodology was repeated for each direction between Tikal and Calakmul. In Figure 11, it can be seen that the original path from Tikal to Calakmul is very close to the SRTM DEM path. The original path is very similar to the new path with short deviations in the low green elevation area and in the higher elevation area. The maximum distance that the paths deviate from each other in the same direction is 2.5 kilometers.

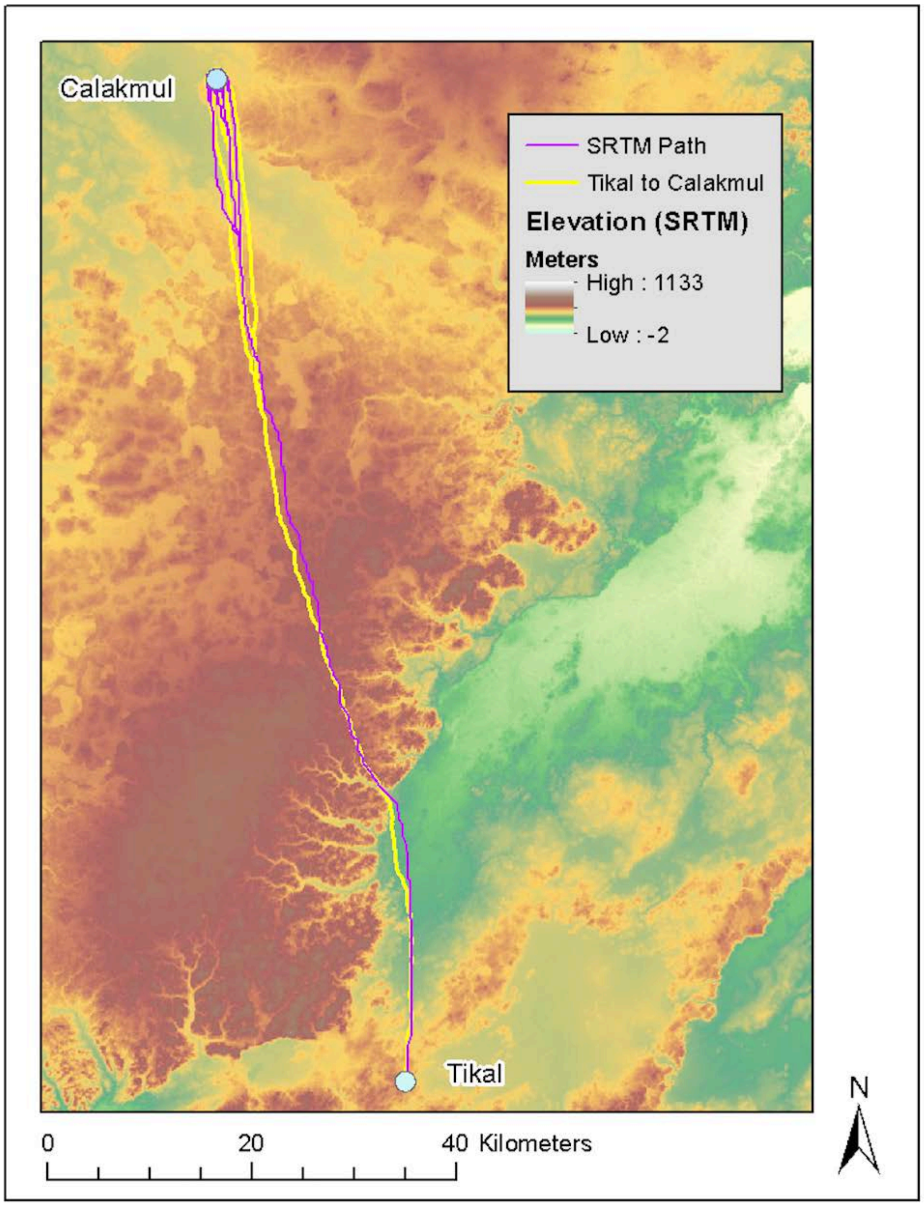

Figure 11 Results of Tikal to Calakmul DEM resolution sensitivity analysis

In Figure 12, the SRTM DEM path is split into two branches from the origin point and then splits again in the high elevation area, although the original ASTER DEM path follows the eastern branch of the SRTM path. The buffers create multiple destination points for the paths, although in the reverse SRTM DEM path, the presence of a lower elevation region near the start of the path causes the path to split as it initially heads downhill. The two western branches of the SRTM DEM reverse path avoid the original path entirely. The maximum distance that the paths deviate from each other in the same direction is 11.0 kilometers.

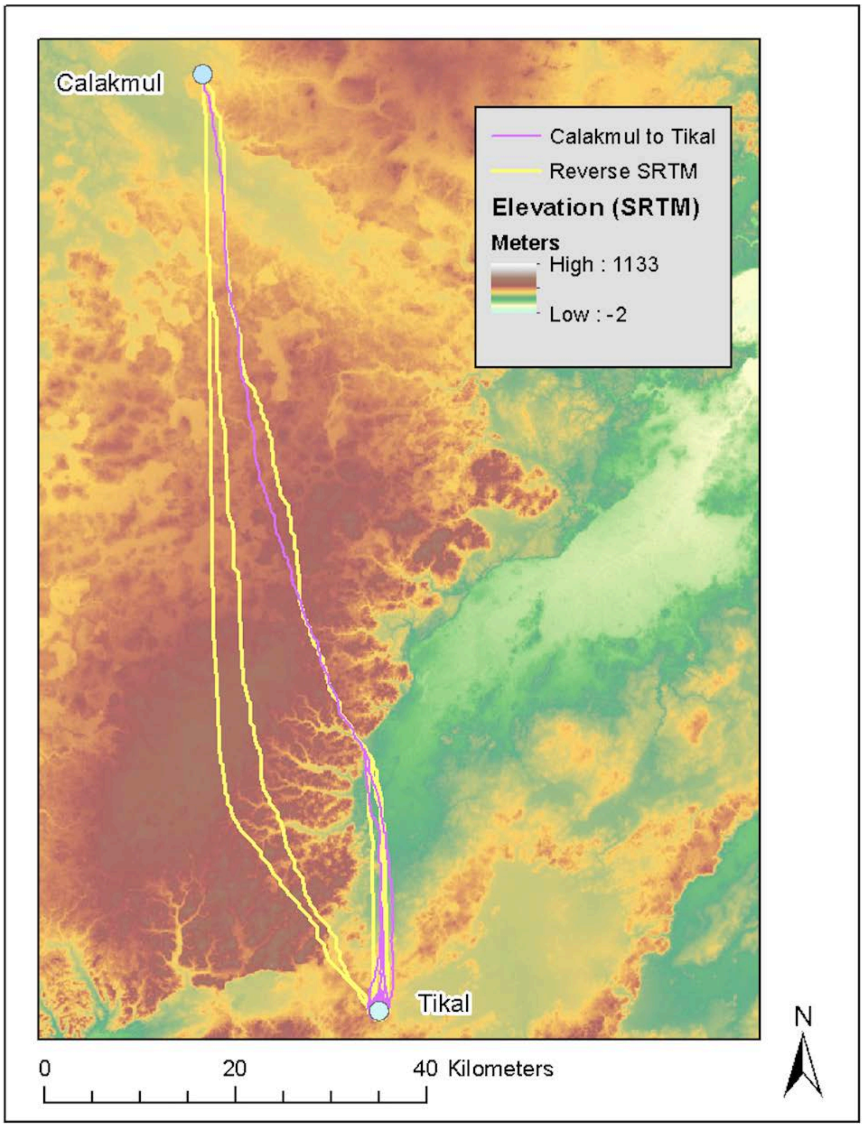

Figure 12 Results of Calakmul to Tikal DEM resolution sensitivity analysis

Chapter 5 Discussion and Conclusion

The objective of this thesis project was to model least cost paths across the Maya Lowlands. The paths model possible military thoroughfares between Tikal and its neighboring rival cities in the Maya region. This analysis used Tobler's hiking function to evaluate the modeled routes. This chapter discusses the significance of the results and describes possible future applications for least cost path analysis in the Maya region.

5.1 Discussion

In the least cost path analysis shown in Figures 6 to 8, a reverse path was modeled for each path-pair, interchanging the origin and destination pairs. The two paths for each path-pair intersect each other at some points along the routes. The path intersections in Figures 6 and 7 are in areas of high elevation where there is no lower elevation course for the path to take. Figure 8 shows the opposite where as soon as the Caracol to Tikal path reaches the lowest elevation area, the two paths intersect until a higher elevation is reached. This is due to least cost paths always being driven towards the area of least resistance. However, in Figures 7 and 8, although there were some points of convergence between the paths, at least one branch from each path did not converge with the opposite path. Reverse paths may significantly diverge from the original path due to these paths being modeled in the opposite direction over high slope regions where the vertical factor imposed by the Tobler's hiking function varies considerably.

The isochrones provide useful visual aids when overlaid over the least cost paths as shown in Figure 9. The labeled isochrone lines enable quick reference to the approximate length of time that it would take for an individual to cross the terrain. Deviations in the isochrones lines are more pronounced where the isochrones pass through sudden changes in slope from high to lower elevations. The time to walk from Tikal to Calakmul was estimated to be over 20 hours, Tikal to Naranjo at 8 hours, and Tikal to Caracol at 16 hours.

As the specific point locations for the endpoints of paths used in this project were uncertain in terms of their exact positions, buffers were created to simulate the full extent of each site. Thus, rather than using zero-dimension points, the origins and destinations of these paths were modeled using the contiguous set of raster cells contained within these buffer polygons. In each of the modeled least cost paths, the buffers resulted in the creation of multiple destination points for the modeled paths, although as seen in Figure 12, the buffer results in the creation of branching paths from the origin. The sensitivity analysis illustrated in Figure 10 revealed the insensitivity of the precise placement of the buffers around the approximate site locations. The difference in slope in the areas around the new origin and destination was marginal enough to cause the paths to follow parallel routes that merged where the terrain forced travel up a canyon.

In the DEM sensitivity analysis, least cost paths were remodeled on the Tikal-Calakmul extent using the SRTM DEM, with a 90 m cell resolution, as the elevation base. These paths were then compared to the original paths modeled using the ASTER DEM, which has a 30 m cell resolution. The DEM sensitivity analysis showed that the DEM resolution did impact the least cost paths modeled. Although the SRTM DEM path did not deviate substantially from the original when Tikal was used as the origin (Figure 11), the path did deviate considerably from the original when Calakmul was used as the origin (Figure 12). The SRTM DEM path in Figure 12 is split into three sections, the first adhering closely to the original modeled path from Calakmul to Tikal; however, the other paths are situated very far apart from the original. This marked divergence from the original path is likely due to the lower spatial resolution of the SRTM DEM. Comparing Figures 3 and 11, it can be seen that the original ASTER DEM is shown to have higher elevation in this area; thus, the lower resolution SRTM DEM has smoothed the elevation range, creating lower peak heights. The alternate paths in Figure 12 are the result of the lower spatial resolution of the SRTM DEM, which caused this region to have a lower overall slope through which viable least cost paths could be modeled.

These results support the observations of Doyle et al. (2012, 794) who noted the unsuitability of the SRTM DEM for least cost path analysis. In particular, they observed that a path created using an elevation raster with 90 m resolution would calculate a path that would be 90 m wide. A higher resolution DEM such as the ASTER DEM provides a better representation of the least cost path.

The least cost paths modeled in this analysis were not meant to describe actual paths that the inhabitants of the Maya region took during inter-site travel. The aim of this thesis was to utilize Tobler’s hiking function in the least cost path process in order to approximate the cost-effort of human travel across the terrain. The least cost paths modeled were intended to provide a visualization of the relationships between the prominent sites of the region in a manner similar to Newhard et al. (2008)’s study of inter-regional interaction in archaeological contexts. As Schild (2016) suggests, inhabitants of a region typically preferred to use the easiest routes to traverse a given area. The paths modeled in this project are only possible reconstructions of the lowest cost effort of travel from the origin to destination. In the event of conflict interactions, the parties involved might be expected to seek the quickest and easiest routes available to them in order to possess the advantage in the warfare event, though other characteristics of the terrain, notably vegetation cover and visibility, might lead to different choices. Although the least cost paths depicted in Figures 6 to 8 are only approximations, they may represent some realistic paths between rival sites.

5.2 Avenues for Future Analysis

Future least cost path analyses for this region may include additional destination points in the least cost path analysis. The number of destination points in a future project could be expanded from three to as many as eight additional sites for a more comprehensive study of the social dynamics of the region. These sites could be selected using Figure 2 which shows all local known rival sites that had conflicts with Tikal. Analysis of these paths could provide insight to the possible routes that may have been used between these sites. Further studies may also be used in order to determine if the possible least cost routes overlap when additional sites are added into the analysis. As this analysis would encompass sites that did not have as frequent conflict interactions as those in the original study, a comparison might also be made as to the cost-effort of travel to these sites from Tikal.

A more thorough version of this study may be able to compare inter-site travel based on other documented interactions between Tikal and its neighboring sites. Figure 2 shows Tikal also maintained diplomatic contacts and familial ties with many sites in the Maya area. Tikal also subjugated several cities in the Lowlands that were situated near the destination points modeled in this project. The analysis could cover all three interaction categories—conflict, diplomacy and subjugation—using least cost path analyses. These diplomatic contacts would have constituted an area of safe travel while subjugation might have required additional administrative travel.

Expansion of this least cost path analysis would also include vegetation as a cost factor. The Maya Lowlands were subtropical and contained numerous swampy regions that may have created natural obstacles to travel. In addition, although these paths modeled in this project may represent the route of least cost-effort, it is possible that they may not have been ideal for a warfare party. Future analysis could analyze these paths in terms of the area visible from the path through Viewshed analysis. Viewshed analysis creates a raster of visible and non-visible areas from a vantage point based on elevation (Doyle et al. 2012,794). Viewshed analysis could be used to determine the visibility of the route as well as blind spots.

A possible future extension of this least cost path analysis may be to display results using ArcGIS 3D Analyst. Using this tool, the terrain that the path travels through could be visualized in a three-dimensional view. This would allow for a better understanding of the terrain, in particular where the paths go through multiple slope changes along the route. In addition, ArcScene allows for complex line symbology, which is integral to displaying the least cost paths as some of the modeled paths are split into several branches. ArcScene's animation capacity for moving an object along a path would also be useful for visualizing traversing the path from the origin to the destination.

Overall, this study was successful in achieving its stated goal of generating least cost paths between Tikal and some of its rival sites. The use of Tobler's hiking function to simulate the cost-effort caused by changes in the steepness of the terrain produced credible routes through the Maya Lowlands that could plausibly function as paths along which the warring parties might travel. Further least cost path analysis may be able to expand on this study using the suggestions for future studies outlined above.

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