

Spring 5-10-2014

GIS Least-Cost Route Modeling Of The Proposed Trans-Anatolian Pipeline In Western Turkey

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GIS LEAST-COST ROUTE MODELING OF THE PROPOSED TRANS-ANATOLIAN PIPE-
LINE IN WESTERN TURKEY

by

AUSTIN KELLY

Under the Direction of Timothy Hawthorne

ABSTRACT

The routing of the Trans-Anatolian Pipeline plays an important role in the future energy security of the European Union. The natural gas pipeline is planned to run from the natural gas fields in the Caspian Sea through Turkey. This project is a case study for a Geographic Information System (GIS) least-cost route analysis of a section of the proposed pipeline in Western Turkey. The route analysis comprised of weighting multiple types of criteria in a compiled risk assessment map that was analyzed by a least-cost algorithm to display the least hazardous route through the study area. Multiple varieties of criteria were considered such as, lithology, slope of terrain, environmental and social risk factors, e.g. proximity to natural reserves and urban centers, to provide the least hazardous route through the region. The derived least cost paths were more efficient than the proposed route in the relative cost associated with each route.

INDEX WORDS: GIS, Trans-Anatolian, pipeline, Least-cost analysis, Routing, GIS analysis, Natural gas, European Union

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AUSTIN KELLY

A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of

Master of Science

in the College of Arts and Sciences

Georgia State University

2014

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AUSTIN KELLY

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Office of Graduate Studies

College of Arts and Sciences

Georgia State University

May 2014

DEDICATION

I would like to dedicate this thesis to my mother for it was her that taught me everything I know in life. Without her guidance I would not have become the man I am today. Through the ups and downs you have always been there to help me persevere and overcome. I cannot thank you enough for everything you have done. I love you, Mom.

ACKNOWLEDGEMENTS

I would like to thank all of the Georgia State Department of Geosciences Faculty that have helped me along the way in this project. I especially would like to acknowledge the support and guidance of my committee chair and members, Dr. Timothy Hawthorne, Dr. Jeremy Diem, and Dr. Lawrence Kiage. I would also like to thank the support from all of my friends and family.

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1 PROJECT SUMMARY

1.1 Geo-Political Background and Least-Cost Analysis

The geo-political tensions between Russia and the European Union (EU) over the routing of newly discovered Caspian gas from Azerbaijani, Turkmen, and Iranian fields is a current topic of great importance in European Union energy security. The Trans-Anatolian natural gas pipeline (TANAP) aims to connect Caspian Sea natural gas to Southeastern Europe via Turkey. This pipeline will allow the EU freedom from Russian and Ukrainian gas sources, which have plagued the European Union in recent decades by controlling prices and limiting the supply to the continent (Erdogdu 2010; Varol Sevim 2013; Stern 2006). This study demonstrated a strategic GIS least-cost routing analysis of a determined geographic area through which a section of the pipeline will pass through Western Turkey. The route model determined the most economically and environmentally safe route through the given geographical area by taking into consideration geological, environmental, and social hazards. By incorporating these multiple criteria (lithology, slope, population density, environmentally sensitive areas, and geologic hazards) this study provides a case study for which future large-scale projects can plan simultaneously, the most economical and least hazard prone route.

Major criteria that were considered in the GIS analysis are geologic factors such as, lithology, proximity to faults, slope, and landslide susceptibility. These factors were implemented alongside environmental and social factors such as: proximity to water bodies, proximity to dense urban areas, and the proximity to areas of high biodiversity. The data was compiled through multiple sources such as United States Geological Survey (USGS) databases, EuroStat, American Geosciences Institute (AGI) databases, and other international GIS repositories dis-

playing physical features of the region. The methodology used to determine this model was referenced from multiple scholarly articles and includes the use of the ESRI ArcGIS Cost Path tool. All criteria were compiled into an ArcGIS geodatabase and rasterized to be given a specific hazard weight. Each criterion's weight factor was combined together through the use of a Boolean query to provide a risk assessment map of the geographical study area, which was then used by the Cost Path tool specified earlier to produce the best route. The final result included multiple route maps of the planned pipeline displaying the most economical and least hazardous route through the specified geographic study area and provided an innovative new case study to further advance Geographic Information Science by incorporating both physical and environmental risk factors.

1.2 Study Region

The study region for this thesis is shown in Figure 1 below and covers an area of 150,960 square kilometers. The study region is located in Northwestern Turkey and includes the major metropolis of Istanbul and the Sea of Marmara. This area represents the extreme western portion of the Trans-Anatolian Pipeline where it will eventually connect to other major pipelines on the Greece-Turkey border and Bulgaria-Turkey border. The economic hub of Istanbul and the major shipping lane from the Black Sea to the Mediterranean via the Turkish Straits are located within this region. This congested and vital shipping lane is one key reason why this area was chosen for this thesis.

This shipping lane handles enormous amounts of tanker traffic moving both oil and natural gas from Russian ports on the Black Sea coast to the Mediterranean to be sold in Western Europe. The TANAP Project plans to alleviate some of this traffic through the straits by bypassing Istanbul and routing the pipeline under the Sea of Marmara.

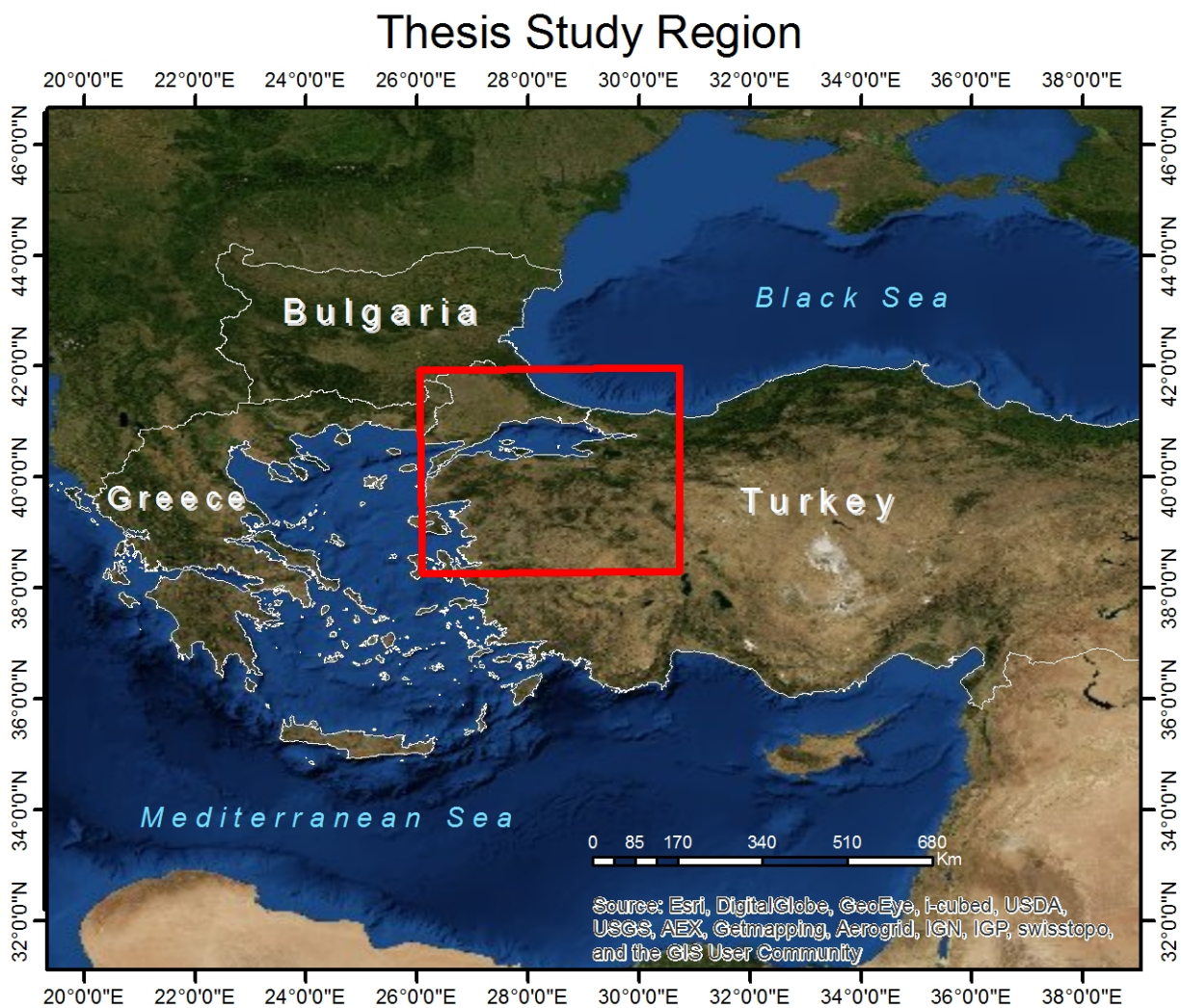


Figure 1. Red rectangular outline details the thesis study region and the maximum extent of the cost accumulated surfaces.

Within this study region extent each of the criterion rasters were created. Figures 2 through 4 display the criterion rasters for three of the five criteria that were assessed in this thesis. The criterion rasters display the reclassified values for each raster where the red locations correspond to the areas of highest risk for that specific criterion and areas of green correspond to areas of lowest risk. The color spectrum for these figures indicating highest risk to lowest risk is from red to orange to yellow to green.

Slope Criterion Raster

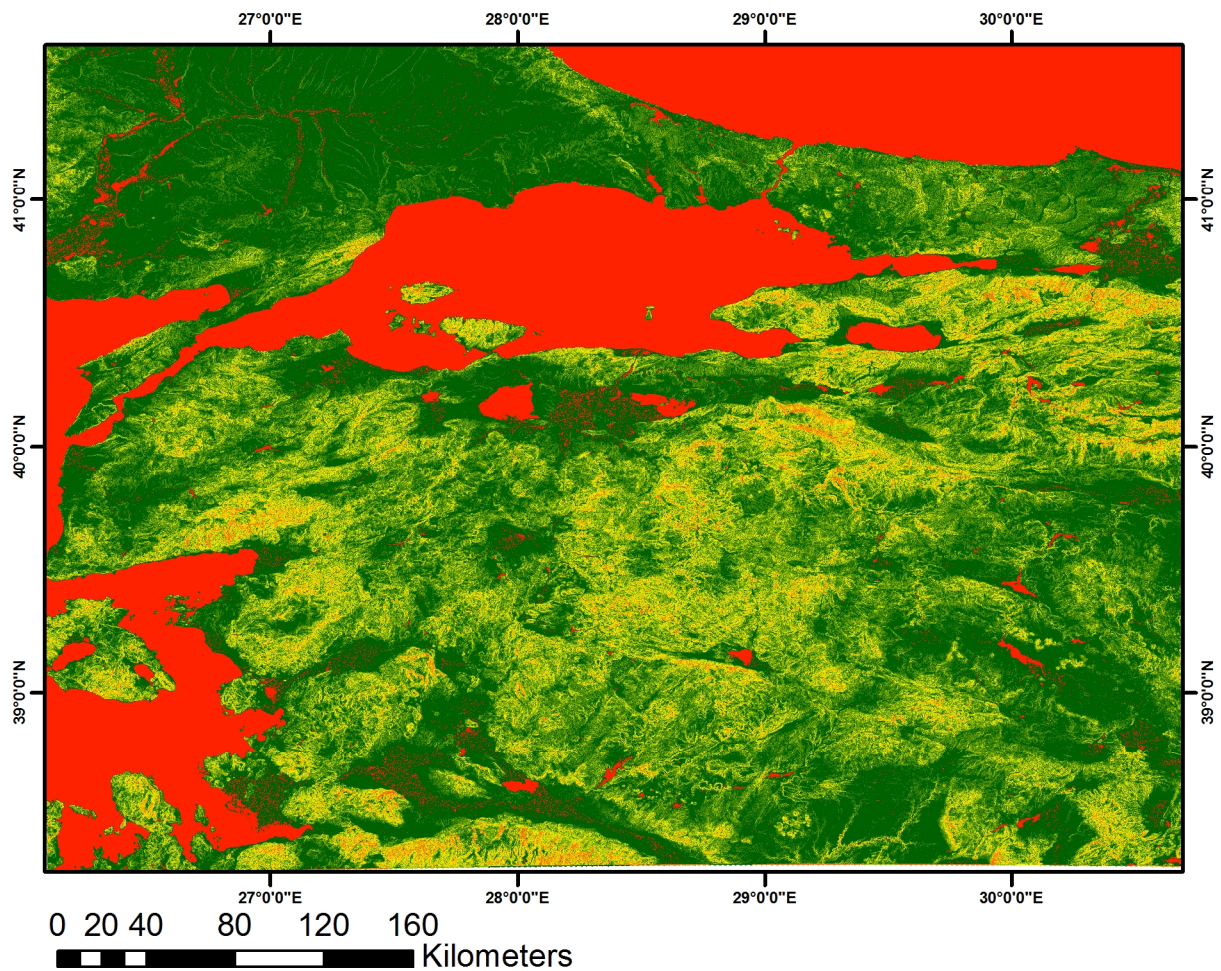


Figure 2. Slope criterion raster for the study region where red areas equal areas of high risk and green areas equal areas of low risk. Areas of zero slope have also been included in the areas of high risk as they indicate water bodies.

Population Criterion Raster

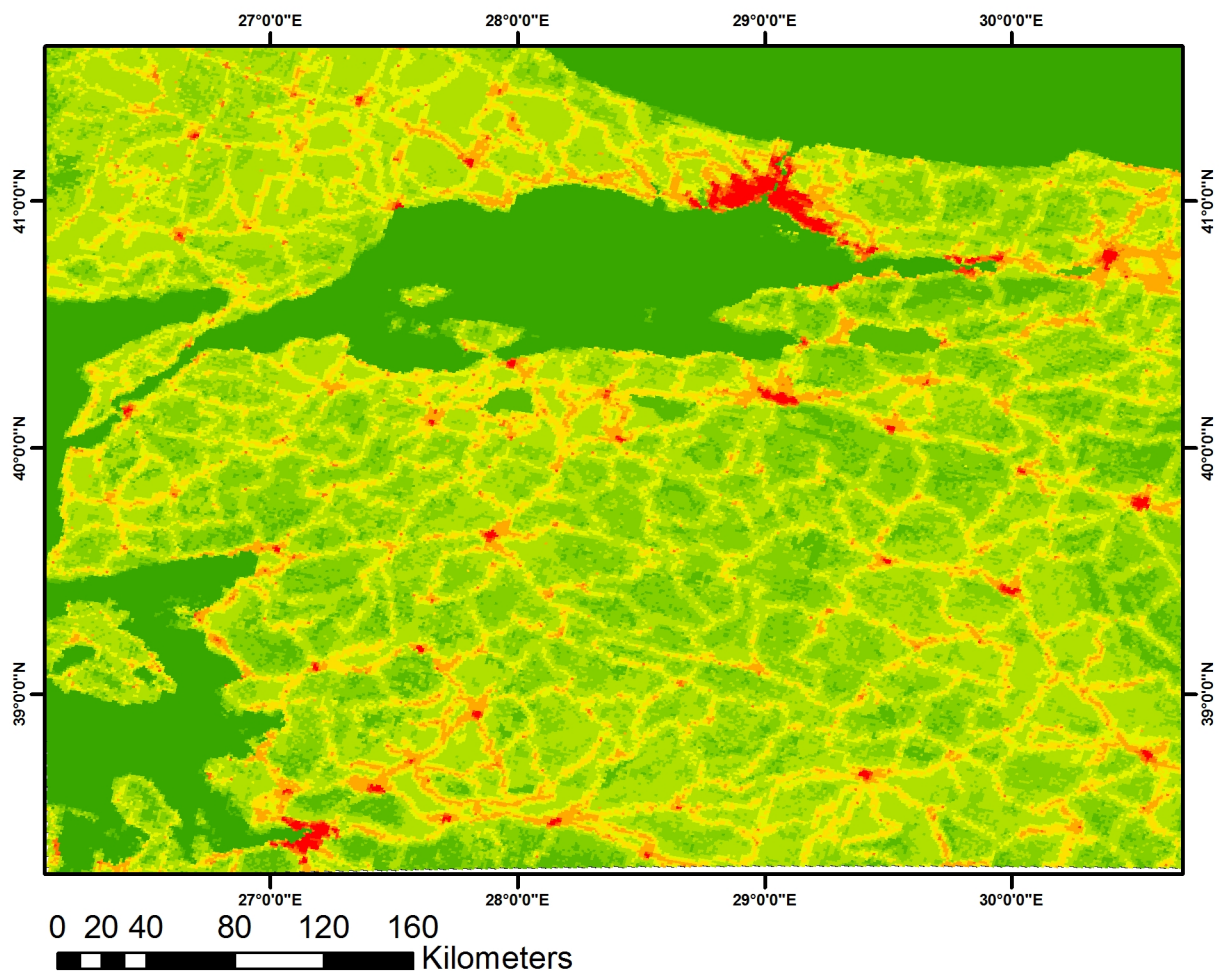


Figure 3. Population criterion raster representing the population density throughout the study region. Red areas indicate areas of high population density and green areas represent areas of low population density.

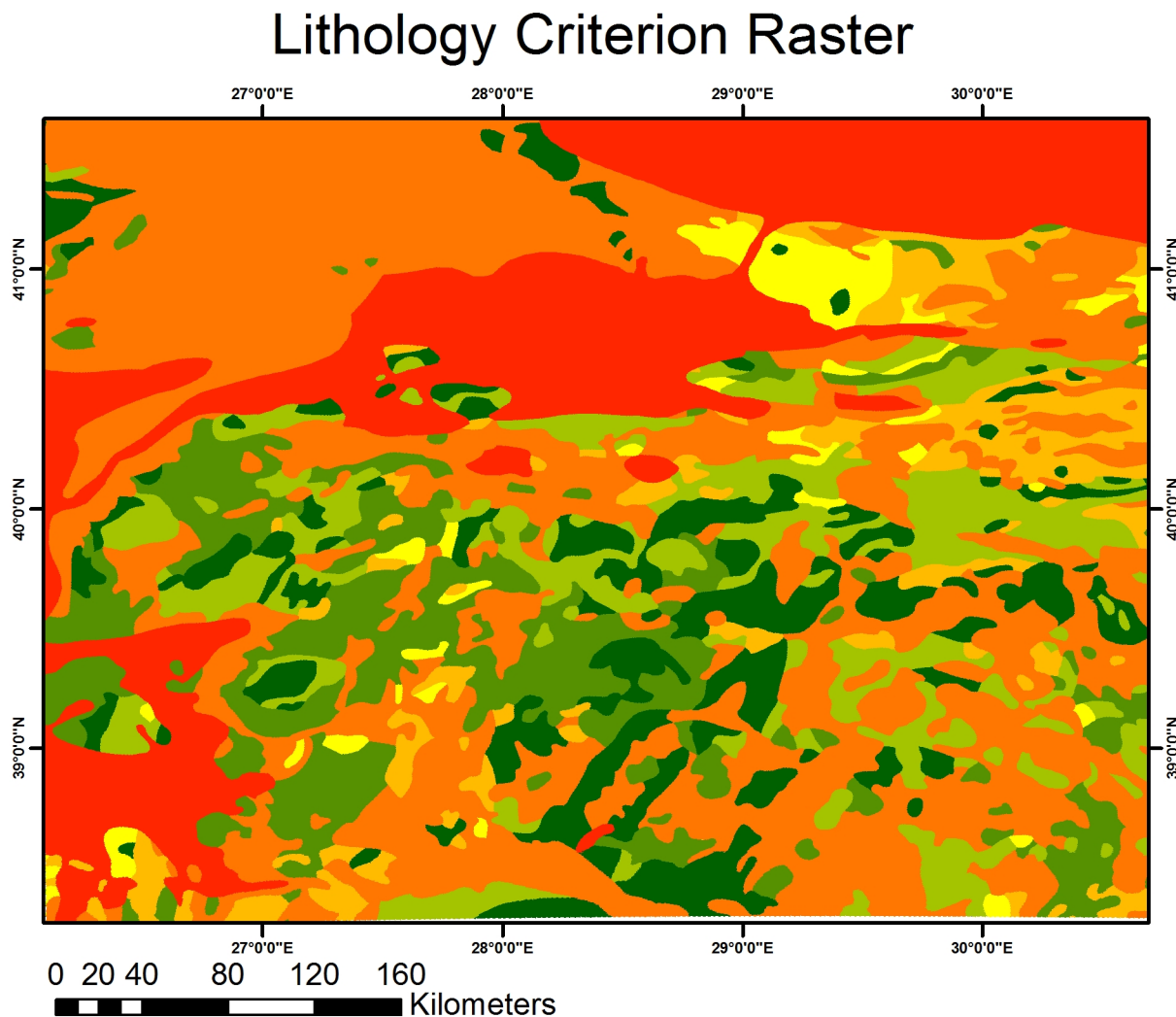


Figure 4. Lithology criterion raster displaying the different lithologic units within the study area. Red indicates units of high risk and green represents areas of low risk.

As of March 2013 the proposed route of the TANAP project was compiled by Cindar Engineering and Consulting Inc and displayed in Figure 5 (“Environmental Independent Assessment Application” 2013). This proposed route of the pipeline was used to compare the least cost paths that were created to determine their validity. More detail on this proposed route will be discussed in the Results section of this thesis.

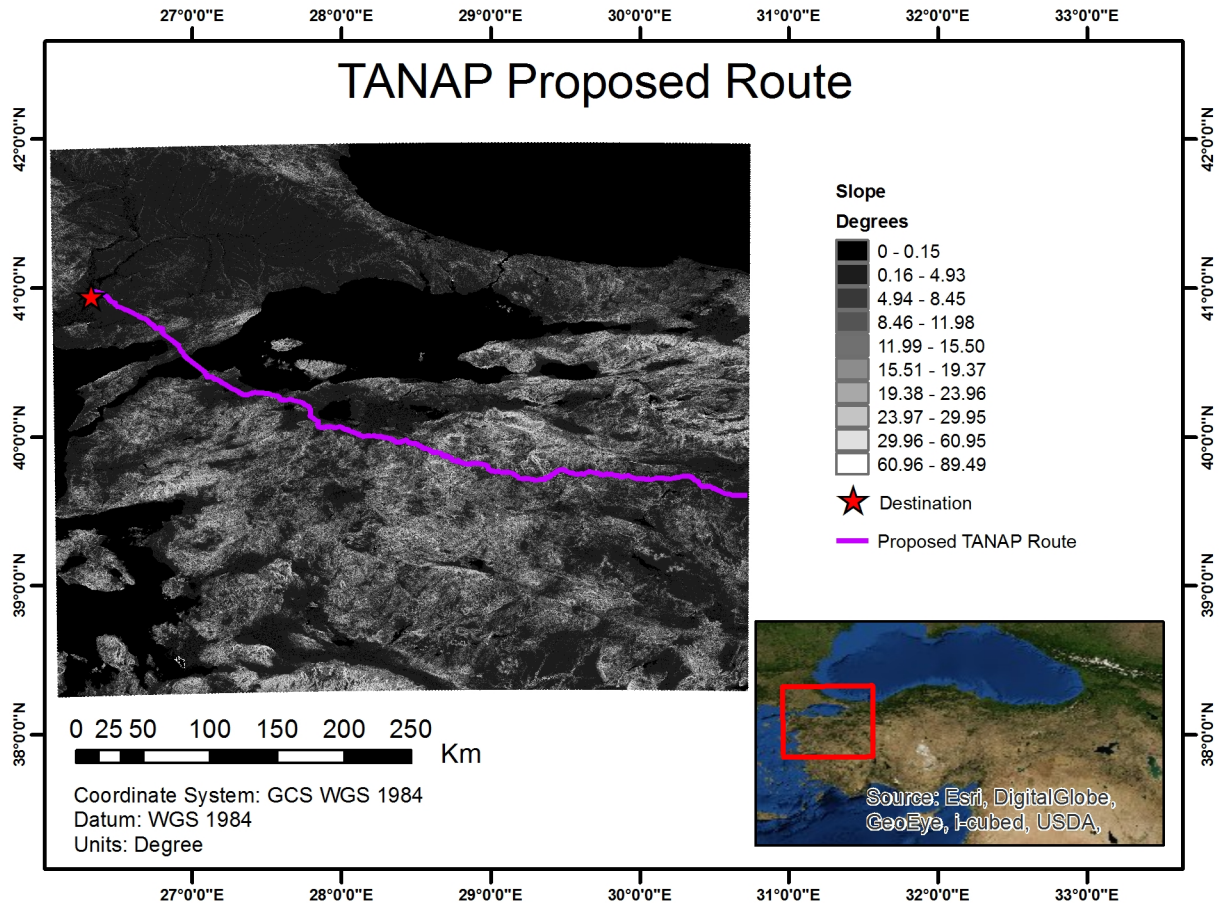


Figure 5. Proposed TANAP route overlain onto the slope raster of the study area. Route was compiled by Cindar Engineering and Consulting Inc.

2 INTRODUCTION

2.1 Purpose of the Study

With its already high demand for natural gas set to increase in the next few decades, the European Union is at a crossroads in determining from where it will import its natural gas (Omonbude 2009). At the current state, Russia accounts for the largest exporter of natural gas to the European Union, as it holds the world's largest natural reserves and is conveniently located geographically to the east. The easiest and most economical transport routes and techniques involve the use of pipelines to transport and carry pressurized gas from the production fields locat-

ed around the Caspian Sea and more recently the Yamal Peninsula to markets in Europe (Gazprom 2011). Liquefied Natural Gas (LNG) transported through the use of specific LNG tanker ships offers the other main option to transporting natural gas but due to extremely high costs of refining and construction of LNG terminals the pressured pipeline transport remains the most favorable. These LNG tankers also pose a specific problem for this particular route due to the chokepoint that occurs within the Turkish Straits and therefore are not considered to be a viable option (Cemal&Güven et al. 2008; Bolat and Yongxing 2013). The Russian natural gas pipelines are primarily routed through the country of Ukraine to provide the quickest access to main gas terminals in Central Europe. In the past decade numerous disputes over transit fees and the pricing of gas through these pipelines led the Russian government to shut off the supply of gas resulting in massive shortages throughout Europe (Stern 2006). This high profile political incident led the leaders of the European Union to begin to diversify their imports of natural gas from other markets in order to have stable sources of natural gas (Guili 2008; Baev and Øverland 2010). Recent discoveries of large natural gas fields in the Caspian region in Azerbaijan, Turkmenistan, and Iran have become the focus of European leaders, with the main route of transit being through the Anatolian Peninsula (Varol Sevim 2013; BP Exploration Ltd. 2013). The most prominent project that is being proposed is the Trans-Anatolian Pipeline linking the Caspian gas fields to the transit pipelines in Southeastern Europe (Erdogdu 2010). This pipeline will eventually have the capacity to transport up to 60 billion cubic meters (bcm) of natural gas per year into the European Union and bypassing Russia and Ukraine completely (“TANAP – Trans Anadolu Doğal Gaz Boru Hattı Projesi | 2 Devlet, Tek Millet!” 2014).

This thesis addressed the next key phase in the Trans-Anatolian Pipeline production, which is the route that the pipeline will take through the Western Anatolian Peninsula. The rout-

ing of this pipeline is of great importance in the final investment costs of the project due to the fact that pipelines are static infrastructure features and are therefore more susceptible to damage from natural hazards. The costs of pipeline failures, both financially and environmentally, are enormous and can easily shut down a project like TANAP (Brody, Bianca, and Krysa 2012; Hindery 2004; Yang et al. 2010). Thus, the GIS analysis of the region and the use of this analysis to determine the least hazardous and most cost effective route are of great importance to the completion of the pipeline. The least-cost route model that was developed through this project displays more efficient routes for the Trans-Anatolian Pipeline through this region based on the most readily available data for each specific criterion.

It is pertinent to point out that in this study the “least cost” route is designated by the least hazardous route across the physical features of where the pipeline will be located not the construction costs of these locations. The calculated cost value of the route by the model should be regarded as relative to the costs associated with the pipeline in the long term.

2.1.1 Research Questions

There are three research questions that were answered with the development of this routing model. They are as follows:

- 1) What is the least hazardous route for the Trans-Anatolian Pipeline through the study region within Western Turkey?
- 2) What criteria are the most influential in costs of routing this pipeline?
- 3) When comparing the official proposed route to the experimental results of this thesis, how relevant and viable are the experimental results that were obtained?

2.1.2 Literature Review

Large-scale linear projects, such as natural gas pipelines, are planned and designed around a concise route to limit the costs and materials of production. The most efficient process to determine this route is through the use of GIS and a least-cost routing model (Aissi, Chakhar, and Mousseau 2012; Rees 2004; Feldman et al. 1995). Current GIS techniques allow for large amounts of cost-analysis data to be collected, stored, and analyzed and thus improve the route accuracy for large-scale projects (Luettinger and Clark 2005). Through the research of multiple studies such as, Feldman et al. 1995 and Saha et al. 2005, the methodology was formulated to create these least cost models for various criteria evaluations and to incorporate multiple criteria into one least cost model. The complexities of the least cost model have limited the categories of criteria that have been examined. Most of the criteria examined have been physical characteristics of the given geographic area due to the more straightforward approach to weighting the variations of a specific factor (Atkinson et al. 2005; Collischonn and Pilar 2000; Saha et al. 2005; Aissi, Chakhar, and Mousseau 2012). Very few studies have included the biological impacts when determining the routing of a pipeline and included those criteria into the model. One, Lovett et al. 1997, used a least cost model to route hazardous waste through specific paths and provided a risk assessment due to biological hazards such as population and environmental risk (Lovett, Parfitt, and Brainard 1997).

Questions on how to develop a process to determine the shortest and least costly routes have had scholars analyzing different techniques for many years. One of the first academics to provide a solution to the problem was Edsger Dijkstra who developed an algorithm to determine the shortest path between two points connected in a network (Dijkstra 1959). This algorithm is one of the key pieces that is included in most least-cost routing models. Along with a cost-

accumulated surface the algorithm is able to selectively choose the least costly route through a given area. This type of analysis focuses on the neighborhood of cells around the proposed starting location and moves outward from that location to eventually encompass the entire study area. There are many types of patterns that the algorithm can take to create the cost accumulated surface, with each different pattern offering a different approach to solve the problem at hand (Iqbal, Sattar, and Nawaz 2006; Luettinger and Clark 2005). The Dijkstra Algorithm is one of the most commonly used tools to determine the least cost route through a surface and one of the simplest methods. This is due to the fact that once all of the criteria are compiled together into a cost accumulated surface the algorithm need only analyze the nodes across the surface. One limitation, however, to using this type of algorithm is that it is computationally demanding and produces large amounts of data to be stored (Saha et al. 2005).

In order to improve on this computationally demanding process that was used more and more companies began to develop new GIS extension packages to limit computation time and also expedite results. The Environmental Systems Research Institute (ESRI) extension, PATHDISTANCE, uses a smaller scale neighborhood analysis in order to try and control the effects of the model and make the path created more realistic (Saha et al. 2005). In effect the use of this smaller scale would make the compiled path less erratic and much more smooth. This is key when planning pipeline route design due to the fact that a pipeline is connected together much more rigidly than, say, a road. Extensions, such as PATHDISTANCE, became much more prominent in studies due to their accessibility and this option to create much smoother designs. Although their downside was that the limitation of the neighborhood analysis meant they could not accurately predict points in mountainous areas (Saha et al. 2005). The rapidly changing topography would be generalized too much in the cost accumulated surface for an accurate assessment

of the route to be determined. Therefore for these types of areas alternative methods must still be applied. In recent years ESRI has developed more complex cost path extensions and included them in their main ArcGIS products. One of these extensions that have been of significant use is the Cost Path tool. This tool allows for the creation of both a Cost Direction surface as well as a Backlink surface that are then used alongside the main Cost surface to determine a more accurate and precise Cost Path from a source point to a destination point, all the while calculating the cost that the path acquires across the surface (Collischonn and Pilar 2000; Rees 2004).

Real world case studies have been performed to determine the least cost routes of major pipelines and are mainly funded by major operators in the industry. In the studies researchers utilize both remotely sensed and GIS data to develop the necessary criteria for analysis. The Bechtel Corporation in its analysis to develop a route for a proposed pipeline in the Caspian Sea region provided one such case study. The researchers factored in criteria from the terrain, land use, geology, etc. through the use of geospatial data sets (Saha et al. 2005; Feldman et al. 1995). The use of remotely sensed data allows for areas all over the globe to be examined and evaluated without the researchers physically traveling to the specified location. The costs associated with the construction in each specific criterion were determined from a previous study that was unpublished by Bechtel, allowing the researchers to obtain a greater accuracy on the actual real world costs. Factoring into these costs were also the environmental and future liability costs should the pipeline be located within areas that were deemed likely for future hazards to occur, e.g., close proximity to faults, river/stream crossings (Feldman et al. 1995). Feldman et al. 1995 is one of the first studies to actively integrate these types of criteria into the least cost routing model due to the availability of remotely sensed and previously researched cost data. Through the use of ESRI's ArcGIS software package, the route that was proposed was 9 km longer than

the straight line path but 14% less costly to construct (Feldman et al. 1995). This offers a case where the least cost route can be examined efficiently through the use of geospatial data.

View-shed analysis offers another approach to determine the least costly routes through a specified area (Lee and Stucky 1998). The same general methodology that is discussed earlier in this thesis is used in creating a cost accumulated surface and a least cost algorithm or program extension is used to calculate the least costly route through that surface. In using view-shed analysis by Lee and Stucky 1998 a digital elevation model (DEM) was used to select types of paths through the study area based on visibility. While this model is useful for environmental planning and civil engineering, when tested for pipeline construction, the analysis returned results that were infeasible for construction (Lee and Stucky 1998). This specific study also did not factor in other factors that would have accounted for this problem such as geology, terrain, and land use (Saha et al. 2005; Lee and Stucky 1998). Therefore for pipeline routing and the focus of this thesis, view-shed analysis was not incorporated into the methodology when developing the least cost path for TANAP.

Other studies that have been done more recently focus on the costs of crossing water bodies and the built environment (e.g. roads, bridges, etc.) and on the slope of the terrain (Iqbal, Sattar, and Nawaz 2006). The area analyzed in the research by Iqbal et al. 2006 was again in a very mountainous region of northern India, where the changing gradient of the terrain in short distances played a key part in determining where a pipeline could be located. The criteria that were analyzed were first reclassified through a Spatial Decision Support System (SDSS) in order to make the entire system more result oriented and simpler to process (Iqbal, Sattar, and Nawaz 2006). The result of the study displayed that while the least cost route was 1 km longer than the existing pipeline in the area, it was 29% less costly to construct. The use of the least cost model

accurately displayed a more economical route and can be integrated into many other fields such as the planning of water/sewer pipelines which also require economical route planning (Iqbal, Sattar, and Nawaz 2006).

Other linear features similar to natural gas pipelines that have used least-cost routing models to more accurately plan economic routes are roads and canals. With these features the impact of topography is very important, especially in canals, and influences the cost accumulated surface by making the weighting values direction dependent. With this specific requirement the algorithm used to process the cost accumulated surface must be adapted to accommodate this restriction (Collischonn and Pilar 2000). This type of restriction seems to be more prevalent in areas where the topography is fairly consistent due to the fact that the algorithm must employ a function describing the slope into its calculations.

These past studies have employed methodologies to obtain the same result of a thin route that is created by linking individual cells from the cost accumulated surface together from the starting point to the destination. The process of also incorporating a specified path width to the route selection process is advantageous when the proposed route is required to be wider than one of the raster cells used in the cost accumulated surface (Gonçalves 2010). This method of routing uses an adapted algorithm with a larger moving window to incorporate the expanded route width. This type of routing can drastically alter the most economical route through a surface due to the restricting parameters but allows planners to develop routes that include specific sizes of easements or right of ways that accompany most major projects, especially pipelines (Gonçalves 2010). With this type of routing planners are able to incorporate right of way distances into their calculations and obtain the most accurate results possible.

This review clearly demonstrates the multitude of applications that GIS based least cost routing has in the planning of major linear projects. Past and current developments through updating algorithms and applying more diverse criteria into a cost accumulated raster allow least cost routing extensions in multiple GIS platforms to efficiently assess the criteria and display the most economical and least hazardous route through a given geographical area. New advancements in GIS and remote sensing technology have allowed researchers to incorporate multiple categories of data such as topographic, environmental, and geological data to more accurately and realistically predict the costs associated with routing linear features such as natural gas pipelines.

3 EXPERIMENT

3.1 Methods and Data

In order to apply least-cost routing models to an area, geospatial datasets are required to assess the multiple criteria that will be evaluated. These maps need to be of a high enough resolution to accurately display the changing topographic and geologic features in the area. In this area of Western Turkey the Digital Elevation Model (DEM) that was used was downloaded from the NASA JPL Shuttle Radar Topography Mission (SRTM) and had a resolution of 90m cell size. This DEM and resolution was used due to its availability to cover the entire study region and keep the storage size of the raster files low. Due to the large geographic extent of the study region a finer resolution DEM would have created large raster file sizes that are not easily manipulated within ArcGIS. The DEM scenes were mosaicked together in one continuous raster surface covering the entire study area using the Mosaic tool in ArcGIS. Sinks and holes in the data were filled through the use of the Spatial Analyst Extension within ArcGIS in order to dis-

play more accurate results This filled DEM surface was then used to create a criterion raster displaying the slope of the terrain over the geographic area that was studied through the use of the Spatial Analyst toolbox within ArcGIS. This criterion and the other four criteria rasters were then projected in the Lambert Conformal Conic Projection with the median latitude 30° N due to the location of Western Anatolia around the mid latitudes. This projection of the data ensured that it was skewed as little as possible. This type of projection must be performed for accurate measurements due to the elliptical shape of the earth and trying to accurately project points from this ellipsoid onto a planar surface. The conformal aspect of the projection ensured that the accuracy of the distances that were measured would not be compromised. All of the criteria rasters were compiled into a personal geodatabase to later be combined into a cost accumulated surface. The creation of these criteria rasters were completed in order to reclassify and rank the different costs associated with each specific criterion. When reclassifying and ranking the created criteria rasters the scale from 0-10 was used where 10 would indicate the highest cost value and 0 the lowest. This scale was used both for simplicity and for the ability to easily recognize high/low cost areas visually on the cost accumulated surface when all of the criteria rasters were combined together. For example, steeper slopes are much more hazardous and difficult to construct large linear features; therefore, the areas encompassing the steepest slopes were assigned the highest values in the output raster (Rees 2004). The determinants for the specific rankings for each criterion was done arbitrarily but referenced specific case studies such as Feldman et al. (1995) and geotechnical engineering reports that related to pipeline site evaluation (Topal and Akin 2009).

The geologic maps of the area of Western Turkey were extracted from a compiled dataset from the United States Geological Survey and the American Geological Institute from their database *Global GIS*. The dataset details the different geologic formations located within the area by

their different composition and age range. This geologic dataset was used to create the lithologic criterion cost surface, which displayed the lithologic hazards that are present within the study region. These formations were mapped at a scale of 1:1,000,000 (1 km grid cells) and formatted in a vector shape file. This shape file was first converted to a raster in order to display a continuous surface at the same spatial resolution as the slope criterion raster. The resulting raster was then clipped to the extent of the study region and reclassified on the same 1-10 scale and then stored within the personal geodatabase for accessibility. The raster that was created displayed the highest cost values in areas that contain geologically young, less consolidated lithologies (sandstones, shales, etc.) due to their instability and the lower cost values in areas that contain geologically old, harder, denser lithologies (igneous intrusives, volcanics, etc.) due to their higher stability and load bearing properties (Topal and Akin 2009; Paige-Green 2011). This is due to the fact that the ranking scheme was focused on the cost that would affect the pipeline due to natural hazards such as landslides, rather than the actual cost of construction within that specific lithology which coincides with the overall theme of the route model.

Water bodies were a critical criterion that was evaluated and derived from multiple electronic sources including the USGS/AGI dataset and the World Wildlife Fund's Global Lakes and Wetlands Database (GLWD). Within this shape file I also created features, which represented the geographic extent of endangered ecological habitats within the study region. The ecological habitats were referenced from the UNESCO World Database on Protected Areas (WDPA). This was done due to the fact that both of these criteria were to be reclassified the same way in the criteria raster. Similar to the lithologic criterion the water bodies' dataset was initially in vector format and first needed to be converted to a raster. The spatial resolution was set to the same as the slope and lithology rasters and the raster was clipped to the extent of the study area. The wa-

ter bodies' raster was then reclassified in the same 1-10 but much differently from the other criteria rasters. Since crossing a water feature or endangered ecological habitat is very hazardous and usually avoided at all costs when routing an overland pipeline every water body or environmental area within the study area was given a value of 10 (highest risk) within the criterion raster (Iqbal, Sattar, and Nawaz 2006; Saha et al. 2005; Feldman et al. 1995). All of the other areas in the criterion raster were given a value of 0 in order to not skew the results when calculating the cost accumulated surface. This value was also designated due to the spatial extent of these water bodies and ecological habitats. A value of NoData or null may also be used instead of 0. This criterion raster was also stored within the personal geodatabase for accessibility. From henceforth this criterion raster is referred to as Environmental Areas.

From the AGI datasets a population density raster with a resolution of 936 x 936 m cells was reclassified using the same 1-10 ranking system as the previous criterion rasters and clipped to the study area. Higher population density indicated a higher cost value as most highly urbanized areas do not allow natural gas pipelines to pass through and the hazard risk associated with a large concentration of people in close proximity to a pipeline is very high (Feldman et al. 1995). The spatial resolution of this criterion raster was not fined to the 90 x 90 m spatial resolution of the other criterion rasters (slope, lithology, environmental areas) due to the lack of reliable data that could be acquired at the finer spatial resolution.

Also within the AGI datasets a shape file detailing geologic faults within the study region was converted into a raster of the same spatial resolution as the slope criterion raster and clipped to the extent of the study area. Faults were reclassified the same way as the water bodies and environmental areas rasters in order to highlight the presence of the fault. The Northern Anatolian Fault Zone, which is located within the study region, is one of the most highly active right lat-

eral, strike-slip faults in the world and the displacement along the fault trace could easily sever a pipeline causing tremendous consequences both environmentally and economically (A. Okay 2008; Mattiozzi and Strom 2008; Wang and Yeh 1985; Krushensky 1980). Once reclassified the faults criterion raster was also stored within the same personal geodatabase as the other 4 criterion rasters (slope, lithology, environmental areas, population).

3.1.1 Accumulated Cost Surface Creation

In order to create the least-cost path two separate techniques were used when combining the criteria rasters. First, each of the criteria rasters were combined together with equal weighting where each of the 5 factors accounted for 20% of the influence in routing the pipeline. Each of the criteria had already been ranked on a similar scale and clipped to the same geographic extent therefore they could simply be added together using the Map Algebra tool within ArcGIS. Using simple map algebra each of the criteria rasters were added together so that each cell from the resulting cost surface was the sum of all the criteria costs at that specific geographic location. The final spatial resolution of the cost accumulated surface was equivalent to the coarsest criterion raster (population) and therefore was 936 x 936 m.

For the second technique, each of the five criteria rasters were arbitrarily weighted according to the impact that each criterion would have on the costs associated with the natural hazards that affect the pipeline. These weighting values were determined through the review of recent case studies discussed in the previous literature review and from relevant engineering reports that explain the typical siting specifications (Feldman et al. 1995; Saha et al. 2005; Bagli, Geneletti, and Orsi 2011; Aissi, Chakhar, and Mousseau 2012; “Environmental Independent Assessment Application” 2013). Therefore each criterion was weighted a specific amount and then

combined together again using simple map algebra creating a cost accumulated surface. All of the weights of the five criteria had to add up to account for 100%.

When arbitrarily weighting these five criteria into a weighted overlay I decided to highlight one criterion for each weighted overlay by designating that criterion to have the highest percentage of influence. Routes that were calculated from each weighted overlay could then be compared to the proposed pipeline route and the major contributing criterion could be correlated from the least skewed path.

The weighting scheme that was designed for the first weighted overlay cost surface detailed a heavy slope and topographic bias. This was due to the structural considerations that must be accounted for when routing a pipeline of this size and complexity. Furthermore the terrain that includes the steeper slopes are more likely to fail and cause landslides which are a major hazard within this geographical area (Gökceoglu and Aksoy 1996; Saha et al. 2005; Topal and Akin 2009). This overlay stresses the importance of the criterion of slope much more than the other factors.

The second weighted overlay cost surface takes into account the heavy population and environmentally sensitive areas and weights them higher than the other criteria. Locations with a very high population density were given the most weight to avoid a route through those areas as well as environmentally sensitive areas, which were given the second highest weighting.

The third weighted overlay cost surface was designed to take into account the underlying geology and the geological stability of the area. This weighting scheme was designed to highlight areas of high geologic hazards such as faults or unconsolidated sediments and avoid them when routing. These unconsolidated sediments were determined from the AGI datasets that provided lithologic composition and age.

The different weighting schemes allow for specific criteria to be highlighted with its importance in the costs associated with the route of the pipeline. The weighting schemes were arbitrarily constructed but were referenced from both past literature on the subject of pipeline routing and the current environmental assessment report that was compiled for this specific pipeline project (BP Exploration Ltd. 2013; “Environmental Independent Assessment Application” 2013; Iqbal, Sattar, and Nawaz 2006; Feldman et al. 1995; Topal and Akin 2009).

3.2 Least-Cost Routing Tool

After the creation of these cost accumulated surfaces the ArcGIS least-cost extension tool, Cost Path, was utilized to determine the least cost route through the given study area. Starting and ending points were assigned to the cost accumulated surface based on the current planned route of the Trans-Anatolian Pipeline that is available to the public (Varol Sevim 2013; “Environmental Independent Assessment Application” 2013). These points were located at Eskisehir, Turkey on the eastern boundary of the study area where the main pipeline decreases in size from 56 inches in diameter to 48 inches, and Kipoi, Greece on the Western boundary where the pipeline is planned to connect with the future Trans-Adriatic Pipeline (BP Exploration Ltd. 2013). While the diameter of the actual pipes are quite small compared to the scale of the study area the routing process takes into account the right of way (ROW) allocations on either side of the pipeline. The actual ROW that will be used for the construction is 36 m, but for the routing process a strip around 1 km wide was determined for small scale studies such as this one (“Environmental Independent Assessment Application” 2013).

From these source and destination locations the Cost Path tool located in the Spatial Analyst Toolbox in ArcGIS was used on each separate cost accumulated surface that was created.

The cost accumulated surfaces were input into the tool input window along with the starting and ending locations for the tool to then calculate the Cost Distance and the Backlink rasters for each cost surface. These Cost Distance and Backlink rasters were then used in conjunction within the Cost Path tool to create a linear path between the two points that highlights the least hazardous and thus least costly, route between the two points.

The created routes were compared to one another and also a straight-line path through the study area to determine the cost benefits of the analysis and to make sure that the routes were realistic. Multiple routes were created with differing weights for each criterion in order to see what geographic locations are most affected by each specific factor. The relative cost calculations that were derived from the tool were also compared to one another to identify if the weighting system increased the costs associated with the pipeline or decreased them. Figure 1 displays the flow chart of gathering and editing the data, then implementing it into the Cost Path tool for the least-cost path analysis.

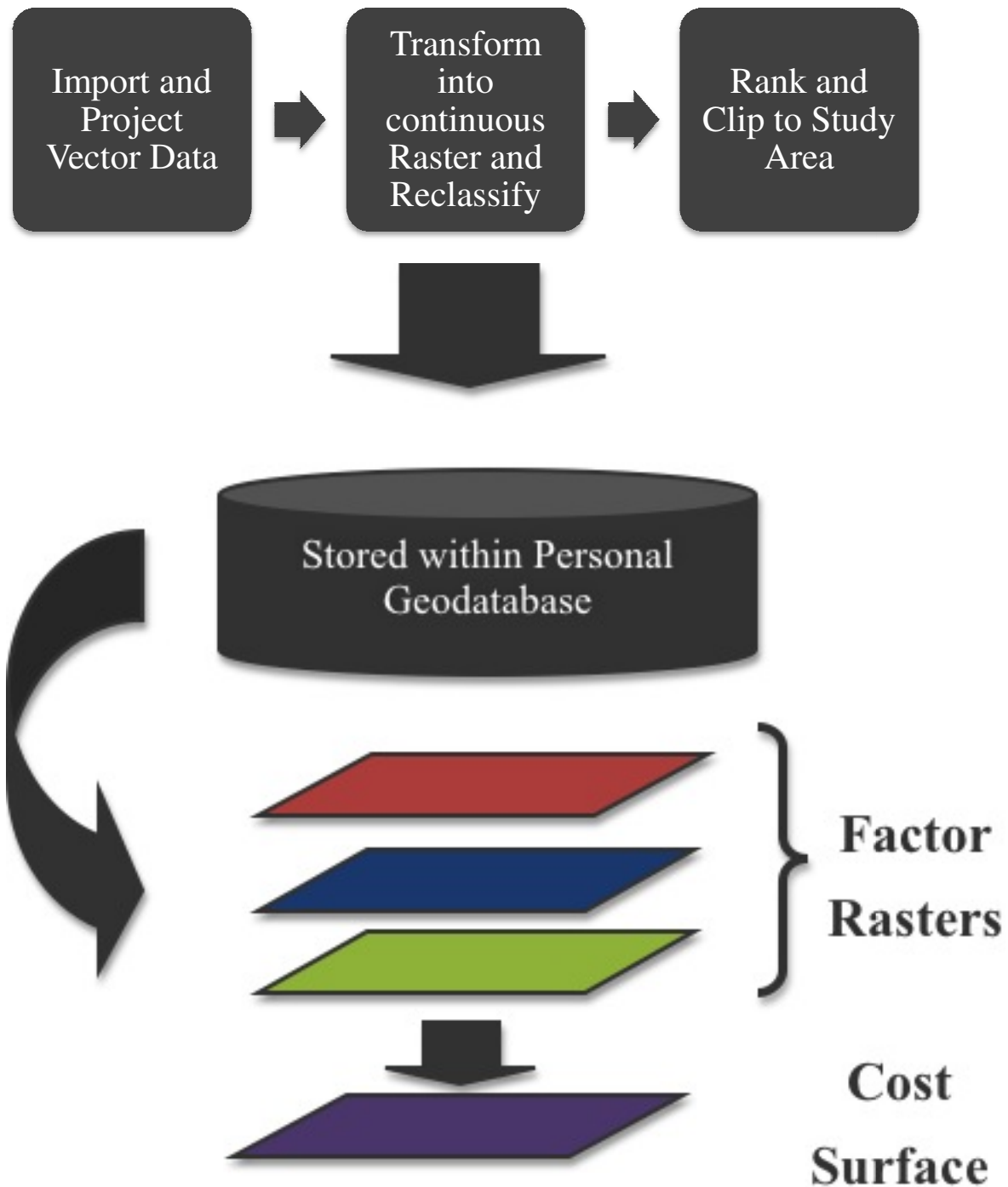


Figure 6. Process used to format each individual criterion into a continuous raster surface, and then combine those factor rasters into a cost surface. This info graphic details the process for the Equal Weighted Cost Surface. For the Weighted Overlays each factor raster was designated a specific weight percentage using the Weighted Overlay tool within ArcGIS, otherwise the main steps are identical.

4 RESULTS

4.1 Equal Weighting

The initial cost surface that was generated combined all 5 criteria (slope, lithology, faults, population density, and environmental areas) for pipeline routing equally where each criterion accounted for 20% of the total cost value per cell. The five factors as stated in previous sections generated a continuous cost surface across the study area that is displayed in Figure 7.

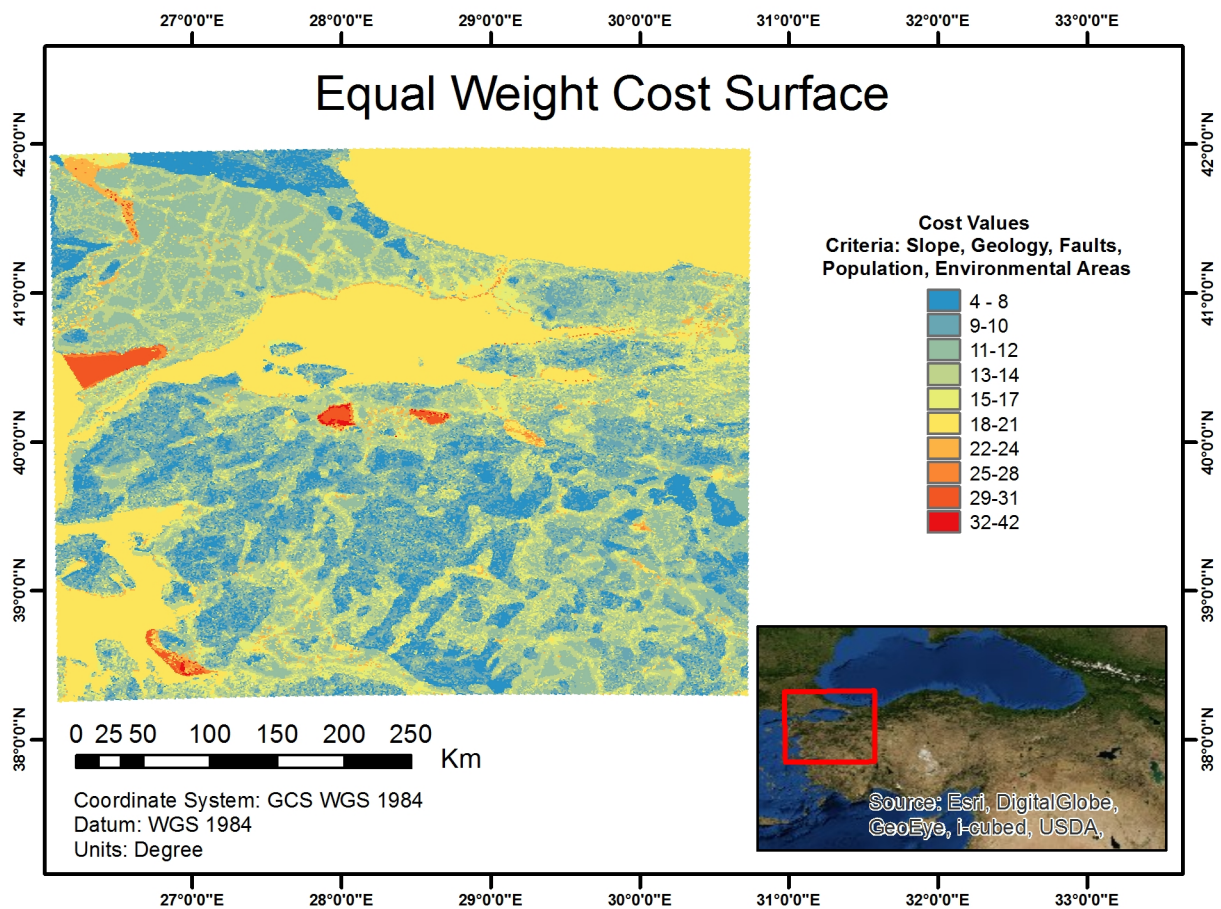


Figure 7. Equal Weight cost surface that was created for the study area. It was from this surface that the least-cost path was derived.

The least-cost path derived from this cost surface is displayed in Figure 8 with its main statistics of length and relative cost value of this route compiled in Table 1.

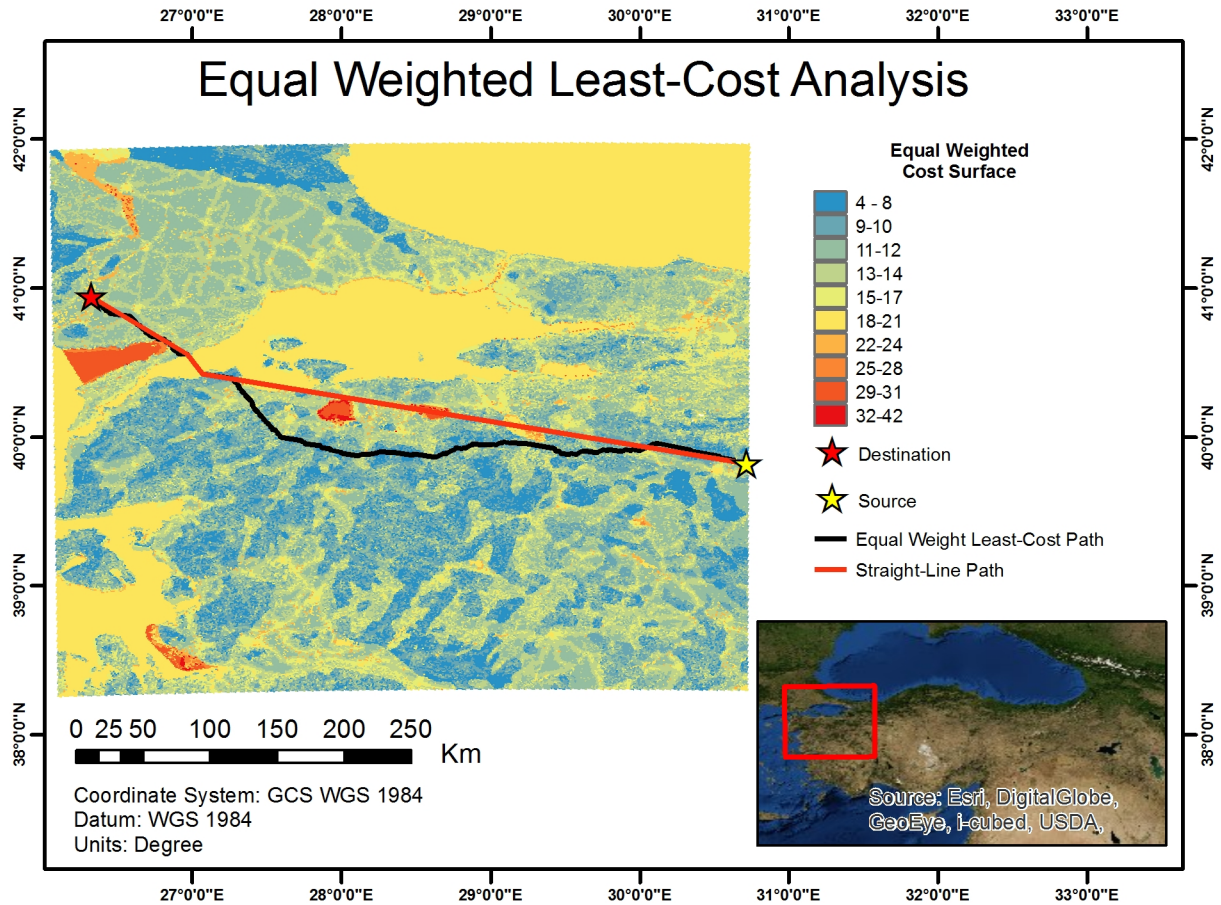


Figure 8. Least-cost route and straight-line path that was created for cost surface Equal Weights.

Table 1. Least-Cost Path and Straight-Line Path lengths in km and relative cost values using the Equal Weighted Cost Surface. GCS: WGS-84, Projection: Lambert Conformal Conic.

Route	Length (km)	Relative Cost	Percent Effective (LC Path/SL Path)
Least-Cost Path	441.00	4084	+37.93%
Straight-Line Path	392.24	6580	

The relative cost associated with the path cannot be used as a definite quantitative measurement of the cost of the pipeline but instead is a relative indicator of the risks associated with locating a pipeline along this route. When the cost associated with the path is compared to the

straight-line path cost that would be accumulated across the cost surface from the starting location to the destination, one can determine the percentage of relative risk that is avoided by the least-cost route and essentially the effectiveness of the least-cost route.

Table 1 displays the relative costs that are associated with each route and also the percent effectiveness that the least-cost path obtains when compared to the straight-line path across the same cost surface. The least-cost path is almost 50 km longer than the straight-line path but is 2500 units less in relative cost indicating that the least-cost path is 38% more effective.

In Figure 8 the highest risk areas that are displayed in red correspond to lakes and environmental preserves that are located within the study region. These regions are assigned higher risk values in the cost surface than other water bodies due to the fact that they are ‘doubly’ risky. These areas are represented as high risk for multiple criteria, environmental areas and being a water body. This is why they are of higher cost than the larger water bodies in the study region.

4.2 Weighted Overlay

Multiple cost surfaces were created using the Weighted Overlay tool in the ArcMap software that designated specific weights to each criterion. Table 2 below displays the weight amounts for each of the weighted cost surfaces that were created. Each Weighted Overlay surface that was created highlighted a specific criterion or criteria more than others to detail the impact that they had on the least-cost path.

Table 2. Weight Percentages for each criterion in all 3 Weighted Overlay Cost Surfaces.

Cost Surface	Criterion	Weight Percentage
Weighted Overlay 1	Slope	45%
	Geology	20%

	Population	15%
	Environmental Areas	10%
	Faults	10%
Weighted Overlay 2	Slope	25%
	Geology	15%
	Population	30%
	Environmental Areas	20%
	Faults	10%
Weighted Overlay 3	Slope	20%
	Geology	35%
	Population	10%
	Environmental Areas	15%
	Faults	20%

The figures below (Figure 9, Figure 10, and Figure 11) display the selected routes for each of the weighted overlay cost surfaces. The lengths and the associated relative cost for each path are detailed in Table 3.

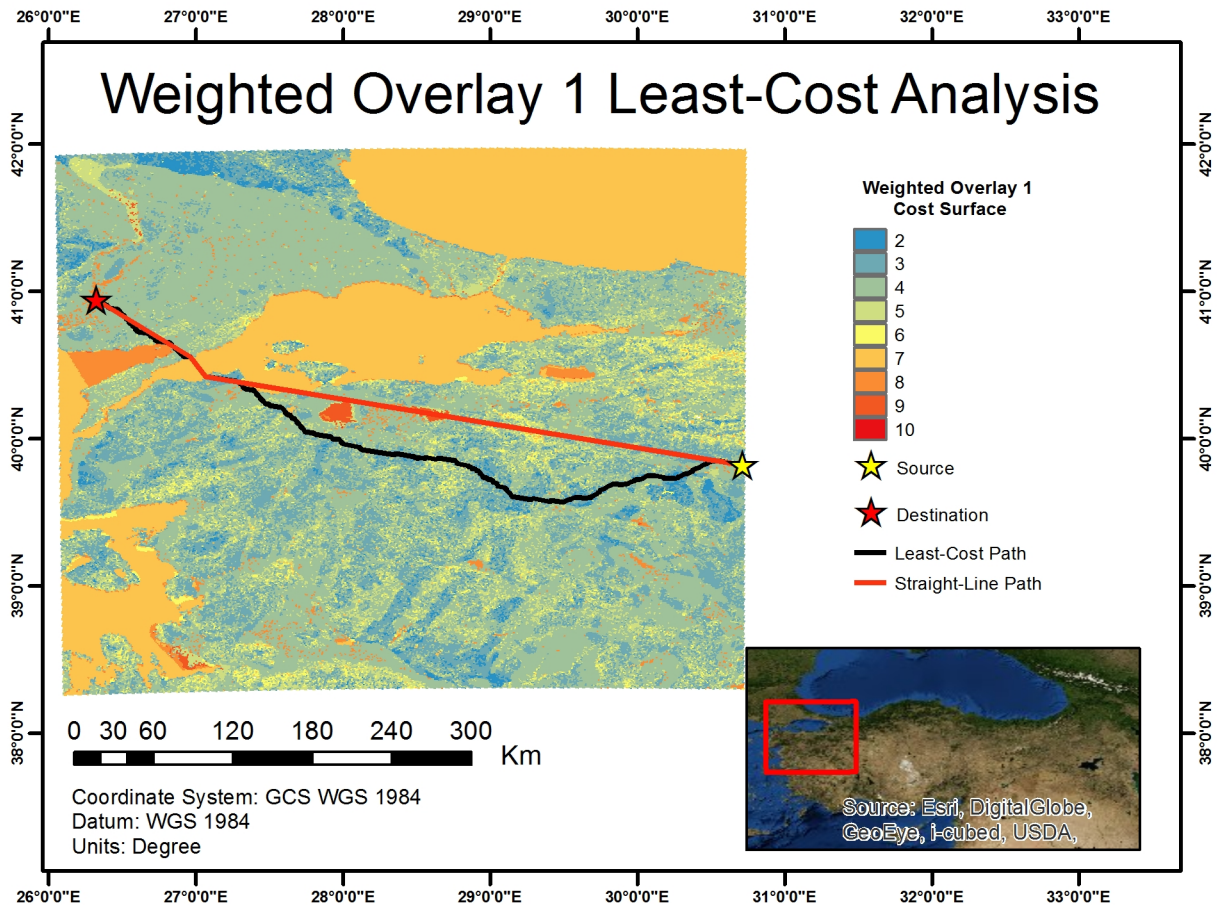


Figure 9. Least-cost route and straight-line path that was created for cost surface Weighted Overlay 1.

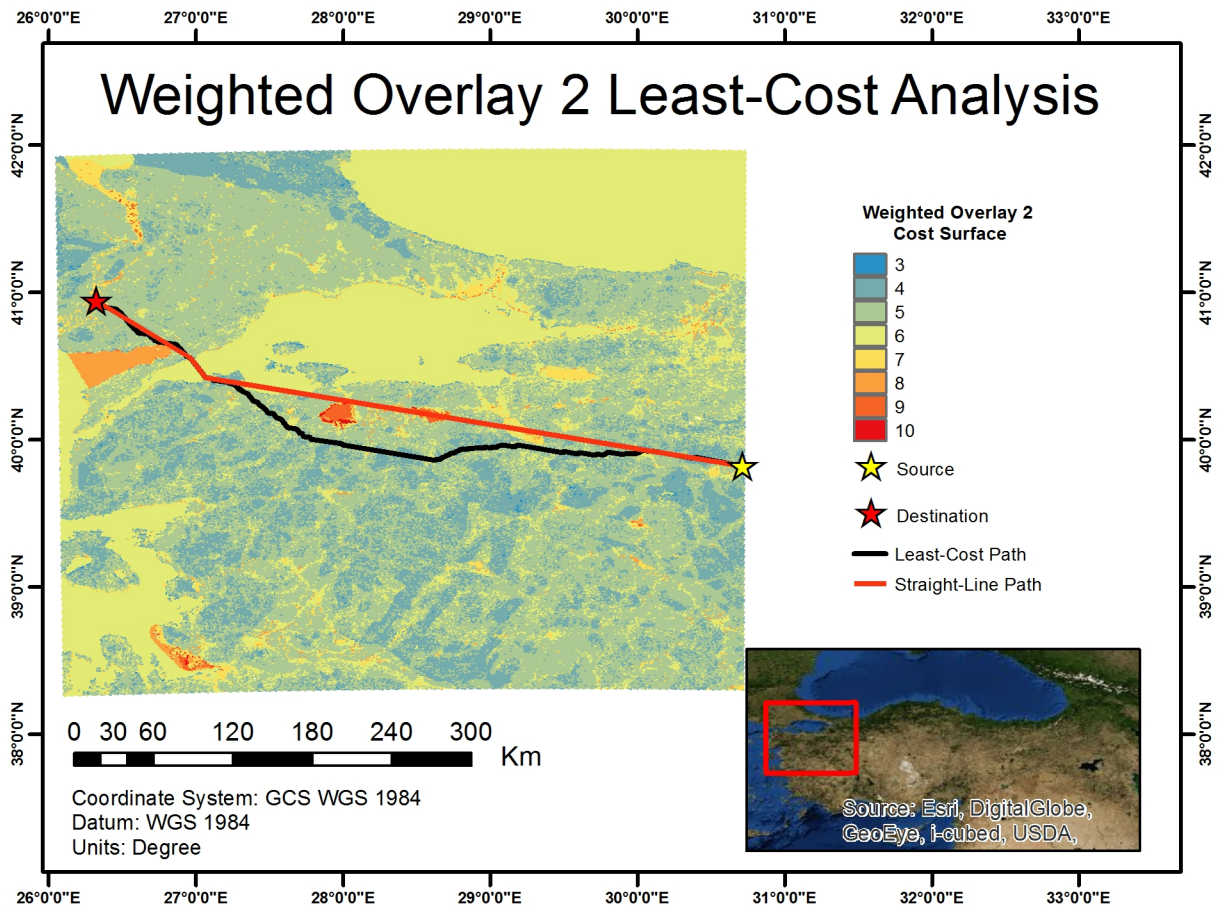


Figure 10. Least-cost route and straight-line path that was created for cost surface Weighted Overlay 2.

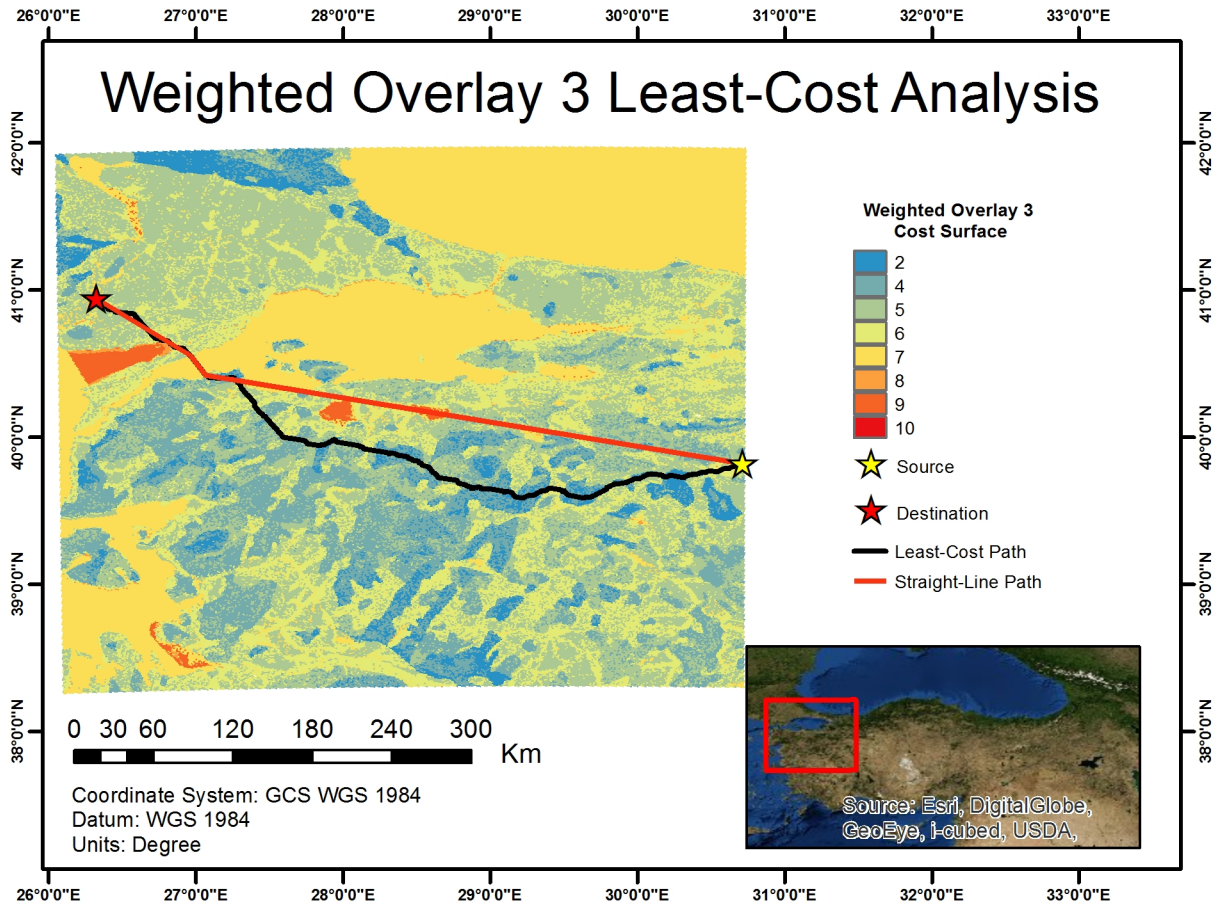


Figure 11. Least-cost route and straight-line path that was created for cost surface Weighted Overlay 3.

Table 3. Least-Cost Paths and Straight-Line Paths for each of the specified Weighted Overlay Cost Surfaces. Detailed lengths in km and relative cost values for each path on the respected cost surface. GCS: WGS-84, Projection: Lambert Conformal Conic.

Route	Cost Surface	Length (km)	Relative Cost	Percent Effective (LC Path/SL Path)
Least-Cost Path	Weighted Overlay 1	448.000	1349	+36.07%
Straight-Line	Weighted Over-	392.238	2110	

Path	lay 1			
Least-Cost Path	Weighted Over- lay 2	427.343	1848	+23.83%
Straight-Line Path	Weighted Over- lay 2	392.238	2426	
Least-Cost Path	Weighted Over- lay 3	460.391	1532	+38.96%
Straight-Line Path	Weighted Over- lay 3	392.238	2510	

The costs for the straight-line paths through each of these cost surfaces are higher than the costs for the least-cost paths, although the lengths of the least-cost paths are longer. By examining each Weighted Overlay surface one can see that the highest percent effectiveness was calculated from the third weighted overlay surface with its value of 38.96%. The third weighted overlay surface placed emphasis on the geological hazards within the area more so than any of the other criteria. This indicated that the major criteria for the routing in this study region were the geological hazards that are present.

4.3 TANAP Proposed Route

The main proposed route of TANAP was sourced from the Environmental Assessment Application that was compiled by Cindar Engineering and Consulting Inc. (“Environmental Independent Assessment Application” 2013). The 2749 GPS points that make up the entire pipeline length from the Turkish-Georgian border westwards to the border with Greece, which includes an expanded section that is proposed to link up to the Nabucco West pipeline to transit

gas to Central Europe, is documented within this assessment (“Environmental Independent Assessment Application” 2013). The proposed route is displayed in Figure 12 alongside the multiple least cost routes that were created and with Table 4 detailing specific properties of the proposed path.

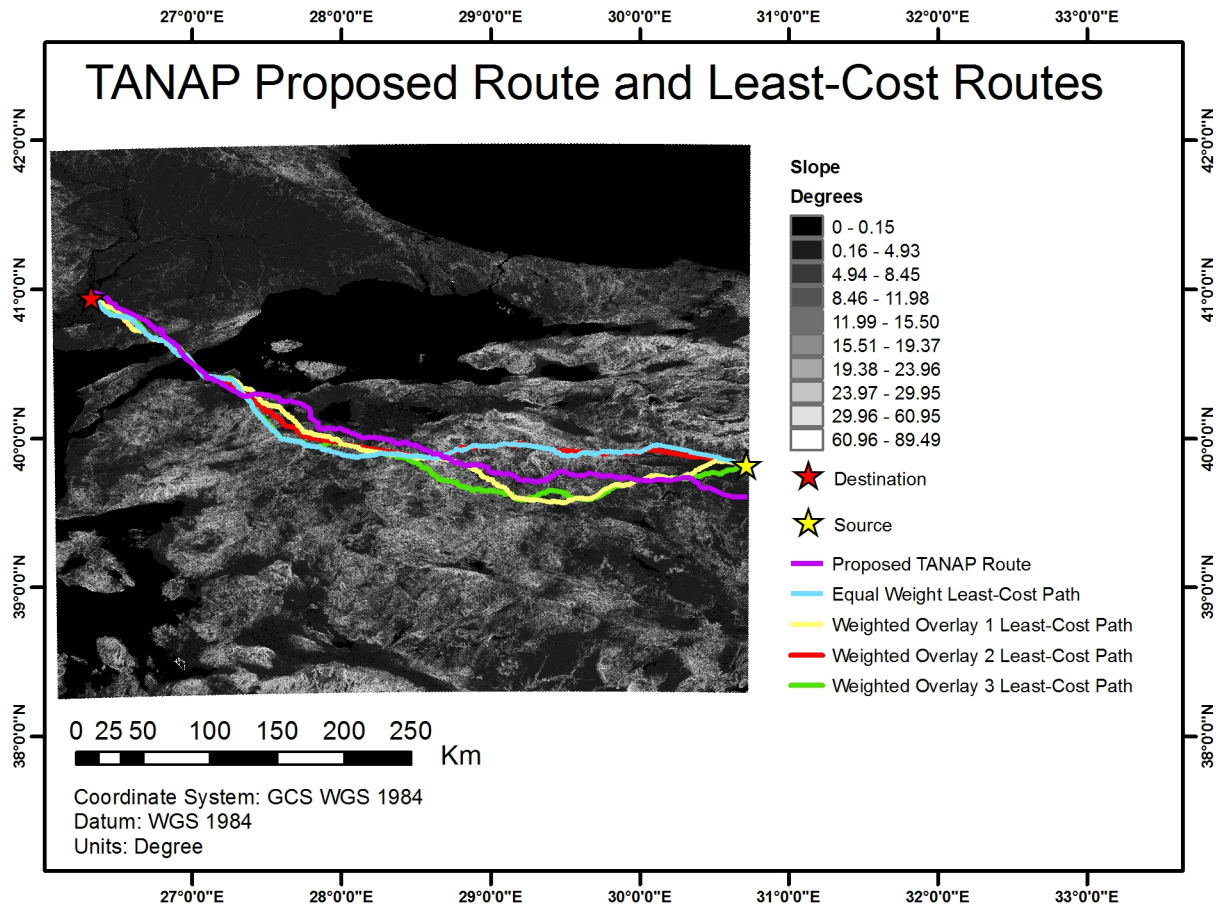


Figure 12. Displays the least-cost routes derived from all 4 cost surfaces and the proposed TANAP route that was referenced from Cindar Engineering and Consulting Inc. 2013.

Table 4. Detailed length in km and relative cost for proposed TANAP route through each separate cost surface. Does not include connection from Canakkale to Tekirdag-Bulgarian border. GCS: WGS-84, Projection: Lambert Conformal Conic.

Route	Cost Surface	Length (km)	Relative Cost
Proposed Pipeline	Equal Weighted	470.615	7519

Route from TANAP EIA Report	Weighted Overlay 1	470.615	2429
	Weighted Overlay 2	470.615	2999
	Weighted Overlay 3	470.615	3053

Table 5. Error polygon areas between each created route and the proposed TANAP route. Area is calculated between two linear features.

Error Polygon	Area (km²)
Equal Weighted vs. TANAP	5644
Weighted Overlay 1 vs. TANAP	3311
Weighted Overlay 2 vs. TANAP	4871
Weighted Overlay 3 vs. TANAP	4142

The detailed length and relative cost quantities were compiled using the ESRI ArcMap 10.1 software with the detailed geographic coordinate system and projection listed in the table above. The costs of the proposed path were extracted from all four different cost surfaces that were created and excluded the 167 km section that travels north from Çanakkale to Tekirdag and the Bulgarian-Turkish border. When examining Table 4 the relative costs that were calculated for the proposed TANAP route from each of the four cost surfaces detail the costs that would be associated with that route for each surface. These costs were then compared to the least-cost path for each specific cost surface to obtain a general cost effectiveness for each least-cost path.

5 DISCUSSION

5.1 Trans-Anatolian Natural Gas Pipeline Least-Cost Analysis

When examining the results that were generated from the four cost surfaces within the study it is clearly evident that the least-cost routing tool is more efficient than a typical straight-line path. Beginning with the Equal Weighted cost surface, the least-cost route that was determined detailed a relative cost that was around 38% lower than the straight-line path. The straight-line path was used as a comparison in that the shortest distance between two points is a straight-line and would in theory traverse the fewest amount of cells within the cost surface. This in effect would be assumed to generate the lowest cost through the study area. This is not the case though due to the specific criteria that were combined together to form the cost surface. This is where the logic of the least-cost algorithm that is coded within the ArcGIS tool displays its worth in navigating the highest cost cells while traversing the cost surface from source to destination.

These costs that are accumulated for each derived path are not quantitative figures that can be used in projects such as engineering designs as these values only display the relative cost that is associated from traversing the specific cost surface. This relative cost can be compared to one another in a ratio as shown in Tables 1 and 3 to determine the effectiveness of the least-cost path but the actual values cannot be listed as official quantitative statistics for the route of the pipeline. It is also relevant to note that the relative cost values that were calculated for the Equal-Weighted cost surface cannot be compared directly to the values that were calculated for the Weighted Overlay cost surfaces due to the different scaling of cost values between the two types of cost surfaces (Equal Weighted and Weighted Overlay). For this reason also the ratio of effectiveness is the best calculation to compare each path to one another.

When the effectiveness of each route was compared to one another the higher the effectiveness of the route, the better the route was at crossing that specific cost surface. As displayed in Table 3 the least-cost path that was created across Weighted Overlay 3 was the most efficient route when compared to the straight-line route. This cost surface focused mainly on highlighting the geologic hazards that would effect the routing of the pipeline. These geologic hazards were characterized by the age and lithology present at each location. These ages and lithologic descriptions were derived from the AGI dataset and provided general descriptions of the surficial rocks at that geographic location. Younger rocks that were essentially basin infill as the final tectonic plates converged together to form the Anatolian peninsula were determined to be of higher risk than older more consolidated rocks in the area (A. Okay 2008; A. I. Okay et al. 2012; Tamer Y. Duman et al. 2005). These younger basin infill rocks were composed of mainly flysch and alluvium that was derived from the weathering of the converging volcanic island arcs. The ages of these geologically young rocks were from mainly Cenozoic to Late Mesozoic and consisted of these flyshes and marine sedimentary sequences. These specific lithologies are not able to withstand very much strain and thus are very prone to fail (T. Y. Duman et al. 2005; Tamer Y. Duman et al. 2005). Older rocks within this region mainly consist of igneous intrusives and mélanges of Precambrian to Late Paleozoic age that were created from the compaction of accretionary wedges. These consolidated and extremely compacted lithologies are able to withstand more strain due to the physical structure of the rocks and are thus less likely to fail (A. I. Okay et al. 2012; A. Okay 2008; Krushensky 1980). These more structurally sound rocks are less prone to landslides which are a key hazard in pipeline construction. These pipelines are designed to last 30-40 years and thus the geologic characteristics as well as the terrain are key elements in siting. Weighted Overlay 3 also takes into account the terrain by weighting the slope of the area

second most important to the geology. These criteria are intricately linked together in the occurrence and spatial extent of landslides.

At the beginning of the study the main assumptions of pipeline routing was that landslides and terrain hazards would be the most controlling factor in the selection of a viable route through the study area. The terrain dictates much more so in where the pipeline can be placed than other criteria such as population. Large diameter pipelines like TANAP can be placed through urbanized areas if needed but they are not able to traverse very steep gradients composed of brittle rock. It is due to these reasons and more that the results are not surprising that the Weighted Overlay 3 cost surface and least-cost route were the most efficient. When comparing the proposed route, which was highlighted in Appendix 5 of the Environmental Independent Assessment (published March 2013), to the least-cost route through Weighted Overlay 3 they are very similar (See Figure 12). This clearly indicates that certain criteria are much more important than others in the selection process of where to construct these large diameter pipeline projects. However when comparing the relative costs between the proposed TANAP route and the weighted overlay routes the Weighted Overlay 1 route was the most efficient and had the smallest error area from the proposed route. This error was calculated from the area between the two linear routes with the smallest area inferring the least error between routes. This weighted overlay also had a heavy bias in the slope and lithology of the study area. The teams of engineers at Cindar Environmental and Consulting Inc that calculated the proposed TANAP route documented in their investigations when the investigation area in their assessments had to be expanded in order to fully investigate the geological and geomorphologic structures that were present (“Environmental Independent Assessment Application” 2013). This process also indicates how important these criteria are at controlling where large pipelines can be routed.

The fact that the heavy population bias of Weighted Overlay 2 did not result in the highest efficiency was a surprise to the assumptions that were compiled at the beginning of this study. One would think that the highest population density areas would be a major controlling factor in the site selection of where large-scale projects like TANAP would be routed due to the influence that citizens would have on construction sites traversing their private land. While this factor is obviously prominent in the routing process it does seem to take a secondary role to the other criteria, mainly the geologic and terrain, due to the fact that it is not as definitively fixed as the other criteria. Land can be acquired and houses moved in part to allow the pipeline to traverse a more suitable gradient of terrain whereas a mountain or steep cliff valley cannot be as easily remedied. In this sense the construction firm can manipulate this criterion in order to best suit their needs when constructing the pipeline, whereas the natural landscape and terrain pose a much more rigid set of criteria.

A key observation to take into account when examining the results from the proposed TANAP route and the least-cost routes that were experimentally created was that even though these experimental routes only took into account a very select few criteria they almost mimicked the proposed route. In Figure 12 one can see that the experimental routes were not sourced from the exact location where the proposed route entered the study area. This is due to the ever-changing circumstances when routing large projects such as this pipeline. Cindar Engineering and Consulting Inc. released these proposed route points after the experimental routes had been calculated from the listed geographic location from TANAP. Although the source locations for each route were different, this did not affect the experimental routes significantly enough to document. This in turn meant that the other criteria that Cindar Engineering used were responsible for the slight deviations that the proposed route took away from the experimental routes. Cindar

Engineering used many more criteria in their routing process such as: land cover, archaeological sites, ground conditions, transport access, etc (“Environmental Independent Assessment Application” 2013). Although these criteria have their own specific importance the fact that the five major criteria that were used provided very similar routes leads one to believe that the processes used in this thesis could be more efficient. When examining the small-scale restrictions to the pipeline route all of these minor criteria may come into play more so but for large-scale siting purposes only major physical criteria need be applied. From this strategy engineers could then hone the route model in to fit their needs and save time and money in the process by having a general route plan already calculated.

5.2 Limitations of this Route Model

While this thesis provides a case study on what to consider and how to efficiently create a least-cost route for a major pipeline project, there are some limitations that are to be considered. Firstly the scale of the study limits its ability to be very precise about the specific route to construct this pipeline. The study area consists of more than 150,000 square kilometers and the resolution of the data that was used was 90-meter cells. This cell size is very coarse for specific, detailed engineering work that is mandated for a project of this cost and size. Therefore in order to obtain a more specific and detailed least-cost route, along with a more site specific cost surface, many small-scale experiments at the proposed sites in Turkey must be performed. This type of multiple siting investigations was done in the Environmental Independent Assessment, which is why that assessment was used to display the proposed TANAP route and used as a control to compare the results of this thesis. Due to timing and the funds of this study I was unable to travel to the field to collect these measurements. This in part was why the created least-cost paths were very coarse in resolution and occupy an area of at least 90 meters in width compared to the inde-

pendent assessment right of way width of only 50 meters (“Environmental Independent Assessment Application” 2013). If I had been able to travel to the actual study region and assess the proposed pipeline corridor more accurately defined specific areas of higher risk would have been compiled.

Another key limitation of this study was the acquisition of accurate and precise data for the study area. The area of Western Turkey is not as extensively studied as most parts of the world therefore it was very difficult to acquire very precise GIS data to implement into the analysis. One key dataset that was used extensively in the environmental assessment by Cindar Engineering Inc but not within this study was the land use classification for the study area. Land use classification identifies what the current use of a specific geographic location is and helps with the routing of this large scale project by helping the planners to find areas of land use that are not extensively developed. These land use classifications can be determined from remotely sensed data from satellites such as the Landsat program. In order to make sure that your classifications are indeed correct from these remotely sensed images you would then need to actually obtain verification of the land use by either going out to the specific locations or obtain verification from another person who is there. In this study I was unable to ground-truth any classifications that I would have interpreted due to the unavailability to travel to these locations firsthand. This land use dataset would have greatly increased the accuracy and relevance of the least-cost path analysis by implementing the current use of the land into the created cost surfaces. This extra criterion would have allowed the least-cost paths to take into account types of land that are most suitable for construction and therefore less risky.

The lack of precision in other datasets that were used such as population density and fault traces also factored into the limitations of the study. The coarseness of some of the raster datasets

did not allow for the most precise results on where the least-cost path should be routed. Similar datasets in locations such as the United States allow for more detail to be implemented into the analysis due to the level of detail that is compiled within the datasets. This level of detail only comes from the amount of previous studies that have taken place within a study area. The General Directorate of Mineral Research and Exploration of Turkey (MTA) provided some GIS data for the region but overall this data was not very precise. This lack of precision within the datasets was a key factor in the least-cost analysis and limited the accuracy of the study to only a regional scale and not site specific.

6 CONCLUSION

The created least-cost paths from this thesis provides the least hazardous pipeline routes by using the available data that covers the region of Western Turkey. When comparing the created routes to the proposed TANAP pipeline route that was recently released to the public in March 2013, the least-cost paths accurately detail routes that are strikingly similar and effective in providing a path from the documented source and destination points within Western Turkey. This thesis, using similar studies as background and for reference, combined the key factors in routing a large-scale pipeline project into a relevant cost surface that was then able to perform a least-cost path analysis and deliver a connected route. While the thesis had some limitations with the amount of data available and its precision, the overall result was a viable least-cost path that satisfied the main regulations with routing this type of infrastructure.

With more precise and higher resolution data the limitations of this study may be overcome in order to enhance the quality of the least-cost routes. Future studies will be needed to en-

hance the quality of this model and in turn help to route the Trans-Anatolian Natural Gas Pipeline in the least hazardous areas and deliver another stable supply of natural gas to the European market.

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