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FINDING ALTERNATIVE RIGHT OF WAY USING MULTI-CRITERIA DECISION ANALYSIS BASED ON LEAST COST PATH:

A CASE STUDY OF 20''ANOH PIPELINE

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A CASE STUDY OF 20’’ANOH PIPELINE

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DECLARATION OF ORIGINALITY

I declare that the work described in this document is my own and not from someone else. All the assistance I have received from other people is duly acknowledged and all the sources (published or not published) are referenced.

This work has not been previously evaluated or submitted to NOVA Information Management School or elsewhere.

Lisbon, February 2023

Madu Franklin Chinedu

DEDICATION

I would like to dedicate this thesis to the memory of my beloved parents for they taught me everything i know in life. Without their guidance, i would not have become the man i am today. Through every facet of life, they tutored me to ride the storms and overcome them.

ACKNOWLEDGMENTS

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ABSTRACT

A multi-criteria decision analysis was conducted using a geographic information system (GIS) coupled with analytical hierarchy process (AHP) methods to evaluate and prioritize the pipeline project areas for Assa North Ohaji South. Alternative Right-of-Ways (ROWs) with two optimal routes were determined and compared with the existing ROWs. During the analysis, several criteria were considered to determine the least cost alternative ROW, including slope, geology, waterbodies, roads, land use, and land cover. The optimum route for connecting the source and destination was then determined. The LANDSAT 8 imageries of the study area were processed and classified into various land use and land cover types, which were then modeled using ArcMap 10.8 GIS software for routing analysis. It was used in the study to demonstrate the efficiency of MCDA LCP and AHP integration in generating optimum routes for the ANOH project. By avoiding steep slopes, built-up areas, and waterbodies, the optimal route avoided the limitations of the existing ROW. This route has a 22% reduction in length and will decrease construction costs, which is an indication of its efficiency.

KEYWORDS

ANOH

GIS

Least Cost Analysis

Multi Criteria Decision Analysis

Pipeline

Right Of Way

ACRONYMS

ANOH – Assa North to Ohaji pipeline

DEM – Digital Elevation Model

ESRI – Environmental Systems Research Institute

GIS – Geographical Information System

LCP – Least Cost Path

MCDA – Multi Criteria Decision Analysis

Osgof – Office of the Surveyor General Of the Federation (Nigeria)

ROW–Right Of Way

SPDC – Shell Petroleum Development Company

SRTM – Shuttle Radar Topography Mission

USGS – United States Geological Survey

INDEX OF THE TEXT

INDEX OF TABLES

INDEX OF FIGURES

1. INTRODUCTION

1.1. Background of the study

A right-of-way location (ROW) for a linear facility frequently involves a preliminary assessment in which one or multiple corridors are selected. It ensures at this stage, the proper delineation of land parcels for possible routing rather than identifying precise figures for the linear facility (Aissi et al., 2012). An optimal pipeline design involves determining a route corridor that traverses two locations, ensuring regulatory compliance and cost efficiency, as well as meeting the deliverables and objectives of the Least cost path analysis (Seel et al., 2014). Based on the least cost path, multi-criteria decision analysis provides an efficient medium for conveying petroleum products, evaluating appropriate alternatives, and helping with decision-making. Geographic information systems (GIS) can be used to compute the least cost paths for structures that are strongly affected by topography in route planning (Bachmann et al., 2018). By combining multiple criteria, the least cost path analysis allows the planner/designer to find the cheapest way to connect two locations within a cost surface. Finding an efficient right of way is a recurring challenge in many real-world applications addressing the choice of cost-efficient routes for pipelines (Feldman et al., 1995), and highways (Collischonn & Pilar, 2000). It adopts a pixel-based approach as opposed to a single-line application for linear engineering structures (LESs) that incorporate weighted overlay, corridor analysis, and optimum route analysis to indicate a way to conceptualize the route information using the given criteria (Yildirim & Bediroglu, 2019)

Nigeria's plans for more industrial and power projects, which involve supplying gas through its gas network to the Western Domestic Gas Market, are what's driving the country's increase in domestic gas production (Www.Nsenergybusiness.Com/Projects/Assa-North-Ohaji-South-Project/, n.d.) The SPDC JV's OML 21 and SEPLAT JV's OML53 are the targeted reservoirs. The Assa North-Ohaji South (ANOH) is currently in the construction stage, and it's expected to start commercial production in 2022. An investment decision (FID) was approved in 2019 for the $650 m project. The Assa North-Ohaji South (ANOH) conventional gas development will involve the drilling of approximately six wells. The field will generate an upstream facility that will aggregate and divide field output between the two end facilities, each of which has a processing capacity of 600 MMscf/d, depending on the availability of reserves and the need to supply two separate 300 MMscf/d plants ("Assa North-Ohaji South (ANOH) Conventional Gas Field, Nigeria," 2021). The pipeline's projected length is 28 km, and the right of way is in Nigeria's Imo State's Ohaji Egbema Local Government Area. The current route includes certain stretches fully in gallopy seasonal marshy terrain and is entirely within the right of way of the Consortium partners. Using the conventional field survey method, a preliminary investigation survey was carried out to help identify an alternate right of way. In this thesis, the Asa-North Ohaji (ANOH) pipeline route is developed using a least-cost alternative right of way using Geographic Information System, Multi-Criteria Decision Analysis. The routing model establishes the cheapest and safest path through the specified study region while avoiding geological, social, and environmental risks. This study will identify potential alternate routes, evaluate them using all relevant criteria, and finally choose the best one.

1.2. Statement of the problem

The concern of stakeholders about insufficient information on the distribution of the geological factor along the existing right of way has caused conflicts in the decision-making process for the mainline construction. Insufficient Right of Way access due to difficult terrain has hampered the distribution of construction materials and easy access by construction personnel. There is a high construction cost due to abrupt bends along the existing route and overly long distances. Several factors were considered when evaluating unit cost value, including route length, wetlands, road transitions, forest areas, transitions of dangerous geological areas, proximity to settlements, corridor width, average slope, etc. Environmental Impact Assessments (EIAs) and Strategic Environmental Assessments (SEAs) hinge on alternatives generation which is perhaps the most underdeveloped part of the assessment process (Steinemann, 2001). To improve EIA and SEA and thus decision-making Keshkamat (2007) concluded that a rational, transparent stakeholder-based process is needed.

1.3. Objectives of the study

The goal of this study is to identify all the risks connected to the many criteria used to select the right of way that has the least negative environmental impact. Finding alternate rights of way between the end facilities and evaluating them to ascertain their acceptability using multiple criteria decisions based on the least cost route accomplishes this. It is crucial to establish the prerequisites and defining standards for the alternative right of way, as well as its suitability categorization and least cost route. Therefore, this thesis explores the boundary between theory and practice, discussing how the method can assist in the decision-making process to avoid the steep slope encountered by the pipeline as much as possible in order to reduce construction costs. This allows different paths to be obtained that will subsequently be compared through multicriteria evaluation (MCE) (Iqbal et al., 2006). Finally, a path that was previously determined using traditional techniques and constructed in the field is also studied to compare the two routes.

1.4. Research Questions

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

i. What is the best alternative route with the least cost?
ii. How relevant and feasible is the initial route when compared with the alternative right of way that was obtained?
iii. Which criteria are used to ensure optimal planning while minimizing costs when routing this pipeline?

1.5. Significance of the study

The results of this study's findings show how stakeholders can improve the choice and design of the ideal pipeline route while increasing constructability and productivity. It underlines the significance of taking this into account for smooth right-of-way access and logistical planning. These results will make it clear to all relevant parties how crucial it is to gather precise geological factor distributions for pipeline route selection before mainline construction by reducing construction time and operating costs, extending operational life, and avoiding environmental harm. A GIS-based least-cost path analysis route selection technique, which has the potential to lower project costs by around 15–30%, would be the ideal method for locating an alternate right of way for pipeline routing. To distinguish this study from other works, topographic classifications, such as ridges, flat terrain, steep terrain, and water channels, were specifically considered and classified through various GIS-based analyses. Furthermore, this research is supplemented by a number of other studies (Gyabeng, 2020; Huseynli, n.d.; Yildirim & Bediroglu, 2019) that were conducted to determine the most suitable route between many routes or corridors, replacing the traditional method of selecting routes.

1.6. Organization of this thesis

There are five chapters in this thesis. The background, problem statement, the objective of the study, research questions, prior studies, significance of the study, and the structure of the thesis are all presented in the introductory chapter together with the study's main topic. A review of related literature and research is covered in the second chapter. The importance of GIS Multi-Criteria Decision Analysis and the formulation of the least cost course is highlighted. The engineering and environmental factors to choose the optimal route are also covered in this chapter. In chapter three, the methodology and software are introduced, along with the study area and data that were utilized to identify the best route based on the selected criteria. The findings and discussion of the results are contained in the fourth chapter. The study's summary, conclusion, and recommendations for the future are presented in the last chapter.

2. LITERATURE REVIEW

2.1. A GIS-based approach

The choice of a pipeline's right-of-way direction necessitates a complex process of deliberation and examination of a vast array of factors that decide the prospective route (Sadek et al., 1999). The shortest path-finding techniques and network analysis in raster GIS are directly related to determining the right-of-way for a linear facility, such as a pipeline, that runs through a certain terrain linking two extreme facilities (Wasi & Bender, 2004). The problem of choosing a suitable site that best serves the goal is involved in this procedure, which entails several surface assessments of the proposed route (Herzog, 2016). The engineering and environmental design requirements largely determine the design and operation of a pipeline route. The topography and terrain features, such as slopes, wetlands, water bodies, rivers, streams, road crossings, geology, etc., define most engineering criteria. Considering the least amount of disruption to both private and public property, length, accessibility to transportation, preservation of natural resources, utilization of existing corridors, adoption of suitable terrains, constructability, maintainability, and operability are also considered. The oil and gas industry is increasingly relying on GIS technology as a real instrument capable of supporting decision-makers in choosing an ideal path when laying up new pipelines. This lessens the negative effects of development on the environment and lowers operational and construction expenses (A. Balogun, Matori, et al., 2012).

2.2. Multi-Criteria Decision Analysis

Multicriteria Decision-Making (MCDM) is frequently used to analyze complex information and choose between several alternatives. Since its inception, it has been shown to be a promising and expanding topic of study (Yakar & Celik, 2014). Numerous applications in civil and environmental engineering fields have been documented to deal with issues whose potential solutions are already known, allowing decision-makers to rate potential solutions (Ouma et al., 2014). In the past, choosing a pipeline route required manually calculating the shortest path between two places on a topographical map and compiling all necessary data along the route to assess its viability (Isa Adekunle Hamid-Mosaku et al., n.d.; Wasi & Bender, 2004). Because it ignores important aspects that could alter the pipeline's route, the conventional approach is ineffective. Nowadays, an optimal route can be found automatically thanks to the potent technologies included in GIS (Yildirim, Yomralioglu, Nisanci, Colak, et al., 2017). In land use planning activities, the current spatial information is supported, modified, and reevaluated using GIS and MCDA. To identify areas of potential interest and implement a crucial strategy to create a pipeline route with the least-cost path, it analyses the geographical correlation between several layers of spatial data (Gyabeng, 2020). For the decision-maker, the integration of GIS and MCDA (Jankowski, 1995; Malczewski, 2010) GIS methodologies offer a mechanism to pick and assess numerous alternative solutions. We need to meet several requirements for the available area or surface to build a new route alignment. At the same time, route planners face a significant problem in minimizing costs (Singh & Singh, 2017). Designing numerous other pathways is possible with multi-criteria decision-making (Effat & Hassan, 2013; Yakar & Celik, 2014). Using GIS and a least-cost routing model to find this path is the most effective method. The integration of data from different sources serves as the foundation for engineering and environmental design requirements (Wasi & Bender, 2004).

2.3. Least Cost Path (LCP)

Research on the least-cost path problem was conducted before the creation of contemporary GIS. Warntz (1957), who believed that goods must be transported over two sizable zones, each with a separate cost of transportation, is credited with some of the early work on the subject (Warntz, 1957). For many years, researchers have studied various methods to establish a mechanism that can identify the quickest and least cost routes. Edsger Dijkstra was one of them and created an algorithm to find the shortest route between two nodes in a network (Dijkstra, 1959). One of the essential components found in most least-cost routing models is this algorithm. The algorithm can select the least cost path through a particular area together with a cost-accumulated surface. This kind of analysis concentrates on the vicinity of cells around the suggested starting point and expands outward from there to eventually cover the full study area. The least-cost paths algorithm (Collischonn & Pilar, 2000) is an example of how the Dijkstra algorithm can be modified for raster representation. The algorithm only needs to examine the nodes across the surface once all the criteria have been combined into a cost-accumulated surface, making it computationally expensive and producing a lot of data that needs to be saved. Different businesses started to create new GIS extension packages to speed up results and reduce computation time to improve this computationally taxing process. This was made possible by the development of today's fast, powerful computers, which also made it possible to use the least-cost path analysis to solve real-world problems. As a result, the routing procedure has been able to accommodate various weighting scenarios and points of view while also properly weighing and combining components to build adequate cost surfaces (Abudu & Williams, 2015; Atkinson et al., 2005).

Today, least-cost path analysis is a technology that can be found in the majority of commercial GIS and has been used to solve a variety of issues, with infrastructure design being one of the most used. With the endpoints, terrain, slope, and cost as inputs, (Collischonn & Pilar, 2000) provided an algorithm for the definition of least-cost pathways to be used for the building of roads and canals. With the aid of a digital elevation model (DEM) that represents the topography, this alternative technique can determine the ideal route for a road or canal. Using a predefined function, the cost of passage is connected to the direction-dependent slope. Since the procedure is iterative, even when the best path is extremely complicated, like a spiral, the problem can still be solved. To support various discretization schemes, LCPA is used with criteria that are weighted by expert judgments. As a result, a performance score is created for the set of alternative routes that incorporates an exclusive set of criteria that is not considered in the cost surface calculation. It makes use of factors including environmental quality, human health, and existing infrastructure corridors. Using a decision support system, the different routes are then sorted by these performance scores.

Another strategy to lessen the visual impact of a suggested alternate path is Viewshed Analysis, which could use the center points of buildings as observer points. For environmental planning and civil engineering (Stucky, 1998) developed a different method that used a digital elevation model (DEM) to choose four (4) different types of paths through a study area depending on visibility. To lessen the zigzag-like paths that LCPA-based techniques typically produce, a straightening technique is used. In many other disciplines that assess linear infrastructures like highways, energy transmission lines, or new pipeline routes, the adoption of the least cost model accurately revealed a more cost-effective approach. ESRI has created more intricate cost path extensions recently and incorporated them into their primary ArcGIS products. The Cost Path tool is one of these enhancements that has shown to be very useful. Today, least-cost path analysis is a technology that can be found in the majority of commercial GIS and has been used to solve a variety of issues, with infrastructure design being one of the most used. This tool enables the creation of a Cost Direction surface and a Cost Backlink surface, which are then used in conjunction with the primary Cost surface to determine a more precise and accurate Cost Path from a source point to a destination point while also calculating the cost that the path incurs across the surface. An accumulated Cost Map is created by keeping track of the lowest accumulated cost for each grid cell as the expanding ripples move across the discrete cost surface. This method allows for a quick calculation of the total cost to build the desired route from the beginning point to every place within the project area. The wavefront's route to the end location is retraced by simply taking the steepest downward path across the surface; theoretically, this line has the lowest total cost connecting the start and end locations, giving rise to the Optimal Route. These create a collection of almost ideal alternate paths that are valuable for drawing limits for in-depth data collection (Alhaj, n.d.).

2.4. Review of previous studies on raster-based least-cost path analysis

Several studies have already demonstrated a trend in the technique used to develop these least cost models for evaluating numerous criteria and combining many criteria into a single least cost model (Chakhar & Martel, 2003; Hamurcu & Eren, 2018). The required criteria for determining the least-cost routes of large pipelines have been developed in recent studies using both remotely sensed and GIS data (Feldman et al., 1995). Numerous attempts are being made to automate the route-planning process utilizing MCDA and GIS technologies. An examination of several studies suggested that similar approaches are still being actively developed today (Chakhar & Martel, 2003; Dano Umar et al., 2013). The approach described in this thesis is an enhancement and a refinement of earlier studies, such as those carried out by (Isa Adekunle Hamid-Mosaku et al., n.d.), for a route that starts offshore from Bonny Island and ends in Lagos, Nigeria. The goal of the study was to determine the best path for a pipeline that would connect Eastern gas supplies with Western domestic gas demand. By combining the spatial modeling and visualization power of geospatial techniques (GIS & RS) with the trustworthy criteria weighing powers of the AHP decision-making model, this research intended to choose appropriate choices for an optimal pipeline route (Reisi et al., 2018; Suleiman et al., n.d.). The findings of this study show that the environmental and geological considerations received the highest priority for proper route selection, while the economic element received the lowest priority. The second alternative route, out of the four analyzed alternatives, was ultimately determined to be the best option due to its minimal route length, short passage through sensitive settlement zones, and a low number of rivers, streams, and existing platform crossings.

Other studies include (A. Balogun, Chandio, et al., 2012) and (Effat & Hassan, 2013). Due to the complexity of the least cost model, which uses a raster analysis for every square millimeter of the route's land, the categories of criteria that have been analyzed are limited. Consequently, the changes of a certain element are weighted more simply, the physical qualities of the analyzed geographic area have been most of the criteria (Atkinson et al., 2005; Mousseau et al., 2012).

Bagli (2011) provides more details on a method for power-line routing based on LCPA and multi-criteria evaluation of suggested pathways. Human health, geography, and habitat fragmentation (length outside of current infrastructural corridors) were all considered. This is one of the few studies that considered biological effects while deciding how to route a facility and incorporated those factors into the model.

Kelly (2014), The project is a case study for a least-cost route analysis using a GIS on a segment of the proposed pipeline in Western Turkey. This analysis showed the use of a strategic least-cost routing analysis. The Caspian Sea natural gas reserves were connected to Turkey by a natural gas pipeline project aimed to liberate the EU from Russian and Ukrainian gas supplies, which would significantly contribute to the future energy security of the EU. To determine the least hazardous path through the study area, a least-cost algorithm was used to weigh several sorts of criteria in a risk assessment map and several types of variables were considered, including lithology, the slope of the terrain, social risk, and environmental concerns, such as proximity to nature reserves and urban centers. In terms of the relative cost of each route, the determined least-cost paths were more effective than the suggested route. By including both physical and environmental risk factors, the study offered a fresh new case study that will promote geographic information science.

Durmaz (2019) The major route of an ongoing Turkish natural gas project in the east-western region, from Erzurum through Mus and subsequently to Bingöl, was the subject of this study's automatic natural gas pipeline design study. The project seeks to meet Turkey's energy needs. After conducting alternate research using a conventional approach, an autonomous route for a natural gas pipeline was found utilizing GIS and a least-cost path algorithm. In addition, the high vertex points were removed using a point removal technique and a cartographic line simplification process, and a simplified path was found. To assess the various consequences, the results were contrasted with those of a completed Mus natural gas project built by The Turkish Petroleum Pipeline Corporation. It was determined that a 20% cost reduction through simplicity was achieved using GIS capabilities and the lowest cost path distance method. The study recognized that determining the best route is an intricate multi-criteria problem with competing goals that must be balanced. LCPA was used to determine alternate paths that are not necessarily the shortest distance but are the most cost-effective. A pairwise comparison matrix and MCE were used to weigh and evaluate various factors necessary for determining optimal routes.

Volkan thoroughly contrasts a GIS-based pipeline routing strategy with Turkey's traditional route selection strategy in the (Volkan Yildirim & Sevket Bediroglu, n.d.) study. Volkan was able to demonstrate that a GIS-based pipeline route selection would be less expensive overall than a manual pipeline route approach by 14%. He highlights again how user-friendly the GIS program is. Feldman determined that identifying the variables influencing the route is the most crucial component of a GIS-based strategy (Feldman et al., 1995) and carried out a least-cost study for the pipeline layout using remotely sensed data and GIS analysis. Urban areas, geology, wetland, and other factors were considered to determine the cost of passage, and remote sensing data were used to map the land cover. On a portion of the Caspian oil pipeline, the technique was tested. When utilized correctly, GIS approaches outperform conventional/manual techniques in terms of speed, quality, cost, and efficiency (Atkinson et al., 2005), using the following fundamental procedures: (i) For each evaluation criterion, a friction surface was built, and a value was given to each cell in the grid depending on the relative cost of passing through that cell. The methodology prepares, weighs, and combines construction factors using GIS. (ii) To represent the entire cost of passing through each cell, a cost-of-passage surface was made by weighing and combining several friction surfaces. (iii) To calculate an accumulated-cost surface, a spreading function was used to merge the cost-of-passage grid with two additional grids representing source points and destination locations. (iv) The accumulated-cost surface was traversed from an origin point to a destination, following the lowest cost line.

This evaluation illustrates the wide range of uses for GIS-based least-cost routing in the design of significant linear projects. To facilitate route development based on several environmental and financial criteria, it proposes a GIS based approach that combines LCP analysis on a continuous surface and MCE. The least-cost routing extensions in various GIS platforms can efficiently assess the criteria and display the most cost-effective and least hazardous route through a given geographic area thanks to past and present developments that involve updating algorithms and applying more varied criteria to a cost-accumulated raster. Researchers can now 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, like natural gas pipelines, thanks to new developments in GIS and remote sensing technology.

3. MATERIALS AND METHODS

3.1. Overview

This chapter discusses the geospatial datasets required to evaluate the multiple criteria that were considered in applying least-cost routing models to the study area and the method for evaluating the routes considering all the necessary criteria. The study's routing factors were determined by using literature to gather expert opinions on which factors should be considered most crucially. By doing so, it was possible to identify the study's major factors and their relative significance in selecting pipeline routes. The AHP model was also used to determine a final ranking for all criteria. Detailed information about these procedures will be presented in the next sections.

Using GIS multi-criteria analysis, the main purpose of this study is to determine the optimum pipeline route that has the least environmental impact in terms of land use while assessing all the criteria and possible risks. By comparing the new route with the existing right of way, it addresses the Research Questions regarding the most suitable alternative route with the lowest cost, relevance, and feasibility. Provides an overview of how the routing of the pipeline is optimized while minimizing costs.

As the oil and gas industry continues to expand, GIS technology is becoming a more relevant tool for assisting decision-makers when selecting an optimal route for new pipelines. In addition to reducing construction and operational costs, this can minimize negative environmental impacts. Three systems are commonly used to establish evaluation criteria for a project: analyzing relevant literature, conducting analytical studies, and consulting experts (Jones, 1999). Every set of evaluation factors/criteria is specific to a given problem and there is no universal methodology for determining them. Engineering and environmental design criteria play a significant role in pipeline route optimization. Several factors are considered during the process, which involves making decisions and assessing the results. Moreover, it involves analyzing and interpreting geographical data related to the alternatives under consideration Bender (2004)

3.2. Method – Research Framework

For optimal pipeline routing, GIS was used to prepare, weigh, and evaluate various factors. The relative importance of every major criterion was calculated by using a multi-Criteria Evaluation of pairwise comparisons. Various data sources were integrated into the research workflow as indicated in figure 1 below.

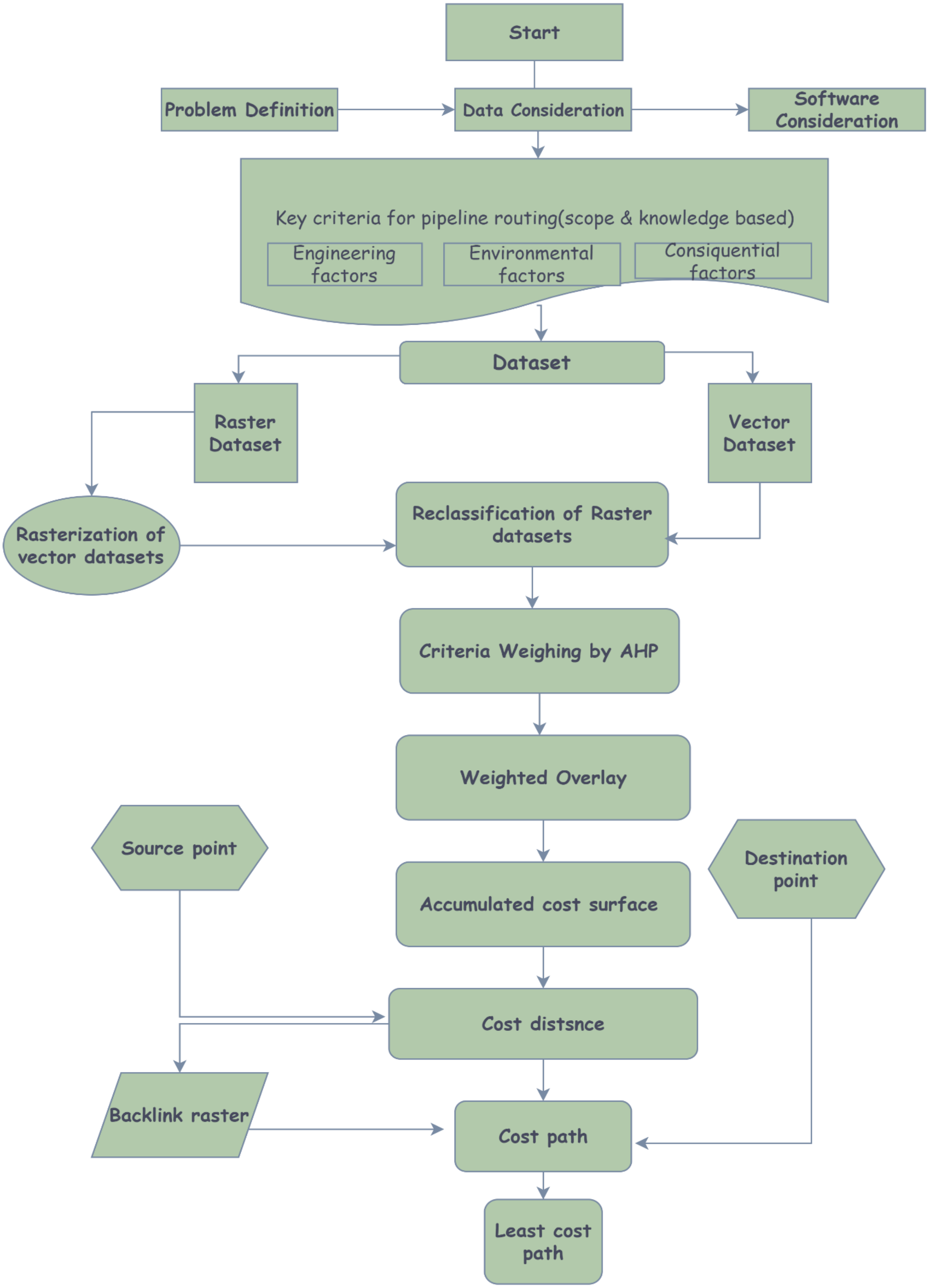


Figure 1. Workflow diagram

3.3. Study Area

This research project covers a study area of 719.84km^2 within the Ohaji Egbema Local Government Area in Imo State as shown in figure 2 below. The location is about 70 km NW of Port Harcourt in Rivers State. The proposed 28km pipeline originates in Assa, Imo State (5° 22' 45", 6° 46' 24"), passes through Egbeda, and ends in Obite, Rivers State (5° 15' 36", 6° 39' 1", respectively). A majority of these are located in the oil- and gas-rich Niger Delta areas, which are located within the lower reaches of the Niger River in the southern part of Nigeria. As such, ethnicities within the South-South and South-East regions of the country are covered by the project.

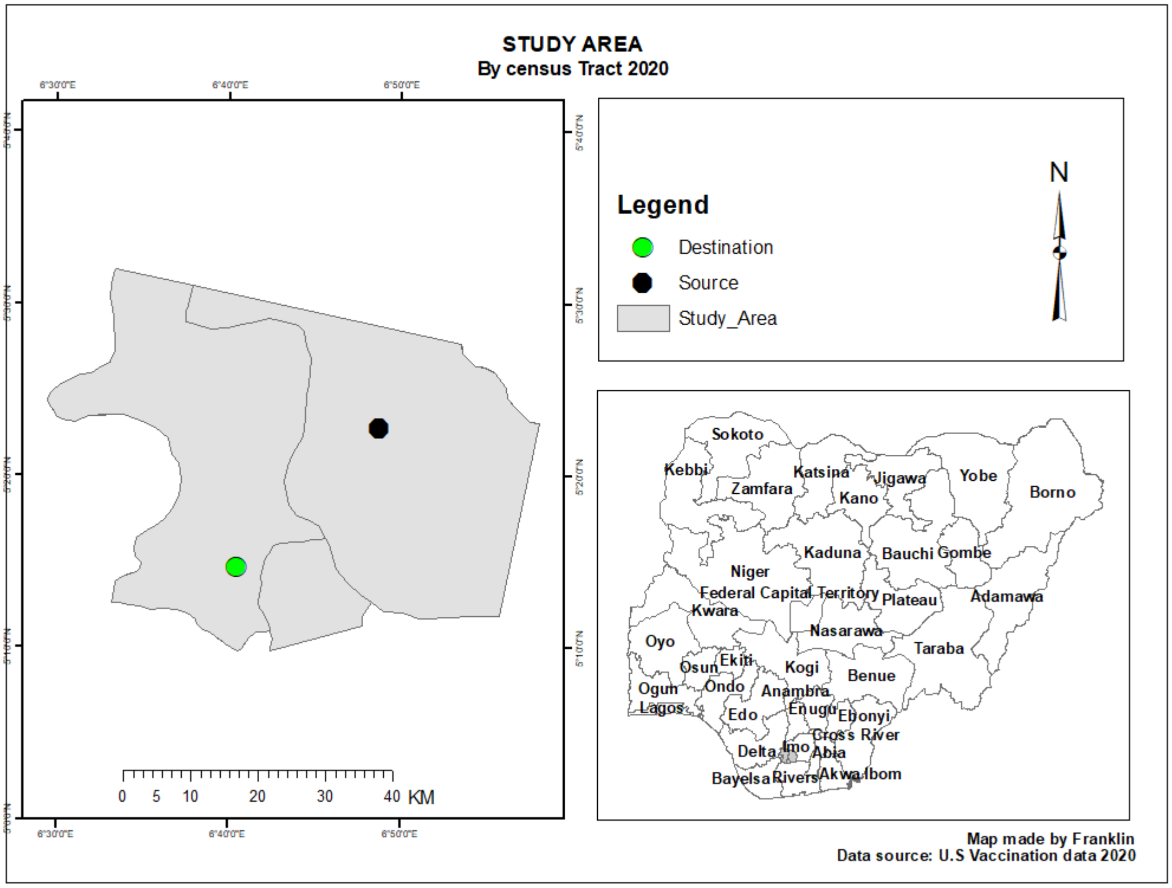


Figure 2. The Study Area

3.4. Data collection

Using GIS analysis techniques, the following data was acquired to select a pipeline route. GIS datasets used include roads, slopes from DEM, geological data, remotely sensed data such as LANDSAT 8 imagery. Criteria data from the expert opinion derived from literature review was used for the AHP weighting process. The data types used in the study are presented in Table 1

Data type	**Source**
Landsat 8 imagery	USGS official website (www.earthexplorer.usgs.gov)
Study area	National Boundary commission (osgof), Abuja
Road and Stream Network Dataset	Office of the surveyor General, (osgof) Abuja (OSGOF, n.d.) 2022
Digital Elevation Model (DEM)	Shuttle Radar Topography Mission USGS official website (www.earthexplorer.usgs.gov)
Geological Map of Nigeria	Nigerian Geological Survey Agency ("Geological Maps," n.d.) 2022
Criteria data for AHP weighting	Literature review: (Goepel, 2018)
Existing right of way	Geomatics section Shell petroleum development company (*SPDC – The Shell Petroleum Development Company of Nigeria | Shell Nigeria*, 2021)

Table 1. Research datasets.

3.5. Data analysis

A fundamental part of route alignment design is the preparation of spatial datasets. GIS and MCDA are used in the proposed model. Route alignment is evaluated using various GIS analytical procedures, including reclassification, buffer analysis, conversion, and weighted overlay based on multi-criteria analysis. For the development of this model, the following datasets are prepared.

3.5.1. Digital Elevation Model (DEM)

The Digital Elevation Model (DEM) data were obtained using the NASA Shuttle Radar Topography Mission (SRTM) model, from which the slope of the study area was determined. The data is projected to WGS1984 UTM zone 32N and contains elevation information for Nigeria in a 90mx90m grid. The DEM for the study area is prepared by clipping the DEM of the country within the study area boundary as indicated in the figure below.

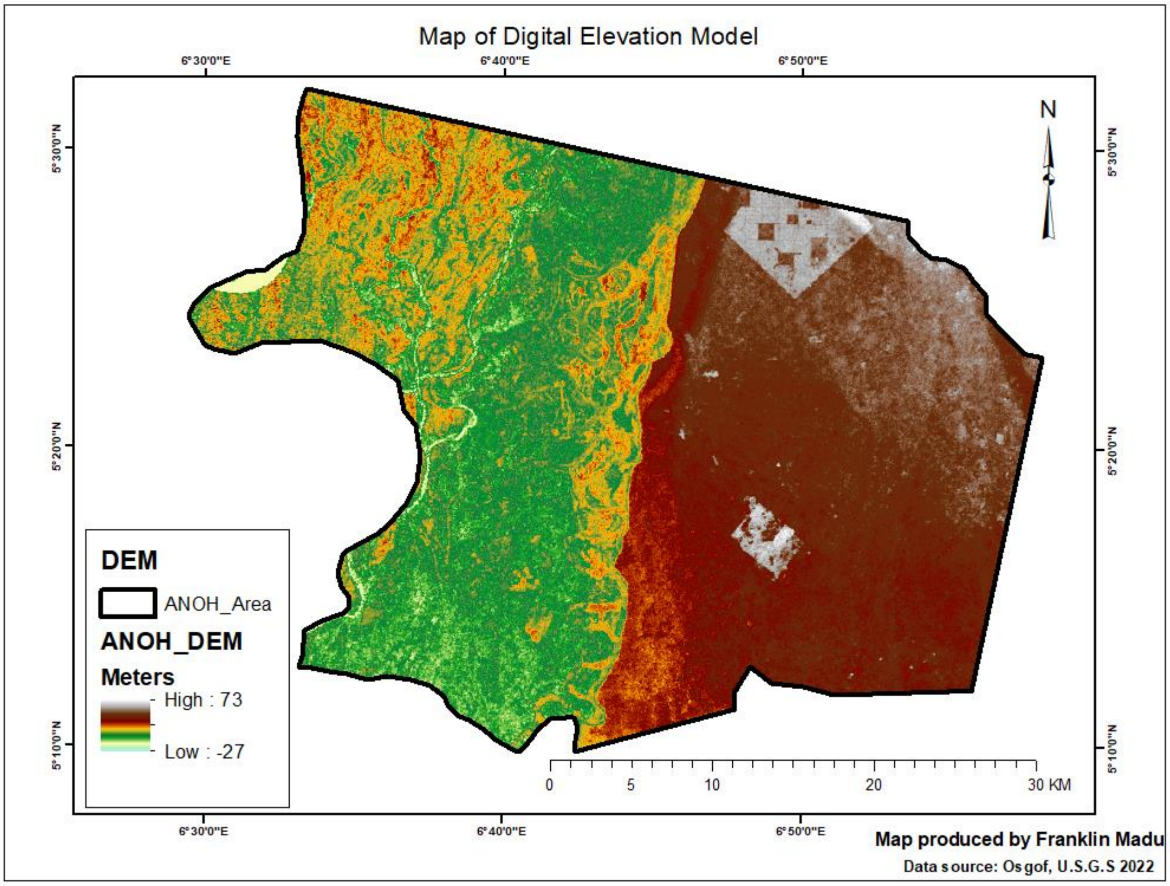


Figure 3. Digital Elevation Model (DEM)

3.5.2. Land-use of the Study Area

Supervised classification of the LANDSAT 8 satellite imagery of the study area was done in order to extract other relevant geospatial data. Based on the selected criteria, the composite bands were further classified into five Land use and Land cover classes (built-up area, bare land, forest, water body, and cropland). Figure 4 below shows the various classes.

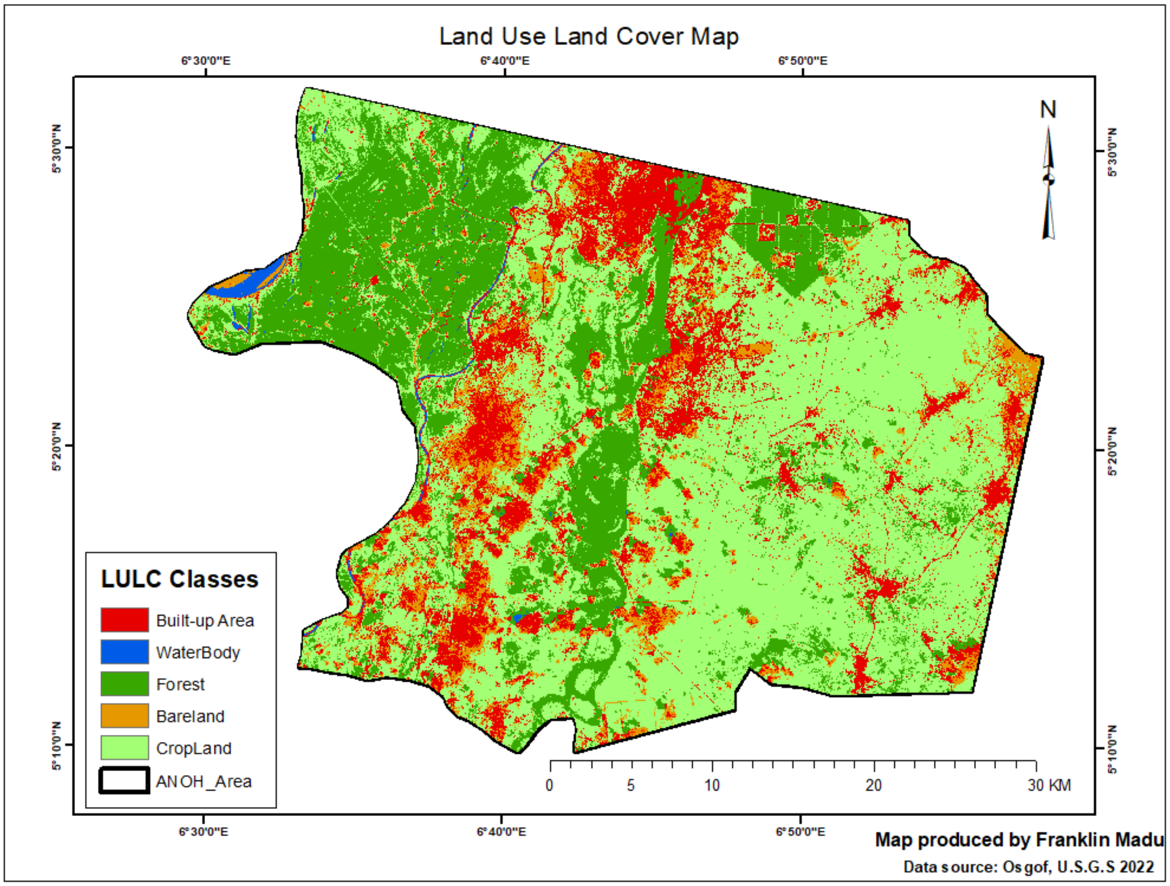


Figure 4. Land-use of the Study Area

3.5.3. Geological Map

The geological map of the study area includes different kinds of sedimentary strata, such as red shale (Pleistocene), ash (Holocene), and Cenozoic. The geological map shows rock compositions and is used to satisfy environmental requirements. This is shown in the figure below.

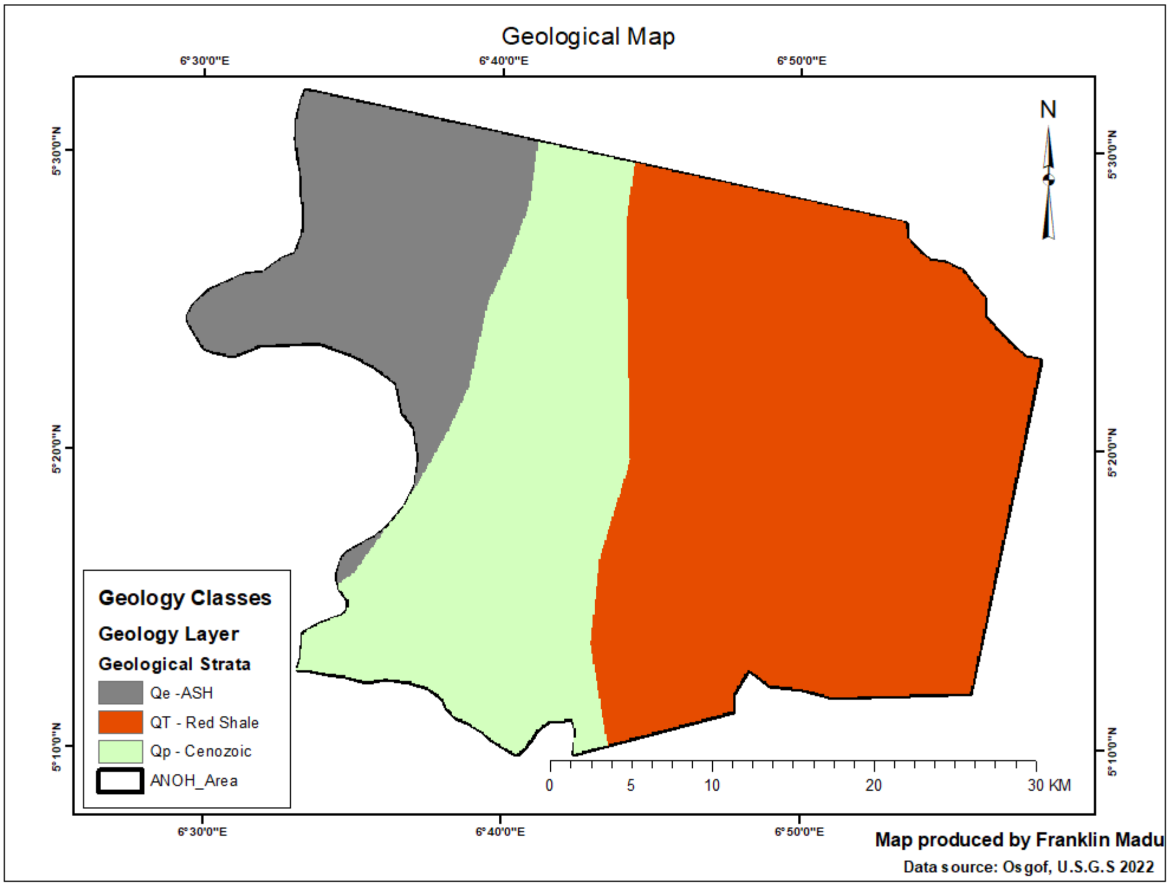


Figure 5. Geological Map

3.5.4. Existing right of way

The existing pipeline route was needed to identify the source and destination points of the ROW and to route a model through it so that it would be used for comparison to determine the most suitable route with the least cost.

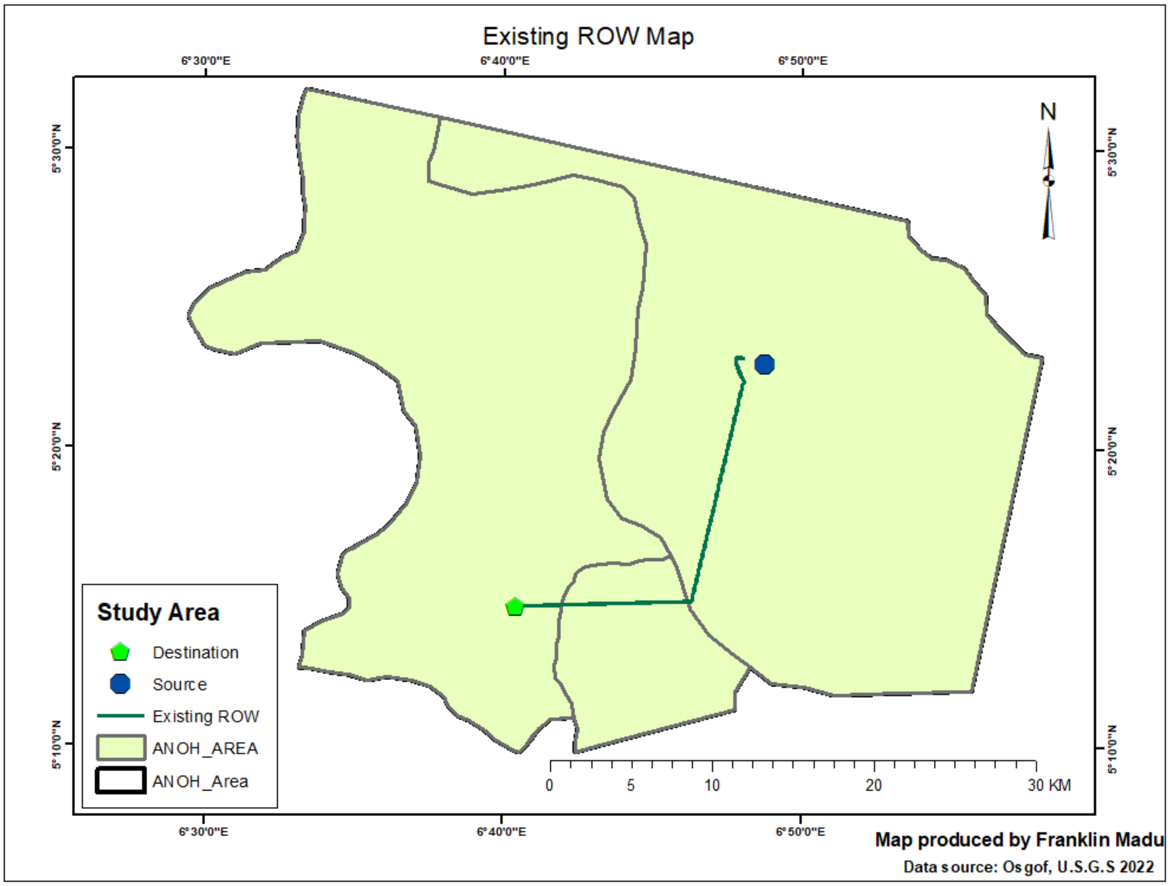


Figure 6. Existing right of way

3.5.5. Criteria data for AHP weighting

The main criteria and sub-criteria for the study were selected based on information from the literature, experts' opinions, and the study area's peculiarities. These factors were reviewed in the context of the geospatial multi-criteria evaluation model adopted in this study and is shown in the tables below.

S/N	**Factor**	**Sources**
1	Environmental	Balogun (A.-L. Balogun et al., n.d.)
2	Engineering	
3	Socio-cultural	(A. Balogun, Chandio, et al., 2012)
4	Manmade	(Chakhar & Martel, 2003; Jafari & Zaredar, 2010)
5	Natural	(Antoine et al., 1997)
6	Economical	(Yildirim et al., 2012)

Table 2. Main criteria for pipeline routing project in Nigeria

Criteria	**Sub-criteria**	**Sub sub-criteria**
Environmental	Land use, Land cover	Forest, builtup, cropland, waterbody, Bareland
Engineering	slope	Steep slope. Gentle slope
Man made	Roads	Double lane, single lane
Natural	Geology	Red shale, ash, cenozoic

Table 3. List of criteria influencing optimal pipeline route selection.

3.6 The Analytical Hierarchy Process (AHP)

The analytical hierarchy process (AHP), created by (Saaty, 1980), is one of the techniques categorized under the Multicriteria Evaluation Utility Theory. Employing objective mathematics to analyze the subjective and individual preferences of subject matter experts in decision-making provides an excellent framework for complex decision-making issues. The method is based on the idea that arranging difficult situations into a clear and understandable hierarchical structure might help with decision-making.

3.6.1. Steps of Analytical Hierarchy Process (AHP)

The following are the general steps of the analytical hierarchy process:

I. Develop a hierarchical structure with a goal at the top level, the attribute / criteria at the second level and the alternatives at the third level. It defines the issue while establishing the connections between the requirements and potential solutions.

II. Determine the relative importance of different attributes or criteria with respect to the goal. Compare criteria in pairs to determine the decision maker's preferred criterion for the evaluation of alternatives. This creates a pairwise comparison matrix.

III. Pair-wise comparison of each criterion's alternatives compares options in pairs depending on how well they performed against each criterion.

IV. From a matrix of outcomes from pairwise comparisons, compute the vector of criteria weights. The criteria weight vectors that represent normalized criteria weightings are calculated by AHP via a variety of matrix transformations.

V. Create a matrix showing the normalized performance (score) of each option for each criterion using the results of the pairwise comparisons on alternatives inside each criterion.

VI. Use the vectors of criteria weights and the matrix of alternative scores to rank the alternatives.

3.6.2 Problem Hierarchy

A systematic, frequently visual method of modelling the decision being made is provided by the problem hierarchy. Making a hierarchy that models the decision problem as the first stage in the analytical hierarchy process enables decision makers to better comprehend the problem, its context, and, in the case of group decision making, see potential approaches to the problem across many stakeholders. The AHP problem hierarchy consists of a choice (the goal), several options for achieving the goal, and several criteria that can be used to evaluate the options in relation to the objective.

3.6.3 Pair wise Comparisons in AHP

Pairwise comparison in AHP refers to the process of contrasting two entities side by side to determine which is preferred and by how much. To identify the relative importance of the many alternatives within each criterion, comparisons are made. Pairwise comparison matrix is created with the help of the scale of relative importance as shown in table 4 below.

Scale	**Relative Importance**
1	Equal importance.
3	Moderate importance
5	Strong importance.
7	Very strong importance.
9	Extreme importance.
2,4,6,8	Intermediate values
1/3, 1/5, 1/7, 1/9	Values for inverse comparison.

Table 4. Scale of Relative importance.

The pair's least preferred member receives the opposite score; for instance, the least preferred member where the most preferred member exhibits extremely strong preference would receive a score of 1/7. Every alternative value within a single criterion and all criteria within the goal are subjected to groups of pairwise comparisons. The result of the pairwise comparison is entered into a matrix for each group. The matrix's results would give the normalized weights for all the criteria (A1 through A4, B1 to B4, C1 to C4 for instance, and when comparing criteria A, B, and C, similar matrices would be produced). To fill matrices for each criterion comparing the performance of each alternative within that criterion, pair-wise comparisons would then be conducted (Saaty, 2008).

3.6.4. Consistency across pair wise comparisons

A significant challenge is the consistency of decision makers across several pairwise comparisons. Consider the straightforward comparison of A, B, and C. If the person making the judgement determines that A is more desirable than B and that A is less preferable than C, then B cannot be determined to be preferable than C. Loss of consistency is a mostly inevitable result of complex decision processes within AHP when there are many pairwise comparisons or when there is no gap between moderate and very strong preference. The AHP technique employs a consistency index that is a function of opposing comparisons to overcome the consistency problem. A lack of consistency is noted over a certain point, and no analytical findings are shown. A regrettable result is that decision-makers start to make pair-wise comparisons based less on their actual judgements and more on the need to keep acceptable consistency. Utilizing a multi-criteria hierarchy and minimizing the number of pairwise comparisons made inside each group is an efficient way to mitigate the consistency problem.

3.6.5. Rank reversal

A rank reversal happens if the addition or elimination of a duplicate alternative, non-outperforming alternative, or both affects the ranking of the remaining alternatives. Experienced users need to be aware that the AHP approach and other MCDA methods are prone to rank reversal. Recording the decision-making process and the subjectivity of the decision-makers is important. A documentation of the decision-making process is helpful because it provides some insight into the decision-making process. The problem hierarchy sheds light on the decision's organizational structure. The majority of AHP tools let users view pair-wise comparison matrices that display the preference values assigned to each pair. The subjectivity of the decision maker's judgments is not made plain in this, however, and the justification and comprehension for those straightforward judgments are lost (Ghamgosar et al., 2011).

One of the most significant steps in determining the route of a natural gas pipeline is to identify the criteria and weights to be used. This is to determine the effect they will have on the route. As a result of these criteria and weights, importance ratings are assigned values; Yildirim (2017). This methodology will be based on engineering and environmental categories of cost factors. There is a set of objectives associated with each category, and these objectives are accompanied by spatial data inputs that are necessary to accomplish them. By combining spatial data from diverse sources, this methodology generates a cost-of-passage surface that can be analyzed via least-cost path analysis to generate alternative routes The optimal route selection index model based on optimization concepts such as suitability analysis, least cost path analysis, was developed with the aid of ArcGIS model builder shown in Figure 2. As independent variables, the model incorporates the reclassified LU raster and the reclassified slope raster, while the weights from the overall priorities are applied using the Weighted Overlay tool. In addition, alternative pipeline routes were generated using the same GIS principle of optimal route selection in order to generate weighted alternative routes. All datasets were processed to determine the final weighted optimal route.

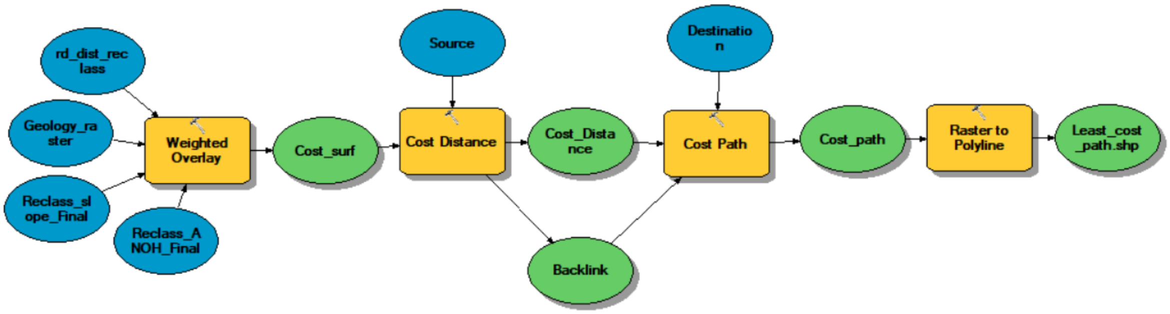


Figure 7. Spatial model

3.7. Result validation

The result of this analysis will be validated using two approaches:

i. Consistency Ratio.
ii. Topographic map of the study area.

The acceptable level of consistency ratio (CR) is less than 0.10, then the decision is given by the experts satisfactory.

CR=CI/RI

Where CI (λmax n) / (n 1) − − =, RI=Random consistency index , N= Number of criteria

λmax is priority vector multiplied by each column total.

n	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48	1.56	1.57	1.59

Table 5. Random Indices for matrices (Malczewski, 1999)

The optimal routes will be overlayed on the topographical map of the study area. This will be used to validate the optimal routes by examining how they traverse the topography and existing utilities within the study area.

4. RESULTS AND DISCUSSION

This chapter discusses the results obtained by evaluating the multiple criteria used to determine the least-cost routing models across the study area. The model incorporates Reclassified Land Use raster, Reclassified Slope raster, Geology raster, Euclidean distance to road, and existing Right of Way as independent variables. The overall priorities were weighted, and GIS principles of optimal route selection were also applied to generate weighted alternative routes. The results are presented in the following sections.

As opposed to vector data models, raster data models are more suitable for analyzing movements from cell to cell. A reclassification of the criteria layers was carried out to produce standardized and weighted attributes. In the case of Geology, a uniform value of 3 was assigned to each class. The results of the study indicate that most of the region's geological structure is stable enough to support the construction of the proposed pipeline. For the reclassification of land use, very low values of 4 and 5 were assigned to built-up areas and water bodies while Bare land was given a very high value while forest and cropland got medium values.

4.1. Results

4.1.1. Slope Layer

The slope layer was created and reclassified from the DEM of the study area. According to the figure below, the slope layer was reclassified into five classes (from 1 to 5) based on its degree of steepness. The obtained classes (numbered 1-5) indicate the suitability ranking of the slope layer.1 indicates very low corridor constraint and hence, very high corridor suitability and 5 indicate very high corridor constraint and very low corridor suitability as contained in the unified scale for constraints and suitability ranking in table 6.

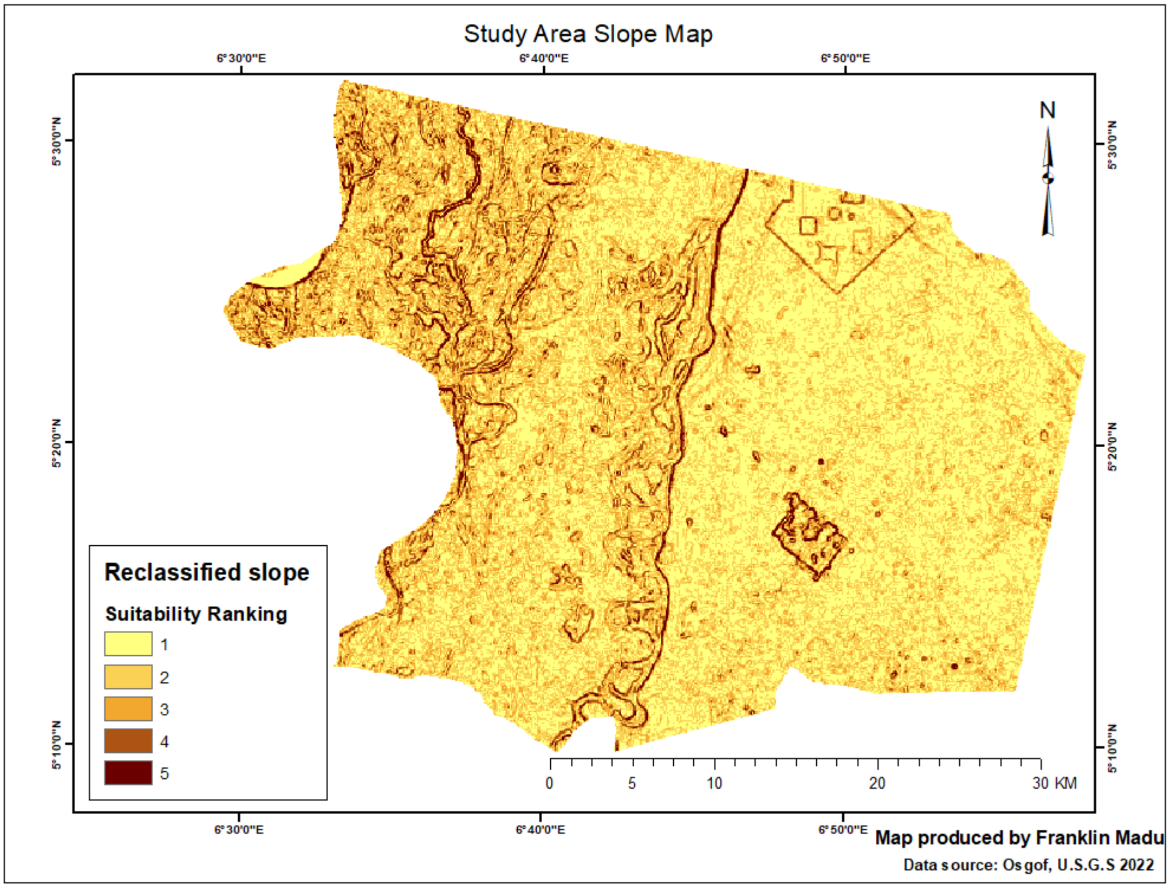


Figure 8. Slope map of the study area.

4.1.2. Linear Infrastructures (Roads and Existing ROW)

The linear datasets (roads and existing ROW) were reclassified into five classes with the ranking decreasing in importance from the existing facility. To protect roads and reduce construction costs, road buffers were placed every three kilometers in the study area. Buffers were installed at 150 meters, i.e., 50 meters on each side of the existing ROW, and subsequently at intervals of 2 kilometers. The obtained classes (numbered 1-5) indicate the suitability ranking of the linear infrastructure.1 indicates very low corridor constraint and hence, very high corridor suitability and 5 indicate very high corridor constraint and very low corridor suitability as contained in the unified scale for constraints and suitability ranking in table 6.

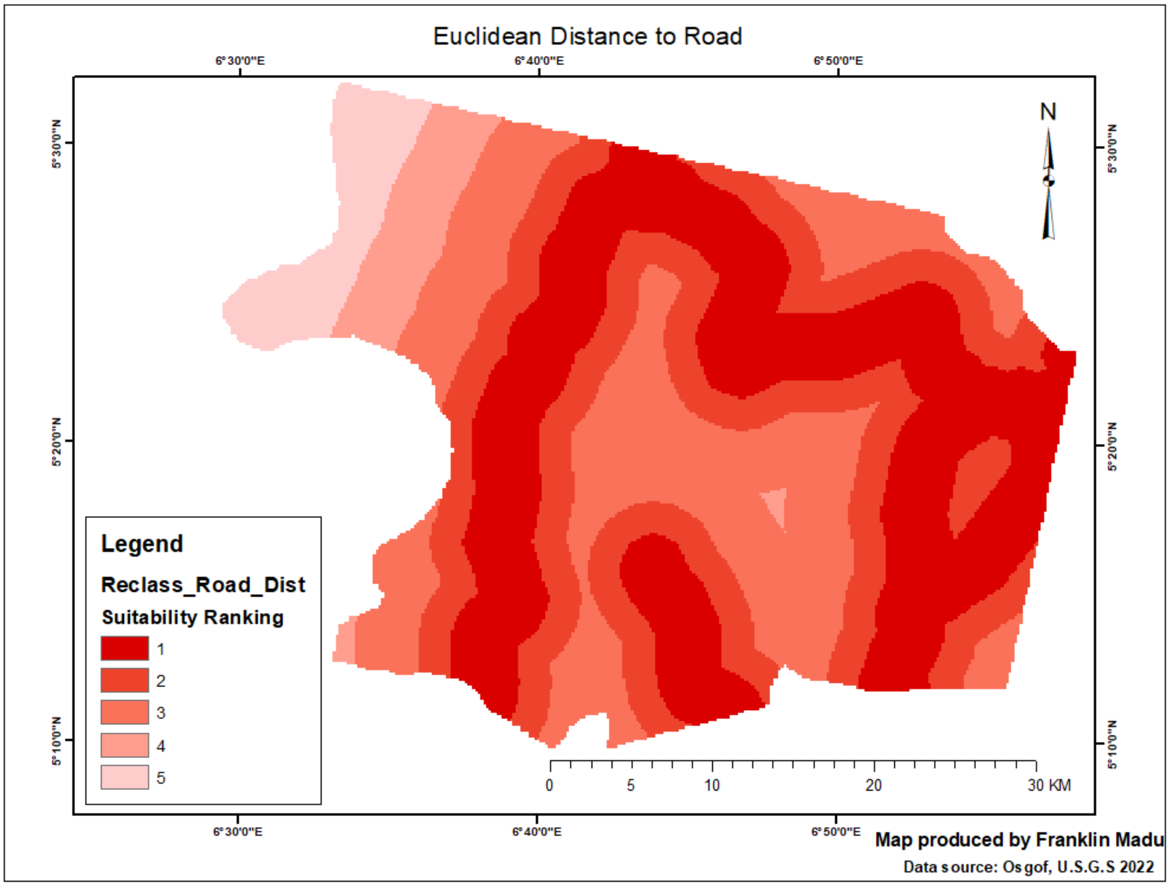


Figure 9. Map of the linear infrastructure in the study area.

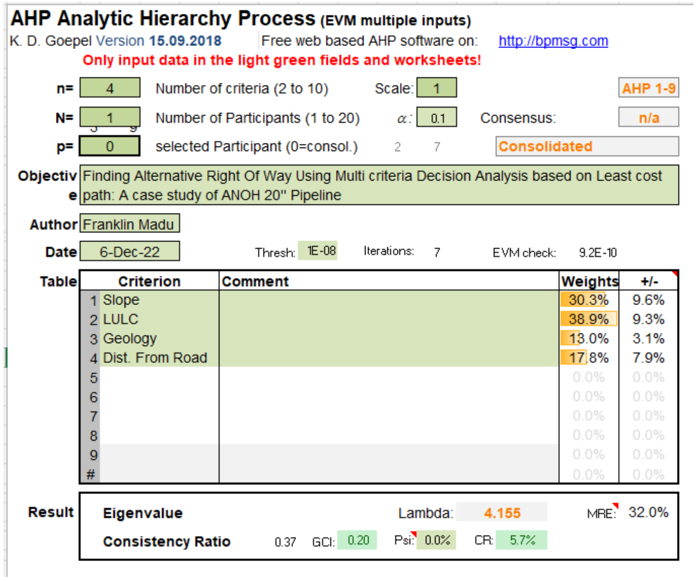
4.1.3. Weights from AHP Model

After reclassification, the corridor suitability and constraints ranking criteria were assigned based on a uniform scale of 1 to 5. In this manner, it was possible to capture grades of difference in any given data theme with sufficient refinement. In addition, it reduced the number of categories to a number that could be easily interpreted and understood (Gilbrook, 1998). See table 6 below.

Ranking	**Corridor Constraint**	**Corridor Suitability**
1	Very Low	Very High
2	Low	High
3	Medium	Medium
4	High	Low
5	Very High	Very Low

Table 6. Unified scale for constraints and suitability ranking (modified from (Gilbrook, 1998)).

Weights related to each criterion were generated according to the decision maker’s pairwise comparisons using the AHP model.



AHP Analytic Hierarchy Process **(EVM multiple inputs)**
K. D. Goepel Version **15.09.2018** Free web based AHP software on: http://bpmsg.com
Only input data in the light green fields and worksheets!

n=	4	Number of criteria (2 to 10)	Scale:	1	AHP 1-9
N=	1	Number of Participants (1 to 20)	α:	0.1	Consensus: n/a
p=	0	selected Participant (0=consol.)	2	7	Consolidated

Objective Finding Alternative Right Of Way Using Multi criteria Decision Analysis based on Least cost path: A case study of ANOH 20" Pipeline

Author Franklin Madu

Date 6-Dec-22 Thresh: 1E-08 Iterations: 7 EVM check: 9.2E-10

Table

	Criterion	Comment	Weights	+/-
1	Slope		30.3%	9.6%
2	LULC		38.9%	9.3%
3	Geology		13.0%	3.1%
4	Dist. From Road		17.8%	7.9%
5			0.0%	0.0%
6			0.0%	0.0%
7			0.0%	0.0%
8			0.0%	0.0%
9			0.0%	0.0%
#			0.0%	0.0%

Result
Eigenvalue Lambda: 4.155 MRE: 32.0%
Consistency Ratio 0.37 GCI: 0.20 Psi: 0.0% CR: 5.7%

Figure 10. AHP for LCP Model 1

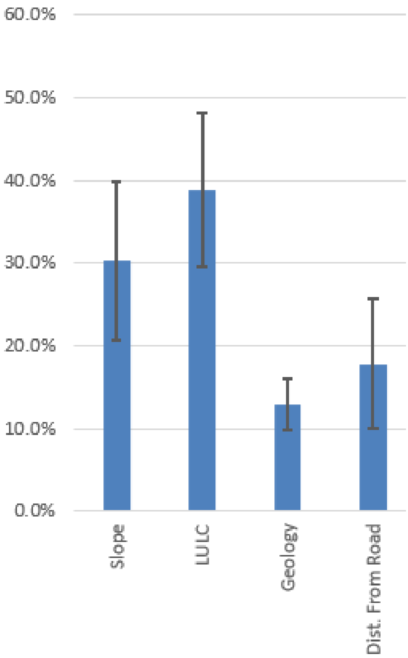
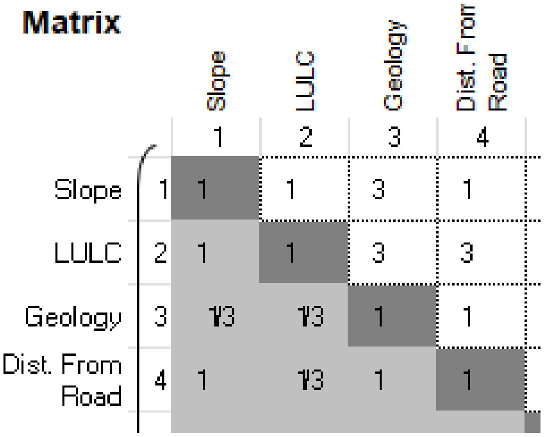
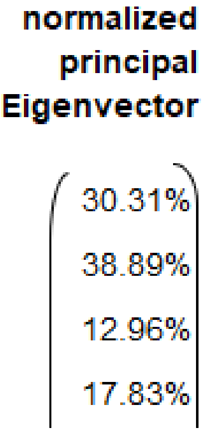


Figure 11. Criteria bar chat



Matrix

		Slope 1	LULC 2	Geology 3	Dist. From Road 4
Slope	1	1	1	3	1
LULC	2	1	1	3	3
Geology	3	1/3	1/3	1	1
Dist. From Road	4	1	1/3	1	1



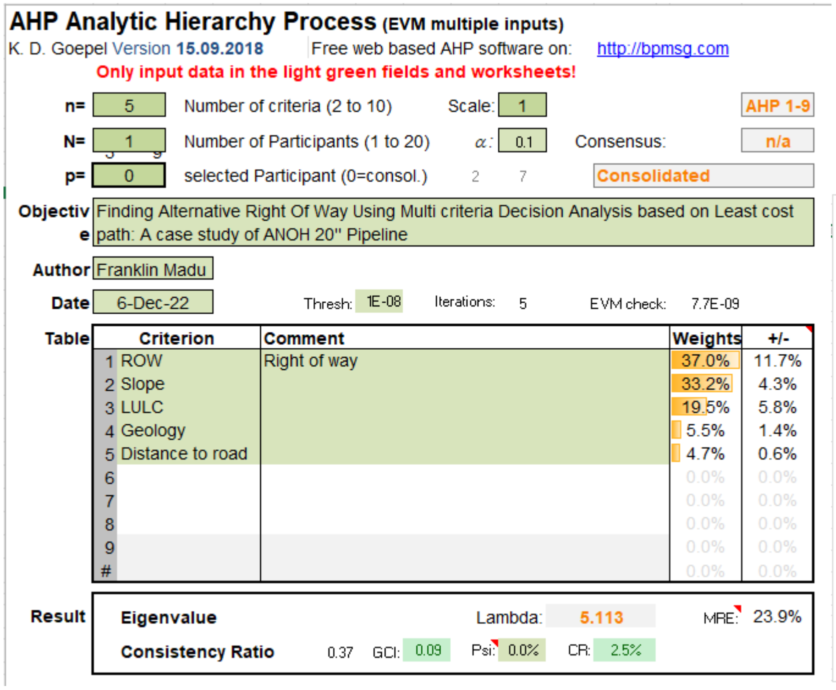
normalized principal Eigenvector

30.31%
38.89%
12.96%
17.83%

Figure 12. Consistency matrix

Figure 13. Criteria Weights

A Pairwise comparison matrix is used to compute the CI. The maximum eigenvalue evaluated was determined as (λmax = 4.155). For a hierarchical level of n=1, the CI is calculated as (CI = 0.051), and the corresponding random index (RI) is obtained as 0.9. The consistency ratio (CR) is determined to be 5.7%, which falls below the 10% threshold, so the Pairwise comparison matrix is acceptable.



AHP Analytic Hierarchy Process (EVM multiple inputs)

K. D. Goepel Version 15.09.2018 Free web based AHP software on: http://bpmsg.com

Only input data in the light green fields and worksheets!

n= 5 Number of criteria (2 to 10) Scale: 1 AHP 1-9

N= 1 Number of Participants (1 to 20) α: 0.1 Consensus: n/a

p= 0 selected Participant (0=consol.) 2 7 Consolidated

Objective: Finding Alternative Right Of Way Using Multi criteria Decision Analysis based on Least cost path: A case study of ANOH 20" Pipeline

Author: Franklin Madu

Date: 6-Dec-22 Thresh: 1E-08 Iterations: 5 EVM check: 7.7E-09

Table

	Criterion	Comment	Weights	+/-
1	ROW	Right of way	37.0%	11.7%
2	Slope		33.2%	4.3%
3	LULC		19.5%	5.8%
4	Geology		5.5%	1.4%
5	Distance to road		4.7%	0.6%
6			0.0%	0.0%
7			0.0%	0.0%
8			0.0%	0.0%
9			0.0%	0.0%
#			0.0%	0.0%

Result

Eigenvalue Lambda: 5.113 MRE: 23.9%

Consistency Ratio 0.37 GCI: 0.09 Psi: 0.0% CR: 2.5%

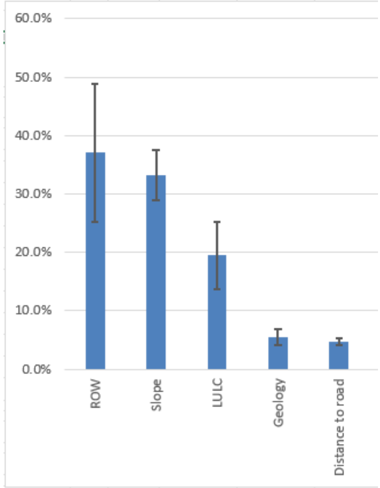
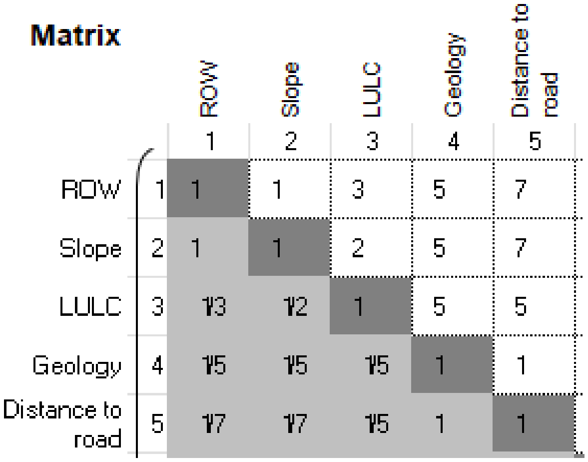
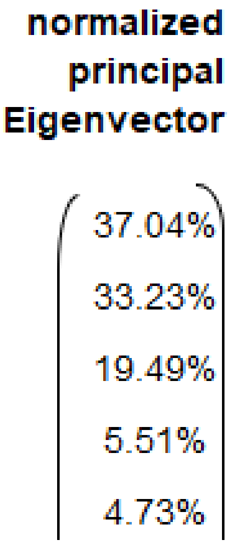


Figure 14.AHP for LCP Model 2 Figure 15. Criteria bar for model



Matrix

		ROW	Slope	LULC	Geology	Distance to road
		1	2	3	4	5
ROW	1	1	1	3	5	7
Slope	2	1	1	2	5	7
LULC	3	1/3	1/2	1	5	5
Geology	4	1/5	1/5	1/5	1	1
Distance to road	5	1/7	1/7	1/5	1	1



normalized principal Eigenvector

37.04%
33.23%
19.49%
5.51%
4.73%

Figure 16. Consistency Matrix for model 2 Figure 17. Criteria Weights Model 2

The maximum eigenvalue evaluated was determined as (λmax = 5.113). CI is calculated as (CI = 0.025), random index (RI) is obtained as 1.12. The consistency ratio (CR) is determined to be 2.5%, which falls below the 10% threshold (Goepel, 2018)

4.1.4. Discrete cost map (cost surface)

After constructing a weighted overlay model for movement through space, the cost of movement through the surface is determined according to the weights and criteria ranking of the AHP. Essentially, the costs represent the combination of factors affecting travel across the surface. The suitability of an area or cell for travel, or how much it costs to travel through a cell, is determined. To obtain the ultimate cost surface map for the built-up area and waterbody criteria, the overlay is set to impose the constraint factor ("no-data" map) on the composite cost surface results. To ensure that the LCP model does not pass through restricted areas, it ensures there are no data values in the built-up area and waterbody. Based on the final cost surface map, the restricted areas have the least or no membership within the study area. From the cost surface map, one can determine the least-cost or most optimal route based on the different surface friction levels in the region. The classes obtained (numbered 0-5) indicate the suitability ranking of the cost surface. 0 shows that no cost was calculated because the area is restricted. 1 indicates very low corridor constraint and hence, very high corridor suitability and 5 indicates very high corridor constraint and very low corridor suitability.

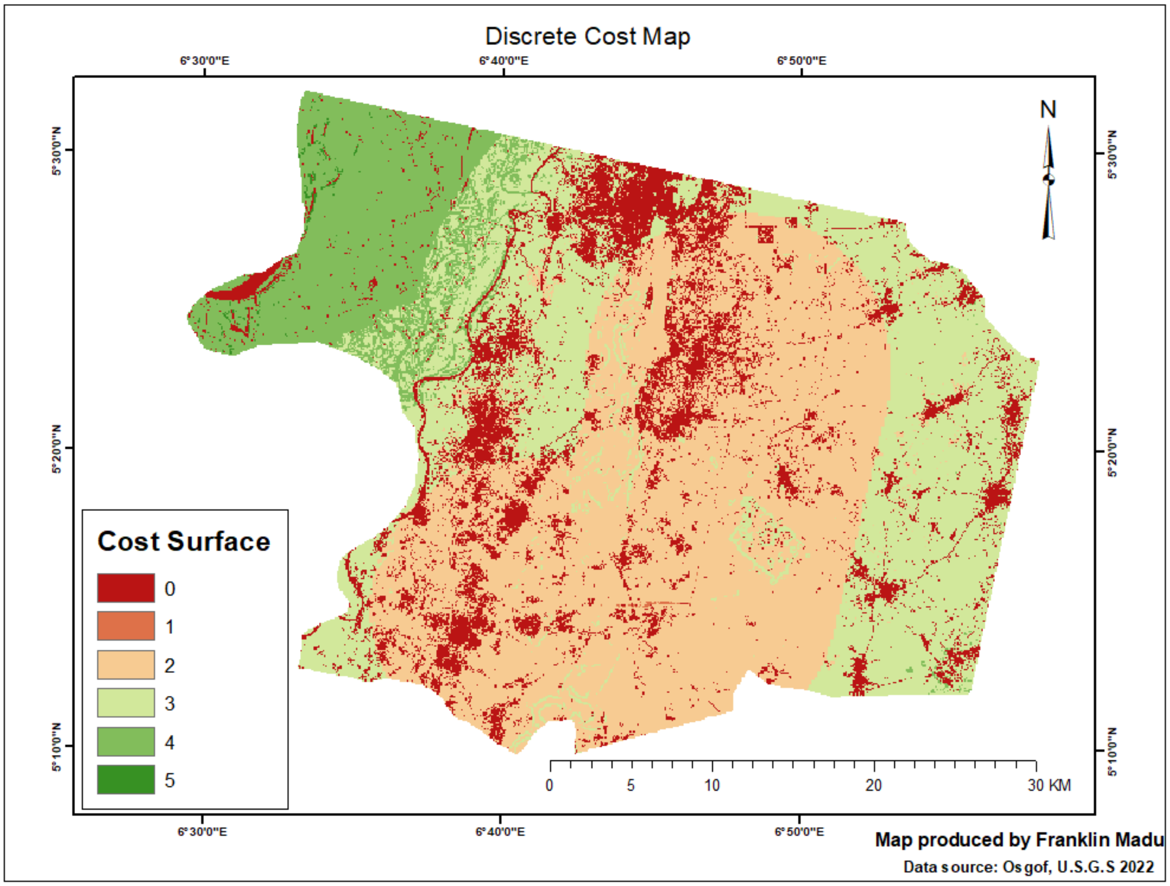


Figure 18. Discrete cost map.

4.1.5. Cost Distance Map

According to the working principle of the MCDA-LCPA algorithm, the accumulated total cost surface is generated over the weighted cost surface. Creating an accumulated cost surface from a cost surface containing frictions for movement and tracing a minimum cost from a source point to a destination are the two steps necessary for finding a minimum path over a surface partitioned into regions of different frictions for movement. A cost distance map is created by assigning a number to each cell indicating the least distance to the destination. From the source node to the destination node, this direction surface is used to draw the LCP.

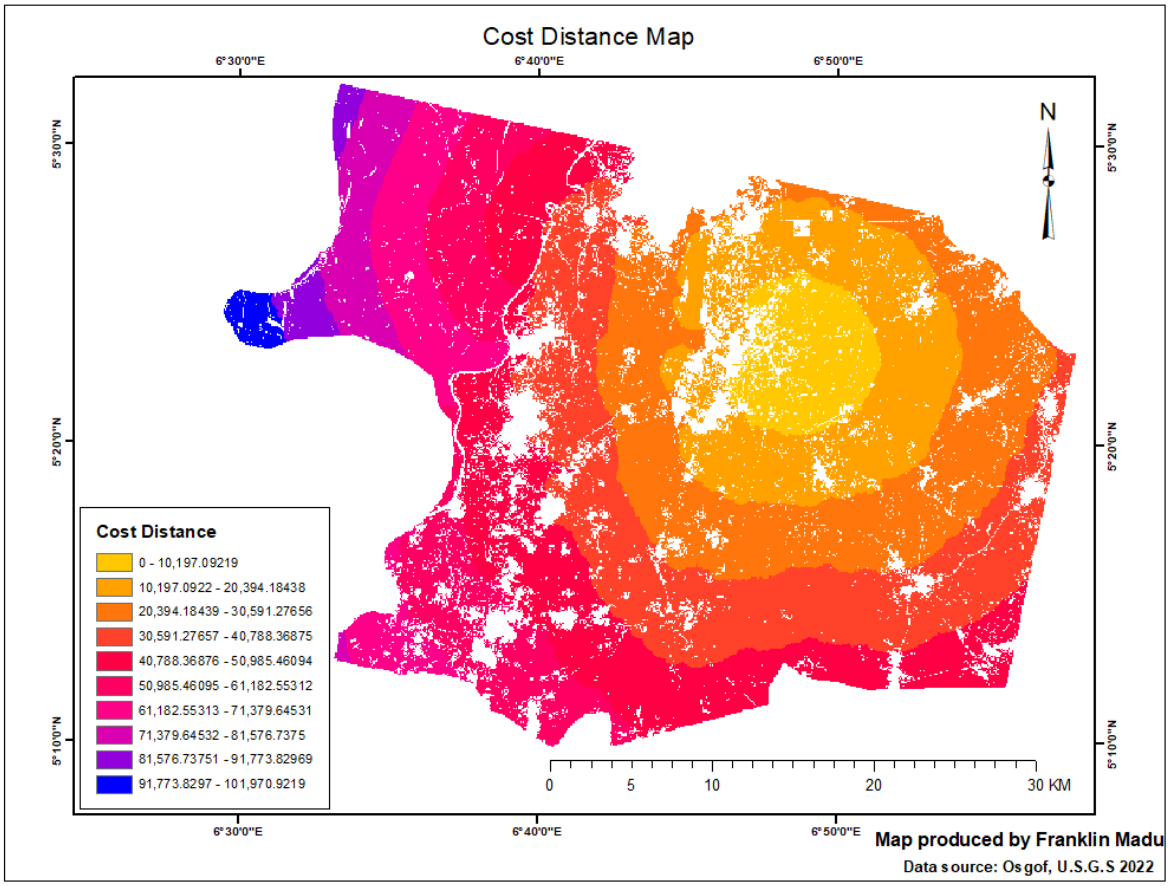
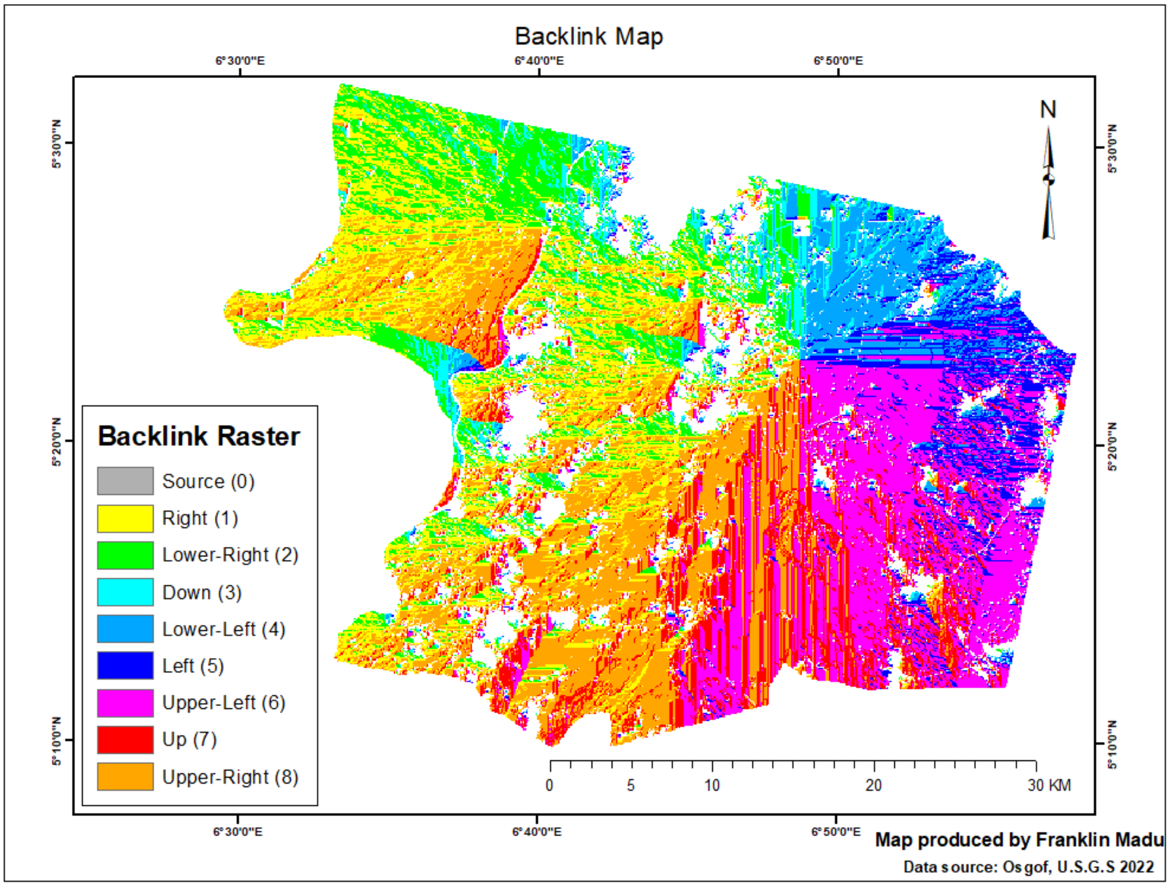


Figure 19. Cost Distance map.

4.1.6. Backlink Raster

The costs of passage in this model are anisotropic and depend on the location and direction of travel. The whole surface is, however, oriented in one direction. As a starting point, it is easier to move right and down. In this case, the costs vary over the surface and are dependent on the direction. A backlink raster surface suggests the smallest accumulated cost surface for each cell to the proximate source point. Using an output backlink, or direction raster, you can determine the shortest and least expensive route from any cell to the proximate destination. According to the algorithm for calculating the direction of the raster in each cell, the code in each cell is identical to the code in the neighboring cell. It is the fastest method of returning to the nearest integer numbered 0 to 8. The Value 0 is used to represent the source location. Assuming the least cost path leads from the existing cell to the lower right diagonal cell, the existing cell will receive the value 2. However, if the path leads directly down or south, the existing cell will receive value 3, etc (Gyabeng, 2020)

Figure 20. Cost Backlink coding



Map produced by Franklin Madu

Data source: Osgof, U.S.G.S 2022

Figure 21. Backlink map.

4.1.7. Least Cost Path

The weighted alternative routes are generated based on the overall criteria considered as input data. The reclassified raster layers from the previous step are included in this step. Using the cost path tool in Arc Toolbox, the least-cost path from a source to a destination has been calculated for optimal routes 1 and 2, which is approximately 22.87 and 21.78 kilometers respectively. The original route was 28 kilometers long. Two alternative routes were generated and analyzed after considering all factors and pixel calculations on the GIS raster layers. Based on an overlay of the alternative routes onto the composite raster image of the study area, Table 7 presents a comparative evaluation of all the potential routes. In terms of geology, the optimal routes traversed the red shale strata and the Cenozoic strata, completely avoiding the ash strata (Holocene) and all major road crossings. Land use layer optimizations avoided buildings and water bodies by prioritizing bare land, cropland, and forest, respectively. This alignment passes through surfaces with slopes less than 10% when placed on a slope raster. Generally, the optimal route passes through surfaces with slopes ranging from 0% to 8%. A second optimal alignment was found to have a slightly longer length than the first based on the aforementioned criteria and existing rights of way.

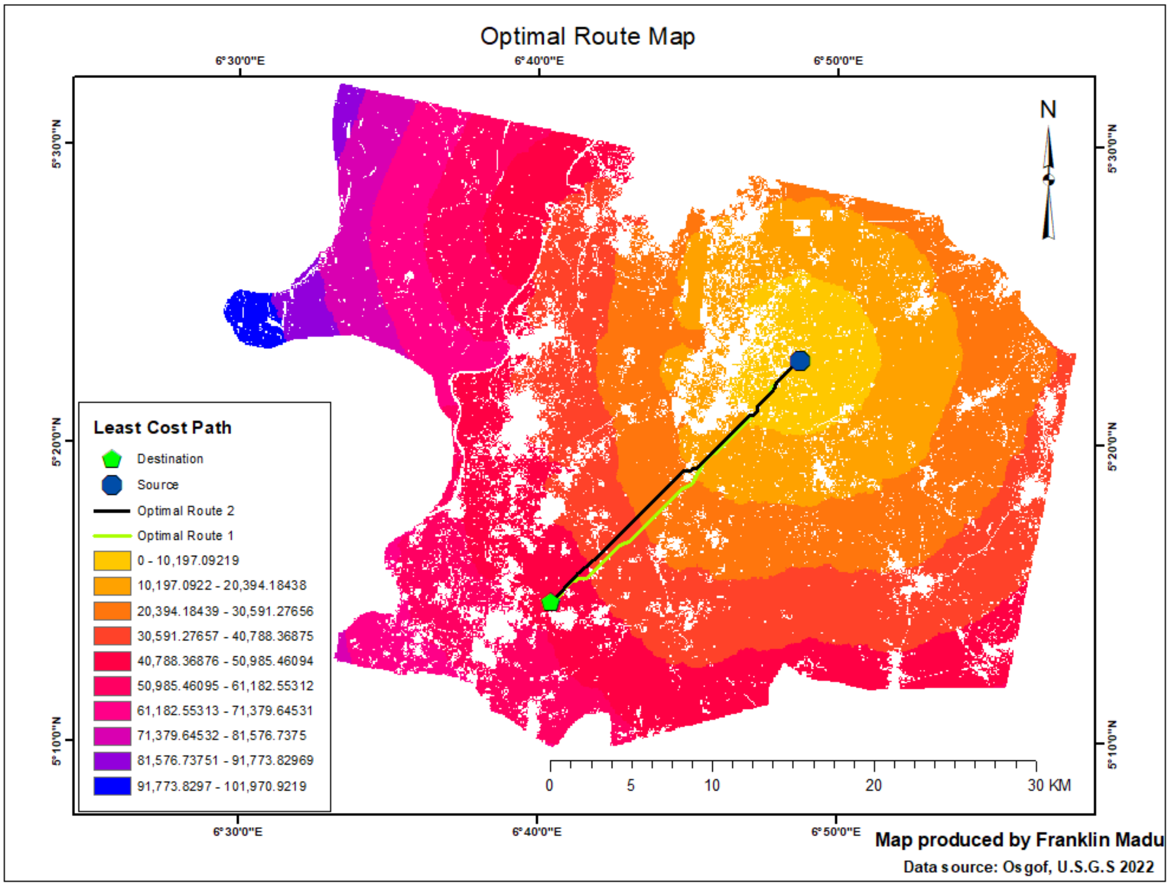


Figure 22. Least Cost Path map

Costs	Existing ROW	Optimal Route 1	Optimal Route 2
Lengths (km)	28	22.42	21.78
No of River crossings	1	0	0
No of Road crossings	7	0	0
No. of pipeline crossings	5	0	0

Table 7. Comparison of the alternative routes

Optimal Route Alternatives	Accumulated Cost Distance	Pipeline Length (km)	Length Diff. from the existing ROW	Percentage (%) Diff. in Length
Optimal Route 1	101,970.9219	22.42	5.58	19.92
Optimal Route 2	126,432.3828	21.78	6.22	22.21

Table 8. Costs and lengths of the optimal routes.

4.2. Discussion

MCDA-LCP analysis is powerful because it can store geographical data and analyze it more effectively and conveniently than paper maps (O'Looney, 2000; Wasi & Bender, 2004). All spatial criteria are combined and analyzed to produce a cost surface for the entire study area. The LCP evaluates a variety of data over a large area consistently and quickly to determine the least cost path. Based on the two cost surfaces in this study, the least-cost routing tool performs better than the existing ROW. Nevertheless, when it comes to factors that determine the cost of construction, the AHP optimal route is the most advantageous due to several factors.

There are several advantages to using the least cost paths over existing ROWs. The first is that they cross fewer steep areas, making them more cost-effective, and the second is that they have a shorter length than existing routes. As the pipeline route traverses less stepped terrain and passes fewer water resources and other significant features than the existing route, it is considered safe and economically viable. These are the top priorities during route design. In agreement with previous studies (A. Balogun, Chandio, et al., 2012; A. Balogun, Matori, et al., 2012; A.-L. Balogun et al., n.d.; Volkan Yildirim & Sevket Bediroglu, n.d.; Yildirim et al., 2012; Yildirim & Bediroglu, 2019, 2019), this study produced similar results.

The findings of this study demonstrate that the classification of LANDSAT 8 imageries enhances understanding of LULC patterns and characteristics of routing corridors, even though some earlier studies did not include Remote Sensing image processing in their works (A. Balogun, Matori, et al., 2012). According to the LANDSAT 8 images used in this study, as well as the GIS analysis, the optimal routes are suitable for the construction of the gas pipeline from source to destination. This confirms (Volkan Yildirim & Sevket Bediroglu, n.d.; Yildirim et al., 2012; Yildirim, Yomralioglu, Nisanci, Çolak, et al., 2017) results that integrated approaches can facilitate a better understanding of the pipeline routing procedure. The integrated model has been successfully demonstrated in Nigeria, even though their studies were conducted in Europe. The high ranking of environmental factors emphasizes the importance of preserving the LULC of the study areas and reducing the number of river crossings and built-up areas within the study areas. Additionally, environmental protection is an important issue for stakeholders in general. The more effective a route is compared to the existing right of way, the greater its effectiveness since it crosses a specific cost surface. Table 8 illustrates that optimal route 2 is the most efficient route. The objective of this cost surface was to highlight the combined cost of all criteria when traversing from the source to the destination. It is imperative to consider geological characteristics and the terrain regarding the sitting of pipelines designed for a lifespan of 30-40 years. More than any other factor, the terrain determines where a pipeline can be constructed.

Therefore, it is not surprising that optimal route 2 was the most efficient route. It is clear from the above analysis that certain criteria are more significant than others in the selection process of where to construct these pipeline projects. Despite this, the results of this study suggest that combining the MCDA-LCP- AHP model can result in environmental as well as socio-economic benefits by minimizing the possibility of environmental hazards and reducing the overall project cost. It is consistent with some previous studies in which 15–21% cost savings were achieved by integrating Geospatial-MCDM routing techniques (Allen, 2008; Dedemen, 2013).

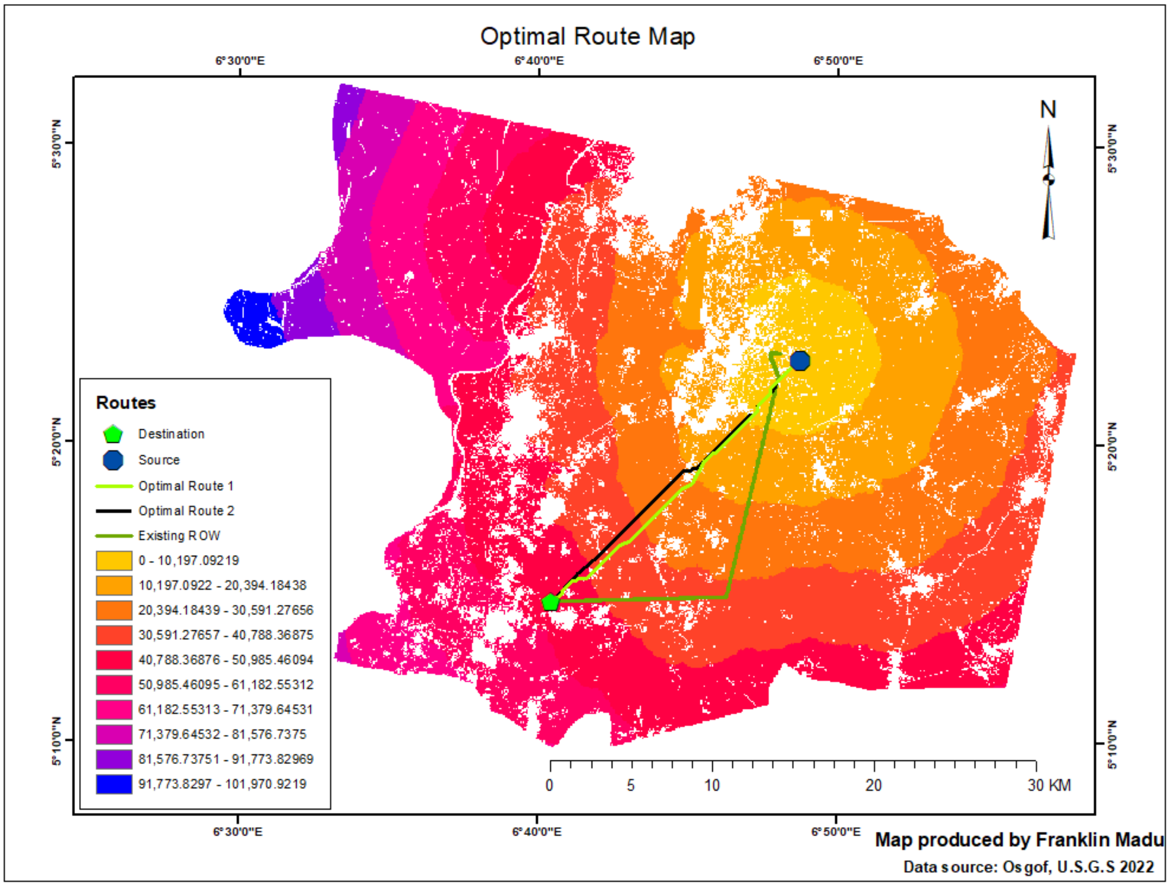
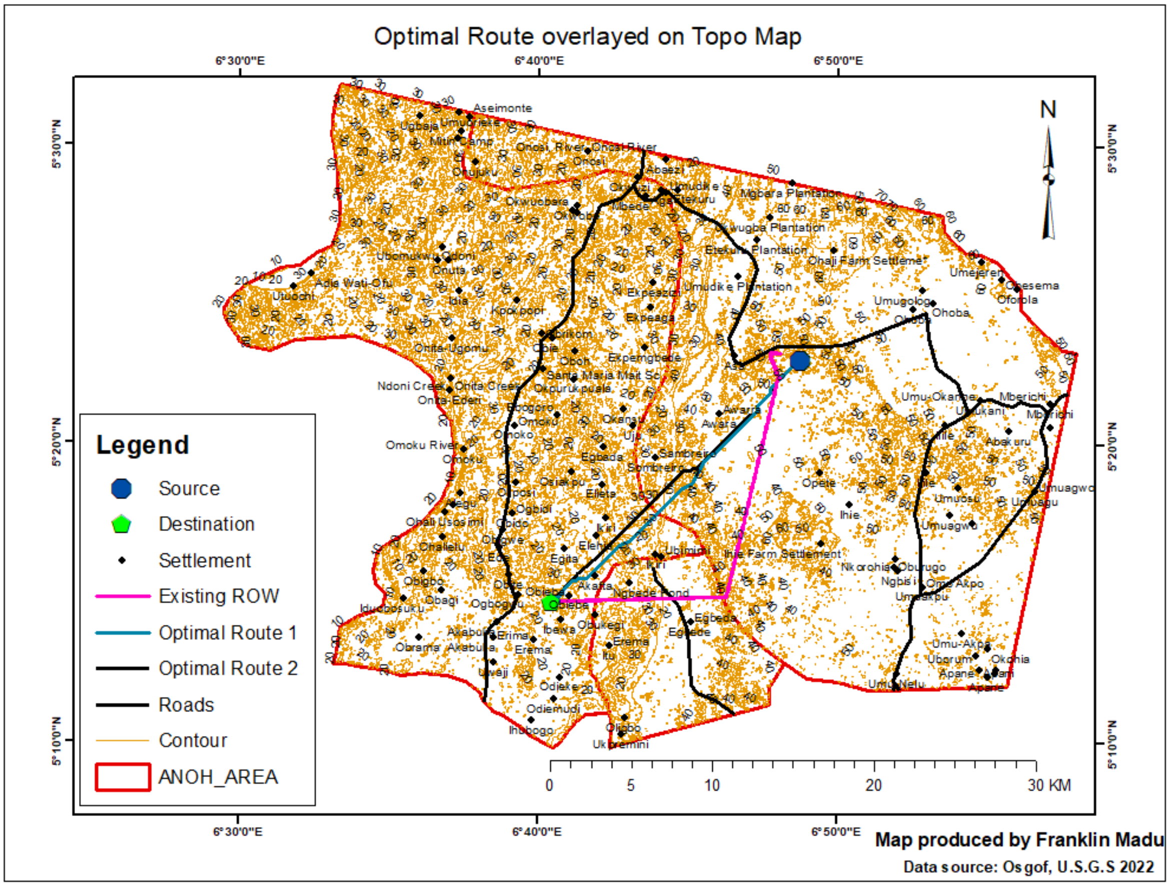


Figure 23. Least Cost Path and existing ROW

4.3. Model Validation

By overlaying the optimal routes over the topographic map of the study area, the plausibility and suitability of the modeled optimal routes were validated. The results of the analysis agree with those presented in Table 7. Additionally, it highlights the shortcomings of the existing ROW where it crosses steep slopes. As illustrated in the figure below, the result confirms the ground reality and has been verified for criteria such as the number of pipeline crossings, roads, and river intersections.



Map produced by Franklin Madu

Data source: Osgof, U.S.G.S 2022

Figure 24. Optimal Route overlayed on Topo map.

5. CONCLUSION

5.1. Summary

This section summarizes the general characteristics and significant contributions of the optimal route sitting approach. Secondly, discusses the implications of this approach for the planning decision-making process. As a final point, discuss some conceptual and technical issues associated with the proposed methodology. This study aimed to determine the optimal pipeline route using Multi-Criteria Decision Analysis based on the Least Cost Path. Based on the results of this study, the following conclusions can be drawn:

- To determine the optimal path for the pipeline, Arc GIS and MCDA-LCP were used.
- Using the Analytic Hierarchical Process (AHP) toolbox, it is possible to select the optimal path for a weighted overlay suitability map by using criteria such as land use, slope, road, geology, and existing ROW.
- Using the ArcGIS weighted overlay tool, the discrete Cost Map was derived from the weighted overlay of these criteria (layers).
- Optimal routes indicate the path that will result in the least cost for the pipeline project. The cost distance map and backlink map were generated from the discrete cost map by determining the least cost path between the source and destination points.

5.2. Conclusions

This thesis presents a GIS-based multicriteria evaluation approach for determining the optimal paths for constructing a linear facility. To construct these routes, criteria are collected and evaluated. This is done to determine whether they are suitable for traversing the study area from source to destination at the lowest possible cost. As a result of the Least Cost Path (LCP) models applied within the study area, built-up areas, water bodies, and steep slopes could be avoided, thus fulfilling the objective of this study within the given criteria. When compared to the existing ROW, the least-cost paths indicate the most efficient routes that provide a path between the documented sources and destinations.

In this thesis, similar studies were used as background and as a guide to combine the key factors in routing a large-scale pipeline project into a cost surface that was then able to be used for least-cost path analysis and determination of the optimal route. The thesis had some limitations in securing expert opinions for the AHP model, but by adopting a literature-based approach, the overall result was a viable least-cost path that met the main regulations involved in routing such infrastructure. Detailed studies are recommended since the use of the Least Cost Path (LCP) is essential in route planning and field investigations before final decisions can be made. To satisfy more detailed construction criteria, some improvements to the route design are usually required. To conclude, if the MCDA-LCPA algorithm can be incorporated into the early planning system, it can offer economic and time-saving advantages for the design of a sustainable route. Additionally, the technique provides multiple alternatives and the ability to compare them is a valuable tool for designers because it can eliminate many location problems.

5.3. Recommendations

Considering the use of MCDA-LCPA criteria for the selection of the optimal pipeline path in the study area, the following can be recommended for consideration in future research:

- There is a possibility of linking the output of this methodology with linear infrastructure design software. In this way, the methodology will be taken to a new phase, which is the preliminary design of alternatives. In addition, it will enable the construction cost to be recalculated based on the outputs provided by linear infrastructure design software.
- All route selection tasks should be conducted using this method as a preliminary investigation.
- Involvement of expert opinion in the process of selecting the necessary criteria and determining their appropriate weights and influences.
- For more accurate results, use recent images and current datasets with high resolution.

5.4. Strengths and limitations

This methodology has the advantage of being applicable to routing applications of all types. To develop alternative routes, several study areas, and different criteria can be compared and weighted. For this methodology to be applied to other locations and applications, it is necessary to identify appropriate routing criteria and the data to represent those criteria. This methodology can easily be extended to handle additional criteria and more accurate data within the context of this study area and application. This methodology has the capability of allowing different groups or experts to evaluate criteria and produce routes. Compared to manual methods, this methodology could produce a variety of routes relatively quickly. There is a limitation to this methodology in that it relies heavily on spatial data. There are two primary issues related to data availability and scale. In this project, we have gained a more comprehensive understanding of how data sets can be used within a GIS and LCP analysis to determine alternative ROWs for pipeline construction. The methodology provides a framework for further research as well as alternative routes to those previously proposed. Upon further refinement, the methodology may be used by developers and decision-makers with more expert knowledge to create other routing options. As better data becomes available and digital storage and processing capabilities improve, improved routes can be generated for this project and other routing applications.

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