ROAD ALIGNMENT OPTIMIZATION IN A HILLY REGION OF SRI LANKA USING GIS TECHNIQUES.

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ABSTRACT

This study focuses on road alignment optimization in a landslide-prone hilly region of Sri Lanka, specifically the Yatiyanthota and Yatiyanthota town areas. The research employs Geographic Information System (GIS) techniques to optimize the design of a proposed bypass road, considering economic, environmental, and societal factors. Traditionally, engineers have used manual drafting techniques to design road alignments, but this method has limitations, particularly in simultaneously analyzing multiple spatial factors. Therefore, GIS techniques, such as the Least Cost Path algorithm in ESRI's ArcGIS, were utilized to generate optimal alignment alternatives for the bypass road. The methodology incorporated digital elevation models, land use data, geological information, and hydrological features to create a comprehensive suitability analysis, with cost surfaces developed by assigning weighted values to each factor based on their relative importance to road construction feasibility and safety. Multiple scenarios were modeled to evaluate different prioritization schemes for environmental protection, construction cost minimization, and social impact reduction. The study compares and assesses these alternatives to bypass landslide-prone areas in Yatiyanthota while considering multiple factors simultaneously. Results indicate that the least-cost optimal alignment better coincides with engineering factors than with other assessment criteria. Additionally, the optimal alignment is shorter and has reduced cut/fill costs compared to the existing alignment. This research provides valuable insights into using GIS techniques to optimize road alignment design in hilly regions with complex geography and geology prone to landslides and earthquakes, with implications for road development projects in Sri Lanka and other similar regions.

Key words – Remote sensing, Geographic information system, Optimization techniques, least cost path analysis, Multi criteria decision making

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LIST OF ABBREVIATIONS

RS	Remote sensing
GIS	Geographic information system
GPS	Global positioning system
GND	Grama Niladari Divisions
DSD	Divisional secretary divisions
AHP	Analytical hierarchy process
MCDM	Multi criteria decision making
TRN	Terrain ruggedness index
LULC	Land use Land cover
MSS	Multi-spectral sensor
NDVI	Normalized difference vegetation index
WGS	World Geodetic system
UTM	Universal transverse Mercator
USGS	United states geological survey

CHAPTER 1 – INTRODUCTION & PROBLEM STATEMENT

1.1 Introduction

Roads play a crucial role in a country's economic and social development. In Sri Lanka, the development of the transportation sector is of great importance to connect rural areas with urban centers, enhance tourism, and create job opportunities. Yatiyanthota is a hilly region in Sri Lanka that suffers from natural disasters such as landslides, floods, and soil erosion, which makes transportation through the area challenging. The Colombo Hatton highway that passes through Yatiyanthota is a popular tourist route in Sri Lanka, and the existing road faces frequent landslides and heavy traffic congestion during peak seasons (Yatiyanthota Divisional Secretariat, 2018).

Therefore, there is an urgent need to identify optimized road alignments to the existing route in this region to ensure safe and efficient transportation for the residents and visitors. GIS is an effective tool for road alignment optimization as it can simultaneously analyze and simulate several factors (Li & Li, 2012). By considering several criteria, such as cost, safety, and environmental impact, GIS can help identify the optimal road alignment that minimizes the negative effects of natural disasters and enhances connectivity.

This research aims to use GIS techniques to optimize the road alignment in the landslide-prone area near Yatiyanthota town, which is part of the Colombo Hatton highway. The research will consider several factors, including environmental and socio-economic impacts, and propose a new route that will be more efficient and safer than the existing one.

The study area, Yatiyanthota, is in the Kegalle district of Sri Lanka and is a region rich in natural resources such as waterfalls, forests, and tea plantations. The new road alignment will not only enhance the region's connectivity but also boost the tourism industry in the area, which is a significant source of income for the local community. Furthermore, the proposed road will minimize the negative impacts of natural disasters on the transportation sector, enhancing the region's resilience.

In conclusion, optimizing road alignment in the hilly region of Sri Lanka using GIS techniques is a crucial step toward developing the transportation sector in the region. This research will propose a new road alignment that considers several criteria, including cost, safety, and environmental impact, to ensure the residents' and visitors' efficient and safe transportation. The proposed road alignment will also enhance the tourism industry in the area and minimize the negative effects of natural disasters on the transportation sector.

1.2 Research objective and Organization

The research objectives aim to address road alignment optimization in the hilly region of Sri Lanka using GIS techniques, specifically focusing on identifying the impact groups, criteria, and factors relevant to the study area. To achieve these objectives, the research will generate optimal alignments based on various factors such as engineering, environmental, economic, social, and transport. The study will also evaluate the total impact groups and identify the optimum alignment using GIS tools and CAD basis techniques (Li & Li, 2012).Objectives can be summarized as follows,

I. Identifying specific impact groups, criteria, and factors relevant to the study area.
II. Generating optimal alignments respective to Engineering, Environmental, Economic, Social, Transport and additional alignment generated by combining the above-mentioned impact groups.
III. Evaluating the total impact groups finds the optimum alignment using GIS tools and CAD basis techniques.

CHAPTER 2 - LITERATURE REVIEW

2.1 Literature review

A developing country like Sri Lanka seeks the most economical roadway types to improve its deficit of transportation requirements. Proposing roadway alignment for a hilly landslide susceptibility area of Sri Lanka is challenging due to its complex geography, geology, and vulnerability to landslides(Link 2020a).Landslides perchance to damage economically and physically to road networks(Donnini et al. 2017) . In Sri Lanka, road terrains mainly located in the hilly areas are frequently subjected to landslides. It increases the maintenance costs. Since roads have to be closed, the heavy traffic occurs(Padmani and Sudath 2016).

Economic and urban development of small cities leads to traffic congestion, safety, noise, air pollution, etc. Bypass roads have been introduced to overcome these cons. The main objective of a bypass road is to mitigate traffic congestion while increasing mobility. Transport and other urban planning agencies should perceive their proposals' potential physical and socio-economic impacts. Especially towns located in the hilly area will be challenging, and many variables should be considered(Sewwandi and Jayasinghe 2021).

Connecting the start and endpoint for a roadway section has unlimited alignment alternatives. The traditional highway design process requires experienced engineers, enormous time, and tools to determine the best alternative(Awwad 2005). Indeed, in some cases, it is a manual process. The following drawbacks were excerpted in the study (Yakar and Celik 2014).

I. Essential criteria such as environmental, economic, social, and traffic techniques could not be considered during the alignment proposing stage.

II. The proposed alignment could not be optimum; consequently, criteria cannot be handled simultaneously.

III. Environment and society could not be considered sufficient.

IV. Since inadequate proposed structure data at the planning stage, structures like bridges and retaining walls might be needed during the construction phase, leading to more costs.

Many studies were conducted related to "Highway alignment optimization" using different methods. The intention of "Highway alignment optimization" would be single or multi-objective In single objectives studies, the principal objective is minimizing the cost(Link 2020a). Moreover, the proposed alignment should be satisfied with the engineering design standards such as including curvature, gradient, sight distance etc.(Jha and Schonfeld 2000)

Single objective optimization can be solved using calculus of various network optimization, dynamic programming, genetic algorithms, etc.(Maji and Jha 2009). Genetic algorithms are a widely used mathematical optimization method (Zhao, Liu, and Mbachu 2019). The study (Jha, McCall, and Schonfeld 2001) is a comprehensive approach to solving a highway optimization problem. To solve the optimization problem, genetic algorithms were used. The study uses cost formulation techniques, and right of way, environmental, pavement, construction, maintenance, and earthworks costs were considered here. Using a cost formulation technique, these costs were formulated into a cost surface, and a Genetic algorithm found the optimum (least cost alignment) among the multiple alignments. As shown in figure 1, there are multiple orthogonal cutting straight lines perpendicular to the connecting line of origin and destination points. According to the engineering standards, the optimal points in each orthogonal cutting straight lines are connected using curves and lines (Jha et al. 2001).

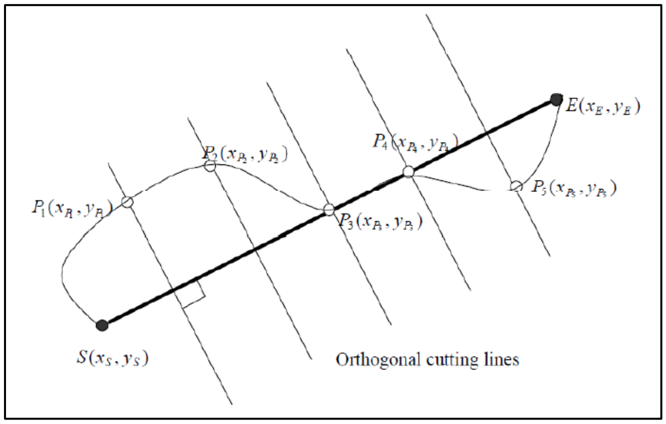

Figure 1 – Alignment representation

Even though this model produces accurate and significant results, it takes considerable time and resources. The intervention of geographical information systems is limited here. It is used only to create the database and maps such as the right of way and environmental costs. Lots of spatial variables and factors such as landslide susceptibility were not considered here (Jha et al. 2001).

That mathematical optimization method was improved by (Jha and Schonfeld 2004a; Maji and Jha 2009) , and they achieved more accurate and sound results by developing a multi-objective genetic algorithm. Search space was limited using feasible gates, which narrow the horizontal search space. It reduces the computational time significantly (Jha and Schonfeld 2004a). The study (Maji and Jha 2009) is a multi-objective highway alignment optimization study. Diminution of travel time cost, vehicle operating cost and accident cost tend to make the alignment straight .furthermore, minimization of the land acquisition cost, earthwork cost and pavement construction cost tend to make the alignment circuitous (Maji and Jha 2009). In this approach, the cost makes the alignment straight and circuitous are grouped and evaluated simultaneously. Nevertheless, the inadequate intervention of geographic information system techniques can be identified same as (Jha et al. 2001; Jha and Schonfeld 2000) studies.

GIS is a widely used technique in optimization riddles of spatially distributed linear objects such as railways, roads, and highway engineering. Using GIS, spatial variables such as environmental, topography, built-up areas, land use/land cover and geology-related variables can be easily modelled(Mackenzie and Cusworth 2007). Analyzing and understanding various parameters for planning and designing alignment of transport communication has become more accessible due to the ability to consider many spatial variables simultaneously(Van Loon, Rietveld, and Brons 2011). Then the use of GIS in road alignment optimization and design can be considered mandatory. Since several cost types are sensitive to geography; GIS will be more efficient(Jha et al. 2001).

The least-cost path algorithm is an efficacious tool in GIS to determine the optimum roadway alignment (Lee and Stucky 1998).Cost surface is created using least-cost path tool, and there are many past studies regarding the algorithm(Awwad 2005; Bailey 2003; Subramani et al. 2014; Yakar and Celik 2014). The least-cost path tool algorithm slightly depends on the type of software used. The study (Yakar and Celik 2014) uses IDRISI software to simulate the least cost path, and the study (Link 2020a) uses ArcMap to proceed with the optimization.

The study (Awwad 2005) only considered Land cost, land slope, and the environmental feature criteria, and it was implemented by ArcGIS software. The methodology was applied to two case studies in each study, and two optimal alignments were proposed. It was concluded that the right of way costs are significantly lower than the proposed alignments for both case studies.

Multiple methods are used to define weights for different criteria. The study (Yakar and Celik 2014) uses Multi-criteria decision-making (MCDM) and GIS to determine highway alignment. Fuzzy functions were used to standardize criteria maps, and Analytic Hierarchy Process (AHP) was used to determine criteria weights. Moreover, the weighted linear combination method was used for the combination of criteria maps.

The study (Link 2020a) developed (Yakar and Celik 2014) works by extending the least cost path algorithm to control the slope of the optimized alignment by restricting the vertical cost factor. ArcGIS path distance tool was used to control the slope here. A case study was done, and seven alternative alignments were generated using the least-cost path algorithm. Finally, the length of the alignment, geometric feasibility, and cut/fill of the alignment were assessed using the CAD system.

2.2 Findings

The literature review reveals significant limitations in traditional highway design processes, which are time-consuming, manual, and often fail to simultaneously consider essential criteria like environmental impact, economic factors, and social concerns. This inadequacy leads to suboptimal alignments and unexpected costs during construction, particularly in challenging terrains like Sri Lanka's landslide-prone hilly regions. These traditional approaches also insufficiently address the specific challenges faced by developing countries with economic constraints.

Recent research demonstrates a clear evolution toward more sophisticated optimization methods, progressing from single-objective (primarily cost-focused) to multi-objective approaches that balance competing factors using genetic algorithms. The integration of GIS has proven particularly valuable, enabling the modelling of spatial variables and the application of least-cost path algorithms for determining optimal alignments. Advanced methodological approaches including Multi-criteria decision-making (MCDM), Analytical Hierarchy Process (AHP), and path distance tools to control slope further enhance the optimization process, though research gaps remain in effectively balancing computational efficiency with comprehensive spatial analysis in complex terrains.

CHAPTER 3 – METHODOLOGY

In this chapter a descriptive review has been done for the complete of main objectives. Aim of the study is to identify impact groups, criteria and generate the optimum alignment. The methodology/main steps of the research include following steps.

3.1 Software and hardware tools

ArcGIS 10.8.1 is the major GIS-based software used for the study, and most of the analysis has proceeded on this platform. Spatial Analysis extension is needed, including the Least cost path tool(Link 2020a). Moreover, Civil 3D and AutoCAD software are used, which is based on CAD. The civil 3D 2018 version is used for horizontal and vertical alignment design and further cut and fill volume calculations(Abdul, Hadi, and Alhaydary 2018). In addition, differential global positioning machines are also used for field surveying and verification purposes(Specht 2023).

3.2 Data

This section contains the spatial data which is used for the research study. All data types are clipped or masked casually to reduce the data sizes and processing time. Except for the Digital elevation model, all the other types of data are in vector format. The raster data and proceeded data are resampled into a 30-meter resolution size. The following table is listed out the spatial data used in the study.

Table 1 : Data types

	Data	Source	Format	Description
1	Building footprint	Survey department Sri Lanka	Shapefile (Polygon)	Digitized from Google earth software and high-resolution satellite imagery
2	Rivers/Drains	Survey department Sri Lanka	Shapefile (Polyline)	Digitized from google earth and existing topographic maps
3	Land use land cover	Survey department Sri Lanka	Shapefile (Polygon)	Digitized from Google earth software ,high-resolution satellite imagery and existing topographic maps
4	Road Network	Survey department Sri Lanka	Shapefile (Polyline)	Digitized from Google earth software ,high-resolution satellite imagery, existing topographic maps and street maps
5	Origin/Destination	Road development authority Sri Lanka	Shapefile (Point)	Origin and destination are suggested by the experts in the industry (RDA Sri Lanka)
6	Landslide Hazard Zones	National building research organization Sri Lanka	Shapefile (Polygon)	Digitized using the maps which developed according to the landslide investigations and surveys from NBRO Sri Lanka
8	Tourist sites	Survey department Sri Lanka	Shapefile (Points)	Digitized from Google earth software ,high-resolution satellite imagery, existing topographic maps, and street maps

3.3 Road alignment design

Road alignment design is a crucial element in the development of road networks. It is the process of determining the geometric layout of a road, including its curves, grades, cross-sections, and horizontal alignment. The road alignment design plays a significant role in ensuring the safety, efficiency, and sustainability of transportation infrastructure. A well-designed road alignment considers traffic volume, speed limits, terrain, climate, and environmental impact. This involves using engineering principles and software tools to develop a design that minimizes construction costs while maximizing the operational performance of the roadway. However, the research study is based on GIS techniques; only the geometric design has been considered(American Association of State Highway and Transportation Officials 2018).

3.4 Origin and destination

The starting and ending points for the proposed road alignments are selected as the origin and destination, respectively. These points are linked to the existing road network, with this study's origin point connected to a bridge and the destination point connected to an existing junction. The selection of these two points helps to define the study area, limiting it to a specific geographic region and fastening the analysis's processing time(Choi and Koo 2019).

3.5 horizontal alignment

Horizontal alignment design is a crucial component of road design that concerns the layout of the roadway in plain view. It involves designing the curves and transitions that connect the origin and destination points, creating a smooth and efficient travel path for road users. The selection of appropriate origin and destination points is essential in determining the horizontal alignment of a road, as it directly impacts the road's overall geometry(Link 2020b). The radius of curvature for the curves and transitions in the horizontal alignment is determined based on the design standards specified by the relevant transportation authority. In this study, the Road Development Authority Sri Lanka (RDA) design standards were used to ensure that the horizontal alignment meets the required safety and efficiency standards.

3.6 Vertical alignment

A major element of road design is vertical alignment, which involves arranging the roadway in a vertical plane. It includes the design of the grade or slope, which connects different points on the road. The grade of a road is a significant factor in ensuring that the road is safe and efficient for motorists to navigate. The selection of appropriate grades is critical to determine the vertical alignment of a road, with steep grades potentially causing safety issues and flat grades impacting the road's efficiency(Austroads 2018).

Design standards play a critical role in determining the appropriate grades for vertical alignment. In road design, design standards are used as a basis for the design process, ensuring the road's safety and functionality. The relevant transportation authority typically specifies these design standards. In this study, RDA (Road Development Authority) design standards were used to determine the appropriate grades for the vertical alignment. These design standards include specifications for maximum and minimum grades, the length of grades, and other parameters(American Association of State Highway and Transportation Officials 2018).

Using RDA design standards in the design process ensures that the designed roadway is safe, efficient, and conforms to the relevant regulatory requirements. The standards also help ensure consistency in road design, which is critical in enhancing road safety and promoting ease of use for motorists.

3.7 Approach

The methodology of the approach involves the composition of a GIS-based road alignment optimization method and the comparison of road alignments designed using traditional approaches with those designed and optimized using the GIS-based method. The approach is primarily based on the works of Awwad (2005) and Yakar & Celik (2014). However, it is contextualized to conform to hilly regions by using additional data, extending the methodology by incorporating constraints on the grade of the road alignment in the optimization process and using engineering CAD systems like Civil 3D to assess the cut/fill volume and cost realistically. The design criteria considered are the same as the research study by Padmani and Sudath (2016), in which the criteria are maximized. The

GIS-based optimization of road alignment is then performed between the two obligatory points, origin, and destination, using various spatial criteria to generate six alternative road alignments. The optimal alignment is found using the Least Cost Path Analysis (LCPA) method and then drawn inside an engineering CAD environment to calculate the cut/fill volume and check the geometric feasibility of the alignments based on road design standards. The final process involves assessing the six alternative road alignments based on various spatial and non-spatial criteria, such as cumulative cost, length, and cut/fill volume.

The approach is a combination of GIS-based optimization and traditional road alignment design methods that considers additional data and constraints to optimize road alignment in hilly regions. The approach has been developed by building on previous research, such as the works of Awwad (2005) and Yakar & Celik (2014) and has been adapted to conform to hilly regions. The design criteria used in the approach are based on the research study by Padmani and Sudath (2016). Finally, the approach uses various spatial and non-spatial criteria to assess six alternative road alignments generated using the LCPA method, to select the optimal road alignment based on factors such as cumulative cost, length, and cut/fill volume.

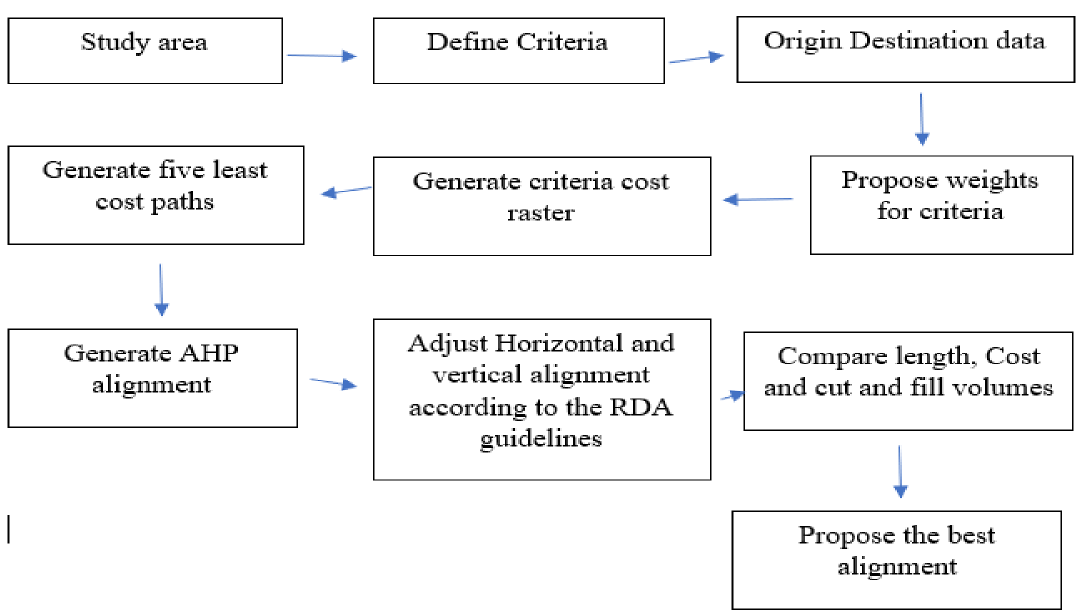

Figure 2 : Methodology flow chart

3.8 GIS based road alignment optimization

GIS road alignment optimization is optimizing the road network alignment using GIS tools. The main objective of GIS road alignment optimization is to generate the optimal alignment of a road network that can minimize the construction cost and maximize the social and environmental benefits (Bhatta, 2010; Padmanabhan & Sudhath, 2016). The use of GIS technology in road alignment optimization can help improve the process's efficiency by providing tools that can assist in analyzing and selecting the best alignment for a given road network (Awwad, 2005). One of the most commonly used tools for GIS road alignment optimization is the Least Cost Path Analysis (LCPA) tool (Yakar & Celik, 2014).

The LCPA tool is a geoprocessing tool that helps to determine the least cost path or route between two points on a cost surface map (Sithole & Vosselman, 2004). Cost surface maps are created using criteria such as topography, land use, soil type, and other factors that affect the construction of roads (Bai et al., 2018). These cost surfaces are represented by raster grids, where each cell has an associated cost value that reflects the difficulty of constructing a road through that cell (Sithole & Vosselman, 2004). The LCPA algorithm calculates the least cost path by minimizing the cumulative cost of traversing through each cell, starting from the origin and ending at the destination (Bai et al., 2018).

The LCPA tool has several stages, including creating the cost surface map, identifying the source and destination points, and calculating the least cost path (Yakar & Celik, 2014). The first stage involves the creation of the cost surface map, which is used to assign a cost value to each cell in the raster grid based on the criteria chosen for the road construction (Bai et al., 2018). The second stage involves identifying the source and destination points, which are the starting and ending points for the road construction (Sithole & Vosselman, 2004). The third stage involves calculating the least cost path using the LCPA algorithm, which minimizes the cumulative cost of traversing through each cell (Yakar & Celik, 2014).

Cost surface maps are crucial in the LCPA tool as they provide the basis for calculating the least cost path. The criteria chosen for the cost surface map must be carefully selected to ensure that the resulting path is optimal for road construction (Bai et al., 2018). For example, in hilly regions, the cost surface map must consider the area's topography to ensure that the road alignment is safe and feasible (Awwad, 2005). Other factors such as land use, soil type, and hydrology must also be considered to ensure that road construction is socially and environmentally sustainable (Padmanabhan & Sudhath, 2016).

3.9 LCPA algorithm

The Least Cost Path Analysis (LCPA) tool is a geoprocessing tool commonly used in GIS to determine the least cost path between two points on a cost surface map. The LCPA algorithm calculates the least cost path by minimizing the cumulative cost of traversing through each cell, starting from the origin, and destination at the destination. This tool is handy for optimizing road network alignment, as it can help to reduce construction costs and maximize social and environmental benefits (Bhatta, 2010; Padmanabhan & Sudhath, 2016).

Here are the stages involved in the Least Cost Path Analysis (LCPA) tool in GIS:

1. Creation of the cost surface map: The first stage of LCPA involves the creation of a cost surface map. This is used to assign a cost value to each cell in the raster grid based on the chosen criteria for road construction. Cost surfaces can be created using different criteria, such as topography, land use, soil type, and other factors that affect the construction of roads (Bai et al., 2018). These cost surfaces are represented by raster grids, where each cell has an associated cost value that reflects the difficulty of constructing a road through that cell (Sithole & Vosselman, 2004).

2. Identification of the source and destination points: The second stage of LCPA involves identifying the source and destination points. These are the starting and ending points for the road construction. The source and destination points can be defined using different criteria, such as road networks, buildings, or other features on a map (Sithole & Vosselman, 2004).

3. Calculation of the least cost path: The third stage of LCPA involves calculating the least cost path. This is done using the LCPA algorithm, which minimizes the cumulative cost of traversing through each cell. The algorithm calculates the least cost path by finding the path with the minimum cumulative cost, starting from the source, and ending at the destination. This involves finding the path with the least resistance based on the cost values assigned to each cell in the cost surface map (Bai et al., 2018).

The LCPA algorithm is based on Dijkstra's well-known shortest-path algorithm widely used in computer science. The Dijkstra's algorithm is a graph search algorithm used to find the shortest path between two nodes in a graph. In the LCPA algorithm, the cost surface map is converted into a graph, where each cell in the raster grid represents a node, and the cost of traversing between adjacent cells represents the weight of the edge connecting the nodes (Sithole & Vosselman, 2004).

Once the cost surface map is converted into a graph, Dijkstra's algorithm finds the shortest path between the source and destination nodes. The LCPA algorithm modifies the Dijkstra's algorithm by using the cost values assigned to each node to determine the most optimal path for road construction. The LCPA algorithm calculates the cumulative cost of traversing through each cell, starting from the origin and ending at the destination. The least cost path is then determined by selecting the path with the lowest cumulative cost (Yakar & Celik, 2014).

The LCPA tool has several advantages over traditional road alignment optimization methods. It is a faster and more efficient way of finding the optimal path for road construction, as it can process large datasets quickly and accurately. It can also analyze multiple scenarios and select the most optimal path based on different criteria. The LCPA tool is also user-friendly and can be easily integrated into existing GIS software (Awwad, 2005).

3.10 Limitations of the LCPA

One of the limitations of the LCPA tool is that it assumes a continuous and homogenous cost surface, which may only sometimes be the case in the real world. The cost surface can be discontinuous and heterogeneous due to various factors such as land use, slope, soil type, and other environmental variables (Bai et al., 2018). The LCPA algorithm does not account for these variations and thus may produce suboptimal results in some situations (Sithole & Vosselman, 2004).

Another limitation of the LCPA tool is that it is a local search algorithm, meaning that it only considers the path between the source and destination points and does not consider the global optimum (Awwad, 2005). This can lead to situations where the resulting path could be more optimal for the entire road network (Yakar & Celik, 2014).

The LCPA tool also assumes that the cost of traversing each cell is independent of the path taken to reach that cell (Bai et al., 2018). However, this may only sometimes be the case, especially in situations where the construction of a road through a cell affects the cost of constructing roads in nearby cells. The LCPA tool may produce a different path than the most optimal (Sithole & Vosselman, 2004).

Another limitation of the LCPA tool is that it does not consider other factors that may affect the construction of roads, such as legal and regulatory constraints, socio-economic factors, and environmental considerations (Padmanabhan & Sudhath, 2016). These factors may limit the range of options available for road construction, and thus, the LCPA tool may need to be more effective in generating optimal paths in such situations. However, this limitation is eliminated since many criteria are considered simultaneously.

3.11 multi-criteria decision making (MCDM)

Multi-Criteria Decision Making (MCDM) techniques are widely used in GIS-based platforms to solve complex decision-making problems involving multiple criteria (Jankowski & Nyerges, 2001). MCDM techniques integrate multiple criteria or attributes in decision-making, allowing decision-makers to evaluate alternatives based on their relative importance (Malczewski, 2006). In GIS, MCDM techniques are used to solve various problems, such as site selection, land use planning, environmental management, and urban planning (Chen et al., 2017).

MCDM techniques involve using mathematical and statistical methods to analyze and evaluate decision alternatives based on multiple criteria (Jankowski & Nyerges, 2001). The use of MCDM techniques in GIS-based platforms has grown in popularity due to the increasing availability of geospatial data, the development of powerful software tools, and the increasing demand for decision support in various fields (Malczewski, 2006). MCDM techniques can be classified into three categories: compensatory, non-compensatory, and interactive (Chen et al., 2017).

Compensatory MCDM techniques assume that the different criteria can be aggregated into a single overall score, and trade-offs can be made between the different criteria (Malczewski, 2006). Non-compensatory MCDM techniques do not allow for trade-offs between criteria, and alternatives are evaluated based on pre-defined criteria or rules (Jankowski & Nyerges, 2001). Interactive MCDM techniques involve visual and interactive tools to support group decision-making processes (Chen et al., 2017)

3.12 Analytical Hierarchy Process (AHP)

The Analytic Hierarchy Process (AHP) is one of the most widely used MCDM methods that helps decision-makers to evaluate and prioritize alternatives based on a hierarchical structure of criteria and sub-criteria. AHP involves pairwise comparisons of the criteria and alternatives to derive priority weights, and a consistency ratio is calculated to ensure the consistency of the decision-making process (Saaty, 1980).

The first step of the AHP method is to develop a hierarchical structure of criteria and sub-criteria. This involves breaking down the problem into a set of criteria and sub-criteria that are relevant to the decision-making problem. The criteria and sub-criteria are arranged in a hierarchical structure, with the primary objective at the top and the sub-criteria at the bottom.

The second step is to carry out pairwise comparisons of the criteria and sub-criteria. The pairwise comparisons involve comparing the relative importance of each criterion and sub-criterion concerning each other. The comparisons are made using a scale of 1 to 9. One indicates that the two elements are equally important, and nine indicates that one is more important than the other.

The third step is to calculate the priority weights of the criteria and sub-criteria. The priority weights are calculated by synthesizing the pairwise comparison judgments using a mathematical formula that produces a normalized priority vector. This vector gives the relative weights of each criterion and sub-criterion.

The fourth step is to check the consistency of the pairwise comparisons. The consistency of the pairwise comparisons is measured using the consistency ratio, which compares the degree of inconsistency in the judgments to a random inconsistency index. The consistency ratio should be less than or equal to 0.1 to ensure the consistency of the pairwise comparisons.

The AHP method is a valuable tool in the MCDM process that helps decision-makers systematically evaluate and prioritize alternatives based on criteria and sub-criteria. The method involves developing a hierarchical structure, pairwise comparisons of the criteria and sub-criteria, calculation of priority weights, and consistency checking to ensure the quality of the decision-making process.

3.13 Euclidean distance mapping

The Spatial Analyst Extension of ArcGIS includes Euclidean Distance, which calculates the straight-line distance between cells in a raster and a given source (ESRI, 2018). The resulting output raster displays the measured distance from each cell to the nearest source, measured in the projection units of the raster, such as feet or meters, and computed from the cell center to the cell center. The distance calculated by Euclidean Distance is an important input to the Least-Cost Path Analysis (LCPA) tool, as it helps to determine the optimal route that avoids or minimizes impacts on natural or built environments. The distance of areas from certain factors or criteria, such as landslide-prone areas or sensitive ecosystems, can be conceptualized using the Euclidean Distance tool (Pascual et al., 2017). For instance, the tool can calculate the distance of each cell in the raster to the nearest landslide-prone area, and then the LCPA tool can be used to find the least-cost path that avoids these areas.

Example**:** The Euclidean Distance tool in ArcGIS calculates the distance from each cell in a raster to the nearest town (represented by yellow dots) in a hilly region of Sri Lanka. This distance was then used in conjunction with the LCPA tool to find the optimal route for a proposed road alignment that avoids or minimizes impacts on the towns and their surrounding natural and built environments (Bamunawala, 2016)

3.14 Weighted linear combination (WLC)

The Weighted Overlay Analysis tool in ArcGIS Spatial Analyst Extension is used to combine two or more criteria raster into a composite raster, with each raster weighted according to its relative importance (ESRI, 2018). This tool is handy when multiple factors or criteria are considered in a decision-making process, and each factor is assigned a weight that reflects its relative importance. For example, if three criteria raster are used and assigned the following weights: Ras1 = 0.4, Ras2 = 0.35, and Ras3 = 0.25, then the combining equation would be:

$$Output\ Ras = (0.4 \times Raster1) + (0.25 \times Raster2) + (0.35 \times Raster3) \quad (Eq - 1)$$

The weights of the criteria raster can be defined using Multi-Criteria Decision Analysis (MCDA) techniques, which incorporate the decisions of stakeholders and relevant literature (Malczewski, 2006). By using weighted overlay analysis, decision-makers can combine multiple criteria and obtain a single composite raster that reflects an area's overall suitability or constraint for a given purpose, such as road alignment.

Example: The Weighted Overlay Analysis tool in ArcGIS was used to combine three criteria raster representing slope, distance to roads, and land use, with weights assigned based on the preferences of stakeholders and literature. The resulting composite raster was used to identify potential road alignment options in a hilly region of Sri Lanka that minimized impacts on natural and built environments (Jayasekara, 2018).

3.15 Phases of LCPA

The phases of LCPA for road alignment optimization typically include:

3.15.1 Data Acquisition and Preparation

This phase involves gathering and organizing spatial data related to the study area, including terrain data, land use data, and other relevant information. This data is then processed and prepared for use in LCPA.

In this phase of LCPA, experts and decision-makers must choose which factors are important for finding the best paths through an area. This is a crucial step because the accuracy of the results depends on these factors. In this research, the factors were taken from the industrial expertise and previous studies and modified for the hilly region. All the factors considered are related to space. Each factor needs to be turned into a map that shows how favorable it is for road construction. For example, areas near water are less favorable because building roads there is more expensive. The cost of each factor is shown on a map so that we can find the best places to build roads.

3.15.2 Cost Surface Development

This phase involves creating a cost surface that reflects the relative difficulty of moving through different types of terrain. This cost surface can be based on various factors, such as slope, elevation, and land cover.

Cost surface maps are created by combining multiple criteria maps into a criteria group (CG) using a Weighted linear cost (WLC) method. The WLC method assigns weight to each criterion map based on its relative importance to the higher-order criterion. The resulting Criteria Group cost surface is a composite of each criterion's individual cost surfaces. For example, if there are five criteria, such as deforestation, air pollution, water pollution, and erosion, they can be combined into a higher-order criterion using WLC. The combining equation for the WLC method is as follows:

$$Output\ Cost\ ras = (w1 \times cost1) + (w1 \times cost1) + \ldots\ldots + (wn \times costn) \quad (Eq-2)$$

Where w is the weight assigned to each criterion map and cost represents the cost surface map for each criterion(O'Callaghan & Mark, 1984).

3.15.3 Path Analysis

This phase uses the cost surface to calculate the least cost path between the start and endpoints. This is typically done using a GIS-based tool, such as the Cost Distance or Path Distance tools.

In the case of performing this analysis, the Cost Path tool is available in the Spatial Analyst extension of ArcGIS. This tool requires two input raster datasets: the Cost Distance raster and the Cost Backlink raster.

Cost Distance raster: The tool called Path Distance in ArcGIS is used to create the Cost Distance raster. This raster calculates the accumulated cost distance from each cell to the nearest source, considering both surface distance and costs that vary in both horizontal and vertical directions.

Cost backlink raster: The Path Distance Backlink tool identifies the neighboring cell that follows the least accumulative cost path to the source. This considers surface distance and both horizontal and vertical cost factors. The Cost Backlink raster is then used to find the least-cost path back to the source. The backlink raster contains values ranging from 0 to 8, indicating the direction of the following neighboring cell along the least accumulative cost path to reach the source. The value 0 is used for the source cell. In contrast, the remaining values indicate the direction of the neighboring cell in a clockwise direction, with 1 for the right neighborhood and 2 for the lower suitable diagonal cell, and so on.

Least cost path: After generating the cost distance raster and cost backlink raster, the Cost Path tool determines the least-cost path between a specified source and destination location. The source and destination locations can be provided as point features or raster. Once the Cost Path tool is executed, it produces an output raster that depicts the least-cost path between the source and destination, considering the cost distance surface. This output raster represents the least-cost path as a continuous line, which can be converted into a polyline using available conversion tools(Yue & Wang, 2010).

3.15.4 Path Refinement and Validation

This phase involves refining the initial path to account for additional factors, such as environmental constraints or land ownership. The final path is then validated and tested to ensure it meets the project objectives and constraints(Jiang & Liu, 2010).

3.16 Road alignment analysis in CAD software

The least cost path generated as a polyline can be imported into the CAD engineering module, such as Civil3D, where the detailed road design is carried out based on specific engineering standards and project requirements. Cut and fill volume estimation can also be accurately calculated within the CAD, which is crucial in assessing the best alignments. The horizontal and vertical alignments are designed based on a road template. Drawing road alignments typically involves five main steps, including importing terrain and least cost path and origin/destination, designing horizontal and vertical alignments, and calculating cut/fill volume.

3.16.1 Import terrain

The USGS Earth Explorer retrieved a digital representation of the terrain's topography, boasting a spatial resolution of 1 arc second. A fishnet tool was utilized within ArcMap to tease out the precise X, Y, and Z coordinates from this dataset, culminating in a precise 10 m by 10 m mesh. These coordinates were then imported into Civil 3D in a CSV format. Leveraging the tools available in Civil 3D, contour lines, surface features, and various road-related elements were synthesized with remarkable accuracy.

3.16.2 Import least cost path & origin/destination

The least-cost path is created using GIS, and the starting and ending points are incorporated into the terrain model. A 20-meter buffer is then produced around this path, creating a corridor boundary that will guide the horizontal design of the road alignment. Compliance with this least-cost corridor is mandatory for road design purposes, and the GIS files used in the LCPA process are directly imported in Shapefile format.

3.16.3 Horizontal alignment design

Here are the main steps for creating a horizontal alignment design using Civil 3D 2018, with references to RDA design standards in Sri Lanka where applicable:

1. Create a new drawing and set the drawing units to the desired units. This can do by the "Application Menu" by choosing "New," "Drawing," and then "Specifying Units" in the dialogue box for a "New Drawing". (Autodesk, 2017)
2. Open the alignment creation tool by going to the "Home" tab and selecting "Create Alignment" in the "Create Design" panel. Choose the alignment type, such as tangent or spiral-curve-spiral, and set the starting and ending points for the alignment. (RDA, 2013)
3. Set the alignment properties, including the alignment name, description, and style. This can do by the "Alignment Layout Tools" panel by selecting "Properties". The alignment style in the RDA design template should be set to "RDA_General_Alignment_Style" (RDA, 2013).
4. Add alignment elements, such as curves or spirals, by selecting them from the "Alignment Layout Tools" panel and placing them along the alignment. This can be done by selecting "Curve" or "Spiral" from the panel and then clicking on the alignment.
5. Edit the alignment elements as needed by selecting them and using the grips to adjust their parameters. Grips are small squares that appear on the selected element, allowing the user to adjust its properties.
6. Add horizontal geometry points by selecting "Geometry Editor" from the "Alignment Layout Tools" panel and clicking on the alignment where you want to add a point. This will create a point at the selected location.
7. Edit the horizontal geometry points as needed by selecting them and using the grips to adjust their parameters.
8. Verify the alignment design using the "Alignment Station and Offset Report" or other design verification tools. In the RDA design template, the alignment station and offset report should be generated using the "RDA_Station_and_Offset_Report" style (RDA, 2013).

9. Save the alignment design. This can be done by selecting "Save" from the "Application Menu" or by using the keyboard shortcut "Ctrl + S".

3.16.4 Vertical alignment design

Creating a vertical alignment design using Civil 3D 2018 with RDA design standards for Sri Lanka involves several main steps. Firstly, a new drawing must be made, and the drawing units must be set to the desired units (Autodesk, 2017). Secondly, the vertical alignment creation tool should be opened by selecting "Create Alignment" in the "Create Design" panel on the "Home" tab. The alignment type, such as parabolic or circular, should be chosen, and the starting and ending points for the alignment set (RDA, 2013).

Next, the vertical alignment properties should be set, including the alignment name, description, and style. This can be done from the "Alignment Layout Tools" panel by selecting "Properties". In the RDA design template, the vertical alignment style should be set to "RDA_General_Alignment_Style," which includes the RDA standard label styles for vertical alignment elements such as station labels, grade labels, and curve data labels (RDA, 2013).

Once the alignment properties have been set, the vertical curves can be added. This can be done by selecting the "Vertical Curve" option in the "Design Criteria" panel and setting the curve type, such as crest or sag curve, and the curve parameters, such as length and grade (Autodesk, 2017). The vertical curves should be added at each intersection of the horizontal alignment and the design grade line.

Finally, the vertical alignment can be reviewed and adjusted as necessary using the various alignment editing tools provided by Civil 3D 2018. This may include adjusting curve parameters or realigning the vertical alignment to meet design criteria or constraints (Autodesk, 2017).

3.17 Cost approach

The evaluation of road alignments will be based on three factors: the cost of the alignment in each section, its length, and the cost of cut and fill. These factors will provide information on how well the assessed alignments perform in different areas of evaluation.

This will enable decision-makers to consider different options and choose the best alignment. This section will also discuss other factors to consider in the assessment process.

3.17.1 Cost of alignment in each CG

All the cost cell values under the least cost corridor are added to calculate the total cost of the least expensive road alignment for a particular Criteria Group cost surface. In Fig-3, the blue lines outline the least-cost corridor, and the sum of the green cells represents the cost of the least expensive path for that Criteria Group. This process is carried out using the Zonal Statistics as Table tool in ArcGIS, which summarizes the values of a raster within a defined zone (in this case, the least cost corridor) and reports the result as a table. This cost calculation process is repeated for all Criteria Group cost surfaces using the same least cost corridor (Sithole & Venter, 2014).

If there are two alternatives least-cost paths and two Criteria Group cost surfaces, the cost of the first path is calculated on the two Criteria Group cost surfaces first. Then the cost of the second path is calculated on the two Criteria Group cost surfaces again. This allows for comparing the performance of the two least-cost paths on the two Criteria Groups and enables informed decision-making.

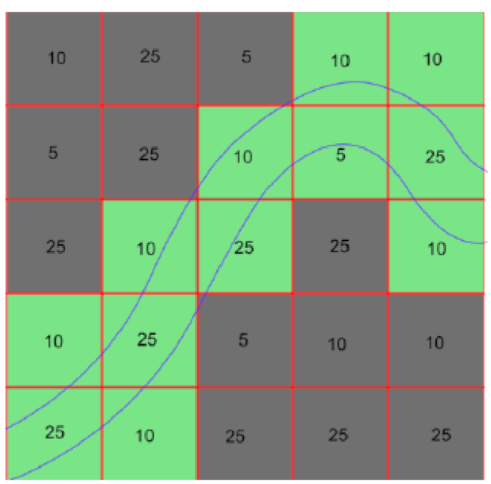

Figure 3 : Road alignment cost calculation of cost surface

3.17.2 Road length

The length of a road is a critical factor in determining its construction cost and operating expenses. Longer roads may require more land acquisition, construction materials, and maintenance costs. On the other hand, shorter roads may lead to more traffic congestion, travel time, and fuel consumption. Therefore, determining the appropriate road length is crucial regarding the project's cost-effectiveness and traffic efficiency.

Several factors must be considered when determining the appropriate length for a proposed road. These factors include traffic volume, road function, topography, land use, and environmental considerations. The length of a road should also comply with the relevant design standards and regulations(Moshinsky 1959).

3.17.3 Cut and Fill volume

The cut and fill volume calculation is crucial in road design as it determines the amount of earthwork required to construct the proposed road. Inaccurate calculations can lead to significant cost overruns, delays, and safety hazards. Therefore, the cut-and-fill volume calculation method is essential for determining the road's feasibility and ensuring that the design meets safety standards.

In recent years, computer-aided design (CAD) software has become an integral part of road design, including cut and fill volume calculations. Civil 3D, a CAD software developed by Autodesk, is commonly used in the construction industry for road design, allowing engineers to create 3D models of the terrain, analyze the surface, and calculate the cut and fill volumes (Autodesk, 2022). This software provides tools that enable engineers to design roads and earthworks efficiently, making the design process faster and more accurate.

Pythagoras, another CAD software, is also commonly used for cut and fill volume calculations. The software uses a digital terrain model (DTM) to calculate the cut and fill volumes, giving engineers an accurate terrain representation (Trimble, 2022). Pythagoras allows the user to easily create a DTM from survey data and then analyze the surface to determine the cut and fill volumes. With these tools, engineers can determine the road's feasibility, estimate construction costs, and ensure the design meets safety standards.

CAD software for cut and fill volume calculations offers numerous benefits compared to traditional methods. The software provides more accurate results, faster analysis, and the ability to create 3D models of the terrain. Moreover, the software reduces the amount of manual labor required and provides more accurate results with fewer errors (Morgado, Alves, & Oliveira, 2017). This results in more efficient and cost-effective road designs that are safer and more reliable.

3.17.4 Standardization of cost values and assessment table

As an example, the cost associated with the six criteria of evaluation are first noted down in a table (Table-2) in their respective cost units. Due to variations in cost units and calculation methods, a linear standardization process is carried out using *Eq-3* to transform the costs into a scale ranging from 0 to 100. This is done to enable a relative comparison between the different road alignments listed in Table-3. Standardizing the costs as percentages make comprehending the cost values and factor strengths easier.

$$Standardized\ Value = \{(Val)/(Max)\} \times 100 \qquad (Eq - 3)$$

‘Val‘ - cost value of an alignment for a particular CG

‘Max‘ - maximum cost value within a CG for all the alignment alternative

The values are the same so that the highest value in a group is 9, and all the other values are adjusted to align with this (eq3). An example of these same values is shown in Table-3. We add the costs in each group using weights to calculate the cost for a specific arrangement. This gives us a total cost for that arrangement, and we do this for all the possible arrangements. This total cost helps us to compare the different arrangements by looking at all the costs in each group. Table-3 shows all the costs for each arrangement in each group, which can help people who need to make decisions.

Table 2 : Example alignment cost in different assessment criteria

	Criteria Group 1	Criteria Group 2	Criteria Group 3	Cut and Fill cost	Length(km)
Alignment 1	452	856	756	12.1	5
Alignment 2	852	125	486	15	6
Alignment 3	146	425	785	13.2	4

The least cost arrangement is the one we want, but deciding on the best placement depends on what stakeholders think. The table that shows the costs is just a summary of information that stakeholders can use to make choices and trade-offs.

Table 3 : Example alignment assessment table

	Criteria Group 1	Criteria Group 2	Criteria Group 3	Cut and Fill cost	Length
Alignment 1	53.05	100	96.31	80.67	83.33
Alignment 2	100	14.6	61.91	100	100
Alignment 3	17.1	49.65	100	88	66.67

CHAPTER 4 - PROCESSING AND ANALYSIS

The approaches and procedures used to process and evaluate the data gathered for the research study are described in this part. In particular, the section thoroughly explains the analysis methods utilized for the study and the analysis findings. The findings will be arranged and presented logically, with appropriate output maps and figures to back them up. The section will also go into how the results affect the research aim and objectives and how these generally progress the research topic.

4.1 General description of the case study area

The Colombo-Hatton Main A type road is a major transportation route that passes through the town of Yatiyanthota in Sri Lanka. It is a significant road that links Sri Lanka's central regions with the rest of the country. The road passes through a mountainous region with steep slopes, which makes it vulnerable to landslides, especially during the rainy season(Gamage & Karunananda (2016)).

Yatiyanthota town, which is located along the Colombo-Hatton Main A-type road, has also experienced several landslides in the past. In 2017, a major landslide occurred in the area, which resulted in several fatalities and caused significant damage to property and infrastructure. This event highlighted the need for effective measures to manage the landslide susceptibility of the area.

Considering the landslide susceptibility of the area, there have been proposals to construct a bypass road to divert traffic away from Yatiyanthota town. This proposed bypass road would provide an alternate route for travelers and reduce the risk of landslides and other natural disasters.

However, constructing a bypass road would require a thorough assessment of the geological and environmental conditions of the area. It would also require the consideration of the social and economic impacts of the proposed road on the local community. Additionally, the design of the road would need to be based on sound engineering principles to ensure its safety and sustainability(Senevirathna & Ratnayake (2019)).

4.2 Criteria identification

Various parties and stakeholders may have different viewpoints and priorities in road construction projects. Segmenting criteria into groups is thus essential to incorporate these diverse perspectives. This study used five criteria groups (CG) to generate five optimal paths. These criteria groups and their weights were synthesized from previous works and were then readjusted and selected according to the study area requirements.

The weighted linear combination method was used to combine all criteria groups into a single viewpoint. This method involves assigning weights to each criteria group based on the expert's preference and opinion.

The cost approach was used in this study to conceptualize the criteria. Favorable areas are assigned lower costs, while unfavorable areas have higher costs. Criterion maps (raster) were prepared with cell values representing the relative cost of passing through that cell. These cell values were then standardized to a range of 0-9, where the least cost cells have 0, and the highest cost cell has 9. Standardization is necessary for consistency in comparison and assessment across the factors and criteria.

Table 4 : Criteria groups

Criteria Group	Criteria
Engineering(A)	Landslide Hazard(A1)
	Lithology(A2)
	Slope(A3)
	Flood Risk(A4)
Transportation(B)	Travel Comfort(B1)
	Travel Safety(B2)
	Accessibility(B3)
Environment(C)	Water Pollution(C1)

	Noise Pollution(C2)
	Deforestation(C3)
	Soil Erosion(C4)
Economic(D)	Acquisition Cost(D1)
	Construction Cost(D2)
Social(E)	Public facility disturbance(E1)
	Resettlement(E2)

The resulting viewpoint is called the Analytic Hierarchy Process (AHP) viewpoint, and a least-cost path is generated based on this viewpoint, resulting in six optimal paths.

In Table 4, five criteria groups are presented with the individual criteria and the corresponding weights assigned to each criterion group. The letters A, B, C, D, and E in block capitals represent in for the various criteria groups. Block capital letters followed by numbers, such as A1, A2, B1, B2, C1, etc., are used to identify the criteria for each group. The forthcoming sections elaborate on the criteria groups, criteria, and sub-criteria in-depth.

4.2.1 Engineering (A)

The reason for this group of criteria is to consider the engineers' opinions. This group helps find the best road route by considering areas with favorable terrain that are safe from natural calamities and suitable from a geological and climatic point of view. The group comprises four criteria: slope, landslide hazard, flood risk, and lithology (Smith & Jones, 2010).

4.2.1.1 Landslide Hazard (A1)

Road construction engineers prioritize areas less susceptible to natural disasters, such as landslides, especially in hilly regions, such as the study area.

Land areas highly susceptible to landslides were extracted from data from the National Building Research Organization in Sri Lanka. A Euclidean distance map was then generated using the Euclidean distance tool in ArcMap 10.8. Next, a questionnaire survey was conducted to obtain insights from industry experts, and their responses were used to determine new scale values. The Euclidean distance map was reclassified according to these new scale values, resulting in a reclassified landslide hazard zone map. The output

Table 5 : Euclidean Distance from landslide hazard zones question survey scores

Criteria	**Distance range (m)**	**Proposing Score value**
Euclidean Distance from landslide hazard zones	0 - 300	9
	300 - 700	7
	700 – 1000	5
	1000 – 1500	3
	More than 1500	0

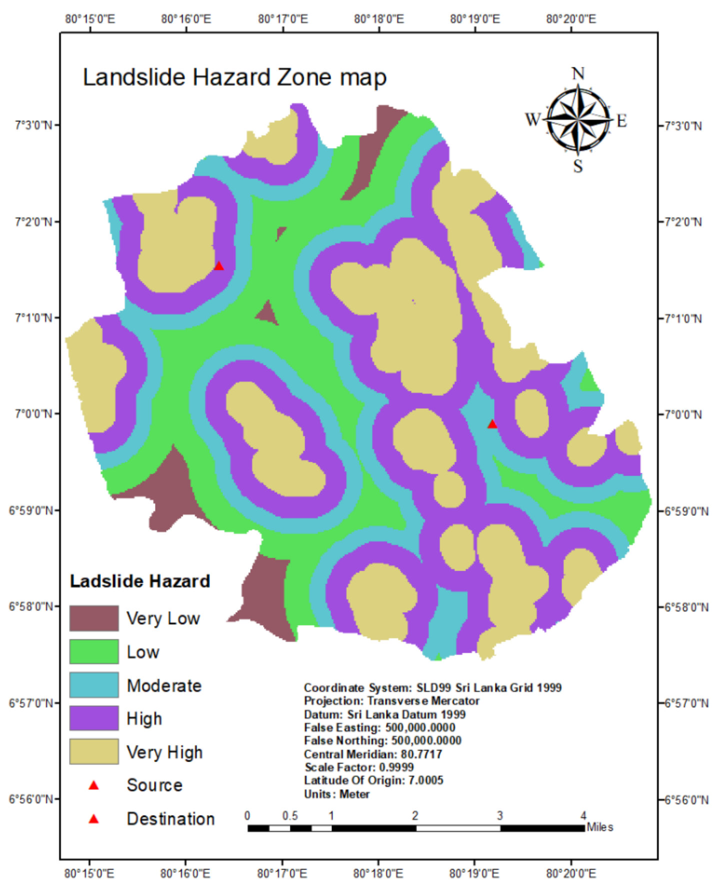

Figure 4 : Landslide Hazard Zone raster

4.2.1.2 Lithology(A2)

The strength of soil is a critical factor to consider when constructing roads, as it can affect the stability and durability of the road over time. In this case, the strength of two types of soil can be compared: red yellow podzolic soils with strongly mottled subsoil and red-yellow podzolic soils.

Red yellow podzolic soils with strongly mottled subsoil are typically composed of sand, silt, and clay, with a high degree of mottling or uneven coloring caused by variations in soil moisture and oxidation. These soils are generally considered to have lower strength and stability than other types due to their high-water content and uneven structure.

On the other hand, red, yellow podzolic soils are sandy soil typically rich in iron and aluminum oxides, giving them their characteristic reddish-yellow color. Due to their relatively uniform texture and better drainage properties, these soils are generally stronger and more stable than red yellow podzolic soils with strongly mottled subsoil(Seneviratne & Adikari, 2019).

When it comes to road construction, soil strength is critical for ensuring the road's longevity and safety. Roads constructed on stronger soils are less prone to damage and require less maintenance over time. Therefore, red, yellow podzolic soils may be better for road construction than red-yellow podzolic soils with strongly mottled subsoil due to their higher strength and stability(Hettiarachchi et al., 2017).

From an engineering perspective, the favorability of a region for the construction of roads differs based on the area's lithology, which is considered in this criterion. To reflect this perspective, the Red yellow podzolic soils with strongly mottled subsoil Partings areas are given a cost value of three, and the Red and yellow podzolic soil areas have a six-cost value. These cost values are attributed to the respective polygon features of Geology data and then the polygon data is converted to a raster based on the cost value.

The output of the survey and the reclassified data are shown in the following table and figure.

Table 6 : Lithology question survey scores

Criteria	Soil Type	Proposing Score value
Lithology	RYPS with strongly mottled subsoil	3
	Red, yellow podzolic soil	6

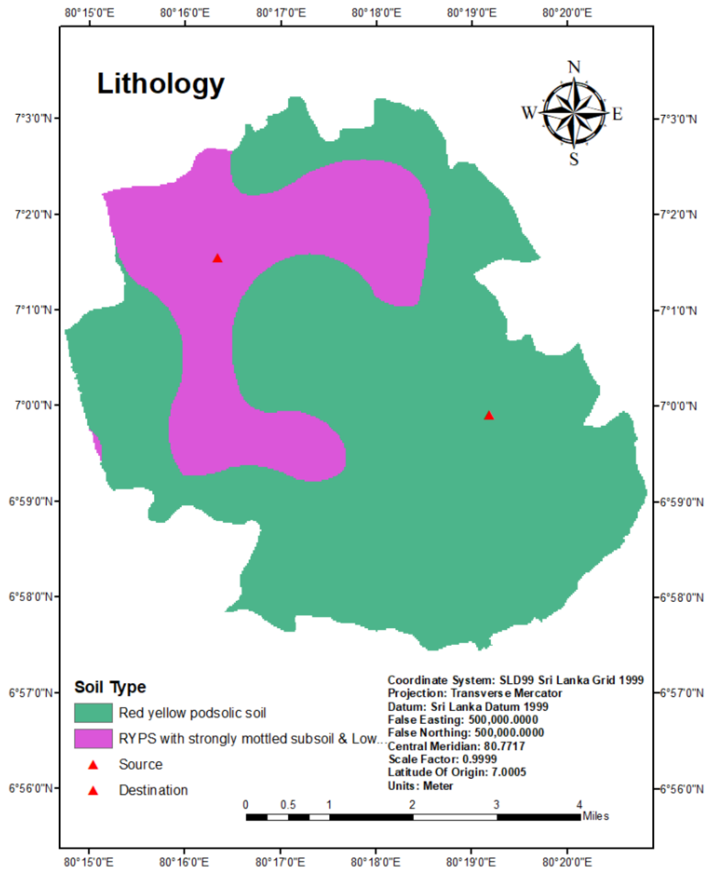

Figure 5 : Lithology Raster

4.2.1.3 Slope(A3)

Areas with flatter terrain are more desirable than those with steeper slopes. To determine the slope values, a slope raster is created from digital elevation model (DEM) data .The slope values are then classified into classes and assigned costs based on Table 7. These cost values are determined using the Analytical Hierarchy Process (AHP) method. The output of the survey and the reclassified data are shown in the following table and figure.

Table 7 : Slope (percent) question survey scores

Criteria	Parameter range	Proposing Score value
Slope (percent)	Flat (0% – 10%)	0
	Rolling (10% – 25%)	3
	Mountainous (25% – 50%)	7
	Higher slopes (above 50%)	9

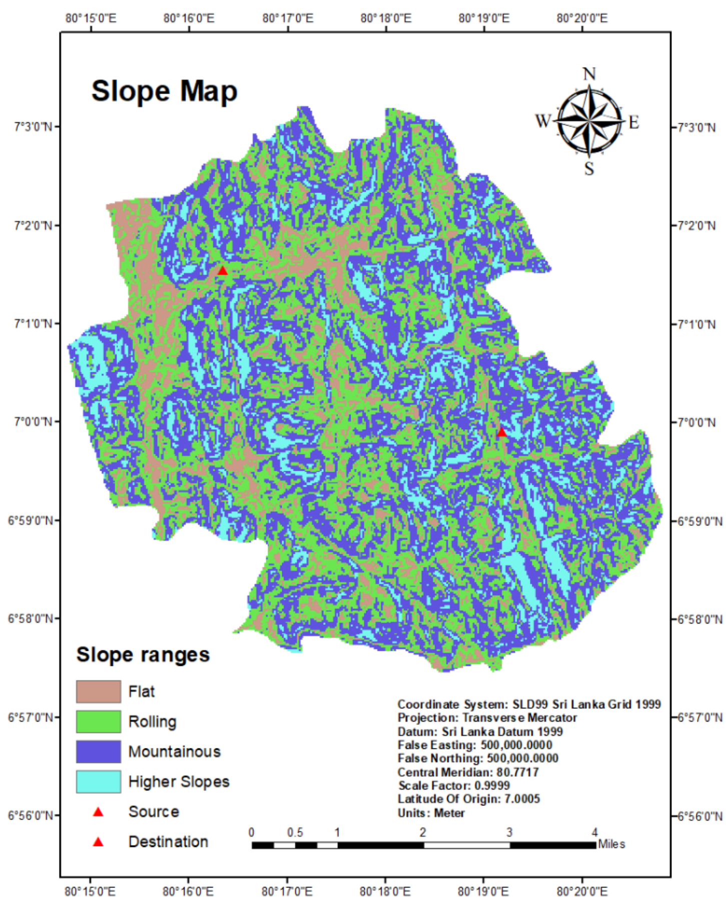

Figure 6 : Slope raster

4.2.1.4 Flood risk (A4)

Road construction engineers prioritize areas less susceptible to natural disasters, such as flood risk, especially in hilly regions, such as the study area. Since not available of flood risk zonation map in particular study area a map is created using following criteria.

Pairwise comparison was conducted by taking ideas from an expertise as bellow. Then the pairwise comparison matrix was implemented. Final weightages from the pairwise comparison is shown below.

Table 8 : Primary Questionnaire sheet: Effective criteria and pair wise comparison (Flood Risk Map)

Primary Questionnaire sheet: Effective criteria and pair wise comparison (Flood Risk Map)																		
Factor	Factor Weighting Score																	Factor
	More importance than								Equal	Less importance than								
Rainfall Intensity	9	8	7	6	5	4	3	2	1	2	3	**4**	5	6	7	8	9	Elevation
Rainfall Intensity	9	8	7	6	5	4	3	2	1	2	**3**	4	5	6	7	8	9	Slope
Rainfall Intensity	9	8	7	6	5	4	3	2	1	2	**3**	4	5	6	7	8	9	LULC
Rainfall Intensity	9	8	7	6	5	4	3	2	1	2	3	**4**	5	6	7	8	9	Flow accumulation
Rainfall Intensity	9	8	7	6	5	4	3	2	1	2	**3**	4	5	6	7	8	9	Geology
Rainfall Intensity	9	8	7	6	5	4	3	2	1	2	3	4	**5**	6	7	8	9	Drainage distance
Elevation	9	8	7	6	5	4	**3**	2	1	2	3	4	5	6	7	8	9	Slope
Elevation	9	8	7	6	5	4	**3**	2	1	2	3	4	5	6	7	8	9	LULC
Elevation	9	8	7	6	5	4	3	**2**	1	2	3	4	5	6	7	8	9	Flow accumulation
Elevation	9	8	7	6	5	4	3	**2**	1	2	3	4	5	6	7	8	9	Geology
Elevation	9	8	7	6	5	4	3	2	1	**2**	3	4	5	6	7	8	9	Drainage distance
Slope	9	8	7	6	5	4	3	2	1	**2**	3	4	5	6	7	8	9	LULC
Slope	9	8	7	6	5	4	3	**2**	1	2	3	4	5	6	7	8	9	Flow accumulation
Slope	9	8	7	6	5	4	**3**	2	1	2	3	4	5	6	7	8	9	Geology
Slope	9	8	7	6	5	4	3	2	1	2	**3**	4	5	6	7	8	9	Drainage distance
LULC	9	8	7	6	5	4	3	2	1	**2**	3	4	5	6	7	8	9	Flow accumulation
LULC	9	8	7	6	5	4	**3**	2	1	2	3	4	5	6	7	8	9	Geology
LULC	9	8	7	6	5	4	3	2	1	2	**3**	4	5	6	7	8	9	Drainage distance
Flow accumulation	9	8	7	6	5	4	3	**2**	1	2	3	4	5	6	7	8	9	Geology
Flow accumulation	9	8	7	6	5	4	3	2	1	**2**	3	4	5	6	7	8	9	Drainage distance
Geology	9	8	7	6	5	4	3	2	1	2	3	4	**5**	6	7	8	9	Drainage distance

Table 9 : Pair-wise comparison matrix

	Rainfall Intensity	Elevation	Slope	LULC	Flow Accumulation	Geology	Draiange Distance
Rainfall Intensity	1	0.25	0.333	0.333	0.25	0.333	0.2
Elevation	4	1	3	3	2	2	0.5
Slope	3.003003003	0.3333333	1	0.5	2	3	0.333
LULC	3.003003003	0.3333333	2	1	0.5	3	0.333
Flow Accumulation	4	0.5	0.5	2	1	2	0.5
Geology	3.003003003	0.5	0.333333	0.333333	0.5	1	0.2
Draiange Distance	5	2	3.003003	3.003003	2	5	1

Table 10 : Normalized Pair-wise comparison matrix

	Rainfall Intensity	Elevation	Slope	LULC	Flow Accumulation	Geology	Draiange Distance	Weight
Rainfall Intensity	0.043461237	0.0508475	0.032745	0.032745	0.03030303	0.020388	0.065231572	0.039388924
Elevation	0.173844949	0.2033898	0.295005	0.295005	0.242424242	0.122451	0.16307893	0.213599776
Slope	0.130514226	0.0677966	0.098335	0.049167	0.242424242	0.183677	0.108610568	0.125789302
LULC	0.130514226	0.0677966	0.19667	0.098335	0.060606061	0.183677	0.108610568	0.120887026
Flow Accumulation	0.173844949	0.1016949	0.049167	0.19667	0.121212121	0.122451	0.16307893	0.132588497
Geology	0.130514226	0.1016949	0.032778	0.032778	0.060606061	0.061226	0.065231572	0.069261296
Draiange Distance	0.217306186	0.4067797	0.2953	0.2953	0.242424242	0.306129	0.32615786	0.298485179

Table 11 : Consistency ratio

	Rainfall Intensity	Elevation	Slope	LULC	Flow Accumulation	Geology	Draiange Distance	WEIGHTED SUM	WEIGHTS	
Rainfall Intensity	0.039388924	0.0533999	0.041888	0.040255	0.033147124	0.023064	0.059697036	0.290840257	0.04	7.271006
Elevation	0.157555696	0.2135998	0.377368	0.362661	0.265176994	0.138523	0.149242589	1.664126632	0.22	7.564212
Slope	0.118285057	0.0711999	0.125789	0.060444	0.265176994	0.207784	0.099395564	0.948074243	0.13	7.292879
LULC	0.118285057	0.0711999	0.251579	0.120887	0.066294249	0.207784	0.099395564	0.935424313	0.13	7.195572
Flow Accumulation	0.157555696	0.1067999	0.062895	0.241774	0.132588497	0.138523	0.149242589	0.989377965	0.14	7.066985
Geology	0.118285057	0.1067999	0.04193	0.040296	0.066294249	0.069261	0.059697036	0.502562968	0.07	7.179471
Draiange Distance	0.19694462	0.4271996	0.377746	0.363024	0.265176994	0.346306	0.298485179	2.274882578	0.3	7.582942

Lamda max	7.30758103
CI	0.0512635
CR	0.03883599
TRUE	

Here are the selected criteria and weightages taken from the pairwise comparison.

Table 12 : Flood risk final weights

Flood Risk Map	Rainfall intensity	0.04
	Elevation	0.22
	Slope	0.13
	Land use land cover type	0.13
	Flow accumulation	0.14
	Geology	0.07
	Drainage distance	0.30

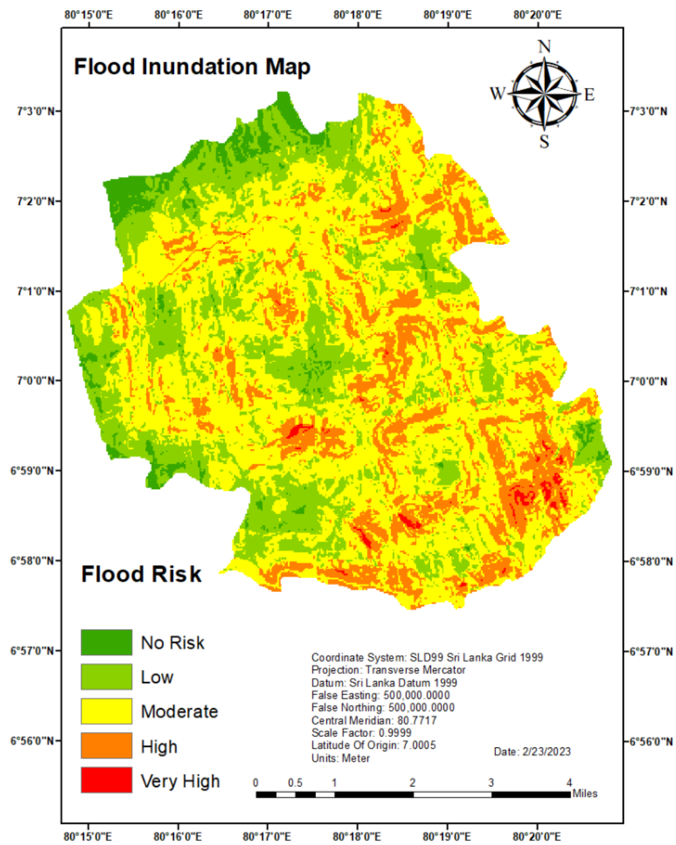

Figure 7 : Flood inundation map

Finally, all the high landslide hazardous areas are removed from the study area.

The four criteria; A1, A2, A3 and A4, are combined to form the criteria group A using the equation below Eq-4, producing the CG map (Figure 8) by the WLC method. The corresponding weights of the criteria are established by their relative significance in contribution to the Engineering criteria group. In addition, that following weightages were extracted from the pairwise comparison.

$$A = (A1 \times 0.41) + (A2 \times 0.11) + (A3 \times 0.34) + (A4 \times 0.17) \qquad (Eq - 4)$$

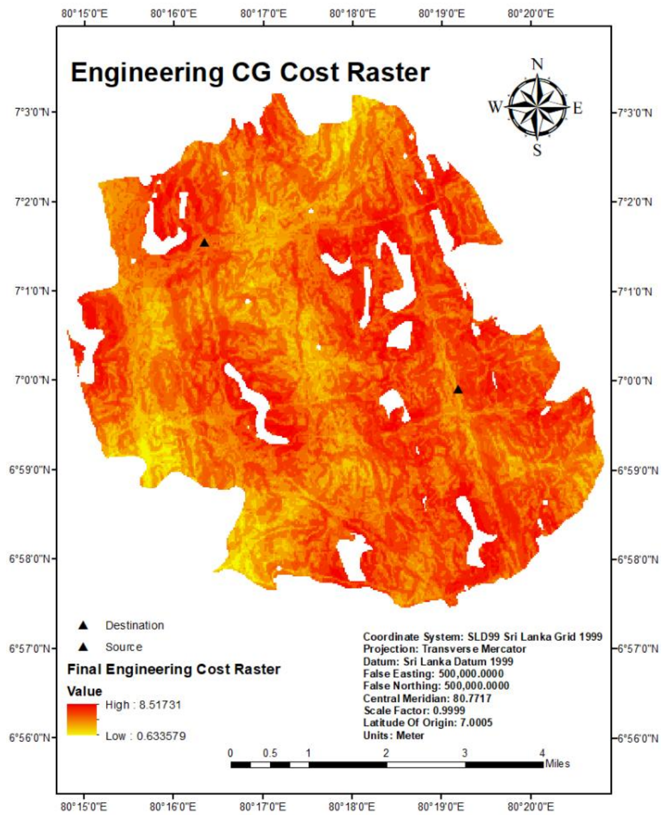

Figure 8 : Engineering criteria group cost raster

4.2.2 Transportation (B)

One group of criteria for road construction is aimed at assessing the impact on the transportation development of the region and the comfort and safety of the designed roads in relation to geographic factors. This criteria group consists of three criteria: accessibility, travel comfort, and safety. By considering these factors, the aim is to identify the optimal road alignment that is most suitable for transportation and helps to develop the region's transportation system. (Wang, Liu, Li, & Li, 2017)

4.2.2.1 Comfort (B1)

The comfort criterion for road construction considers geographic factors such as terrain ruggedness and settlement. Roads constructed over less rugged terrain will likely be more comfortable for road users. In contrast, routes that pass through densely populated settlement areas may be less comfortable due to heavier traffic. Additionally, excessive road intersections can also cause discomfort to both road users and vehicles. This criterion is divided into three sub-criteria: Terrain Ruggedness, Settlement Area, and Road Intersection. (Sahoo, Sahoo, & Panda, 2013)

4.2.2.1.1 TRN (B11)

Slope data is analyzed using Focal Statistics to calculate the terrain ruggedness index. This involves calculating the range of values within a 5x5 cell window and assigning the value of the focal cell to this range. The resulting raster is then reclassified into five classes according to the expertise ideas, each given a cost value ranging from 0 (lowest cost) to 9 (highest cost). The highest ruggedness class is assigned the highest cost, while the lowest ruggedness class is assigned the lowest cost. (Hossain & Ahmed, 2018)

Table 13 : TRN Question survey scores

Criteria	**Parameter range**	**Proposing Score value**
Terrain Ruggedness Index	1-10	0
	10-40	2
	40-70	5
	70-100	7
	100-162	9

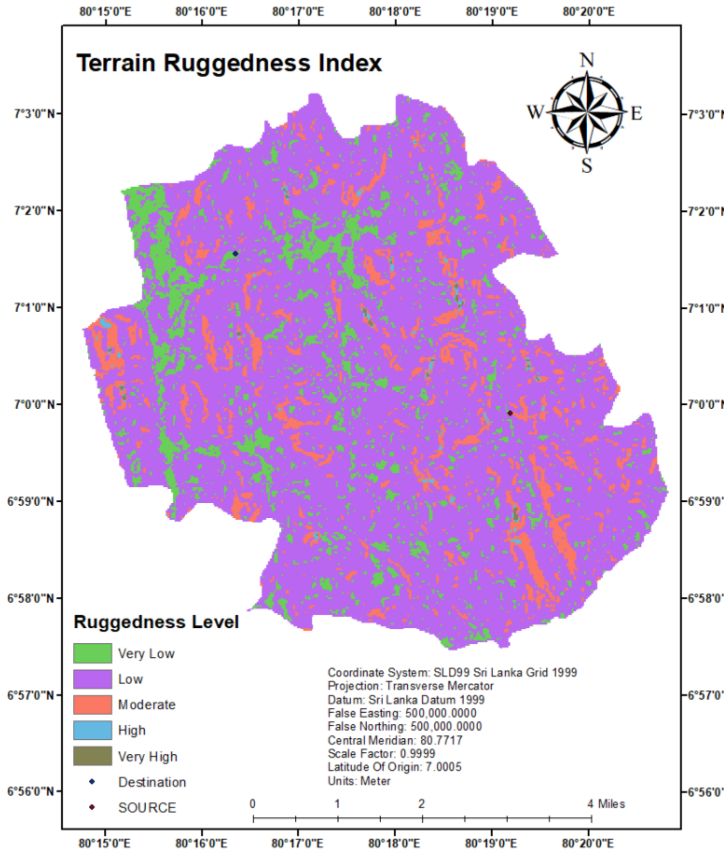

Figure 9 : Terrain ruggedness index cost raster

4.2.2.1.2 Settlement area (B12)

Roads that pass through densely populated settlement areas tend to be less comfortable to travel on. As a result, it is generally desirable to avoid these areas when planning road construction. The level of urbanization is directly related to the level of discomfort experienced by road users. To incorporate settlement areas into the cost analysis, different cost values are assigned to different types of settlement areas. The distances from the building footprints are considered here as the expertise. The settlement area polygons are then converted into a raster based on their cost attribute.

Table 14 : Distance from Settlement areas question survey scores

Criteria	**Parameter range**	**Proposing Score value**
Settlement areas (m)	0-50	9
	50-150	7
	150-300	5
	300-500	2
	500-750	0

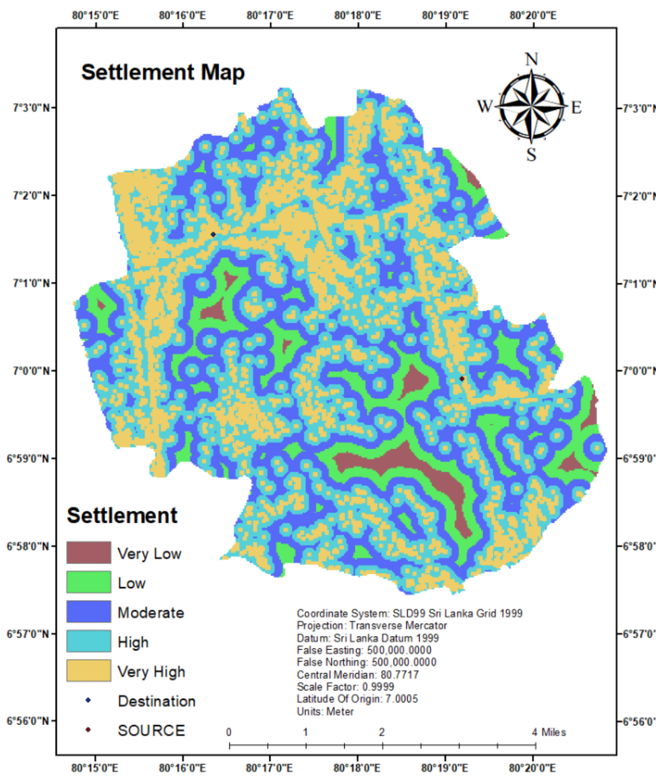

Figure 10 : Settlement cost raster

4.2.2.1.3 Road intersections (B13)

Intersections can be uncomfortable for drivers, and as such, they are typically avoided in road construction. To incorporate intersections into the cost analysis, a buffer of 40 meters is generated around A-class roads, a buffer of 20 meters is generated around B-class roads. Following weights were given as the consultations. The polygon data is then converted into a raster based on the cost attribute. (Kotru, 2015)

Table 15 : Road intersection areas question survey scores

Criteria	Parameter range	Proposing Score value
Road Intersection areas	40 m buffer from A class roads	9
	20 m buffer from B class roads	6
	Other data	0

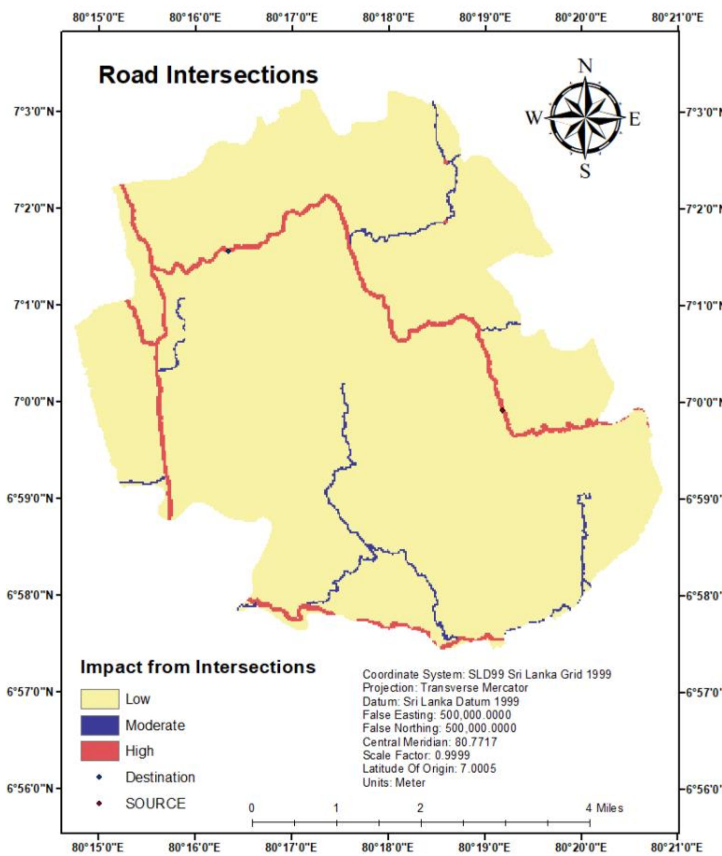

Figure 11 : Road intersections cost raster

The three sub-criteria are combined using WLC method to generate Criteria-B1 cost raster using the expression below *Eq - 5.* The corresponding weights of the sub-criteria are defined by pairwise comparison.

$$B1 = (B11 * 0.14) + (B12 * 0.0.34) + (B13 * 0.52) \qquad (Eq - 5)$$

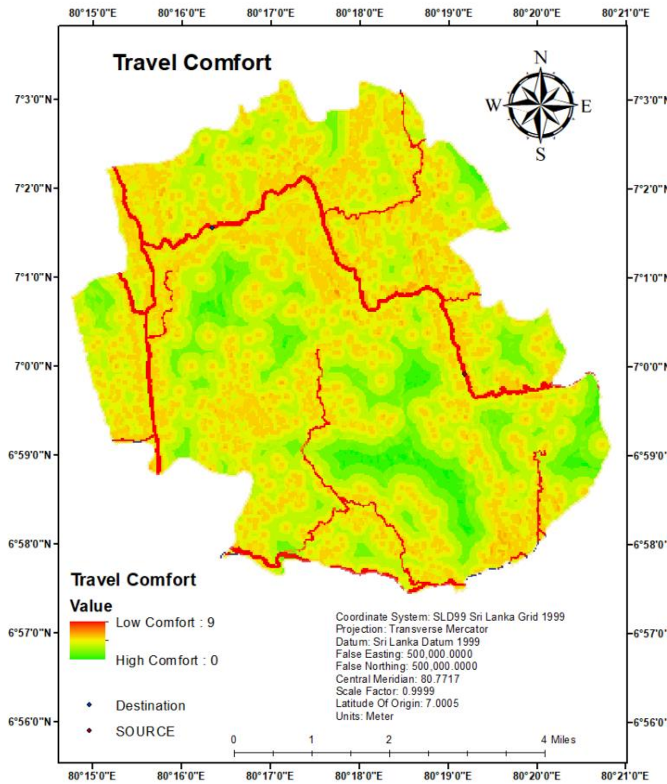

Figure 12 : Travel comfort cost raster

4.2.2.2 Safety (B2)

In this criterion, the safety of roads is assessed from a geographic perspective. Safety is evaluated by analyzing various factors, such as slope and road intersections. High slopes are generally considered less safe for vehicles, as accidents can result in vehicles rolling long distances. Additionally, intersections are often hotspots for collision accidents and should be avoided. The safety criteria are further subdivided into two sub-criteria: slope and road intersection.

4.2.2.2.1 Slope (B21)

In this criterion, the safety of roads is evaluated based on the slope of the terrain. High slopes are considered less safe for vehicles, as they increase the risk of accidents. To account for slope in the cost analysis, the slope data is reclassified into classes and each class is assigned a cost value (as shown in Table 12). Higher slope values are assigned higher costs, while lower slope values are assigned lower costs. The resulting slope cost raster can be used in the road alignment optimization process. These intervals are generated according to the RDA design manual. (Mahajan, 2017)

Table 16 : Slope question survey scores

Criteria	Parameter range	Proposing Score value
Slope (Degrees)	Flat (0% – 10%)	0
	Rolling (10% – 25%)	3
	Mountainous (25% – 50%)	7
	Higher slopes (above 50%)	9

4.2.2.2.2 Intersections (B22)

To incorporate intersections into the cost analysis, a buffer of 40 meters is generated around A-class roads, a buffer of 20 meters is generated around B-class roads. Following weights were given as the consultations. The polygon data is then converted into a raster based on the cost attribute.

Table 17 : Road intersection areas ranges question survey scores

Criteria	Parameter range	Proposing Score value
Road Intersection areas	40 m buffer from A class roads	9
	20 m buffer from B class roads	6
	Other data	0

The tow sub-criteria are combined using WLC method to generate Criteria-B2 raster using the expression of *Eq-6*.The corresponding weights of the sub-criteria are defined by pairwise comparison.

$$B2 = (B21 * 0.14) + (B22 * 0.34) + (B23 * 0.52) \quad (Eq - 6)$$

.

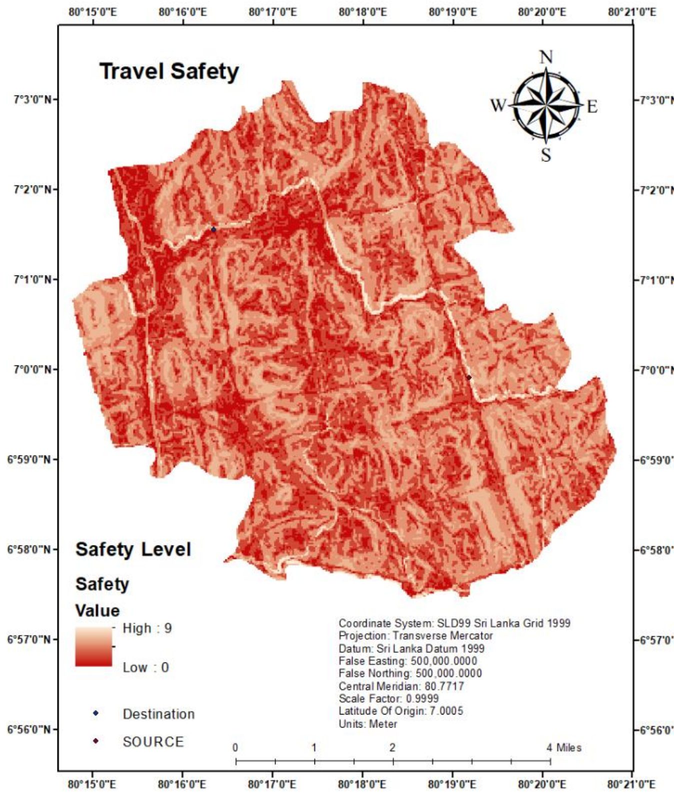

Figure 13 : Travel safety cost raster

4.2.2.3 Accessibility (B3)

Constructing roads close to settlements can provide better access and linkage to those areas but can also cause disruption and resettlement issues if the roads are too close. To determine the optimal distance, a Euclidean distance map is generated around the settlement areas and reclassified into different cost categories using the Raster Calculator tool of ArcGIS Spatial Analyst Extension. The accessibility cost raster is depicted in Figure 14, where green regions represent the least costly (and, therefore, most preferred) areas for road construction based on this criterion. The cost decreases linearly from 9 to 0 up to 100 meters, then increases linearly from 0 to 9 up to 500 meters, after which the cost remains constant at 9. The reclassification scheme is shown in *Eq-6_1*.

If distance ≤ 100m:

Value decreases from 9 to 0 linearly,

If distance > 100m & ≤ 500m:

Value increases from 0 to 9 linearly,

If distance > 500m:

Value = 9

Map Algebra Expression of ArcGIS

Con("%Euc_Dist_Buildingfp%"<=100,-0.09*"%Euc_Dist_Buildingfp%"+9,Con("%Euc_Dist_Buildingfp%"<=500,0.0225*"%Euc_Dist_Buildingfp%"+-2.25,Con("%Euc_Dist_Buildingfp%">500,9))) Eq-6_1

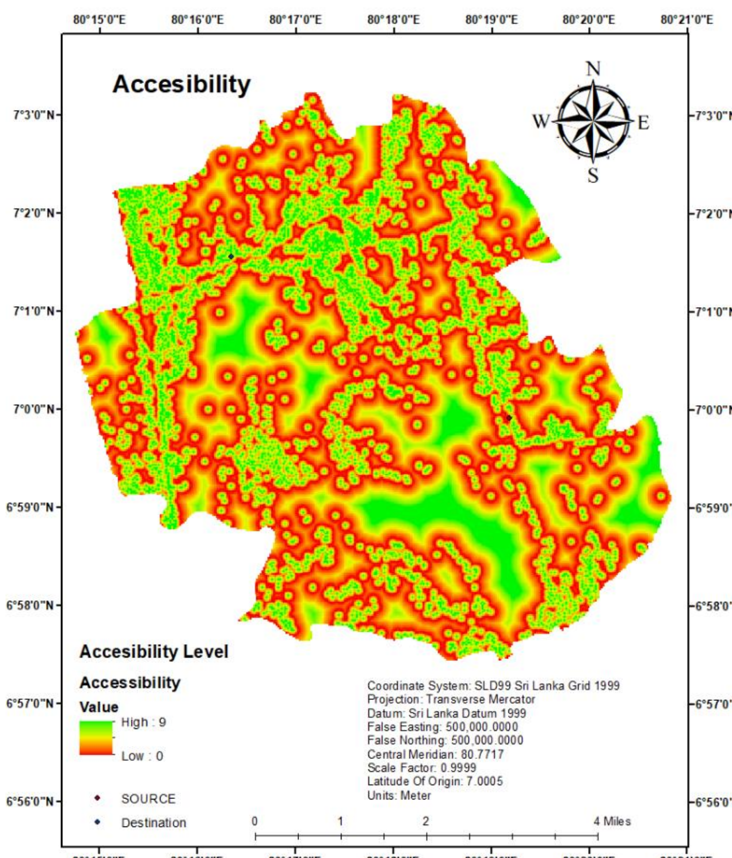

Figure 14 : Accessibility cost raster

The four criteria, B1, B2, and B3, are merged to create a criteria group named 'B' using the following equation $(Eq-7)$ by the WLC method. Their relative significance establishes the importance of each criterion in contributing to the Transportation CG, and the resulting CG map B is shown in Figure 15

$$B = (B1 * 0.15) + (B2 * 0.36) + (B3 * 0.49) \qquad (Eq-7)$$

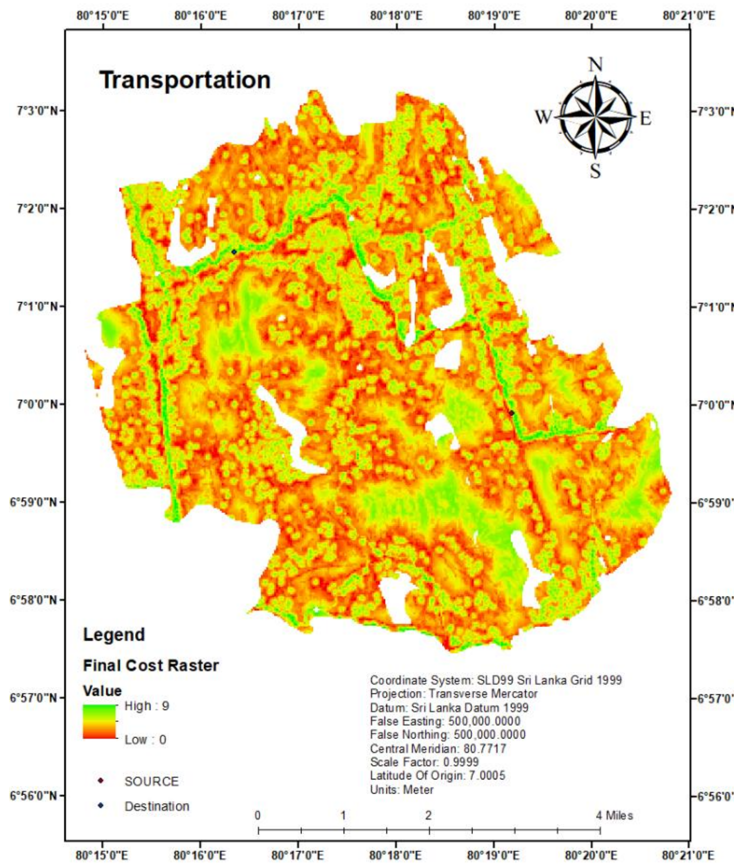

Figure 15 : Transportation criteria group final cost raster

4.2.3 Economic (D)

The purpose of creating this criteria group (CG) is to assess the impact of road construction on the economy, focusing on three criteria: construction cost, tourism, and trade. The CG is intended to assist in identifying the most suitable road alignment from the perspective of its potential contribution to the local economy, measured by cost savings and revenue generation.

4.2.3.1 Construction Cost (D1)

The road type and the area's geographical features influence the cost of building roads. As the road type is predetermined for a given project, geography is the critical variable factor. This criterion provides map data on the comparative cost of constructing roads derived from the combination of two geographical factors: surface type and slope.

4.2.3.1.1 Surface type (D11)

The cost of constructing roads over water bodies is considerably greater than that of constructing on land. This is due to the requirement to build bridges to cross water bodies, which incurs much higher costs. To reflect this concept, the cost assigned to water bodies is set to a maximum and gradually decreases as the distance from them increases. Here the drainage order has been considered. The drainage order was digitized using the data available in Survey department of Sri Lanka.

In addition, that the following score values were extracted by the survey conducted in the RDA Sri Lanka.

Table 18 : Drainage order question survey scores

Criteria	**Parameter range**	**Proposing Score value**
Drainage order	1	9
	2	7
	3	5

4.2.3.1.2 Slope (D12)

The area is composed of higher slopes, construction of roads is significantly more costly than in lower slope areas. The score values are given as follows.

Table 19 : Slope question survey scores

Criteria	**Parameter range**	**Proposing Score value**
Slope (Degrees)	Flat (0% – 10%)	0
	Rolling (10% – 25%)	3
	Mountainous (25% – 50%)	7
	Higher slopes (above 50%)	9

The two sub-criteria are then combined using WLC method to generate Criteria-D1 raster using the expression of Eq-8. The corresponding weights of the sub criteria are defined by their relative significance in contribution to Construction cost criterion.

$$D1 = (D11 * 0.3) + (D12 * 0.7) \qquad (Eq - 8)$$

4.2.3.2 Acquisition Cost (D2)

Acquisition cost refers to acquiring the land required for constructing the road, including purchasing the land and any compensation paid to landowners. This cost can vary widely depending on the location, size, and type of land needed for the project.

If the acquisition cost is not considered when proposing a road alignment, it can lead to higher project costs, delays, or even abandonment of the project if the cost becomes too high. By considering the acquisition cost early in the planning phase, road planners can identify the most cost-effective route requiring the least amount of land acquisition. This can reduce the project's total cost and increase its feasibility.

In addition to cost considerations, acquisition costs can also impact a road construction project's social and environmental aspects. Land acquisition can impact local communities; some land may be more ecologically sensitive or valuable than others. By carefully considering acquisition cost along with other factors such as social and environmental impacts, road planners can propose an alignment that is not only cost-effective but also socially and environmentally responsible.

Here I have selected two types of land types of crops and lands with buildings, following score values were taken from a question survey.

Table 20 : Building types of question survey scores

Criteria	Building type	Proposing Score value
Building type	Private buildings	5
	Temples/Mosques/Church/Hindu kovil	9
	Schools	9
	Building under construction	2
	Factory buildings	8
	Commercial buildings	7
	Bus stand	7
	Government buildings	6
	Other	0

Table 21 : Crop types of question survey scores

Criteria	Crop type	Proposing Score value
Crop type	Rubber	7
	Scrub land/Barren land	0
	Tea	8
	Paddy	6
	Coconut	6
	Chena	3
	Water body	9
	Rock	9
	Open forest/Unclassified Forest	2
	Dense forest	9
	Home gardens	5
	Abandoned paddy	4
	Playground	1
	Other	0

Final weightages are given below.

The two sub-criteria are then combined using WLC method to generate Criteria-D2 raster using the expression of Eq-6. The corresponding weights of the sub criteria are defined by their relative significance in contribution to Construction cost criterion and according to the expert ideas.

$$D2 = (D21 * 0.6) + (D22 * 0.4) \qquad (Eq - 9)$$

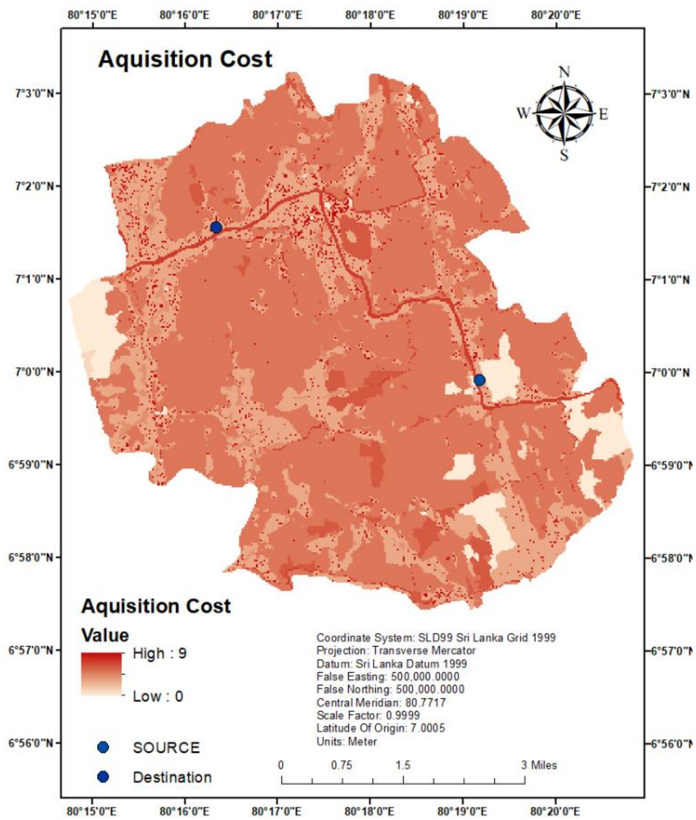

Figure 16 : Acquisition cost raster

The two criteria, D1 & D2, are combined to form the criteria group D using the equation below (Eq-10), producing the CG map D (Figure 16) by the WLC method. The corresponding weights of the criteria are established by their relative significance in contribution to the Societal CG.

$$D = (D1 * 0.667) + (D2 * 0.333) \qquad (Eq - 10)$$

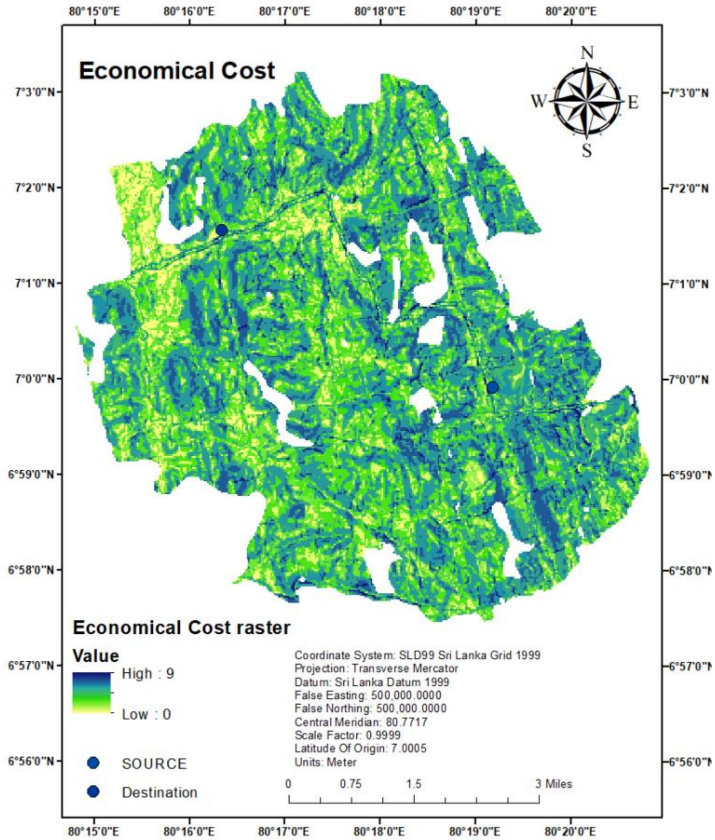

Figure 17 : Economical criteria group final cost raster

4.2.4 Environmental (C)

The purpose of this criteria group (CG) is to consider environmentalists' views and evaluate how road construction could impact the environment in the surrounding area. The goal of the CG is to identify the most environmentally friendly road alignment that will minimize negative environmental impacts. The CG consists of five criteria: , Water pollution, Deforestation, Noise/Air pollution, Soil erosion. It aims to facilitate the search for the optimal road alignment that considers environmental sustainability a key factor.

4.2.4.1 Water Pollution (C1)

Roads can lead to pollution of water bodies and surrounding drainage systems, primarily due to waste generated by people using the roads and vehicle-generated waste such as tire scrapes, oil leaks, and exhaust. The waste runoff from the roads can eventually flow into water bodies and drainage systems, causing environmental damage. Therefore, it is recommended that roads be constructed as far away as possible from water bodies and drainage systems, and areas near them should be given a higher cost to reflect the potential environmental impact.

Buffer distances were created as 50 m from drainage order 1, 30 m from drainage order 2, 10 m from drainage order 3 and scored as follows according to the expertise ideas.

Table 22 : Buffered distances from drainage lines question survey results

Criteria	Parameter range	Proposing Score value
Buffered from drainage lines	50 m buffer from drainage order 1	9
	30 m buffer from drainage order 2	7
	10 m buffer from drainage order 3	4
	Other areas	0

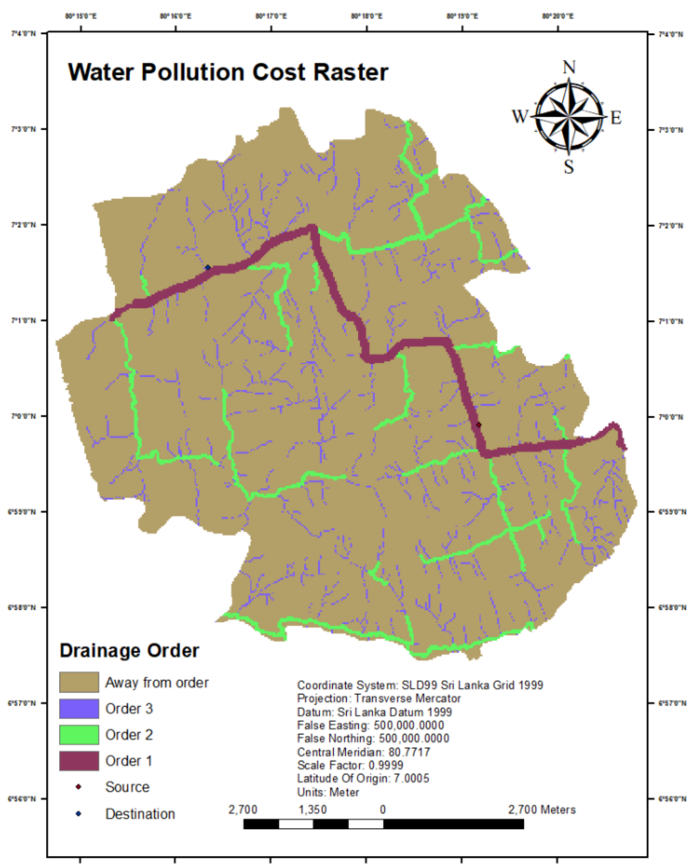

Figure 18 : Water pollution cost raster

4.2.4.2 Noise Pollution (C2)

The presence of roads significantly amplifies the level of noise in the surrounding areas, which can negatively affect nearby human settlements and make the environment less desirable for inhabitants. Therefore, when proposing road construction, the location of existing settlements and buildings is considered, and roads are preferably built far away from these settlements to reduce the potential noise pollution impact.Distances from the buildings were considered here and Euclidean distances map created. Then the map is reclassified by giving score values according to the expertise.

Table 23 : Distances from settlement areas question survey scores

Criteria	**Parameter range**	**Proposing Score value**
Distance from Settlement areas (m)	0-50	9
	50-150	7
	150-300	5
	300-500	2
	500-750	0

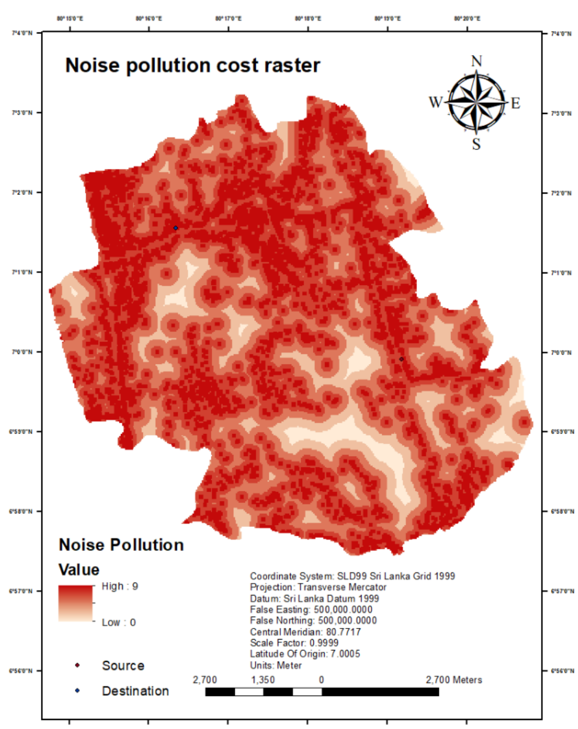

Figure 19 : Noise pollution cost raster

4.2.4.3 Deforestation (C3)

This criterion considers the potential deforestation that may occur as a result of road construction. The severity of the deforestation impact varies based on the type of forest cover in the affected areas. For instance, clearing dense forest covers is more environmentally costly than clearing open forest areas for road construction. The forest cover data is obtained from the Land use/ land cover data, and cost values for different forest cover classes are assigned based on Table-24. These cost values are then assigned to the corresponding forest cover polygons and converted to raster, resulting in the Deforestation cost map – C3 (Figure 20).

Following score values were extracted by expertise ideas.

Table 24 : Land use land cover type question survey scores

Criteria	**Forest cover class**	**Proposing Score value**
LULC	Rubber	0
	Scrub land	2
	Barren land	2
	Tea	0
	Paddy	9
	Coconut	7
	Chena	7
	Water body	2
	Rock	0
	Open forest	2
	Unclassified Forest	5
	Dense forest	2
	Home gardens	2
	Abandoned paddy	2
	Playground	0
	Quarry	0
	Livestock farms	2
	Mixed-perennial crops	0
	Other cultivation	0
	Cemetery	5
	Other	2

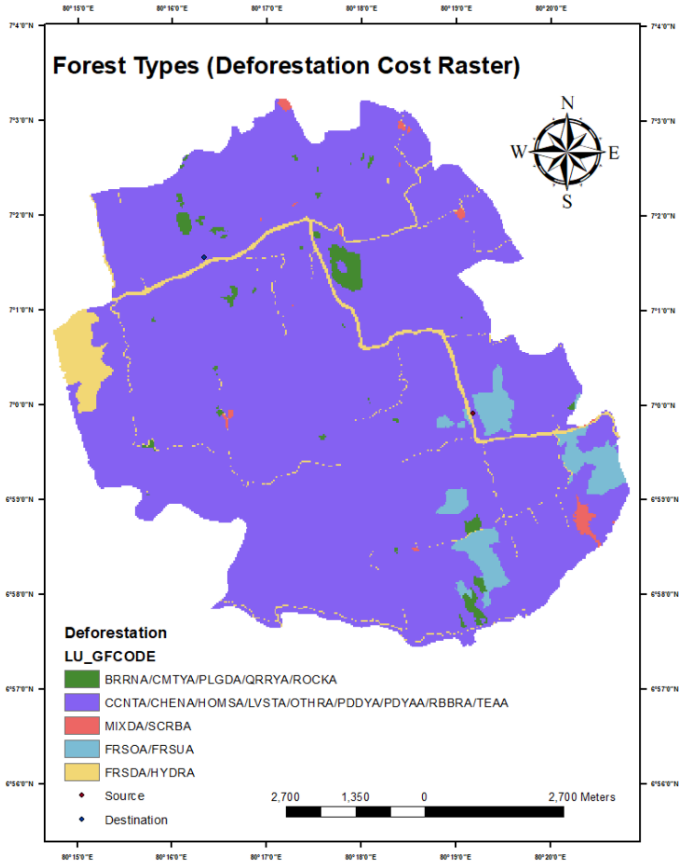

Figure 20 : Forest types cost raster

4.2.4.4 Soil Erosion (C4)

Constructing roads in areas highly resistant to soil erosion is preferable only. Building roads in such areas can increase the susceptibility to erosion, resulting in more negative impacts on the surrounding environment. Two sub-criteria are considered to model erosion susceptibility: slope and land use/land cover.

4.2.4.4.1 Slope (C41)

The slope of an area is a crucial factor in determining its susceptibility to erosion. Areas with steeper slopes are more prone to erosion and are assigned a higher cost. The DEM data is rescaled according to the RDA manual.

Table 25 : Slope ranges question survey scores

Criteria	**Parameter range**	**Proposing Score value**
Slope (percent)	Flat (0% – 10%)	0
	Rolling (10% – 25%)	3
	Mountainous (25% – 50%)	7
	Higher slopes (above 50%)	9

4.2.4.4.2 Land use land cover type (C42)

The erosion susceptibility of an area varies based on its land use or land cover. For example, scrublands are more prone to erosion than dense forest areas due to the higher concentration of vegetation in the latter. The cost values of different land use/land cover classes are assigned, which are attributed to the corresponding polygons of land use/land cover data. The polygons are then converted to a raster, resulting in the land use/land cover cost map.

Following score values were extracted by expertise ideas.

Table 26 : Crop types of question survey scores

Criteria	**LULC type**	**Proposing Score value**
Crop type	Rubber	7
	Scrub land	6
	Barren land	9
	Tea	7
	Paddy	6
	Coconut	6
	Chena	7
	Water body	8
	Rock	0
	Open forest	1
	Unclassified Forest	2
	Dense forest	0
	Home gardens	4
	Abandoned paddy	7
	Playground	8

	Quarry	0
	Livestock farms	6
	Mixed-perennial crops	6
	Other cultivation	6
	Cemetery	5
	Other	0

The two sub-criteria are combined using LWC method to generate Criteria-D4 raster using the expression of Eq-11. The corresponding weights of the sub-criteria are defined by their relative significance in contribution to erosion criterion.

$$C4 = (C41 * 0.6) + (C42 * 0.4) \quad (Eq - 11)$$

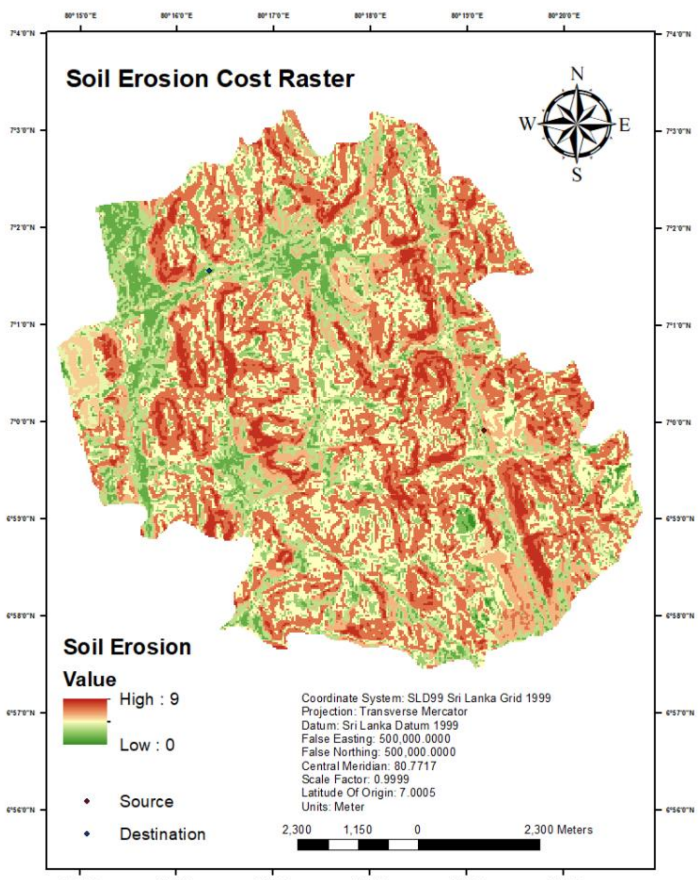

Figure 21 : Soil erosion cost raster

4.2.5 Social (E)

4.2.5.1 Public facility disturbance (E1)

To avoid any adverse social effects from constructing roads through public facilities such as parks and recreational areas, it is preferable to build them elsewhere. This is because construction costs increase significantly in public facilities areas and decrease as we move further away. To determine the appropriate distance, a Euclidean distance map is created based on the polygon data of the public facilities, which is then rescaled as follows.

Table 27 : Building types question survey scores

Criteria	**Building type**	**Proposing Score value**
Building type	Unspecified buildings	2
	Temples/Mosques/Church/Hindu kovil	9
	Schools	9
	Building under construction	2
	Factory buildings	5
	Commercial buildings	5
	Government buildings	5
	Hospitals	9
	Other	0

4.2.5.2 Resettlement (E2)

If road construction is likely to harm the people living in the area, then relocation becomes imperative. Therefore, it is preferable to build roads at a distance from residential areas. The expense of construction increases as it comes closer to the settlements and decreases as it moves further away. The Euclidean distance map was created with weights assigned as before.

The two sub-criteria are combined using WLC method to generate Criteria-E raster using the expression of Eq-12. The corresponding weights of the sub-criteria are defined by their relative significance in contribution to erosion criterion.

$$E = (E1 * 0.25) + (E2 * 0.75) \quad (Eq - 12)$$

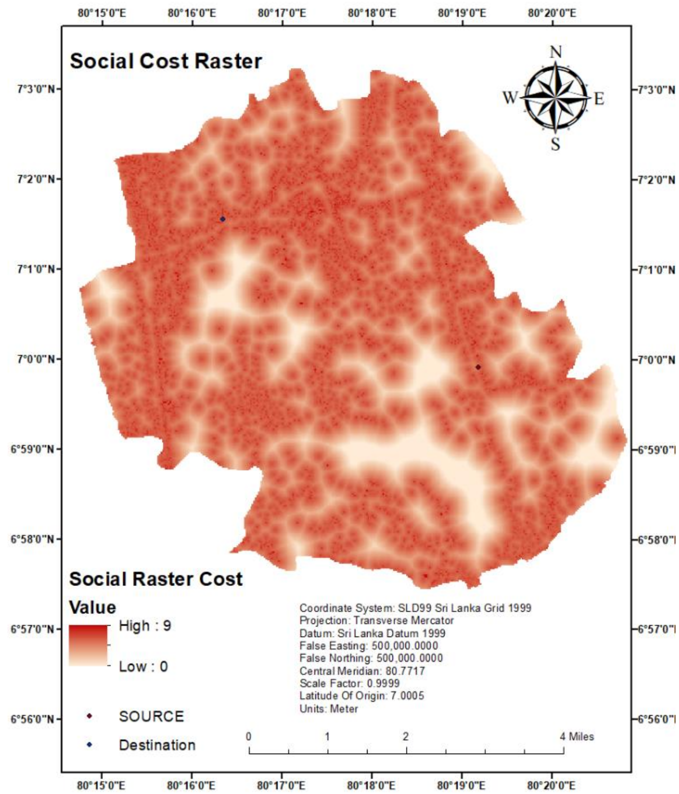

Figure 22 : Social criteria group final cost raster

4.6 Least cost path by AHP

The ArcGIS spatial analyst extension's Cost Path tool is utilized to generate the least cost paths. This tool requires three inputs: Origin/Destination data, Cost Distance raster and Cost Backlink raster. The O/D data is already available. Suitable horizontal and vertical alignments are created after the analysis (Botejue, 2019).

Another least cost path, AHP, is generated by combining all the Criteria Group maps using the Weighted Linear Combination (WLC) method to create a composite cost raster based on Equation 13. The resulting road alignment, shown in blue in Figure 23, considers all the criteria with weights determined according to the approach of Yakar and Celik (2014) and consultation with an engineer on the relative importance of the criteria groups in road alignment design (Botejue, 2019)

$$AHP = (A * 0.33) + (B * 0.15) + (C * 0.22) + (D * 0.19) + (E * 0.13) \qquad (Eq - 13)$$

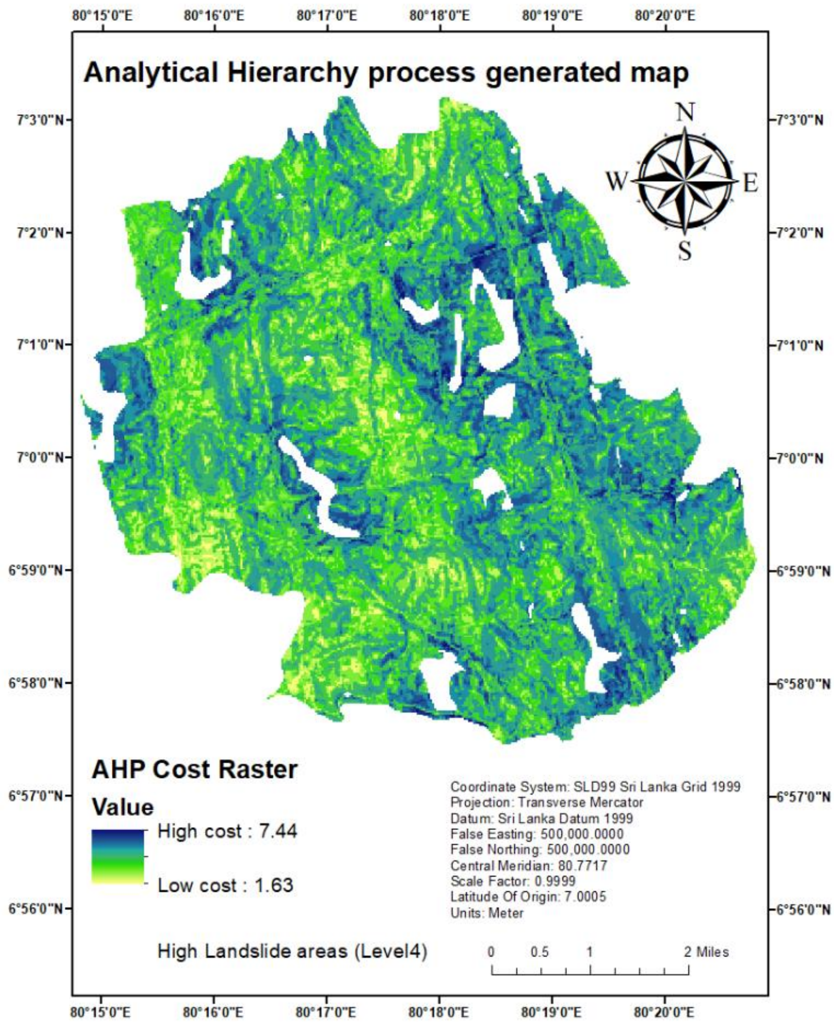

Figure 23 : AHP Criteria group final cost raster

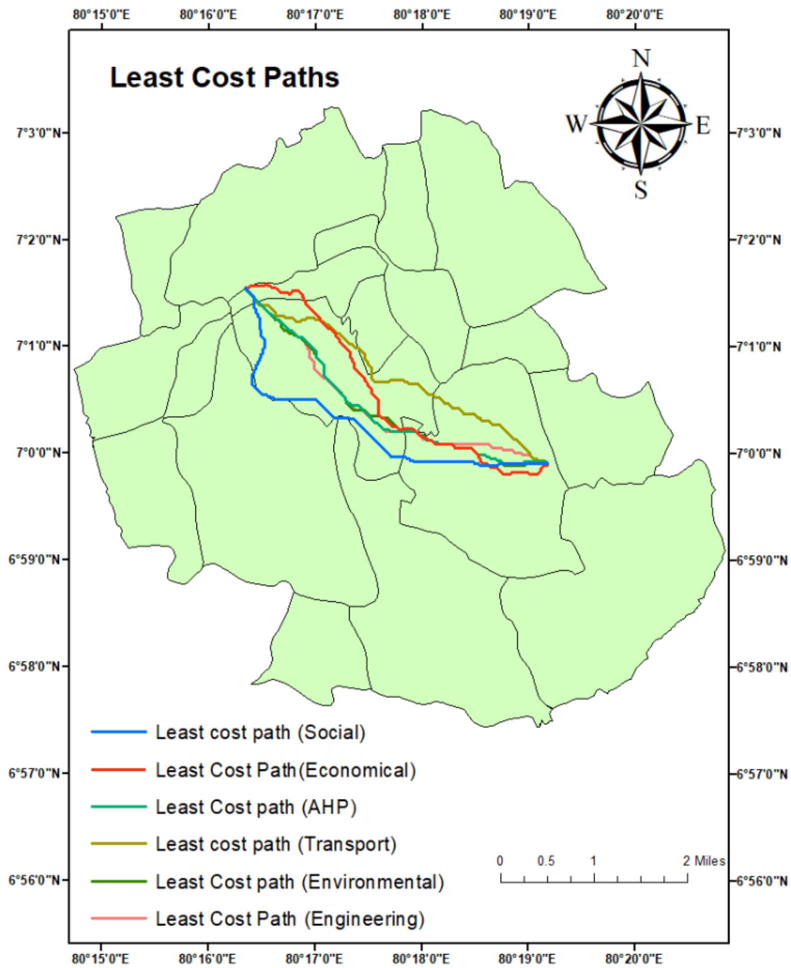

Figure 24 : Six Least cost paths

4.7 CAD Analysis

The six road alignments produced previously will undergo a process of conforming to engineering design standards, assessing geometric feasibility, and calculating precise cut and fill volume. The design standards for this road align with the Geometric Design Standards of the Road Development Authority (RDA) in Sri Lanka.

4.7.1 Road Template

The road template is the cross-sectional geometry of the designed road. The dimension of the different components of the road template is defined in Table-28.

Table 28 : Selected Road class specifications

Parameters	Value
Length	Average 6769m
Standard	National highway (2 lanes)
Road class	B Class
Carriageway width	9m
Shoulder width	2m
Bridge	1 (no design)

The shoulder on the cut side of the road includes a ditch with a width of 0.6 meters and a remaining width of 0.9 meters. The total width of the shoulder and ditch is 1.5 meters. Although the cut slope of the template may vary depending on the soil type, a constant slope of 1:3 (0.3333) is utilized throughout the road length for simplicity in implementation and due to the lack of terrain composition data for this analysis.

4.7.2 Alignment adjustment

The 6 alternative road alignments generated in the LCPA were drawn in CIVIL 3D using the defined road template and road class. The least cost paths were adjusted to conform to the RDA design road template, resulting in alignment alternatives that comply with the horizontal curve design standard, with only negligible portions of the design roads deviating from the least cost road corridor by approximately 3-5 meters. This deviation falls within the minor threshold. Once the vertical alignment was designed and optimized, the cut and fill volume of all the road alignment corridors were calculated and presented in Table-29. The cut and fill volume calculation assumed that the earth composition in the study area was similar, as there was no available earth composition data for the study area.

Designed horizontal and vertical alignments are attached into the annexes.

Table 29 : Cut and fill costs

Alignment	Cut volume (m3)	Fill volume	Cut-fill cost
Engineering	724150	84640	411.9
Transportation	2204845	185712	1195.04
Environmental	2511840	218844	1367.40
Economic	1007822	299895	722.46
Social	1485896	389752	1022.52
AHP	985952	145258	585.45

The total cost of cut/fill (right most column in Table-14) is calculated using the formula below (Eq-14) which is the prevailing rate for cut and fill works in the study area located in India. The Indian rupees values have been converted into rupees.

$$C = Rs. (474 \times A) + (823 \times B) \qquad (Eq - 14)$$

C – Cut and Fill cost

A – Cut volume

B – Fill volume

4.7.3 Standardization and combined assessment

Different alignments' cost and length values are standardized to a common scale to enable a relative comparison between them. This is done by stretching the values using a linear equation mentioned in section 3.17.4 and presented in Table-29 to fall within the range of 0-100. The resulting standardized values are then added together for each alignment to create a total cost that considers all assessment criteria. Different assessment criteria are weighted differently to calculate this total cost, as shown in bold in Table-30. These weights are derived from the literature and consultation with engineers.

This approach is crucial because it allows for comparing different alignments based on multiple assessment criteria. Although each alignment may perform best in its respective assessment criterion, adding Cut/Fill cost and Length is critical in determining the overall performance of an alignment. These two factors are considered the main deciding factors in assessing road alignment alternatives and are therefore given substantial weight in calculating the total weighted cost.

The distribution of weights is flexible and should be carefully planned using Multi-criteria decision-making procedures and preferably a large group of experts. The best alignment is determined based on the decision makers' preferences and the assigned weight values. The Engineering Alignment has the least weighted cost, followed by the AHP Alignment and the Economic Alignment. The Economic and Societal alignments have similar total weighted costs but differ in cut/fill cost, which could be used to select the better alignment between the two.

Thus, Table-30 comprehensively compares different alignments based on multiple assessment criteria. However, the best alignment selection ultimately depends on the decision-makers and weight values, which are determined using the AHP pairwise comparison method and the input of stakeholders.

Table 30 : Final criteria cost values

		Criteria							Total Cost
		Engineering	**Economical**	**Transportation**	**Social**	**Environmental**	**Length**	**Cut and Fill**	
	Weights	**0.2**	**0.1**	**0.03**	**0.02**	**0.05**	**0.25**	**0.35**	**1**
Alignment	**Engineering**	80.53	79.02	93.66	100	86.79	88.5	30.12	65.8243
	Economical	49.53	35.43	53.31	64.3	47.44	94.52	87.39	72.9228
	Transportation	51.33	59.61	33.33	79.37	55.94	90.88	100	79.3313
	Social	100	100	100	62.33	100	100	52.83	82.7371
	Environmental	66.58	64.08	71.94	68.07	65.64	88.66	74.78	74.8636
	AHP	71.33	68.85	74.86	80.2	73.48	89.51	42.81	66.0358

CHAPTER 5 - RESULTS AND DISCUSSION

5.1 Comparison based on the total cost

The analysis identified six optimal alignment alternatives in order to bypass the Yatiyanthota landslide area. These alternatives were then assessed based on various criteria, and an assessment table (Table-30) was produced to assist decision-makers in comparing the alignments and selecting the most preferred one. The assessment results showed that the existing alignment is the best option, with the Social and Transportation alignments having higher total costs. The Social alignment had the highest cost among the alternatives, almost 30% higher than the least expensive alignment, which was the Engineering alignment.

It is important to note that the assessment should not only consider the total weighted cost but also take into account other factors such as the alignment's performance in other assessment criteria, its length, and the cut/fill costs. The cut/fill cost and the length of the road are particularly significant when selecting the best alignment. Therefore, they should be included in the assessment, as they are major deciding factors (IRC, 2002). The Engineering alignment, which had the least total weighted cost, was also ranked highest in terms of the cut/fill cost (having the least cut/fill cost) and was the shortest alignment. Consequently, it was determined to be the best alignment alternative, with little chance of variation in its rank when assessment weights were altered.

The position with the second-best alignment, though slightly more variable, AHP alignment can be identified as the second-best alternative based on the total cost and cut-and-fill cost perspective. However, the AHP alignment is longer than the Environmental alignment.

The decision between the Economic and Environmental alignments for the third best option is currently undecided. The Economic alignment has a total cost of 72.92, while the Environmental alignment has a slightly higher cost of 74.86, with a negligible difference between them. However, the Economic alignment has a cut/fill cost value of 87.39, whereas the Environmental alignment has a lower value of 74.78. Additionally, the Environmental alignment is very little longer by approximately 0.16 kilometers.

Ultimately, the choice between these alignments will depend on the priorities of the decision-makers and industrial experts, whether they place more importance on minimizing cut/fill costs or prioritizing a shorter length for the alignment.

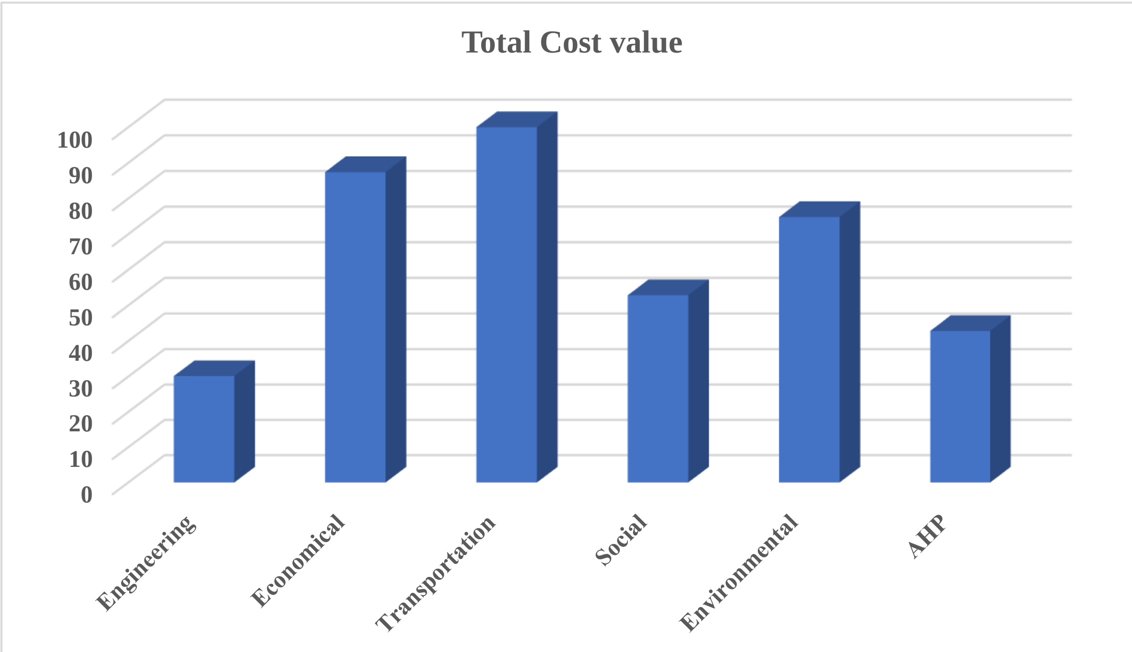

Figure 25 : Total cost values comparison

Social impact group has the highest total cost according to the study. Moreover, the highest length is investigated in the social alignment. In contrast, the cut and fill volume cost is recorded as the fourth highest value.

5.2 Advantages of optimal alignment

Except for the AHP alignment, the Engineering alignment is considerably more cost-effective according to all the assessment criteria. The Engineering alignment complies better with engineering standards and is environmentally friendly, promotes better transportation with shorter length, and is less expensive in cut and fill costs. The most favorable optimal alignment is the Engineering alignment, which is shorter, resulting in significant savings in terms of construction cost, time, and fuel consumption. Cost savings as the Engineering alignment in terms of cut-and-fill costs, which is impressive from an engineering and economic perspective. All these benefits make it conclusive that the optimized alignment, the Engineering alignment, is preferable, although the final decision ultimately depends on the decision maker's preference.

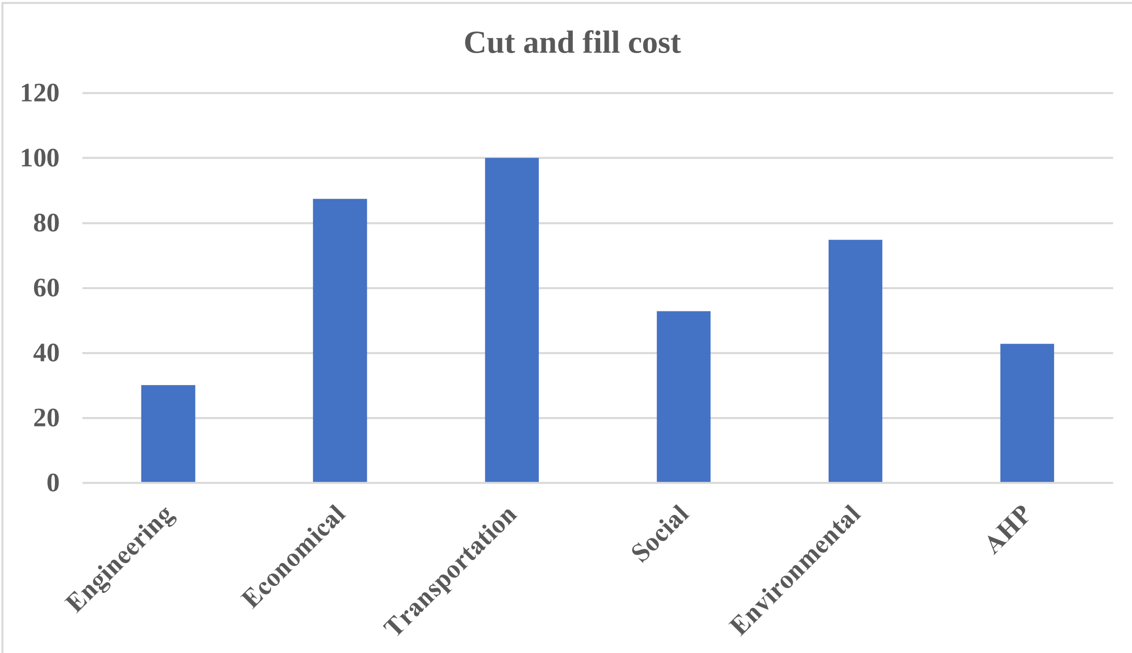

Figure 26 : Cut and fill cost comparison

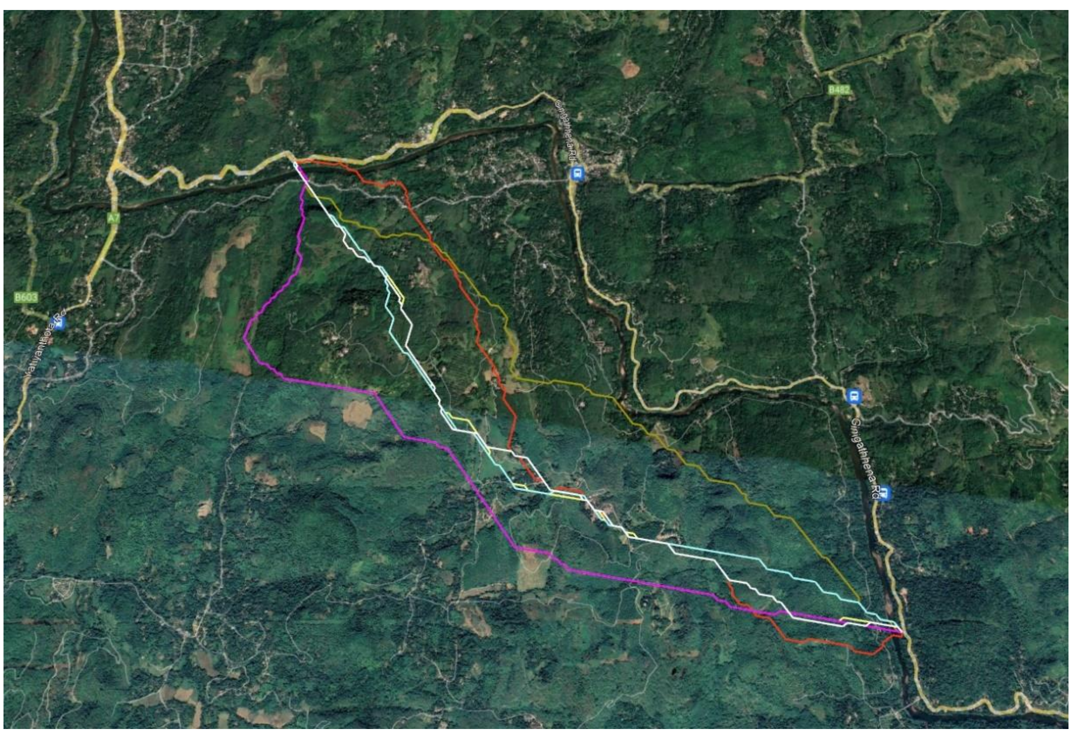

Figure 27 : Six optimal alignments on Google earth

5.3 Comparison with Previous Studies and Research Implications

This study's findings demonstrate both similarities and differences when compared with previous research in roadway alignment optimization. Our results align with Jha and (Jha and Schonfeld 2004b) in confirming that multi-criteria optimization produces more balanced solutions, though our study found Engineering standards can sometimes outweigh earthwork considerations, unlike their finding that cut/fill costs typically dominate. The superior performance of our Engineering alignment validates (Link 2020c) demonstration that GIS-based path distance tools effectively control slope constraints, though our study in landslide-prone terrain shows environmental factors having greater influence on alignment selection than previously documented in stable terrain studies. The total cost comparison reveals critical implications for developing regions like Sri Lanka, where the 30% cost difference between Social and Engineering alignments highlights the economic challenges of prioritizing social factors in resource-constrained environments. The minimal difference (approximately 2%) between Environmental and Economic alignments challenges traditional assumptions that environmentally conscious planning necessarily increases infrastructure costs substantially. Furthermore, the strong performance of the AHP alignment across multiple criteria validates the Analytical Hierarchy Process as an effective decision-making framework for complex infrastructure projects in geographically challenging regions. These findings suggest that GIS-based multi-criteria optimization approaches can successfully identify economically viable solutions while addressing environmental and engineering constraints in landslide-prone areas, offering valuable guidance for transportation planning policy in developing countries where balancing limited budgets with infrastructure needs remains an ongoing challenge.

CHAPTER 6 - CONCLUSION

6.1 Conclusion

The research approach described in this study offers a specific application in the design of road alignments by utilizing GIS technology. The methodology generates optimal road alignment alternatives based on different perspectives or criteria groups, which are then incorporated into the Civil 3d CAD design process. The final assessment of the alternatives is done in the GIS platform, combining the assessment criteria from both GIS and CAD. This approach provides decision-makers with more flexibility and mitigates the landslide hazard, which can be fine-tuned to meet the specific needs of a particular geography or application.

The methodology used in this study also provides decision-makers with multiple alternatives to choose from rather than a single "optimal" solution. This not only increases the likelihood of finding a more suitable alignment but also provides the opportunity to balance different criteria, such as cost, safety, and environmental impact. Additionally, the transparency and manageability of the GIS alignment optimization system used in this study make it easier to regulate and calibrate the system to user-specific applications and stakeholder preferences.

It is important to note that the optimal alignments generated using this methodology should not be considered as universally optimal with absolute global optimization. Instead, they should be viewed as a robust indication of the best route through a region, considering various factors such as terrain, economy, environment, society, engineering aspects, and transportation efficiency. After the optimal alignment is selected, a detailed ground survey is recommended to check the alignment's real-world feasibility and fine-tune the curves to accommodate any minor adjustments required.

6.2 Potential Applications

This research methodology can be directly applied by transportation planning agencies and civil engineering firms in developing countries facing similar geographical and economic constraints. Highway authorities in mountainous regions of countries like Nepal, Colombia, or the Philippines could implement this GIS-based multi-criteria approach to efficiently bypass landslide-prone areas while minimizing construction costs. The methodology is particularly valuable for preliminary planning stages of infrastructure development projects, as it enables rapid assessment of multiple alignment alternatives before committing significant resources to detailed engineering designs.

The methodology's adaptability extends beyond roadway planning to other linear infrastructure projects such as railways, pipelines, and power transmission lines in challenging terrains. By adjusting the criteria weights and constraint parameters, engineers can tailor the approach to various infrastructure types and regional priorities. For example, railway planners could emphasize gradient constraints and curve radii, while pipeline engineers might prioritize geological stability and environmental sensitivity. Urban planners could also apply this methodology when designing ring roads or bypass corridors around growing cities in hilly regions, where balancing development needs with landslide risk mitigation is essential. The transferability of this approach across different infrastructure types and geographical contexts makes it a valuable tool for sustainable development planning in hazard-prone areas worldwide.

6.3 Recommendations

A higher-accuracy digital elevation model would improve the precision of the vertical grade restrictions and cut and fill volume calculations. This would enhance the accuracy of the assessment and design. To determine the weight definition for the criteria in the least cost path analysis and assessment procedure, it is recommended to use statistical methods for calculating criteria weights, such as those employed in work by Çevik & Topa (2003). These statistical index weights can then be directly used in various phases of the LCPA and assessment methodology. To import the results of the GIS LCPA into CAD, the alignment corridor should first be exported to shapefile format and then imported into CAD. Enhancing the interoperability process between GIS and CAD would make the methodology significantly more robust. It is advisable to conduct sensitivity analysis on the different weights to address the subjectivity and variability in the weights used in LCPA and assessment.

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