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Geospatial Approach for Road Alignment Optimization in Hilly Regions- A Case Study of Aizawl Link Road, Mizoram, India

by

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the degree of
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Aizawl, February, 2020

Science Pledge

By my signature below, I certify that my project report is entirely the result of my own work. I have cited all sources of information and data I have used in my project report and indicated their origin.

Aizawl, February 2020

Place and Date Signature

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Abstract

The design of roads is an important aspect in the development of road infrastructures which significantly impacts the economy, environment and society of the region. The design of road alignments, which defines how the road will traverse the terrain and geography, is particularly interesting as there can be virtually infinite number of alternatives on how the road alignment is planned. Thus, there is a need to carefully design the alignment in order for that road alignment to be most economical, environmentally friendly, comply to society and promotes good transportation. In other words, there is a need to optimize the alignment process based on constraints and factors. The traditional method of designing road alignment in modern history after the advent of computer-based design system mainly involves manual drafting or drawing of alignments by engineers on top of topographic data and some limited geographic data considered. This method of alignment design does not produce optimal alignments due to human limitation in considering many spatial factors simultaneously. A few methods have been developed in the aim of optimizing road alignments in which the use of GIS and the tools it provides is particularly attractive in this design process due its capability to consider many spatial data simultaneously. This is particularly critical in hilly areas having complex geography and geology which is under high landslide and earthquake susceptibility zone. The research develops a methodology using Least Cost Path algorithm in GIS (ESRI's ArcGIS) to produce optimal alignment alternatives on a case study in which the alignment alternatives are compared and assessed with the existing alignment of the case study which was pre-designed using traditional approach. The least cost optimal alignment (best optimal alignment) generated by the method is significantly better than the existing alignment based on all the assessment criteria. There is also a notable reduction in length and cut/fill cost in the optimal alignment compared to the existing alignment.

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Chapter-1: Introduction

The human civilization throughout history have been using roads to travel from one place to another for their survival and all form of activities and thus roads have been vital to the survival of human beings. As such, a significant amount of resources is utilized in the development of road infrastructures especially in modern history due to higher need for connectivity due to modernization and expansion of settlements throughout the globe. Due to the importance of roads in human civilizations, the necessity to properly design and construct the roads is of immense importance to us. The thesis deals with finding optimal road alignment using GIS and comparing them to traditional alignment design method using CAD.

1.1 Background of road alignment design

The road in the context of this research deals particularly to the vehicle roads like highways and in-city roads and exclude pathways like trails and sidewalks etc. Road is defined by the Organisation for Economic Co-operation and Development (OECD) as "a line of communication (travelled way) using a stabilized base other than rails or air strips open to public traffic, primarily for the use of road motor vehicles running on their own wheels" (Wikipedia, 2019c).

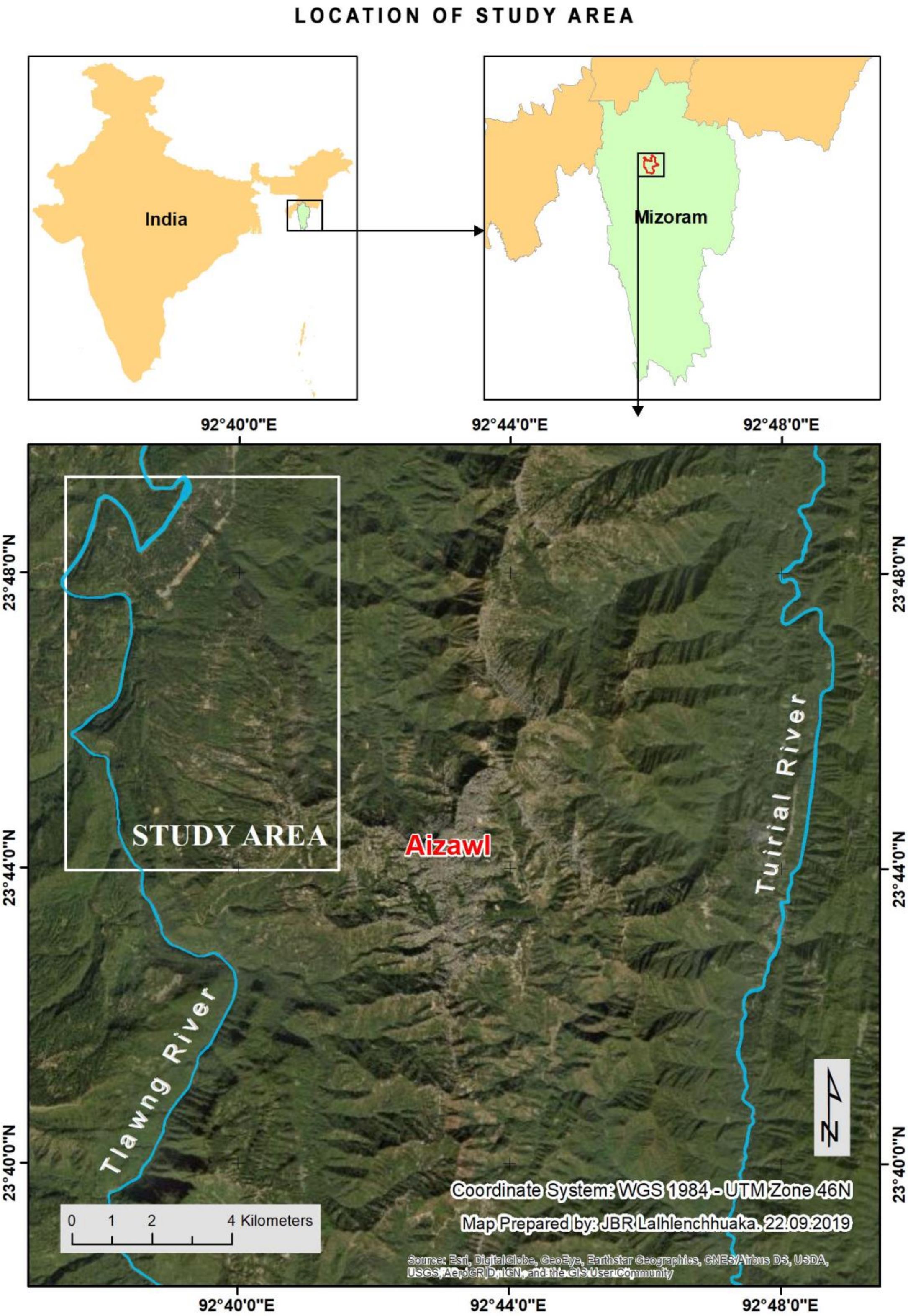
The construction of roads requires a design and this is inevitable as even before engineering practices were used, we have been designing roads subconsciously whether the designers intend it or not before constructing the roads. The design can be generalized into two categories namely – the design of how the alignment will go from one place to another and the structural design of the road itself like composition of the road surface, thickness etc. The design for this research context deals mainly with the alignment design which is how the road would traverse from the origin to destination along the terrain which can be segmented into horizontal alignment design and vertical alignment design. Given any two location, there are an infinite number of possible combinations of line and grade or we can say alignments joining them (Parker, 1977). According to Parker (1977), the fundamental route location problem may be stated as that of finding the best or optimum path between the termini, as a function of one or a number of factors.

Road infrastructure construction greatly impacts the society and economy of the region and the way the construction impacts the region depends on the way the roads are designed and constructed. In the design phase of road construction, one of the most important factors is the alignment of the road which greatly affects the cost of the road, the impact it brings to the area and the feasibility for transportation.

According to the Indian Rural Roads Manual (IRC, 2002), the prevailing method of designing road alignment in the country predominantly relies on plotting road centrelines on top of terrain information in a CAD environment based on the engineering standards of the manual.. This method, despite being very practical and time tested, needs to be re-assessed as it generates only satisfactory alignments and not optimal alignments.

1.2 Study area and geography

The study area lies in the western part of Aizawl town near in the outskirt areas (white rectangle in Map-1). Aizawl is the largest city as well as the capital of the north eastern Indian state of Mizoram. The city is located just north of Tropic of Cancer and is situated on a ridge approximately 1000 meters above the mean sea level, surrounded by Tlawng River to its west and Tuirial River to its east (see Map-1) and thereby the city sits on the valley of Tlawng and Tuirial separated by a ridge running north-south. It has a population of about 404,050 (NIC, 2011). In the summer the temperature ranges from 20-30 degrees Celsius, and in the winter 11-21 degrees Celsius (NIC, 2011). The town is a rapidly growing settlement area due to its centricity within the state and being the capital, immigrants from every part of the state rapidly populates the region. The rapid growth and development in Aizawl create a demand for better transportation infrastructures.



Map-1. Study area

The geography of this region is that of rolling hills, valleys and rivers where the hill rages are oriented in north-south direction with valleys between the ranges and plain area scattered throughout the area. The hills have average height of about 1000 meter in this region and the elevation at the rivers falls to about 10 meters above MSL and some areas have higher ranges which go up to a height of over 2,000 meters (Wikipedia, 2019a). The folded structure (rolling hills) of this regions is at the junction of two moving tectonic plates (Indian plate and Burmese plate) of which the movement of the two plates is the formation mechanism of the rolling hills in this region (Wikipedia, 2019a). The folded hills and mountainous North South belts, with perpendicular faults, comprise sediments of the Surma, Barail and Tipam groups. There is Alluvium soil in river beds consisting of deposits of argillaceous and arenaceous sandstones, shale, siltstones and mudstones and greywacke. The rock system is generally weak, unstable, weathered and prone to seismic and weather influence producing landslides and also the area is under the highest zone 5 of earthquake susceptibility (Wikipedia, 2019a). The soil majorly comprises of sandy loam, clay loam that has been heavily leached due to the high slopes leaving it porous and weak. Thus, the geography and geology of the region is particularly complex and intricate which makes the design and construction of roads particularly challenging.

1.3 Problem description

Road design and construction is an important endeavour in a nation’s infrastructure development especially in places like Mizoram State in India where there is still enormous need and opportunity for road infrastructure development. Mizoram is located in the north-east region of India bordering Myanmar to the east and Bangladesh to the west having Aizawl as the capital city. The state has a population of about 1,091,014 according to a 2011 census and grows at a rate of 22.8% since 2011 census (Wikipedia, 2019b). Transportation planning is the most important planning activity for a developing city (Shang, Tjader, & Ding, 2004) and thus, to compensate and support for its relatively rapid growth rate and closeness to international boundaries, road infrastructure growth is essential to accommodate for the upliftment of the culture, economy and society of the region. For such developments, proper planning and design of roads is essential as the construction of roads is an expensive and time-consuming process. For this reason, it is desirable that the roads are constructed in such a way as to reduce the cost and negative effects as ideally as possible while still maintaining design standards, in other words, to optimize the design of the roads.

The engineers of the study area rely on the traditional method in the design of road alignments, in which the extensive consideration of geographical data and integration of Geographic Information Systems in their alignment design process is absent. Such pattern of design is also evident throughout the engineering community in other countries as well during the recent past (Liu & Sessions, 1993). Since the design and planning phase is the most critical part of road construction (Abdelrazig & Moses, 2015) in which road alignment design is the most important factor (Yakar & Celik, 2014), prime concern should be given to way in which road alignments are designed. Selecting the best route location and road alignment process is a complicated one with many spatial variables that must be taken into consideration for achieving the best results. Geographic Information Systems (GIS) is a great tool to solve such a problem as it can easily model such diverse and extensive spatial variables (Dawwas, 2005; Jha, McCall, & Schonfeld, 2001). The use of spatial information and GIS is particularly essential in areas like Mizoram having complex geography, geology and also being vulnerable to landslide and earthquake where one must consider and take into account the various spatial factors to find most suitable road alignment.

1.4 Literature review

For a developing country like India, road transportation infrastructure development is considered as one of the most important aspect to modernization and development

(Singh, 2015). Considering the importance of this, the design of the road alignment plays a major role in the road construction process. The core motive of the road alignment design is to find the most economical (or we can say the least cost) alignment connecting two points in perspective of topography, socio-economic factors and environmental impacts while simultaneously satisfying engineering design standards (Awwad, 2005). According to Awwad (2005), the two principal criteria to consider in road alignment design are –

- Most economic path (based on topography, society, economy & environment)
- Conform to engineering road design standards

The design of alignments in this context differs from that of flight line alignment design or trip distribution model (Rao, 1994) which are mainly for optimizing trips and mainly deals with Origin-Destination analysis. The design of road alignment traditionally involves mainly considering the topography of the region and fit the gradient and curve of the alignment in accordance with the topography which involves manually marking segments of lines in horizontal and vertical perspectives based on a large-scale topography (Liu & Sessions, 1993; Saha, Arora, Gupta, Virdi, & Csaplovics, 2005). A trial and error process is involved in the establishment of location of new roads which require the engineers to draw the trial alignment, checking to see if the trial alignment is in compliance with the horizontal and vertical standards or controls and then repeating this step in iteration until satisfactory results are established (Awwad, 2005). Such a process requires an enormous amount of time, resources and is expensive. It does not produce the optimal alignment and rarely considers the diverse geographic factors involved. Even though some thematic factors are considered in the alignment design like settlement area, water bodies, slope etc., the spatial factors considered in this traditional approach is limited and thus considers only one principal of road alignment criteria, which is mainly satisfying the geometric road design standards. The quality of the road alignment designed depends mostly on the planner’s experience and thus can vary significantly which is undesirable. According to Yakar & Celik (2014), the traditional method of designing road alignment faces these drawbacks-

- Criteria affecting the alignment cannot be handled simultaneously due to human limitations on information processing which results in alignment that cannot be defined as optimum.
- Since a concrete procedure is not determined, some irrational changes can be made in the alignment due to local and political pressures and mistakes by the engineer.
- Many important factors related to economic, environmental, social, land use, engineering, and traffic technique subjects cannot be considered during the alignment determination.

CAD method cannot find the best alignment with the lowest total road cost which is composed of factors like is construction, maintenance, economic, social, and environmental costs (Aruga, Sessions, Akay, & Chung, 2005).

Apart from the traditional design method, the systematic finding of optimal road alignment can be categorized broadly into two ways. In one approach, mathematical optimization algorithms are used to optimize road alignment geometry according to defined standards of design considering the topography and some thematic spatial factors. In another approach, GIS tools are used along with extensive geographic data including topography to find optimal alignments. Both approaches produce significant and applicable results which have been utilised rigorously.

The work of Jha, McCall & Schonfeld (2001) is a comprehensive approach in the use of mathematical optimization algorithms to solve road alignment design problem. The particular optimization method used in their work is Genetic Algorithm (GA) and also used computer visualizations for presentation of the results. GIS is used in this method for obtaining the relevant databases and maps such as right of way costs and environmental cost. The approach uses cost formulation technique where the optimal alignment is the least cost alignment and the cost considered in this case are right of way, environmental, pavement, construction, maintenance and earthwork (by considering terrain data as well). These costs are formulated into a cost surface and the GA algorithm finds the best solution within each orthogonal cutting lines which lies perpendicular along the straight line connecting the origin and destination (see Fig-1). The optimal points in each orthogonal line are then connected using curves which are also generated such as to follow engineering standards. Although the algorithm produces significant results, the algorithm is time consuming and requires enormous amount of computational resource. The geographic criteria considered in this method is limited and does not comprise the various critical spatial factors in road alignment design and neglects the very foundation of the problem which is that finding the best route through an area is one of the oldest spatial problems (Subramani, Krishnan, Kathirvel C., & S.K., 2014).

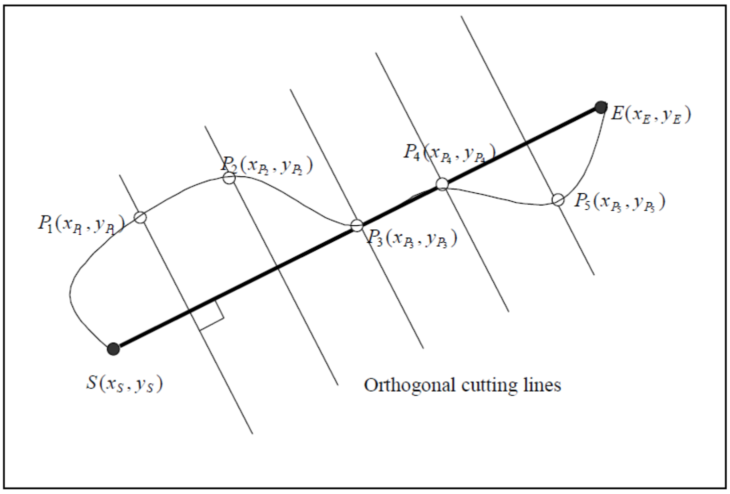


Fig-1. Alignment representation in Genetic Algorithm approach of road alignment optimization (Jha & Schonfeld, 2004)

This mathematical optimization approach is utilized in other works with variation of the algorithm and improvement attempts (Jha & Schonfeld, 2004; Kang, 2008; Kang, Schonfeld, & Jong, 2007; Maji & Jha, 2009). Kang (2007) further develops the GA method by limiting the search space of the algorithm by using feasible gates which narrows the horizontal search space based on user preferences and environmentally sensitive area and thus decreasing computation time significantly. According to Maji (2009), the single objective highway alignment optimization process has limited capability in handling the cost components separately which cannot yield a set of alternative solutions. This limitation was dealt with in his research by using multi-objective GA which is used to find alternative local optimal alignments using user cost and construction cost only. However, the same limitation of considering insufficient geographic information in also evident in these approaches.

GIS is an efficient tool for solving optimization tasks with linear objects like railways, roads, pipelines etc., and GIS is increasingly used in civil engineering applications (Kumar, Panchal, Ashish, & Singh, 2017). GIS produces necessary information needs of many disciplines within a common framework and initiates a higher order systematization of geographic thinking which is crucial in any transportation projects (Wang & Stauffer, 1995). GIS is the most suitable tool for highway engineering as it has the capability to model and analyse various spatial variables simultaneously. The use of GIS in road alignment design is mandatory as several costs of highway alignments are sensitive to geography and using GIS as a tool to calculate these costs is efficient (Jha et al., 2001). The objective is then to find an alignment which minimizes these costs while still maintaining engineering design standards.

In determining the optimal paths from origins to destinations, least cost paths calculation is one of the most useful tool (Stucky, 1998). Formulating a cost surface raster and using Least cost path tool is frequently utilized by a significant amount of literatures in which the cost surface formulation is the part where the majority of the difference lies (Abdelrazig & Moses, 2015; Awwad, 2005; Bailey, 2003; Musa & Mohamed, 2002; Shanmugam & K, 2017; Subramani & Pari, 2015; Sunusi, Agrawal, Lal, & Suleiman, 2015; Yakar & Celik, 2014). The geographic criteria considered by one paper differ with another because of difference in perspectives and also due to difference in goal of the optimization. The least cost path algorithm also differs slightly based on the software used. For example, ESRI's ArcGIS least cost path tool is different from the IDRIS cost and pathway tools but both does more or less the same process. For the multi criteria decisions, analytical hierarchy process (AHP) is generally used for the calculation of weights using pairwise comparison in these papers. The majority of the works, although considers important geographic criteria, are still limited and is not satisfactorily comprehensive. For example, Subramani (2015) considers topography, geomorphology, geology, drainage, land use and land cover which is adequate but not satisfactory. In the extreme simpler side of the application, some only considers the topography (slope and surface distance) for the calculation of least cost paths (Collischonn & Pilar, 2000).

The works of Awwad (2005) and Yakar & Celik (2014) is the foundation of the approach used in this research. Awwad (2005) used ESRI's ArcView 8.1 GIS for calculating least cost paths based on three criteria namely- land cost, slope and environmental features like lakes and wetlands. The methodology is applied on two case studies in which two optimal alignments are found. For both case studies, assessment of the optimal paths is done and the right-of-way costs are found to be significantly lower for the two output optimal alignments than the already designed proposed alignment. Here, the assessment for the alignments is only based on right-of-way cost which is not suitable and is not comprehensive and the criteria for calculating the least cost paths are also limited. Yakar & Celik (2014) also used the same approach of least cost path but using IDRISI GIS, specifically using Cost and Pathway tools. It considers six criteria groups – Economic, Engineering, Traffic, Environmental, Social and Land use to generate cost surfaces for each criteria group. Based on these surfaces, six least cost paths or we can say, optimal paths are generated. All the weighting of criteria and factors are done using pairwise comparison of AHP (Analytical Hierarchy Process). The alternative alignments are assessed by calculating their cost in each criteria group to find the least costing alignment in all the criteria combined.

This research develops on the work of Yakar & Celik (2014) by extending the least cost path algorithm to control the slope of the optimal alignment by restricting search parameters (specifically restricting vertical cost factor). This control of slope (grade) is executed using ESRI's ArcGIS Path Distance tool. This control is critical to comply with engineering standards of road design and this is majorly neglected in earlier GIS approaches. The spatial criteria are generally adopted from Yakar & Celik (2014) but specifically revised to the needs of the special case study by adding and removing criteria. The assessment of the least cost paths is not limited to comparing among the generated optimal alignments (Yakar & Celik, 2014), but is extended by taking into the assessment process an already designed road alignment based on an actual government project. Finally, three important factors in the assessment of road alignment design are considered i.e. length of the alignment, geometric feasibility (or compliance to engineering standards) and cut / fill cost of the alignment. These factors cannot be assessed directly using GIS and thus, engineering CAD system is used in this phase of assessment.

1.5 Research question and objectives

The research uses a GIS based road alignment optimization method and compares the optimal alignments with those generated using traditional CAD process. The comparison is set on a specific study area of hilly regions where the geography is complex.

Objectives:

1. Identifying criteria / factors which are relevant for the specific study area.
2. Generate optimal road alignments based on five scenarios – Economic, Engineering, Environmental, Societal and Transportation using specialized Least Cost Path technique which considers vertical restriction (slope of

alignment). Additional optimal alignment is generated by combining all the five scenarios using AHP, thus resulting in six optimal alignments.

3. Based on different criteria of evaluation, compare the road alignment alternatives generated using GIS process with that of the alignment designed using traditional CAD process.

1.6 Thesis organization

Chapter-1 introduces the research and constructs the background on which the paper will progress and also covers the literature review and research questions. Chapter-2 entails the methodology of the research and provides details of tools and data used. Chapter-3 uses the research method on a specific case study to compare the method used in the research with the traditional method. The results of the research are elaborated in Chapter-4 along with discussion of the results. In Chapter-5, the paper concludes and final further recommendations are written.

Chapter-2: Methodology

2.1 Software and hardware

ArcGIS 10.6.1 is the principal GIS used for the research and all the tools and spatial processing is done on this platform. The Spatial Analyst Extension of ArcGIS is particularly essential for this analysis which contains the Least Cost Path tool. Softree RoadEng is the CAD system used for the engineering drawings and to generate accurate cut/fill volume. Necessary data are collected using handheld GPS (Garmin Montana).

2.2 Data

The following sections describe the data used in the research. All the spatial data mentioned is clipped to the study area to minimize data size and computation time. Spatial data are all in Shapefile format except for the Digital Elevation Model (DEM) which is in raster format. A cell size of 10 meters is used for all the raster data in this research. The table below lists all the spatial data used for the research (Table-1).

Table-1. Spatial data list

Sl. no	*Data*	*Source*	*Format*	*Description*
1.	Buildings footprint	BGSS[1]	Shapefile (Polygon)	Footprints of buildings are digitized from high resolution satellite imagery.
2.	Cyclone hazard	Natural Resources Atlas of Mizoram (MIRSAC, 2009)	Shapefile (Polygon)	Cyclone hazard zones are digitized from scanned paper map of the source atlas.
3.	Digital Elevation Model (DEM)	BGSS	Raster (10 meter)	Extracted from stereo image (Cartosat-1 PAN) using Photogrammetry.

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[1] BGSS (Buannel Geo Solution & Services), Aizawl, Mizoram (BGSS, 2019)

4.	Geology	Natural Resources Atlas of Mizoram	Shapefile (Polygon)	Geological units depicted as zones/areas are digitized from scanned paper map of the source atlas.
5.	Geomorphology	Natural Resources Atlas of Mizoram	Shapefile (Polygon)	Geomorphological type depicted as zones/areas are digitized from scanned paper map of the source atlas.
6.	Groundwater potential	Natural Resources Atlas of Mizoram	Shapefile (Polygon)	Groundwater potential zones are digitized from scanned paper map of the source atlas.
7.	Land use / Land cover (LULC)	Natural Resources Atlas of Mizoram	Shapefile (Polygon)	Land use / Land cover are digitized from scanned paper map of the source atlas.
8.	Landslide susceptibility	BGSS	Shapefile (Polygon)	Landslide susceptibility zones segregated into degree of susceptibility. Data is the product of Landslide Susceptibility Analysis Project undertaken by BGSS in collaboration with the Government of Mizoram.
9.	Origin / Destination	Summary of Project Report[2]	Shapefile (Point)	The origin and destination point of the existing proposed road design are extracted by digitizing paper maps supplied by the Public Works Department of Mizoram (PWD, 2017).
10.	Public facilities	GPS Survey	Shapefile (Polygon)	Facilities and infrastructure which are under public recreational use are surveyed using handheld GPS and converted into GIS data.
11.	Rivers / Drains	BGSS	Shapefile (Polyline)	Drainage system of the area is digitized from Topographic Maps of India and corrected using Satellite Imagery.

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[2] Summary of the Project Report (March, 2018) prepared by Public Works Department, Government of Mizoram named ‘Construction of two-lane road from Sihhmui to Ramrikawn under Central Road Fund (CRF) during the year 2017-2018 in the State of Mizoram’ (PWD, 2017).

12.	Road network	BGSS	Shapefile (Polyline)	Existing road networks are surveyed using DGPS by traversing all roads. Data is then post processed and topology corrected to form road network data.
13.	Tourist site	GPS Survey	Shapefile (Polygon)	Tourist sites are locations of tourist attraction which are surveyed using handheld GPS and converted into GIS data.
14.	Trade Centre	GPS Survey	Shapefile (Polygon)	Trade centers are places of economic and social exchange like markets and malls. They are surveyed using handheld GPS and converted into GIS data.
15.	Traditional alignment	Summary of Project Report	Shapefile (Polyline)	Alignment designed by Public Works Department of Mizoram using prevailing traditional design methods. The Road alignment from the given paper map is scanned, scaled and digitized into GIS data.
16.	Transportation hub	GPS Survey	Shapefile (Polygon)	A transport hub is a place where passengers and cargo are exchanged between vehicles or/and between transport modes. They are surveyed using handheld GPS and converted into GIS data.

2.3 Basic terms in road alignment design

The basic terms involved in road alignment design is described in the following sections for ease of explanation of concepts throughout the paper. These terms are a subset of the immense amount of technical terms associated with road designs and so only the necessary terms which encompass the concepts involved in this research paper are described.

2.3.1 Origin / destination

The origin and destination (see ‘O’ and ‘D’ in Fig-2) of the road alignment to be decided is one of the first decision to be made in designing road alignments. The origin or destination usually connects existing roads and they are the obligatory points from where the road will start or end. This is a constraint in the design process.

2.3.2 Horizontal alignment

The horizontal alignment of a road consists of a set of straight lines from the origin (O) to destination (D) separated by intersection points (IPs) shown as black circular dots numbered 1, 2, 3 in Fig-2. Curves (with defined radius) are added at the location of the intersection points and accordingly, the straight lines are adjusted to form a horizontal alignment (red dashed line in Fig-2). In some context, the straight lines are referred to as tangents and the curves referred specifically as horizontal curves. The radius of the horizontal curves is limited by the design standards used for the particular project.

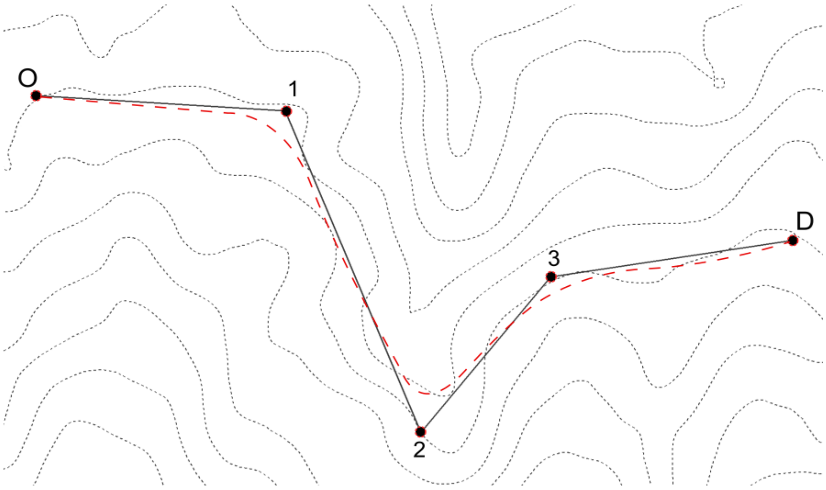


Fig-2. Conventional road alignment design process

2.3.3 Vertical alignment

The vertical alignment of a road is the defined by the presence of ascend and descend in vertical axis with respect to horizontal axis of the road alignment. It is composed of Grades and Vertical curves. The vertical curves (red dotted lines C1 and C2 in Fig-3) smooth the passage of vehicles from one grade to another (or we can say from one-line segment O-D to another line segment 1-2 as shown in Fig-3). Convex vertical curves (C2) are called summit or crest curves, and concave vertical curves (C1) are known as sag curves. The radius of these curves is defined by the standard of design used by the engineers which may differ from region to region and for different road types. The grade of a segment of road (for example- segment O-1) is defined as the ratio of the rise by run, which in this example (Fig-3) is defined by Eq-1. The grade is considered an important aspect of the road design and is also restricted by the road design standard used by the engineers.

$$\boldsymbol{Grade\ (0-1) = \frac{Rise}{Run} = \frac{x1}{y1}} \qquad \textbf{(Eq-1)}$$

where, x1 and y1 are shown in the figure below (Fig-3).

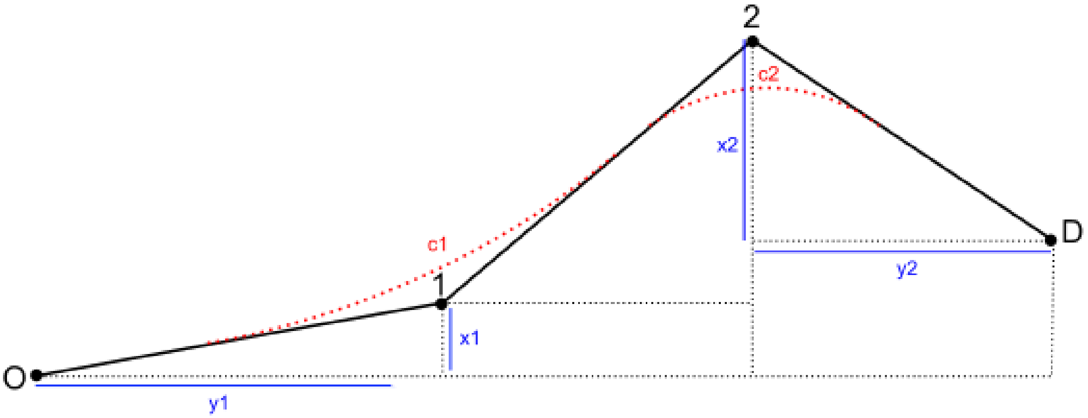


Fig-3. Geometry of vertical road alignment

2.3.4 Cut / fill volume

In constructing roads, there is a requirement to cut or fill earth to transform the terrain on which it runs in order to conform to the road designs. For demonstration, as we can see from Fig-4, there is earth cutting (vertically hashed) of terrain in the uphill side while earth filling (horizontally hashed) the downhill side of the road. The cut and fill volume of a particular cross-section of a road design depends mainly on the width of the road, the elevation of the road surface from the terrain and the slope/structure of the terrain at that particular location. However, the total cut/fill volume is evidently dependent on the horizontal and vertical alignment design.

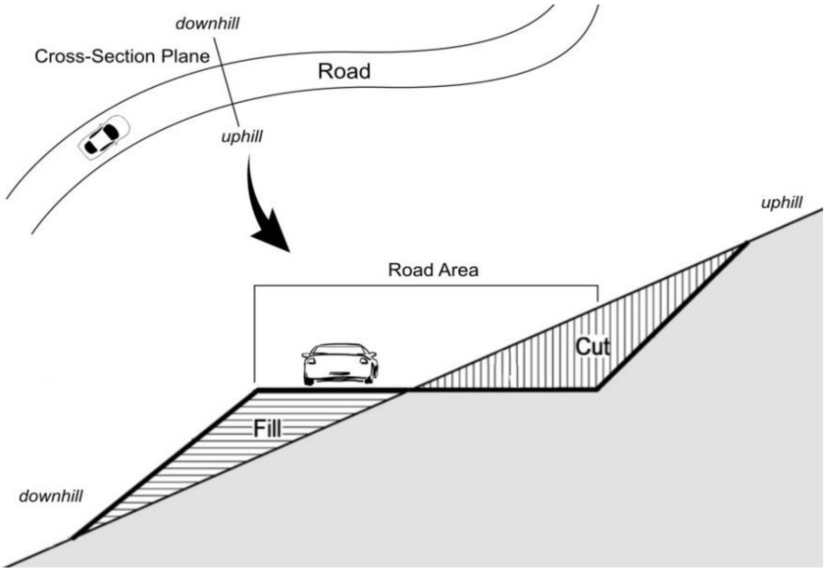


Fig-4. Cross section of road design showing Cut/fill areas

As the terrain of an area and the width of the road are fixed for a particular project, the cut/fill volume is primarily determined by the horizontal and vertical design of the road.

2.4 Research design and approach

The research approach is schematically shown in Fig-5. The approach deals with composition of a GIS based road alignment optimization method and eventually, the comparison of road alignments designed using traditional approach and those designed (optimized) using the GIS based method. The methodology is primarily based on the works by Awwad (2005) and Yakar & Celik (2014), contextualizing the method to conform to hilly regions by using additional data, extending the methodology by incorporating constraint on the grade (Eq-1) of the road alignment in the optimization process and then using Engineering CAD system to realistically assess the cut/fill volume and cost.

The traditional road design (Fig-5, Process-1) is already undertaken and the resulting alignment is finalized by the Government of Mizoram, India, which will be referenced as ‘Traditional Alignment’ for convenience in the rest of the paper. On the other hand, the GIS based optimization of road alignment is then performed between the two obligatory points using various spatial criteria to generate 6 alternative road alignments.

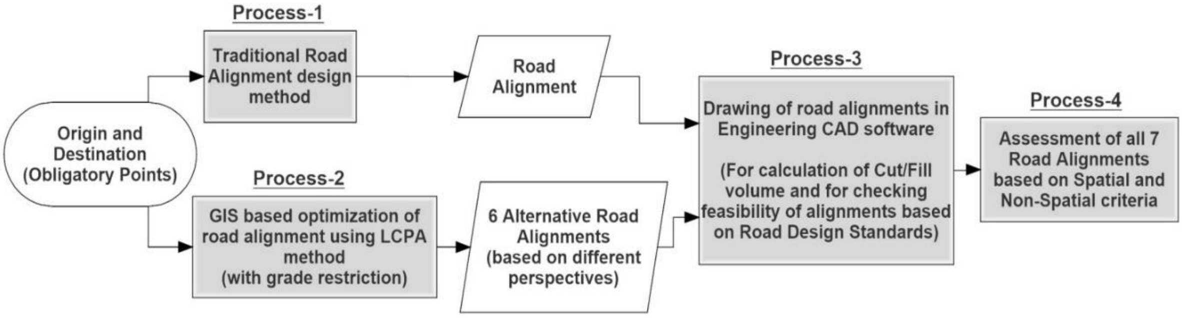


Fig-5. Research approach flow chart

The method used for finding the optimal alignment is the Least Cost Path Analysis (LCPA) method with the Vertical Parameter restricting the slope of the alignment (grade restriction) to confine to road design standards. All the 7 alternative alignments including the traditional alignment will then be drawn inside an engineering CAD environment to calculate cut/fill volume and also to check the geometric feasibility of the alignments based on read design standards. The final process is to assess the 7 alternative road alignments based on various spatial and non-spatial criteria.

2.5 Process-1: Traditional road alignment design

The conventional or we can say the traditional road design method, which is still the prevailing approach to design road alignments in this part of the world, is based predominantly on the manual drawing of road alignments by engineers and planners on top of topographic data. It relies heavily on the engineer's skill which involves trial and error processes of finding and drawing alignments on top of topographic maps (contour maps), checking whether the alignment meets the horizontal and vertical standards of road design and repetitive iteration of this process to minimize cost of construction (Musa & Mohamed, 2002).

The process first involves drawing of alignment centerline from the origin (O) to destination (D) (see Fig-2) by inserting IPs (Intersection Points) shown as 1, 2, 3 in Fig-2 and joining them with line segments (O-1, 1-2, 2-3, 3-D). This drawing is carried out with the contour/topography (dotted black line in Fig-2) considered in the background to follow the vertical and horizontal geometric standards. The next phase is fitting horizontal curves (red dashed line in Fig-2) through the IPs. After the final alignment is selected, ground verification and surveys are carried out to check the reality of the design on the ground and accordingly, re-adjust the design. Then estimate is made for the construction of the road using standard estimate parameters. The whole process is then repeated to find alternative alignments. The final decision of the alignment is generally based on the consideration of right of way cost, land acquisition cost, construction costs, maintenance cost and user cost (Abdelrazig & Moses, 2015).

This conventional method generally only considers topographic information such as gradient and curve and avoiding certain sensitive areas, settlement areas etc. (Saha et al., 2005). According to Yakar and Celik (2014), the criteria affecting the road alignments cannot be handled simultaneously by the engineer and thus, we can argue that the alignment cannot be defined as optimal. Environmental, economic, social, land use, engineering and traffic information are not taken into consideration or not considered significantly enough which are critical factors in road alignment design. Also, the designed alignment can vary considerably from engineer to engineer due to no concrete structure in the selection process which is not ideal.

2.6 Process-2: GIS road alignment optimization

The Least Cost Path Analysis (LCPA) is used as an optimization method in this process. LCPA is a distance analysis tool within GIS which finds the least cost path from a source/origin to destination by calculating costs of paths using a cost raster where the cost in each cell can be a function of time, distance or other user defined criteria (Briney, 2014). Optimization, as defined by Cambridge Dictionary is the process of making something as good or effective as possible and the LCPA process is thus, an optimization approach of finding the most efficient path through a cost surface raster. LCPA involves three phases (see Fig-6) namely - Criteria Map Generation, Cost Surface Map Generation and then performing Least Cost Path Algorithm on the cost surface map.

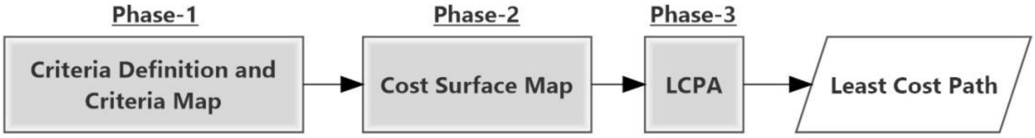


Fig-6. Process-2: Phases of Least Cost Path Analysis

2.6.1 Terms and explanations

Prior to moving forward into the phases of LCPA, specific tools involved in the process which will be referred frequently is elaborated in the following sections to facilitate and assist explanation of the methodology.

2.6.1.1 LCPA tool algorithm

ArcGIS Path Distance Tool (available in Spatial Analyst Extension) is the specific tool used for the LCPA which has a robust mechanism with comprehensive parameters and works on raster data format. From cell perspective, the objective of the tool is to determine the least costly path to reach a source for each cell location in the analysis window i.e. it calculates the accumulated travel cost from each cell to the nearest source location. The least cost path is not necessarily the least distance path (Yusof & Baban, 2004) but the least frictional path based on a cost surface.

For demonstration (ESRI, 2019b), suppose we have a source location (cell-1 in Fig-7 Left diagram) and destination (cell-2 in Fig-7 Left diagram), and the right diagram of Fig-7 is the accumulated cost raster, the accumulated least costly way of getting from source cell 1 (dark orange) to destination cell 2 (school icon) is 10.5. In other words, it costs at least 10.5 to get from the source to destination. The next question of what path to take from the source to destination is answered by using Back link direction raster which is generated before least cost path tool is executed. The back-link algorithm assigns codes to each cell (see Fig-8).

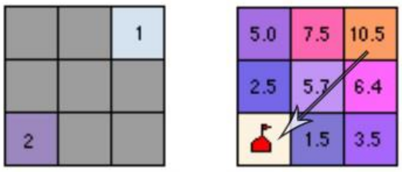


Fig-7. (ESRI, 2019b) Least cost path demonstration (Left: Input source locations, Right:Cost weighted distance)

Fig-8. Backlink raster coding (ESRI, 2019b)

For example, if an output cell is assigned the value 5 as part of the least-cost path to a source, the path should move to the neighboring cell on the left. If that cell has 7, the path should move due north, and so on. The algorithm notes all the movement direction of the path as codes in order for it to be used in the Least Cost Path tool to generate an output path. In our example (see Fig-7), the direction of movement from source to destination is shown with a white arrow which will be recorded by backlink algorithm as direction codes in a raster (as shown in Fig-8 right diagram). This raster will then be used in the generation of least cost path. A more detailed in-depth explanation of how the Path Distance Tool work can be found in the tool description and definition pages in ESRI's website (ESRI, 2019a).

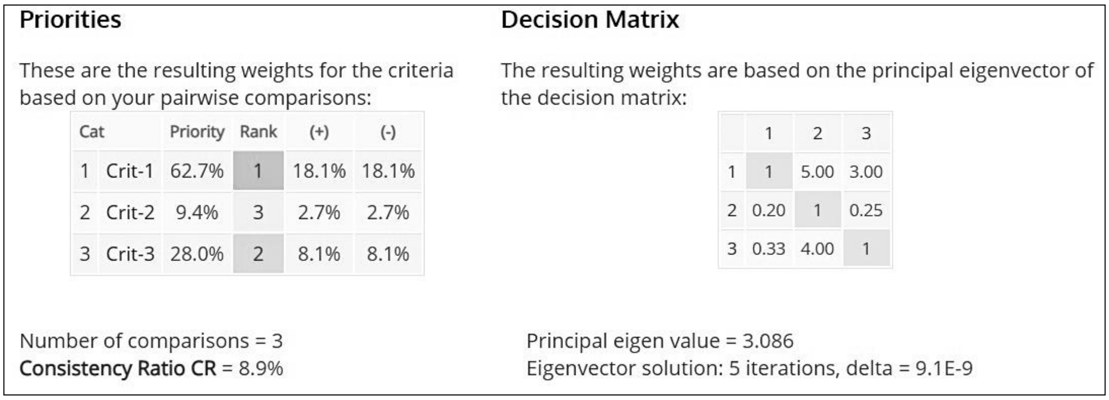
2.6.1.2 Multi-Criteria Decision Making (MCDM)

In order to incorporate and quantify the several decisions involved in the analysis, we use MCDM process. This tool provides analysis and quantification of the complex trade-offs between choice alternatives and is widely used in many applications which combine GIS and MCDA (Carver, 1991; Gomes & Lins, 2002; Huizingh & Vrolijk, 1997; Kaya, 2006;

Kaysi, Sadek, & Al-Naghi, 2007; Kumar et al., 2017; Sunusi et al., 2015). MCDA is primarily used for giving proportional weights to different criteria and factors which is used extensively in the definition of criteria, criteria map creation and cost surface map creation.

Analytical Hierarchy Process (AHP) is the specific MCDA method used in this research due to its simplicity and applicability in diverse practices. “AHP is a flexible and yet structured methodology for analyzing and solving complex decision problems by structuring them into a hierarchical framework” (Saaty, 1980). The use of GIS and AHP is particularly essential in this research and it has been thoroughly used in the Geospatial community (Abdi, Majnounian, Darvishsefat, Mashayekhi, & Sessions, 2009; Djenaliev, 2007; Huizingh & Vrolijk, 1997; Kaysi et al., 2007; Kumar et al., 2017; Malczewski, Moreno-Sanchez, Bojorquez-Tapia, & Ongay-Delhumeau, 1997; Ronald, Weigen, & Peter, 1995; Subramani et al., 2014; Sunusi et al., 2015; Wahdan, Effat, Abdallah, & Elwan, 2019; Yakar & Celik, 2014).

The AHP procedure is used for rating or ranking a set of alternatives or for the selection of the best in a set of alternatives based on pairwise comparison between the alternatives (Boroushaki & Malczewski, 2008). The first step of the AHP is to compare the alternatives/criteria pair by pair based on a scale. The scale of comparison is generally 1 to 9 where 1 being equal importance of both alternatives/criteria and 9 being one alternative/criteria is 9 (nine) times more important than the other relatively. Fig-9 (decision matrix) shows an example of a pairwise comparison between three criteria – Crit-1, Crit-2 and Crit-3. Crit-1 is 5 (five) times more important than Crit-2, Crit-1 is also 3 (three) times more important than Crit-3. After the pairwise comparison, it is mathematically converted into importance percentages and ranking (Fig-9 Priorities). The details of the operations of AHP can be found in the paper by Saaty (1980).



Priorities

These are the resulting weights for the criteria based on your pairwise comparisons:

	Cat	Priority	Rank	(+)	(-)
1	Crit-1	62.7%	1	18.1%	18.1%
2	Crit-2	9.4%	3	2.7%	2.7%
3	Crit-3	28.0%	2	8.1%	8.1%

Number of comparisons = 3
Consistency Ratio CR = 8.9%

Decision Matrix

The resulting weights are based on the principal eigenvector of the decision matrix:

	1	2	3
1	1	5.00	3.00
2	0.20	1	0.25
3	0.33	4.00	1

Principal eigen value = 3.086
Eigenvector solution: 5 iterations, delta = 9.1E-9

Fig-9. Pairwise comparison in AHP methodology

The percentages are then essentially converted into proportional weights (total sum of weights turning out to 1) such that for our example in Fig-9, Crit-1 has a weightage of 6.27, Crit-2 has 0.93 and Crit-3 has 2.80. The consistency ratio (CR) is an important indicator of the consistency of decision making regarding the pairwise comparison of the alternatives. The value of CR should preferably be lower than 10% for practical applications.

2.6.1.3 Euclidean distance mapping

The Euclidean Distance is a tool inside Spatial Analyst Extension of ArcGIS. It assigns the distance value (straight line distance) of the cell from a source to that cell. The Euclidean distance output raster contains the measured distance from every cell to the nearest source and the distances are measured as the crow flies (i.e. horizontal) in the projection units of the raster, such as feet or meters, and are computed from cell center to cell center. In the example below (Fig-10), the distance to each town (yellow dots) is identified.

The effects of certain factors or criteria which will be later used in the LCPA depends on the distance of areas from the location of these factors/criteria and for conceptualizing such effects, the Euclidean distance tool is used.

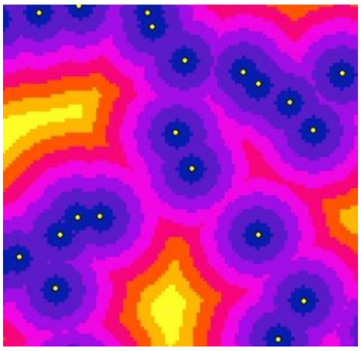


Fig-10. Euclidean distance raster showing the distance to the nearest town (yellow dots) for each cell location

For example, the favorability of constructing roads decreases as we get closer to settlement areas and so, distance from settlements are generated using this tool and then rescaled to cost values using functions which will be discussed in the next section.

2.6.1.4 Raster rescale by function

The effects of certain factors which depend on distance from those factor locations are sometimes non-linear in nature. For example, in a habitat suitability model of a bird species, the preferences of a location as habitat decreases logistically with the increase in distance from the food source (see Fig-11). After certain distance, the favorability of that location as a habitat decreases abruptly as at this threshold, the bird species tend to hesitate the travel distance to get food which is entirely dependent on the bird species.

Fig-11. Habitat favorability function

In order to quantify the effects of factors/criteria at certain distance, functions are used to rescale the original distance values into new values. Two functions in particular are utilized namely – ‘Logistic Decay’ and ‘Large’. These are the tools available in Spatial Analyst extension of ArcGIS. It takes a source raster and rescales the raster based on the defined function and parameters to produce a rescaled version of that original raster.

2.6.1.4.1 Logistic decay function

This transformation function fits a logistic decay function within a specified minimum and maximum X values using a defined ‘Y’ intercept percent (ESRI, 2016c). This function is used in cases where smaller input values (or distance values for this research) have higher weights/cost and larger input values have lower weights/cost. As the input values increase, the weight/cost rapidly decreases to a point where the lowest weight/cost level off at the higher input values (see Fig-12). The input values for this research is the distance values of cells from the Euclidean distance raster mentioned in section 2.6.1.3 and the evaluation scale is the cost associated with that particular factor.

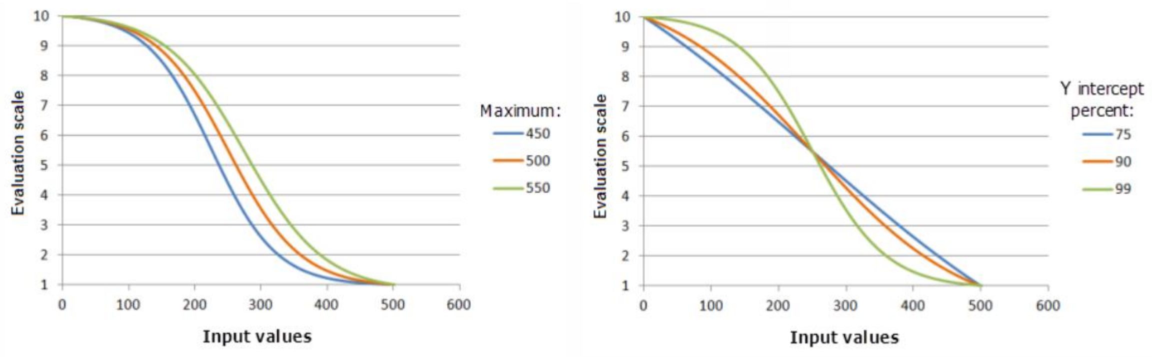


Fig-12. Logistic decay function graph (ESRI, 2016c)

The function has four important parameters namely- minimum, maximum, y-intercept and range.

Minimum: The parameter controls the starting point of the logistic decay. The greater the minimum value, the faster the preferences will decrease in the main decay portion of the function and the curve will be steeper as we can see from Fig-12 left graph (ESRI, 2016c).

Maximum: The parameter controls the ending point of the logistic decay. The smaller the maximum value, the faster the preferences will decrease in the main decay portion of the function and the curve will be steeper (Fig-12).

Y-Intercept: The parameter determines the degree of curvature of the inverted ‘S’ curve in the logistic decay graph (see Fig-12 right graph). The larger the value of this parameter, the greater the inverted ‘S’ curvature and the smaller the value of Y-intercept, the flatter the line resembling a straight line (ESRI, 2016c).

Range: This parameter determines the output value range (evaluation scale as shown in Fig-12).

2.6.1.4.2 Large function

This transformation function is used when the larger input values have higher cost/weights and lower input values has lower cost/weights and more preferable (ESRI, 2016c). The defined midpoint parameter identifies the transition point for the function (i.e. the point of transition of the ‘S’ curve). Values greater than the midpoint increase in weight/cost and values below the midpoint decrease in weight/cost. How quickly the values will increase and decrease as they move from the midpoint is determined by the Spread parameter (ESRI, 2016c). The function has three parameters namely- midpoint, spread and range.

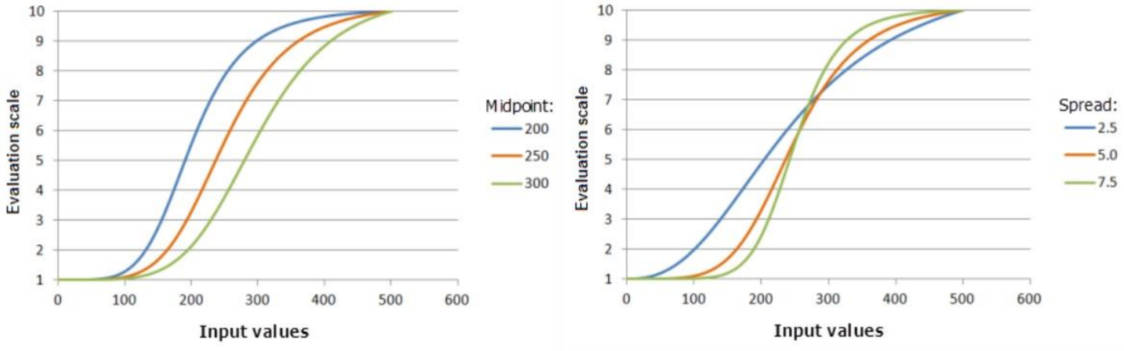


Fig-13. Large function graph (ESRI, 2016c)

Midpoint: The parameter defines the transition point of the function. As we can see from Fig-13 (left graph), the midpoint determines the start of the transition of the curve which effects how input values are transformed (ESRI, 2016c).

Spread: The parameter controls how quickly the preference increases and decreases (i.e. degree of curvature). As the spread value increases, input values greater than the midpoint will more quickly increase in preference to the upper threshold, and input values less than the midpoint will more quickly decrease in preference to lower threshold (see Fig-13 right graph) (ESRI, 2016c).

Range: This parameter determines the output value range (evaluation scale as shown in Fig-13).

2.6.1.5 Weighted linear combination (WLC)

The Raster Calculator tool in ArcGIS Spatial Analyst extension is utilized for addition of two or more raster in which the weight of each raster is taken into consideration in the addition process. This is particularly used to combine two or more criteria raster into a composite single criteria raster. In Fig-14, two raster InRas1 and InRas2 are combined (added) having different weights (InRas1=0.75 & InRas2=0.25). The equation below (Eq-2) gives the equation of the weighted addition for the example shown in Fig-14. Applying Eq-2 of the top right cells of Fig-14, we get the weighted addition of 3 and 2 resulting in 2.75.

$$\boldsymbol{OutRas} = (\mathbf{0.75} \times \boldsymbol{InRas}\mathbf{1}) + (\mathbf{0.25} \times \boldsymbol{InRas}\mathbf{2}) \qquad \textbf{(Eq-2)}$$

where, InRas1 and InRas2 are example rasters shown in the following figure (Fig-14).

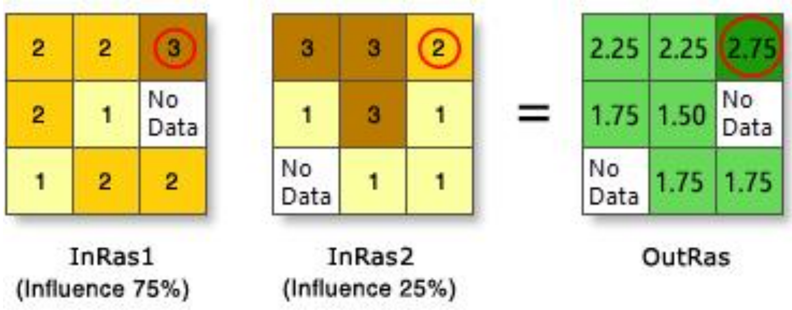


Fig-14. Weighted linear combination

The weights of these raster are defined using MCDA process mentioned earlier by incorporation the decision of stakeholders and literature.

2.6.2 LCPA Phase-1: Criteria definition and criteria maps

In this phase of LCPA, the stakeholders, decision makers, GIS experts and experts in other fields should decide on which geographic/ spatial criteria and factors are important for the analysis to find suitable paths through a region. This is an important phase in the LCPA as the accuracy, reliability and applicability of the resulting optimal alignments largely depends on these criteria and factors. For the purpose of this research, the criteria and weights are mainly extracted from the mentioned literatures in consultancy with the consultant engineer where some criteria are modified, added or rejected for the particular case of hilly regions.

The factors or criterion considered are all spatial in nature and for such, a conceptualization system is necessary for each of the criterion. The conceptualization comes from a general idea about a spatial factor and how it contributes to the favorability of road construction. For example, roads are preferably being constructed in areas away from water bodies due to high cost of construction on water bodies. This general proposition needs to be conceptualized in the form of spatial factor and eventually to maps. The criteria are conceptualized in terms of cost such that high cost represents least favorable location for road construction and vice versa. For this conceptualization, two essential aspect of the criterion needs to be addressed –

- *How the particular criterion contributes to the suitability of road construction*: This can be a negative or positive effect that the criterion brings to the suitability of road construction. For example, areas of dense forest covers are preferable avoided to reduce deforestation. On the other hand, open vegetation has sparse tree cover and thus, relatively better for road construction. Thus, the areas of dense forest covers have comparatively or relatively high cost in terms of road construction (see Fig-15).

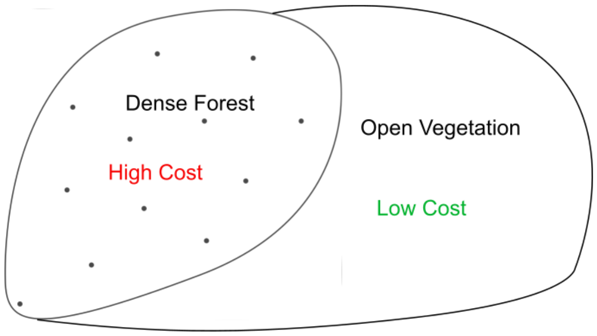


Fig-15. High cost low cost concept

- *The spatial variation of how this criterion affects the suitability of road construction:* This aspect is conceptualized using two approaches based on the type of the spatial data used for the criterion. If the criterion is a polygon feature covering the whole study area (see Fig-15) in which spatial units segregates the region, then the spatial units/ features are directly given costs (using AHP) based on literatures and expert’s opinion and the polygon is converted to raster based on the cost values. If the criterion is a point, line or polygon feature which does not cover the entire study area without gaps, Euclidean distance is first generated around these features and the resulting raster is reclassified using the raster rescale functions mentioned in section 2.7.1.4 to produce a cost raster (see Fig-16) for that particular criterion. The rescale is done in such a manner as to reflect the criterion’s positive or negative contribution to the suitability of road construction. The cost may decrease or increase functionally as we move away from the criterion features. In Fig-16, red represents highest cost areas and gradually the cost decreases to yellow, green and then lowest cost in the blue region.

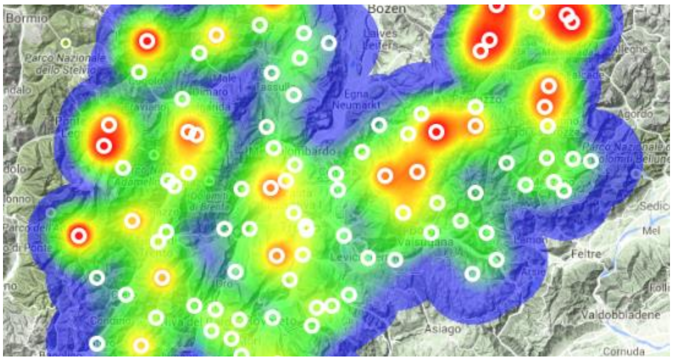


Fig-16. Spatial cost variation concept

2.6.3 LCPA Phase-2: Cost surface map

Cost surface maps are prepared based on grouping of criteria into a criteria group (CG). Two or more criteria maps (cost maps) are combined based on their mutual contribution to a higher order criterion to produce Criteria Group cost surface. For example, five criteria – Deforestation, Air pollution, Water pollution and Erosion are combined into higher order criteria – Environmental Criteria Group (see Fig-17).

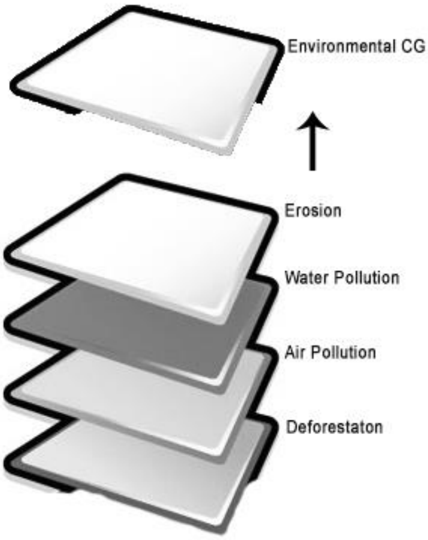


Fig-17. Criteria group creation process

This combination of criteria maps into criteria group map is done using LWC method mentioned earlier. The formula given in Eq-3 applies for each corresponding raster cell of the resulting CG cost map.

$$CG = \sum_{i}^{n} w_i c_i \qquad \textbf{(Eq-3)}$$

where CG is the value of the particular cell in the resulting CG raster, i=first criterion and n=last criterion, w_i = weight of the criterion (i) and c_i = particular cell value of criterion (i). The weights are normalized such that $\sum w_i = 1$. The resulting raster is a cost raster which will be the foundation in the least cost path generation.

2.6.4 LCPA Phase-3: Least cost path generation

The least cost path tool used for this particular analysis is the Cost Path tool under Spatial Analyst extension of ArcGIS. The tool requires two raster data as inputs namely- Cost Distance raster and Cost Backlink raster.

2.6.4.1 Cost distance raster

The Cost Distance raster is generated using the tool – Path Distance (ArcGIS) which calculates, for each cell, the least accumulative cost distance to the nearest source, while accounting for surface distance and horizontal and vertical cost factors. The cost distance values are calculated based on a cost raster which is mentioned in section 2.6.2.

The specialty of this tool is that it takes into account the vertical factor which is particularly useful for this analysis as we require accounting for the grade of the road and restricting the grade to the engineering standards. This is made possible by the vertical factor where we can make the tool give high cost to high slope alignments and limit the search such that the alignment maintains the required grade. This vertical grade restriction works in such a way that high angle value from one cell to another is given higher cost and vice versa and, in the process, also validate whether the next cell is at an angle above the threshold in which case the next cell is eliminated from generating cost distance. For this vertical factor to take into account, the digital elevation model of the region is a requirement.

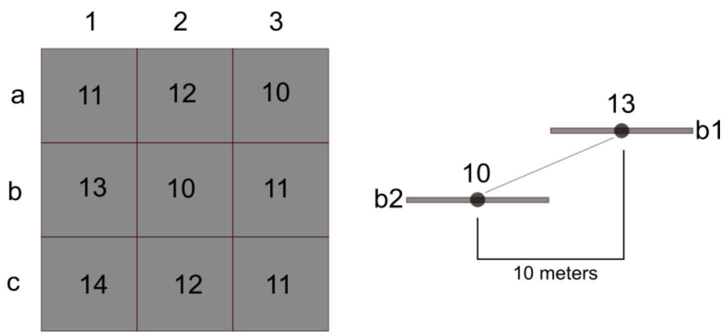


Fig-18. Grade calculation in cost distance generation

For example, in Fig-18, the raster has a cell size of 10 meters and the grade from one cell to another is calculated based on the elevation difference (cell values) and the distance of one cell center to another. The grade from one cell to another is calculated based on the following formula –

$$\boldsymbol{Grade = Rise \div Run} \tag{Eq-4}$$

where, 'Rise' is the elevation difference between the two cells and 'Run' is the cell size of the raster (or distance between cell centroids). The grade value can be positive or negative.

Suppose the grade threshold is ±0.1, all the grades above (in case of positive value) or below (in case of negative value) this threshold is neglected and cost distance is not generated for these cells. Let us assume that the cost distance is calculated from the centre cell 'b2', then the cells – a2, b1, c1 and c2 will not have cost distance values as the grade from cell 'b2' to these cells is greater than the grade threshold i.e. 0.1. The grade between cell ‘b2’ and cell ‘b1’ is – [(10-13) / 10] = (-3/10) = -0.3 which is lower than the -0.1 threshold and thus the cell is excluded from the search of the path.

In this process, the grade defined by the engineering standards can be incorporated into the alignment search process by eliminating possible alignment where the grade from cell to cell exceeds the grade threshold.

2.6.4.2 Cost backlink raster

The Path Distance Backlink tool defines the neighbor that is the next cell on the least accumulative cost path to the source, while accounting for surface distance along with horizontal and vertical cost factors. The cost back link raster is used to determine the path to return to a source via the least-cost path. The back-link raster contains values of 0 through 8, which define the direction or identify the next neighboring cell (the succeeding cell) along the least accumulative cost path from a cell to reach its source. If the path is to pass into the right neighbor, the cell will be assigned the value 1, 2 for the lower right diagonal cell, and continuing clockwise (see Fig-19). The value 0 is reserved for source cells (ESRI, 2016a).

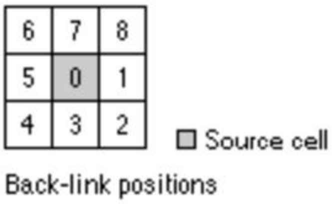


Fig-19. Cost backlink coded values (ESRI, 2016a)

2.6.4.3 Least cost path

With the cost distance raster and cost backlink raster generated, the Cost Path tool then calculates the least-cost path from a source to a destination given a source and destination locations which are in the form of point features or raster. The Cost Path tool produces an output raster that records the least-cost path from selected source and destination defined within the accumulative cost surface, in terms of cost distance (ESRI, 2016b). The resulting least cost path (see Fig-20) is in the form of a raster which can be converted to polyline using conversion tools. Fig-20 shows an example least cost path (black line) from source (green point) to destination (red point) on top of a cost distance raster. The white areas having no cost distance value are the cells which exceed the grade threshold value and thus alignments are not searched through these regions.

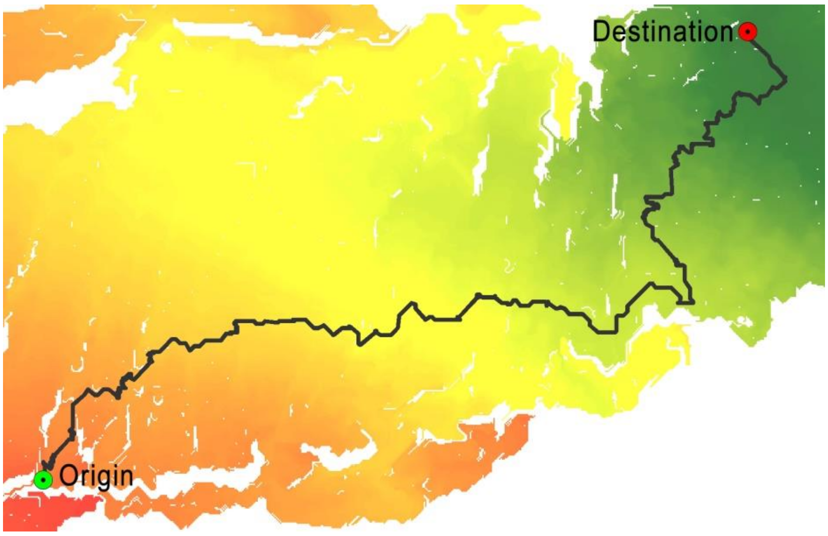


Fig-20. Lest cost path with origin and destination on top of cost distance raster

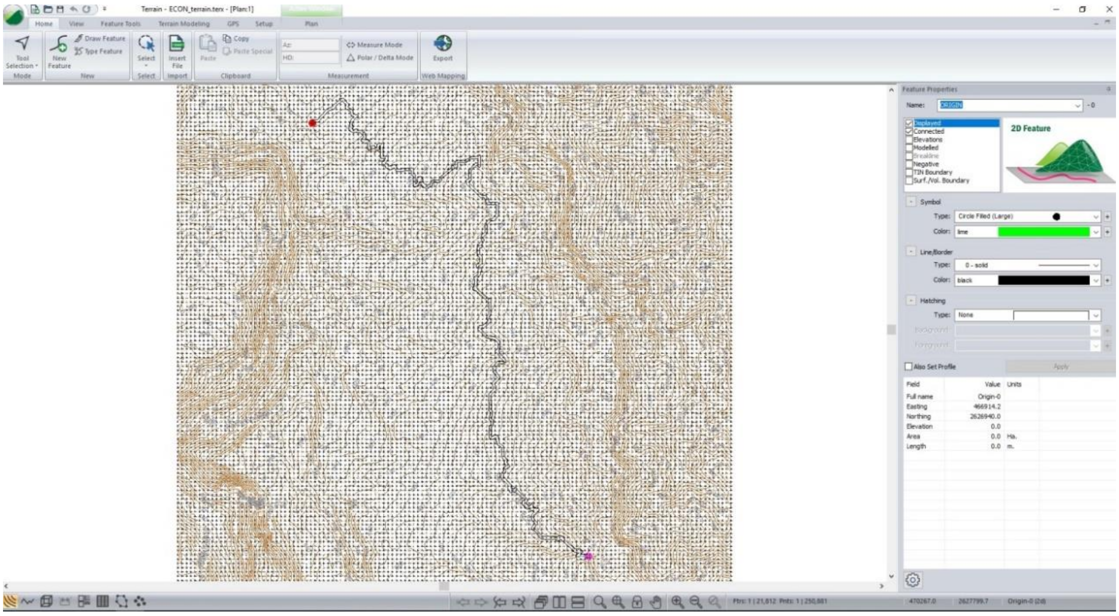
This least cost path has a grade within the limits of the engineering standards, and is the least accumulated costing path through a cost surface. This cost surface can be any raster data which is pre-generated based on criteria definitions.

2.7 Process-3: Road alignment analysis in CAD software

The generated least cost path which is in the form of a polyline can now be imported into CAD engineering module (Softree's RoadEng) where detailed design of the road alignment is carried out based on specific engineering standards which is pre-defined depending on project requirements. The estimated cut and fill volume can also be accurately calculated inside the CAD which is also very important in the assessment of best alignments. The alignments are designed horizontally and vertically based on a road template. The road template is a set of defined values and rules which defines the geometry of the road. The process of drawing road alignments for this analysis involves five main steps – Import terrain, import least cost path & origin/destination, Horizontal alignment design, Vertical alignment design and Cut/Fill volume calculation.

2.7.1 Import terrain

The digital elevation model used in the LCPA is converted into contours inside the GIS which are then imported into Terrain Module of Softree RoadEng (see Fig-21).



Name: ORIGIN -0

☑ Displayed
☑ Connected
☐ Elevations
☐ Modelled
☐ Breakline
☐ Negative
☐ TIN Boundary
☐ Surf./Vol. Boundary

Symbol Type: Circle Filled (Large)
Symbol Color: lime
Line/Border Type: 0 - solid
Line/Border Color: black
Hatching Type: None

☐ Also Set Profile

Field	Value	Units
Full name	Origin-0	
Easting	466914.2	
Northing	2626940.0	
Elevation	0.0	
Area	0.0	Ha.
Length	0.0	m.

Ftrs: 1 | 21,812 Pnts: 1 | 250,881 470267.0 2627799.7 Origin-0 (2d)

Fig-21. RoadEng Terrain module user interface showing imported terrain, least cost path and origin/destination

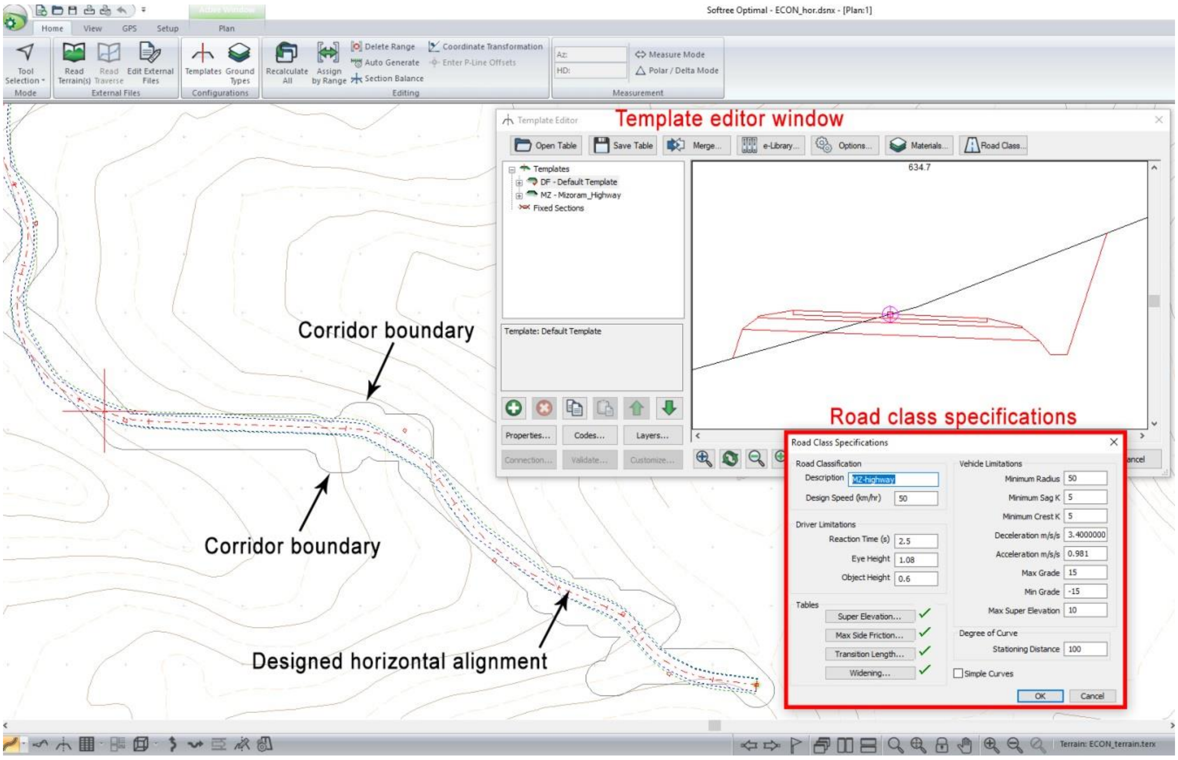
The brown lines are contours in Fig-21 from which a terrain surface in the form of TIN (Triangulated Irregular Network) is generated inside the module. This terrain surface is the base terrain from which all the cut/fill volume are calculated and thus, the more accurate the terrain model, the better the estimation of the cut/fill volume.

2.7.2 Import least cost path & origin/destination

The GIS designed least cost path (for example the LCP shown in Fig-20) is imported into the terrain module (see Fig-21) including the origin and destination points (shown as red and pink in Fig-20). A buffer of 15 meters is generated around the least cost path to form a corridor threshold within which the horizontal design of the road alignment is permitted. This import is a requirement for the design of the road as the horizontal alignment needs to be within this imported least cost corridor between the origin and destination. These files are directly imported in Shapefile GIS format which is pre-generated in the LCPA process.

2.7.3 Horizontal alignment design

After the terrain, least cost path corridor and origin/destination data are imported into the terrain module, the next procedure is to import these data into Location Module of RoadEng for the horizontal alignment design process.



Road Class Specifications

Road Classification
Description: MZ-highway
Design Speed (km/hr): 50

Driver Limitations
Reaction Time (s): 2.5
Eye Height: 1.08
Object Height: 0.6

Tables
Super Elevation... ✓
Max Side Friction... ✓
Transition Length... ✓
Widening... ✓

Vehicle Limitations
Minimum Radius: 50
Minimum Sag K: 5
Minimum Crest K: 5
Deceleration m/s/s: 3.4000000
Acceleration m/s/s: 0.981
Max Grade: 15
Min Grade: -15
Max Super Elevation: 10

Degree of Curve
Stationing Distance: 100

☐ Simple Curves

OK
Cancel

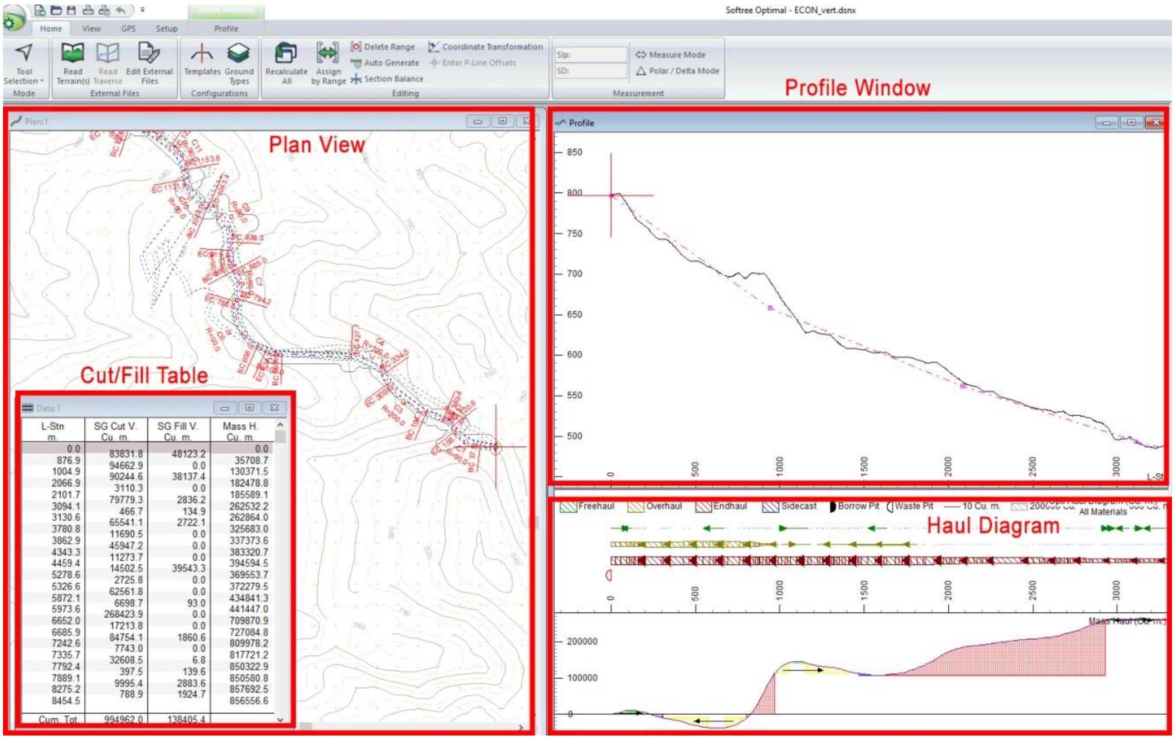
Fig-22. RoadEng Location module user interface showing imported terrain, least cost path corridor and designed horizontal alignment

The first step of the horizontal alignment design is to define the road template for the project which is a set of values which control the geometric design of the roads (see Fig-22). This is defined using the Road Template editor window where the cross-sectional geometry of the road is displayed and the geometry changes simultaneously after changing the template values. The road class specification window can be accessed inside the template editor window in which the important road design specifications like design speed, super-elevation, max side friction, transition length, widening, minimum radius, minimum sag K, maximum crest K, maximum & minimum grade etc. are defined. All these specifications are entered in consultancy with the engineer consultant following the Indian National Highway 2-Lane standards - IRC:38-1989 (IRC, 1989).

After the road class and specifications are entered, the alignments are drawn by placing intersection points (IPs) along the imported least cost path corridor. The IPs is joined with line segments (see Fig-22) and these set of line segments from the origin to destination forms the basis for horizontal alignment. Curves are then fitted at the IPs such as to facilitate gradual transition from one line segment to the other and the radius of the curves is defined by the road specification and road class type. The line segments with the curves define the final horizontal alignment from which the vertical alignments will be further designed.

2.7.4 Vertical alignment design

After the horizontal alignment is designed, the vertical alignment design is the next step where the climb and descend curves of the road is set according to and controlled by geometric standards. A series of points are entered along the vertical profile of the road (see Fig-23 Profile window) such that the vertical profile is segmented into several line sections separated by the intersection points (IPs). The grade of the line should be in accordance with the road class specifications mentioned in section 2.8.3 and if the grade is violated, the vertical alignments need to be adjusted accordingly. After the grade is maintained, curves are generated between line segments at the IPs in which the curves are controlled within the limits of the Minimum Sag K and Maximum Crest K defined earlier in the road class specifications. This curve fitting at the IPs are done for all IPs to facilitate gradual transition from one road section to another.



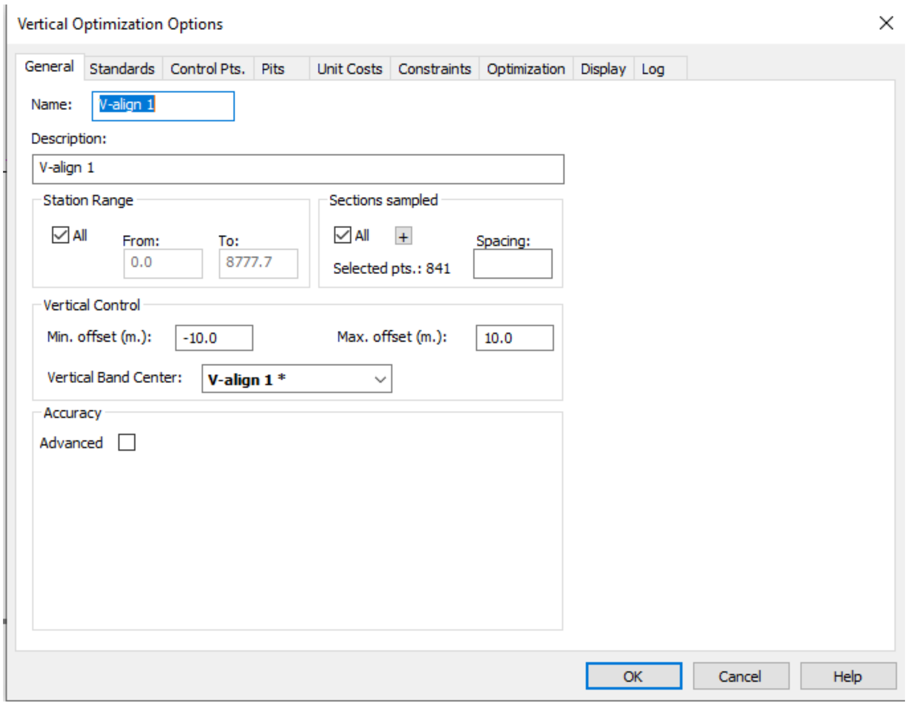
L-Stn m.	SG Cut V. Cu. m.	SG Fill V. Cu. m.	Mass H. Cu. m.
0.0	83831.8	48123.2	0.0
876.9	94662.9	0.0	35708.7
1004.9	90244.6	38137.4	130371.5
2066.9	3110.3	0.0	182478.8
2101.7	79779.3	2836.2	185589.1
3094.1	466.7	134.9	262532.2
3130.6	65541.1	2722.1	262864.0
3780.8	11690.5	0.0	325683.0
3862.9	45947.2	0.0	337373.6
4343.3	11273.7	0.0	383320.7
4459.4	14502.5	39543.3	394594.5
5278.6	2725.8	0.0	369553.7
5326.6	62561.8	0.0	372279.5
5872.1	6698.7	93.0	434841.3
5973.6	268423.9	0.0	441447.0
6652.0	17213.8	0.0	709870.9
6685.9	84754.1	1860.6	727084.8
7242.6	7743.0	0.0	809978.2
7335.7	32608.5	6.8	817721.2
7792.4	397.5	139.6	850322.9
7889.1	9995.4	2883.6	850580.8
8275.2	788.9	1924.7	857692.5
8454.5			856556.6
Cum. Tot.	994962.0	138405.4	

Fig-23. Vertical alignment design interface in RoadEng Location module

This manual vertical alignment design is not optimal in the sense that it does not optimize (finding minimum) the cut and fill volume which is to be done preferably. By manually designing the vertical alignment, it is not possible to compare cut/fill volume of different alignments as user decision is not fixed and depends largely on the user. To facilitate comparison, the vertical road alignment design must be optimized to minimize cut/fill and apply the optimization algorithm to all other alignment designs. This optimization process is done after the manual design of the vertical alignment using Softree's Optimal Module. This module is an extension of the RoadEng which optimizes the vertical alignment based on optimization options. The default options are used for this process (see Fig-24) in order to simplify the procedure and remove unnecessary complications to the process.

2.7.5 Cut / fill volume calculation

After the horizontal and vertical alignment of the road has been designed, the software automatically calculates the cut and fill volume for the particular alignment for each section of the design and also gives the total cut and/or fill volume (see Fig-23 cut/fill table). The accuracy of this cut / fill volume largely depends of the accuracy and precision of the digital elevation model used for the project.



Name: V-align 1

Description: V-align 1

Station Range
☑ All From: 0.0 To: 8777.7

Sections sampled
☑ All
Selected pts.: 841
Spacing:

Vertical Control
Min. offset (m.): -10.0 Max. offset (m.): 10.0
Vertical Band Center: V-align 1 *

Accuracy
Advanced ☐

Fig-24. Softree optimal Optimization options window

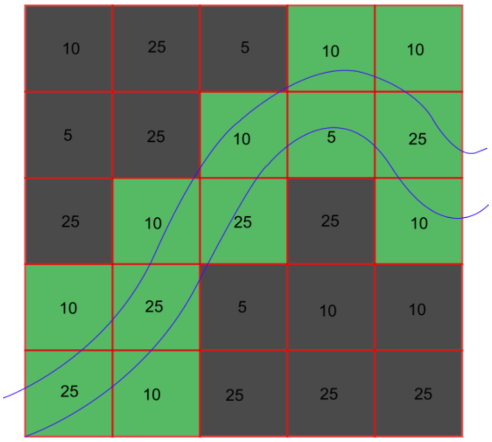
2.8 Cost assessment of the alignments

Road alignments will be assessed based on three measures namely – Cost of alignment in each CG, Length and Cut/Fill cost. These measures will give perspective of how the assessed alignments perform in different criteria of assessment which will provide the decision makers with alternatives and information on how to choose the best alignment. The other assessment criteria will also be discussed in this section.

2.8.1 Cost of alignment in each CG

The calculation of total cost for a least cost road alignment corridor on a particular Criteria Group cost surface is done in such a way that all the cost cell values under the least cost corridor is added. In Fig-25, area bounded by the blue lines is the least cost corridor and the sum of all the cost values of the cells (green) is the cost of the least cost path for that particular Criteria Group. This process is executed using the Zonal Statistics as Table tool of 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 CG cost surfaces using the same least cost corridor.

Suppose we have two alternative least cost paths and two Criteria Group cost surfaces, the cost of the first path will be calculated on the two CG cost surface first, then the cost of the second path will be calculated on the two CG cost surface again. Therefore, we can have the information on how the two least cost paths perform on the two Criteria Groups and thus make assessments accordingly.



10	25	5	10	10
5	25	10	5	25
25	10	25	25	10
10	25	5	10	10
25	10	25	25	25

Fig-25. Road alignment cost calculation on CG cost surface

2.8.2 Length

The length of a road is one of the most important criteria in assessing the best road alignments (Aissi, Chakhar, & Mousseau, 2012) as the length greatly impacts the cost of construction and the goal often is to minimize the length as much as possible. This minimization of length is already addressed in the LCPA but the different least cost paths generated based on different perspective have different lengths and thus, their lengths should also be taken into consideration in assessing the road alignments.

2.8.3 Cut / fill cost

A substantial portion of the road construction cost comes from the cut and fill of earth to fit the designed alignment to the original ground (Parker, 1977) and thus is an important assessment criteria. This is calculated in the CAD design process (Process-3 Section 2.8.5). This cut and fill earth volume is the converted into cost based on the cost of cut / fill per meter cube which is given in the Geometric Design Standards for Rural (Non-Urban) Highways (Vol. 73-1980) (PWD, 2015). The total cut volume is multiplied by cost per meter cube and the same is done for fill volume of which the two costs are added together to generate total cut/fill cost for a particular road alignment.

2.8.4 Standardization of cost values and assessment table

For demonstration, the cost values in the fives measures of assessment are then recorded into a table (see Table-2) in their own cost units. Since the cost units and how the costs are calculated differs, they are then standardized linearly into a range of 0-100 using the equation below (Eq-5) to facilitate relative comparison between the alternative road alignments (see Table-3). Thus, costs are standardized as percentages for ease in comprehension of costs and factor strengths.

$$\boldsymbol{Standardized\,Value} = \{(\boldsymbol{Val}) \div (\boldsymbol{Max})\} \times \mathbf{100} \qquad \textbf{(Eq-5)}$$

where ‘Val’ is the cost value of an alignment for a particular CG and ‘Max’ is the maximum cost value within a CG for all the alignment alternatives.

The values are standardized such that the maximum value within a CG is standardized to 100 and all the values below the maximum value is standardized accordingly (see Eq-5). The example standardized values are shown in Table-3. For a particular alignment, the total cost in each CG is added using weights to calculate a weighted total cost for that alignment. This is done for all the alignment alternatives (see Table-3 last column). This total cost facilitates the assessment of alignment alternatives combining all the costs in different CG. Also, this table (Table-3) shows all the cost of the alignments in each CG and thus is informative to decision makers in the final assessment.

Table-2. Example alignment cost in different assessment criteria

	CG-1	*CG-2*	*CG-3*	*Cut/fill cost (x1,00,00,000)*	*Length (Km)*
Alignment-1	2345	3245	2212	13.2	10.2
Alignment-2	3425	6754	1242	12.1	15.5
Alignment-3	3344	3512	5690	10.2	12.1

The least cost alignment is the most preferable but the decision of the best alignment is subjective and the assessment table is only synthesized information on which trade-offs and decisions are to be made by stakeholders.

Table-3. Example alignment assessment table

	0.2	**0.1**	**0.1**	**0.4**	**0.2**	
	CG-1	*CG-2*	*CG-3*	*Cut/fill cost*	*Length*	*Total weighted cost*
Alignment-1	70.13	48.05	38.88	100.00	65.81	70.13
Alignment-2	100.00	100.00	21.83	91.67	100.00	100.00
Alignment-3	97.64	52.00	100.00	77.27	78.06	97.64

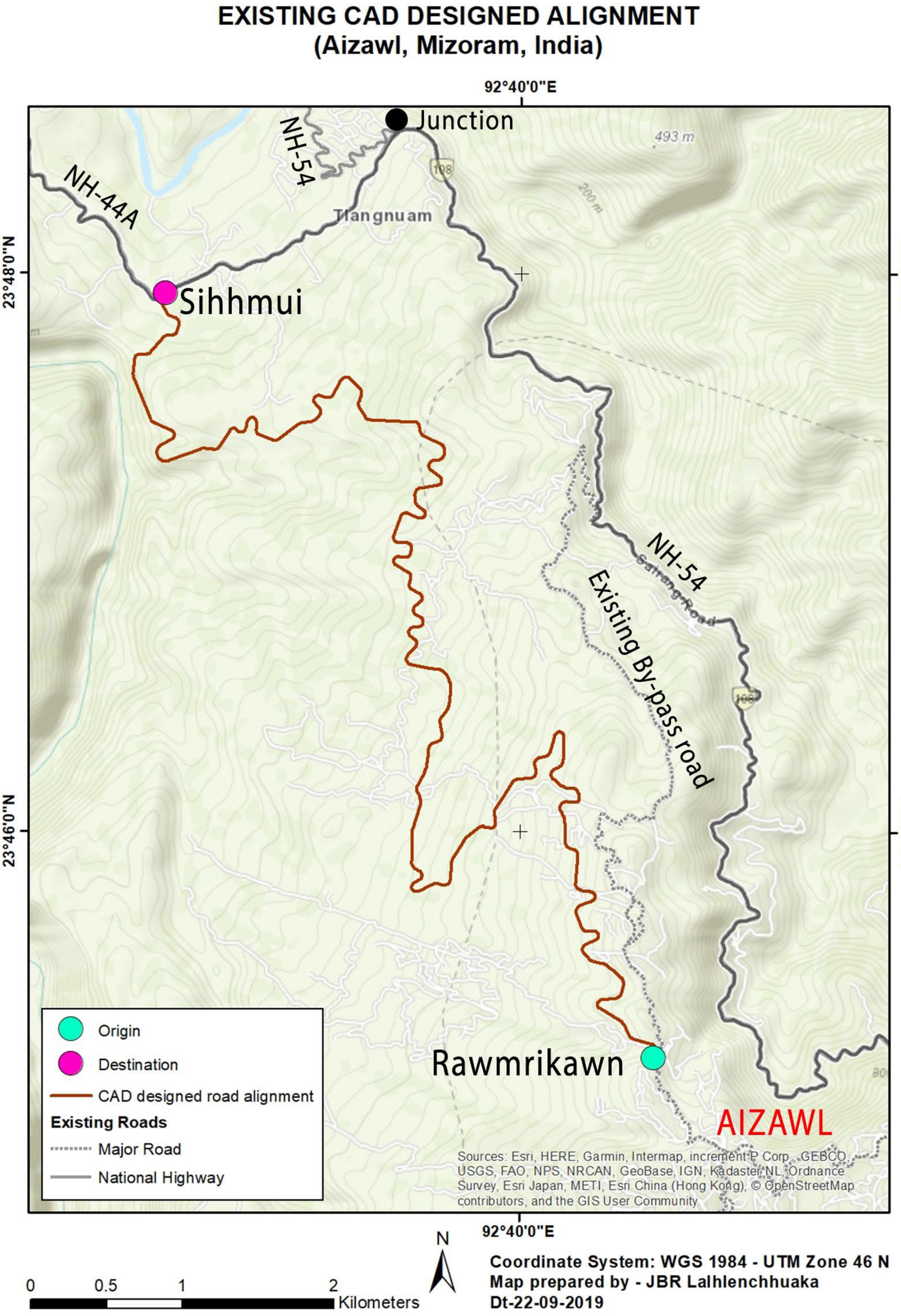
Chapter-3: Processing and analysis

The research methodology is applied to a case study project using the same origin and destination. The project report is already published with the alignment designed using the traditional design process mentioned in methodology section. The summary of the project along with a paper map of the designed road alignment is obtained from the Public Works Department of Mizoram, India. The research method will be applied on this same project framework to generate six other road alignment alternatives based on six different perspectives on criteria definition.

3.1 General description of the case study project

The case study is based on the project named – "Construction of two-lane road from Sihhmui to Ramrikawn under Central Road Fund (CRF) during the year 2017-2018 in the State of Mizoram". The proposed road Sihhmui to Ramrikawn road (dark brown line in Map-2) would connect the state capital 'Aizawl' from the western part of the city to National Highway-44A at Sihhmui which is just half kilometers from NH54 and NH44A junction (see Map-2).

NH-54 is the major life line for the state of Mizoram. However, traffics had been interrupted by major landslide area at two places during monsoon season near Aizawl. Traffic interruption during monsoon season in this route is a critical problem for the state of Mizoram (Government of Mizoram, 2018). As there could be no immediate solutions to the problems addressed above, it is proposed to construct a by-pass road, by-passing these major landslide areas. There is an existing small and narrow by-pass road which connects the origin to NH-54 which is narrow with steep gradient and is not suitable for heavy vehicles.


EXISTING CAD DESIGNED ALIGNMENT
(Aizawl, Mizoram, India)

Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), © OpenStreetMap contributors, and the GIS User Community

Coordinate System: WGS 1984 - UTM Zone 46 N
Map prepared by - JBR Lalhlenchhuaka
Dt-22-09-2019

Map-2. Project map showing proposed alignment design and existing road network

At the same time the existing road is beyond repair economically. There is no scope of up-gradation due to the fact that the road had been adjoin by private properties, household and plantation. The table below describes the brief summary of the proposed road –

Table-4. Summary of the proposed road (case study project)

Particulars	*Description*
Length	14.50 Km
Standard	National Highway (2 Lane)
Formation width	10 meters
Carriageway width	7 meters
Shoulder width	2.4 meters
Bridge	Nil

The designed project alignment in the form of paper map is scanned, georeferenced and digitized inside ArcGIS to generate the digital traditional road alignment shown in Map-2.

3.2 Relevant criteria identification

The Least cost paths (or we can say optimal alignments) are generated based on five Criteria Groups (see Table-5) resulting in five optimal paths. The segmentation of criteria into groups is essential to incorporate the diversity of viewpoints and priorities often involved in road projects from different parties and stakeholders. These criteria and criteria groups to be used are dependent on the study area i.e. Aizawl, Mizoram and what type of roads to be constructed, their properties, type and aim of the project. The criteria for constructing a highway will not be the same as that of in-city roads. The criteria groups and weights used in this analysis is synthesized from the works of Awwad (2005), Piantanakulcha (2005) and Yakar & Celik (2014) which is then finalized, readjusted and selected in context to the study area requirements.

Table-5: Criteria Groups, criteria and corresponding weights used in the analysis

Criteria Groups	*Criteria*	*Weights*
ECONOMIC (A)	Construction Cost (A1)	0.60
	Tourism (A2)	0.15
	Trade (A3)	0.25
ENGINEERING (B)	Topography (B1)	0.35
	Natural disaster (B2)	0.30
	Geology (B3)	0.20
	Solar insolation (B4)	0.15
ENVIRONMENT (C)	Deforestation (C1)	0.35
	Noise/Air pollution (C2)	0.15
	Water pollution (C3)	0.20
	Ground water potential disturbance (C4)	0.20
	Erosion (C5)	0.10
SOCIETY (D)	Public facility disturbance (D1)	0.60
	Resettlement (D2)	0.40
TRANSPORTATION (E)	Accessibility (E1)	0.30
	Comfort (E2)	0.10
	Intermodal unity (E3)	0.20
	Safety (E4)	0.40

An additional viewpoint combining all the CG is created (using WLC method) in which each CG is given a weight based on expert's preference and opinion. This viewpoint is named 'AHP' and based on this viewpoint; a least cost path will also be generated resulting in total of 6 optimal paths.

For conceptualizing the criteria, the cost approach is used in this procedure in which favorable areas have lower cost and unfavorable areas have higher cost. The cell values on the criterion maps (raster) represent the relative cost of passing through that cell and criterion maps are prepared in such strategy. The cell values (cost) are standardized to a range of 0-100 where the least cost cells have 0 and highest cost cell has 100. This standardization is necessary for consistency in comparison and assessment across the factors and criteria.

Table-5 shows the five criteria groups used with the criteria within each group and the corresponding weights associated in contributing to the criteria group. The criteria groups (CG) are labeled as block capital letters – **A, B, C, D** and **E** while the criteria under each CG are labeled as block capital letters followed by numbers –**A1, A2, B1, B2, C1** etc. The following sections describe the criteria groups, criteria and sub-criteria in detail.

3.2.1 Economic (A)

The rationale for this criteria group (CG) is to consider the influence of constructing roads on the economy based on three criteria namely- construction cost, tourism and trade (see Table-5). This CG would facilitate the search for finding optimal road alignment in perspective of contribution to the economy of the area expressed by cost saving and revenue generation.

A1. Construction cost

The construction cost of roads depends on the type of road and geography of the area. Since the type of road is fixed for a project, the main varying aspect is the geography. This criterion produces map information on the relative cost of construction of roads which is based on the combination of three spatial factors – surface type, terrain and expropriation cost.

(i) Surface type: The cost of road construction in water bodies is significantly higher than that of the ground. Bridges have to be constructed to pass over water bodies which are much more expensive. This notion is conceptualized by giving maximum cost to water bodies and gradually decreasing the cost the further an area is away from it. Using the Rivers / Drains data (see Table-1 for data description) three drainage classes are present in the study area- River, Stream and Drain. Buffers are generated around these features and the distance of the buffer depends on the size of the drainage - 50 meters for River, 30 meters for Stream and 10 meters for Drain. The buffered features are then merged, Euclidean distance mapping done to generate distance raster which is then rescaled using Logistic decay function with parameters – Min: -50, Max: 100, Y-intercpt:99, Range: 1-100. The resulting map is a raster having maximum cost inside the buffered areas of the drainage and cost gradually decreasing from 100 to 1 based on the logistic function.

(ii) Terrain: The area is composed of two geomorphological units namely- Low Structural Hills (LSH) and Medium Structural Hills (MSH). According to engineers, the construction of roads is significantly costly in MSH than that in the LSH. The LSH are given a cost value of 50 and the MSH has 100 cost value. These cost values are attributed to the respective polygon features of Geomorphology data (see Table-1 for data description) and then the polygon data is converted to a raster based on the cost value.

(iii) Expropriation: The cost of acquiring land for the construction of road differs based on the land use or land cover of an area. For example, the expropriation cost is significantly higher in settlement areas like cities than that of scrubland areas and abandoned areas. The cost values mentioned below are attributed to the respective polygon features of Land use/ Land cover (LULC) data (see Table-1 for data description) and then the polygon data is converted to a raster based on the cost value.

<u>Cost values for different LULC classes-</u> Abandoned Jhum-60, Agriculture Plantation-80, Bamboo-50, City-100, Current Jhum-70, Dense Forest-50, Forest Plantation-40, Medium Dense Forest-40, Open Forest-30, Scrubland-25, Town-10, Village-80, Waterbody-100

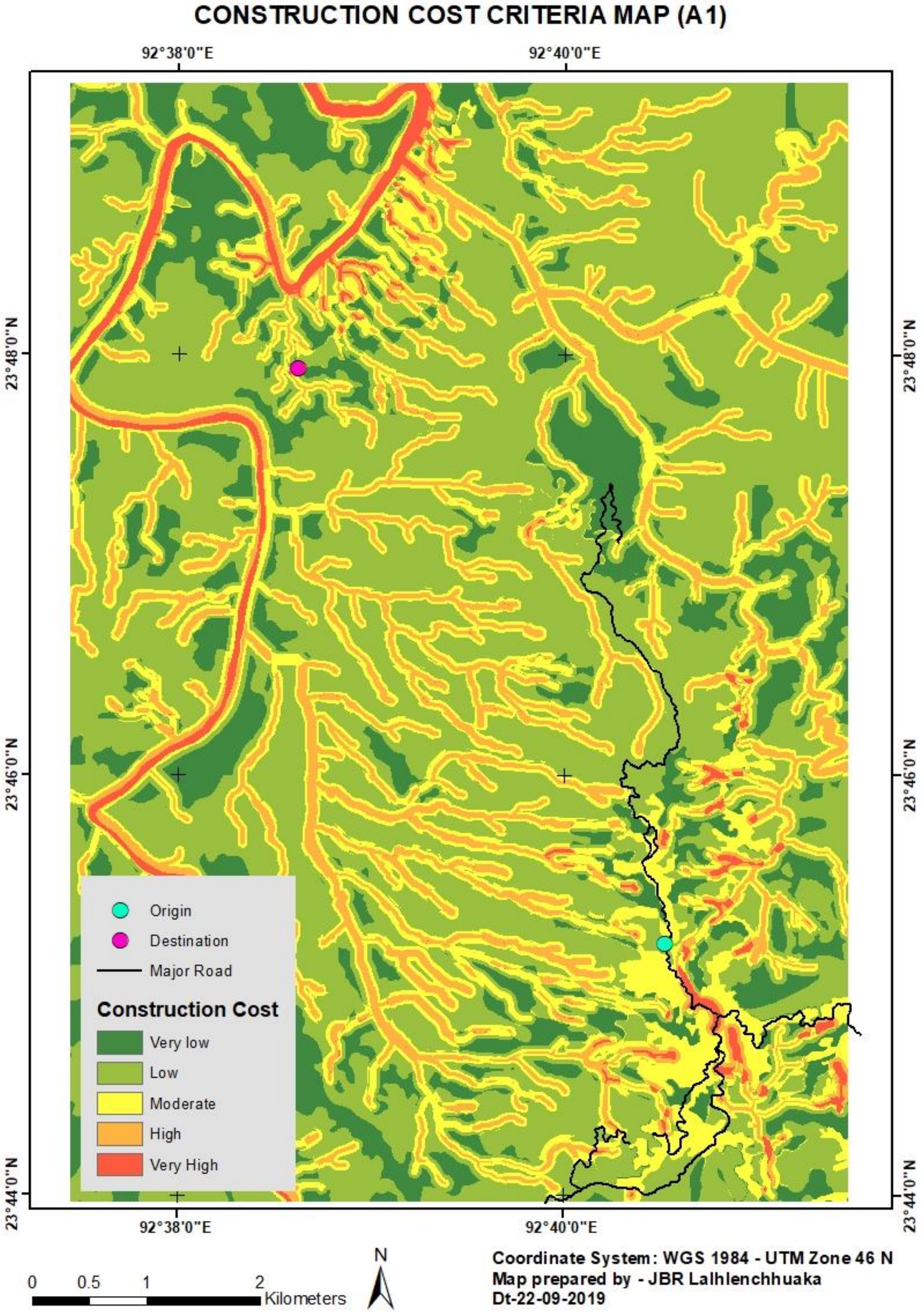
The three sub-criteria are then combined using LWC method to generate Criteria-A1 raster (see Map-3) using the expression of Eq-6. The corresponding weights of the sub-criteria are defined by their relative significance in contribution to Construction cost criterion.

$$\boldsymbol{A1} = [\mathbf{0.4} \times (\boldsymbol{i})] + [\mathbf{0.1} \times (\boldsymbol{ii})] + [\mathbf{0.5} \times (\boldsymbol{iii})] \qquad \textbf{(Eq-6)}$$

where, A1 is Construction cost criteria, (i) is Surface type, (ii) is terrain and (iii) is expropriation cost. In Map-3, areas having dark green color are least costly in terms of construction of roads and areas having bright red have the highest cost.

A2. Tourism

To have better access to tourist sites, it is preferable that roads are constructed close to these tourist sites. However, there is a negative preference if roads are too close to these sites as they would disrupt the area of the sites and actually have negative impacts to the region. Thus, regions which are 100-200 meters away from tourist sites are most preferable for road construction, thus these regions will have least cost. This notion is conceptualized by generating Euclidean distance around the tourist sites using the Tourist site data (see Table-1 for data description) and reclassified such that the cost decreases linearly from 100 to 10 starting from the tourist sites up to a distance of 100 meters and remains constant between 100 to 200 meters and increases linearly from 10 to 100 again up to the distance of 500 meters from which the cost remains constant at 100.



Map-3. Construction cost criteria map (A1)

This reclassification scheme is shown in Eq-7 of which the implementation is done through Raster Calculator tool of ArcGIS Spatial Analyst Extension by using the map algebra expression which is also shown below.

```
If distance $\leq 100$:
    Value decreases from 100 to 10 linearly
If distance $> 100$ & $\leq 200$:
    Value $= 10$
If distance $> 200$ & $\leq 500$:
    Value increases from 10 to 100 linearly
If distance $> 500$:
    Value $= 100$
```

(Eq-7)

Map Algebra Expression of ArcGIS:

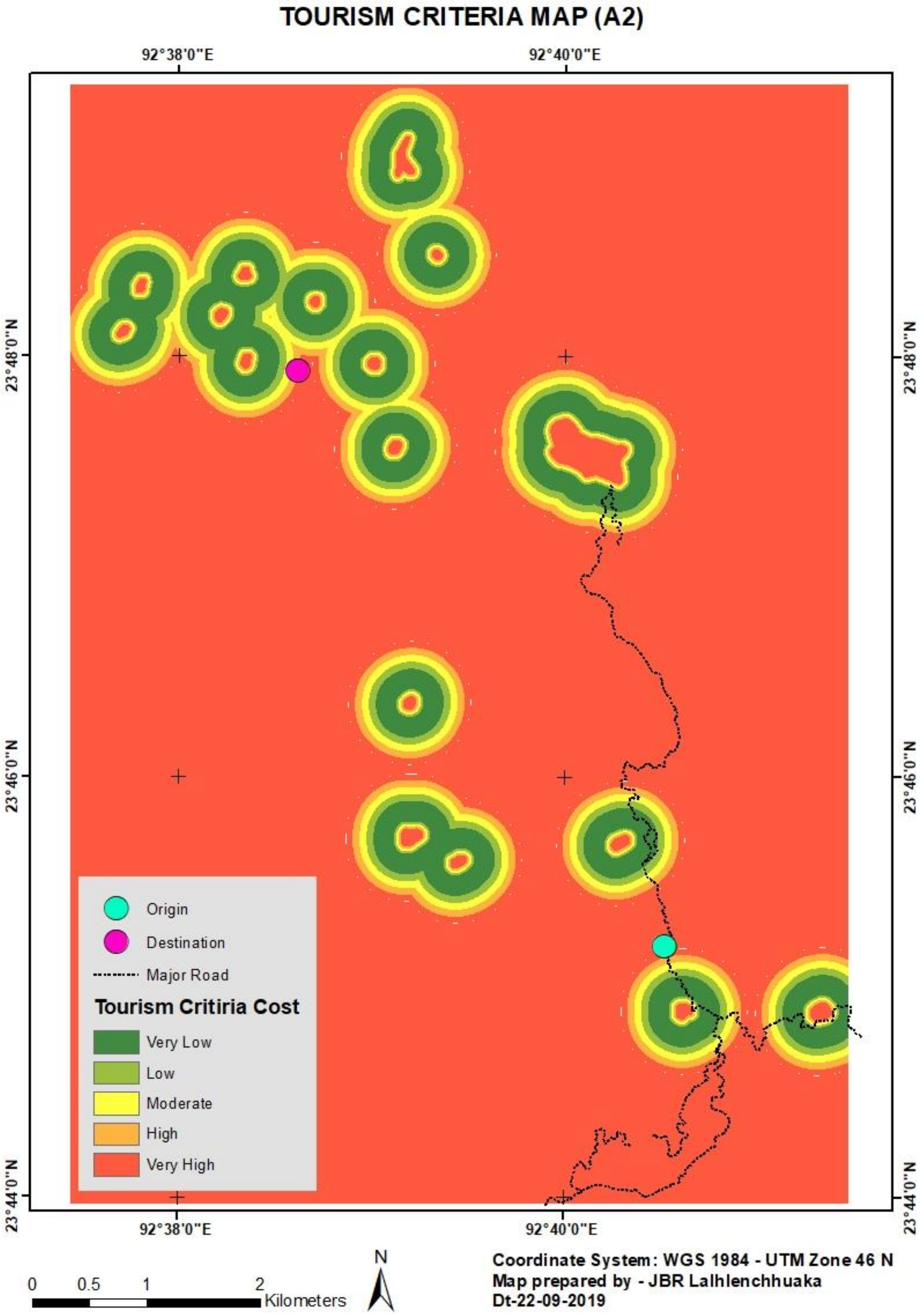
```
Con("%t_dist%\\"" 100,-
2.3*"%t_dist%100,Con(\""%t_dist%"<200,10,Con(\"t_dist"%"<500,0.75*
\"%t_dist%\""-125,Con("%t_dist%" >500,100))))
```

where, ‘t_dist’ is the distance raster to be reclassified.

The Tourism cost raster is shown in Map-4. The green regions are the least costly regions where road construction is most preferable based on this criterion.

A3. Trade

The concept used for this criterion is similar to that of Tourism criterion. To provide better access to the trade centers where majority of economic activities take place, it is preferable that roads are constructed close to these areas. However, there is a negative preference if roads are too close to these sites as they would disrupt the sites and actually have negative impacts to the region. Thus, regions which are 100-200 meters away from trade centers are most preferable for road construction, thus these regions will have least cost. Using the Trade center data (see Table-1 for data description), the same geo-processing as that of Tourism criterion is performed resulting in the Trade cost map shown in Map-5 where the reclassification is done through Raster Calculator tool of



Map-4. Tourism criteria map (A2)

ArcGIS Spatial Analyst Extension by using Eq-8.

$$
\begin{array}{l}
\textbf{If distance} \leq \textbf{100:} \\
\qquad \textbf{Value decreases from 100 to 10 linearly} \\
\textbf{If distance} > \textbf{100} \ \& \leq \textbf{200:} \\
\qquad \textbf{Value} = \textbf{10} \\
\textbf{If distance} > \textbf{200} \ \& \leq \textbf{500:} \\
\qquad \textbf{Value increases from 10 to 100 linearly} \\
\textbf{If distance} > \textbf{500:} \\
\qquad \textbf{Value} = \textbf{100}
\end{array}
\qquad \textbf{(Eq-8)}
$$

Map Algebra Expression of ArcGIS:

```
Con("%tr_dist%\""≤100,-2.3 *"%tr_dist% + 100,Con(\"" %tr_dist%"<200, 10,"
"Con(\"" %tr_dist"%"<500,0.75* \"%tr_dist%\""-125,Con"100")))
```

where, ‘tr_dist’ is the distance raster to be reclassified.

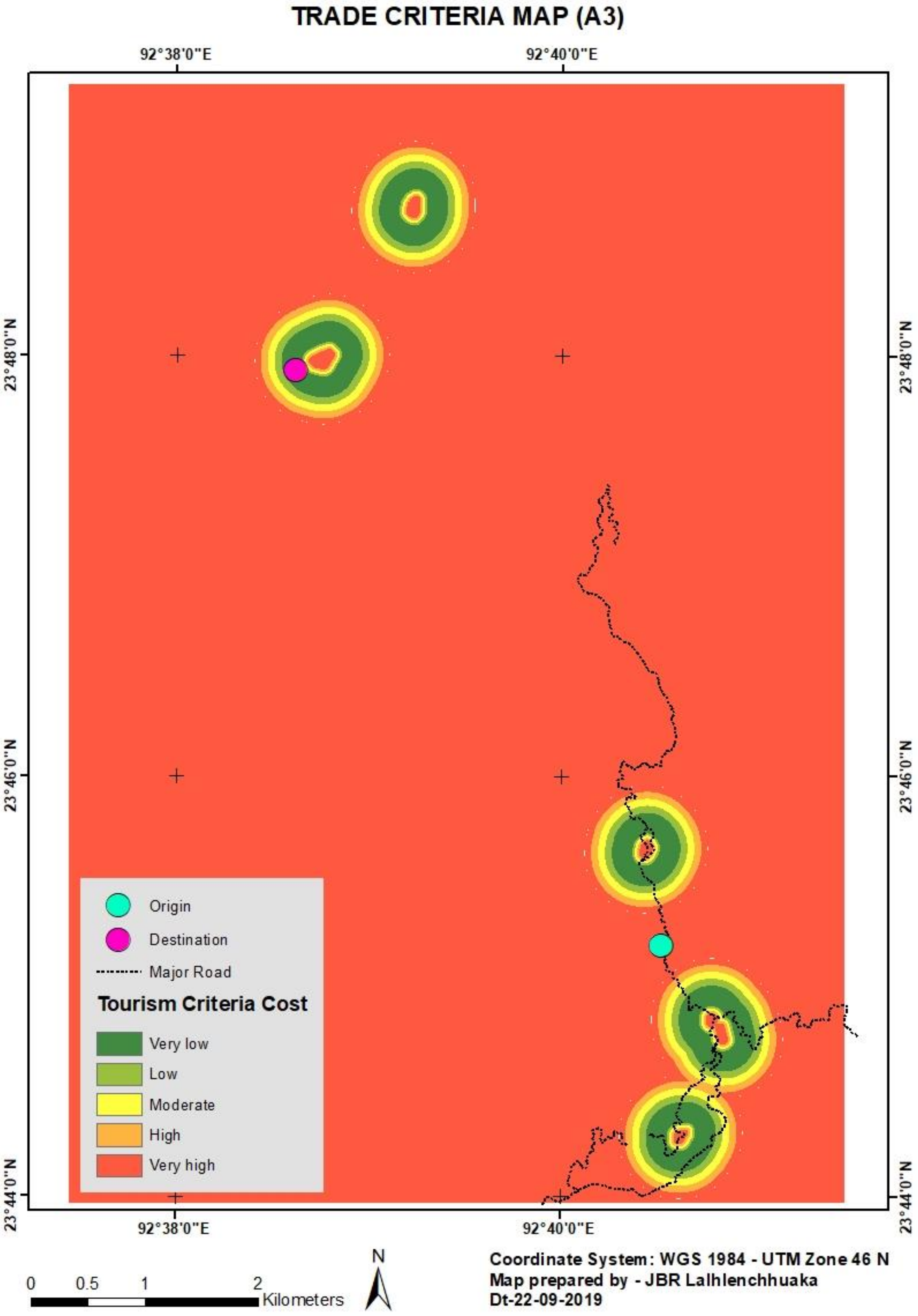
In Map-5, the green regions are the least costly regions where road construction is most preferable based on this criterion.

The three criteria – A1, A2 and A3 are combined to form the criteria group ‘A’ using the equation below (Eq-9) producing the CG map A (see Map-6) by LWC method. The corresponding weights of the criteria are established by their relative significance in contribution to the Economic CG.

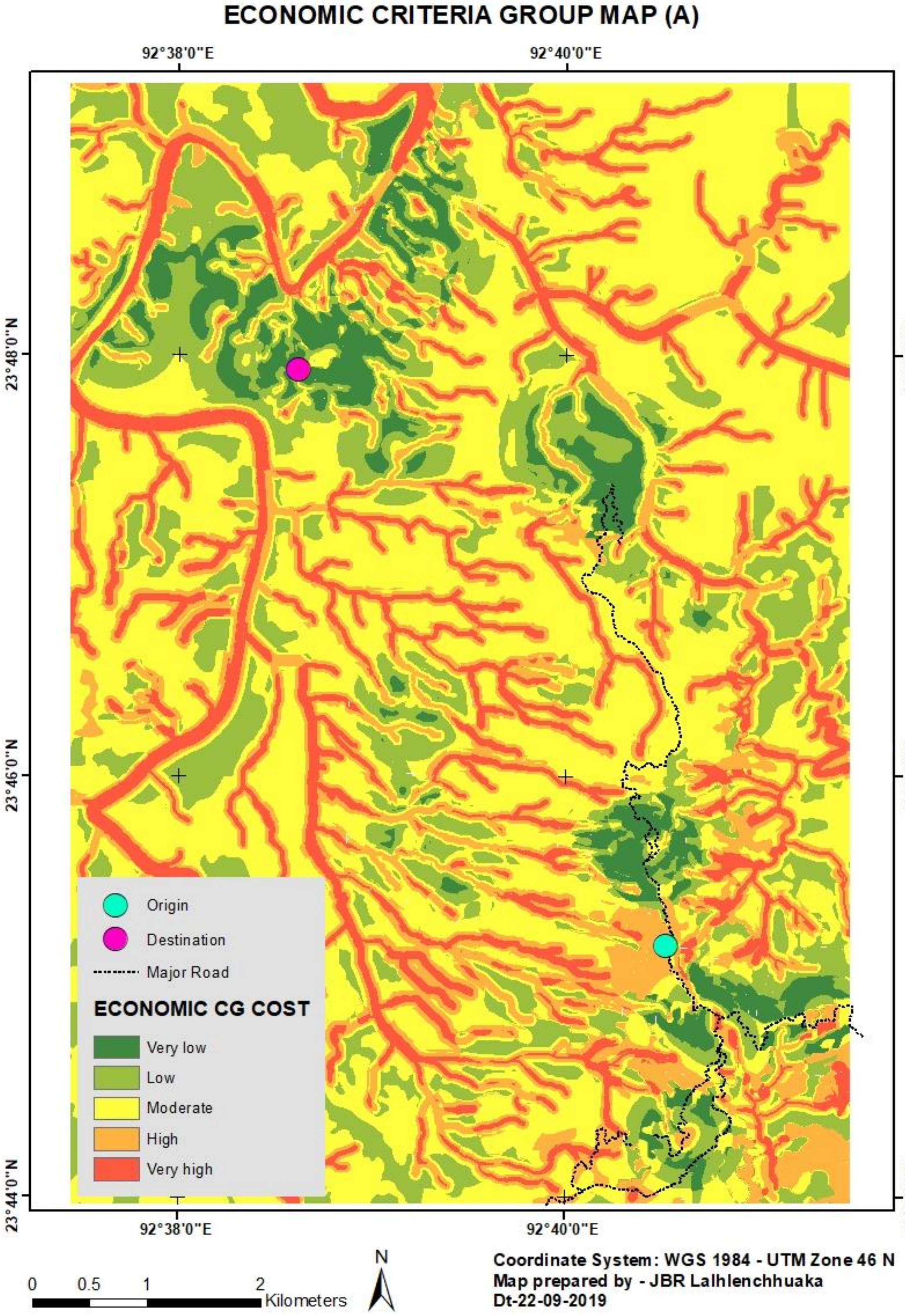
$$\boldsymbol{A = (0.60 \times A1) + (0.15 \times A2) + (0.25 \times A3)} \qquad \textbf{(Eq-9)}$$

3.2.2 Engineering (B)

The rationale of this criteria group (CG) is to consider the perspective of engineers. This CG would facilitate the search for finding the optimal road alignment considering areas having the most suitable topography, safe from natural disasters, climatically and geologically suitable. The CG has four criteria – Topography, Natural disaster, Geology and Solar insolation.



Map-5. Trade criteria map (A3)



Map-6. Economic Criteria Group map (A)

B1. Topography

From engineering point of view, some areas are more preferable than the other due to more suitable topography for road construction. This criterion considers two sub-criteria- Slope and Landform.

(i). Slope: Flatter areas are more preferable than high slope areas. Slope raster is generated from DEM data (see Table-1 for data description) and the slope values are reclassified into classes and the classes are given cost based on Table-6. The cost values are generated using AHP method.

Table-6. Slope classes and costs

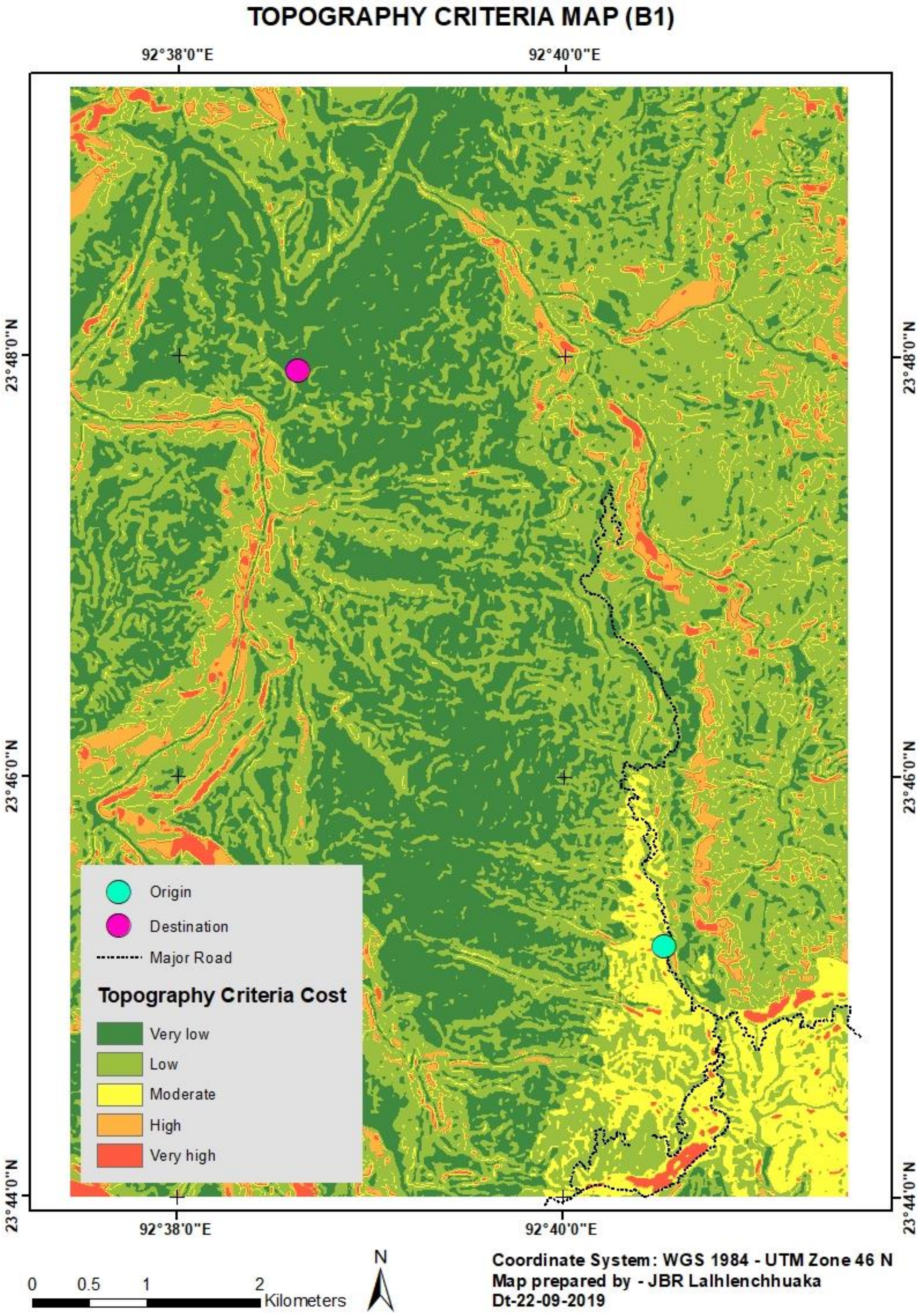
Slope values (classes)	*Cost*
0-15	10
15-30	20
30-40	30
40-50	60
50-76.6	100

(ii). Landform: According to engineers, the construction of roads is more suitable in Low Structural Hills (LSH) than that in the Medium Structural Hills (MSH). To reflect the earlier statement, the LSH areas are given a cost value of 70 and the MSH areas have 100 cost value. These cost values are attributed to the respective polygon features of Geomorphology data (see Table-1 for data description) and then the polygon data is converted to a raster based on the cost value.

The two sub-criteria are combined using LWC method to generate Criteria-B1 raster (see Map-7) using the expression of Eq-10. The corresponding weights of the sub-criteria are defined by their relative significance in contribution to Topography criterion.

$$\boldsymbol{B1} = [\mathbf{0.7} \times (\boldsymbol{i})] + [\mathbf{0.3} \times (\boldsymbol{ii})] \qquad \textbf{(Eq-10)}$$

Where, B1 is Topography Criteria, (i) is Slope and (ii) is Landform.



Coordinate System: WGS 1984 - UTM Zone 46 N
Map prepared by - JBR Lalhlenchhuaka
Dt-22-09-2019

Map-7. Topography criteria map (B1)

B2. Natural disaster susceptibility

Engineers prefer to construct roads in areas having less susceptibility to natural hazards like landslide and cyclone particularly in hilly areas such as that of the study area.

(i). Landslide: Landslides are the most widespread and damaging among natural hazards (Kalamaras, Brino, Carrieri, Pline, & Grasso, 2000). Areas of high landslide susceptibility are given higher cost and are considered less preferable and areas of low susceptibility are given lower weights and considered more preferable. The cost values of the different susceptibility classes are assigned based on Table-7. These cost values are attributed to the respective polygons of Landslide susceptibility data and the polygon converted to raster.

Table-7. Landslide susceptibility classes and cost

Landslide susceptibility class	*Cost*
Very Low	10
Low	20
Moderate	40
High	80
Very High	100

(ii). Cyclone: Areas of high cyclone hazard are given higher cost and are considered less preferable and areas of low susceptibility are given lower weights and considered more preferable. The cost values of the different hazard classes are assigned based on Table-8. These cost values are attributed to the respective polygons of Cyclone hazard data and the polygon converted to raster.

Table-8. Cyclone hazard classes and cost

Cyclone hazard class	*Cost*
Moderate	60
High	100

The two sub-criteria are combined using LWC method to generate Criteria-B2 raster (Map-8) using the expression of Eq-11. The corresponding weights of the sub-criteria are defined by their relative significance in contribution to Natural disaster susceptibility criterion.

$$\boldsymbol{B2} = [\mathbf{0.7} \times (\boldsymbol{i})] + [\mathbf{0.3} \times (\boldsymbol{ii})] \qquad \textbf{(Eq-11)}$$

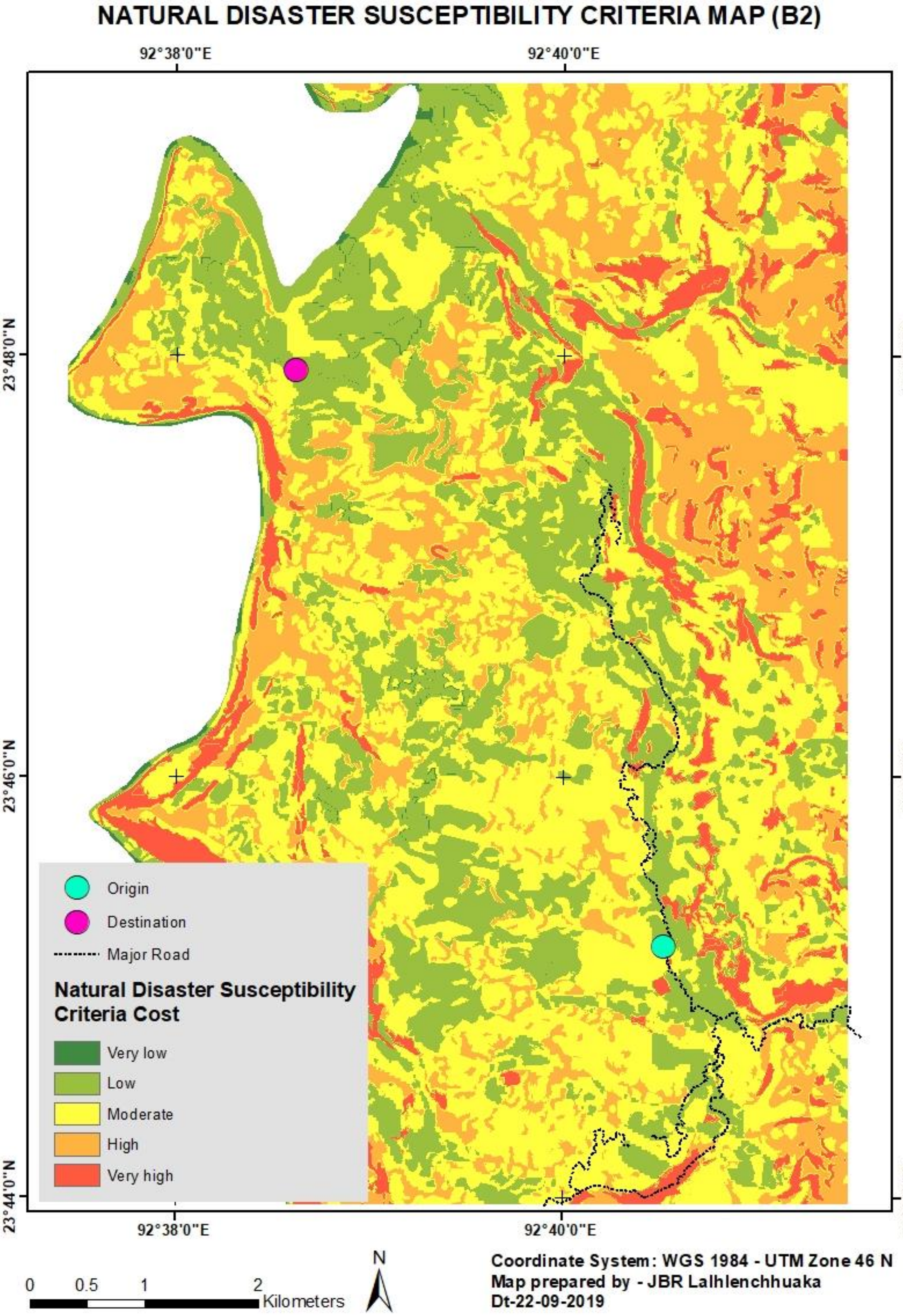
Where, B2 is Natural disaster susceptibility criteria, (i) is landslide and (ii) is cyclone.

B3. Geology

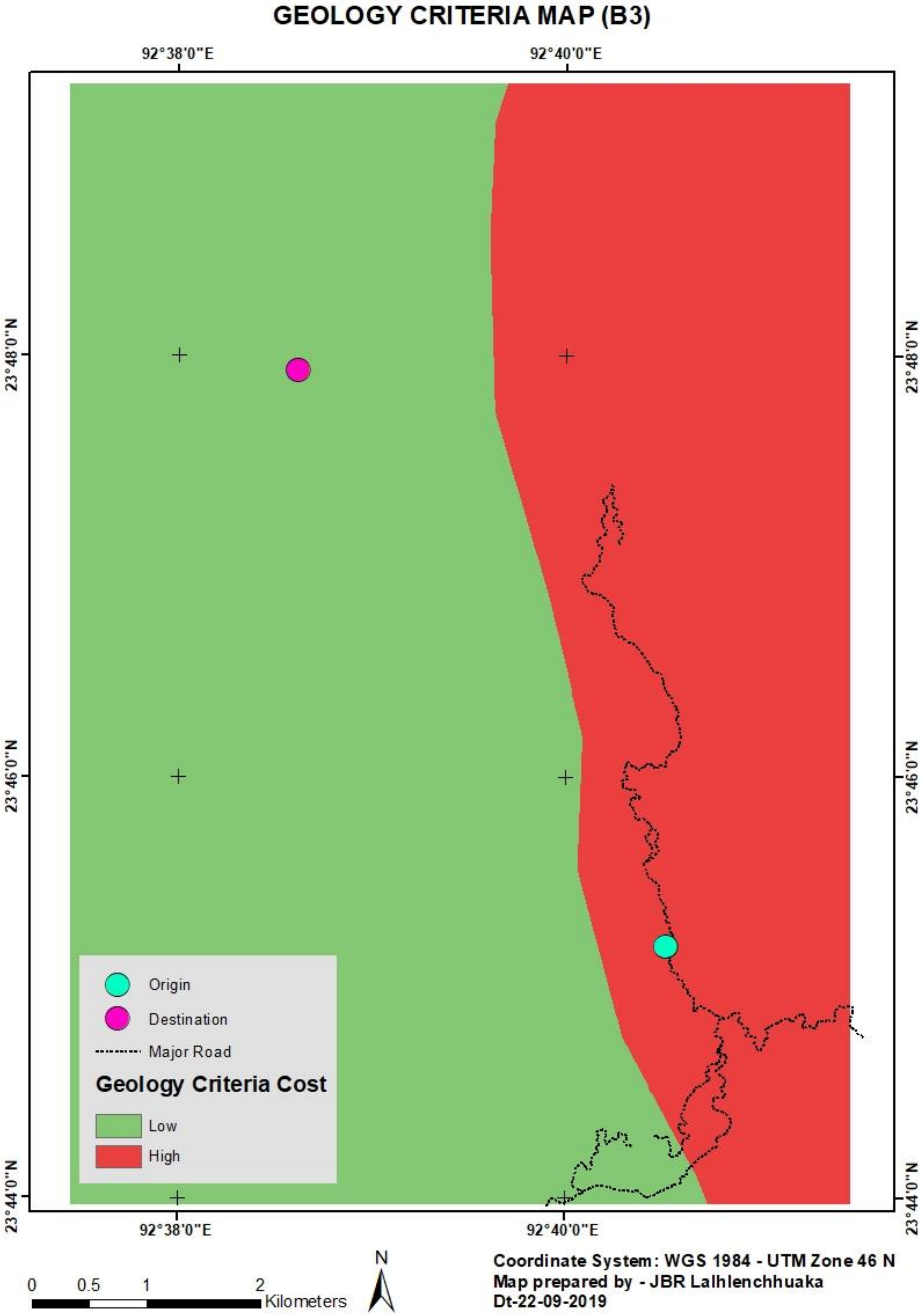
From engineering perspective, the favorability of a region for construction of roads differs based on the geological unit of the area which is taken into account in this criterion. To reflect this perspective, the Shale with Sandstone Partings areas is given a cost value of 100 and the Shaly Sandstone areas have 60 cost value. These cost values are attributed to the respective polygon features of Geology data (see Table-1 for data description) and then the polygon data is converted to a raster based on the cost value (Map-9).

B4. Solar insolation

The climate of a region is of significant importance in road design (Gustavsson, Bogren, & Eriksson, 1998) due to the effects it has on the longevity of the road and the maintenance cost. Areas receiving total amount of solar radiation throughout the year are more preferable for roads to be constructed. This will reduce the wear and tear water causes to road surfaces as areas with high solar insolation will be dryer than those having low solar insolation, making the roads in high solar insolation areas more durable. The total solar insolation is calculated using Area Solar Radiation tool of ArcGIS which takes DEM data, Latitude value (23.777298924 N for this case), year (2019) and hour interval (1 hour) as parameters.



Map-8. Natural disaster susceptibility criteria map (B2)



Map-9. Geology criteria map (B3)

The output raster gives total solar insolation for each cell calculated for the particular year in which the higher the cell value, the more preferable it is and thus having lower cost and vice versa. This raster is then reclassified into standardized costs based on the Table-9 to produce Solar Insolation Cost Map-B4 (Map-10).

Table-9. Solar insolation class and cost

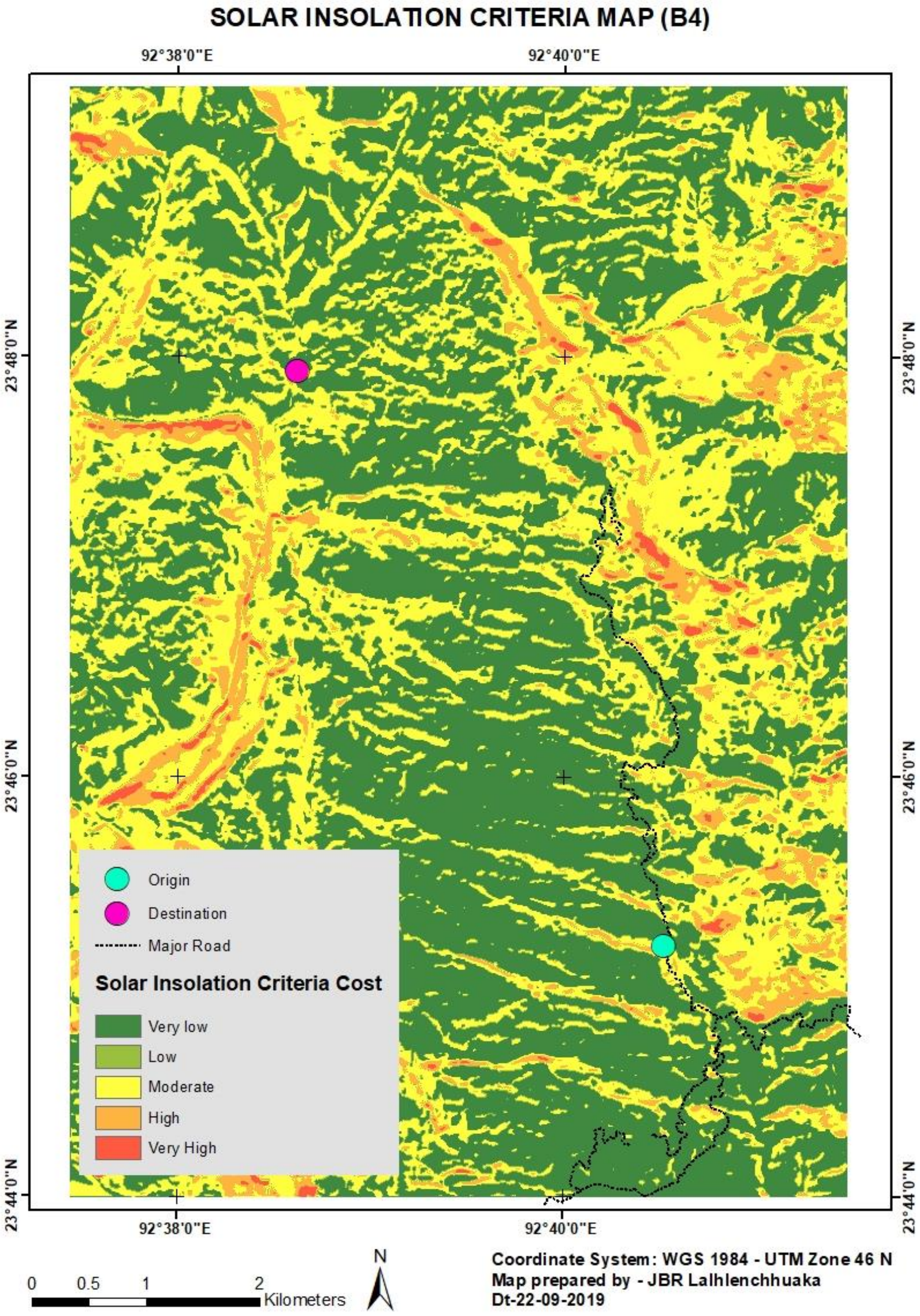
Insolation values	*Cost*
326552- 623279	100
623279 - 920006	70
920006 - 1216733	50
1216733 - 1513460	30
1513460 - 1810187	10

The four criteria – B1, B2, B3 and B4 are combined to form the criteria group 'B' using the equation below (Eq-2) producing the CG map B (Map-11) by LWC method. The corresponding weights of the criteria are established by their relative significance in contribution to the Engineering CG.

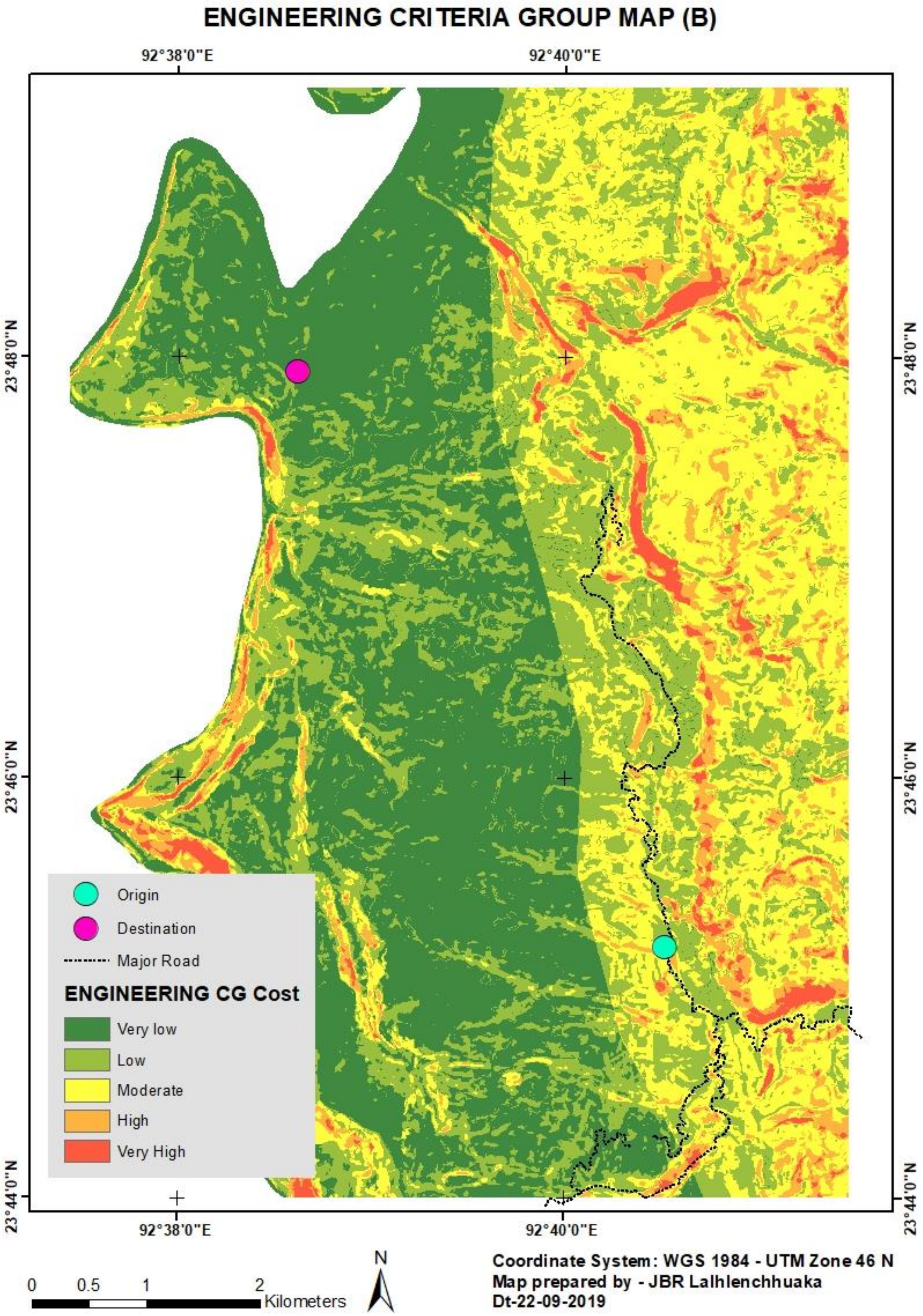
$$\boldsymbol{B} = (\mathbf{0.35} \times \boldsymbol{B1}) + (\mathbf{0.30} \times \boldsymbol{B2}) + (\mathbf{0.20} \times \boldsymbol{B3}) + (\mathbf{0.15} \times \boldsymbol{B4}) \qquad \textbf{(Eq-12)}$$

3.2.3 Environmental (C)

The rationale of this criteria group (CG) is to consider the perspective of environmentalist and how the construction of roads would affect the surrounding environment. This CG would facilitate the search for finding the optimal road alignment which is most environmental friendly and produces least negative impact on the environment. The CG has five criteria –Deforestation, Noise/Air pollution, Water pollution, Ground water potential disturbance and Erosion.



Map-10. Solar insolation criteria map (B4)



Map-11. Engineering Criteria Group map (B)

C1. Deforestation

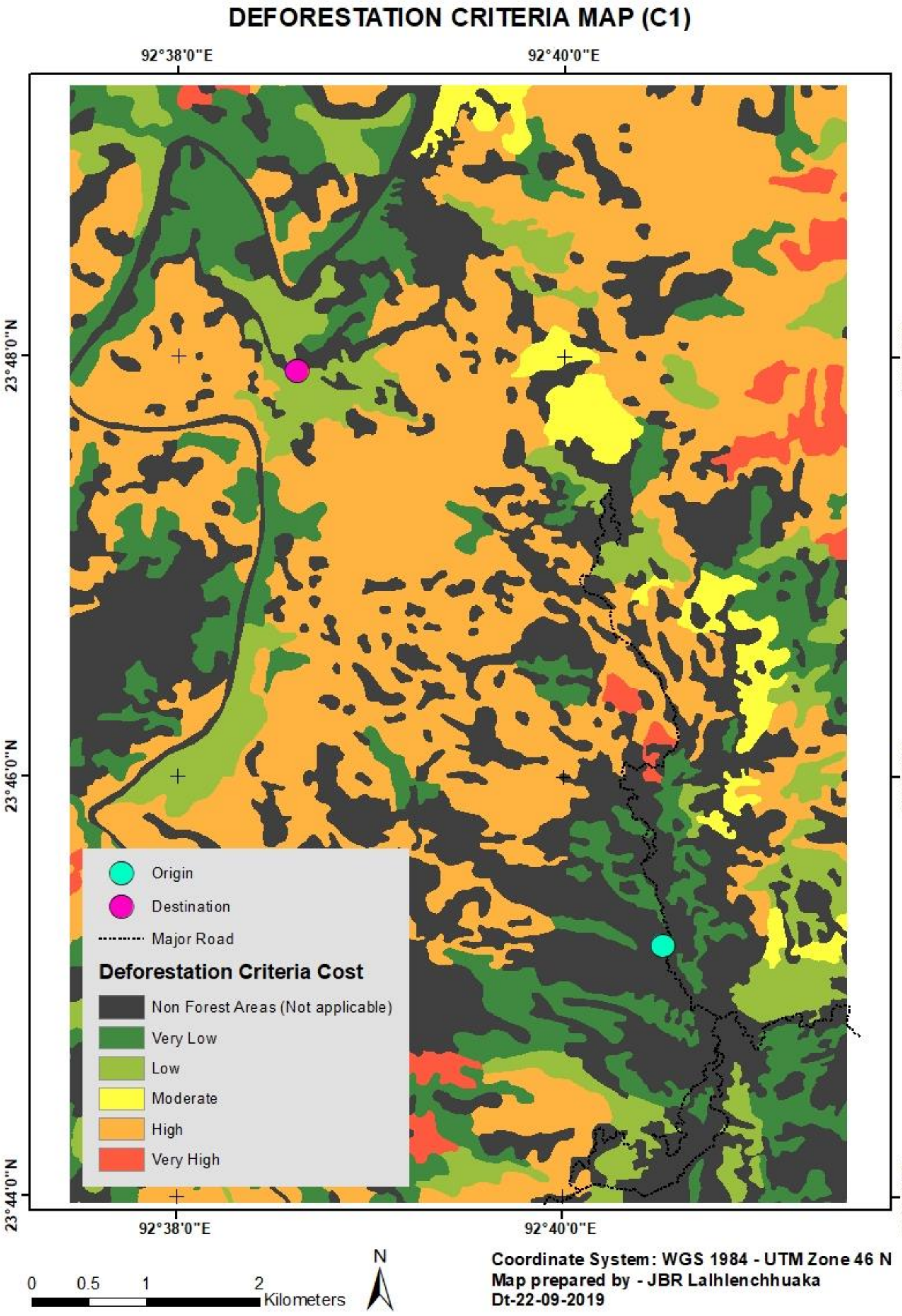
This criterion considers the expected deforestation which would occur because of road construction. The severity of the effects of deforestation differs in different types of forest cover areas. For example, it is more environmentally costly to clear dense forest covers than to clear open forest areas for road construction. The forest cover data is extracted from Land use/ land cover data. The cost values of the different forest cover classes are assigned based on Table-10. These cost values are attributed to the respective polygons of forest cover data and the polygon converted to raster producing Deforestation cost map – C1 (Map-12).

Table-10. Forest covers class and cost

Forest cover class	*Cost*
Open Forest	30
Medium Dense Forest	50
Forest Plantation	70
Bamboo	80
Dense Forest	100
Other land cover/ land use	0

C2. Noise/Air pollution

The presence of roads greatly increases noise in the peripheral areas it runs through. The noise pollution caused by roads effects human settlements particularly making the environment less preferable for the inhabitants. Thus, the location of existing settlements and buildings are taken into consideration and roads are preferably constructed far away from these settlements. Euclidean distance map is created around the Buildings footprint polygon data and rescaled using Logistic decay function with parameters – Min: 0, Max: 100, Y-intercept: 99, Range: 1-100. The resulting map (Map-13) is a raster having



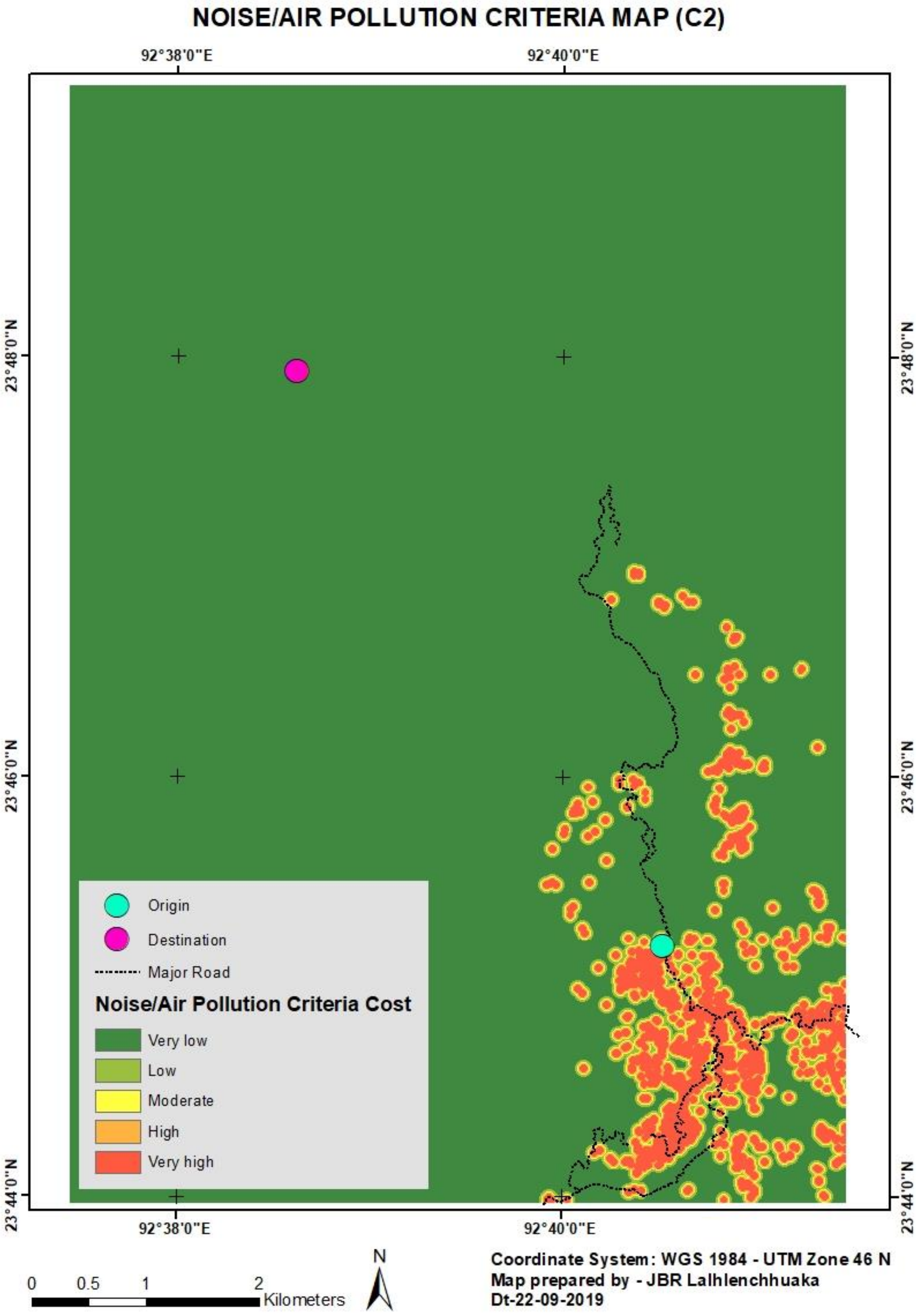
Map-12. Deforestation criteria Map (C1) maximum cost close to the building areas and the cost gradually decreasing away from the buildings from 100 to 1 based on the logistic function.

C3. Water pollution

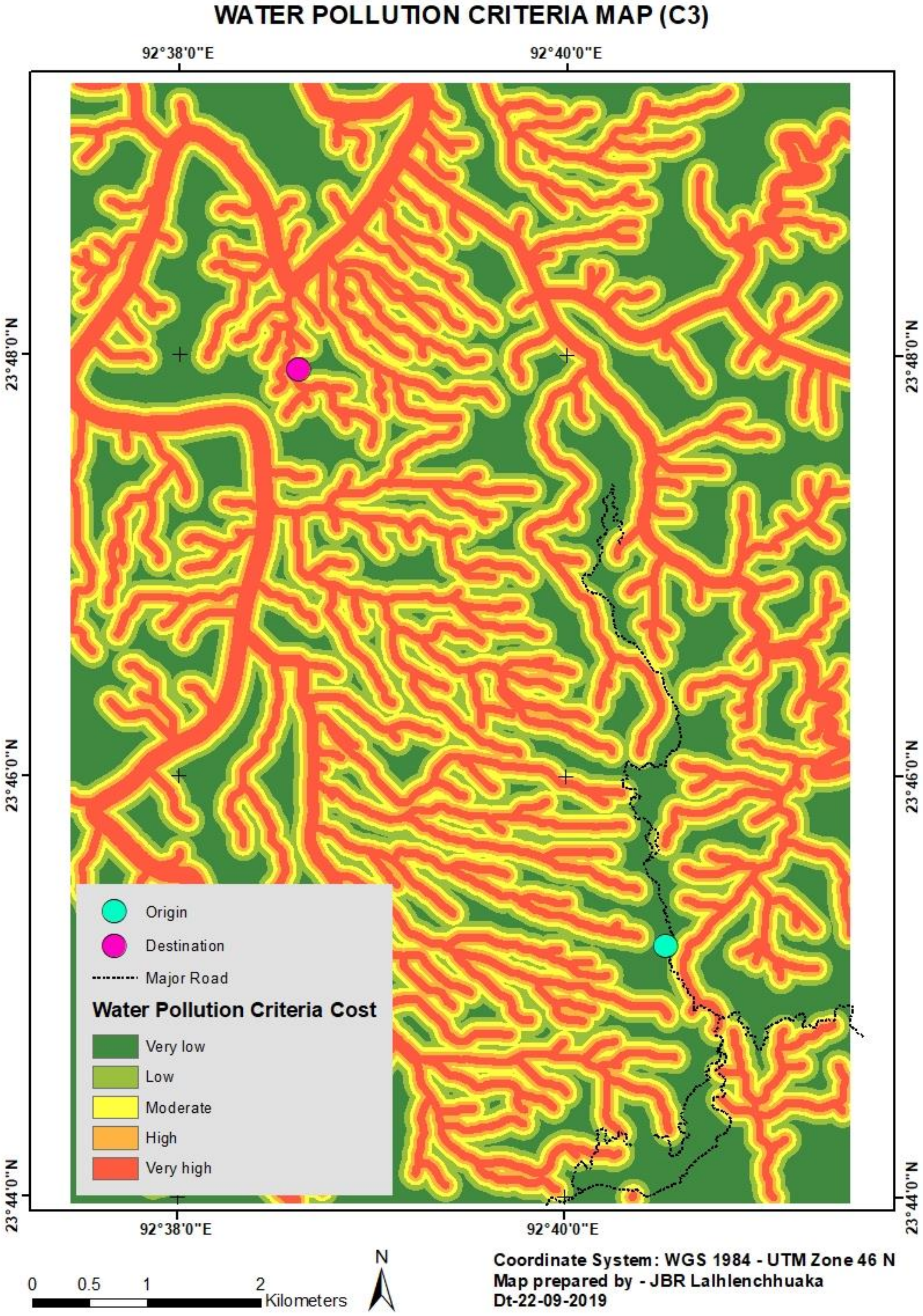
The presence of roads pollutes water bodies and drainages in the peripheral areas it runs through which is mainly due to waste disposed on the roads by the people using the roads and also wastes from vehicles such as tire scrapes, oil leaks and exhaust. The waste runoff from the roads then flows into the drainages system and water bodies eventually. Thus, it is preferable that roads are constructed as far away as possible from water bodies and drainages and areas close to them are thus given higher cost. This rationale is conceptualized by giving maximum cost to water bodies and gradually decreasing the cost away from it. Using the Rivers / Drains data three drainage classes are present in the study area- River, Stream and Drain. Buffers are generated around these features and the distance of the buffer depends on the size of the drainage system- 50 meters for River, 30 meters for Stream and 10 meters for Drain. The buffered features are then merged, Euclidean distance map produced to generate distance raster which is then rescaled using Logistic decay function with parameters – Min: -50, Max: 150, Y-intercept: 90, Range: 1-100. The resulting map (see Map-14) is a raster having maximum cost inside the buffered areas of the drainage systems and cost gradually decreasing from 100 to 1 (based on the logistic function) as we move away from the drainage areas.

C4. Ground water potential disturbance

The presence of roads disturbs ground water potential due to disturbance in rock structure and geology of the region. For such reason, it is preferable to avoid areas of high ground water potential and give high cost to those areas. Using the Ground water potential data (see Table-1 for description of data) the cost values of the different ground water potential classes are assigned based on Table-11.



Map-13. Noise/Air pollution criteria map (C2)



Map-14. Water pollution criteria map (C3)

These cost values are attributed to the respective polygons of the Ground water potential data and the polygon converted to raster producing Ground water potential disturbance cost map – C4 (Map-15).

Table-11. Ground water potential classes and cost

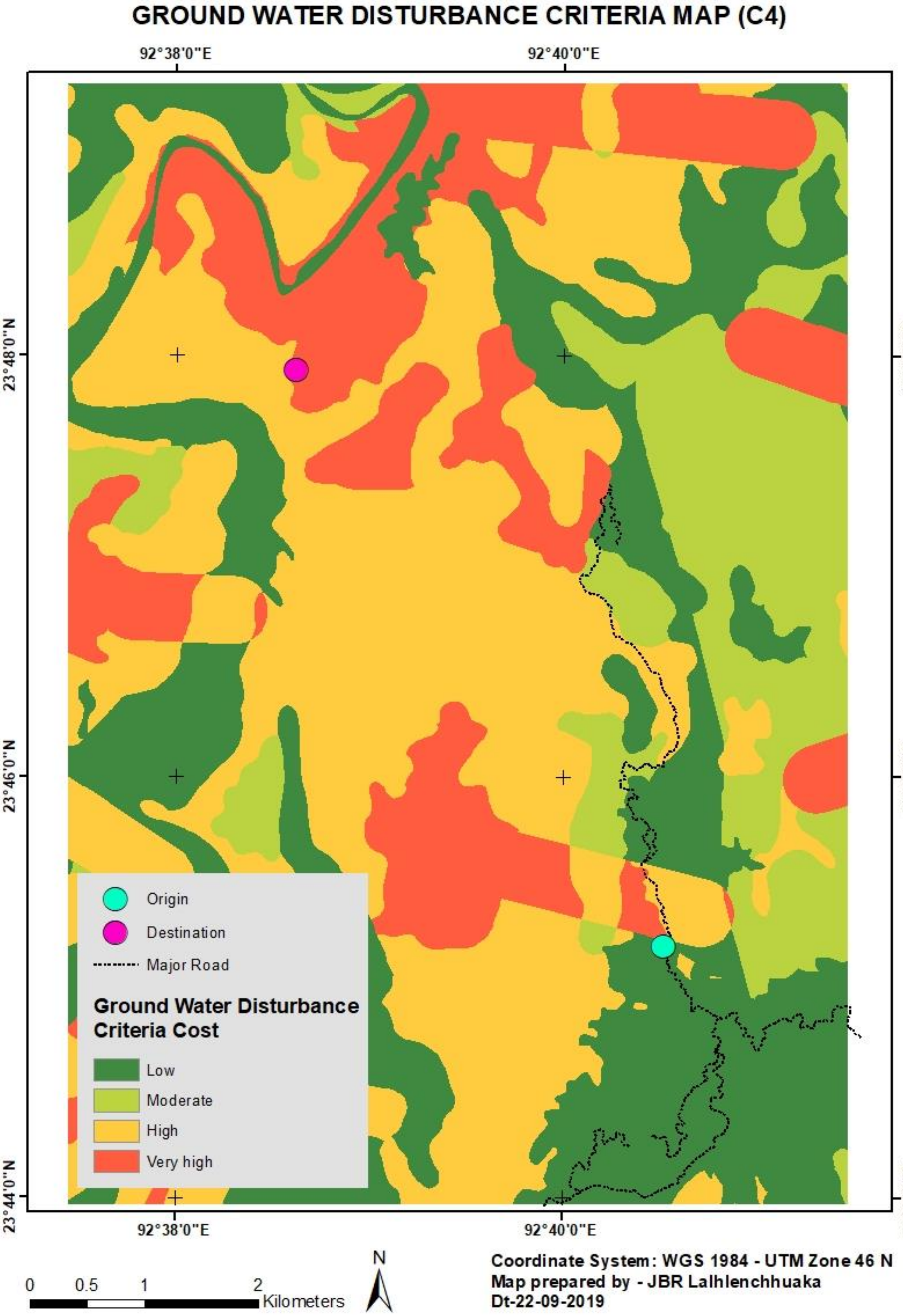
Ground water potential classes	*Cost*
Poor	10
Moderate	40
Good	70
Very Good	100

C5. Erosion

It is preferably that roads do no pass-through areas having high soil erosion susceptibility. Constructing roads in these areas will increase the erosion susceptibility causing more negative impacts on the environment of the area. Two sub-criteria are considered to model the erosion susceptibility- Slope & Land use/ land cover.

(i). Slope: Areas having greater slope are considered more prone to erosion and thus, higher slope areas are given higher cost and vice versa. The slope data is generated from the DEM data and rescaled using ‘Large’ function with the following parameters - Midpoint: 35, Spread: 3, Range: 1-100 to generate slope cost raster.

(ii). Land use/ land cover: Based on the land use or land cover of an area, the erosion susceptibility of erosion differs. For instance, erosion is more susceptible in scrublands than in dense forest areas as dense forest areas have higher concentration of trees and vegetation which prevents erosion.



Map-15. Ground water potential disturbance criteria map (C4)

The cost values of the different land use/ land cover classes are assigned. These cost values are attributed to the respective polygons of forest cover data and the polygon converted to raster producing land use/land cover cost map.

The two sub-criteria are combined using LWC method to generate Criteria-C5 raster (see Map-16) using the expression of Eq-13. The corresponding weights of the sub-criteria are defined by their relative significance in contribution to Erosion criterion.

$$\boldsymbol{C5} = [\boldsymbol{0.5} \times (\boldsymbol{i})] + [\boldsymbol{0.5} \times (\boldsymbol{ii})] \qquad \textbf{(Eq-13)}$$

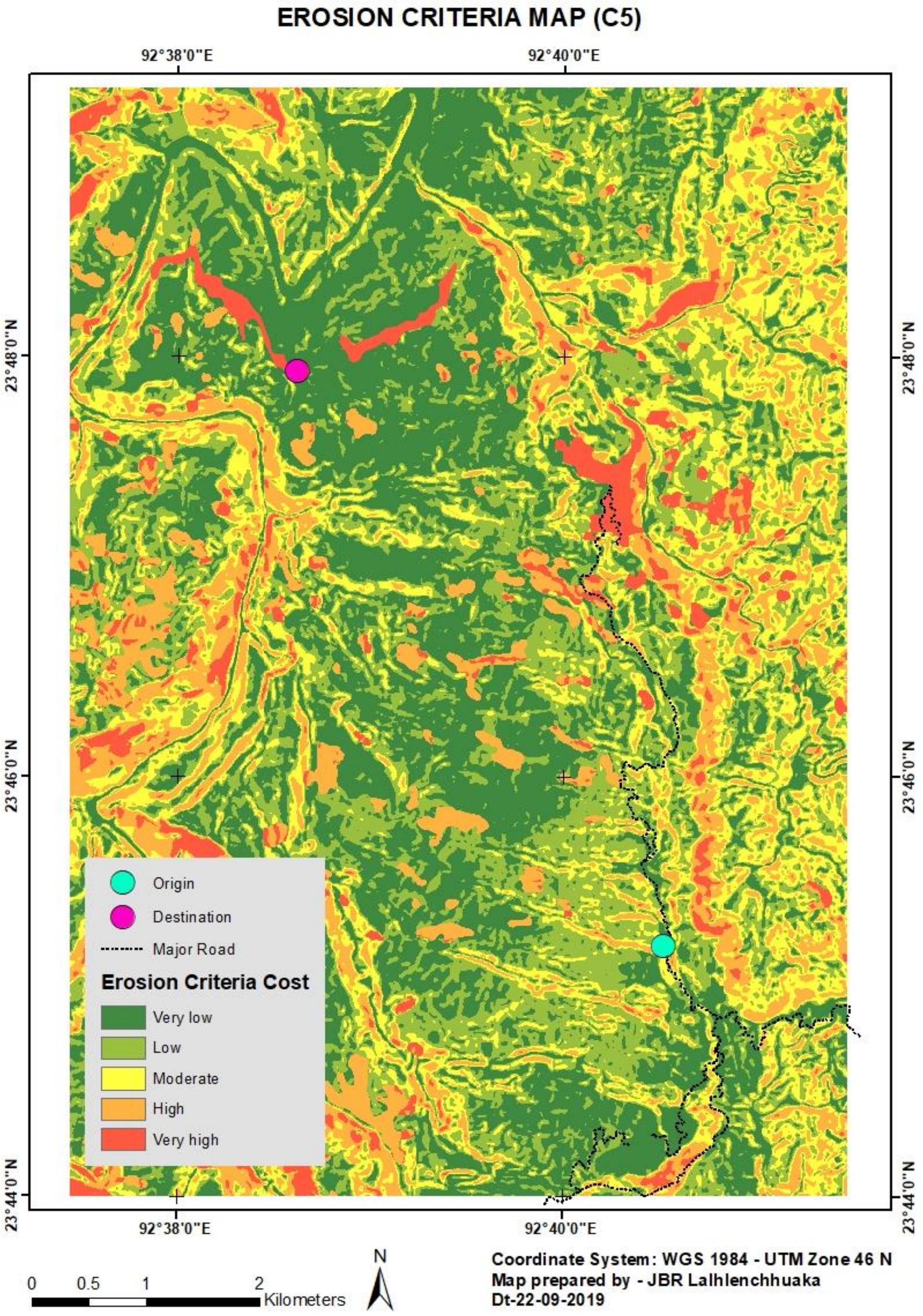
where, C5 is Erosion Criteria, (i) is Slope and (ii) is LULC.

The five criteria – C1, C2, C3, C4 and C5 are combined to form the criteria group 'C' using the equation below (Eq-14) producing the CG cost map C (Map-17) by LWC method. The corresponding weights of the criteria are established by their relative significance in contribution to the Environmental CG.

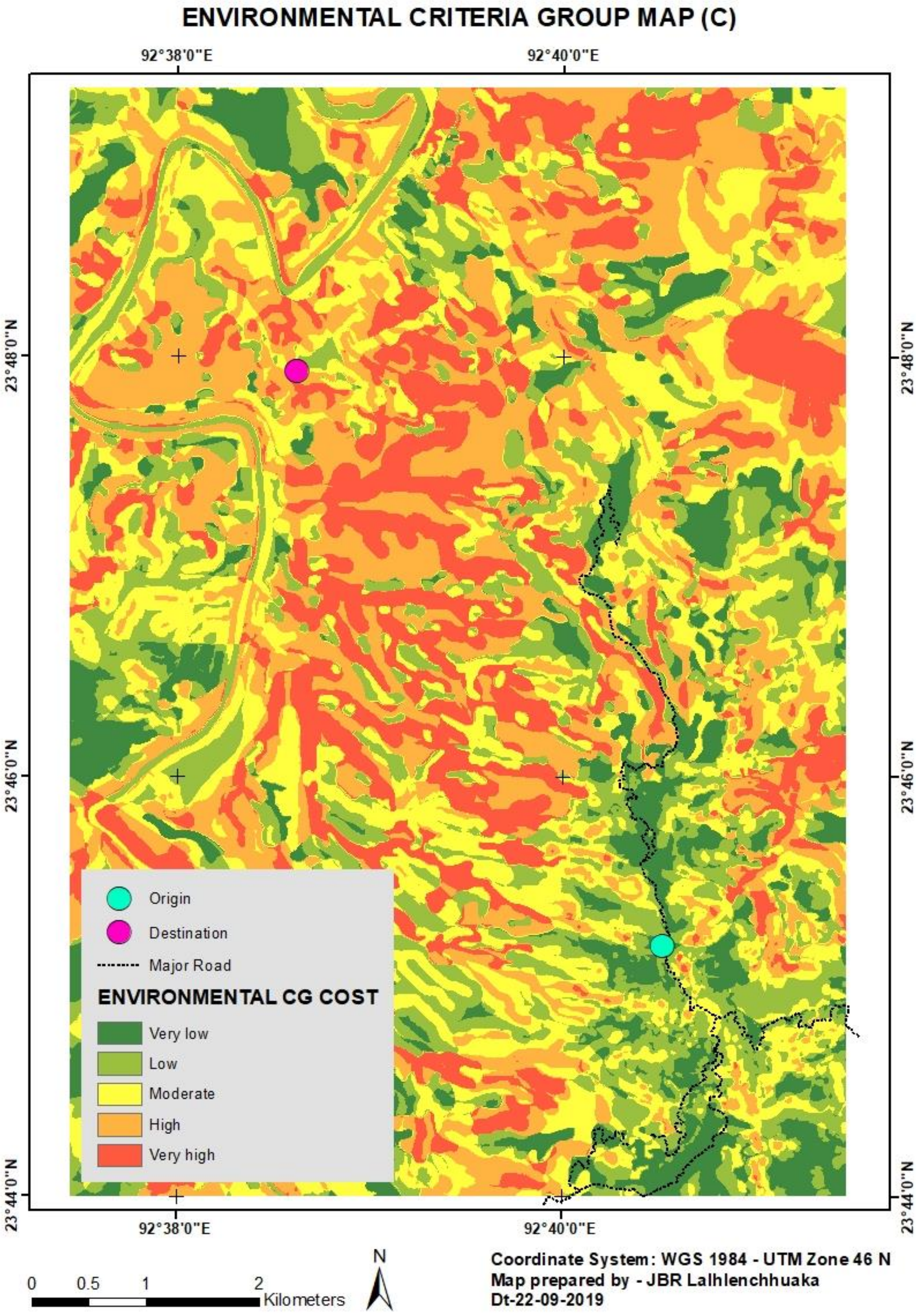
$$\boldsymbol{C} = (\boldsymbol{0.35} \times \boldsymbol{C1}) + (\boldsymbol{0.15} \times \boldsymbol{C2}) + (\boldsymbol{0.20} \times \boldsymbol{C3}) + (\boldsymbol{0.20} \times \boldsymbol{C4}) + (\boldsymbol{0.10} \times \boldsymbol{C5}) \qquad \textbf{(Eq-14)}$$

D1. Public facility disturbance

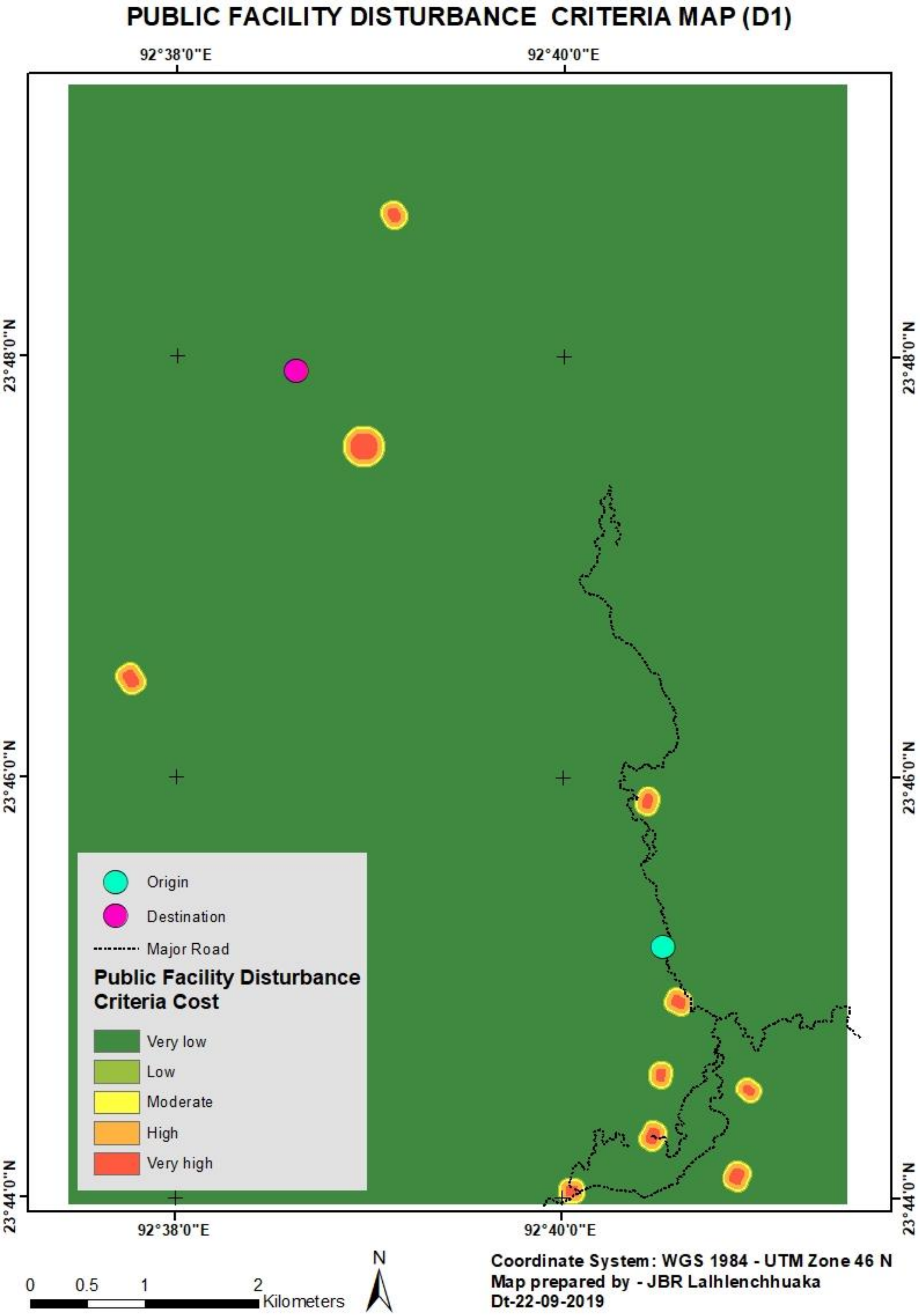
It is desirable to construct roads away from public facilities like parks and recreational areas due to negative social impacts it would cause if otherwise constructed across these facilities. High cost is attributed to public facilities areas and the cost decreases as we move away from these areas. Euclidean distance map is created around the Public facilities polygon data and rescaled using Logistic decay function with parameters – Min: 0, Max: 100, Y-intercept: 97, Range: 1-100. The resulting map (see Map-18) is a raster having maximum cost in and close to public facilities areas and cost gradually decreasing away from the buildings from 100 to 1 based on the logistic function.



Map-16. Erosion criteria map (C5)



Map-17. Environmental Criteria Group map (C)



Map-18. Public facility disturbance criteria map (D1)

D2. Resettlement

Resettlement is necessary if the proposed road passes through settlement areas which cause negative impact to the society of the region. Thus, it is desirable to construct roads away from settlements.

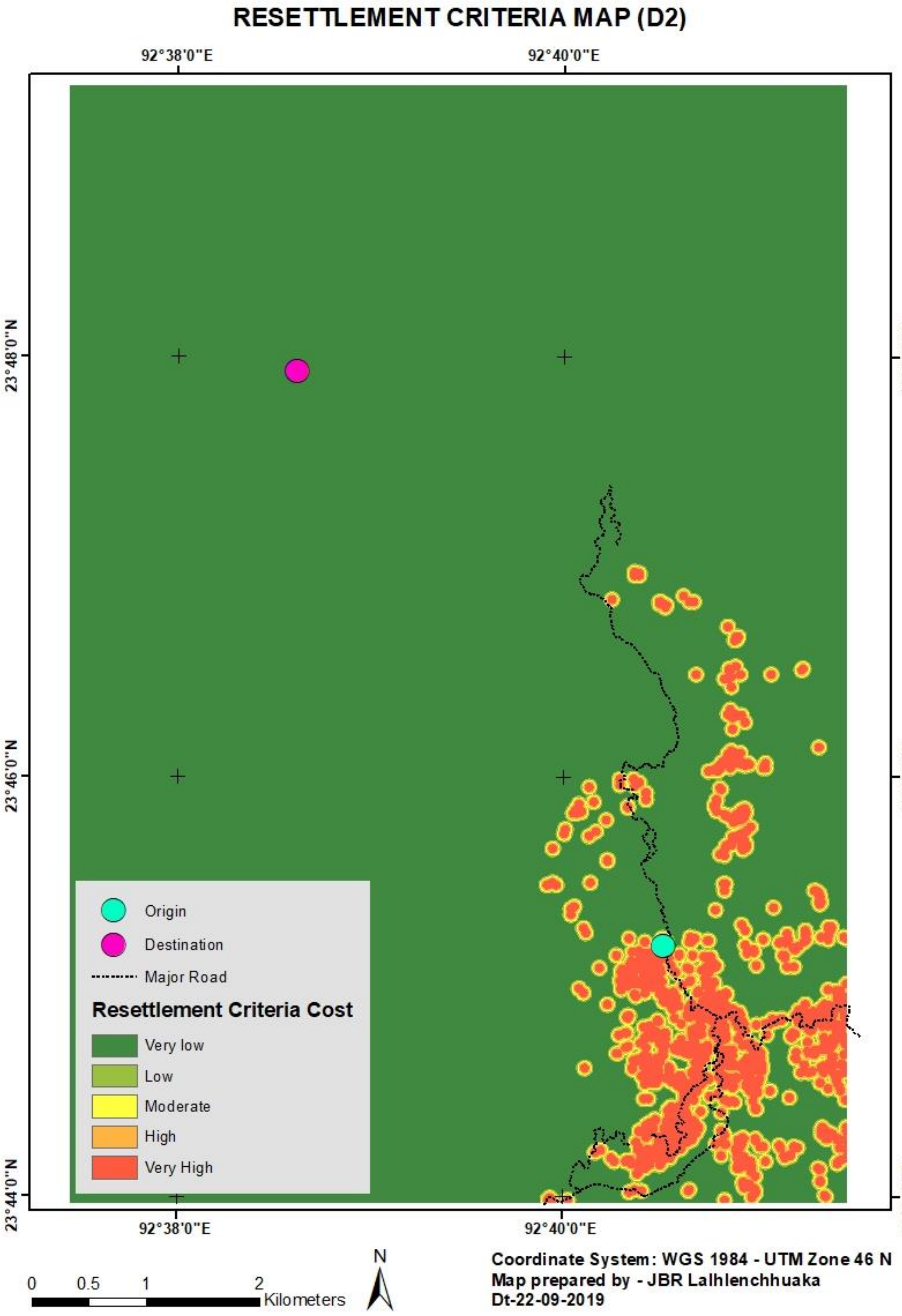
High cost is attributed to settlement areas and the cost decreases as we move away from these areas. Euclidean distance map is created around the Buildings footprint polygon data and rescaled using Logistic decay function with parameters – Min: 0, Max: 100, Y-intercept: 99, Range: 1-100. The resulting map (Map-19) is a raster having maximum cost in and close to Buildings and cost gradually decreasing away from the buildings from 255 to 1 based on the logistic function.

The two criteria – D1 & D2 are combined to form the criteria group 'D' using the equation below (Eq-15) producing the CG map D (Map-20) by LWC method. The corresponding weights of the criteria are established by their relative significance in contribution to the Societal CG.

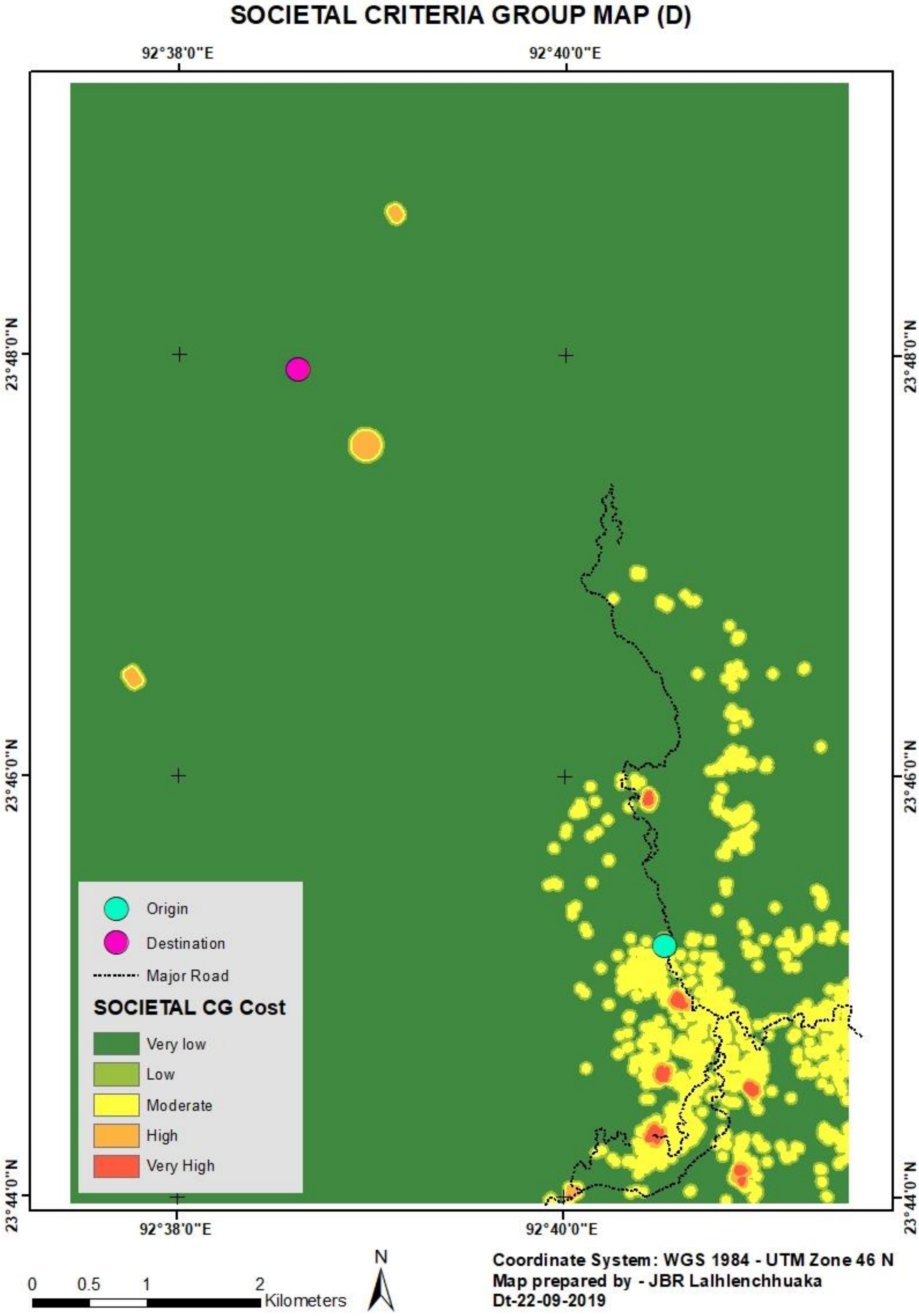
$$\boldsymbol{D} = (\mathbf{0.60} \times \boldsymbol{D}\mathbf{1}) + (\mathbf{0.40} \times \boldsymbol{D}\mathbf{2}) \qquad \textbf{(Eq-15)}$$

3.2.5 Transportation (E)

The rationale of this criteria group (CG) is to consider the effects of road construction on the transportation development of the region and how the construction of roads would affect the existing transportation system. It also takes into consideration the comfort and safety of the designed roads based on geographic factors. This CG would facilitate the search for finding the optimal road alignment which is most suitable transportationally and helps to develop the transportation system of the region. The CG has four criteria – Accessibility, Comfort, Intermodal unity & Safety.



Map-19. Resettlement criteria map (D2)



Map-20. Societal Criteria Group map (D)

E1. Accessibility

To provide better access and linkage to settlements, it is preferable that roads are constructed close to settlements. However, there is a negative preference if roads are too close to settlements as they would disrupt the area and resettlement problems would arise. Euclidean distance map is generated around the settlement areas extracted from Land use/ land cover data and reclassified such that the cost decreases linearly from 100 to 10 starting from the settlement areas up to a distance of 100 meters increases linearly from 10 to 100 again up to the distance of 500 meters from which the cost remains constant at 100. This reclassification is done through Raster Calculator tool of ArcGIS Spatial Analyst Extension by using the scheme shown in Eq-16.

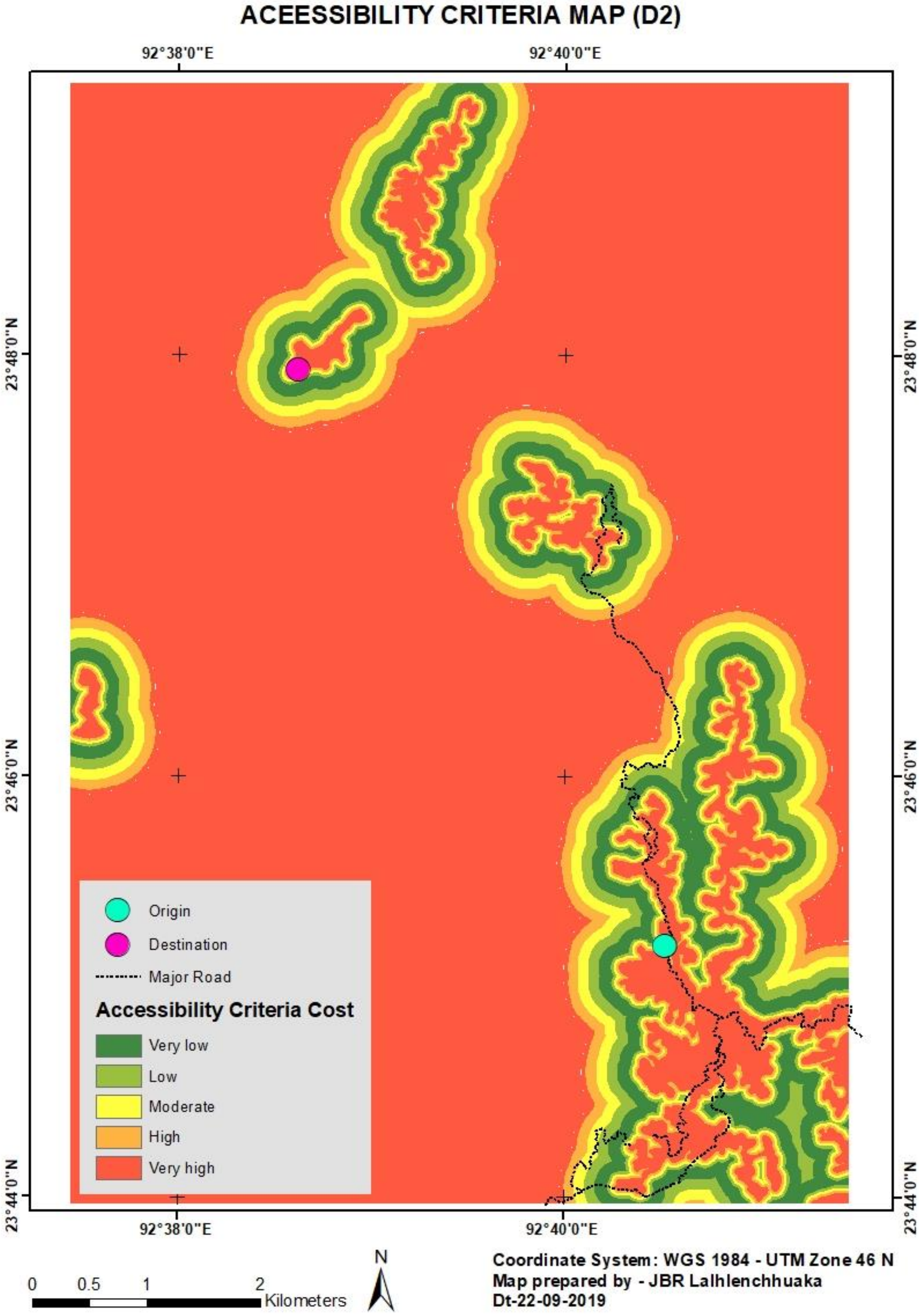
The accessibility cost raster is shown in Map-21. The green regions are the least costly regions (most preferred) where road construction is most preferable based on this criterion.

$$\begin{array}{l} \textbf{If distance} \leq 100\textbf{:} \\ \qquad \textbf{Value decreases from 100 to 10 linearly} \\ \textbf{If distance} > 100 \ \& \leq 500\textbf{:} \\ \qquad \textbf{Value increases from 10 to 100 linearly} \\ \textbf{If distance} > 500\textbf{:} \\ \qquad \textbf{Value} = 100 \end{array} \tag{Eq-16}$$

Map Algebra Expression of ArcGIS:

```
Con("%t_settle_dist%"<=100,-25*"%t_settle_dist%"+100,Con("%t_settle_dist%"<500,0.5625 * "%t_settle_dist%"-31.25,Con("%t_settle_dist%">500,100)))
```

where, ‘t_settle_dist’ is the distance raster to be reclassified.



Map-21. Accessibility criteria map (E1)

E2. Comfort

In this criterion, the comfort of using a road is conceptualized by using geographic factors like terrain ruggedness and settlement. Road constructed over suitable terrain (less rugged terrain) will be more comfortable for road users and likewise, roads which are inside settlement areas are less comfortable due to comparatively heavier traffic. Too much road intersection also causes discomfort to road users and vehicles. Three sub-criteria define comfort criteria– Terrain ruggedness, Settlement area and Road intersection.

(i). Terrain ruggedness: Terrain ruggedness index is calculated using Focal statistics on slope data such that the range of value within a 5X5 cells is calculated and given as the value of the focal cell. The product raster of this tool is then reclassified into five equal interval classes and given the cost from the lowest class to the highest as follows – 4,40,60,80 & 100. The highest ruggedness class has highest cost and vice versa.

(ii). Settlement area: Roads running through settlement areas are less comfortable to use. Thus, it is preferable to avoid these areas in road construction. The more urban the area, the more uncomfortable the roads are to travel and vice versa. The settlement area polygons are given costs as follows – City: 100, Town: 80, Village: 40 and Other areas: 4. The settlement polygon is the converted to raster based on the cost attribute.

(iii). Road intersection: Road intersection causes discomfort for vehicle drivers and thus are preferably avoided. A buffer of 10 meters in generated around roads and given a cost of 100 to these buffered areas. All other areas are given a cost of 5. The polygon data is then converted to raster based on the cost attribute.

The three sub-criteria are combined using LWC method to generate Criteria-E2 cost raster (Map-22) using the expression below (Eq-17). The corresponding weights of the sub-criteria are defined by their relative significance in contribution to Comfort criterion.

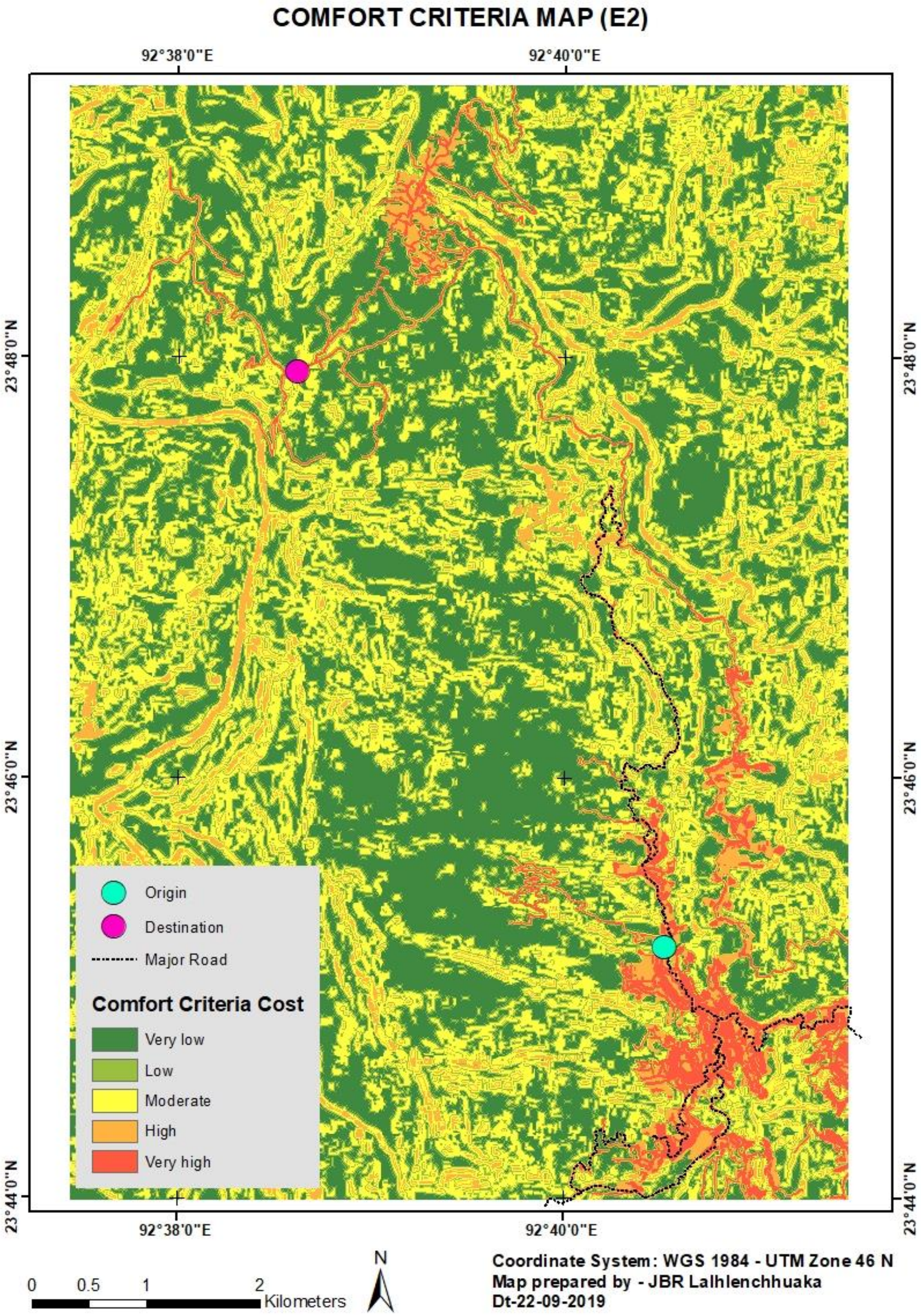
$$\boldsymbol{E2} = [\mathbf{0.30} \times (\boldsymbol{i})] + [\mathbf{0.30} \times (\boldsymbol{ii})] + [\mathbf{0.4} \times (\boldsymbol{iii})] \qquad \textbf{(Eq-17)}$$

where, E2 is Comfort criteria, (i) is Terrain ruggedness, (ii) is Settlement area and (iii) is Road intersection.

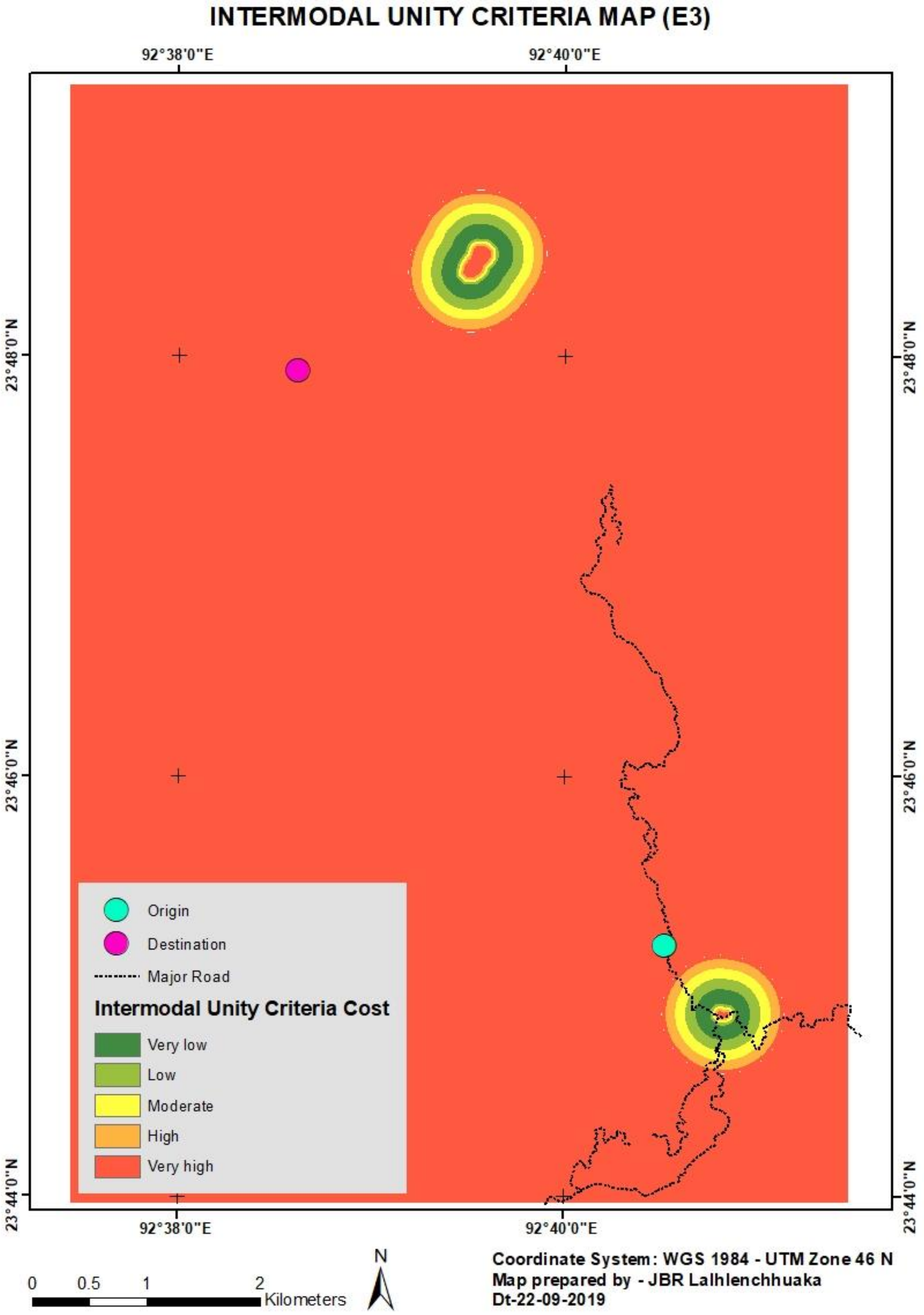
E3. Intermodal unity

This criterion considers the effects of road construction in increasing intermodal unity by linking two or more modes of transportation. This linkage is possible by connecting different transportation hubs. It is desirable that roads are close to these transportation hubs but being too close is then a negative impact due to possible disturbance caused in the hub’s infrastructure. Euclidean distance map is generated around the Transportation hub data (see Table-1 for description of data) and reclassified such that the cost decreases linearly from 100 to 10 starting from the transportation hubs up to a distance of 100 meters and then increases linearly from 10 to 100 again up to the distance of 500 meters from which the cost remains constant at 100. This reclassification is done through Raster Calculator tool of ArcGIS Spatial Analyst Extension by using Eq-18. The Intermodal unity cost raster is shown in Map-23. The green regions are the least costly regions (most preferred) where road construction is most preferable based on this criterion.

$$\begin{array}{l} \textbf{If distance} \leq \mathbf{100:} \\ \qquad \textbf{Value decreases from 100 to 10 linearly} \\ \textbf{If distance} > \mathbf{100} \ \& \leq \mathbf{500:} \\ \qquad \textbf{Value increases from 10 to 100 linearly} \\ \textbf{If distance} > \mathbf{500:} \\ \qquad \textbf{Value} = \mathbf{100} \end{array} \qquad \textbf{(Eq-18)}$$



Map-22. Comfort criteria map (E2)



Map-23. Intermodal unity criteria map (E3)

Map Algebra Expression of ArcGIS:

```
Con("%tranHub_dist%"<=100,-
2.25*"%tranHub_dist%"+255,Con("%tranHub_dist%"<500,0.5625 *
"%tranHub_dist%"-31.25,Con("%tranHub_dist%">500,255)))
```

where, ‘tranHub_dist’ is the distance raster to be reclassified.

E4. Safety

The viable safety of roads is considered in this criterion by taking geographic perspective to assess safety. The higher the slope, the less safe it is for vehicles due to the possibility of rolling long distances in case of accidents. Also, road intersections are areas where most of collision accidents occur and thus, to be avoided. Two sub-criteria are considered – Slope & Road intersection.

(i). Slope: The steeper the slope, the less safe it is for vehicles. Thus, higher slope values are given higher cost and vice versa. The slope data is reclassified into classes and each class given a cost value (see Table-12) to produce slope cost raster.

Table-12. Slope classes and costs

Slope values (classes)	*Cost*
0-15	10
15-30	20
30-40	30
40-50	60
50-76.6	100

(ii). Road intersection: Road intersection is unsafe for vehicle drivers and thus should be avoided preferably. A buffer of 10 meters in generated around roads and given a cost of 100 to these buffered areas. All other areas are given a cost of 10. The polygon data is then converted to raster based on the cost attribute.

The tow sub-criteria are combined using LWC method to generate Criteria-E4 raster (Map-24) using the expression of Eq-19. The corresponding weights of the sub-criteria are defined by their relative significance in contribution to Safety criterion.

$$\boldsymbol{E4} = [\mathbf{0.70} \times (\boldsymbol{i})] + [\mathbf{0.30} \times (\boldsymbol{ii})] \qquad \textbf{(Eq-19)}$$

where, E4 is Safety criteria, (i) is Slope and (iii) is Road intersection.

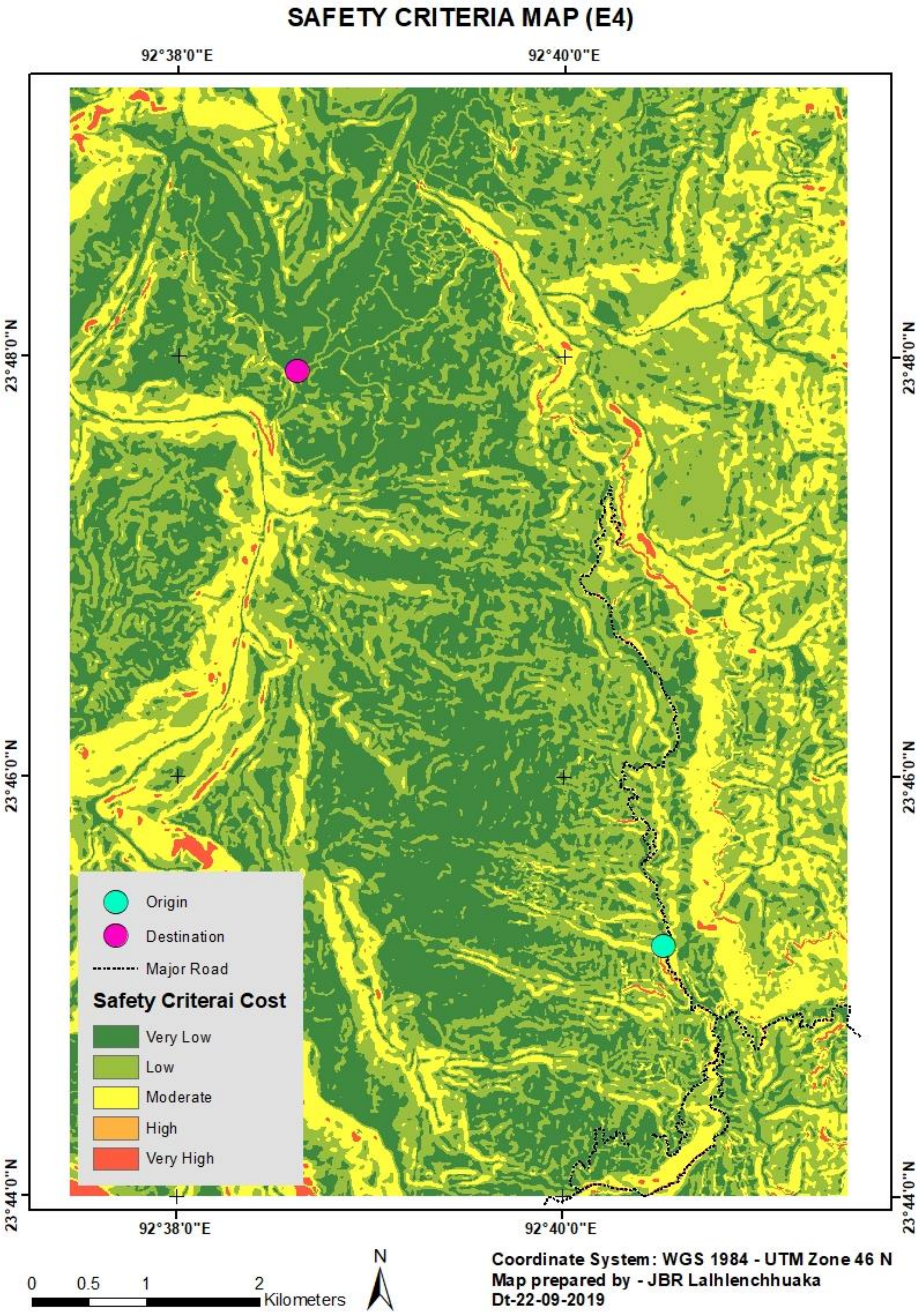
The four criteria – E1, E2, E3 and E4 are combined to form the criteria group 'E' using the equation below (Eq-20) producing the CG map E (see Map-25) by LWC method. The corresponding weights of the criteria are established by their relative significance in contribution to the Transportation CG.

$$\boldsymbol{E} = (\mathbf{0.30} \times \boldsymbol{E1}) + (\mathbf{0.10} \times \boldsymbol{D2}) + (\mathbf{0.20} \times \boldsymbol{E3}) + (\mathbf{0.40} \times \boldsymbol{E4}) \qquad \textbf{(Eq-20)}$$

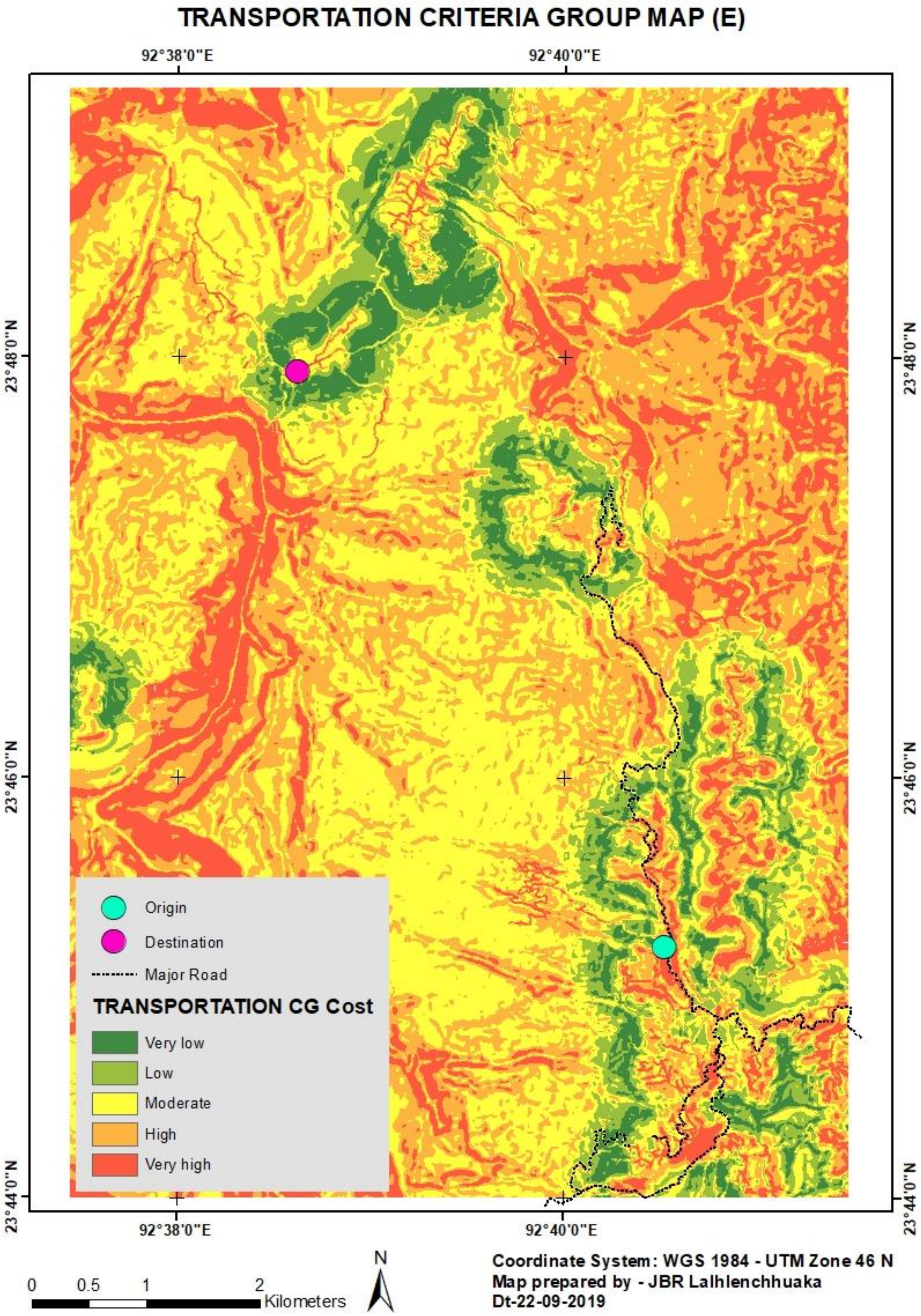
3.3 Least cost path analysis (LCPA)

The least cost paths are generated using Cost Path tool of ArcGIS spatial analyst extension which requires three data namely – Origin/Destination (O/D) data, Cost Distance raster and Cost Backlink raster. The O/D data is already available. The Cost Distance raster is generated using the Path Distance tool with Vertical Parameters of 5^o (5 degrees) threshold (which is according to the engineering standard used) which is particularly essential and critical to the analysis. This vertical parameter provides restriction to the grade of the road alignment to be searched.

An additional LCP (named as AHP) is generated in which all the Criteria Group maps are combined (Eq-21) using LWC method to produce a composite cost raster. The resulting alignment (Orange color in Map-26) takes into consideration all the criteria by using weights based on the work of Yakar & Celik (2014) with consultancy of an engineer on the relative importance of the criteria groups in road alignment design.



Map-24. Safety criteria map (E4)



Map-25. Transportation Criteria Group map (E)

$$AHP = (0.25 \times A) + (0.35 \times B) + (0.15 \times C) + (0.10 \times D) + (0.15 \times E) \qquad \textbf{(Eq-21)}$$

where, ‘A’ is Economic CG, ‘B’ is Engineering CG, ‘C’ is Environmental CG, ‘D’ is Societal CG and ‘E’ is Transportation CG.

We have now a total of 6 optimal road alignment alternatives based on 6 different perspectives (see Map-26).

3.4 CAD Analysis

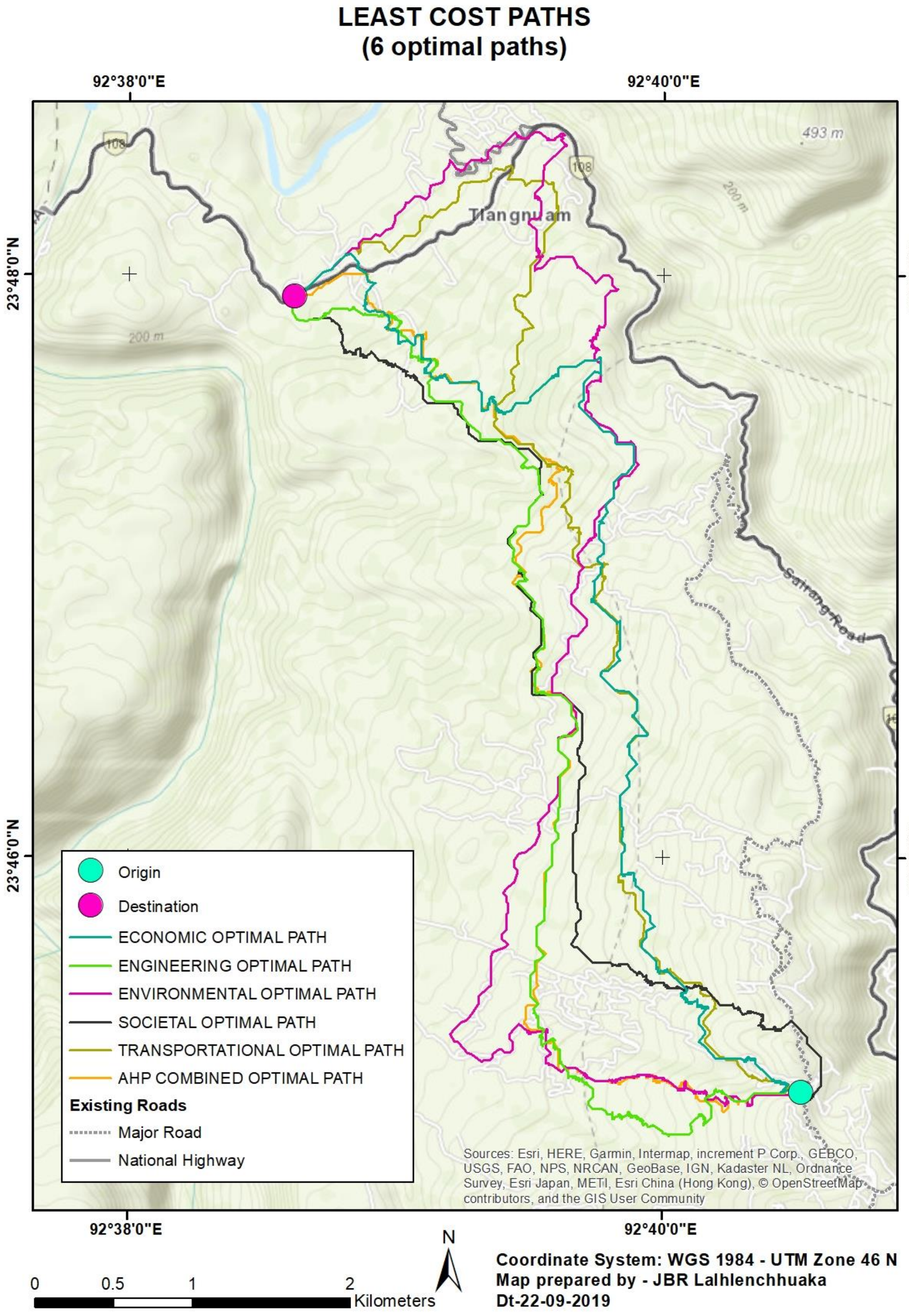
The 6 road alignments generated earlier along with the traditionally CAD designed alignment is analyzed in the CAD environment to conform to engineering design standards and check feasibility of the alignment geometrically and also to calculate accurate cut and fill volume. The standard for this road design is based on the Geometric Design Standards for Rural (Non-Urban) Highways Vol. 73-1980 (PWD, 2015) which is the same format used in the case study project and the details of the design standards is elaborated in the following sections.

3.4.1 Road template

The road template is the cross-sectional geometry of the designed road (see Fig-26). The dimension of the different components of the road template is defined in Table-13.

Table-13: Road template values

Feature	*Value*
Formation	10 meters
Carriageway	7 meters
Shoulder	1.5 meters
Cut/Fill Slope	1:3
Ditch width	0.6 meters
Ditch depth	0.5 meters



Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), © OpenStreetMap contributors, and the GIS User Community

Coordinate System: WGS 1984 - UTM Zone 46 N
Map prepared by - JBR Lalhlenchhuaka
Dt-22-09-2019

Map-26. Least cost paths based on 6 different perspectives including existing designed road

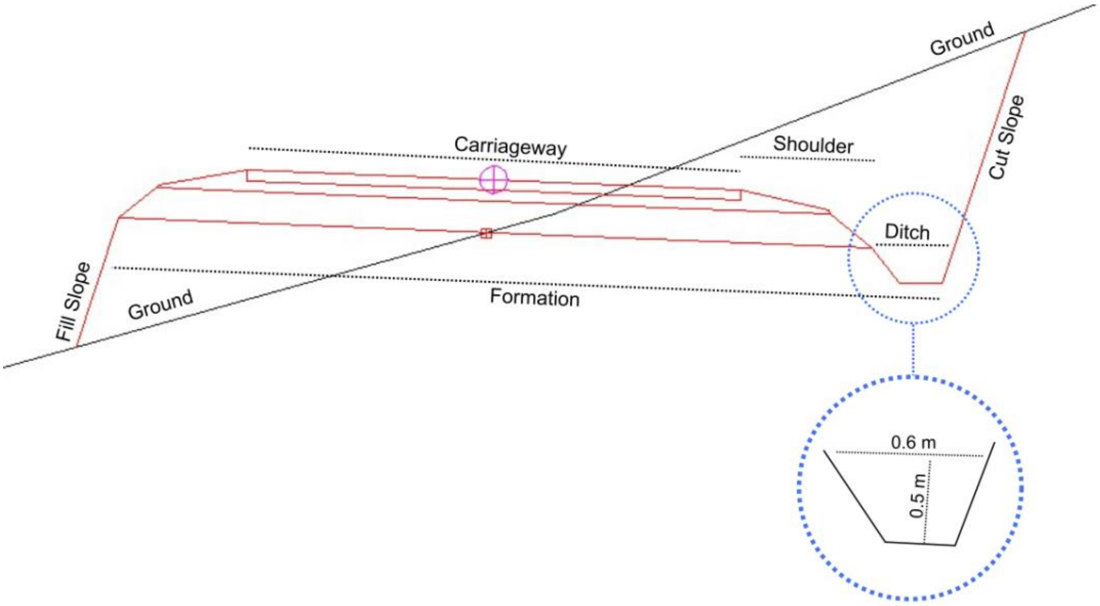


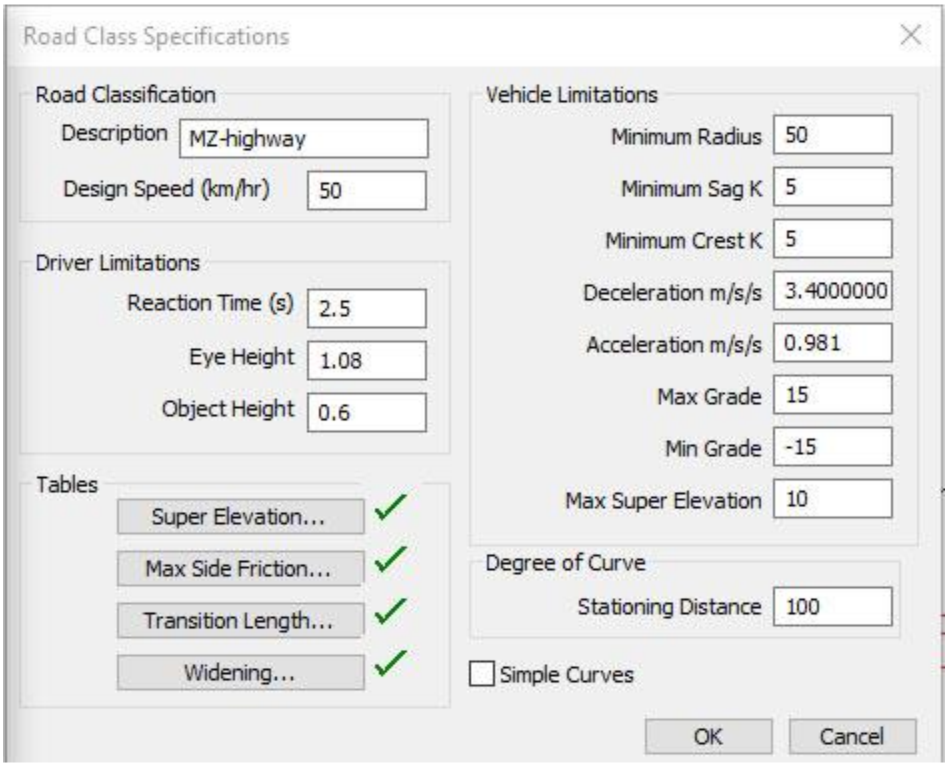
Fig-26. Road template with labels

On the cut side of the road, the ditch is included in the shoulder with a total width of 1.5 meters where the width of the ditch is 0.6 meters and the remaining 0.9 meters as the shoulder. In real applications, the cut slope of the template varies depending on the earth type to be cut but for this analysis, the constant slope of 1:3 (0.3333) is used throughout the length of the road for simplicity in application and also due to the unavailability of terrain composition data.

3.4.2 Road class

The specifications of the road class define the way the horizontal and vertical alignments are designed and act as a controlling framework for the design of the road.

The right window of Fig-27 shows the road class specification values which is adopted from the case study project specifications and in accordance with the Geometric Design Standards for Indian Rural (Non-Urban) Highways Vol. 73-1980 (PWD, 2015). The left window shows super-elevation values at different design speeds and radius.



Road Classification
Description: MZ-highway
Design Speed (km/hr): 50

Driver Limitations
Reaction Time (s): 2.5
Eye Height: 1.08
Object Height: 0.6

Tables

Vehicle Limitations
Minimum Radius: 50
Minimum Sag K: 5
Minimum Crest K: 5
Deceleration m/s/s: 3.4000000
Acceleration m/s/s: 0.981
Max Grade: 15
Min Grade: -15
Max Super Elevation: 10

Degree of Curve
Stationing Distance: 100

☐ Simple Curves

Fig-27. Road class specification values

3.4.3 CAD based analysis

Using the road template and road class defined, the 6 alternative road alignments generated in the LCPA and the existing designed alignment predesigned are drawn/ imported in the CAD module (RoadEng Location).

Out of the seven road alignments drawn, only the Transportation Alignment alternative violates the road class specifications. The horizontal curves could not be fitted inside the alignment corridor at a single particular section of the alignment (see Fig-28). All the alignment alternatives comply with the horizontal curve design standard more or less in which only negligible portions of the design roads fall out of the least cost road corridor by about 3-5 meters which is within the negligible threshold.

After the vertical alignment is designed and optimized, the cut and fill volume of all the road alignment corridors are calculated which is shown in Table-14. The cut and fill volume calculation assumes that the earth composition is similar in the study area. This assumption is made due to unavailability of earth composition data for the study area.

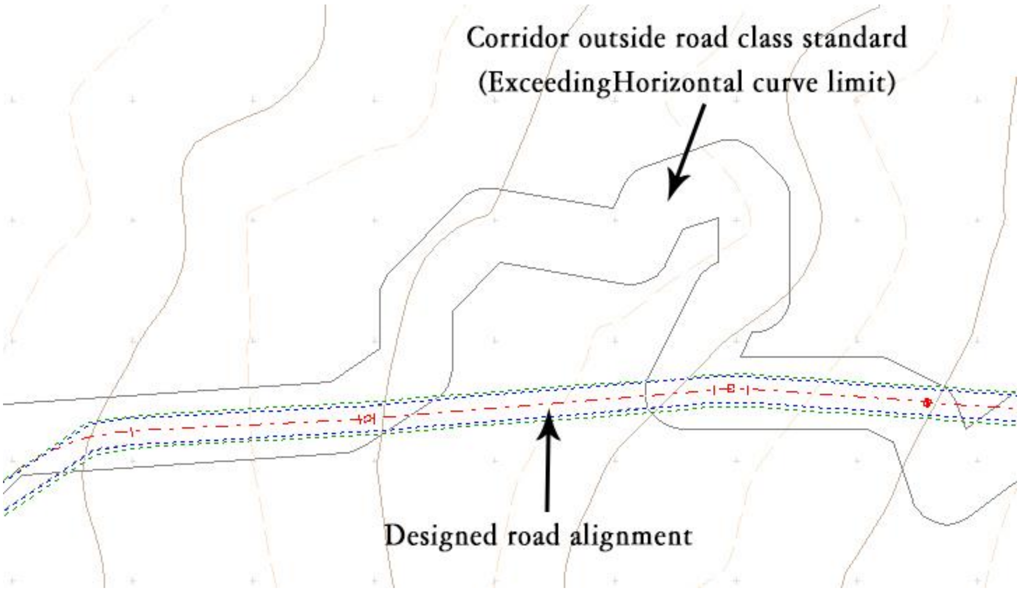


Fig-28. Road alignment corridor violating road class limits

Table-14. Cut and fill earth volume of the alternative alignments

Alternative alignments	*Cut volume (cubic meters)*	*Fill volume (cubic meters)*	*Cut-fill Cost (Rs. 1,00,00,000)*
ECON	1,002,613	138,412	15.03
ENGI	604,161	74,640	8.87
ENVI	2,611,940	218,422	36.19
SOCI	1,458,253	319,425	24.35
TRAN	3,204,721	148,915	41.90
AHP	1,097,924	23,005	13.76
EXIS	1,689,819	180,915	24.24

The total cost of cut/fill (right most column in Table-14) is calculated using the formula below (Eq-22) which is the prevailing rate for cut and fill works in the study area (PWD, 2015).

$$C = Rs.(121 \times A) + (210 \times B) \quad \text{(Eq-22)}$$

where ‘C’ is the total cost of cut and fill in Indian Rupees, ‘A’ is the cut volume and ‘B’ is the fill volume where the volume is expressed in cubic meters.

3.5 Alignment assessment

This section deals with the assessment of the six optimal paths generated using the GIS method and comparing them to the CAD designed alignment to find which alignment is the most optimal based on assessment criteria.

3.5.1 Cost calculation of alignments based on the Criteria Groups

The 7 alternative alignments (CAD alignment included) are assessed such that the corridor (buffered area around least cost paths) generated from the respective road alignments are put on top of all the Criteria Group cost raster one by one (method explained in Section 2.9.1) and cost calculated for each alignment alternative on the five CG. The resulting alignments and costs are shown in Table-15.

Table-15. Cost values of alternative alignments in each CG along with corresponding lengths

Alternative alignments	*ECON*	*ENGI*	*ENVI*	*SOCI*	*TRAN*	*Length (Km)*
Economic	521951.31	321939.06	335048.25	16797.05	441153.72	12.20
Engineering	507852.93	341977.07	354772.33	19192.63	439219.23	11.09
Environmental	521756.99	303272.66	347306.28	15076.56	421547.98	15.08
Societal	699697.30	431903.81	402196.34	16533.75	564504.03	10.01
Transportation	482944.24	292719.24	347635.10	5029.58	386441.34	11.42
AHP	572864.58	345478.66	393023.26	15689.34	411624.57	11.55
Existing traditional CAD	647088.55	422991.94	482593.66	13761.86	550112.15	13.37

3.5.2 Standardization and combined assessment

The cost values and length values are standardized into a common scale of reference and facilitate the relative comparison of the alignments. The standardization procedure linearly stretches the values of Table-15 into the range of 0-100 using Eq-5 as mentioned in section 2.8.4. For a particular alignment, the standardized values (see Table-16) in all the assessment criteria are then added to form a total cost. The addition is weighted (bold letters of Table-16) of which the weights are synthesized from the concerned literature and consultancy with engineers.

This particular approach is important to find the performance of the alignment alternatives in other assessment criteria. Every alignment will have the best performance (least cost) in their respective assessment criteria but the cost values in other assessment criteria may be extremely high making the alignment alternative non-preferable. The addition of Cut / Fill cost criteria and Length is critical to the assessment procedure as they are considered as the main deciding factor in the assessment of road alignment alternatives (IRC, 2002) and accordingly are given substantial weights in the calculation of total weighted cost. The distribution of weights is not fixed and the selection of the weights should be carefully planned and should involve Multi-criteria decision-making procedures and preferably a large group of experts.

The Engineering Alignment has the least total weighted cost, AHP Alignment coming second and followed by Economic Alignment in third. The Economic alignment and Societal alignment has almost similar total weighted cost but largely differs in cut / fill cost which could be used to select the better alignment between the two. Thus, the comparison of alignments is comprehensive using Table-16 and the best alignment selection depends on the decision makers and weight values. The weight values are produced using the decisions of the stakeholders using pairwise comparison of AHP.

Table-16. Alternative alignment assessment scores

		Assessment Criteria							*Total Weighted Cost*
		ECON	*ENGI*	*ENVI*	*SOCI*	*TRAN*	*Cut / Fill*	*Length*	
	Weights of CG→	***0.10***	***0.20***	***0.05***	***0.02***	***0.03***	***0.35***	***0.25***	***1.00***
Road Alignments	ECON	72.58	79.18	73.51	100	77.81	35.87	80.90	63.88
	ENGI	74.57	70.22	71.96	78.5	74.67	21.17	73.54	54.71
	ENVI	100.00	100.00	83.34	86.1	100.00	86.37	100.00	94.12
	SOCI	69.02	67.77	72.04	26.2	68.45	58.11	66.38	63.57
	TRAN	81.87	79.99	81.44	81.7	72.92	100.00	75.73	86.01
	AHP	74.60	74.54	69.43	87.5	78.15	32.84	76.59	60.58
	EXIS	92.48	97.94	100.0	71.7	97.45	57.85	88.65	80.60

Chapter-4: Results and discussion

4.1 Comparison of alignments based on total cost

The analysis produces 6 optimal alignment alternatives besides the traditionally designed alignment. These alignment alternatives are then assessed based on different criteria and producing an assessment table (see Table-16) which provides the decision makers with comprehensive information for comparison of the alignments and selection of most preferred alignment. The result clearly shows that the existing traditionally designed alignment is not the most optimal alignment based on the research methodology and comes fifth (5th) in the overall ranking (see purple bar in Fig-29) with the Environmental and Transportation alignments having more total cost. The Environmental alignment has the highest cost among the alternatives with nearly double that of the least cost alignment i.e. Engineering alignment (see Fig-29). The assessment should not be limited only considering the total weighted cost but also should involve all the spectrum of the assessment like how an alignment perform in other assessment criteria, its length and the cut/fill costs.

The consideration of cut / fill cost and length of the road is essential in the assessment besides the other cost values as they are the major deciding factor in selecting best alignments and we have to incorporate this perspective into the assessment as well (IRC, 2002). The Engineering alignment having the least total weighted cost also ranks highest in the cut / fill cost (least cut / fill cost) and is also the second shortest alignment and decidedly is the best alignment alternative with little chance of variation in its rank with variation in assessment weights. The second-best alignment position is much more variable since the total weighted cost between the second, third and fourth least cost alignment is marginal i.e. between Economic, AHP and Societal alignments (see Fig-29). AHP alignment has the shortest length and lowest cut/fill cost between the three while being second in the total weighted.

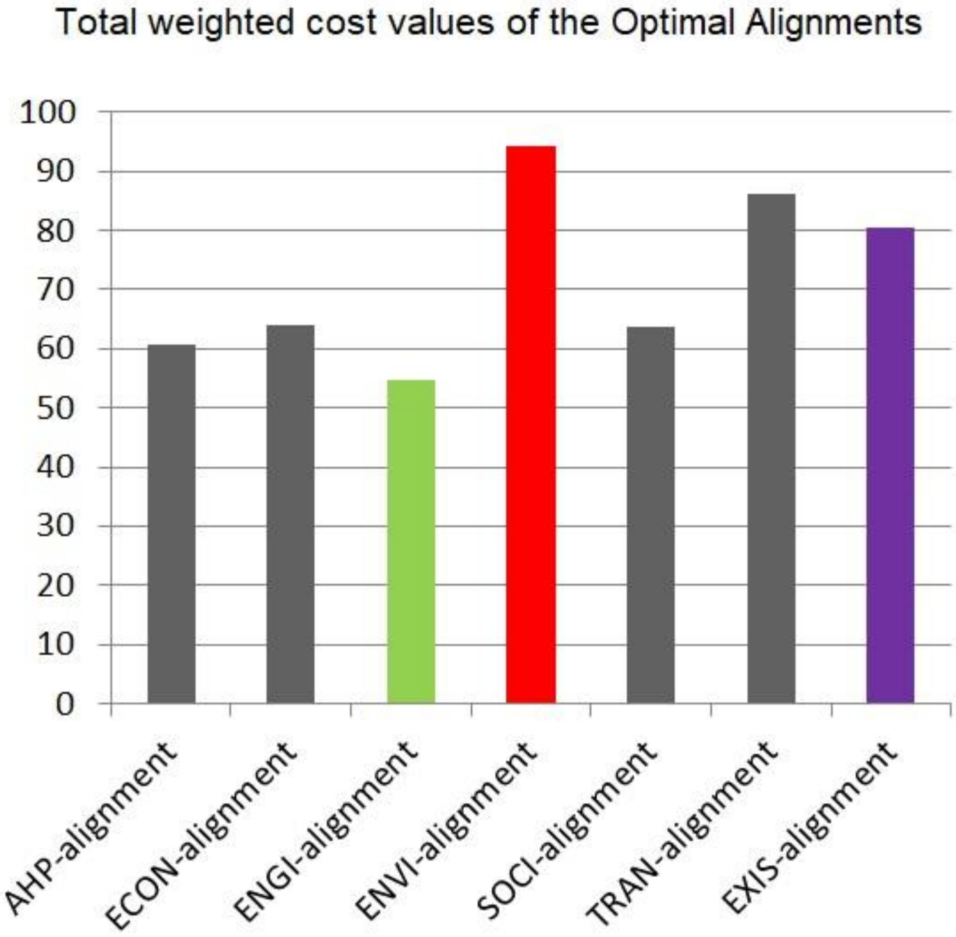


Fig-29. Total Weighted Cost values of the alternative alignments

The third best alignment is open for decision between Economic and Societal alignments. The Economic alignment has the total cost of 63.88 while the Societal has 63.57 and thus the difference between the two is negligible. However, the Economic alignment has 35.87 cut/fill cost value while Societal alignment has 58.11 but the former alignment is longer by about 2 kilometers. The final decision of the third best alignment depends on whether the decision makers put more importance to length or to cut/fill cost.

4.2 Alignment geometry comparison

The geometry of the Engineering alignment and AHP alignment is almost similar (see Map-27) with slight difference in the beginning and ending of the alignments. The mid-section of the alignment is virtually similar following more or less the same path. The difference in the alignment between the traditionally designed alignment (light blue hashed line in Map-27) and the two most preferable alignments (Red-AHP and Green-Engineering in Map-27) can be clearly observed.

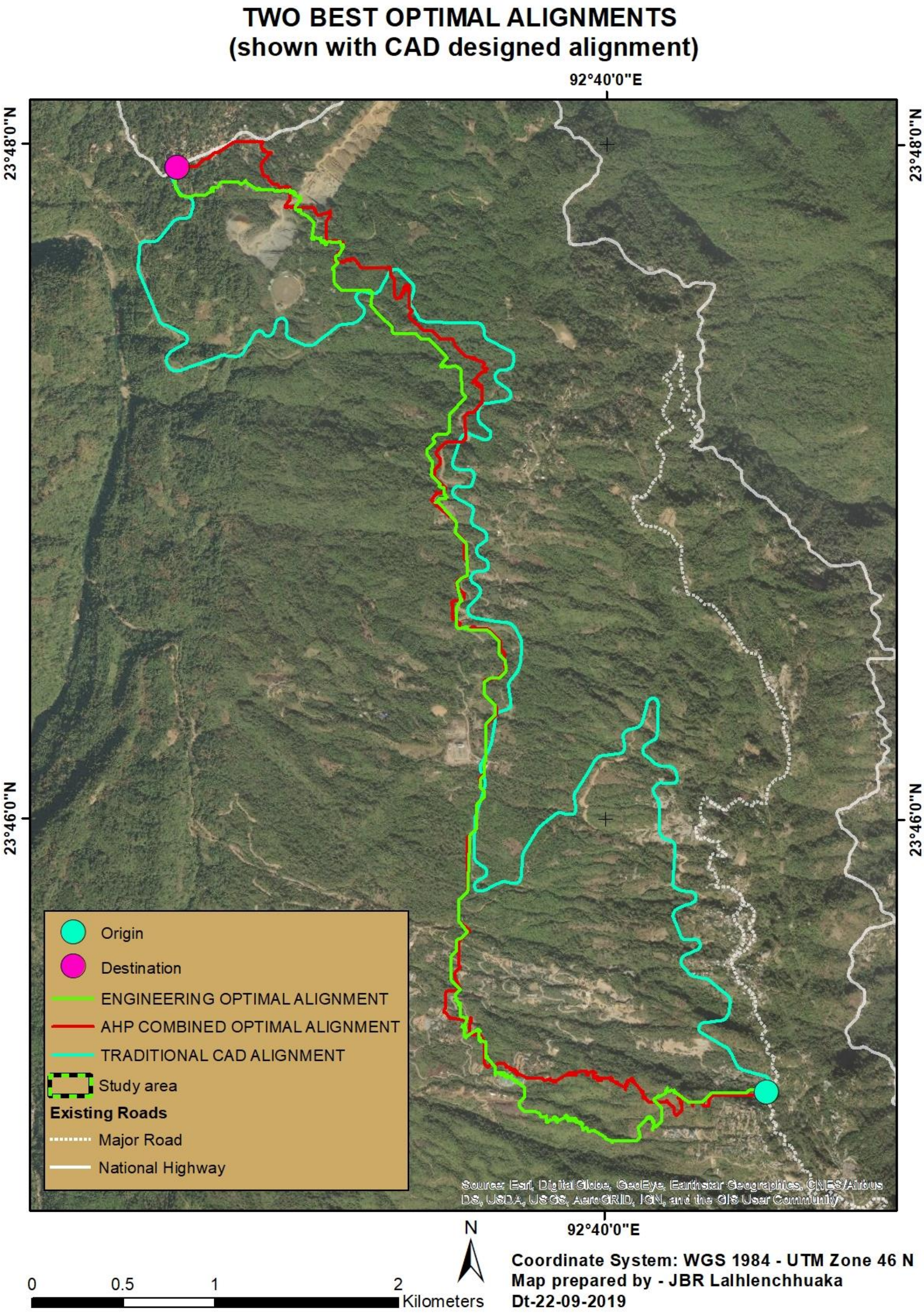
In the beginning section of the alignment, the traditional alignment firs go northward for about 2 kilometers, changes direction to the south-west going for another 1 kilometer then again changes direction to the north on the other hand both the AHP and Engineering alignment directly moves to the west direction for about 1.5 kilometers and then goes north from there onward. The difference in the alignment is also pronounced in the ending sections of the alignment as we can see from Map-27.

4.3 Advantage of optimal alignment

The Engineering alignment has significantly lower cost than the traditional alignment in all the assessment criteria (see Fig-30) except for the Societal Criteria in which the traditional alignment performs marginally better having slightly lower cost. This indicate that that the Engineering alignment is considerably better than the Traditional alignment economically, is more engineering compliance, environmentally friendly, promotes better transportation with shorter length and less cost in cut and fill.

We observe a significant reduction in the length of the road in the most preferable optimal alignment (Engineering alignment) than that of the traditional alignment, a reduction of about 2.28 kilometers (see Table-15) which is a huge difference in all terms of measurements including monetary value and economic perspective.

The length of the road not only dictates the cost of construction and time saving in travel but also significantly affects the long-term expenditure in fuel consumption of vehicles traversing the road. There is notable difference in the cut and fill cost where there is a benefit of saving about 15.37 Crore (15,37,00,000) Indian rupees (about 2.14 million US Dollars) in comparison to the traditionally designed alignment (see Table-14).



Map-27. Two most preferable optimal alignments

As we can see from Fig-30, the traditional alignment is about two times more costly in terms of cut and fills cost than the engineering alignment. In perspective of engineers, this saving of cut and fill cost alone is astounding in terms of the economic perspective and the attractiveness of the alignment.

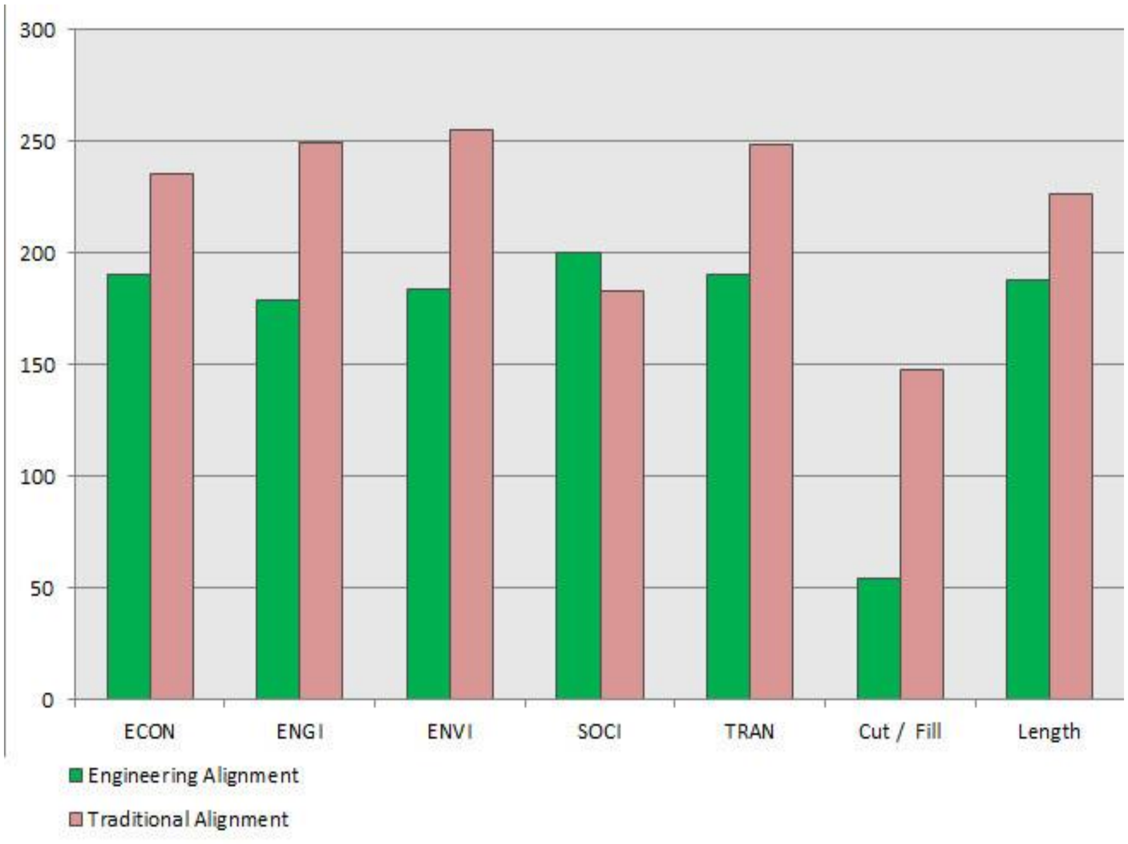


Fig-30. Standardized cost values of Engineering alignment and Traditional alignment on the different assessment criteria.

Considering all the benefits of the optimal alignment (Engineering alignment) over the traditionally designed alignment, it is conclusive that the optimized alignment is more preferable. But the final decision of this is subjective and depends on the decision maker's preference.

Chapter-5: Conclusion

5.1 Conclusions

The approach in this research provides a particular application in the design of road alignments and highlights the benefit of incorporating GIS in the design process of road alignments. The GIS process of optimizing road alignments was not used in isolation but instead used in conjunction with traditional methods. After the optimal road alignment alternatives were generated based on different perspectives (criteria groups), the methodology then transitioned into the CAD design process, thus integrating GIS and CAD. The final assessment of the alternative road alignments is then done in the GIS platform again where the assessment criteria originating from GIS and CAD are then combined in the final assessment.

The methodology not only generates optimal alignments which are superior to the traditionally designed alignment, but also provides the decision makers with alternatives to choose from and a more flexible and transparent approach where the engineers and decision makers could fine tune the methodology to the needs of a specific geography or application. The GIS alignment optimization system used is transparent and manageable which could be regulated and calibrated to user specific applications and to the preference of the stakeholders. The method for the case study is also calibrated to the specific need of the region i.e. hilly areas having complex geography and being prone to landslides and earthquake by using spatial factors and criteria considered relevant by engineers.

As the absolutely ‘optimal’ or ‘least-cost’ path virtually does not exist (Yu, Lee, & Munro-Stasiuk, 2003), the optimal alignments generated should not be considered as universally optimal alignment with absolute global optimization but as a robust indication of best route through a region considering the terrain, economy, environment, society, engineering aspects and transportationally efficient. After the generation and selection of the optimal alignment, a detailed ground survey of this alignment is recommended to check the real-world feasibility and to fine tune the curves to accommodate for minor adjustments required thereof.

5.2 Limitations of the research

The methodology is used for a particular scale of application where in this research; the origin and destination are horizontally at a distance of about 6 kilometers. The method is not tested for large scale application where the distance between the origin and destination might be smaller than 100 meters of which in that case the spatial factors and weights might be significantly different and the approach might not be applicable.

Calculation of weights and decision regarding pairwise comparisons in the different phases of the research is done by a few individuals with support from literatures which, in real applications should include a broad spectrum of decision makers involving sufficient number of engineers and stakeholders.

Weights for the least cost path analysis criteria and assessments are subjective and depend of the project and engineers involved which cannot be applied for every application. The criteria, weights and assessment factors are variable with project geography, project aims and perspective of the stakeholders involved. It is preferable that there is a universal definition of the criteria to be used as well as weights associated with each criterion.

The horizontal curve angle restriction of engineering standards cannot be incorporated in the optimal alignment search process inside GIS which is a limitation of this approach. This has to be checked and validated inside the CAD environment and accordingly adjusts the curves of the alignment.

Bridges or tunnels that are frequently used in real world applications cannot be automatically modeled in this methodology due to unavailability of requried tools in modern GIS (Yu et al., 2003) They have to be designed manually in the CAD system.

Detailed land acquisition costs data are not availabe in the form of maps and thus was not considered in the optimization and assessment procedures. This criteria is in reality one of the most important factor.

5.3 Recommendations

Use of higher accuracy digital elevation model will increase the accuracy of the vertical grade restriction as well as a more accurate cut and fill volume calculation which would increase the assessment accuracy and design.

The weight definition for the criteria in the least cost path analysis and assessment procedure should preferably be generated using statistical methods of calculating weights of criteria such as that of the work by Çevik & Topa (2003) where the statistical index weight for each factor is calculated based on statistical techniques. These weights then can be used directly in this methodology in the various LCPA and assessment phases.

The results of the GIS LCPA was imported into the CAD by first exporting the alingment corridor to shapefile format and then run the import process inside the CAD. If this process of interoperability could be improved such that there is direct link between the GIS and CAD, then the methodology would be significanly more robust.

It is preferable to apply sensitivity analysis on the different weights involved in the LCPA and assessment for dealing with subjectivity and variability in weights resulting in variability in results.

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Appendix: LCPA geo-processing model flowchart (ArcGIS)