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RESEARCH ARTICLE

MANIFESTATION OF OPTIMAL ROUTE ALIGNMENT SELECTION OF RURAL ROAD USING GIS AND LEAST COST PATH (LCP) MODEL WITH ENGINEERING AND ENVIRONMENTAL SUITABILITY PERSPECTIVE: A CASE STUDY IN NEPAL

Rakesh Sunari Magar[a], Pradeep Kumar Shrestha[a*], Prabin Kayastha[b]

[a]Pulchowk Campus, Institute of Engineering, Tribhuvan University, Lalitpur, Bagmati, Nepal
[b]Shellharbour City Council, NSW, Australia
**Corresponding Author E-mail: pradeep.shrestha@pcampus.edu.np*

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ABSTRACT

For the economic growth and sustainable development of any country, the road networks play a pivotal role. Hence, the selection of best route alignment for the road networks becomes even more significant. The Geographical Information System (GIS) integration with the Least Cost Path (LCP) model is used to determine the optimum route to address sustainable road development. In this study, Dupcheswor Rural Municipality, Nuwakot, Nepal and part of Langtang National Park was taken as a study area; and engineering and environmental parameters were selected to create a cost layer. Using the Least Cost Path (LCP) model, fifteen routes were generated in the GIS. All the generated fifteen routes were compared based on cost, and the optimum route was selected based on the least cost. The optimum route in this study was derived from the hybrid theme of engineering and environmental perspectives. This study suggests further research can be done to improve preliminary to detailed road alignment planning and design coordination by considering other factors.

KEYWORDS

GIS, Least Cost Path (LCP), Optimum route alignment, Nepal.

1. INTRODUCTION

Route alignment is one of the important tasks in any transport infrastructure development. In any transportation infrastructure development, today's proper decision of appropriate linear positioning of the road alignment determines or plays a great role on the future performance/service of land utilization/exploitation scenario for cost effective, efficient and sustainable accessibility and mobility to carry out spatial human activities such as business, recreation, education etc. (Mahini and Abedian, 2014). New routes that are proposed should be made such that they (i) consider all the dominating and sensitive costs, (ii) articulate all constraints, (iii) produce realistic alignment; (iv) satisfy the possibility of the construction, (v) satisfy the current and future demands (Singh and Singh, 2017; Acharya et al., 2017).

To find the optimum balance between transport infrastructural development and engineering and environmental concerns is challenging and high demanding in these days. Traditional methods of optimal routing are expensive, tedious, protracted and time consuming methods (Ebrahimpoor et al., 2009; Mahini and Abedian, 2014; Wahdana et al., 2019). In the traditional method, route alignment begins with the source to the destination plan. This method includes acquiring information from published maps, field surveys, aerial photos, and satellite imagery. If the proposed route encounters undefeatable constraints such as engineering, geological, environmental, socio-economic, political etc., a new route must be searched, and the data collection process should be instigated again (Humber, 2004). The Geographical Information System (GIS), remote sensing and network analysis methods can be used as efficient tools by the experts in route alignment exploring the route selection, route planning and finding the optimal route. Among different network analysis methods, the Least Cost Path (LCP) model is widely used as this method allows the users to identify the most economical way to link two locations within a cost surface, which can be calculated by combining multiple criteria, and therefore by accounting for different concerns such as engineering, geological, environmental, socio-economic, political etc. (Effat and Hassan, 2013; Sunusi et al., 2015).

Different researchers in the last three decades used the LCP model in transportation infrastructure planning such as Collischonn and Pillar (2000) used the LCP model to identify the best path based on the topography, the initial and end-points of the linear feature (canal or road) and a function relating slope, distance and cost; Yu et al. (2003) tested the LCP model on two small mountainous regions in Venango County of Pennsylvania, USA by considering spatial distances, anisotropic costs and the presence of bridges and tunnels in the routes; Atkinson et al. (2005) used the LCP model for the route of an all-weather road in Nunavur, Canada; Mahini and Abedian (2014) employed the LCP model in Golestan Province, Iran by considering the important parameters such as slope, geology, landslide, etc.; Loganathan and Elangovan (2017) produced the

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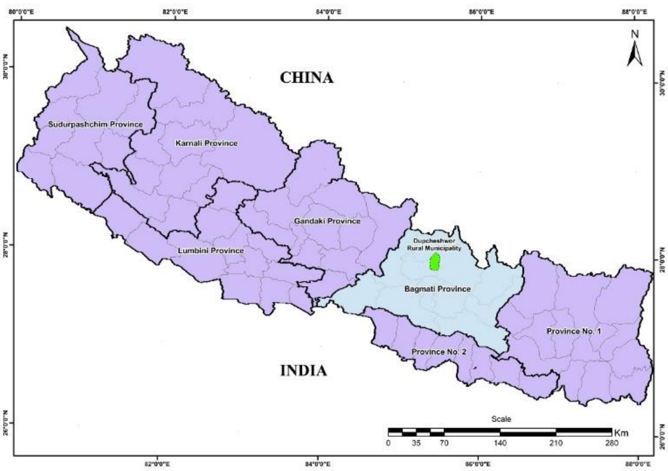
best alignment in the corridors from Perundurai to Palani, Tamil Nadu, India by using LCP; Singh and Singh (2017) used the LCP model by considering the environmental, technical, social, and economic criteria in the outer area of Allahabad City, India; Şari and Şen (2017) used the LCP model in Konya city with economic, environmentally and hybrid approaches; Mahavar et al. (2019) used the LCP model in the Dahod district of Gujarat, India by considering the topography and land use pattern; Rao et al. (2019) used the LCP model to design optimum route alignment between two locations in the Himalayan region of India; Sekulic et al. (2020) applied spatial multi-criteria evaluation and the LCP analysis to find the optimal by-pass road alignment in the Tlokweng Planning Area in Botswana.

In the developing country like Nepal, it is found that road alignment design has been carried out manually with decisive actions which takes a lot of effort and time which might not be efficient or at optimum level. Several factors which are crucial in the selection of route alignment such as socio-economic conditions, land features, topography, and environmental conditions are not holistically considered. This study documents to determine the possible optimal alignment theoretically and check field applicable appropriateness by selecting the factors affecting the road route alignment. Among several possible generated route alignments of the proposed road, this study selects the best alternative. Hence, this study aims to design optimum route alignment for developing a rural road in the Himalayan region of Nepal by considering engineering and environmental factors and selected from the several possible route alignments. The specific objectives to address the main objective of this study are to determine the factors or variables affecting road route alignment selection, to know the accumulated cost required at each grid cell level of road corridor for surpassing them which represents the suitability surface maps for road alignment and to generate the least cost path against several suitability surface maps.

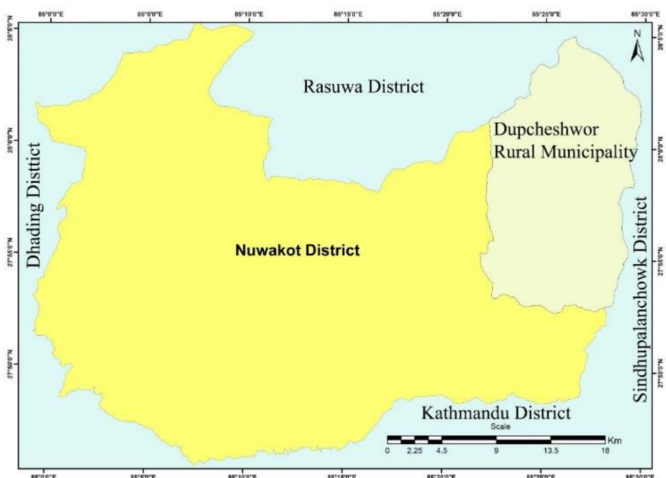
2. MATERIALS AND METHODOLOGY

2.1 Study area

The study area comprises Dupcheswor Rural Municipality and part of Langtang National Park. Dupcheswor Rural Municipality is located in the eastern part of the Nuwakot district of Nepal's Bagmati Province as shown in Figs. 1(a) and (b). This study area lies between latitudes 27° 52′ 0″ to 28° 04′ 30″ N and longitudes 85° 22′ 00″ to 85° 30′ 00″ E as shown in Fig. 2. The study area covers an area of about 220 sq km. The Dupcheswor Rural Municipality is bounded by the Langtang National Park on the north, the Helambu Rural Municipality on the east, the Tadi Rural Municipality, the Panchakanya Rural Municipality and the Rasuwa District on the west, and the Shivapuri Rural Municipality on the south (DRM, 2020). The terrain mostly consists of hills and mountains. The terrain is highly rugged with elevations ranging from 838 m to 5051 m above mean sea level (msl) as shown in Fig. 2. This rural municipality belongs to a sub-tropical climate with few upper tropical climate in the southern part and sub-alpine and alpine climate in the northern part. The annual precipitation ranges from 935 mm to 2280 mm throughout the study area. Similarly, the annual mean temperature of this study area varies from 8°C at the northern part to 22°C at the southern part. This study area also constitutes very rich in biodiversity with vegetation and cultivated area occupying most of its land cover area including some portion area of the Langtang National Park. The hilly steep areas of the rural municipality are vulnerable to landslides and sufficient all-weathered roads are unavailable.



(A) Map of Nepal



(B) Map of Nukawot

Figure 1: Map of study area showing (a) Nepal with seven provinces and (b) Nuwakot district

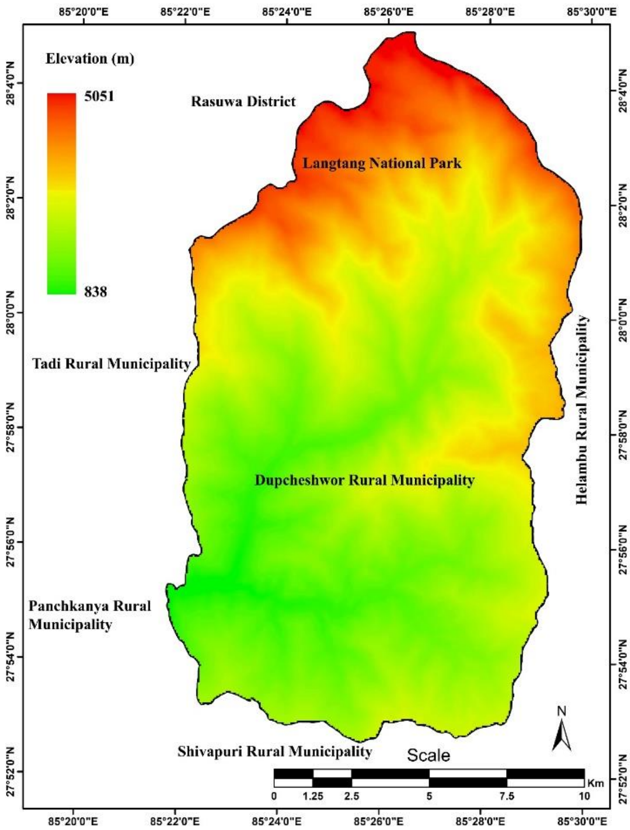


Figure 2: Digital Elevation Model (DEM) of study area

2.2 Model description

The least-cost path (LCP) tool determines least-cost path from a destination point to a source. This path is one cell wide, travels from the destination to the source, and is assured to be the cheapest route relative to the cost units defined by the original cost raster that was input into the weighted-distance tool. In GIS software, a process of determination of the optimum path on a surface analysis is carried out in following three steps.

Step 1: Generation of the cost distance – In this step, one has to calculate the cost in relation to the start point. For instance, for routing the highway, the cost matrix would be the slope. It is obvious that the higher the slope, the more costly it would be.

Step 2: Cost backlink – This analysis provides direction to cost path model. In this case, it would be the direction in which the path will follow with all the eight possible cardinal directions from one cell to the next cell.

Step 3: Cost path – The least cost path can be calculated by using the cost distance, cost backlink and destination source. It should be noted that "no data" cells are excluded from the possibility of travel.

2.3 Methodology

The methodology consists of the procedure of collecting the spatial data from several available maps, digitizing and making processable then classifying each criterion into its distinguishable/scalable categories and then employing their attribute data, analyzing (cartographic processes, standardize/reclassify, weighted overlays, LCP (Least Cost Path) etc.) and finally observing results, following the framework determined as shown in Fig. 3. The first stage includes the identification and determination of classes of different criteria considered in this study. The second stage consists of selecting the region for sample data study, which includes the collection of available spatial data of the subject study area. In the third stage, the collected data of several scales is brought down to the same scale, which is known as reclassifying or standardizing. The fourth stage includes preparation of friction surface map as per predetermined scenarios. Next, in the final stage, LCP function is used to generate several LCPs as per the corresponding scenarios, which are further compared to select the optimal one.

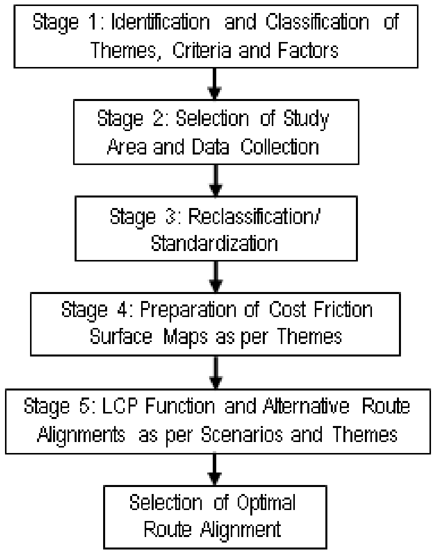


Figure 3: Framework of methodology

2.3.1 Stage 1: Identification and Classification of Themes, Factors and Criteria

Several criteria and factors could be identified and selected for the road alignment. However, the most relevant factors are slope, stream order, vulnerable area, i.e. landslide area, land cover, slope aspect, etc., as shown in Table 1. All the selected factors are obligatory in terms of route alignment. However, the priority level of these factors may differ. The differences in priority level bring out ideas of use of multi-criteria decisions in route alignment selection activities.

Table 1: Factors and decision rules

Thematic Map	Factors /Criteria	Decision rules
Engineering	1. Slope	Maximizing route length in flat and mild slopes to reduce cut and fill costs
	2. Stream order	Minimizing route length intersecting stream networks with high order to avoid the costly constructions of causeways, bridges etc.
	3. Landslide	Maximizing distance from landslide areas to avoid the risk problems lessen the expense of mitigation measures of costly structures
Environmental	1. Land use	Minimizing route length in agriculture, urban areas, archaeological sites to avoid or lessen land acquisition
	2. Slope aspect	Maximizing the south face of land mass for regular sun light/ray to avoid moistness, dampness
	3. Protected Area	Minimizing occupy of land of protected areas

2.3.2 Stage 2: Selection of Study Area and Data Collection

In this study, Dupcheswor Rural Municipality of the Nuwakot district of the Bagmati Province of Nepal was selected. Several thematic data on factors which have been identified in Stage 1 were collected from the different organizations such as remotely sensed data from USGS, topographical data, drainage maps, land cover maps, aerial photos from the Department of Survey, Government of Nepal, and satellite imageries for the different period from Google Earth.

2.3.3 Stage 3: Reclassification

Scores from the different map attributes can only be compared if the measurements units are the same. As all data have a different measurement scale, the measurement units are to be made uniform through the standardization procedure, i.e. reclassification. In this study, the linear transformation was used to convert the criteria attributes into a cost scale that ranges from 1 to 9, where the value 1 is the least cost, and 9 is the highest cost.

2.3.4 Stage 4: Preparation of Cost Friction Surface Maps as per Themes

Once the criteria maps (factors and constraints) have been developed and associated weights have been assigned to each input layer, the cost friction maps for each scenario are generated using the Weighted Overlay function as shown in Fig. 4.

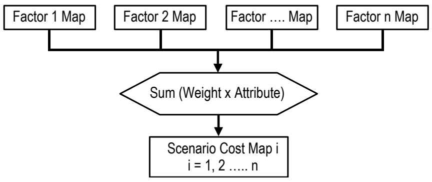


Figure 4: Schematic diagram for generating the cost maps as per various scenarios

2.3.5 Stage 5: Least Cost Path (LCP) Function and Alternative Route Alignments as per the Scenarios

Least Cost Path (LCP) functions with the source and destination points on one hand and resistive friction surface cost map, on the other hand, as shown in Fig. 5. Cost distance function uses two tools, i.e. cost distance and cost back link as per the source point position and resistive friction surface cost map. It is to be noted that the cost backlink is used to retrace the least costly route from the destination to the source over the cost distance surface. The next step is the cost path function, which gives the shortest or least cost path according to the destination/ terminating point against the cost distance generated as output from the cost distance function.

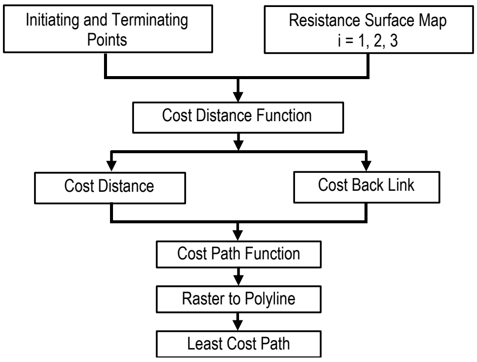


Figure 5: Least Cost Path (LCP) function

3. Results and Discussions

3.1 Creation of each cost-criteria map and calculation of the relative weights for the cost factors

Six cost criteria maps based on engineering and environmental themes were generated (Figs. 6a- 6f) using ESRI ArcGIS 10. Descriptions of each criterion maps are as follows:

a) Slope: The slope map (Fig. 6a) is of the study area was prepared from the Digital Elevation Model (DEM) retrieved from the USGS. The sub-classes of slope along with coverage area and rating values are given in Table 2.

b) Stream order: The stream order (Fig. 6b) in the study area was prepared from the drainage map provided by the Department of Survey, Government of Nepal. The stream order was prepared on the basis of the Strahler method (Strahler, 1957). The sub-classes of stream order along with coverage area and rating values are given in Table 2.

c) Landslide: The landslide (Fig. 6c) in the study area was prepared from the aerial photos, land cover maps from the Department of Survey, Government of Nepal and Google earth images taken on different periods. The sub-classes of landslides, along with coverage area and rating values are given in Table 2.

d) Land use: The land use (Fig. 6d) in the study area was produced from the land cover/ land use map provided by the Department of Survey, Government of Nepal which was updated based on the Google earth images. The sub-classes of land use, along with coverage area and rating values, are given in Table 2.

e) Slope aspect: The slope aspect (Fig. 6e) is of the study area was prepared from the Digital Elevation Model (DEM) retrieved from the USGS. The sub-classes of slope aspect, along with coverage area and rating values are given in Table 2.

f) Protected area: The protected area (Fig. 6f) in the study area was produced from the land cover map provided by the Department of Survey, Government of Nepal. The sub-classes of the protected area along with coverage area and rating values are given in Table 2.

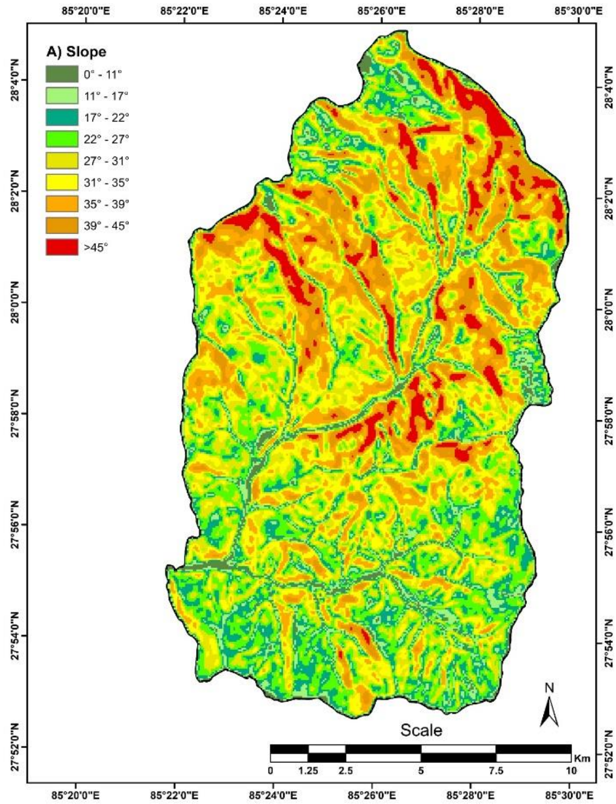


Figure 6: (a) Slope map of study area

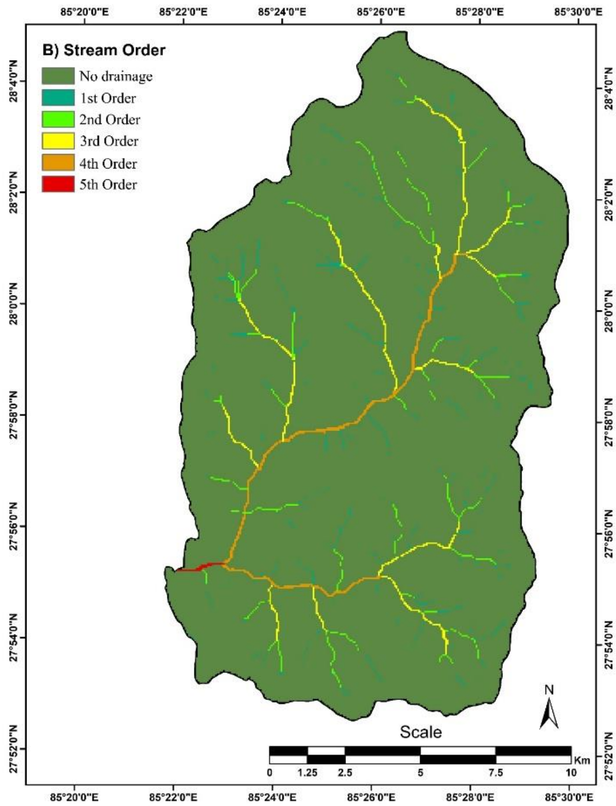


Figure 6: (b) Stream order map of study area

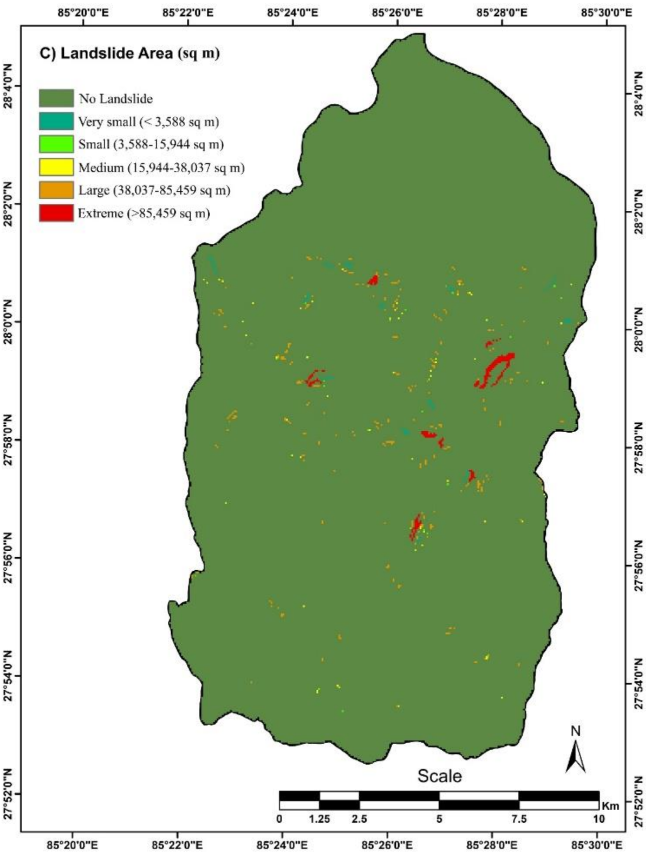


Figure 6: (c) Landslide occurrence map of study area

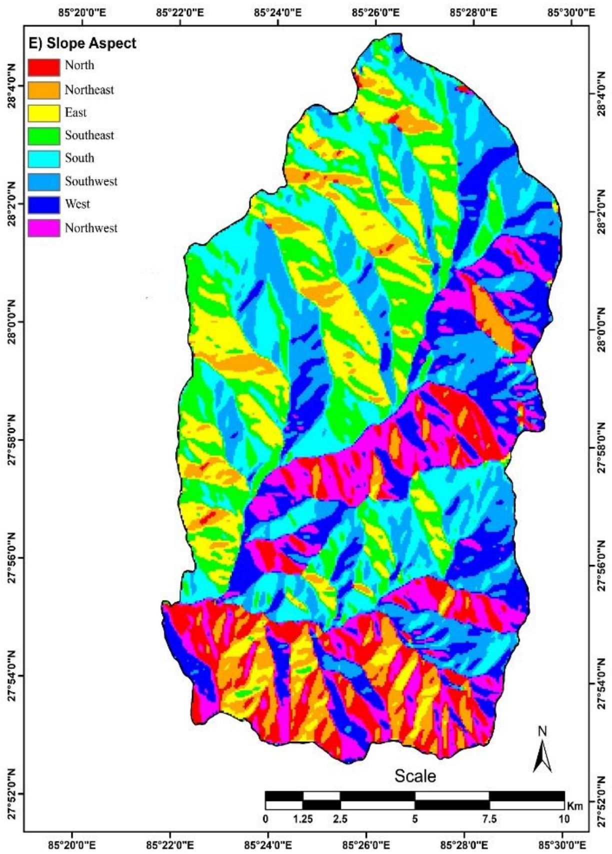


Figure 6: (e) Slope aspect map of study area

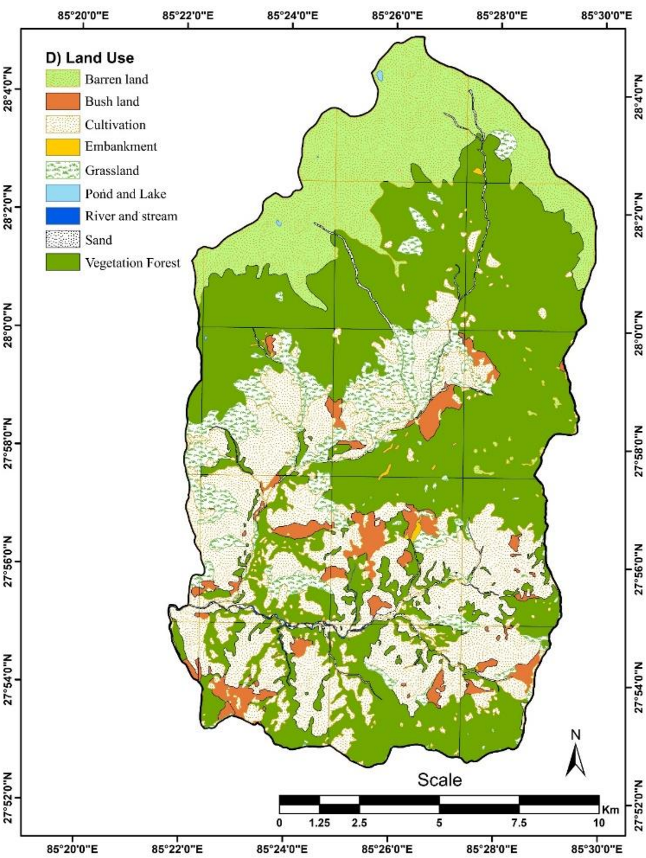


Figure 6: (d) Land use map of study area

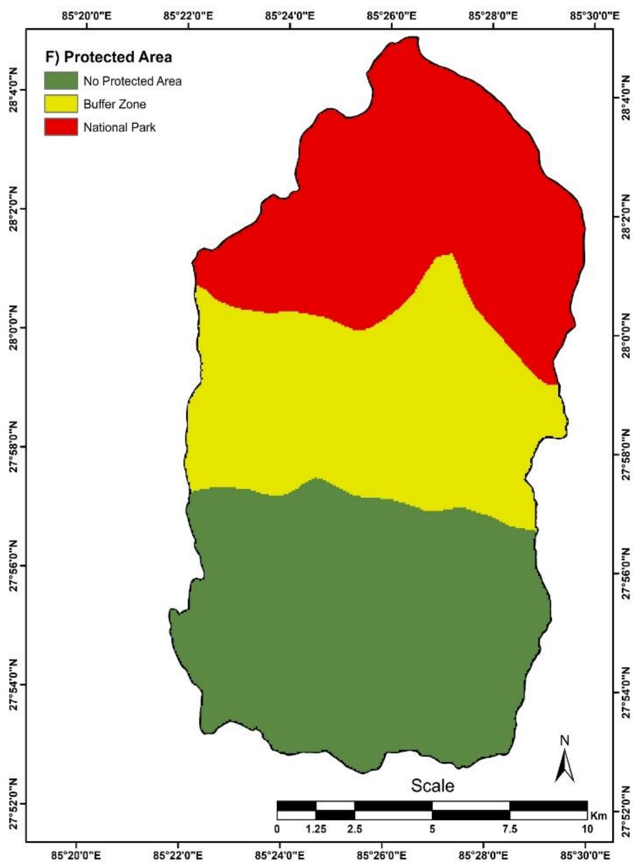


Figure 6: (f) Protected area map of study area

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Table 2: Rating values of different sub-classes of cost factor maps

Factor/ Sub-classes	Description	Coverage %	Cost Rating
Engineering Theme			
(A) Slope			
1. 0^0-11^0	Very Low costly	1.83%	1
2. 11^0-17^0	Low to very low costly	4.92%	2
3. 17^0-22^0	Low costly	8.36%	3
4. 22^0-27^0	Low to moderate costly	12.84%	4
5. 27^0-31^0	Moderate costly	16.91%	5
6. 31^0-35^0	Moderate to high costly	19.83%	6
7. 35^0-39^0	High costly	18.13%	7
8. 39^0-45^0	High to very high costly	11.94%	8
9. >45^0	Very high costly	5.23%	9
(B) Stream Order			
1. No Drainage	Very low costly	96.28%	1
2. 1st order	Low costly	0.90%	3
3. 2nd order	Low to moderate costly	0.95%	4
4. 3rd order	Moderate to high costly	1.05%	6
5. 4th order	High to very high costly	0.76 %	8
6. 5th order	Very high costly	0.05%	9
(C) Landslide area			
1. No Landslide	Very low risk or costly	99.00%	1
2. Very small (<3,588 m^2)	Low risk or costly	0.02%	3
3. Small (3,588m^2 to 15,944m^2)	Low to moderate risk or costly	0.38%	4
4. Medium (15,944m^2 to 38,037 m^2)	Moderate to high risk or costly	0.10%	6
5. Large (38,037 m^2 to 85,459m^2)	High to very high risk or costly	0.07%	8
6. Extreme (>85,459 m^2)	Very high risk or costly	0.30%	9
Environmental Theme			
(D) Land use			
1. Barren Land	Very Low costly	15.50%	1
2. Bush Land	Low to very low costly	3.85%	2
3. Grass Land	Low to very low costly	8.26%	2
4. Vegetation Forest	Low costly	46.03%	3
5. Cultivation Land	Low to moderate costly	24.81%	4
6. Sand	High costly	1.15%	7
7. River and stream	High costly	0.18%	7
8. Pond and lake	High to very high costly	0.03%	8
9. Embankment	Very high costly	0.18%	9
(E) Slope aspect			
1. South	Favourable	15.02%	1
2. South East	Moderately favourable	14.59%	3
3. South West	Moderately favourable	16.25%	3
4. East	Less favourable	12.36%	5
5. West	Less favourable	13.40%	5
6. North East	Unfavourable	8.74%	7
7. North West	Unfavourable	11.02%	7
8. North	Very unfavourable	8.61%	9
(F) Protected area			
1. No Protected Area	No restriction	38.86%	1
2. Buffer Zone	Moderate restriction	30.06%	5
3. National Park	High Restriction	31.08%	9

3.2 Creation of the cost factor maps

In this study, fifteen cost factor maps were created based on fifteen scenarios, as shown in Eqs. 1 to 15.

1. Engineering Thematic Cost Value - Slope only scenario = 100%*Slope (1)
2. Engineering Thematic Cost Value - Stream order only scenario = 100%*Stream order (2)
3. Engineering Thematic Cost Value - Landslides only scenario = 100% Landslides (3)
4. Engineering Thematic Cost Value - Combination of Slope and Stream Order scenario = 50% *Slope + 50% * Stream Order (4)
5. Engineering Thematic Cost Value - Combination of Stream Order and Landslides scenario = 50% * Stream Order + 50% *Landslides (5)
6. Engineering Thematic Cost Value - Combination of Landslides and Slope scenario = 50% *Landslides + 50% *Slope (6)
7. Engineering Thematic Cost Value - Combination of Slope, Stream Order and Landslides scenario = 33.33% *Slope + 33.33% * Stream Order + 33.33%* Landslide (7)
8. Environmental Thematic Cost Value – Land use only scenario = 100%* Land use (8)
9. Environmental Thematic Cost Value – Slope aspect only scenario = 100%* Slope aspect (9)
10. Environmental Thematic Cost Value - Protected area only scenario = 100%* Protected area (10)
11. Environmental Thematic Cost Value - Combination of Land use and Slope aspect scenario = 50% * Land use + 50% * Slope aspect (11)
12. Environmental Thematic Cost Value - Combination of Slope aspect and Protected Area scenario = 50% * Slope aspect + 50% * Protected area (12)
13. Environmental Thematic Cost Value - Combination of Protected area and Land use scenario = 50% * Protected Area + 50% * Land use (13)
14. Environmental Thematic Cost Value - Combination of Land use, Slope aspect and Protected area scenario = 33.33% * Land use + 33.33% * Slope aspect + 33.33% * Protected Area (14)
15. Hybrid Thematic Cost Value - Combination of Slope, Stream Order, Landslides, Land use, Slope aspect and Protected area scenario = 50% * Combination of Slope, Stream Order and Landslides scenario + 50% * Combination of Land use, Slope aspect and Protected area scenario (15)

3.3 Designing the fifteen routes using the Least Cost Path (LCP)

The cost path algorithm of ESRI ArcGIS determines the Least Cost Path (LCP) model. This model was used for the aforementioned fifteen scenarios. The fifteen least cost routes (Fig. 7) were generated from the source to destination calculated by the function as per the input cost distance, backlink raster dataset and destination position. The LCP model uses the cost-weighted distance and the direction surfaces for an area to determine a cost-effective route between source and destination (Singh and Singh, 2017). In the LCP model, the eight neighbors of a cell are evaluated, and the path moves to the cell with the smallest accumulated value. The process would repeat itself until the source and destination are connected (Xu and Lathrop, 1994).

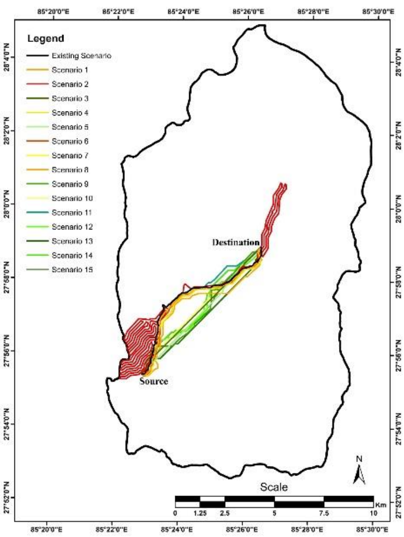

Figure 7: 15 scenarios of least cost paths with the existing scenario

3.4 Comparison of fifteen routes to select the best alignment

The fifteen route alignments were converted to linear features, and a 50 m buffer was created on each side of the centre-line of the route alignment. The area covered by buffered polygons of each alternative route concerning each sub-classes of criteria is derived and analyzed in MS Excel. The rating cost values of sub-classes of criteria were multiplied with the number of count of cells to derive the cost. The relative costs for fifteen scenarios with the route lengths are summarized in Table 3, and calculated relative costs are compared. Except for the Scenario 2 i.e. based on environmental theme - stream order only, all other scenarios are comparable in their distance and relative cost. In this study, Scenario 15 (hybrid theme) shows the least cost and Scenario 2 (environmental theme - stream order only) shows the highest cost. These results depict that the best route alignment in the study area is the one which considers the factors such as slope, stream order, landslide, land use, slope aspect and protected area. Hence, the route alignment derived from Scenario 15 based on the hybrid theme is the optimal path for this study.

Table 3: Summary of 15 least cost path scenarios

S. No.	Scenario	Cost	Rank	Length
0	Existing Road	16,974.00	10th	10.96
1	Slope only	18,018.00	13th	10.03
2	Stream order only	99,552.00	16th	62.92
3	Landslides only	16,724.00	8th	8.87
4	Slope and stream order - Equal combo	17,630.00	12th	10.30
5	Stream order and landslides - Equal combo	15,195.00	2nd	8.93
6	Landslides and slope - Equal combo	18,741.00	15th	10.13
7	Slope, stream order and landslides - Equal combo	17,223.00	11th	10.24
8	Land use only	18,469.00	14th	10.65
9	Slope aspect only	15,682.00	6th	9.58
10	Protected area only	16,793.00	9th	8.87
11	Land use and slope aspect - Equal combo	15,418.00	3rd	9.67
12	Slope aspect and protected area - Equal combo	15,499.00	4th	9.51
13	Protected area and land use - Equal combo	15,862.00	7th	9.05
14	Land use, slope aspect and protected area - Equal Combo	15,591.00	5th	9.53
15	All six factors - Equal combo	15,101.00	1st	9.18

4. Conclusions

Identifying the best route alignment in transport infrastructure management is one of the cumbersome tasks as it requires detail analysis of the enormously large quantity of data and different criteria, parameters and factors depending upon the size of the project.

This study presents the combination of Geographic Information System (GIS) and Least Cost Path (LCP) model for different scenarios in identifying the various route alignment alternatives. Hence, by avoiding steep to the very steep slope, moderate to the high order of stream, instabilities such as landslides, land use such as sand, water bodies, cliff, slope aspect orientating in the north and protected area such as National Park, the planned route should be technically feasible and environmentally sound. In this study, fifteen alternative routes are generated using different scenarios. Among fifteen routes, fourteen routes are comparable in their distance and relative cost. Only one route which is based on environmental theme i.e. stream order only shows the highest cost due to the length of road. In this study area, the existing road is about 11 km long, while the LCP model's best route is about 9.2 km long. Hence, the LCP model applied in these routes were quite successful in addressing the issues as mentioned above. As this model is simple and flexible, similar approaches can be used in different parts of rural areas of Nepal for the selection of the best route alignment to link different rural areas via road.

The study results can be used to select the best route alignment in the study area by the concerned authorities, planners and engineers. This study provides valuable information so that attention can be paid to the steep to the very steep slope, high order stream, the occurrence of landslides, different land use types, slope aspect and protected areas for any kind of road development works. In this study, the LCP model has been applied by considering the engineering and environmental aspects of the road. The results would have been different if the social, economic and political aspects were considered. This study recommends further studies on the determination of impacts of socio-economic and political parameters depending upon data and information availability in the study area. Similarly, the other techniques such as unequal overlay weightage, Analytic Hierarchy Process (AHP), fuzzy logic, genetic algorithm techniques etc. can also be applied for this study's improvisation.

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