Arab J Geosci (2017) 10: 294
DOI 10.1007/s12517-017-3076-z

ORIGINAL PAPER

Multi-criteria GIS modeling for optimum route alignment planning in outer region of Allahabad City, India

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Received: 12 September 2016 / Accepted: 22 June 2017 / Published online: 8 July 2017

Abstract A route alignment planning has various stages. At different stages, multi-criteria decision analysis (MCDA) is required. This paper integrates geographical information system (GIS) and MCDA for designing the optimum route alignment. A GIS-based model using the multi-criteria decision analysis for finding the optimum route alignment to design major road from a source to a destination within two locations is proposed. Three different levels of analysis were performed in this study such as criteria map analysis, surface cost analysis, and least-cost path analysis. The optimum route has the least cost and satisfies other environmental, technical, social, and economic criteria. The proposed model is implemented to design optimum route alignment between two locations in the outer area of Allahabad City, India. Four route alignments are created, and one of the best routes is chosen.

Keywords Route alignment planning · Geographic information system (GIS) · Weighted overlay · Multi-criteria decision analysis · Decision support system

Introduction

Route alignment is an important task in urban infrastructure development. Building new route or expanding existing route requires immense public spending and has dramatic effects on the natural and human environments through which they pass. This important public investment naturally generates strong and conflicting interests among different stakeholder groups, making the design of route alignments a great challenge. For the development of cost minimization model, a number of costs are considered for designing route alignment by the planners, of which the most significant are the right-way and earthwork costs. A good route alignment optimization model should have characteristics like (a) consider all dominating and sensitive costs, (b) formulate all constraints, (c) yield realistic alignment, (d) be able to handle alignments with backward bends, (e) simultaneously optimize a horizontal and vertical alignment, (f) find global and near-global solution, (g) have an efficient solution algorithm, (h) have a continuous search space, (i) consider intersection, interchange bridge, and tunnel cost, (j) automatically avoid inaccessible region, and (k) compatible with the GIS. Highway route alignment optimization techniques have been developed with the integration of genetic algorithm optimization techniques and GIS (Jong et al. 2000; Jong and Schonfeld 2003; Jha and Schonfeld 2003, 2004; Kim et al. 2004, 2005; Cheng and Lee 2006; Jha and Kim 2006; Jha and Maji 2007; Jha et al. 2007; Goktepe et al. 2009; Maji and Jha 2011; Kang et al. 2012; Yang et al. 2014). A criteria-based decision support system is developed for the evaluation of cost-effective 3D highway alignments by Jha (2003).

GIS and multi-criteria decision analysis (MCDA) are used to support, analyze, modify, and reevaluate the existing spatial information within land use planning activities (Carver 1991). The integration of GIS and MCDA (Jankowski 1995; Malczewski 2006) provides a way to select and evaluate various alternate solutions to the decision maker. For the development of a new route alignment, we need to satisfy various criteria for the available area or surface. At the same time, cost minimization is also a big challenge for the route planners.

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Many alternative routes can be designed using the multi-criteria decision analysis (Roh et al. 2008; Effat and Hassan 2013; Yakar and Celik 2014). This can be defined as a process of choices among the available alternatives. Route alignment design problem can be affected by soil condition, socioeconomic factors, and environmental impacts (Jong and Schonfeld 2003) of a particular region.

The purpose of this study is to design optimum route alignment for developing a major road between two locations by considering social, economical, technical, and environmental factors. The designed alternative routes connect Naini and Jhunsi regions of Allahabad district, Uttar Pradesh, India. These alternative routes can be the backbone for controlling traffic in Allahabad City, and it will be helpful to reduce the pollution and accidental cases and will also reduce travel time of commercial vehicles which enter during the peak hours of morning and evening.

Study area

Allahabad is one of the prime cities of India. It embraces a large area and is an inland cape surrounded by the rivers Ganga and Yamuna from three sides with only one side connected to the mainland. The position of Allahabad City is at the confluence of the Ganga (Ganges) and Yamuna rivers. It is situated in the southern part of the state, at 25° 20′ N to 25° 33′ N, latitude, and 81° 42′ E to 81° 55′ E, longitude. Allahabad town has a population of 1,042,229 as per the 2001 census. It is listed as the 32nd most densely inhabited city in India. Allahabad has an area of about 65 km^2 and is 98 m/340 ft above sea level.

Allahabad comes under the northern center region (NCR) of Indian railways and is connected to major Indian cities. The national highway (NH 2) passes through the center of the city, and the national waterway, the longest waterway in India, connects Allahabad and Haldia. The nearest airport is Bamrauli airport. In Fig. 1, the rectangular box shows the political boundary of the study area.

Pre-processing of spatial datasets using GIS

Preparation of spatial datasets is the fundamental part in route alignment designing. The proposed model is based on GIS and MCDA. In our methodology, route alignment is evaluated by applying different GIS analytical procedures, including reclassification operation, buffer analysis, conversion operation, and weighted overlay method based on multi-criteria analysis. For the development of this model, the following datasets are prepared.

(a) Topographic map (63G/15) of Allahabad, scale 1:50,000 (survey of India), published in 2012, is used to extract the physical feature of the study area, and it is also used to select the locations of source and destination where the alignment is to be created.

(b) LISS-III satellite images acquired during 2012, with 23.5-m spatial resolution, were taken from the website of the National Remote Sensing Center (NRSC), India. Land use/land cover (LULC) analysis was performed by supervised classification method using the maximum likelihood classifier. The analysis was carried out using ERDAS IMAGINE 10 software.

(c) ASTER DEM high-resolution satellite image in 14 different bands of electromagnetic spectrum acquired in 2009, with 30-m spatial resolution. It is used to find the slope of the study area.

Spatial datasets were created in ESRI ArcGIS10 software and projected to the Universal Transverse Marketer (UTM) projection, zone 44N. After these spatial datasets were prepared, including all necessary geometric and thematic editing of the original datasets, a topology was created. All vector layers were then converted into raster format with cell size of 23.5 m, and all the spatial information is processed in ESRI ArcGIS10 software. The spatial datasets like the LISS-III satellite image and ASTER DEM data are shown in Figs. 2 and 3.

Cost criteria map preparation

Generation of cost criteria maps has been an important task in this study. A number of cost criteria maps, viz, physical features, land use/land cover, and slope, have been generated using remote sensing GIS techniques.

Cost criteria map for physical features

Four types of digital data of physical criteria for the study area are extracted from the topographical map. These physical criteria are taken as existing road network, rail network, drainage network, and protected areas (religious places). The cost maps for the physical features are defined as a raster map, where the value at each pixel gives the estimated relative cost of passing through the pixel (Fig. 4).

Cost criteria maps for slope factor

Slope is a very crucial factor in road designing; it may a play very important role such as earthwork volume, alignments of road network, and construction cost. Slope is the important and almost unique criterion for geometric design factors. For each cell, the slope tool calculates the maximum rate of

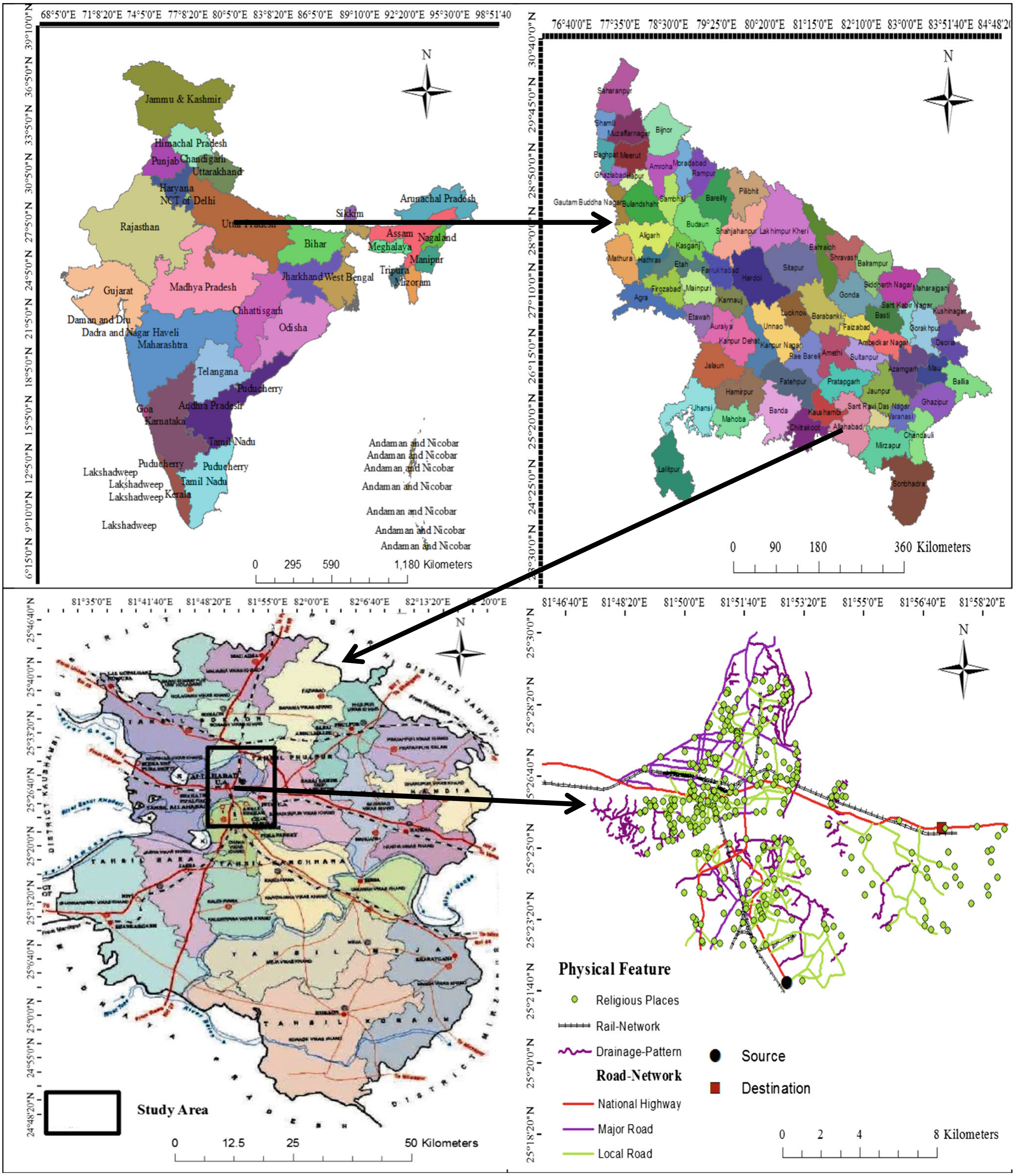

Fig. 1 Study area

change in value from that cell to its neighbors. Basically, the maximum change in elevation over the distance between the cell and its eight neighbors identifies the steepest downhill percentage from the cell. Conceptually, the tool fits a plane to the z values of a 3×3 cell neighborhood around the processing or center cell.

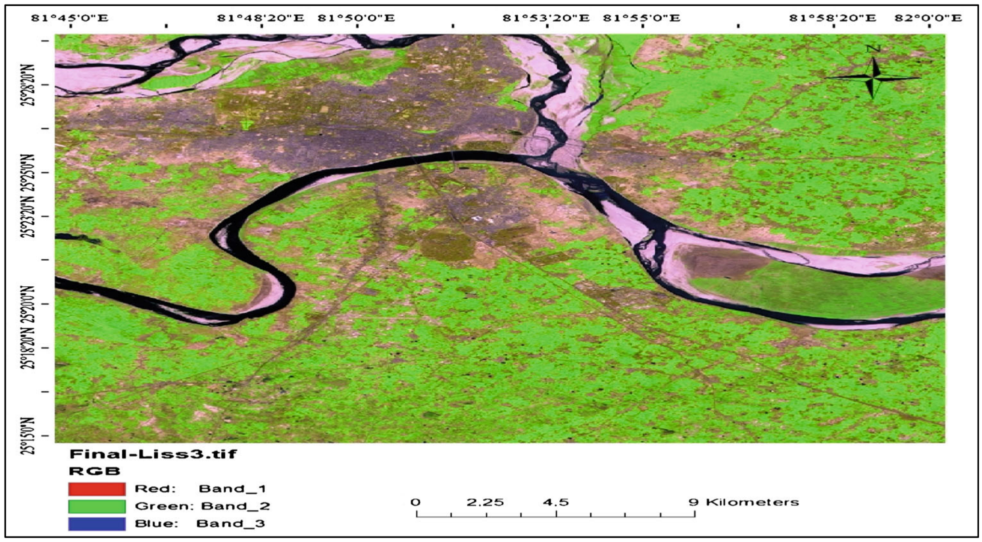

Fig. 2 LISS-III satellite image

The slope algorithm

The rates of change of the surface in the horizontal (dz/dx) and vertical (dz/dy) directions from the center cell determine the slope using the following formula (ESRI ArcGis Help Library 2010).

$$rise/\mathrm{run} = \sqrt{\left[\left(\frac{dz}{dx}\right)^2 + \left(\frac{dz}{dy}\right)^2\right]} \tag{1}$$

The output slope raster can be calculated in two types of units: degrees or percent (percent rise). The percent rise can be better understood as

$$Percent\ rise = \left(rise/\mathrm{run}\right) \times 100$$

The slope criterion in an Indian Road Congress (IRC) specification should be acceptable in the range 0 to 10% for a flat area, 10 to 25% for a rolling area, 25 to 60% for a mountainous area, and more than 60% for the steepest area. In the

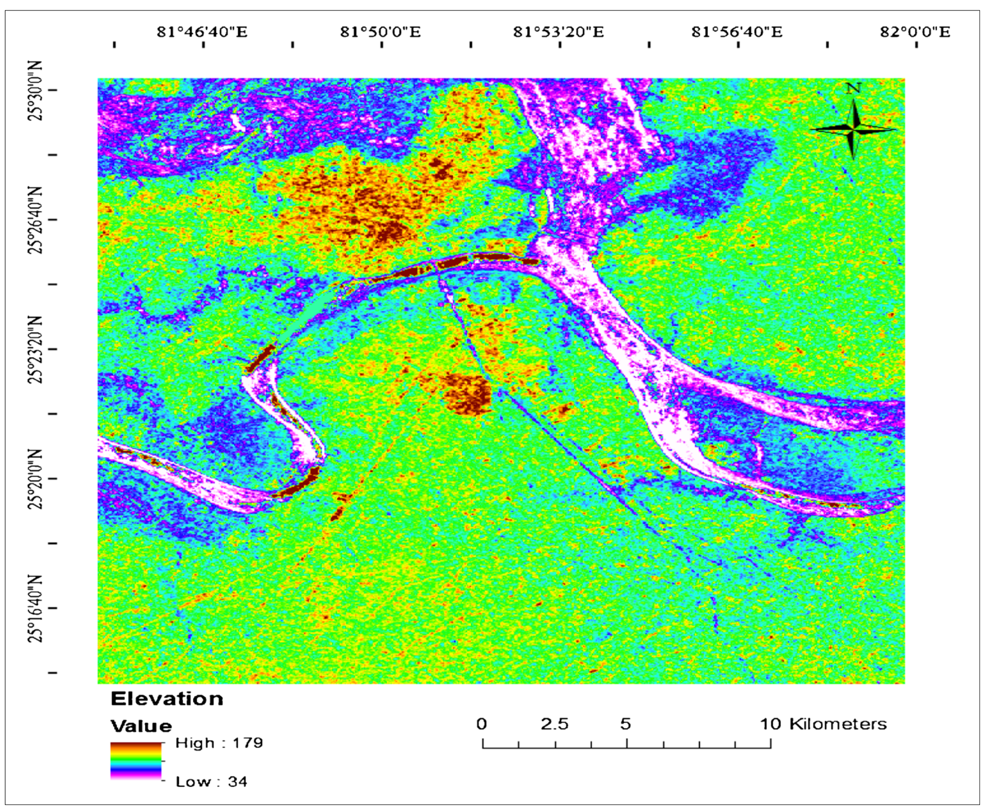

Fig. 3 ASTER DEM data

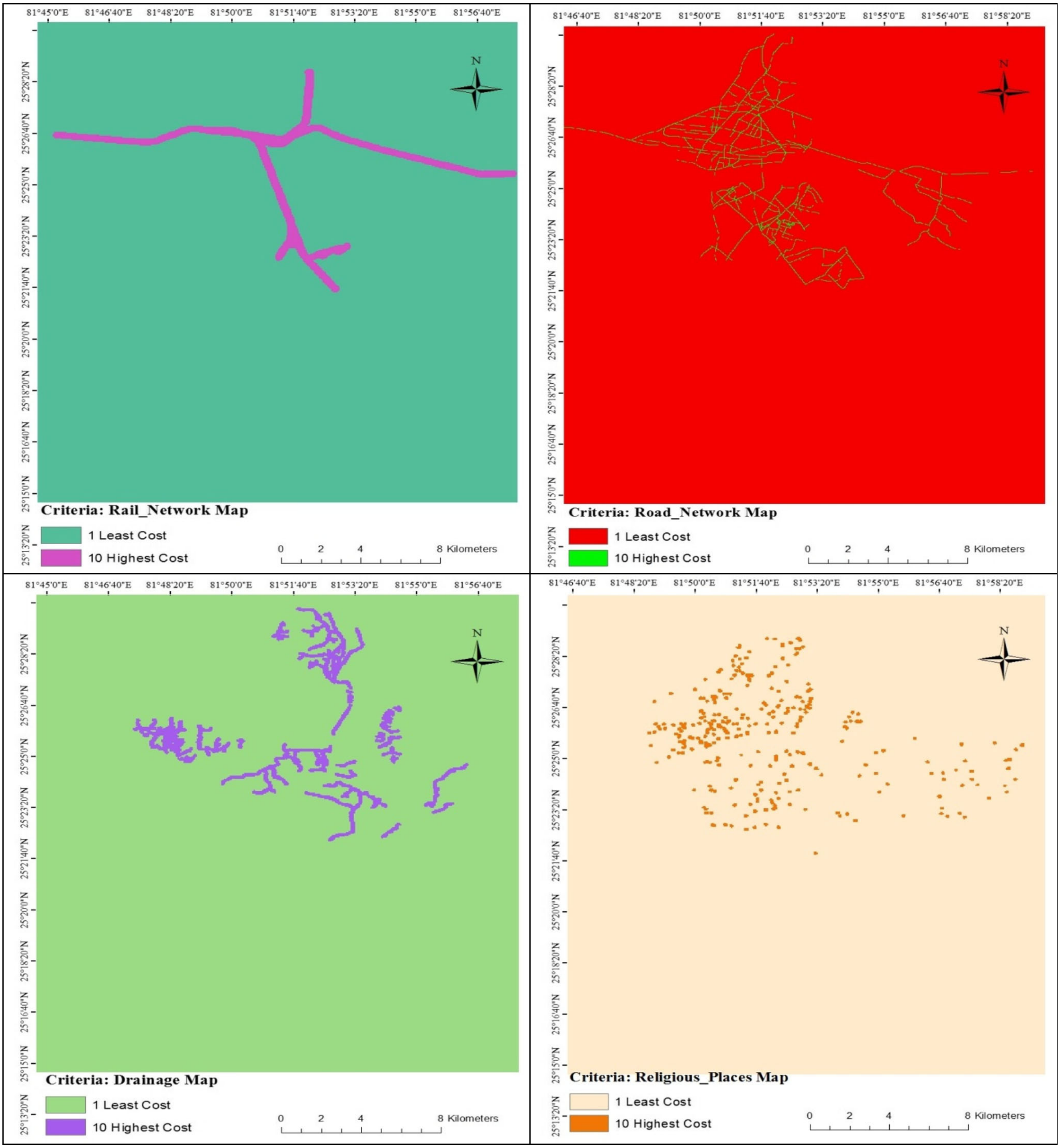

Fig. 4 Cost criteria maps of physical features

present study, slope is classified according to the cost such as a flat surface is of least cost and steeper surface is of highest cost. Since flatter surface allows for more direct, faster, and easier traveling, the slope should be minimized as much as possible. From Fig. 5, it can be observed that the corresponding slope ranges from 0 to 60%.

Cost criteria maps for land use/land cover

Information of land use/land cover is required to analyze the impacts of a proposed route on the surrounding environment, residents, existing infrastructures, etc. In land use/land cover analysis, remote sensing data of LISS-III were used.

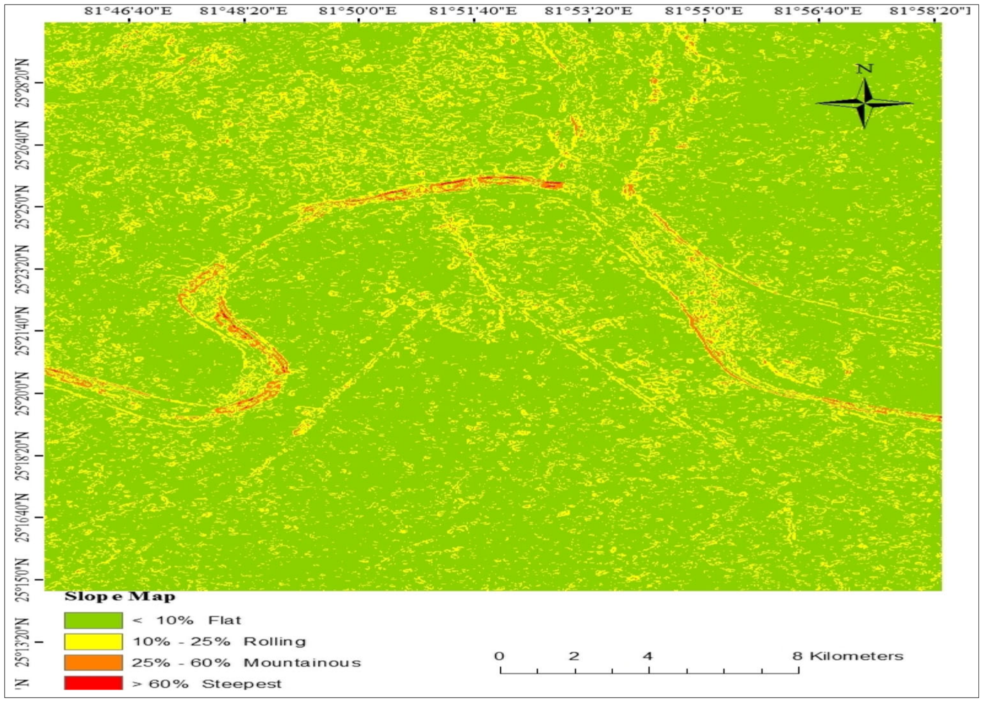

Fig. 5 Slope map of study area

Supervised classification method using the maximum likelihood classifier was performed for land classification. The satellite image is classified for acquiring the available information of land use/land cover. The classified map is given in Fig. 6.

The various land use classes, delineated from the LISS-III image, such as agriculture land, water body, rivers, trees, urban area, and sandbank, are used for analyzing the study area and for creating the least-cost route alignment.

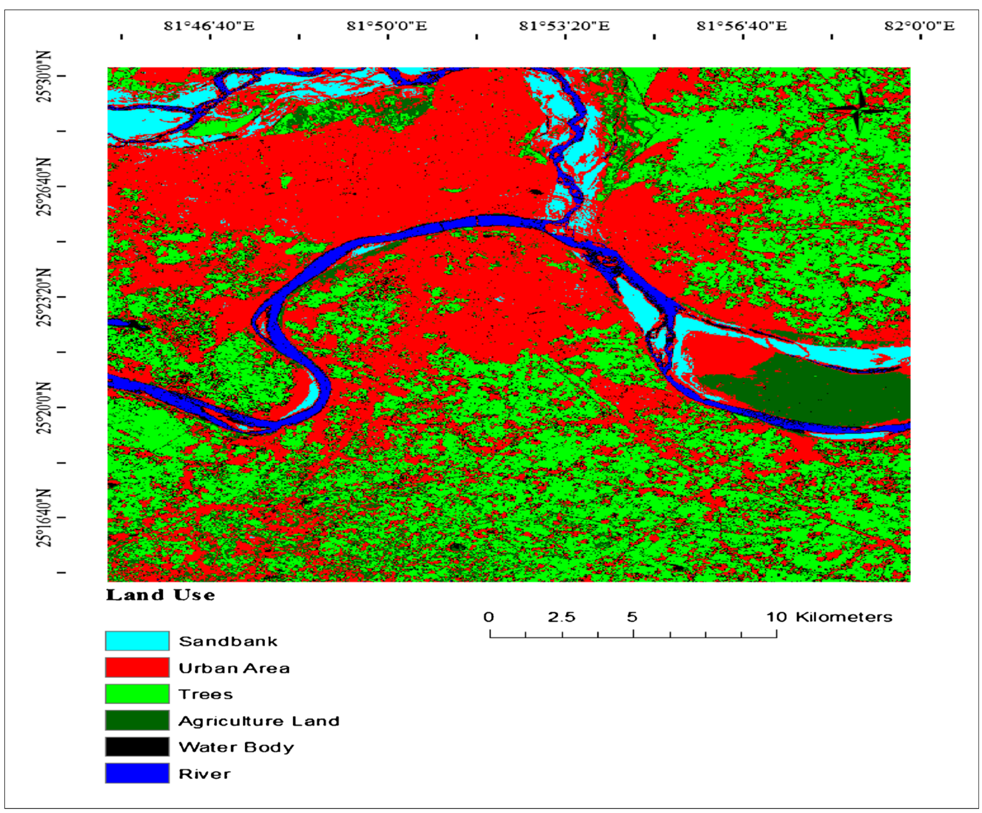

Fig. 6 Land use/land cover classified map

From Fig. 6, all criteria map layers (agriculture land, water body, rivers, trees, urban area, and sandbank) have been extracted with the help of the attribute table of land use/land cover map in ArcGIS. These maps are used to escape the existing infrastructures which have a high negative impact on the study area after designing the route alignment. The maps are summarized in Fig. 7.

Evaluation of criteria map attributes can only be compared if the measurement units are the same. Because the evaluation of the criteria had their own characteristics and extent and each datum of criteria had its own dimension and distribution, it was difficult to directly compare them or include them together in an operational system. The process of setting the relative importance of each criterion is known as the standardization of criteria (Feizizadeh and Blaschke 2013). Standardization of the attributes was performed for each of the cost maps in ESRI Spatial Analyst reclassification module. In this process, scales of 0 to 1, 0 to 10, or 0 to 100 are normally used for criteria standardization. Linear transformation is used to transform the criteria attributes into a cost scale that ranges from 1 to 10 where the value 1 is the least cost and 10 is the highest cost (Effat and Hassan 2013).

Methodology

The task of selecting a particular route alignment for a highway as an alternative is complex and challenging. MCDA is applicable to solving complex and challenging problems that are characterized as a choice among alternatives (Malczewski, 1999a, b, 2004, 2006). The MCDA provides a rich collection of techniques and procedures for structuring decision problems and designing, evaluating, and prioritizing alternative decisions (Carver 1991). A factor is a criterion that enhances or detracts from the suitability of a specific alternative for the

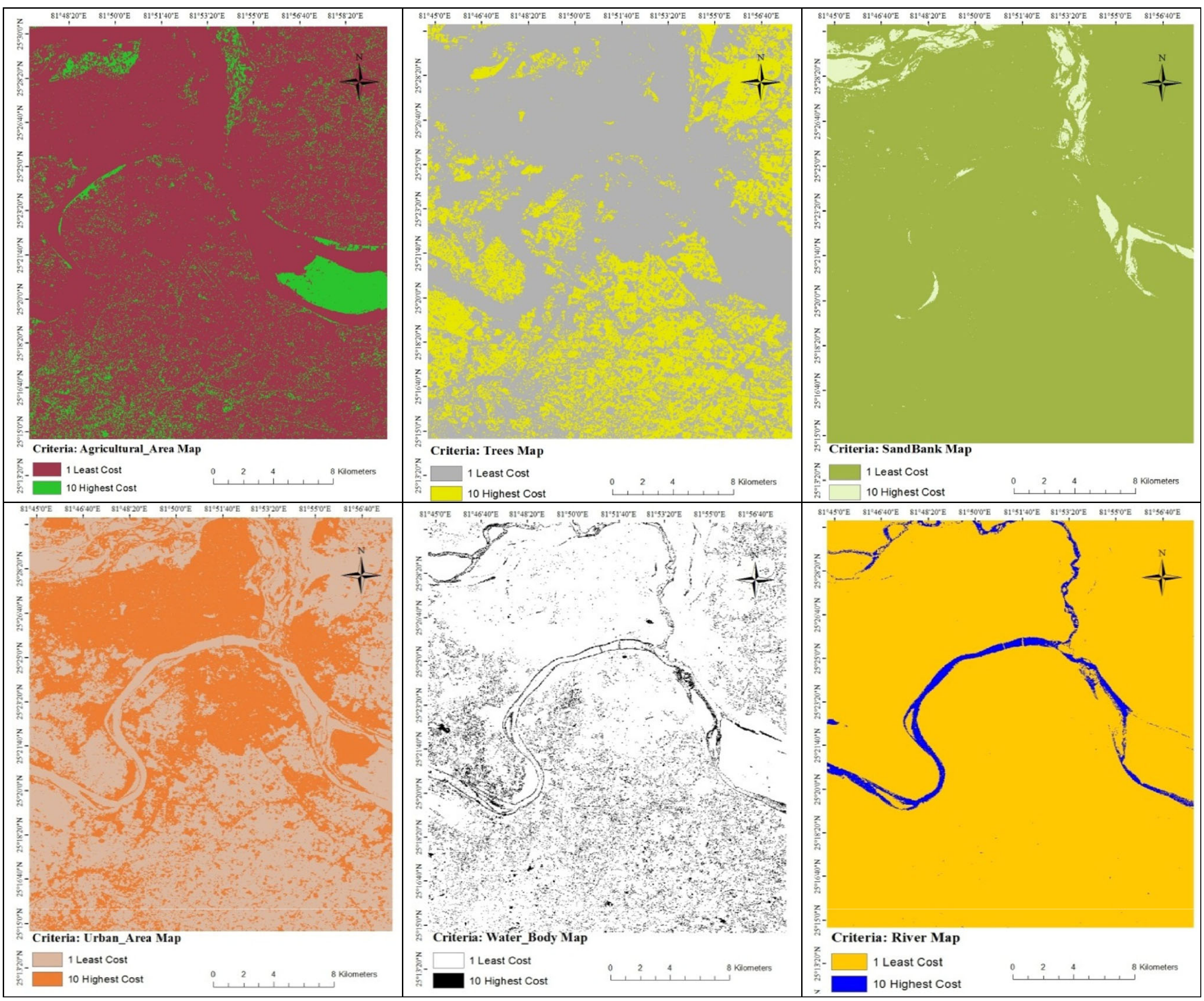

Fig. 7 Cost criteria maps of land use and land cover

activity under consideration (Jankowski and Richard 1994). MCDA problems are consisting of six components:

- Set the goal/define the problem.
- Determine the criteria (factors/constraints).
- Standardize the factors/criterion scores.
- Determine the weight of each factor.
- Aggregate the criteria.
- Validate/verify the result.

For the development and evaluation of any route alignment, social, economic, and environmental impacts are necessary to be studied. In this study, we assessed the effect of all these factors on the existing criteria and infrastructure (Eastman et al. 1995). The evaluation of social effects includes the effects on local urban area along with the consideration of existing road network. From the economic viewpoints, the proposed road alignment should economically be reasonable with respect to the land cost, maintenance and management costs, and benefit on the investment in these road plans. The environmental impacts are assessed on existing forest land and water bodies. The technical factor is evaluated on the slope of the surface area. The flow chart is developed for the proposed method, and it can be summarized in the following steps:

Step 1. Pre-processing of all datasets.
Step 2. Generate cost criteria map from spatial datasets.
Step 3. Create relative surface cost map from cost criteria maps of spatial datasets.
Step 4. Cost distance analysis from each relative surface cost map.
Step 5. Least-cost path analysis for relative surface cost map.
Step 6. Generate the cost path alignment.
Step 7. Convert cost path alignment into polyline features.
Step 8. Buffer analysis on polyline features.
Step 9. Calculate all required information.
Step 10. Selection of optimum alignment on the basis of the information obtained in step 9 (Figs. 8, 9, and 10).

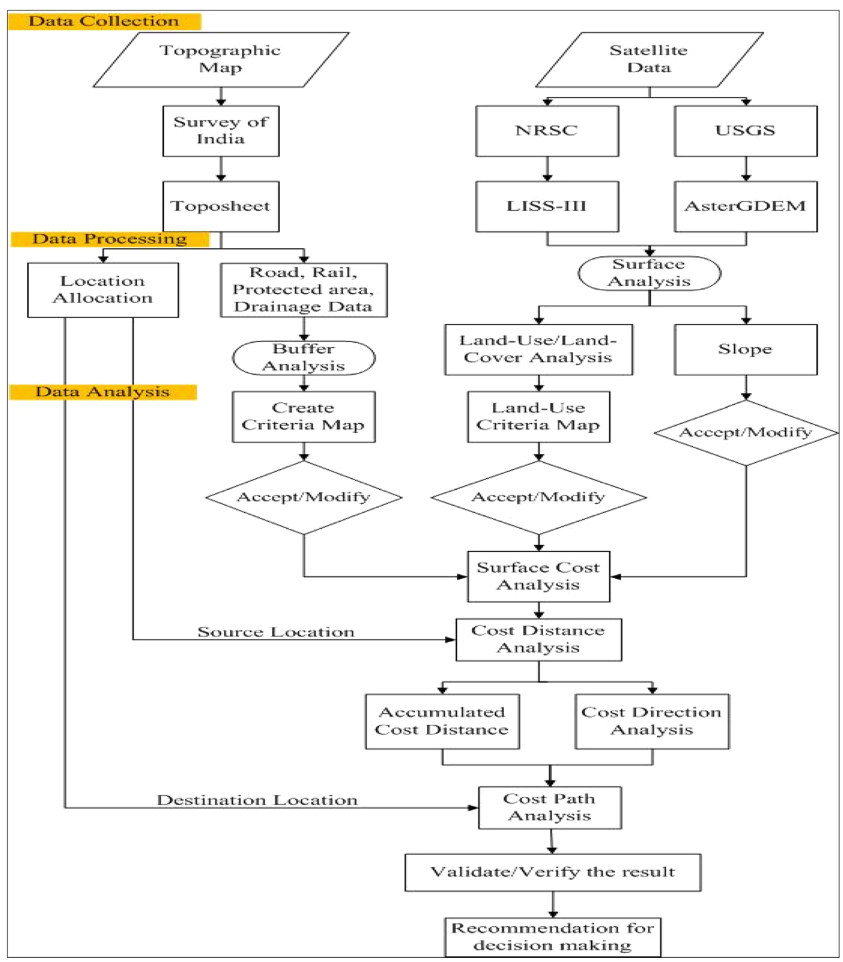

Fig. 8 Flow chart of methodology

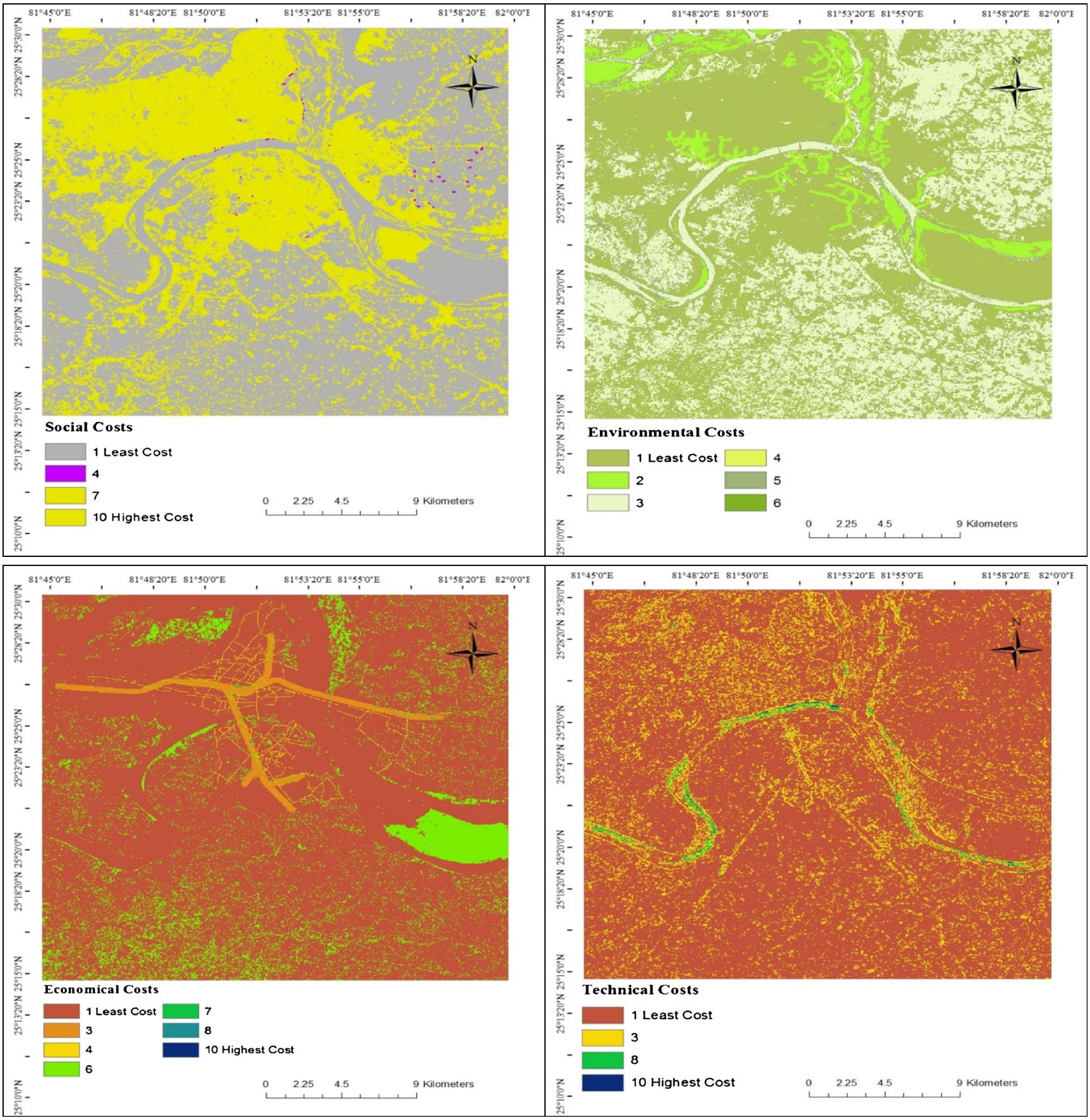

Fig. 9 Relative surface cost maps of four different perspectives

Surface cost analysis

For the evaluation of these impacts, cost analysis is required. To create a surface cost map, all the criteria maps (physical criteria, land use and land cover, and slope) are reclassified into a common measurement scale such as 1 to 10, with 10 being the highest cost and 1 being the least cost. This reclassification operation is performed in ArcGIS (ESRI) with the reclassified module of Spatial Analysis tool.

The surface cost analysis is performed by the weighted overlay analysis (WOA) tool of ArcGIS (ESRI). This is one of the most common approaches for decision analysis of multi-criteria problems. Since the input criteria layers are in different numbering systems with different ranges, to combine them in a single analysis, each raster is assigned a percentage weight. The cell values are multiplied by their percentage weights, and the results are added together to create the output surface cost raster map (Voogd 1983). In the surface cost raster

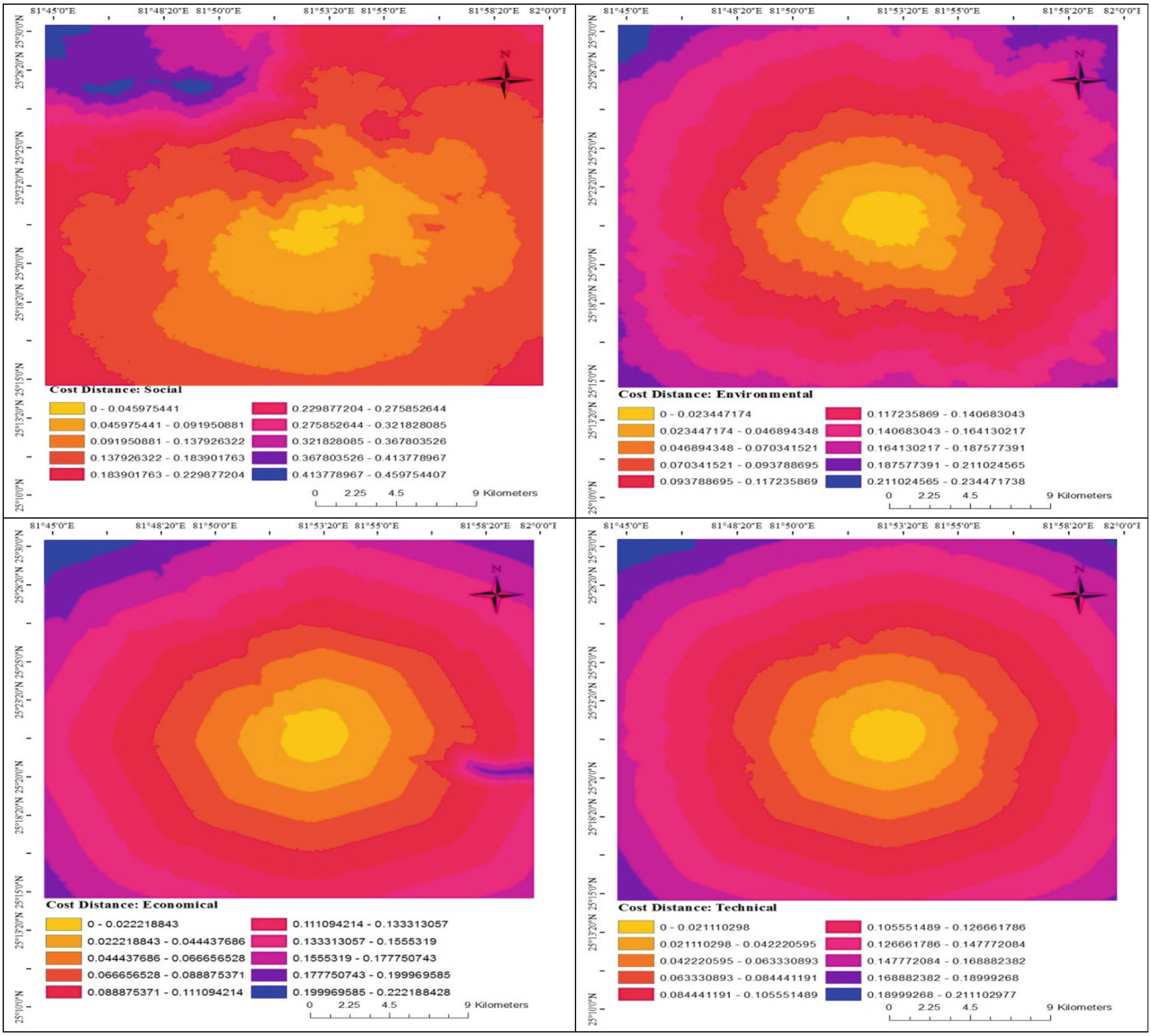

Fig. 10 Cost distance maps

map, the relative cost of each cell is identified by traveling each cell. The relative surface costs for surface cost map are calculated with the given formula (Malczewski 2006) involving social cost, environmental cost, economical cost, and technical cost.

$$\textit{Relative surface}\ \text{cost} = \sum_{i=1}^{n} w_i x_i, \qquad \textit{with} \ \sum_{i=1}^{n} w_i = 100\% \quad (2)$$

where,

w_i Weighted value corresponding to each criterion
x_i Evaluation scale of cost values of each classified criterion.

Using Eq. (2), the following four different perspectives of relative surface cost maps are created.

$$\textit{Social cost} = [\textit{cost of urban areas}] \times 70\% + [\textit{cost of religious places}] \times 30\%$$

$$\textit{Environmental cost} = [\textit{cost of water bodies}] \times 40\% + [\textit{cost of trees}] \times 20\% + [\textit{cost of river}] \times 20\% + [\textit{cost of drainages}] \times 10\% + [\textit{cost of sandbanks}] \times 10\%$$

$$Economical\ cost = [cost\ of\ agriculture\ lands] \times 50\% + [cost\ of\ roads] \times 30\% + [cost\ of\ rail\ networks] \times 20\%$$

$$Technical\ cost = [cost\ of\ slopes] \times 100\%$$

Cost distance analysis

The cost distance algorithm is applied over relative surface cost maps. This process generates an output raster in which each cell is allocated the accumulative cost to the closest source cell (Atkinson et al. 2005; Collischonn and Pilar 2000; Douglas 1994). The working functionality of cost distance algorithm is based on graph theory techniques. Each cell is regarded as a node, and each node is connected to its neighboring nodes by multiple links. Every link has impedance accompanying it. The impedance is resultant from the costs allied with the cells at each end of the link (from the surface cost) and from the direction of movement through the cells. The cost allocated to each cell denotes the cost per unit distance for moving through the cell. Multiplication of cell size and cost value is the final value per cell. To calculate the distance cost through each cell, the following formula is used (Yu et al. 2003).

$$C_i = A_i \times R_i \quad (3)$$

C_i Cost per cell
A_i Assigned cost of the cell
R_i Resolution of the cell

Cost direction analysis

The algorithm for computing the back link raster assigns a code to each cell (Xu and Lathrop 1994). The code is a sequence of integers from 0 to 8. The value 0 is used to represent the source locations, since they have essentially already reached the goal (the source). The values 1 through 8 encode the direction in a clockwise manner starting from the right. This process is done for all cells in the output back link raster, producing output rasters, the direction to travel from every cell in the cost distance raster back to the source (Fig. 11).

Least-cost path analysis

The cost path (ESRI) algorithm determines the least-cost path from a destination point to a source point (Effat and Hassan 2013; Xu and Lathrop 1994; Yu et al. 2003; Yakar and Celik 2014). This algorithm uses two rasters derived from a cost distance algorithm: the accumulated cost distance raster and the back link raster (Douglas 1994). The least-cost path analysis uses the cost-weighted distance and the direction surfaces for an area to determine a cost-effective route between a source and a destination location. In the least-cost path analysis, the eight neighbors of a cell are evaluated and the path moves to the cell with the smallest accumulated value (Xu and Lathrop 1994). The process repeats itself until the source and destination are connected. The complete path represents the smallest sum of cell values between the two points (Figs. 12 and 13).

Application of the least-cost path model

The GIS-based MCDA optimization procedure is used to simultaneously minimize the alignment cost and impacted area of social, economic, environmental, and technical preserved land. The initial cost criteria maps are selected within the study area, and the source and destination points are specified. In this case, the 2D coordinate (81.881, 25.365) is used as the source point and (81.952, 25.425) is used as the destination point of the designed route alignments. The alignments are proposed and planned to design a typical six-lane road with 60-m right of way (Kadiyali 2011). The least-cost path route alignments are converted to polyline features with raster dataset to polyline feature conversion tools in ArcGIS (ESRI) for the proposed alignment. This polyline feature is useful to create a (60 m) buffer analysis around the alignments. This analysis is used to calculate the criteria values along the alignments as shown in Table 1.

Optimal conditions for route alignments

Major road bypass route determination should be located and designed with consideration of optimum time, cost, accessibility, and productivity, whereby optimum cost is the most important factor. The factors which affect the road construction cost are elevation, slope, land use, and existing road network, rail, drainage, and restricted/protected information. The factors that cause high or low expropriation cost by affecting the real country estate value are topography and land use. To locate the optimal horizontal alignment of the suggested bypass, the subsequent data conditions were considered. The selected route should be the minimum affected resources and least-cost alternative. To achieve this, the following factors were further taken into consideration:

(i) The elevation differences through the route should be kept as minimum as possible. The elevations for the study area ranged from 34 to 179 m (Fig. 3).
(ii) The slope should also be kept as minimum as possible, with the suitable slope being between 0 and 25%. The slope of the study area had a maximum of 60%; thus, slopes of up to 25% were considered suitable.

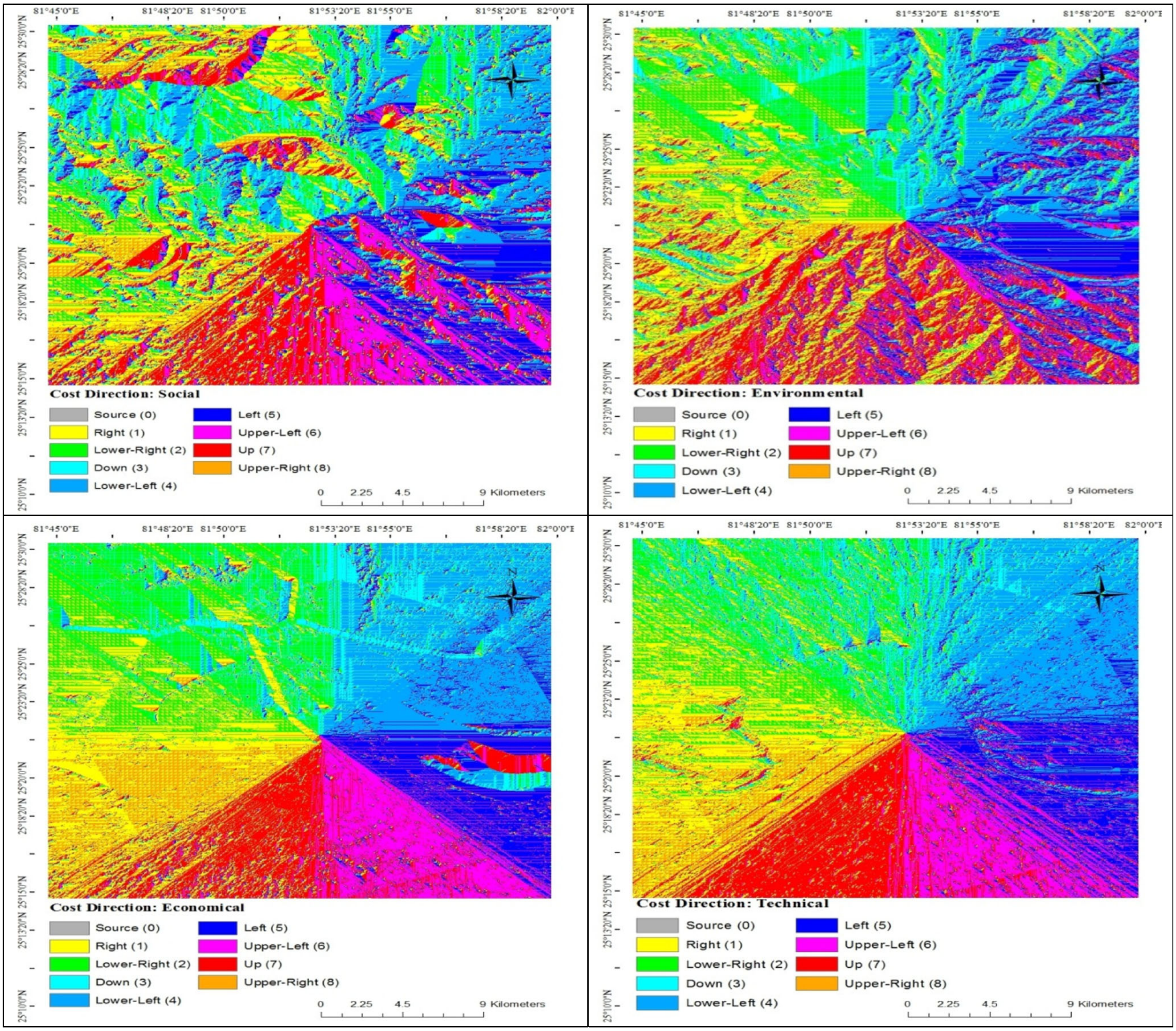

Fig. 11 Cost direction map

(iii) The route should not pass within urban areas in order to reduce the property damage and compensation costs.

(iv) The route should not pass over natural drainage pattern to avoid construction of culverts and possible road destructions caused by overflows in the event of flooding.

(v) The route should not intersect exiting roads to avoid intersection points and accidental cases.

(vi) The route should not pass into the restricted/protected places to avoid delay of construction road and resettlement cost.

Results and discussions

The land use areas, maximum slope, length of the alignments, rail, road, drainage, protected places, and cost path are all important criteria in selecting the optimum route alignments, and this is done by the usual mathematical process in route alignment planning and engineering. The area of land use and length of alignments can be computed with field calculator and calculate geometry tool in ArcGIS software. The values of rail, road, drainage, and protected intersection through overlay techniques on each relevant criteria map were computed. The weight influence of each criteria layer has different values; it totally depends on the decision-making person. Here, we decide that the area of land use, length of alignments, and cost path have higher influence than others. On the basis of the weights, the influence of each alignment by usual mathematical process is calculated. According to Table 1, the

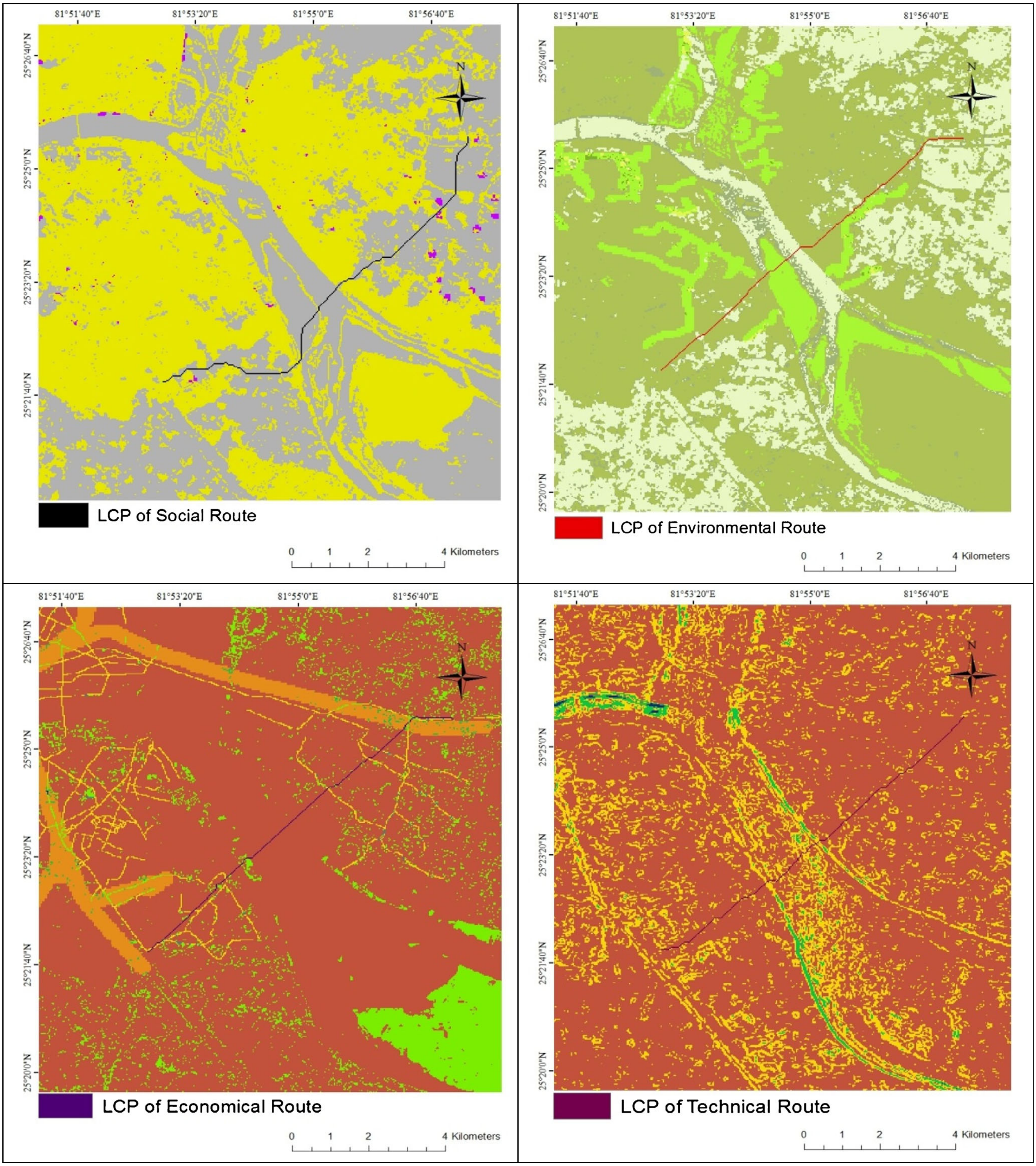

Fig. 12 Least-cost path route alignments from different cost surfaces

alignment which is near to sum of the weights is the optimum alignment. Alignment 4 is near to sum of the weights, so we can decide that alignment 4 is the optimum alignment. Table 1 explains these different computed criteria for each suggested alignment and the results.

Validation and discussion

Table 1 shows that the fourth suggested alignment represents the optimum alignment with a success percent of 95.67%. We checked the ground reality and verified the result for some criteria like number of drainage area intersections, number

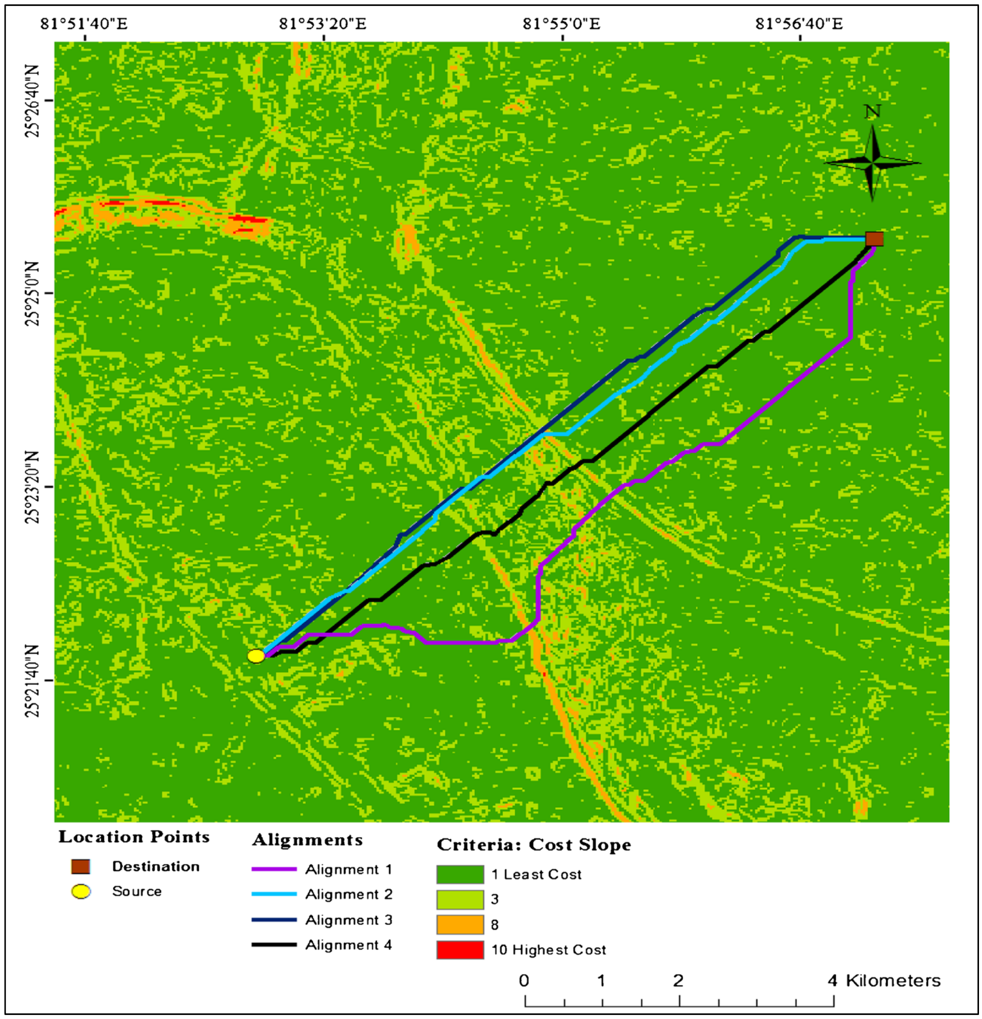

Fig. 13 Representation of all proposed alignments on cost surface map of slope

Table 1 Route selection criteria

Multi-criteria		Maximum priority weights for each criterion (%)	First suggested alignment		Second suggested alignment		Third suggested alignment		Fourth suggested alignment	
			Criteria values	%	Criteria values	%	Criteria values	%	Criteria values	%
Area of land use (ha)	River		6		4		4		5	
	Water body		13		7		7		8	
	Sandbank		16		8		7		9	
	Urban area		23		87		89		71	
	Trees		69		7		12		25	
	Agriculture land		9		7		7		4	
	Total area	20	136.00	17.64	120.00	20	126.00	19	122.00	19.67
Max. slope (%)		8	4.36	5	4.08	5.52	3.25	6.94	2.82	8
Length of alignments (km)		20	12	16.67	10	20	10	20	10	20
No. of rail network intersections		8	1	8	1	8	1	8	1	8
No. of road intersections		8	6	5.33	5	6.40	4	8	8	4
No. of drainage pattern intersections		8	Nil	8	Nil	8	Nil	8	1	8
No. of protected area intersections		8	Nil	8	Nil	8	2	4	Nil	8
Sum of cost path		20	47.14	12.00	30.45	18.60	29.06	19.50	28.32	20
Sum		100		80.64		94.52		92.44		95.67

of road intersections, number of protected area intersections, and number of rail track intersections. In land use areas, no agriculture land and trees are affected within the survey areas. We found the same results as shown in Table 1. Figure 14 shows some intersectional points we have collected through GPS and exported the ESRI file format data with the help of a path finder software.

There are four suggested alignments; alignment 4 is the optimum route alignment. The following discussions are made about the alignment 4:

1. The land use values of each alignment are different. Alignment 4, which has minimum land use values, determines the land use cost and the degree of compensation for any acquired land.
2. Alignment 4 contains minimum percentage slope value of maximum slope criteria layer among three alignments, so we can observe that less percentage slope is of less cost.
3. If the minimum length of alignment is considered, construction and maintenance cost of alignment is minimum.
4. Every alignment has constructed one overpass of bridge because of one rail network intersect.
5. In alignment 4, one culvert will be constructed, because one drainage area is intersecting it.
6. Alignment 4 contains the maximum number of road intersection, so we can observe that the possibility of accidental cases would be maximum than the other three alignments.
7. Alignment 4 contains nil value of protected area intersections, so resettlement cost is removed.
8. In least-cost path analysis, the attribute table of cost path contains the minimum value in alignment 4, so we can estimate that the construction cost of alignment 4 can be considered the minimum than other three alignments.

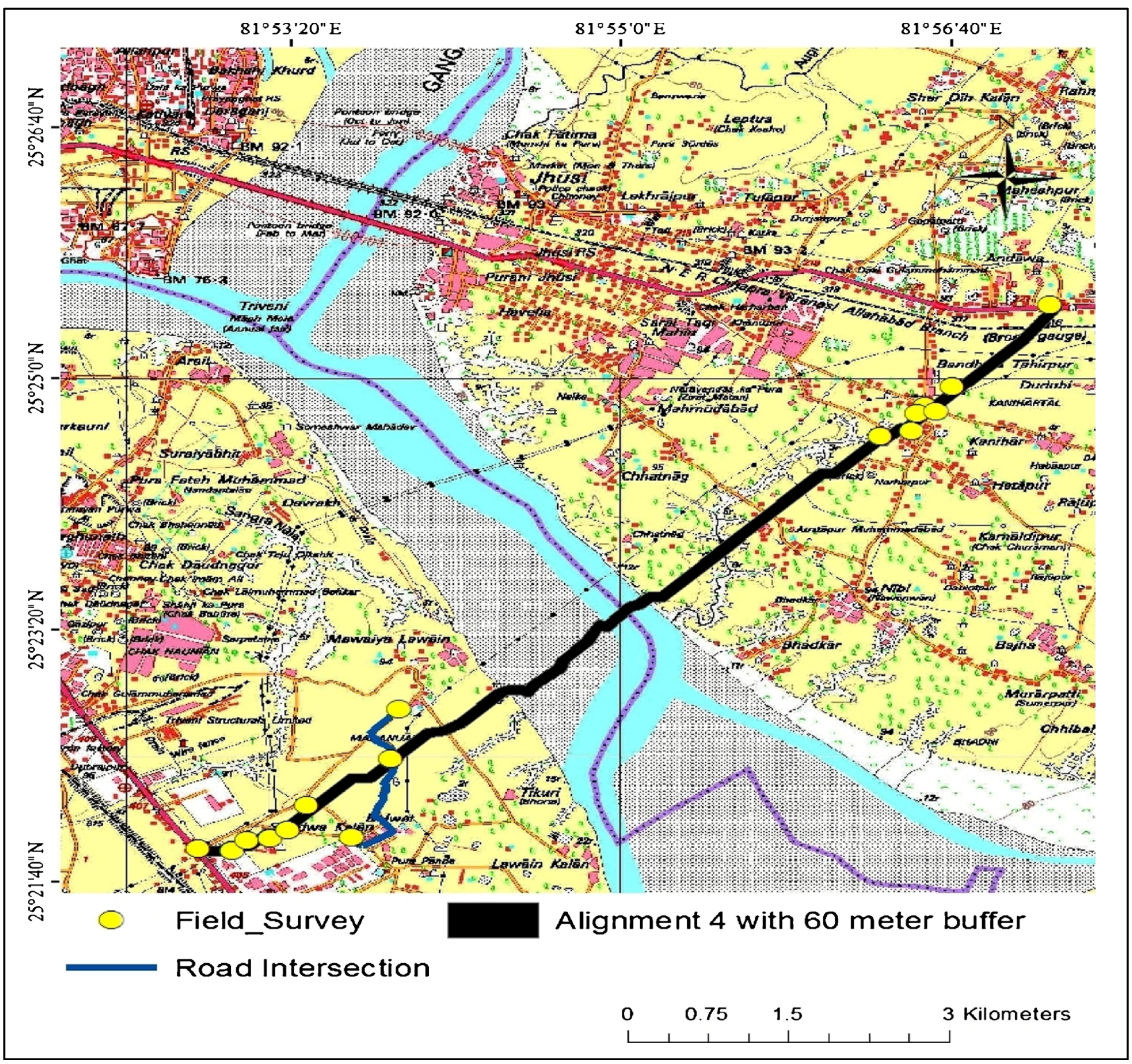

Fig. 14 Field survey of some intersection locations

Conclusions

1. This study presents the combination of GIS and multi-criteria evaluation process in identifying various route alignment alternatives that would link Naini and Jhunsi in Allahabad City. The least-cost path (LCP) analysis modules applied for the mentioned route paths were quite successful in avoiding drainage, religious places, high slopes, minimum road intersection, and minimum land use areas, thus satisfying the optimum condition, the objective of this study, within the given criteria and data.
2. The method which is based on LCP analysis (LCPA) has been applied in considering the social, environmental, economical, and technical aspects of the road with the integration of GIS and MCDA approaches. LCPA is successfully implemented from the source point to the destination point.
3. The study recommends further studies on the determination of impacts of varied and additional physical, socio-economic, and political parameters on route alignment location using the LCP approach.
4. It is concluded that combination of GIS and LCP model is useful in solving practical problems, because vagueness and imprecision can be effectively handled in this model. If the criteria and factors are clearly defined, the present model can be adopted for use in the linear engineering structure industry as a decision tool for optimal location.

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