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Road network designing in a forested watershed using network connectivity indices

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Abstract: Designing and constructing a road network is one of the most critical steps of the development process in managing natural resources. The current research is going to investigate the application of network connectivity indices to the analysis of road networks in the forested watershed. First, the road network suitability map (RNSM) was created to emphasize the technical and physiographic criteria and integrated management scenarios using a weighted linear combination (WLC) and analytic network process (ANP). Subsequently, three road network alternatives (RNA) were assigned based on the priorities in the RNSM. In order to try to determine the appropriate alternative, the network connectivity of the designed alternatives looked into the forest and non-forest land uses, as well as the whole study area, using the values of alpha (α), beta (β), gamma (γ), eta (η), network density (*ND*) and detour indices (*DI*) in the context of the graph theory. Results show that the road density of the RNA2 variant (11.56 $m \cdot ha^{-1}$) is shorter than the other alternatives and the existing road network (ERN). In addition, dealing with the whole study area, we realized that the index values which are related to the number two reflect a better status than the other alternatives of alpha, beta, gamma, eta and detour index, in which they were identified to be 0.44, 1.34, 1.16, 0.45 and 0.83, respectively. RNA2 is chosen as the appropriate road network according to the network connectivity, technical and physiographical criteria, along with integrated management scenarios. Further control measures and field surveys are recommended to achieve more relevant results.

Keywords: graph theory; indexes; network alternative; road network suitability map (RNAM)

In a mountainous forested watershed, forest roads appear to be the leading infrastructure in order to implement the forest management processes, including timber harvesting, tree thinning and planting, along with wildlife and wildfire managing, protecting, and maintaining the forest area (Zhao et al. 2021). Forest roads could significantly alter the landscape of mountainous watersheds (Ramos-Scharrón et al. 2022). Despite all the detrimental effects which forest roads might have on the forest

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and other catchment ecosystems, their design and construction need to connect the land uses and access to the forest area (Akay et al. 2020).

The network consists of nodes or vertices linked together by edges where vertices are fundamental physical constructs and occupy particular positions in space and edges, e.g. roads or railway lines in transportation networks (Gastner, Newman 2006). Generally, road network structures set off both topologic and geometric characteristics (Sreelekha et al. 2016). The connectivity measures among the various indices which are adopted for evaluating road network properties could be referred to by several kinds of research. These measures assess the connection intensity between road segments. A large number of connectivity assessment indices exist to attempt to evaluate the connectivity pattern of the road network, including alpha (α), beta (β), gamma (γ), eta (η), network density, and detour indices (Al-dami 2015).

Previously, connectivity assessment indices have been extensively applied in road network connectivity, including studies such as by Levinson and Huang (2012), Olawale and Adesina, (2013), and Patarasuk (2013), who developed a GIS-based methodology for graph-based approaches (e.g. Loro et al. 2015; Ayo-Odifiri et al. 2017; Abbas, Hashidu 2019; Sarkar et al. 2020).

The road network in the Hyrcanian forests was generally designed on the basis of bottom-up mechanisms to aim at a forestry plan (Hosseini et al. 2012; Jourgholami et al. 2012), most frequently ignoring the fact that the forestry plan is a component of the watershed. Moreover, a public road was typically constructed in order to create a connection between villages and cities, fully disregarding the designing according to watershed management and other land use accesses in the watershed. The road network is the main forest watershed component, even though this point was ignored in most cases in forest road planning. Previous experience with this type of studies (Pentek et al. 2005; Abdi et al. 2009; Hosseini et al. 2012; Hayati et al. 2013) analysed and designed an appropriate road network to create the connections in forestry plan. Nevertheless, in the same way, there is barely any investigation into the forest road network evaluation in the watershed area.

The present study highlights to draw on the graph theory in order to analyse the existing road network and its temporal changes. Furthermore, it has dealt with analysing the existing road network (ERN) in which the new options have been designed according to the technical and physiographical criteria as well as the integrated management scenarios. Subsequently, the new alternatives were analysed by the use of the network connectivity indices, with the aim that the new approach would take into account various features.

The research would serve some purposes such as to: (*i*) evaluate current network connectivity using graph indices; (*ii*) create a suitability map in order to plan a new road network; (*iii*) design the road network alternatives to the study area considering the suitability map; (*iv*) assess the designed road network connectivity applying graph indices and finally to determine the appropriate road network for Chehel-Chai forest watershed.

MATERIAL AND METHODS

Research location

This study tried to focus the attention on the Chehel-Chay watershed, Minoodasht County, in Golestan Province, Northeast Iran. This area has extended between 36°59'N and 36°17'N latitude and 55°22'E and 55°37'E longitude (Figure 1). The Chehel-Chay watershed is about 25 680 ha and includes 30 villages with the population of almost 14 068. The elevation ranges from 190 m a.s.l. to 2 750 m a.s.l., and the mean annual rainfall is about 750 mm. The northern part is covered by forest areas, while in the southern part the forest is mixed with rangelands. The Chehel-Chay watershed territory is surrounded by forest (67%), cropland (28.8%), rangeland (4.09%), and villages (0.053%).

Methodology

Road network suitability mapping. Designing and construction of forest roads are affected by the extensive range of influencing factors to include topological, climatic, demographical, landscape, land use, and vegetation ones (Akay et al. 2020). Although the assessment of scenarios in decision-making tends to be highly critical, there has not been yet any standard practice in the forest road network in connection with the watershed boundary. An initiative aimed to fill this gap can be the efficient use of decision-making as a strong ally. In the current research, the Delphi technique was applied to determine essential criteria for road network planning according to integrated watershed management. There were nine forest engineering experts and also nine watershed management experts

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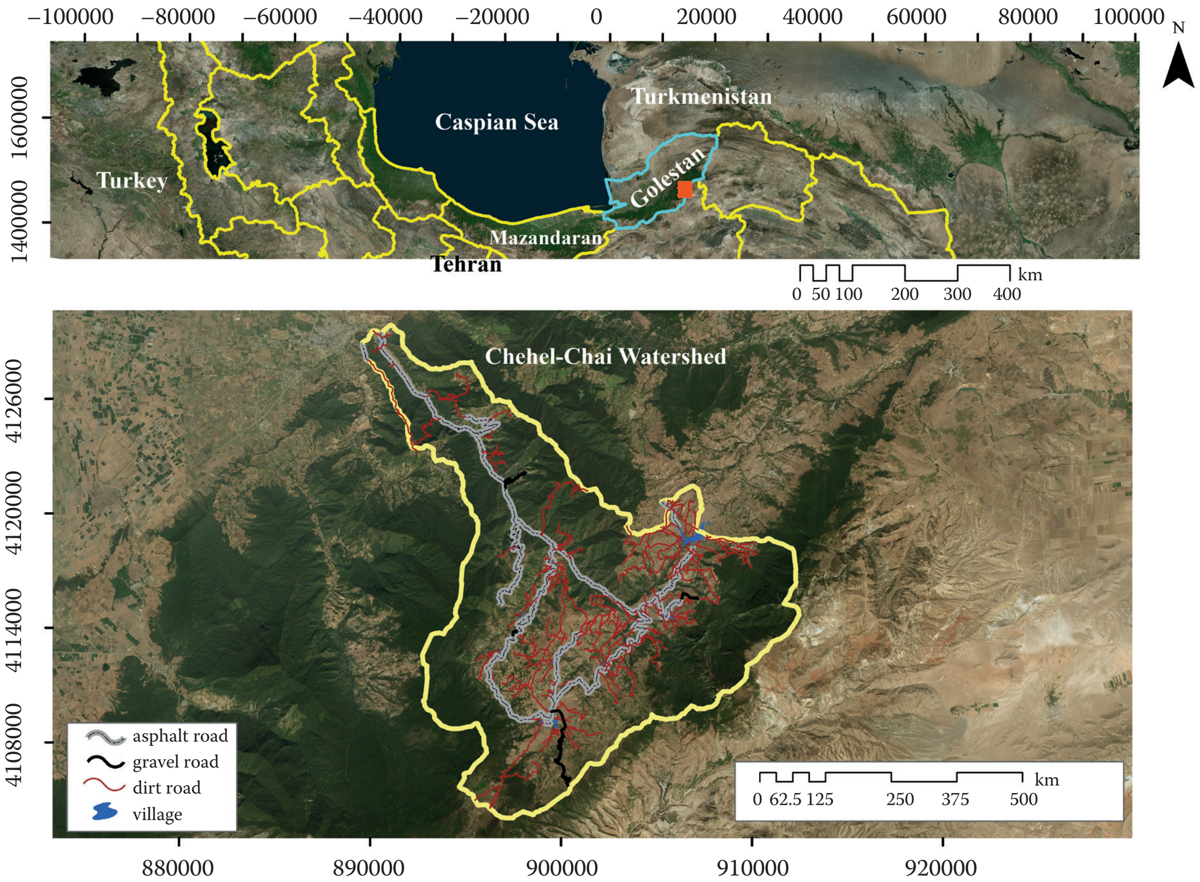

Figure 1. Location of the Chehel-Chai watershed in Iran and Golestan province

who were asked to fill in a questionnaire about the Delphi process. The process was performed in three rounds (Table 1). After each round, all responses were analysed, and the relative importance of each suggested criterion was calculated. At the conclusion, the criteria that could reach the third round were selected to produce the road network suitability mapping.

Quantification of the final criteria weights in analytic network process (ANP). The ANP method consists of two major steps; the first one implements pairwise comparisons for each of the dependency relationships to produce the relative major weights. In the second phase, the supermatrix calculation is generally split into three minor sections: the formation of the supermatrix, the normalization of the supermatrix, and the convergence to the solution (Tsai, Hung 2009). We used the ANP method in order to estimate the relative weights of selected criteria and sub-criteria. The response criteria represent their relative importance in the road network looking at the forest watershed accessibility. Then, we opted for the Super Decision Software (Version 3.2, 2019) to calculate the relative weight.

Data acquisition. In order to plan a new road network following the creation of the suitability map, we have sought to identify the fundamental criteria for putting the Delphi technique in three rounds to use (Table 2).

Physiographic data were drawn from the National Cartography Center, while geology and soil data were obtained from the Geological Survey and Mineral Exploration. Moreover, vegetation, natural and artificial distance, along with land cover data were extracted from different sources which were made available by the Secretariat of Integrated Management of the Chehel-Chay Watershed. In the following, slope and aspect layer were selected as physiographic variables, besides, the soil texture, soil and rock erodibility were performed in Geology and Soil Criteria categories. In the same way, the variable layers consisted of the distance to the residential area, the water resources, the connection point with the adjacent watershed, the location with fire occurrence, the landslide location, the fault, and electricity and the gas line were put in the title of natural and artificial dis-

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Table 1. The criteria categories in the Delphi approach

Criteria category	Round 1	Round 2	Round 3
Physiographic	slope	slope	slope
	aspect	aspect	aspect
	slope length	slope length	–
	elevation	–	–
Geology and soil	soil texture	soil texture	soil texture
	soil depth	soil depth	–
	soil drainage	–	–
	soil erodibility	soil erodibility	soil erodibility
	rock erodibility	rock erodibility	rock erodibility
Vegetation	forest type	forest type	forest type
	forest production capacity	forest production capacity	forest production capacity
	farmland	farmland	farmland
	excluded rangeland	excluded rangeland	excluded rangeland
	rangeland production capacity	–	–
Natural and artificial distance	distance to residential area	distance to residential area	distance to residential area
	distance to industrial area	–	–
	distance to recreational spot	distance to recreational spot	–
	distance to water resources	distance to water resources	distance to water resources
	distance to connection point with the neighbour watershed	distance to connection point with the neighbour watershed	distance to connection point with the neighbour watershed
	distance to occurred fire location	distance to occurred fire location	distance to occurred fire location
	distance to landslide location	distance to landslide location	distance to landslide location
	distance to fault	distance to fault	distance to fault
	distance to flood prone areas	distance to flood prone areas	–
	distance to ancient places	distance to ancient places	–
	distance to biological resources area	–	–
	distance to livestock, poultry, fisheries	distance to livestock, poultry, fisheries	–
	distance to electricity and gas line	distance to electricity and gas line	distance to electricity and gas line
Land cover	terracing	terracing	residential
	orchard	orchard	production forest
	agro-forestry	agro-forestry	agro-forestry
	conservation	conservation	orchard
	production forest	production forest	culture
	culture	culture	terracing
	tourist area	tourist area	conservative area
	residential	residential	tourist area

tance. At that moment, the land cover was divided into eight categories, including terracing, orchard, agro-forestry, conservation area, production and culture forest, tourism, and residential area. Lastly, all of the variable layers were created by geographic information system (GIS) tools (QGIS and ESRI ArcMap). The bar chart in Figure 2 marks the trends of the current research.

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Table 2. Selected variables used for suitability road network mapping

Criteria category	Input	Data	Source
Physiographic	slope aspect	raster / 10 m	National Cartography Center (NCC)
Geology and soil	soil texture soil erodibility rock erodibility	vector / 1 : 25 000 vector / 1 : 25 000 vector / 1 : 100 000	Geological Survey &Mineral Exploration (GSME)
Vegetation	forest type forest production capacity farmland	vector / 1 : 25 000	1 – forest management plan; 2 – integrated management of the Chehel-Chay Watershed; 3 – extensive fieldwork; 4 – satellite image
Natural and artificial distance	distance to residential area distance to water resources distance to connection point with the neighbour watershed distance to occurred fire location distance to landslide location distance to fault distance to electricity and gas line	vector / 1 : 25 000	1 – forest management plan; 2 – integrated management of the Chehel-Chay Watershed; 3 – extensive fieldwork; 4 – satellite image; 5 – Geological Survey & Mineral Exploration (GSME)
Landcover	terracing orchard agro-forestry conservation production forest culture tourist area residential	vector / 1 : 25 000	1 – forest management plan; 2 – integrated management of the Chehel-Chay Watershed; 3 – extensive fieldwork; 4 – satellite image; 5 – Land Affairs Organization (LAO)

Criteria standardized using fuzzy logic approach. The criteria map was prepared in GIS and then converted to a raster format. Then this layer was standardized by the fuzzy function to a byte-level range of 0–255 (0 as the least and 255 as the maximum suitability rate at each criterion) in IDRISI software (Version IDRISI TerrSet, 2020). Among the available options to choose from, whereas the linear membership functions were found fit to represent a scenario to create road network suitability map (RNSM) and include triangular or trapezoidal shapes (Lyimo et al. 2020), then we opted for the linear membership functions. Finally, the produced RNSM was categorized into four categories (high, medium, weak, and very weak) according to the road planning aims and the current limitation (Figure 2).

Designing of the road network. Traditional methods for designing a forest road system used to be heavily reliant on an aerial photo interpretation and extensive fieldwork. Similarly, forest engineers have taken the large-scale contour layers on as the preliminary ways with dividers are known as route projection or 'pegging' (Abdi et al. 2009). The traditional techniques tend to be time- and cost-consuming, in which they evidently come across as simultaneously impossible to get the various affecting layers considered in road designing. In order to strike a balance on the particular downside, we draw on the PEGGER extension in ArcView software (2005).

Graph theory indices

The Network Analyst tool in GIS was run to determine the nodes and edges with the purpose to apply the graph theory. During the use of the graph theory, several network indices are applied to evaluate the accessibility and performance of the network analysis (Dinda et al. 2018). In the present study, alpha (α), beta (β), gamma (γ), eta (η), network density, and detour indices were used in or-

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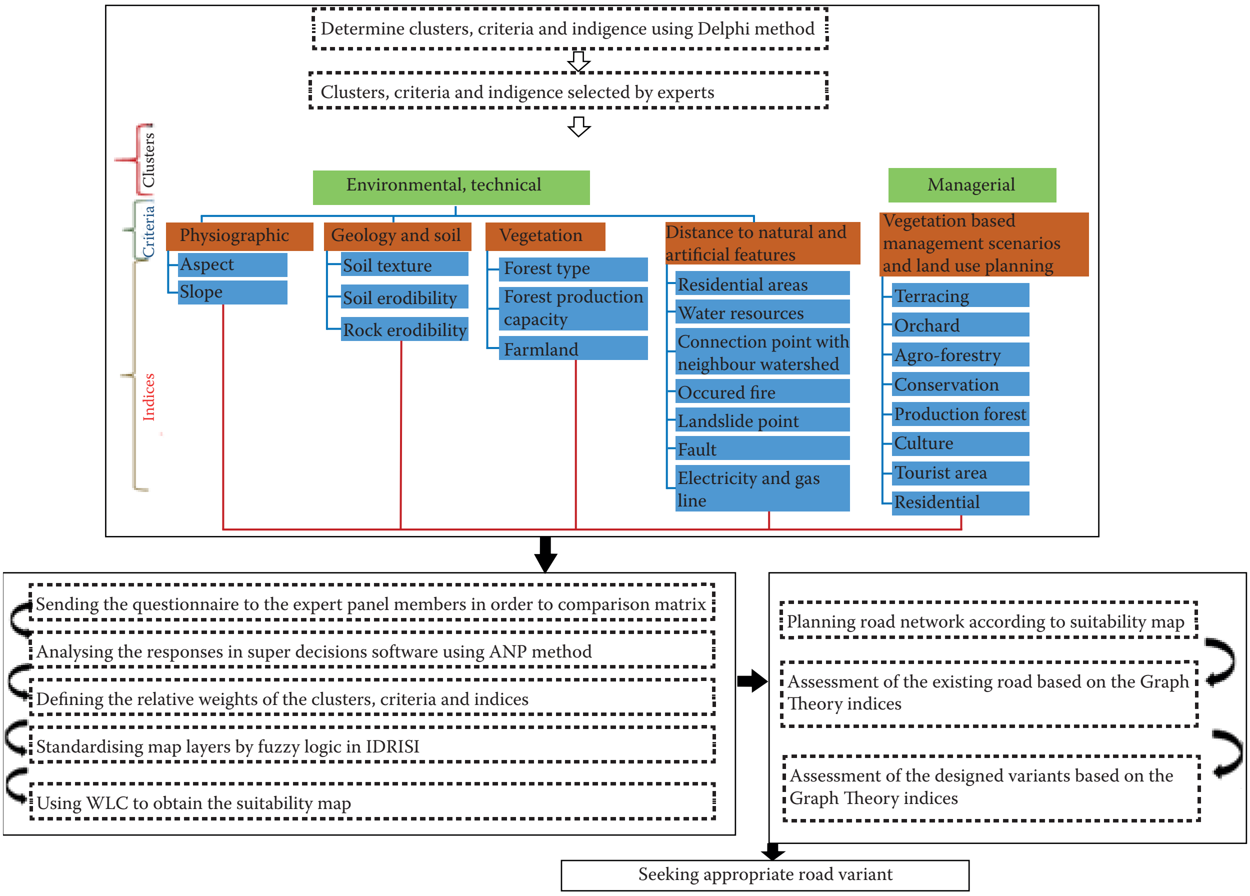

Figure 2. Flowchart of the implemented methodology of the Chehel-Chai watershed

ANP – analytic network process; WLC – weighted linear combination

der to evaluate the existing road network and road network alternatives (RNA) that was designed according to RNSM.

Alpha index (α). The alpha index highlights the ratio between the observed numbers of cycles in a graph in comparison with the maximum number of cycles. For completing the interconnected networks, the index will equal 1, whereas the trees and simple networks will have a value of 0 (Al-dami 2015; Sreelekha et al. 2016). Equation (1):

$$\alpha = \frac{e - v + p}{2v - 5} \tag{1}$$

where:

α – alpha index;

e – number of edges (links/routes);

v – number of vertices (nodes);

p – number of subgraphs in the network.

Beta index (β). The beta index (β) shows the level of connectivity in a graph and is expressed by the link between the number of edges over the number of vertices, as it shows the complexity and the completeness of the network (Rodrigue et al. 2009; Patarasuk 2013). Equation (2):

$$\beta = \frac{e}{v} \tag{2}$$

where:

β – beta index.

Gamma index (γ). The gamma index (γ) is a measure of connectivity that considers the relationship between the number of observed links and the number of possible links (Rodrigue et al. 2009). Equation (3):

$$\gamma = \frac{e}{3 \times (v - 2)} \tag{3}$$

where:

γ – gamma index.

Eta index (η). The eta index (η) measures the average edge length in the network and is used as the traffic network speed index, the summation

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and number of edges in the network need to measure the eta index (Nagne et al. 2013; Sreelekha et al. 2016). Equation (4):

$$\eta = \frac{L(G)}{e} \quad (4)$$

where:

η – eta index;

L(G) – summation of all edges in the network (km);

e – number of edges in the network.

Network density (ND). Road network density is a factor which is to measure the road network development (Nagne et al. 2013). Equation (5):

$$ND = \frac{L}{A} \quad (5)$$

where:

ND – network density;

L – length of road network (m);

A – area (ha).

Detour index (DI). The detour index (*DI*) represents the efficiency of the road network connection and also marks the importance of physical situation for the route selection (Arienti et al. 2009). Equation (6):

$$DI = \frac{D}{I} \quad (6)$$

where:

DI – detour index;

D – straight distance;

I – ground distance.

RESULTS AND DISCUSSION

The watershed consists of two major components, water and land, whose surface and underground waters from rain and melting snow flow into a body of water such as a river, lake or reservoir. (Edwards et al. 2015). Therefore, the transport sector is one of the most important manmade infrastructures inside the watershed area (Reggiani et al. 2011).

Road network suitability map and variable importance

The variables were weighted by ANP, followed by carrying out the road network suitability map. According to the calculated relative weight among the clusters, the weight of the environmental and technical cluster (0.67) was higher than that of the managerial cluster (0.33). In comparison with the other physiographic criteria, it figured the most importance with a value of 0.54, followed by the geology and soil ones, the distance to the natural and artificial features and the vegetation with values of 0.26, 0.14 and 0.06, respectively (Table 3).

The residential index showed the highest value with a relative weight of 0.3 among land cover criteria, followed by the productive forest, agroforestry, orchard, culture, terracing, conservative forest, and tourist area with values of 0.2, 0.13, 0.1, 0.1, 0.07, 0.06 and 0.04, respectively.

The fuzzy map layers of the criteria were combined considering their weights. Then the suitability map was generated and classified into four categories (Figure 3). The results indicated that 36.13% of the study area was classified as the weak suitability category, followed by the very weak suitability category (32.59%), medium suitability category (29.58%) and high suitability category (1.69%) (Figure 3, Table 4).

Existing road network analysis

The investigation finding confirmed that the dirt roads have the highest length and density (243.54 km, 9.47 m·ha^{-1}) (Table 5).

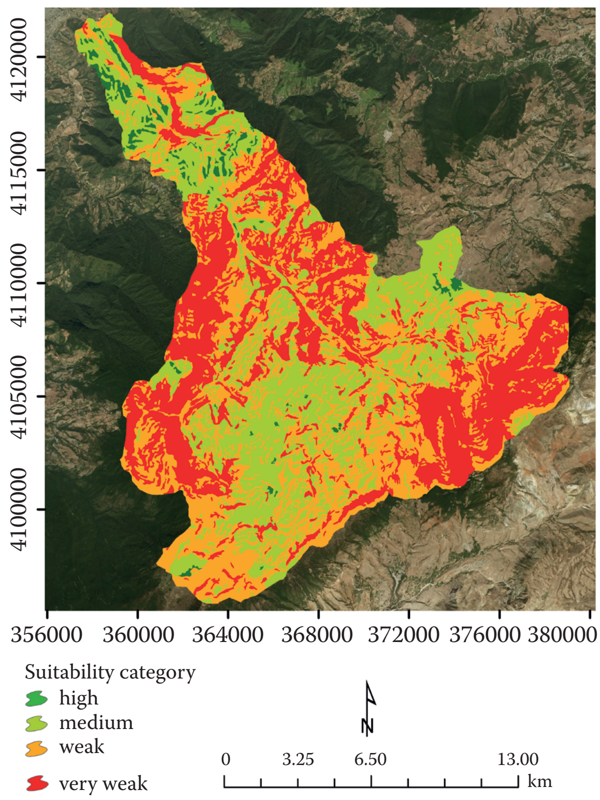

Figure 3. The road network suitability map of the Chehel-Chai watershed

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Table 3. The Analytic Network Process normalized supermatrix for competitive advantage of for road network suitability map of the Chehel-Chay watershed

Cluster	Weight	Criteria	Weight	Indices	Weight
Environmental and technical cluster	0.67	physiographic map	0.54	slope	0.89
				aspect	0.11
		geology and soil	0.26	soil erodibility	0.60
				rock erodibility	0.30
				soil texture	0.10
		vegetation	0.06	forest production capacity	0.72
				farmland	0.19
				forest type	0.09
		distance to natural and artificial features	0.14	distance to landslide point	0.22
				distance to residential area	0.19
				distance to water resources	0.16
				distance to fault	0.14
				distance to electricity and gas line	0.13
				distance to occurred fire location	0.12
				distance to connection point with the neighbour watershed	0.04
Managerial cluster	0.33	vegetation based management scenarios and land use planning	–	residential	0.30
				production forest	0.20
				agro-forestry	0.13
				orchard	0.10
				culture	0.10
				terracing	0.07
				conservative area	0.06
				tourist area	0.04

On the subject of the road network suitability categories, the highest length of existing roads was located in the medium suitability category. After that, the most significant density goes to the dirt roads (17.32 m·ha^{-1}), followed by the asphalt (4.61 m·ha^{-1}) and gravel roads (0.56 m·ha^{-1}). The largest road density in the high suitability category belonged to the dirt roads (8.28 m·ha^{-1}), then to the asphalt roads and the gravel roads with the density of (4.45 m·ha^{-1}) and (0.04 m·ha^{-1}), respectively.

Table 4. Road network suitability map categories area of the Chehel-chay watershed

Suitability category	Area (ha)	Percent of total area
High	435.13	1.69
Medium	7 595.89	29.58
Weak	9 278.86	36.13
Very weak	8 370.12	32.59

In the weak suitability category, the road density – from the most to the least – belongs to the dirt (8.86 m·ha^{-1}), the asphalt (3.42 m·ha^{-1}), and the gravel roads (0.61 m·ha^{-1}). The highest density in the very weak suitability category belongs to the dirt roads (3.09 m·ha^{-1}) (Table 6).

The results indicated that the alpha index values were 0.79, 0.14 and –0. 21 for the forest, non-forest land use and the whole study area, respectively. The calculated beta figures for the forest, non-forest land use and the whole study area were 0.4, 0.78 and 0.56, in turn. The eta figures were 1.2 (the forest area), 0.64 (the non-forest area), and 1.32 (the whole study area). Our results mark that the gamma index is 0.37, 0.19 and 0.27 for the forest, non-forest land use and the whole study area, respectively.

The network density figure for the non-forest land use (27.53 m·ha^{-1}) was the highest, followed by the figure which belonged to the whole study area (13.12 m·ha^{-1}), and the forest land use (6.17 m·ha^{-1}).

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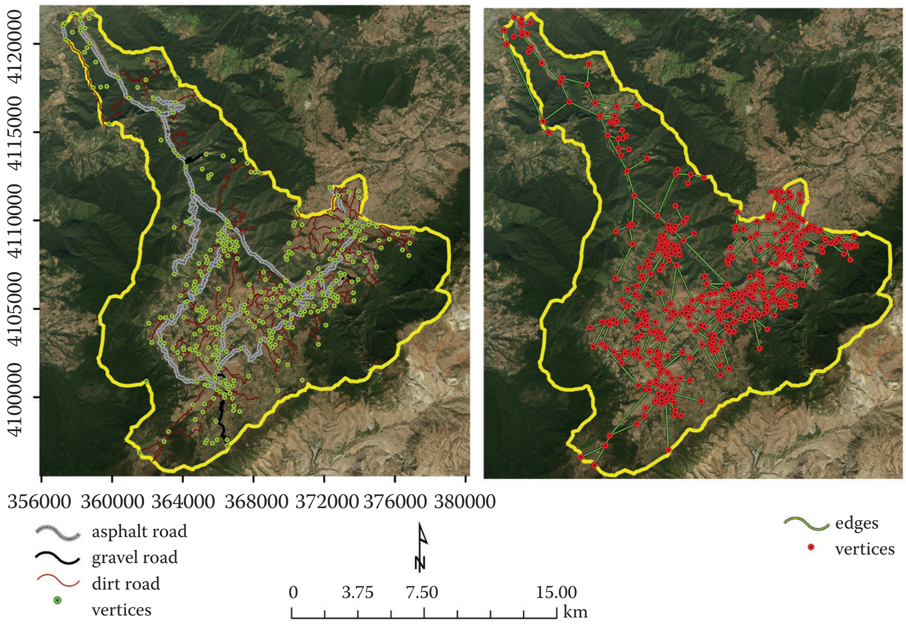

Figure 4. (A) Existing road network, (B) edges and vertices of existing road network of the Chehel-Chay watershed

In addition, the detour index was obtained for the forest, and the non-forest area, and the whole study area, i.e. 0.68, 0.81 and 0.71, in turn (Table 7).

The findings illustrated that network connectivity is relatively suitable for the forest area, however in the non-forest area despite an increase in the network density, the links between vertices (nodes) appear not to be reasonably appropriate. Therefore, the network connectivity ended up in an infirm position. The network density in the forest area came out inadequate, and in the non-forest area, the network connectivity has decreased despite the increasing network density. In addition, on the whole of the study area, the network predicted speed kept a low amount out of the topographic status along with the network development inadequate level.

Table 5. Existing road network and road network alternatives length and density of the Chehel-Chay watershed

Surface type	Road	Length (km)	Density (m·ha^{-1})
Asphalt	existing road network	82.87	3.23
Gravel		10.66	0.42
Dirt		243.54	9.47
Total		337.07	13.12
Asphalt	road network alternative 1	83.96	3.26
Gravel		10.65	0.41
Dirt		238.71	9.29
Total		333.32	12.97
Asphalt	road network alternative 2	77.85	3.03
Gravel		6.60	0.25
Dirt		212.85	8.28
Total		297.30	11.56
Asphalt	road network alternative 3	79.81	3.10
Gravel		19.48	0.75
Dirt		230.62	8.98
Total		329.91	12.83

Road network alternatives assessment

Three road network alternatives were designed based on the suitability map to the study area. Then the variants were evaluated concerning to RNSM and Graph Theory indices.

Road network alternative 1. The results indicated that in RNA 1, the dirt roads marked the highest length and density (238.71 km, 9.29 m·ha^{-1}), followed by the asphalt roads (83.96 km, 3.26 m·ha^{-1}) and the gravel roads (10.56 km, 0.41 m·ha^{-1}) (Table 5).

The road density of RNA1 was extracted from the suitability map. The findings point out that the most extensive road density in high suitability category belongs to the dirt roads (6.77 m·ha^{-1}), then to asphalt roads (0.2 m·ha^{-1}). The study got a mention that there were no gravel roads in such a category. In the medium suitability category, dirt, asphalt and gravel road density revealed 17.32 m·ha^{-1}, 4.62 m·ha^{-1}, and 0.57 m·ha^{-1}, in turn. The largest road density in the weak suitability category was in dirt roads (8.79 m·ha^{-1}), followed by asphalt roads (3.42 m·ha^{-1}), and gravel roads (0.6 m·ha^{-1}).

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Table 6. Detailed length and density of existing road network and road network alternatives on road network suitability map of the Chehel-Chay watershed

Road	Surface type	Suitability category	Length (km)	Density (m·ha^{-1})	% total roads
Existing road network	asphalt	HSC	1.94	4.45	0.58
		MSC	35.04	4.61	10.40
		WSC	31.76	3.42	9.42
		VWSC	14.14	1.68	4.19
	gravel	HSC	0.02	0.04	0.01
		MSC	4.27	0.56	1.27
		WSC	5.65	0.61	1.68
		VWSC	0.71	0.08	0.21
	dirt	HSC	3.84	8.28	1.14
		MSC	131.60	17.32	39.04
		WSC	82.21	8.86	24.39
		VWSC	25.9	3.09	7.68
Road network alternative 1	asphalt	HSC	2.95	6.77	0.89
		MSC	35.12	4.62	10.51
		WSC	31.76	3.42	9.53
		VWSC	14.13	1.68	4.24
	gravel	HSC	0	0	0
		MSC	4.39	0.57	1.31
		WSC	5.56	0.60	1.70
		VWSC	0.70	0.08	0.21
	dirt	HSC	10.34	0.02	3.10
		MSC	130.93	17.32	39.29
		WSC	81.64	8.79	24.49
		VWSC	15.80	1.88	4.74
Road network alternative 2	asphalt	HSC	1.45	1.86	0.49
		MSC	35.95	4.73	12.09
		WSC	31.00	3.34	10.43
		VWSC	9.45	1.13	3.18
	gravel	HSC	0	0	0
		MSC	2.88	0.37	0.97
		WSC	3.46	0.37	1.16
		VWSC	0.25	0.03	0.08
	dirt	HSC	6.38	3.00	2.15
		MSC	119.31	15.70	40.13
		WSC	73.15	7.88	24.60
		VWSC	14.01	1.67	4.71

Table 6. to be continued

Road	Surface type	Suitability category	Length (km)	Density (m·ha^{-1})	% total roads
Road network alternative 3	asphalt	HSC	3.64	8.37	1.11
		MSC	34.72	4.57	10.52
		WSC	26.93	2.90	8.16
		VWSC	14.52	1.73	4.41
	gravel	HSC	0.15	0.34	0.05
		MSC	8.20	1.08	2.49
		WSC	8.62	0.93	2.61
		VWSC	2.51	0.30	0.76
	dirt	HSC	15.67	36.01	4.48
		MSC	96.27	12.67	18.29
		WSC	83.95	9.05	25.45
		VWSC	34.73	4.15	10.55

HSC – high suitability category; MSC – medium suitability category; WSC – weak suitability category; VWSC – very weak suitability category

In the very weak suitability category, the highest road density is related to dirt roads (1.88 m·ha^{-1}), asphalt roads (1.68 m·ha^{-1}) and then gravel roads (0.08 m·ha^{-1}) (Table 6).

According to the RNA1 assessment based on Graph Theory indices, alpha values demonstrate the figure of 0.81, 0.45 and 0.31 for the forest, non-forest land use and the whole study area, respectively. The beta values marked 1.58, 1.22 and 1.1 for the forest, non-forest land use and the whole study area. Research findings revealed that in the three sections of the forest, non-forest land use and the whole study area, the eta index was 1.4, 0.54 and 0.78, resp. The results also showed that the respective gamma values were 0.37, 0.23 and 0.19 for the forest, non-forest land use and the whole study area. The calculated network density in the component of the forest, non-forest land use and the whole study area was 6.48 m·ha^{-1}, 25.74 m·ha^{-1} and 12.97 m·ha^{-1}, respectively. Finally, the measured detour index in the forest, non-forest land use and the whole study area 0.73, 0.72 and 0.74 (Table 7, Figure 5).

Road network alternative 2. According to the metric analysis RNA2, the length and density of the dirt roads were 212.85 km and 8.28 m·ha^{-1} in most cases, followed by the asphalt roads (77.85 km, 3.03 m·ha^{-1}) and the gravel roads (6.6 km, 0.25 m·ha^{-1}) (Table 5).

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Table 7. Existing road network and road network alternatives analyses using Graph Theory of the Chehel-Chay watershed

Road	Land use	α	β	η	γ	*ND* (m·ha^{-1})	*DI*
	forest	0.79	0.40	1.20	0.37	6.17	0.68
ERN	non-forest	0.14	0.78	0.64	0.23	27.53	0.81
	total study area	–0.21	0.56	1.32	0.19	13.12	0.77
	forest	0.81	1.58	1.40	0.40	6.81	0.73
RNA1	non-forest	0.41	1.22	0.54	0.41	25.74	0.72
	total study area	0.35	1.10	0.78	0.37	12.97	0.74
	forest	0.90	2.00	1.62	0.44	6.48	0.73
RNA2	non-forest	0.45	1.30	0.88	0.43	22.21	0.74
	total study area	0.44	1.34	1.16	0.45	11.56	0.83
	forest	0.86	1.45	1.12	0.33	10.54	0.73
RNA3	non-forest	0.44	1.31	0.95	0.44	21.76	0.69
	total study area	0.41	1.05	1.06	0.31	12.84	0.71

ERN – existing road network; RNA – road network alternatives; α – alpha; β – beta; η – eta; γ – gamma; *ND* – network density; *DI* – detour index

Concerning the suitability map, the largest road density of RNA2 in the high suitability category is related to dirt roads (3 m·ha^{-1}), while the second largest went for the asphalt roads (1.86 m·ha^{-1}). Concerning the medium suitability category, the dirt, asphalt and gravel road density obtained 15.7 m·ha^{-1}, 4.73 m·ha^{-1} and 0.37 m·ha^{-1}. In the weak suitability category, the largest road density belonged to dirt roads (7.78 m·ha^{-1}), then to asphalt roads (3.34 m·ha^{-1}) and gravel roads (0.37 m·ha^{-1}). The most significant road density was related to dirt roads (1.67 m·ha^{-1}) in the very weak suitability category. After that, there were asphalt (1.13 m·ha^{-1}), and gravel roads (0.03 m·ha^{-1}) (Table 6).

The investigation came across that the alpha value was 0.9, 0.45 and 0.44 in the forest, non-forest land use and the whole study area, respectively. In the following, we found that the beta value in the forest, non-forest land use and the whole study area

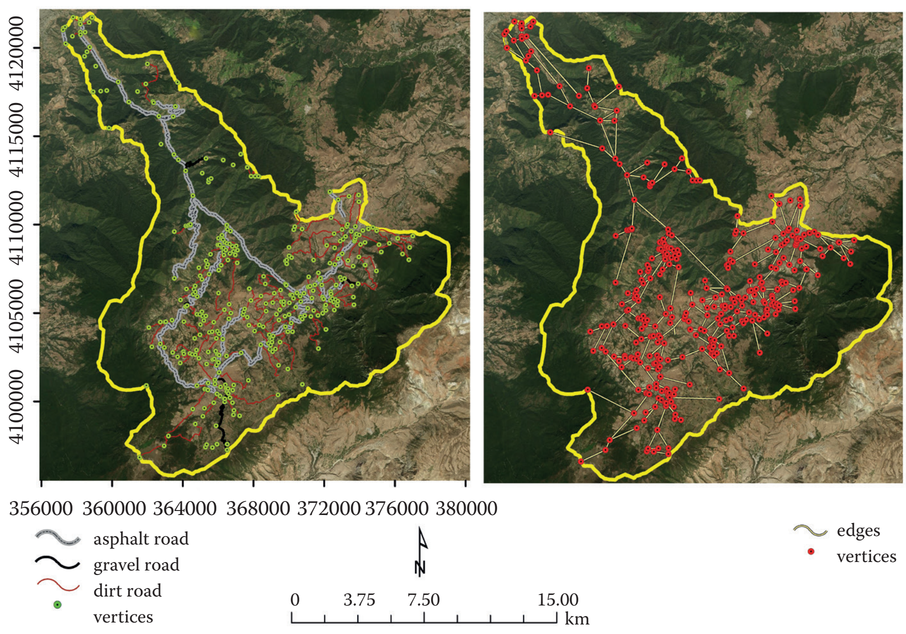

Figure 5. (A) Road network alternative 1, (B) edges and vertices of road network alternative 1 of the Chehel-Chay watershed

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was 2, 1.3 and 1.34, respectively. The respective eta values for the forest, non-forest land use and the whole study area revealed 1.4, 0.54 and 0.78. The results also indicated that the gamma rate was 0.44, 0.43 and 0.45 for the forest, non-forest land use and the whole study area respectively (Table 7, Figure 6).

Road network alternative 3. By carrying out the research, we found that in RNA3, the dirt roads featured the highest length and density (230.62 km, 8.98 m·ha^{-1}), followed by the asphalt roads (79.81 km, 3.1 m·ha^{-1}) and the gravel roads (19.48 km, 0.75 m·ha^{-1}) (Table 5).

The study results also showed that according to the RNSM analysis, the density of the dirt roads in the high suitability category was 36.01 m·ha^{-1}, followed by the asphalt and gravel roads (36.01 m·ha^{-1} and 0.34 m·ha^{-1}) along with the dirt roads with density of 13.67 m·ha^{-1} in the medium suitability category. Our findings revealed that in the weak suitability category, the highest road density was related to dirt roads (9.05 mh^{-1}), followed by asphalt roads (2.9 m·ha^{-1}) and gravel roads (0.93 m·ha^{-1}). Furthermore, in the very weak suitability category, the dirt road density was 4.15 m·ha^{-1}, followed by asphalt (1.73 m·ha^{-1}) and gravel roads (0.03 m·ha^{-1}) (Table 6).

As a result of the graph theory analyses, the alpha value appeared to be 0.86, 0.44 and 0.41 for the forest, non-forest land use and the whole study area, respectively. In the forest, non-forest land use and the whole study area the beta value obtained 1.45, 1.31 and 1.05, respectively. The eta index rate revealed 1.12, 0.95 and 1.06 in the forest, non-forest land cover and the whole study area, in turn. The research noted that the gamma value was 0.44, 0.43 and 0.45 in the forest, non-forest land use and the whole study area, respectively.

The network density index in the forest, non-forest land use and the whole study area was measured as 10.54 m·ha^{-1}, 21.76 m·ha^{-1} and 12.84 m·ha^{-1}, respectively. Ultimately, the detour index in the forest, non-forest land use and the whole study area appeared to be 0.73, 0.69 and 0.71, respectively (Table 7, Figure 7).

The structure or complexity of a road network is identified by the addition of a new linkage and expansion of the existing routes (Nagne et al. 2013). In addition, well-designed roads should be implemented according to the vulnerability of forest ecosystems along with the ecological and technical circumstances. The road construction impacts need to be carefully assessed in terms of physical, biological, economic, and social aspects from place to place. Our results indicated that a larger part of the existing road network has been located in the very weak suitability category, which means that the inherent limitations and technical standards have been remarkably ignored in road designing and construction. Hence, the lower road length was allocated to the very weak suitability category and the maximum amount went to the medium suitability category in RNA1 and RNA2

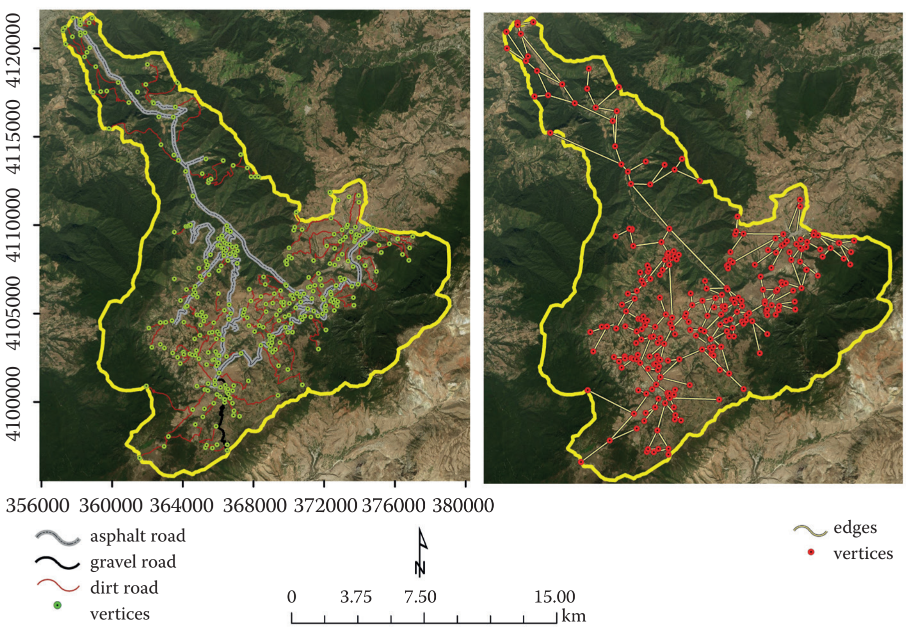

Figure 6. (A) Road network alternative 2, (B) edges and vertices of road network alternative 2 of the Chehel-Chay watershed

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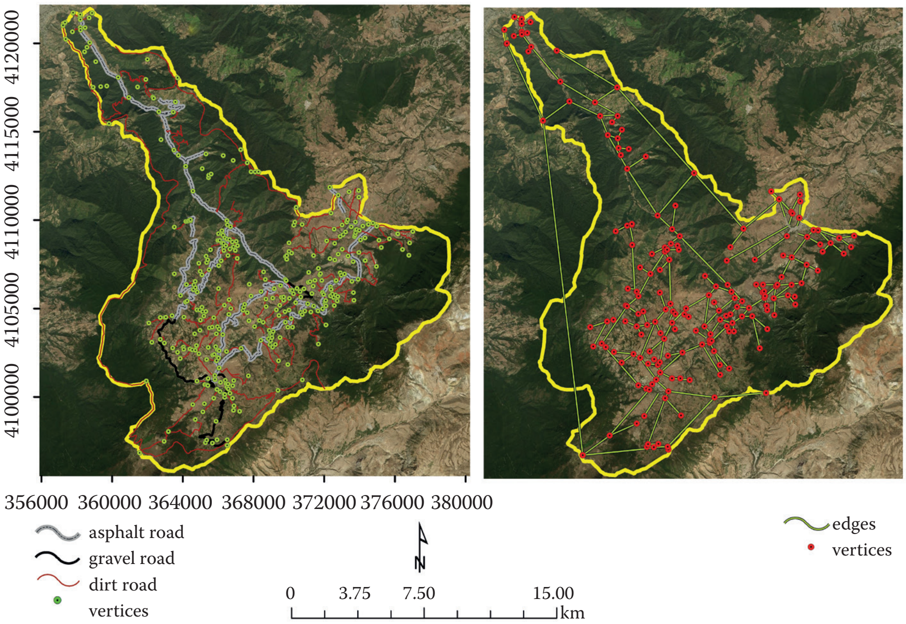

Figure 7. (A) Road network alternative 3, (B) edges and vertices of road network alternative 3 of the Chehel-Chay watershed

during the road network designing process. The described techniques in our findings can be employed to make the experience more valuable for decision-makers in which they would be able to take the multilateral vision in order to mitigate the plenty of road construction side-effects on the ecosystem.

When it comes to the findings, the majority of the existing road network was located in non-forest land use, even though 65% of the research area is covered by forest vegetation. Therefore, there has scarcely been a finely balanced approach in terms of allocating the road design in the forest area, meanwhile, in the non-forest area, a road overlap was observed. Subsequently, the existent inaccessible regions in the forest area lead to the forest management plan disruption such as forest conservation, reforestation, forest harvesting, and wildfire suppression. For this reason, the current and potential road locations and specifications must be pre-defined in the forest road network designing (Akay et al. 2013). In hope to be able to achieve a breakthrough, we designed the three Road Network Alternatives so that RNA2, with the lowest density, would massively cover the most of the study area, especially the forest land use.

The connectivity index serves to mark the accessibility nature of the study area and the land uses, not to mention the accessibility of any region is also determined by a well suited connectivity at that region (Sarkar et al. 2020). The graph theory indices took into account looking closely over the network structure of the study area. Going according to the road network analyses, the alpha index value was positive and higher than in the existing road network in all three designed alternatives while in the whole study area, this index came out negative. The results revealed the weak connectivity in the current existent road network as well as they supported the Al-dami (2015) findings. The alpha value of the road network in RNA2 was higher than in the other ones, as the recent facts have given the impression of more connectivity in this alternative than in the others. The beta value in RNA2 was pointed out as higher than in the other alternatives and the existing road network. The indices measure the level of connectivity in the network (Levinson, Huang 2012). The value of the beta index which is equal to zero is demonstrating the nodes without connecting, while the excellent value for the beta index is 2.5 (Al-dami 2015) and the value 1.4 is explaining the appropriate connectivity throughout the network (Levinson, Huang 2012). As a consequence of the beta index, RNA2 appeared more reasonable than the other alternatives which approved the acceptable connection between the nodes and vertexes. For the study area, the eta amount of the road network in RNA2 is marked higher than the appropriate RNA1, which is indicative of the average length per link, and it shows the network speed (Sreelekha et al. 2016). Therefore, in the light of the eta index, RNA2 figured as the quickest alternative compared to the two others. In view of the gamma value, RNA2 figured as the suited one, followed by RNA1 and RNA3. The value of the gamma index in all alternatives went more than in the existing network, which quantifies the progress of a network in time (Sreelekha et al. 2016). Accordingly, the connectivity between nodes in RNA2 appeared more preferable than in the other variants. Out of the findings, the highest value of the detour index belonged to variant two, which describes the efficient spatial level of the network and would be located in a value range between 0 and 1, which is rare if the network should possess the detour index of 1 (Levinson, Huang 2012). For this reason, RNA2 could be considered as quite an acceptable practical choice compared to the others. The variant two density appeared lower than in the other variants and the current road network, while the other indices of the graph theory for such an alternative went higher than in variant one and three as well as in the existing road network. Patarasuk (2013) indicated that an increase in the road density more probably could not thoroughly improve the graph theory indices, unlike in our research findings, in which the increasing connectivity in all alternatives began to improve in comparison with the existing road network. Thus, the recent finding appears to be in line with Sreelekha et al. (2016), who significantly recommended using the management factors along with the graph theory indices aimed at the road network assessment.

CONCLUSION

Carrying out this study lets us do the existing road network analysis accompanied by making use of new alternatives by applying plenty of network connectivity indices and the road network suitability map. The existing road network was assessed, which marked how such available road connectivity in the study area is not an acceptable way, particularly in forest land use. Although the forest vegetation has been covering more than half of the research area, the current road network has not been able to create a reasonable accessibility standard within the forest watershed. Consequently, it poses numerous obstacles to be overcome in conducting the forest management aims. For this reason, trying to practically implement a long-term road network plan with regard to the forestry approaches is in dire need. The main research findings demonstrate that in all the presented alternatives, the connectivity has distinctly been improved in comparison with the existing road network. In addition, it confirms the impression that the indices values which go in RNA2 featured higher than in RNA1 and RNA3, and in the existing road network. In the end, the study makes it clear that the road network connectivity indices have generally been applicable in order to attempt to analyse the road network in a forest watershed.

REFERENCES

Abbas A.M., Hashidu R.B. (2019): Transportation network analysis, connectivity accessibility indices in North East, Nigeria. Journal of Research in Humanities and Social Science, 7: 60–66.

Abdi E., Majnounian B., Darvishsefat A., Mashayekhi Z., Sessions J. (2009): A GIS-MCE based model for forest road planning. Journal of Forest Science, 55: 171–176.

Akay A.E., Aruga K., Bettinger P., Sessions J. (2013): Using optimization techniques in designing forest roads and road networks. Bartın Orman Fakültesi Dergisi, 1–2: 1–15

Akay A.O., Akgula M., Demir M., Acarb H.H. (2020): Analysis of factors associated with the amount of forest road reconstruction activity in Turkey: Autoregressive distributed lag modelling approach. Forest Ecology and Management, 458: 117800.

Al-dami H.A.N. (2015): Measuring the accessibility of road networks: Diwaniya/Iraq as case study. International Journal of Current Research and Academic Review, 3: 173–182.

Arienti M.C., Cumming S.G., Krawchuk M.A., Boutin S. (2009): Road network density correlated with increased lightning fire incidence in the Canadian western boreal forest. Internal. Journal of Wildland Fire, 18: 970–982.

Ayo-Odifiri O.S., Fasakin J.O., Henshaw F. (2017): Road connectivity approach to eased traffic congestion on market roads in Benin Metropolis, Nigeria. American Journal of Engineering Research, 6: 41–48.

Dinda S., Ghosh S., Chatterjee N.D. (2019): An analysis of transport suitability, modal choice and trip pattern using accessibility and network approach: A study of Jamshedpur city, India. Spatial Information Research, 27: 169–186.

Edwards P.J., Williard K.W., Schoonover J.E. (2015): Fundamentals of watershed hydrology. Journal of Contemporary Water Research and Education, 154: 3–20.

Gastner M.T., Newman M.E. (2006): The spatial structure of networks. The European Physical Journal B – Condensed Matter and Complex Systems, 49: 247–252.

Hayati H., Majnounian B., Abdi E., Sessions J., Makhdoum M. (2013): An expert-based approach to forest road network

https://doi.org/10.17221/8/2023-JFS

planning by combining Delphi and spatial multi-criteria evaluation. Environmental Monitoring and Assessment, 185: 1767–1776.

Hosseini S.A., Mazrae M.R., Lotfalian M., Parsakhoo A. (2012): Designing an optimal forest road network by consideration of environmental impacts in GIS. Journal of Environmental Engineering and Landscape Management, 20: 58–66.

Jourgholami M., Abdi E., Chung W. (2012): Decision making in forest road planning considering both skidding and road costs: A case study in the Hyrcanian Forest in Iran. iForest – Biogeosciences and Forestry, 6: 59–64.

Levinson D., Huang A. (2012): A positive theory of network connectivity. Environment and Planning B: Planning and Design, 39: 308–325.

Loro M., Ortega E., Arce M.R., Geneletti D. (2015): Ecological connectivity analysis to reduce the barrier effect of roads. An innovative graph-theory approach to define wildlife corridors with multiple paths and without bottlenecks. Landscape and Urban Planning, 139: 149–162.

Lyimo N.N., Shao Z., Ally A.M., Twumasi N.Y.D., Altan O., Sanga C.A. (2020): A fuzzy logic-based approach for modelling uncertainty in open geospatial data on landfill suitability analysis. ISPRS International Journal of Geo-Information, 9: 737.

Nagne A.D., Vibhute A.D., Gawali B.W., Mehrota S.C. (2013): Spatial analysis of transportation network for town planning of Auragabad City by using Geographic Information System. International Journal of Engineering Research and Technology, 4: 2588–2595.

Olawale T.N., Adesina K.I. (2013): An assessment of the relationship between Road Network Connectivity and tourists' patronage in Lokoja Metropolis, Kogi State. Journal of Natural Sciences Research, 3: 1–11.

Patarasuk R. (2013): Road network connectivity and land-cover dynamics in Lop Buri province, Thailand. Journal of Transport Geography, 28: 111–123.

Pentek T., Nevečeřel H., Pičman D., Poršinsky T. (2007): Forest road network in the Republic of Croatia – Status and perspectives. Croatian Journal of Forest Engineering: Journal for Theory and Application of Forestry Engineering, 28: 93–106.

Ramos-Scharrón C.E., Alicea-Díaz E.E., Figueroa-Sánchez Y.A., Viqueira-Ríos R. (2022): Road cutslope erosion and control treatments in an actively-cultivated tropical montane setting. Catena, 209: 105814.

Reggiani A., Bucci P., Russo G. (2011): Accessibility and impedance forms: Empirical applications to the German commuting network. International Regional Science Review, 34: 230–252.

Rodrigue J., Comtois C., Slack B. (2009): The Geography of Transport Systems, New York, Routledge: 440.

Sarkar T., Sarkar D., Mondal P. (2020): Road network accessibility analysis using graph theory and GIS technology: A study of the villages of English Bazar Block, India. Spatial Information Research, 29: 405–415.

Sreelekha M.G., Krishnamurthy K., Anjaneyulu M.V.L.R. (2016): Interaction between road network connectivity and spatial pattern. Procedia Technology, 24: 131–139.

Tsai W.H., Hung S.J. (2009): A fuzzy goal programming approach for green supply chain optimisation under activity-based costing and performance evaluation with a value chain structure. International Journal of Production Research, 47: 4991–5017.

Zhao Q., Wang A., Yu Z., Yu J., Liu Y., Zhang G., Liu G., Wang P., Ding S. (2021): Factors contributing to rill erosion of forest roads in a mountainous watershed. Journal of Environmental Management, 326: 116829.

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