Cloud Publications
International Journal of Advanced Remote Sensing and GIS
2021, Volume 10, Issue 1, pp. 3425-3437
ISSN 2320 – 0243, Crossref: 10.23953/cloud.ijarsg.489

Research Article

Off-Road Trafficability for Military Operations Using Multi-Criteria Decision Analysis

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Publication Date: 16 March 2021

DOI: https://doi.org/10.23953/cloud.ijarsg.489

Abstract This study has been carried out in the Pathankot region, having strategic importance in terms of military operations. It explores the ability of remote sensing and GIS in assessing off-road trafficability which is integral part of terrain intelligence. Number of thematic layers has been prepared using Sentinal -2 satellite images and PALSAR Digital Elevation Model (DEM) viz. LULC, Slope, Topographic Wetness Index (TWI), Terrain Roughness Index (TRI) and ground conditions to assess the potential of off-road trafficability in the study area for military operations. Results clearly depict that most of the region is suitable for off-road movement. However, north western part is showing less suitability.

Keywords *PALSAR; Multi-criteria Decision Analysis; AHP; Trafficability*

1. Introduction

Terrain is the time-integrated product of interplay of tectonics and climate where tectonics creates and maintains topography through uplift (Whipple, 2004; Wobus et al., 2006a; Whittaker et al., 2008; Hartley et al., 2011) and climate facilitates erosional processes that erode uplifted areas over time (Allen, 2008; Whipple, 2009; Armitage et al., 2011). Interactions of these processes are responsible to modify landscape appearance (Wobus et al., 2006a; Tucker, 2009). However, terrain has wide applicability as it is used for different purposes such as human settlements and military operations (Parry, 1984). It plays vital role in the military operations and planning such as off-road trafficability. Terrain intelligence is the process of analyzing geographic region to explore the effects of natural and anthropogenic features on military operations where off-road trafficability is the core component of terrain intelligence. It is defined as ability of terrain to support passage for vehicles (Suvinen, 2005), and played a key role in many successful military operations worldwide in world-war I & II (Sonne, 1936; Wasmund, 1937; Kranz, 1940).

Advancement in the computing and sensing technology provides significant aid in the terrain intelligence which is efficiently analysed by the digital elevation models (DEMs). High resolution DEMs can be utilized for the extraction of meaningful information such as slopes, aspect, terrain ruggedness index and topographic wetness index. Derived results are interpreted to formulate hypothesis in order to get information about enemy’s forces deposition and intent (Gridle & Lewis, 2004).

Several studies have been carried out that deal with off-road trafficability. However, hardly any of them has incorporated soil analysis including both soil moisture and soil types at the same time. Pundir and Garg (2019) and Sadiya et al. (2017), have used weighted overlay analysis and divided the study area into suitable trafficability zones by analyzing direct and indirect potential factors that influence off-road trafficability in Roorkee and northeast region of Nigeria respectively.

Antti Suvinen (2002) implemented cost surface model to identify areas favourable for off-road trafficability in southern Finland. He proposed off-road route for an empty forwarder in summer conditions when soil moisture is relatively high and suggested regular cost surface analysis to determine alternative routes in different conditions. In 2005, Suvinen carried out another research work with cost surface analysis. Aleksander Karol Gumos (2008) calculated the Path Distance function, using cost distance algorithm based on source raster and creation of cost raster, by calculating any possible distance between two or more points by using centroid of source raster. Gebreslasie Gebremedhin (2009) comparatively evaluated the Expert systems and Weighted Overlay Analysis for modelling off-road trafficability. The results showed that there was a strong spatial correspondence between the outputs from the two methods.

Primary objective of this study is to explore viability of different zones of study area as suitable for off-road movement. Traffic suitability has been classified into various classes viz. No-Go, Very Slow-Go, Slow-Go and Go according to the ranking and grades of explored parameters. Sentinel-2 Digital Elevation Model (DEM) has been used for this purpose to generate different thematic layers. These thematic layers have been classified and analysed to provide subsequent input for multi-criteria evaluation. The ability of Digital Elevation Model (DEMs) and GIS in modeling off-road trafficability has been analyzed in the Pathankot area.

1.2. Study Area

Pathankot is the northernmost district of Punjab state, aligned with Pakistan border on its western side and lying between 32º 23' 31''N – 32º 23' 52''N and 75º 39' 55''E to 75º 56' 12''E. It is sandwiched between Ravi and Beas River (Figure 1). Average elevation of the district is 332 meter while north-eastern part is flanked by hilly terrain and southern region is plain.

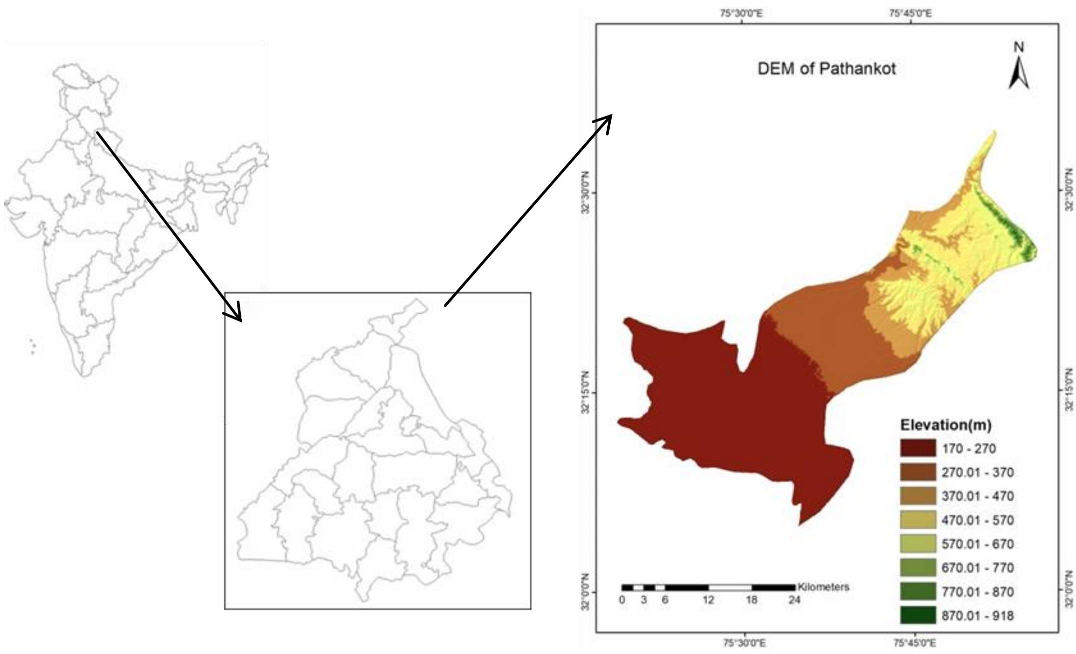

Figure 1: *Shows study area, portraying Digital Elevation Model*

Pathankot has blue eyed landscape, comprising of hilly tract, undulating plain, flood plains of Ravi and Beas. It has well developed canal system which adds substantial growth in agriculture. Geologically, the area comprises of tertiary to quaternary rocks while fertile soil of Ravi and Beas dominates the plain areas (Soil and Land Use Survey of India, 2017). Strategically, the district is important to supply ammunition and other necessities to the army during war situations as well as normal military operations. Hence, it is well connected by roads and rail network with Delhi and other major cities of the country.

2. Materials & Methods

Sentinel-2 satellite imagery obtained from the European Space Agency (ESA) Copernicus Open Access Hub. It was used to prepare land use and land cover map. ALOS PALSAR Digital Elevation Model (12 Meter resolution), has been downloaded from Alaskan Satellite Facility (ASF) and used for preparation of different thematic layers including slope. The soil map (1:200000) of Pathankot region was obtained from European Soil Data Centre (ESDAC) for preparing soil map. The base-map used is the Indian Topographic Map provided online by ArcMap 10.3.

Trafficability is influenced both by constant and dynamic factors (Suvinen, 2004) where constant factors, whether macro-topographic or micro-topographic, are independent of seasons while dynamic factors are influenced by seasonal variation; they are often linked with water content and its winter forms snow, ice, and frost. The main macro-terrain feature is slope while micro-terrain feature is often characterised in terms of ruggedness (Berry, 2013). Different thematic layers viz; LULC, ruggedness, slope, and ground condition have been prepared to calculate different parameters, required for multi-criteria analysis.

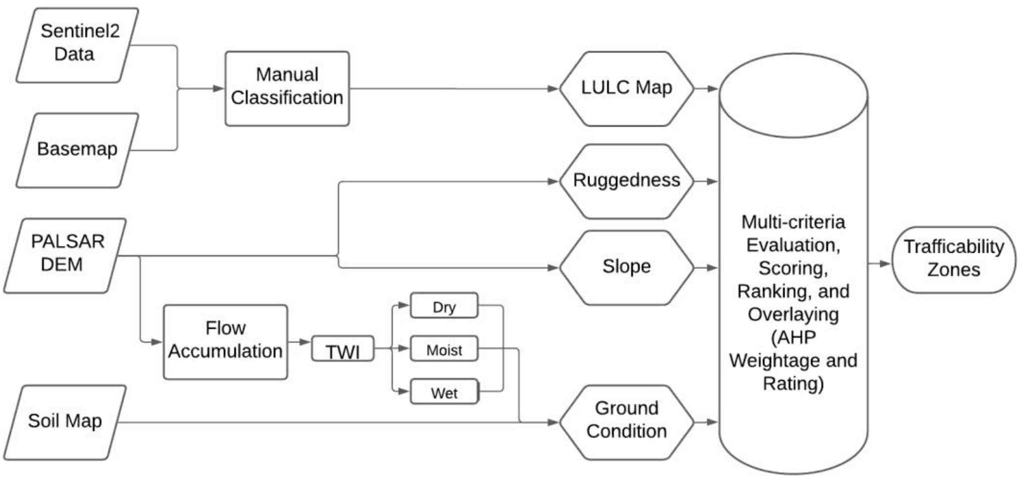

Figure 2: *Flow chart of the study*

3. Results & Discussion

3.1. Land Use Land Cover Analysis

Land use and land cover have potential effects on traffic movements in any terrain of the world. Land use and land cover map was prepared using sentinel-2 satellite imagery and classified into four classes to input derived results into multi-criteria decision analysis (Figure 3).

Cultivated land is the most prominent (around 64% of the total area) in the region. Particularly, it has least effect over trafficability. However, dense vegetation which comprises 27% out of total area may potentially affect off-road trafficability during military operations. Built-up area and natural water bodies are considered obstacle for off-road trafficability (Sadiya et al., 2017).

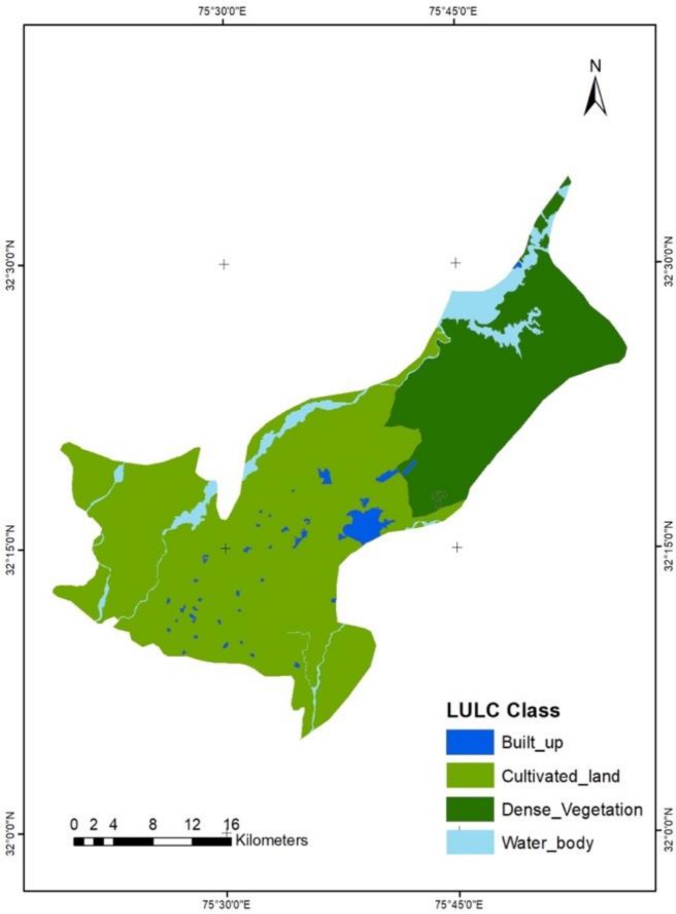

Figure 3: *Land Use & Land Cover Map of study area*

3.2. Slope Analysis

Slope is one of the major terrain parameter which significantly affects the off-road trafficability. It is considered a constant factor since it does not vary under different weather conditions. Steep areas pose extreme challenge in off-road trafficability. In fact, more than 30 degree slopes are completely avoided (Gumos, 2008)

Results of slope analysis reveal that majority of the region is less than 5 degrees of slope, clearly depicting the suitability of area for military operations. In the north-eastern part of Pathankot, small portion of the area is under steep slope (Figure 4).

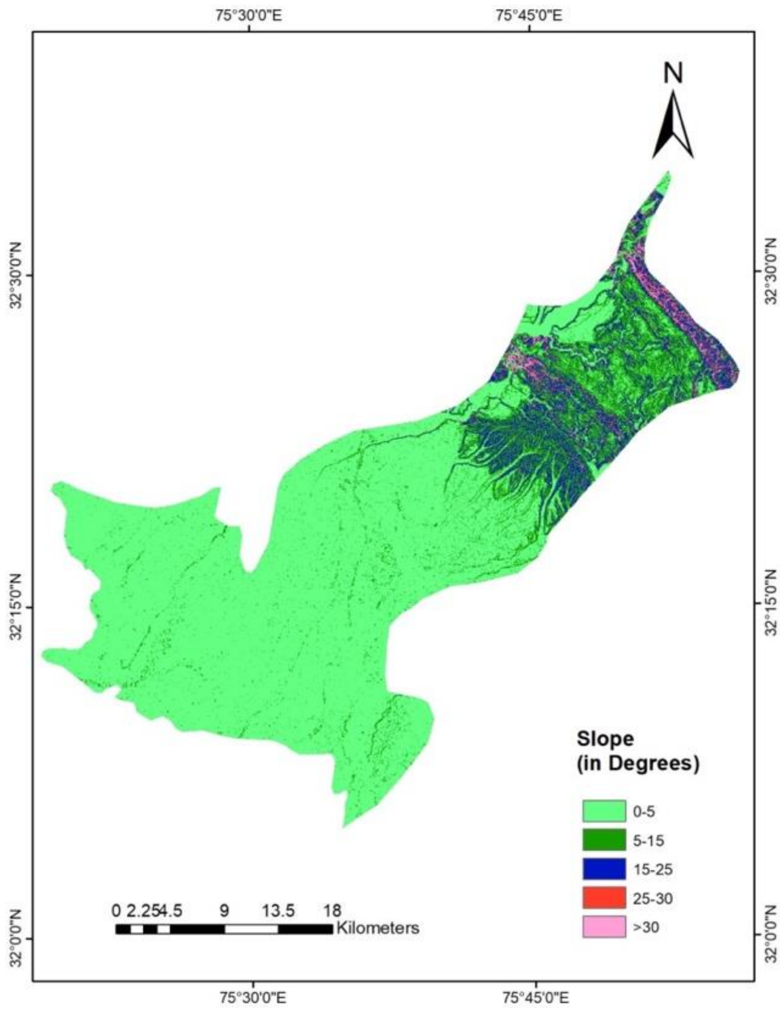

Figure 4: *Slope Map of Pathankot region*

3.3. Terrain Ruggedness Index

Terrain Ruggedness Index was proposed by Riley et al. (1999) to express the bumpiness of the terrain. It is a constant factor, is not influenced by seasonal variations. It was calculated using formula:

Square root (Abs (square ("dem_max")-square ("DEM_Min")))

Where Min DEM and Max DEM was calculated using 3x3 cell raster neighbourhood using focal statistics tool in ArcGIS. Further, output of this has been translated into Terrain Rugged Index (TRI) as per convention, proposed by Riley et al. The values 0-80 is equal to level, 81-116 is equal to nearly level, 117- 161 is equal to slightly rugged terrain, 162- 239 is equal to intermediately rugged, 240-497 is moderately rugged, 498- 958 is highly rugged and 958- 4367 is extremely rugged.

Results of TRI clearly indicate that majority of the study area lies under level (0- 80) while north-eastern part have some higher values of TRI which indicate moderately rugged terrain, resulting obstruction in off-road trafficability (Figure 5).

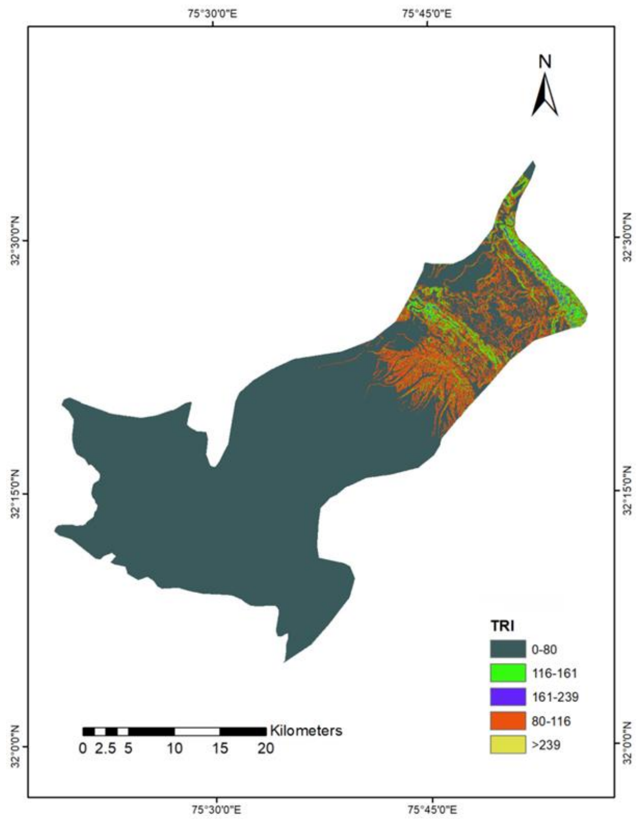

Figure 5: *Shows spatial variation of Terrain Ruggedness Index (TRI)*

3.4. Topographic Wetness Index

Topographic features are considered as first order control on spatial variation of hydrological conditions. Topographic Wetness Index (TWI) was proposed by Beven and Kirkby (1979) to consider it as integral part of TOPMODEL. It is defined as ln(a/tanβ) where a is the upslope area draining through a certain point per unit contour length and tanβ is the local slope (Sorensen et. al.2006) while it is calculated using Digital Elevation Model (DEM) by the formula.

TWI= Log([Flow accumulation+1]*Cell Size)/ (Slope+1)

1 is added as the border pixels have zero flow accumulation value. Values of TWI has been classified as ranges between 0- 8.0 correspond to dry areas, 8.0- 16.0 correspond to moist areas and >16 correspond to wet areas, as per Gumos (2008). Study reveals that most of the Pathankot region lies under moist conditions while northern part of study area having dry and wet conditions (Figure 6).

3.5. Soil Map

The soil map of Pathankot was validated with the published soil map, obtained from European Soil Data Centre (ESDAC). Study area is composed of three types of soil (Figure 7) as palehumultus, paleustalfs and usrtorthents. They belong to the ultisol, ulfisol, and entisol order respectively (Soil Survey Staff, 1999).

These soil types have certain characteristics as plaehumultus is most cohesive. Paleustalfs is older alluvial, also known as Bhangar and is intermediate in terms of cohesion. Finally, ustrothents, otherwise known as Bhabhar, is least cohesive comparatively (Singh et al., 2009).

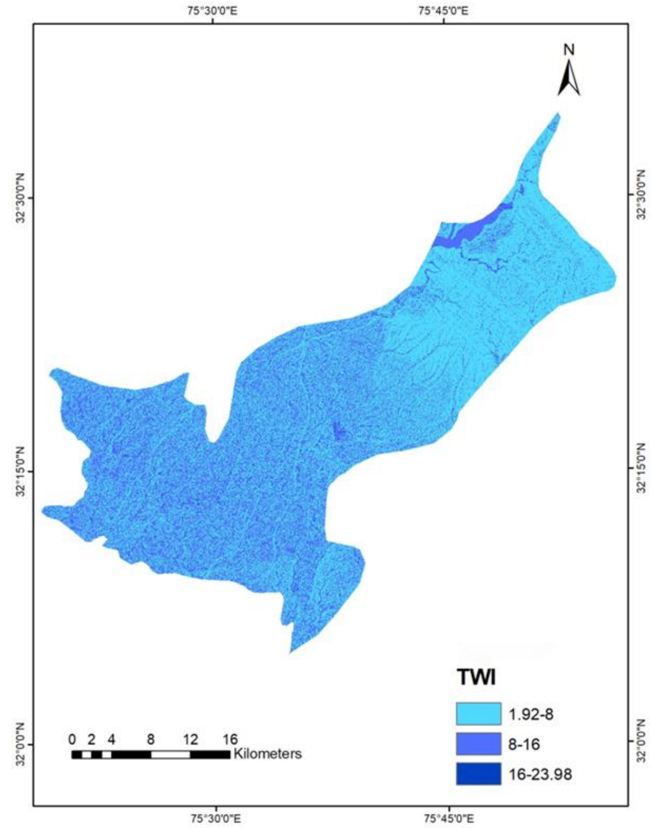

Figure 6: *Shows spatial variation of Topographic Wetness Index(TWI) in Pathankot*

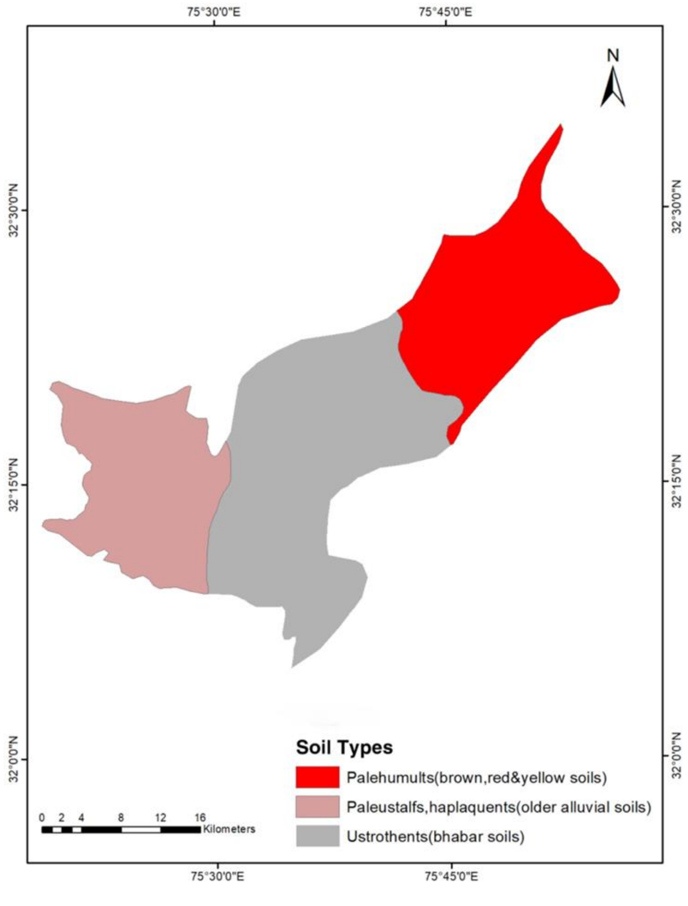

Figure 7: *Shows different type of soils in the study area*

3.6. Soil Strength

Soil strength is a major component to determine response of soil against movement of vehicles over it. It is expressed in the form of tendency of soil particles to stick together to make it more cohesive and internal friction which is determined by the particle size, shape and degree of joining particles. Soil strength is expressed via Mohr Coulomb equation:

$$\tau = c + \sigma \tan\phi$$

where τ is the shear strength of the soil, c is the soil cohesion, σ is the normal stress (at right angles to the slope), and ϕ is the angle of internal friction or shearing resistance (Huggett, 2nd Edition).

In terra-mechanics, soil types can be divided into two groups- frictional soil, and cohesive soil. In frictional soil, the shear strength depends only on internal friction angle and load, since cohesion is zero; this type of soil has rather constant bearing capacity. On the other hand, cohesive soil has zero internal frictional angles, and shear strength consists only of cohesion; this type of soil has varying bearing capacity with moisture (Suvinen, 2002). In general, fine grained textural soils have lower soil strength quality than the coarse grained (Gumos, 2008). Based upon these facts, a soil database has been prepared (Table 1). The grades of soils have been combined with soil map and TWI results to prepare a ground condition map for depicting different scenario of military operations (Figure 8).

Table 1: *Demonstrate the soil types, their grade and percentage of area covered*

Soil type	Wetness condition	Grade	Total Area of Pathankot	Percentage (%) of Total Area Covered
Brown, Red & Yellow Soil	Dry	Moderate	997.56 Sq. Km.	20.28
	Moist	Weak		25.60
	Wet	Weakest		0.57
Older Alluvial Soil (Bhangar)	Dry	Strong		4.50
	Moist	Moderate		23.25
	Wet	Weak		0.15
Bhabhar	Dry	Strong		13.57
	Moist	Strong		11.77
	Wet	Strong		0.32

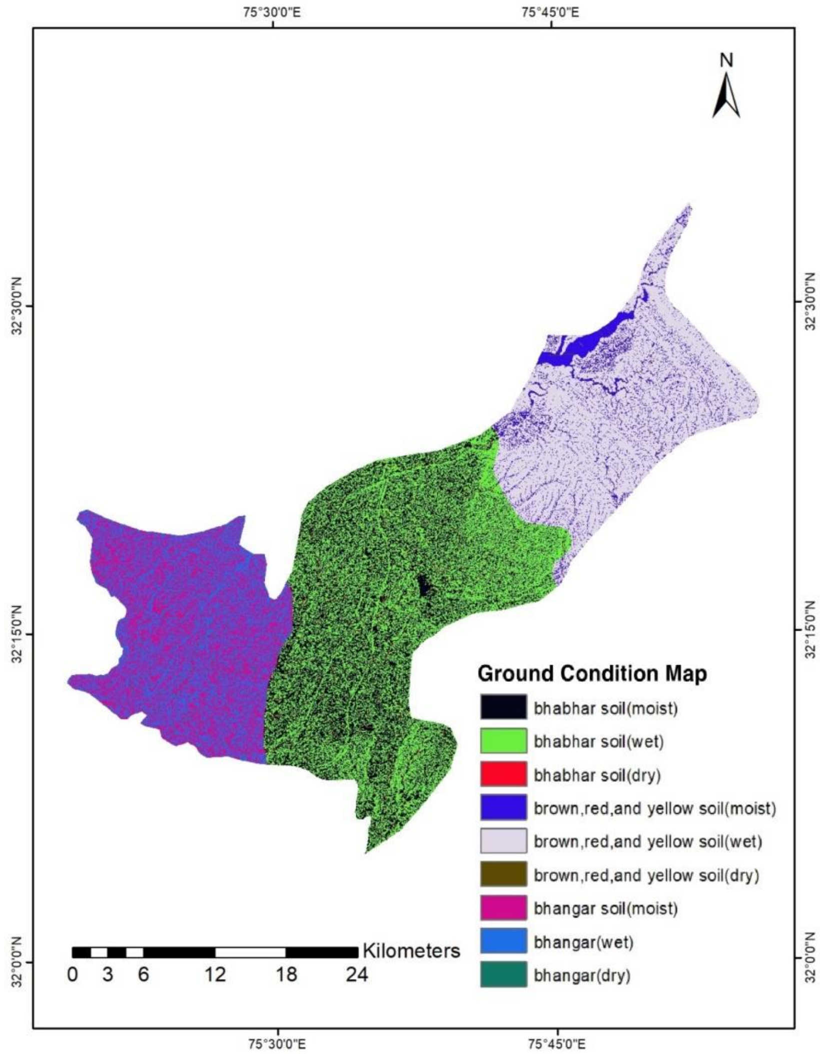

Figure 8: *Ground condition map prepared by intersecting the soil map with wetness index map*

3.7. Assigning Weights, and Overlaying the Layers

Analytical Hierarchical Process (AHP) method was adopted for weighted overlay analysis. Four thematic layers viz. land use and land cover analysis, slope, ruggedness index and soil strength have been used for weighted overlay analysis where each layer has been assigned proper weightage after pairwise comparison through AHP (Table 2).

Table 2: *Comparison Matrix*

Criteria	Slope	Ruggedness	LULC	Soil strength
Slope	1	3	3	1
Ruggedness	1/3	1	1/3	1/5
LULC	1/3	3	1	1/3
Soil strength	1	5	3	1
Σ	2.666	12	7.33	2.533

Table 3: *Show the estimation of weights, produced from comparison matrix*

S. No.	Criteria	Weight assigned
1	Slope	36%
2	Ruggedness	8%
3	LULC	16%
4	Soil strength	40%
	Total	100%

Table 4: *Shows the rating of different parameters on the basis of Analytical Hierarchical Process (AHP)*

Parameters	Rating	Weight
Slope		36
0-5	5	
5-15	4	
15-25	3	
25-30	2	
>30	1	
Ruggedness		8
0-80	5	
80-116	4	
116-161	3	
161-239	2	
>239	1	
LULC		16
Cultivated land	2	
Built-up	Restricted	
Dense vegetation	1	
Water bodies	Restricted	
Soil strength		40
Brown, red, and yellow soil(Dry)	3	
Brown. red, and yellow soil(Moist)	2	
Brown, red, and yellow soil(Wet)	1	
Older alluvial soil(Dry)	4	
Older alluvial soil (Moist)	3	
Older alluvial soil(Wet)	2	
Bhabhar(Dry)	4	
Bhabhar(Moist)	4	
Bhabhar(Wet)	4	

Results of different parameters were overlaid to prepare an off-road trafficability map, with weightage already assigned to each parameter on the basis of Analytical Hierarchical Process (AHP). The result came into four classes viz; Go, Slow-Go, Very Slow-Go and No-Go. There was a restricted class also. On the basis of facts revealed from analysis (Figure 9), it is interpreted that most of the study area (68%) pertains to Go class and is suitable for movement of vehicles during military operations. They are essentially flat and dominated by cultivated land, composed of largely Bhabhar and Bhangar (old alluvium). Slow-Go (over 15%) areas lie in the north-western part and though it consists of moderately rugged and steep hills, it is covered with dense vegetation. Very Slow-Go (7.77%) areas lie in the hilly region, are steep and should be travelled only when utmost necessary. No-go (0.33%) areas are very steep, with slopes higher than 30 degrees. They are to be completely avoided. Built-up areas and the Ravi River which runs through north-western part of study area for a considerable length as well as Chakki river which flows through south eastern extremity are deliberated as restricted zone (8.47%) for movement of military vehicles.

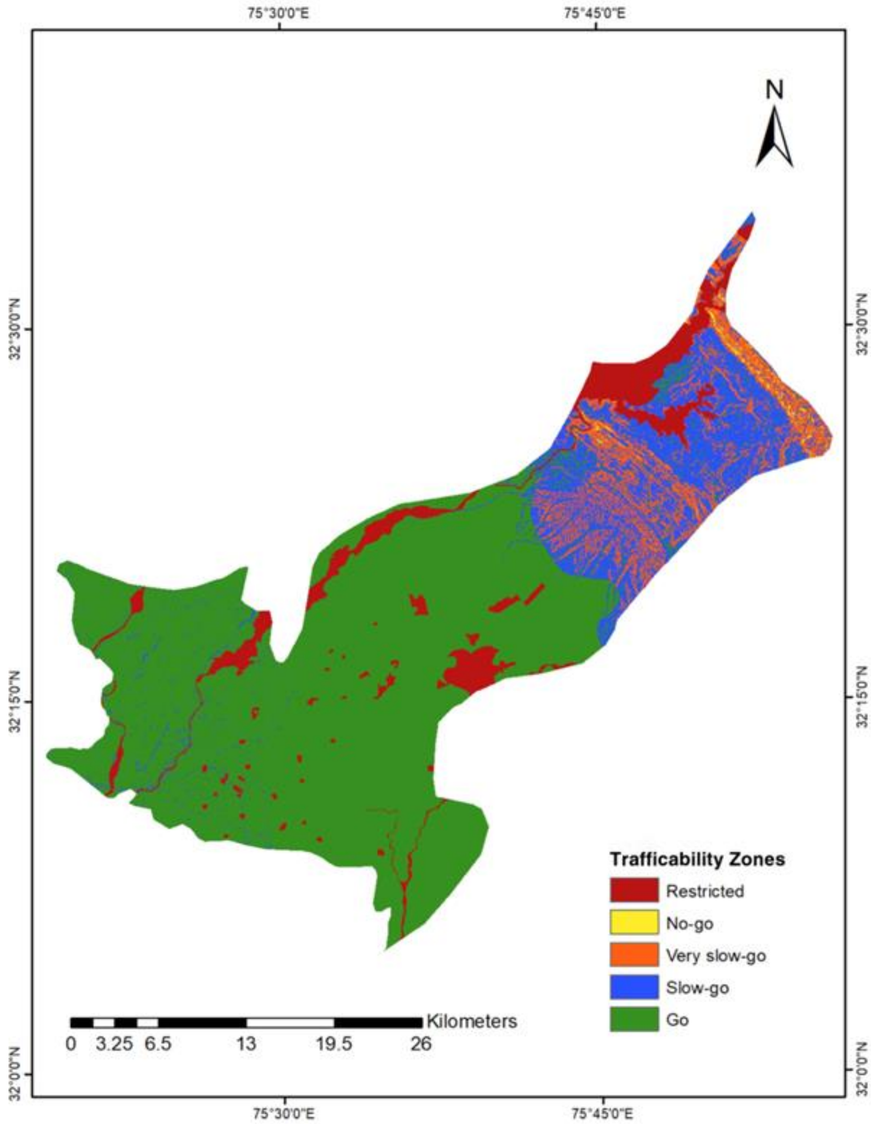

Figure 9: *Trafficability zones and their spatial variation in the Pathankot*

4. Conclusion

In this study, we have presented different parameters and their usability in terrain intelligence for off-road trafficability, specifically during military operations. Remote Sensing and GIS are found more suitable and tranquil processing tools & techniques over conventional methods of terrain analysis.

Multi-criteria decision analysis viz., Analytical Hierarchical Process (AHP) has been used to assess different parameters having substantial importance in terrain analysis for off-road trafficability in Pathankot region. Four causative factors viz. slope, LULC, ruggedness index and soil strength have been considered by assigning weight and ranks to each parameter (Table 4). However, the division of areas into dry, moist and wet is purely relative, based on analysed parameters; must be cross checked by field (real-time) data before implementation.

The terrain analysis can be further improved in future by combining other parameters such as rolling resistance between wheels of vehicles and soil, line of sight analysis and concealment analysis; to make it more precise and deployable in the field for off-road trafficability in the border areas.

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