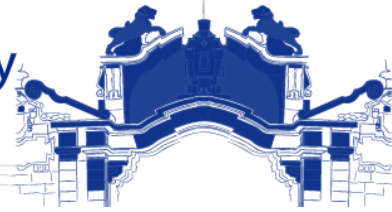




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COLLEGE OF NATURAL AND COMPUTATIONAL SCIENCES

SCHOOL OF EARTH SCIENCES

MODELLING THE TERRAIN FOR CROSS-COUNTRY TRAFFICABILITY WITH FUZZY
ANALYTICAL HIERARCHICAL PROCESS IN NORTH-WEST ETHIOPIA

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A Thesis submitted to

School of Graduate Studies of Addis Ababa University in Partial Fulfillment of
the Requirements for the Degree of Masters of Science in Remote Sensing and
Geo-Informatics, Addis Ababa, Ethiopia

June, 2020



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BY

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List of Acronyms

AHP	Analytical Hierarchy Process
ALOSPALSAR	Advanced Land Observing Satellite Phased Array type L-band Synthetic Aperture Radar
a.m.s.l	Above Mean Sea Level
AOI	Area of Interest
DEM	Digital Elevation Model
DOD	Department of Defense
ENVI	Environment for Visualizing Images
ERDAS	Earth Resource Data Analysis System
ESRI	Environmental Science Research Institute
FAO	Food and Agriculture Organization of the United Nations
FDRE	Federal Democratic Republic of Ethiopia
FM	Field Manual
LULC	Land-use Land-cover
MCDA	Multi Criteria Decision Analysis
MCE	Multi Criteria Evaluation
MoND	Ministry of National Defense
NATO	The North Atlantic Treaty Organization
SRTM	Shuttle Radar Topography Mission
TFNs	Triangular Fuzzy Numbers
USA	United States of America
UTM	Universal Transversal Mercator
WALRIS	Water and Land Resources Information System
WGS	World Geodetic System
WOA	Weighted Overlay Analysis

Modelling the Terrain for Cross-Country Trafficability with Fuzzy Analytical Hierarchical Process in North-West Ethiopia

Misganaw Wubetu, MSc. Thesis

Addis Ababa University, May 2020

Abstract

Cross-country movement is the art of predicting trafficability in off-road terrain. This is done by taking into consideration all factors that have a substantial impact on a vehicle's ability to cross various terrain, objects and obstructions of weather. A problem with CCM is that many of these factors take time to measure and map, because due to weather conditions and geological factors, they change over time. Criteria judgments also come with ambiguities and vagueness. This makes fuzzy logic a more natural approach to this kind of Multi-criteria Decision Analysis (MCDA) problems. Fifteen criteria were adopted in this method including slope, precipitation, soil type, stem diameter, soil texture, temperature, tree density, soil depth, elevation, road network, drainage, urban area, soil drainage, canopy height and land-use and land-cover. Results showed that there was no strong spatial correspondence between the outputs from the Boolean and Fuzzy methods with a spatial correlation of 0.57. Besides, a zonal cross tabulation of the two methods were strongly concurrence to each other in the GO and NO GO trafficability classes with 99.8% and 79.2% summarized in the same zone respectively. However, results of comparison also showed that there was a significant disagreement between the two methods in the VERY SLOW GO and SLOW GO classes with only 30.9% and 22.4% summarized in the same zone respectively. In the case study developed, the influence of the slope data layer, which was one of the fifteen factors used in this study. Literature shows that the incorporation of fuzzy logic to multi-criteria Analysis can improve the results in suitability analysis hence the study to explore these capabilities in the present study area. In conclusion, even though AHP is widely used in the decision analysis, it is not capable of modeling the uncertainties inherent in the criteria and the confidence of the decision maker. Fuzzy AHP is seen to perform better as it incorporates the techniques of AHP, fuzzy numbers and fuzzy extent analysis functions which are able to model the uncertainties inherent in the criteria and confidence of the decision maker since the process of decision making involves a range of criteria and a good amount of expert knowledge and judgments which in turn affect the outcome greatly.

Keywords: Fuzzy AHP, Weighted linear combination, Factor weights, Cost path function, Routing

CHAPTER ONE

1. INTRODUCTION

1.1. Background of the Study

Crossing complex terrain especially for unfamiliar persons to achieve a mission is very challenging. Since recently, the cross-country mobility has a significant impact on the operations of troops both in time and costs. At present, military terrain analysis has become a crucial part of preparing the battlefield intelligence process, because its results can contribute critically information to assist the intelligence preparation, decisions, and operations of the preferred military activities (US Army, 1994; 2000). The term “terrain trafficability” is used to determine the limiting factors that affect the mobility of vehicles outside the road infrastructure (Production of Cross-Country, 1959; Grabau, 1964; Military Geographic Intelligence, 1972; Schreier and Lavkulich, 1978; Donlon and Forbus, 1999; Wong, 2001; Saarilahti, 2002; Birkel, 2003; Rybanský, 2003; Jones et al., 2004; Gumoś, 2005; Kourdian, 2009; Hofmann *et al.*, 2013; Hohmann *et al.*, 2013).

As described earlier, CCM is the art of predicting trafficability in off-road terrain. This is done by taking into consideration all factors that have a substantial impact on a vehicle’s ability to cross various terrain, objects and obstructions of weather. A problem with CCM is that many of these factors take time to measure and map, because due to weather conditions and geological factors, they change over time. In addition, military-geographic maps are used to consider the impact on trafficability of natural and social economic conditions (Rybanský, 2009, 13-14).

The contemporary employment of the ground component of the armed forces, both in war and various peace operations but also as assistance to the civilian population in times of crisis (e.g. natural disasters), includes a wide range of analysis of vehicle terrain trafficability. The significance of armored and mechanized forces has been progressively increasing since the First World War. At all levels of warfare, which incorporates tactical, operational, and strategic elements, the definition of mobility corridors of mobile forces is one of the key tasks in the military decision-making process. Therefore, the methodology of thematic cartography interpretation of vehicle trafficability has always been closely related to the technical and tactical development of vehicles and modern methods of geospatial terrain analysis (Pahernik, 2018).

Terrain mobility depends on the soil’s capacity to resist forces put onto it by a rolling wheel or a moving track (Saarilahti, 2002b). In this paper is focused on the interaction between all types of vehicles and

terrain factors. This interaction takes place through the contact surface. Also, macro- and micro-topography, hydrology (drainage), vegetation, soil (texture and depth), climate (rainfall and temperature) have an effect on terrain mobility, routing and different terrain operations. These components can be managed using GIS techniques. Among these, Fuzzy logic and Multi-Criteria Decision analysis (MCDA) are used to identify most preferred options, to rank options, to list a limited number of options for subsequent detailed evaluation, or to distinguish acceptable from unacceptable possibilities (Dodgson, 2000). Among the techniques of Spatial Multi-criteria Evaluation (SMCE), the Weighted Overlay Analysis (WOA) is commonly used in modeling many spatially indexed problems and selection of suitable sites for several purposes.

Especially when solving routing problems with GIS techniques, the approach based on Fuzzy logic and Analytical Hierarchy Process (AHP) methods were effective. Procedures in the military decision operational process, among other things, includes also military-geographic analysis of terrain, where within them there are always complex analyses of terrain mobility of vehicles. The emphasis is on exploring the physical-geographic factors parameters and their interrelationship with the mobility of vehicle terrains. Parameters made with attributes of slope, precipitation, soil type, stem diameter, soil texture, temperature, tree density, soil depth, elevation, road network, drainage, urban area, soil drainage, canopy height and land-use and land-cover phenomena are the factors of multi-criteria analysis. Data quality and accuracy were specially examined where fuzzy logic methods introduced within the GIS model that carry out vague boundaries between phenomena since it is not possible to clearly define the boundaries within soil types or vegetation cover. Fuzzy logic was implemented in order to create vehicle deceleration coefficients, compared to the maximum possible travel speed of a vehicle, for all present physical-geographic factors on the terrain. Implemented fuzzy logic methods represent vehicle mobility map, as well as an interactive application for optimizing vehicle movement paths with the Cost path function in ESRI ArcGIS program package (Croatian Defense Academy Franjo Tuđman” Zagreb).

1.2. Statement of the Problem

All Ministry of Defense in any country gathers spatial data on routing, filtering, analyzing and presenting information for decision-making. Regional conflicts, rapid deployment and agile response place heavy pressures on military commanders, their personnel and support system to keep the situation on the ground up-to-date (Satyanarayana *et al.*, 2006).

Nowadays, Ethiopia is comparable peace but in a state of no war no peace situation with its neighbor Eritrea after the border dispute that took place more than two decades before. The geographic region in Ethiopia (East Africa) is known to be one of the militarily active and hostile regions in the world. The war taking place at this place with Islamist extremists in Somalia (Al Shabab), construction of Grand Ethiopian Renaissance Dam (GERD) rise dispute between Egypt, Sudan, and Ethiopia are enough to mention the current situation. The defense forces have to be on alert at all times to defend the sovereignty of the nation. In case of any emergent situations, the army has to move towards the border at a very short notice. As a matter of fact, the movement of the troops is highly influenced by the nature of the trafficability of the land under consideration. A cross-country mobility map is therefore necessary to provide the Army with a readymade mobility map.

A problem with CCM is that many of these factors take time to measure and map, because due to weather conditions and geological factors, they change over time. In addition, military-geographic maps are used to consider the impact on trafficability of natural and social economic conditions (Rybanský, 2009, 13-14).

In today's modern battlefield, speed of planning and execution of operations is of prime importance (Baijal *et al.*, 2006). Whereas in reality, military officers manually combine terrain-based information and the tactical significance of various terrain features (Grindle *et al.*, 2004). When every military operation is planned either offensive or a defensive, the commanders should have been to consider the terrain, enemy, its own forces and resources. Moreover, in reality, currently analyzing the battlefield is done manually by intelligence officers using hardcopy maps and human intelligence. This manual process suffers from a number of inefficiencies: Hard-copy maps do not require variable zooming in and out to achieve the desired level of detail in an integrated, quick and consistent way. Second, it takes time to manually annotate the charts. Manually combining terrain information is also very cumbersome for experts and time taking and results vary from expert to expert. Such terrain-based tasks can effectively be automated using GIS and remote sensing-based decision-making tools.

Fuzzy Logic and Weighted Overlay Analysis are widely used in solving many spatial problems and Expert systems are emerging approaches in GIS, it is interesting to test whether the results are comparable for a specific military operation planning. There are very little, if not, at all researches conducted in comparing these widely used decision making tools in military context in Ethiopia. This problem is therefore worth studying as far as the need for selecting appropriate and effective methods of spatial decision-making tools for successful military operations is concerned. This was contributed

towards preparing a Cross-country terrain mobility (traffic-ability) map of the country making military deployment activity easy.

1.3. Objectives of the study

1.3.1. General objective

The main objective of this study is to construct a map of different cross-country trafficability classes with the combination of GIS, fuzzy logic and the traditional AHP methods in identifying optimum and back-up candidate sites for locating cross-country mobility in the North-West Ethiopia.

1.3.2. Specific objectives:

- 1) To assess and identify the influential factors in the cross-country terrain mobility (traffic-ability) modelling.
- 2) To develop a model of cross-country terrain mobility (traffic-ability) map using fuzzy logic and AHP approach.
- 3) To compare the advantage of fuzzy approach and the common crisp (AHP) approach.
- 4) To identify the most accessible/suitable terrains for military movement under different vehicle types for use in the military planning and intelligence preparation.

1.4. Research Questions

The accessibility challenge of Ethiopia's highland for ground vehicles featured in terms of landscape complexity lead the researcher to narrow down several research questions in to five:

1. Have there been previous efforts/studies/models for accessibility done in similar topic for the Highlands of Ethiopia?
2. What approaches are more applicable and what are the main influencing factors for terrain modeling for a particular approach?
3. How to systematize the available approaches mainly; fuzzy and AHP for terrain accessibility modeling?
4. What are the pros and cons of the approaches particularly fuzzy approach comparing to the common crisp (AHP) approach?
5. Which trafficability modelling are more appropriate for Ethiopia's military force and for other users, fireguards brigade, Forest Company or mineral exploration company)?

1.5. Scope of the Study

This research is mainly concerned with off-road trafficability spatial modeling approaches with special emphasis for wheeled military vehicles. And the study also specifically focuses on the Fuzzy Analytical

Approaches (FAA) of spatial modeling. Among the common membership functions, with a special focus on triangular fuzzy function (fuzzifiers).

In this study Cross-country (off-road trafficability) modeling is unstructured parameters i.e. the research is not encompassing advanced algorithms in various computer programs, also in GIS software environment. With regard to spatial scope, this research disregard administrative boundaries instead geographic territories were considered for the analysis.

1.6. Significance of the Study

Compared to other sectors, GIS and remote Sensing have been less exploited technologies by the military and defense sectors. Moreover, the application of these technologies for military and defense purpose is less researched. Manually combining terrain information is tedious and cumbersome for experts and time taking. Off-road trafficability especially wheeled military vehicles deserve to be automated using GIS and remote sensing techniques as it is necessary in daily movement of armed forces. Such models of off-road cross-country vehicle mobility can help military commanders in supplying fuels and ammunition among other things during war times. It is also help to clear landmines using unmanned vehicles and to efficiently secure border territories off-road and anti-terrorist operations. Cognizant to this research gap, the intent of this research is to stimulate scholar to do more research on use of GIS and RS technologies. Specifically, this study endeavored to demonstrate the application of combined Fuzzy Logic and AHP coupled with GIS for terrain related decision making in the military community. Introducing such systems is used to improve efficiency and accuracy of terrain-based decisions in military planning. Applying the methods of generating land accessibility maps for military planning purposes and adopting the appropriate methods for the appropriate reality is an important contribution from the research community.

1.7. Limitations of the study

The present study has some limitations, among others, it is not well supported by similar scientific studies. The main challenges was, lack of relevant literature in a similar field of study. This resulted in properly referring standards i.e. influence of terrain factors, relationships and importance of the various factors during the analysis. To overcome these challenges, the researcher used personal judgments particularly to quantify the weights of the factors. Moreover, due to lack of sufficient budget to extract important information such as chemical properties of soil in the study, the researcher considers only the physical properties of soil. Similarly, due to lack of budget and time the researcher didn't use properly updated vegetation data such as stem diameter, tree height and tree spacing. Moreover, hydrological

data (stream width, depth and velocity) were not included in the study area that in turn affected the quality of the result.

1.8. Organization of the thesis

The thesis has five chapters. Chapter I deals with the introduction which includes: back ground of the study, statement of the problem, objectives of the study, research questions, Scope of the study, significance of the study, limitation of the study, and organization of the study. In Chapter II theoretical and empirical researches are presented through reviewing related literature. Chapter III is the methodology part which assesses the study design, description of the study area, data collection methods and procedures, data analysis methods. Chapter IV is about results and discussions that depicts data analysis part which shows the result and interpretation of the questionnaires collected. Chapter IV also provides a description of the final results and outputs, comparison between crisp and fuzzy methods by using cross tabulation tool. It also reveals the results of the validation and accuracy assessment of the results. Chapter V and the last chapter presented the conclusions and recommendations of the paper.

CHAPTER TWO

2. LITERATURE REVIEW

2.1. Theory behind cross-country trafficability

2.1.1. Cross-Country Movement

Cross-Country Movement, this term frequently abbreviated as CCM, means movement away from roads, movement without using roads. It usually refers to movement by military vehicles, most commonly by tanks, but the concept actually includes movement by all military vehicles on the ground, as well as foot troops. Studies on cross-country movement was planned mainly for use in planning. The strategic studies are intended for use at high command levels such as the Defense Department, the Army Headquarters, theater commands and field armies. Tactical studies are intended for use at one or more echelons of command from corps to battalion (DOD Military Intelligence, 1959).

2.1.2. Trafficability

Trafficability is a measure of the capability for vehicle movement through some region. It is a relationship between some entity (capable of movement) and the area through which it moves (Donlon *et al.*, 1999) Sharply cited after the author, one must also refer more to the inner structure of Donlon's report. He has observed a very important issue, that is there seemed to be no available commercial-off-the-shelf programs or models that could automatically deal with more advanced and complex set of dynamic parameters. The other important notice is provided to describe the common solution for to derive similar areas that are of interests of e.g. army. Producing diagrams from surveyed terrain superimposed on topographic map is done to distinguish puzzle-like areas from resembling cross-country trafficability parameters (unification of the complex study area into more simplified conglomerate of surveyed polygons). The question that arises now leads to the one point - how the terrain interacts with the machine?

Intelligence officers currently manually combine terrain-based data, information on the strategic importance of certain terrain features, as well as information on enemy resources and doctrine to hypothesize the disposition of enemy forces and enemy intent (Grindle *et al.*, 2004). According to Glington *et al.* (2004), manual terrain analysis is time consuming and requires the expertise of a trained specialist. The emergence of GIS and remote sensing as a means of spatial data acquisition has revolutionized decision making in the civil sector and in the military as well. Terrain information

supplies an important context for ground operations. The layout of terrain is a determining factor in arraying of forces, both friendly and enemy, and the structuring of Courses of Action (COAs) (Grindle *et al.*, 2004). The knowledge of the terrain is therefore invaluable to conduct successful military operations or terrain based military planning.

The measure of ease of movement (trafficability) of forces throughout the terrain is important terrain information in military operations planning. Traditionally, the possibility of mobility over a given terrain is manually identified by military topographers and/or commanders in the battle field. This may result in surmountable miscalculations and failures as terrain-based decisions need to be highly accurate for military activity.

A maneuver, i.e. a movement of troops through the terrain, is also one of the prerequisites of successful conducting of battle. It is the reason why commanders study the terrain both before and during military operations. Apart from the terrain reconnaissance and assessing the terrain “in Ethiopia (study area)”, it is possible to study using geographic sources. For centuries, these were maps and verbal description of locations supplemented with sketches and drawings. After invention of photography, the photographs served as a valuable information source before they were replaced with imagery that was acquired from the air. Starting from 1960’s the satellite imagery and other remote sensing data can be used to study the terrain characteristics.

There are now plenty of data sources that provide materials for terrain analysis and thus model cross-country mobility. Digital technology advancement is also reflected in the geographic information domain that is widely available in the form of digital geospatial databases. The use of digital data and GIS technology makes terrain analysis and its impact more effective.

2.1.3. Previous Research and Theoretical Framework

Having in mind some very first in-field research carried out for the purpose of the U.S. Army (e.g. Terrain trafficability studies by Wood and Snell 1960); a strict military aspect of the trafficability issue can be observed, which was done for two general types of vehicles: having tracks (tanks) and having wheels (trucks, jeeps etc.). The idea was later developed and the argument for trafficability models is now focused as much on civilian applications as on armed conflicts because the focus is more on geo-hazards (e.g. flood, earthquake, tsunami, volcano eruptions, etc.), unwilling forest fires, ecological disasters or rescue services. Knowledge about Nature’s accessibility can save human life, reduce cost of expenditure and also reduce the time needed to apply the remedy. Civil vehicles are primarily wheeled

vehicles, and as much recognition as possible must be done before crossing country in order to find the possible or preferred route or corridor of movements in the specific region. There are now various machines and techniques in forestry and agriculture, which are increasingly addressing the problem of analyzing an acceleration of soil erosion due to extensive harvesting and, in particular, the interaction between machine-soil, taking place in different weather and topographical locations. According to the general practice guidelines on sensitive sites, reduction of the risk of erosion (and loss of production) is under investigation, and some initial proposal exists, where vehicle operators are guided to choose an optimal route and asset, e.g. proper tire pressure to prevent compaction of the soil. One of the simplest equations used in these studies to incorporate the factors regarding the path distance for a moving vehicle is (DeMers 2002):

$$\text{Fuel used} = SD \times F \times HF \times VF \quad (1)$$

Where:

SD is the total slope distance

F is the surface friction factor

HF is the horizontal factor

VF is the vertical factor relating to down or up slope movement.

The military SHAKEN project (Gil *et al.*, 2003) was an attempt to let domain experts enter and verify logical rules describing features of a military scenario. The experts used two methods to verify their rules – in a declarative inference engine where rules describing trafficability of terrain used to control whether legal actions are performed by the user. In Birkel (2003) are four Non-GIS Military Models for trafficability presented:

1. Mod-SAF/SIMNET Trafficability (The Modular Semi-Automated Forces environment),
2. CCTT Trafficability (The Close Combat Tactical Trainer),
3. WARSIM Trafficability (The Warfighting Simulation),
4. NRMM II (The NATO Reference Mobility Model II) (Sivertun *et al.*, 2006).

However, in most of the literature they have not implemented their trafficability models into a GIS environment so most of the models had to be transferred to the GIS environment. In this study has used

a more modern GIS approach with classification and combination of different features using the weights from FAHM adding cost functions to different suggested paths. The terrain factors are of greatest interest for the trafficability characteristics. Further on in the Birkel's report, there are mentioned following terrain factors that contribute for performing a drivability weights /ranges/ evaluation: slope, precipitation, soil type, stem diameter, soil texture, temperature, tree density, soil depth, elevation, road network, drainage, urban area, soil drainage, canopy height and land-use and land-cover.

2.2. GIS-aided military cross-country trafficability models

Knowledge of terrain characteristics has been recognized since ancient times as a key element in the decisive planning and operation of warfare strategy which can define the ultimate fate of a war's outcome. Therefore, the accumulation, preparation, and analysis of terrain information for warfare operations have become vital tasks of terrain analysts (trafficability) throughout the known history of military warfare (Bayles, 1993; Kiersch and Underwood, 1998; Guth, 1998; Doyle and Bennet, 2002; Halsall, 2006). At present, military terrain analysis has become a crucial part of the intelligence preparation of the battlefield process because its results can contribute critical information to assist the intelligence preparation, decisions, and operations of the preferred military activities (US Army, 1994; 2000). The analysis typically focuses on 5 main aspects of the terrain's effect on the military operation including; observation and fields of fire, cover and concealment, obstacles, key terrain, and avenues of approach. These processes are formally known collectively as "OCOKA" (US Army, 1990, 2000). One of the main tasks of the military analysts is the construction of a guide map for the off-road movement of military personnel and vehicles called the cross-country movement (CCM) map. This map is usually referred to as an avenue of approach map because it can indicate the appropriate routes by which vehicles or troops can move to an objective when the prepared roads cannot be used as normal (US Army, 1985, 1990). Traditionally, the entire CCM mapping process is operated by military experts based on their prior knowledge of key terrain and environmental characteristics of the area, e.g., topography, soil properties, vegetation characteristics, water resources, land use, and surface configuration (Messmore et al., 1979; Kastella et al., 2000). To produce the CCM map, the individual maps of all the terrain factors were used systematically combined (or overlaid) manually to classify trafficable zones for the concerned vehicles based on some predefined decision rules. The resulting CCM map for a particular vehicle provides its approximate speeds for movement over the entire studied area (US Army, 1990).

In the past, most of the work required in a conventional military terrain analysis, as well as its subsequent applications, had to be processed manually by well-trained staff. This practice makes them laborious and time-consuming tasks, especially in the accumulation and preparation of terrain intelligence from the primary terrain data (Bruzese, 1989; Kiersch and Underwood, 1998). However, due to the tremendous advance of the geographic information system (GIS) technology in recent decades (Berry, 1993; Burrough and McDonnell, 1998; Chrisman, 2001; Bernhardsen, 2002; Longley et al., 2005; Bolstad, 2012), the terrain analysis process as a whole can be done much more conveniently, efficiently, and productively, through the high capability of GIS operating tools in the collection, manipulation, analysis, presentation, and distribution of the relevant spatial data required in a specific working process. These capabilities make the GIS an excellent tool for a built terrain database (Bruzese, 1989; Wilson and Gallon, 2000; Goodchild and Longley, 2005; Harvey, 2008). Conclusive information of the GIS applications in military affairs in general is provided. Although the merit of GIS technology in military affairs management is now well acknowledged, such detailed reports are still fairly rare in public literature. Little research can be found from the reviewed literature particularly for CCM mapping. For example, Khotcharit (2004) applied GIS tools to create a CCM map in Kanchanaburi Province in western Thailand, using the weight-linear-combination method. The considered data were surface slope, soil, vegetation, transportation, obstacle, rainfall, and built-up area. Recently, Talhofer et al. (2011) have developed a GIS-based model for the production of a simple CCM map for the Czech Army based on the direct product of 7 terrain parameters including terrain relief, vegetation, soil, climate, hydrology, built-up area, and road network.

Although factor weights using analytical hierarchy process are used for decision making in GIS Application to Development of Military Cross-Country Movement (Watcharaporn, 2014), However, within the literature it is felt that the conventional AHP technique of expressing decision maker's judgments in the form of single numbers does not fully reflect a style of human thinking in the real-world system. The decision-making process is associated with some inherent uncertainty and imprecision, which needs to be handled appropriately. The ambiguity can be related to the decision-makers characteristics. Therefore an approach is needed which can tolerate this vagueness or ambiguity. The possible approach is to apply a special kind of vagueness called fuzziness, which is based on the fuzzy set theory proposed by (Zadeh, 1965). The fuzzy approach allows decision makers to give interval judgments, which can capture a human's appraisal of ambiguity when complex multi-attribute decision making problems such as water reservoir siting are considered. Integrating fuzzy logic into the AHP

process can give a much better and more exact representation between criteria and alternatives. It is therefore the intent of this research to use a methodology that integrates GIS, fuzzy logic and the traditional AHP to model optimum sites for cross-country mobility map.

2.3. Remote Sensing for Military Application

The advent of remote sensing technology has provided a big flip for defense intelligence units to acquire data from eyes in the sky about enemy activities. Spy satellites are constantly gaining high-resolution satellite data in peacetime to monitor developments in the enemy forces' acquisition of modern warfare gadgets (Satyanarayana *et al.*, 2006). As far as these satellites are concerned, there is no privacy and imageries of very high resolution, commercially found in the market. Developed countries are extensively using remote sensing technology in monitoring enemy activities in the installation of nuclear energy and terrorist activities in the world.

The use of remote sensing data combined with ground information would provide a common platform for analyzing the ground situation in time of war. The introductions of satellites providing high-resolution images in the present era enhanced the ability of accurate map-making by making the latest information available to the forces. For example, satellite remote sensing data can be used to generate a wide range of products such as land-use/land-cover maps, obstacle maps, slope maps, road mobility maps, line of sight plots, etc. A GIS can receive process, create, store, retrieve, update, manipulate and compress digital terrain data to generate a number of products.

GIS and remote sensing techniques are being used in many sectors of in Ethiopia. There are many researches in many fields of study that have used GIS and remote sensing in one way or the other. Yet, there is no (few a single work) in the country that is done regarding the application of GIS and remote sensing for military needs.

2.4. Multi-Criteria Decision Analysis (MCDA)

Multi-Criteria Decision Analysis (MCDA) is one approach that is used to make it easier for decision-makers to consider several criteria. The MCDA is used to objectively analyze and compare multiple criteria which often clash to make the best decision possible. Especially when you have a useful broad range of stakeholders with conflicting interests, values, goals and spatial issues. To do this it considers geographical data models, the spatial dimension of the evaluation criteria and decision alternatives in evaluating the criteria. Some examples of GIS-MCDA applications include vehicle routing, site

selection, scenario evaluation, land suitability, transportation scheduling, impact assessment, location allocation to a variety of sectors (Siobhan Ryan *et al.*, 2019).

2.5. Weighted overlay analysis

Weighted Overlay Analysis is one the components of the methods of spatial modeling using spatial Multi-criteria evaluation. Weighted Overlay Analysis assigns more importance to some criteria over the others. It has been used by several authors (Seid, 2007; Zelalem, 2007; Hailegebriel, 2007; Alemayehu, 2006; Gebreslasie, 2009). They have adopted the Weighted Overlay Analysis method in undertaking spatial modeling for several purposes. The ArcGIS/IDRISI software's are commonly used to generate the weight factors for each criterion in the context of analytical hierarchy process. These authors have adopted the Weighted Overlay Analysis method for a comparison of expert systems and weighted overlay analysis for military planning; site selection of new housing sites in urban areas; mapping vegetation vulnerability analysis; livestock production; crop suitability.

Hopkins (1977) compared the advantages and disadvantages of eight methods of generating suitability maps using GIS, suggesting that using the weighted overlay model is the best approach and concluding that most of the spatial modeling tasks involved in suitability modeling typically use WOA model.

Another comparative research undertaken between Multi-criteria evaluations in GIS environment is conducted of Barredo *et al.* (1998) compared the weighted overlay analysis, and the precedence (ranking) method to allocate urban areas. In their findings, the two approaches have brought about similar result except in a slight difference in the classes that are out of the highly suitable range. Barredo *et al.* (1998) stated that the fact that the accord is not good for intermediate groups is not very important because these places are not of much interest for territorial planning.

Although factor weights using analytical hierarchy process are used for decision making in military operations planning Jaiswal (1997), the weighted overlay analysis of spatial data layers is rarely used if not at all in terrain-based decision making and suitability modeling for various military tasks. Despite the fact that weighted overlay analysis method is a more convenient method and easy to be used Barredo *et al.*, (1998), this method has not been exhaustively used in the military sector, while it is the most prominent method in the civilian sector in handling various decision making processes that are of multiple criteria in nature and spatial in context.

According to Kuznichenko *et al.* (2018) Weighted Linear Combination (WLC) is a simple and intuitive method based on the determining of the weight of criteria and the calculation of sum of the weighted estimates. The method can be applied only for the additive attributes and it is compensatory. The disadvantages of the method include the possibility of data loss as a result of the normalization of criteria, as well as the complexity and subjectivity of the process for assigning the weight, especially when a large number of heterogeneous criteria exist.

2.6. Analytical Hierarchy Process (AHP)

The most popular use for MCDM is the (AHP) method, introduced by Thomas Saaty in the early 1980s. The AHP technique was used as a method for consensus building in circumstances involving a committee or community decision-making. The AHP is more than a criteria-weighting method, as it provides an additive hierarchical aggregation of criteria. It addresses the importance of every factor in a complex system, which includes multiple factors and uses “pairwise comparisons” and matrix algebra to weight criteria, basing its decision on the weights from the evaluation criteria. It distinguishes the factors into different levels that are related to each other based on the judgment of relative importance among the factors on the same level while using the calculated weights of every factor. The AHP has many advantages, such as integrating the tangible and intangible aspects of questions, focusing on group objectives rather than objectives, and constant brainstorming to get better answers. The approach also has some drawbacks, however, such as the presentation of the environmental uncertainty issue, the deuce deficiency resulting from hierarchies and the possibility. Moreover, rank reversal is due to the modification of the relative values between the local priorities, which is a deferent and independent cause of rank reversal due to the right and left inconsistencies. Therefore, the phenomenon of rank reversal is independent of the accuracy of the priority matrix and the method of derivation. While AHP is common and often used in MCDA, it is not enough to remove all data uncertainty because the data characteristics used play a role in whether the data is certain or uncertain. Certain (deterministic) data are expressed in discrete forms whereas the (non-deterministic) uncertain data are represented by distributions (continuous or discrete).

When applying WOA, the method of analytical hierarchy (AHP) is used as a comprehensive logical and structural framework that allows the understanding of complex decisions to be strengthened through decomposing the problem into a hierarchical framework. The incorporation of all relevant decision criteria and their comparison with Pairwise allows the decision maker to determine the trade-

offs among objectives. Such Multi-criteria decision problems are typical for modeling off-road trafficability map. The AHP helps decision-makers to model a complex problem in a hierarchical system that shows the relation of aim, priorities (criteria), sub-objectives, and alternatives. It may also involve complexities and other contributing factors. It not only supports decision-makers by allowing them to structure complexity and exercise judgments, but also enables them to incorporate both objective and subjective considerations into the decision-making process (Saaty, 1980).

2.7. Fuzzy Logic and Fuzzy sets theory

Fuzzy Logic was initiated first in the 1960s and 70s, by Lotfi A. Zadeh, professor for computer science at the University of California in Berkeley (Zadeh, 1965). Basically, Fuzzy Logic is a multivalued logic that allows intermediate values to be defined between conventional evaluations like true/false, yes/no, high/low, and zero/one. Concepts like tall or very fast can be mathematically formulated and processed by computers, to apply a more human way of thinking in computer programming (Zadeh, 1984). Logic is the study of the structure and principles of correct reasoning and, more specifically, attempts to define the principles which guarantee the validity of deductive arguments. The central concept of validity is for logic because when affirming the validity of an argument are saying that it is impossible that its conclusion is false if its premises are true. Fuzzy logic is an intelligent technique widely used by using a list of IF-THEN rules to map an input space to an output space. According to Fuzzy Logic provides a different way to approach a control or classification problem. This method focuses on what the system should do rather than trying to model how it works. One can focus on solving the problem rather than attempting to mathematically model the system if that's even possible. The fuzzy approach, on the other hand, requires sufficient expert knowledge for formulating the rule base, combining the sets, and defuzzification. The fuzzy model represents the actual system in a form that closely corresponds to how it is perceived by humans. The model is thus easily comprehensible, and every parameter has a readily perceivable definition. The model can easily be changed to incorporate new phenomena, and if its behavior is different than expected, it is usually easy to find out which rule should be changed, and how? In addition, the mathematical procedures used in fuzzy modeling have been repeatedly tried and tested, and their techniques are relatively well documented (Garrido *et al.*, 2012).

Fuzzy logic starts with the concept of a fuzzy set. A fuzzy set characterizes classes without a crisp, clearly defined boundary in which the transition from one set to another is gradual rather than abrupt. It can contain elements with a partial degree of membership that rang in value between 0 and 1. In contrast

to Boolean sets theory, the membership of sets is defined as 1 or 0. However, membership of a fuzzy set are defined by the membership functions (MFs) in which represent a continuous increase from non-membership 0 to complete membership 1 (Zadeh, 2008) (Figure 2.1).



Figure 2.1: Representation of Boolean (a) and Fuzzy sets (b).

In general, set theory an element is either a member of a set or not. We can express this fact with the characteristic function for the elements of a given universe to belong to a certain subset of this universe. We call such a set a crisp set.

Definition 1 (Characteristic function). Let A be a subset of a universe X.

The characteristic function X_A of A is defined as $X_A: X \rightarrow \{0, 1\}$ with

$$X_A(x) = \begin{cases} 1 & \text{iff } x \in A \\ 0 & \text{iff } x \notin A \end{cases} \tag{2}$$

In this way we always can clearly indicate whether an element belongs to a set or not. If, however, we allow some degree of uncertainty as to whether an element belongs to a set, we can express the membership of an element to a set by its membership function.

Definition2. Fuzzy Set: A fuzzy set A of a universe X is defined by membership function μ_A such that $\mu_A : X \rightarrow [0, 1]$ Where $\mu_A(x)$ is the membership value of x in A. The universe X is always crisp set.

If the universe is a finite set $X = \{x_1, x_2, x_3, \dots, x_n\}$, then a fuzzy set A on X is expressed as

$$A = \mu_A(x_1)/x_1 + \mu_A(x_2)/x_2 + \mu_A(x_3)/x_3 + \dots + \frac{\mu_A(x_n)}{x_n} = \sum_{i=1}^n \frac{\mu_A(x_i)}{x_i} \tag{3}$$

The term $\frac{\mu_A(x_i)}{x_i}$ indicates the membership value to fuzzy set A for x_i . The symbol “/” is called separator, \sum and “+” function as aggregation and connection of terms.

According to the above definition a membership function assigns to every element of the universe a degree of membership (or membership value) to a fuzzy set. This membership values must be between zero (no membership) and one (definite membership).

2.7.1. Modeling Fuzzy Membership

The fifth stage was standardizing input layers using fuzzy membership function on IDRISI 17.0 Software. Before aggregating the input layers in a model, they must be on the same scale. This process is known as standardization and involves assigning the same dimensionless continuous scale, either 0-255 or 0-1, to all the input layers (Rodney *et al.*, 2011). Fuzzy Membership Functions were used to standardize the criterion scores. Among the known functions from the **Sigmoidal, Linear, J-Shaped** and **user defined** in this study the **user defined** was used. This process indicates the unit of measurement of each factor map as belonging to a set ranging from 0.0 to 1.0 or 1 to 255, indicating a variation from non-belonging to complete-belonging or least valuable to most valuable. In this study, continuous scale (0.0 to 1.0) was used.

2.7.2. Modeling Fuzzy AHP

a) Fuzzy AHP

The AHP is one of the well-known multi-criteria decisions making (MCDM) method invented by Saaty (1980). It is a powerful and useful MCDM approach tool. Saaty suggested the AHP as a decision-making tool to resolve unstructured problems. AHP is based on pairwise comparisons. In this method, decision-maker forms a hierarchical decision tree and determines its indices and options. Although the AHP method is to capture the expert's knowledge by perception or preference, AHP still cannot reflect the human thoughts totally with crisp numbers as compared to fuzzy AHP method due to its interval values instead of simple crisp numbers. Therefore, the fuzzy AHP, which is a fuzzy extension of AHP, which is developed based on triangular fuzzy numbers, was applied in this research to solve the hierarchical fuzzy MCDM problems.

b) Triangular Fuzzy Numbers

Fuzzy numbers are in fact natural generalizations of ordinary numbers. Triangular and trapezoidal fuzzy numbers are usually used to capture the vagueness of the parameters which are related to selecting the alternatives (Lee *et al.*, 2013). In this research, triangular fuzzy number was used to prioritize suitability of land for vehicles CCM map based on the reclassified value of map. Triangular fuzzy numbers are expressed with boundaries instead of crisp numbers for reflecting the fuzziness as decision makers select the alternatives or pairwise comparisons matrix.

A fuzzy number M on R is called a triangular fuzzy number (TFN), as its membership function is given by (Chang, 1996).

$$\mu_A(X_1) = R \rightarrow [0, 1]$$

$$\mu_A(X_1) = \begin{cases} \frac{x-l}{m-l} & x \in [l, m] \\ \frac{x-u}{m-u} & x \in [m, u] \\ 0 & \text{Otherwise} \end{cases} \quad (4)$$

Where l is the lowest possible value, m is the middle possible value and u is the highest possible value in judgment interval of decision makers (Figure 3.24).

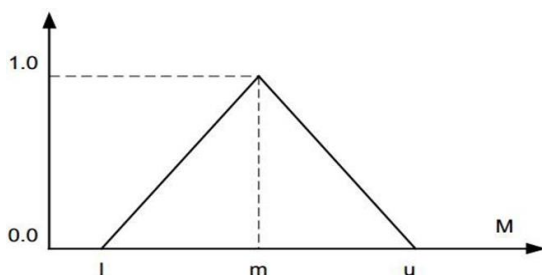


Figure 2. 2: Fuzzy triangular number

Consider two triangular fuzzy numbers (TFNs) M_1 and M_2 , $M_1 = (l_1, m_1, u_1)$ and

$M_2 = (l_2, m_2, u_2)$. Their operations laws are as follows (Lee et al, 2013):

$$(l_1, m_1, u_1) + (l_2, m_2, u_2) = (l_1+l_2, m_1+m_2, u_1+u_2)$$

$$(l_1, m_1, u_1) \times (l_2, m_2, u_2) = (l_1 \times l_2, m_1 \times m_2, u_1 \times u_2)$$

$$(l_1, m_1, u_1)^{-1} = \left(\frac{1}{u_1}, \frac{1}{m_1}, \frac{1}{l_1} \right)$$

2.8. Determining weights of criteria

This research used Fuzzy Extent Analysis method proposed by Chang (1996). According to Chang (1996) to construct pair-wise comparison of alternatives under each criterion, like that was said for traditional AHP, a triangular fuzzy comparison matrix is defined as follows:

$$\tilde{A} = (\tilde{a}_{ij})_{n \times n} \begin{bmatrix} (1,1,1) & (l_{12}, m_{12}, u_{12}) \dots & (l_{1n}, m_{1n}, u_{1n}) \\ (l_{21}, m_{21}, u_{21}) & (1,1,1) \dots \dots & (l_{2n}, m_{2n}, u_{2n}) \\ \vdots & \vdots & \vdots \\ (l_{n1}, m_{n1}, u_{n1}) & (l_{n2}, m_{n2}, u_{n2}) \dots & (1,1,1) \end{bmatrix}$$

Where, $(\tilde{a}_{ij}) = (l_{ij}, m_{ij}, u_{ij}) = (\tilde{a}_{ij})^{-1} = (\frac{1}{l_{ij}}, \frac{1}{m_{ij}}, \frac{1}{u_{ij}})$ for $i, j = 1 \dots \dots, n$ and $i \neq j$.

2.9. Creation of Cross-Country Movement models using fuzzy logic

Criteria and their relevant buffer zones was identified from within the relevant literature because at the time of carrying out this research, Ethiopia (Ministry of Defense) has not clearly standardized procedures for establishing of these factors on Cross-Country Movement siting. Because currently analyzing the battlefield is done manually by intelligence officers using hardcopy maps and human intelligence. But manually combining terrain information is also very cumbersome for experts and time taking and results vary from expert to expert. As a result, the influence of the slope, vegetation, water, soil, weather, urban area, transportation, LULC and vegetation on the CCM establishing decision hierarchy (Rybansky *et al.*, 2014).

2.10. Methods of Integrating Fuzzy Logic and Analytical Hierarchy Process

Weights were applied to each criterion identified in to reflect their relative importance. By assigning quantitative weights it is possible to make important criteria have a greater impact on the outcome than other criteria. There are a number of alternative techniques for assigning weights. In ideal situations it is desirable to apply some or all of the techniques. It can be effective because it forces the decision maker/s to give thorough consideration to all elements of a decision problem. By contemplating different consideration issues through personal experience, knowledge and understanding of the decision-making problem, a set of pairwise comparison matrices are constructed for each of the lower hierarchical levels-one matrix for each element in the level immediately above. An element in the higher hierarchical level was considered to be the governing element for those in the lower level since it contributed to it or affected it in one way or the other. In addition, in a complete simple hierarchy, every element in the lower level affects every element in the upper level. Thus, the elements in the lower level were then compared against each other based on their effect on the above governing element. This was given a square matrix of judgments; in which the comparison was made pairwise in terms of which element

dominated the other. In the traditional AHP, these judgments are then expressed as integers according to scale values 1–9.

However, within the literature above, the conventional AHP technique of expressing decision maker’s judgments in the form of single numbers does not fully reflect a style of human thinking in the real-world system. There is some inherent uncertainty and imprecision associated with the decision-making process, which needs to be adequately handled. This uncertainty can be linked to the characteristics of the decision maker. An approach which can tolerate this vagueness or ambiguity is therefore required. According to (Zadeh, 1973) a possible approach is to apply a special kind of vagueness called fuzziness, which is based on the fuzzy set theory proposed by sets (Zadeh, 1965:338). The fuzzy approach can be allowed decision makers to give interval judgements, which can capture a human’s appraisal of ambiguity when complex multi-attribute decision making problems such as cross-country movement. This approach was adopted for this research, resulting in a special class of fuzzy numbers known as Triangular Fuzzy Numbers (TFNs) representing the uncertain comparison judgements. When using TFNs, the decision maker ‘s judgement is represented as an interval defined by three real numbers or parameters, expressed as (l, m, u) , where l is the lowest possible value m is the middle possible value and u is the upper possible value in the decision maker ‘s interval judgement. Each TFN is associated with a triangular membership function, which describes the TFN domain. Triangular membership functions can be represented mathematically and graphically by Equation 4 and Figure 2.2 respectively. TFNs used to represent vague data were then defined in the order (l, m, u) . Linguistic variables, which are variables whose values are expressed in linguistic terms, were used by the decision makers in situations not well defined to be reasonably described by conventional quantitative expressions:

$u = u_1, u_2, \dots, u_n$ where each u_n is an atomic term. The TFNs and matching linguistic variables related to Saaty’s scale of preference values presented in (Table 2.1) along with their membership functions.

Table 2.1: Proposed TFNs, linguistic variables and membership functions.

Saaty’s scale of relative importance	Definition	Membership function	Domain	TFNs scale (l, m, u)	Linguistic variables
	Just equal			(1.0, 1.0, 1.0)	Just equal
1	Equal importance	$\mu_A = (3 - x) / (3 - 1)$	$1 \leq x \leq 3$	(1.0, 1.0, 3.0)	Least importance

3	Moderate importance of one over another	$\mu_A = (x-1)/(3-1)$ $\mu_A = (5-x)/(5-3)$	$1 \leq x \leq 3$ $3 \leq x \leq 5$	(1.0, 3.0, 5.0)	Moderate importance
5	Essential or strong importance	$\mu_A = (x-3)/(5-3)$ $\mu_A = (7-x)/(7-5)$	$3 \leq x \leq 5$ $5 \leq x \leq 7$	(3.0, 5.0, 7.0)	Essential importance
7	Demonstrated importance	$\mu_A = (x-5)/(7-5)$ $\mu_A = (9-x)/(9-7)$	$5 \leq x \leq 7$ $7 \leq x \leq 9$	(5.0, 7.0, 9.0)	Demonstrate importance
9	Extreme importance	$\mu_A = (x-7)/(9-7)$	$7 \leq x \leq 9$	(7.0, 9.0, 9.0)	Extreme importance
	If numbers (e.g.,3) the reciprocal value is (i.e.,1/3)			Reciprocals of above; $A_1^{-1} \approx (\frac{1}{\mu_1}, \frac{1}{m_1}, 1/l_1)$	

Borders of many geographic elements are, however, only a consequence of human perception, not real state of things. Even in case there is a real discreet border, the borderline can be inaccurate as a result of data ambiguity or their interpretation. Vegetation or soil types are a typical example of geographic elements where there are no natural borders in space. Here, the traditional classification fails completely. However, spatial units are usually represented by sharp borders. (Brown and Hauvelink, 2007) suggests 2 types of inaccuracy that have special meaning in the area of GIS – attribute *ambiguity* and *spatial vagueness*. Using the theory of “*soft classifications*”, where “*fuzzy approaches*” also belong to, is a possibility how to solve these problems.

Fuzzy sets (Zadeh, 1965) offer frameworks for processing predicates, whose level of veracity is given in degrees (“true up to certain level”) and uncertainty is expressed also in degrees. The concept of fuzzy sets deals with representation of classes, whose borders are not clearly (sharply) set. When a sharp boundary separating the set from the surroundings is missing, a question of definite setting of the element’s affiliation to the set and its supplement emerges (Hoskova, 2012; Cristea, Hoskova, 2009). Blurred or fuzzy files are then files, or classes, that do not have sharp borders. With spatial data it means that on considered places, the transition between being a part and not being a part of the file can be gradual. A fuzzy file can be characterized by fuzzy levels in the 0.0 to 1.0 interval, expressing a gradual increase in membership up to full membership. It may be defined using the affiliation function. We distinguish three basic types of geo-elements within the GIS environment: point, lines, and areas. With lines and areas, we sometimes ask a question, how to set exact borders of the given geo-element. If there is an area layer that notes ecological stability of a certain area. Fifteen basic models were created in

order to find a trafficability route. Using these models helps to create so-called least-cost map, which is a raster file that is a basic input underlying for creation of a file of the looked-for route. A cost map is generated using overlaying operations, in this case the so-called map algebra, which offers tools to work with raster files. To set the complete deceleration coefficient when moving through terrain, relations stated in the elaborated methodologies were used. Models for calculation of the individual coefficients were formed using basic operations with raster data by means of in-built tools of “Spatial Analyst” module, which is an extension of ArcGIS system, and also using tools of map algebra – file of operators and functions to work with raster data. (Talhofer *et al.*, 2009). Raster layers which were formed by calculation by conversion of vector data according to appropriate attributes were used as input data. This data base was formed as definite data with clearly defined objects and their borders.

Another step was solved when CCM issue introduced. Some uncertainty was causing bigger activity when making decisions about using the gained results. For each deceleration coefficient there was a new process model that was created, which is applied the principles of fuzzy logic. For the solution of the individual models, various approaches have used regarding the character of its input data and the result which is supposed to be reached. The common denominator of a solution for all coefficients is the use of linear fuzzification function and calculation of distance for blurring the borders of objects (e.g. 100 m for soils) (Talhofer *et al.*, 2015).

For each deceleration coefficient:

Fuzzy Overlay Function: Product & Sum

$$\text{Vehicle Deceleration} = [(F1 * F2 * F3 * \dots * F12) + F15] * \text{Vehicles speed} \tag{5}$$

Where F1-F15 is terrain factors.

CHAPTER THREE

3. MATERIALS AND METHODS

3.1. Description of the study area

The study was carried out in the Amhara Regional State, North Gondar Zone and the Tigray Regional State, West-Tigray Zone, in Northwest of Ethiopia. It is located 844 km from the city of Addis Abeba and 153 km from Gondar town. It is bounded by Kafta Humera and Wolkait in the North, Dabat, Debarq and Wogera in the East, Tach Armachiho, Lay Armachiho and Metema in the South and Mirab Armachiho in the Southwest Districts. Geographically, it is situated from North of Gondar city between 1405249.11–1545324.36 m latitude and 203065.78–375001.16 m longitude covering a total area of about 13,335.57 km² (1,331,379.36 ha). The area is found in the Southern part of the Tekeze basin traversed by the main roads connecting Gondar town with South Western part of the Tigray regional state. The map of the study area is given in (Figure 3.1).

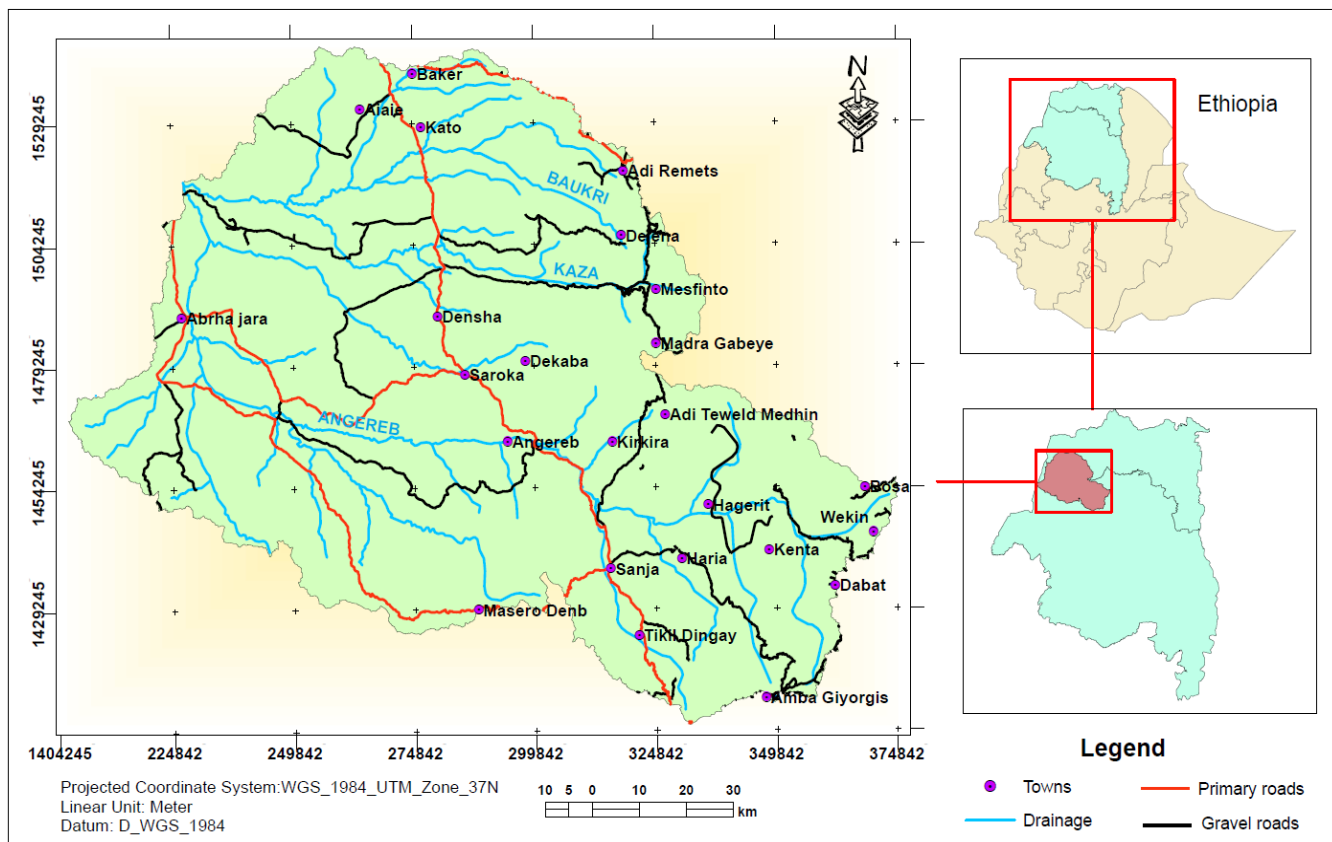


Figure 3.1: Location map of the study area

3.2. Physiography of the area

3.2.1. Surface-configuration of the area

The area is of a rolling landscape with rough ups and downs topography. The elevation ranges from 535 to 3067 a.m.s.l. Northwest of Ethiopia's rugged terrain is characterized by numerous seasonal streams and perennial rivers used for drinking and irrigation. With decrease in elevation, mechanized farm land dominates the land use pattern even in the flat terrain with gentle slopes (up to 0 degrees). The study area 's slope varies from 0 degree in the plain areas up to 83 degree in the rugged highlands where the Ras Dashen Mountain is partially located. The lower elevation of the area is characterized by plain forest covered areas and dominated grasses. Figure 3.2 shows the slope of the study area.

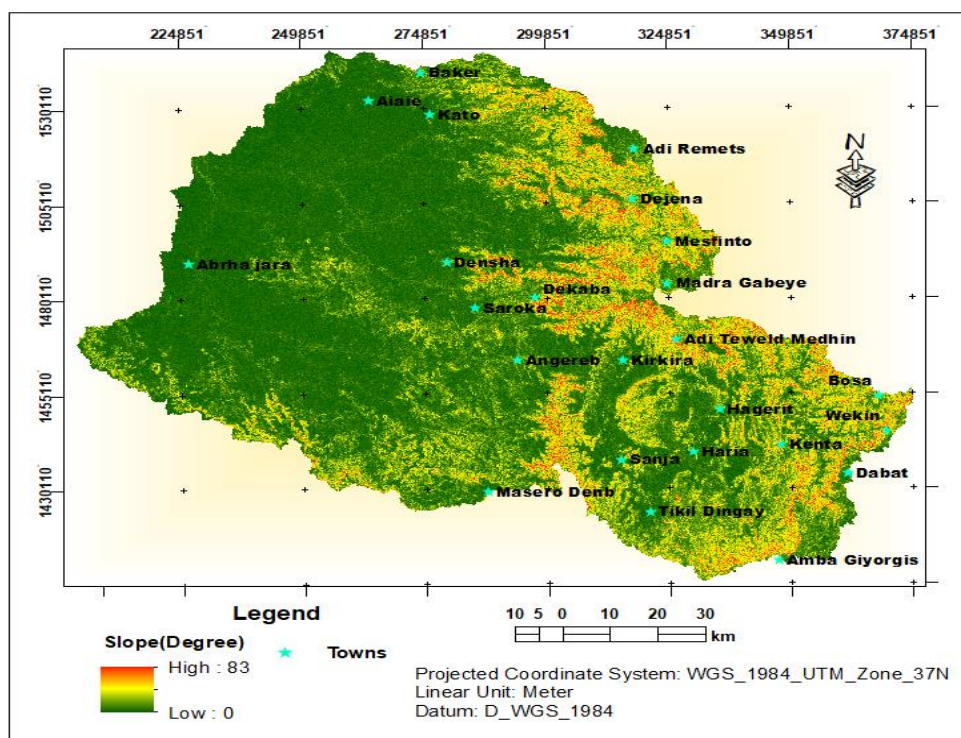


Figure 3. 2: Slope map

3.2.2. Soil

Clay or vertisols are the main types of soil representing about 31.49% of the area's total land mass. The six dominant vertisols in the area are chromic vertisols, duric vertisols, haplic vertisols, pellic vertisols, sodic vertisols and leptic vertisols. Other soil type of major importance area Leptosols which cover about 30.57% of the land mass. According to (FAO, 1998) Umbric Leptosols, Leptic Vertisols, Hyperskeletal

Leptosols, Umbric Leptosols and Leptic Vertisols are the major soil groups in the study area given in (Table 3.1) and (Figure 3.3).

Table 3.1: The major soil types of the study area

No	Soil type	Area (ha)	Area (%)
1	Vertisols	419929.14	31.49
2	Leptosols	407705.73	30.57
3	Cambisols	319961.59	23.99
4	Nitisols	96893.08	7.27
5	Regosols	49326.59	3.70
6	Luvisols	39472.36	2.96
7	Calcisols	202.53	0.02
Total		1331379.36	100

Source: Minister of Water, Irrigation and Energy of Ethiopia

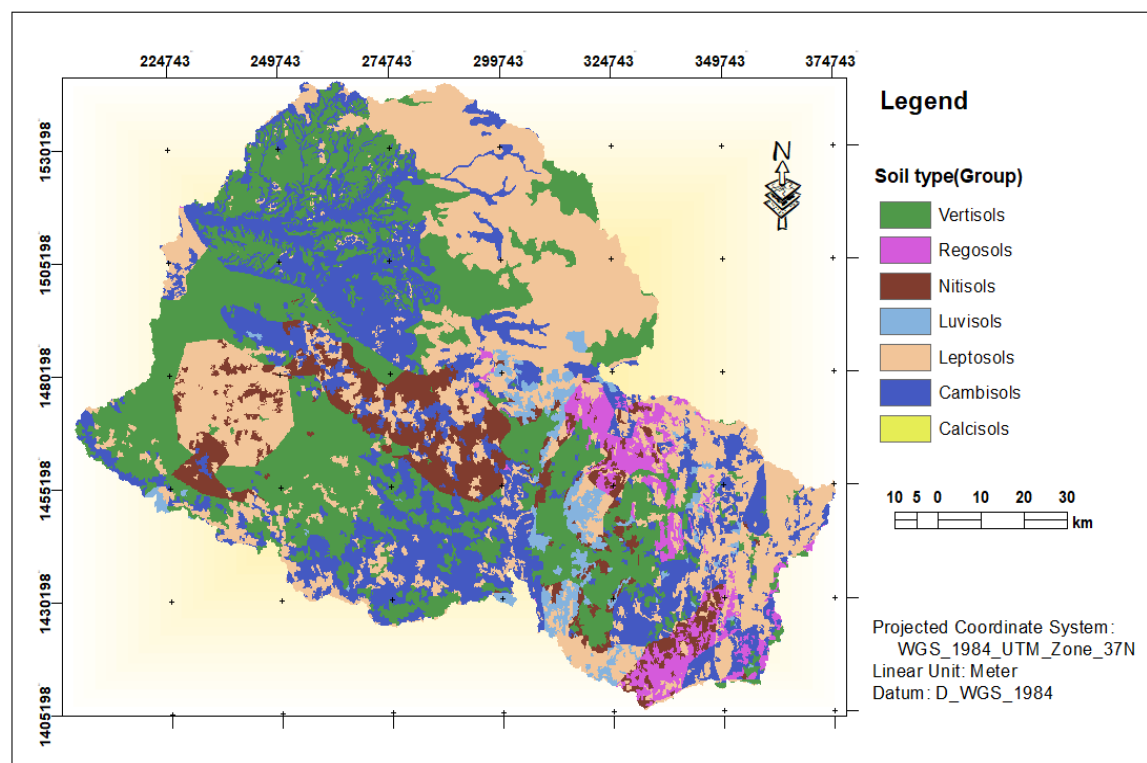


Figure 3.3: Soil description map

3.2.3. Land-use/land-cover

The land-use and land-cover of the study area is dominantly characterized by bush/shrub and degraded landscape. Given that area suffered from extreme human pressure that converts natural landscape to degraded lands, the area has little natural vegetation cover. According to the study made by Water and Land Resources Information System (WALRIS), the majority of the study area appears less vegetated. Compared to other places in the country, difficulty of access due to dense vegetation is insignificant. The area of each land use/land cover class of the area is obtained and given in (Figure 3.4 and 3.5).

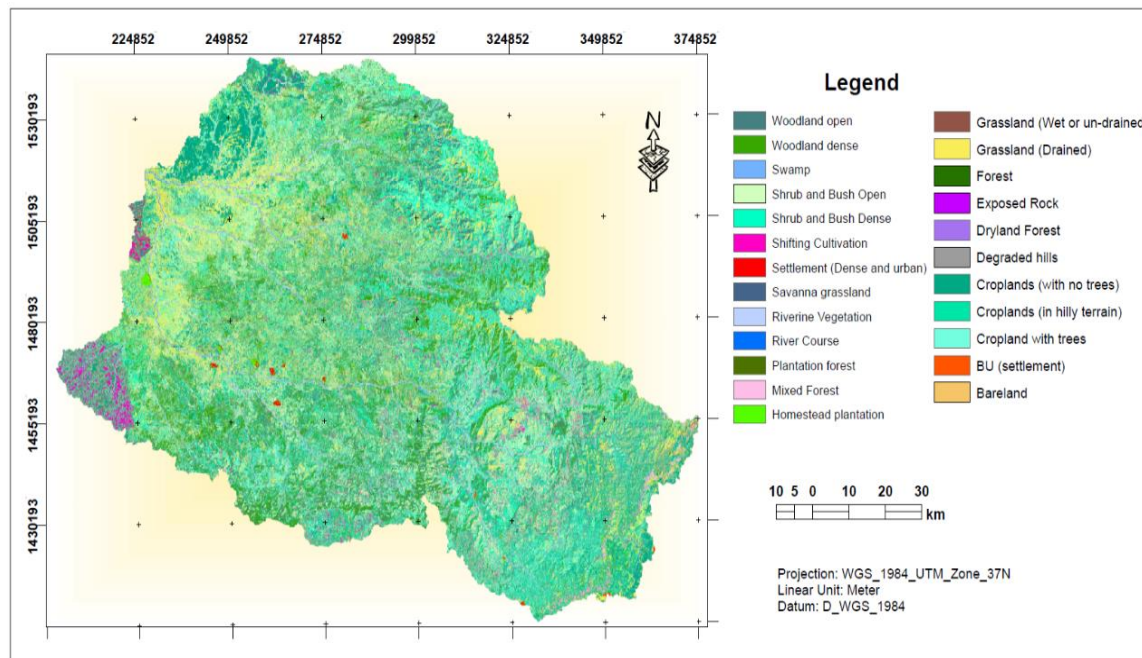


Figure 3.4: Land-use and land-cover map

Source: Water and Land Resources Information System (WALRIS)

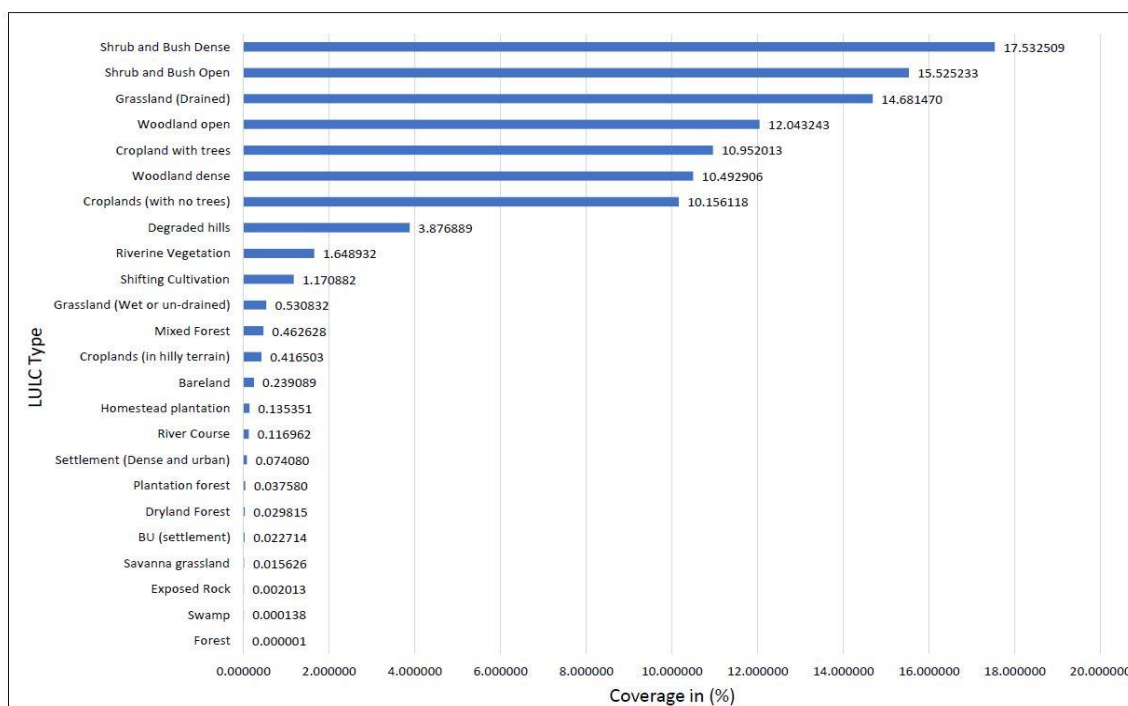


Figure 3.5: Land-use and land-cover area coverage

3.2.4. Climate

Data recorded, according to the Ethiopian Metrological Agency; from 22 weather stations based on the 32-years climate data (1986–2018). The mean annual average temperature varies from 15.7 to 18.8 °C. Thirty-two years rainfall data records for stations within and adjacent to the study area show an average annual rainfall of between 47 mm and 280 mm for the study area. According to the traditional classification system, the study area has three climatic conditions, mainly in the Dega (highland), Woyna Dega (midland) and Kola (lowland) altitudes and temperature zones characterized by medium to cold weather. In summer, from July to mid-September, excess rainfall intensity and distribution occur, while the remaining season is characterized by little or no rain. The mean monthly rainfall and average temperature of the study area for thirty-two years is given in detail in (Figure 3.6).

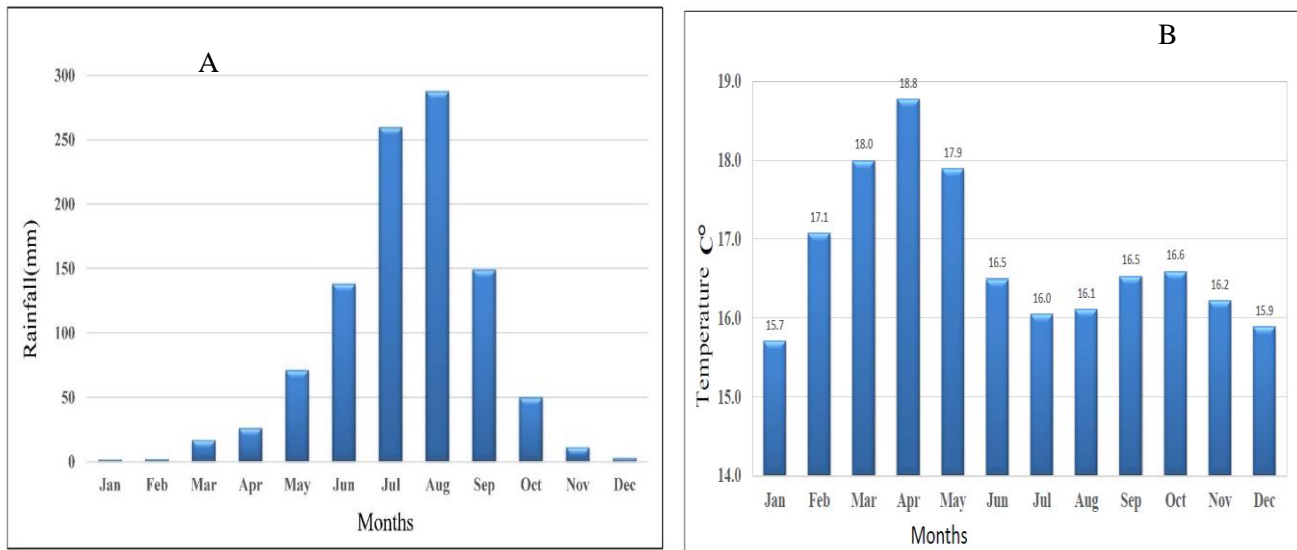


Figure 3. 6: Mean monthly rainfall (A), Average monthly temperature (B)

3.3. Data Description and Software

3.3.1. Data Description

Data were collected and compiled from data sources to attain the stated objective above. The Land-use and land-cover (LULC) map was generated by Water and Land Resources Information System (WALRIS) using a Landsat 8 in 2016. The high-resolution DEM 12.5 m as GeoTIFF format obtained from open source ALOSPALSAR (<https://search.asf.alaska.edu/#/>) for hydrological modeling (drainage), slope and elevation analysis.

The data used for those documents that were published and unpublished by different organizations. The principal source for identifying precipitation and temperature were the National Meteorological Agency. Vegetation cover (stem diameter, tree spacing or vegetation density and canopy height) as well as related data were gathered from environment, forest and climate change commission), Soil data from Minister of Water, Irrigation and Energy of Ethiopia, topographic map from Ministry of National Defense and different data related with high resolution imagery Ethiopian Ministry of Defense (EMOND). Table 3.2 lists all data used and their source in this research.

Table 3.2: Details of data and sources used in this study

No	Type of data/Description	Data type	Acquisition date	Source
1.	Soil conditions map	Vector	2017	Minister of Water, Irrigation and Energy of Ethiopia
2.	Climate conditions (Temperature and Rainfall Data) map	Point	1986-2018	National Metrological Agency (NMA)
3.	Hydrological map (Drainage)	Vector		Delineated from DEM 12 m
4.	LULC	Raster	2016	Water and Land Resources Information System (WALRIS)
5.	Topographic map (1:100,000)	Raster	1975	Ministry of National Defense
6.	Communications/Road network	Vector		Extracted from Geo-Eye Satellite Imagery
7.	Vegetation cover map	point	2016	Ethiopian Environment, Forest and Climate change Commission
8.	Built-up area	Vector		Extracted from Geo-Eye Satellite Imagery
9.	Surface (DEM) 12.5 m	Raster		Ethiopian Geospatial Information Agency
10.	Geo-Eye Image (0.3 m)_for feature extraction	Raster	2019	Ministry of National Defense
11.	Boundary of the study area	Vector		Delineate by researcher

3.3.2. Software packages

The software packages used for this study were ERDAS (Earth Resources Data Analysis System) Imagine 2015 for remote sensing application in order to preprocess satellite images and ENVI for LULC classification, ArcGIS 10.4 for data analysis and storage, visual exploration and map preparation and IDRISI 17.0 software is appropriate for fuzzifying to give weight with FAHP (Fuzzy Analytical Hierarchy Process) and to make aggregation using WLC (Weighted Linear Combination) for dependent factors to develop the final model. Table 3.3 lists all software package used and their application in this research.

Table 3.3: Summary of Software’s used in this study

No	Software used	Remark
1.	ArcGIS 10.4	1. Digitizing and generating the needed data layers (vector and raster data models) in a compatible format for the Knowledge engineer (KE). 2. The FUZZY Logic and WOA Process.
2.	ERDAS Imagine 2015	1. Image preprocessing in order to improve the quality of image OR to acquire good visualization.
3.	IDRISI Andes	Calculation of eigenvector of factors/weight
4.	Global Mapper 19	Patching and DEM file conversion, Watershed Generation

3.4. Methods

The method included the following stages: i) data collection; ii) identification and evaluation of criteria iii) preprocessing; iii) input dataset; iv) reclassified input layers; v) standardizing criteria with fuzzy approach; vi) Pair-wise comparison of criteria and give weight with FAHP; vii) Fuzzy aggregation with multi criteria evaluation and validation (Figure 3. 7).

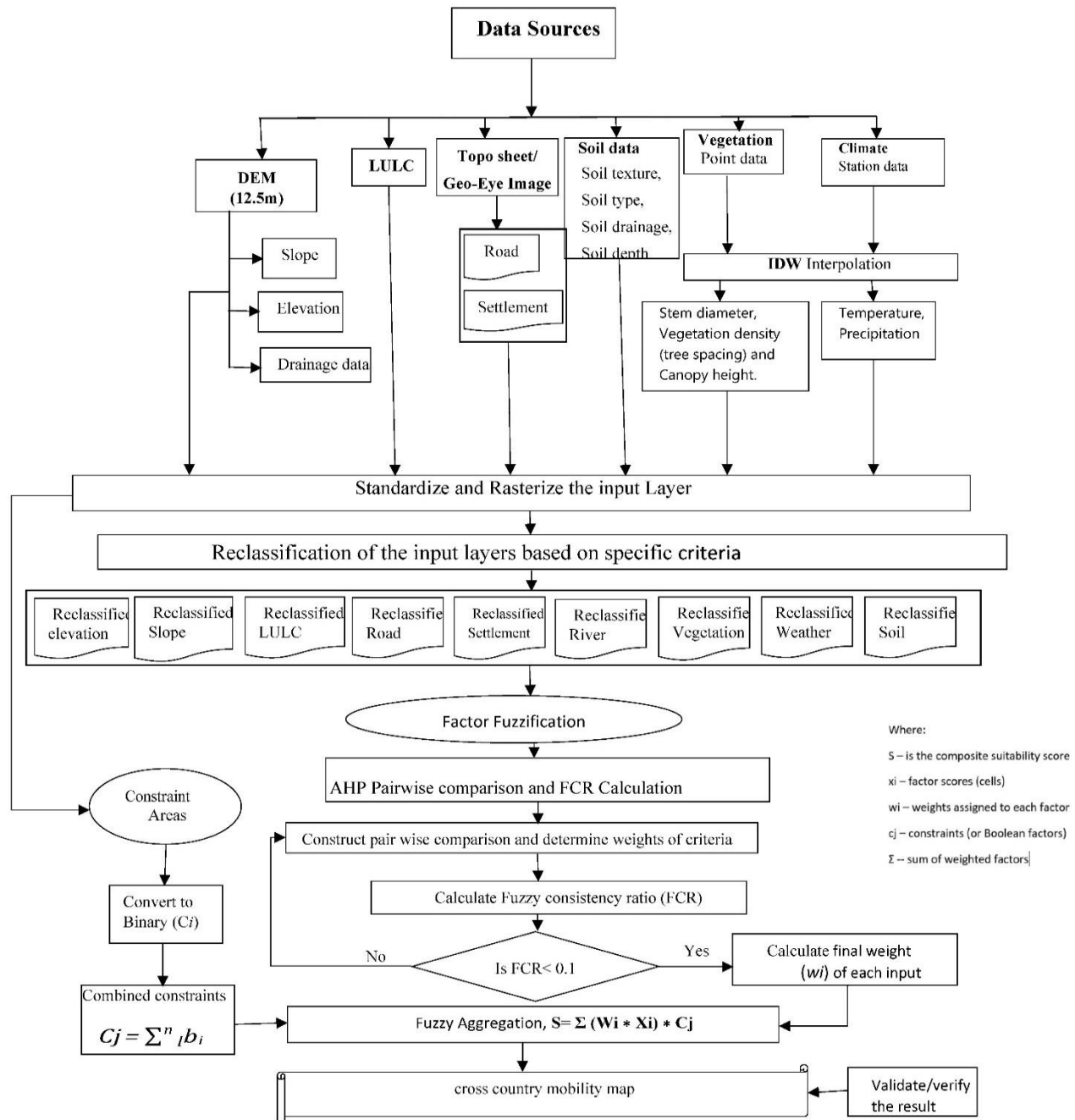


Figure 3. 7: General research methodology

3.4.1. Standardization of Geographic Factors

One of the objectives of this study is to identify the influential geographic factors that affect the cross-country mobility (trafficability of the terrain) and to set some standardized procedures for establishing

of these factors. Influence of the slope, elevation, vegetation, water, soil, climate, urban area, transportation, and other features on the cross-country movement.

In data analysis phases, the techniques for identification of appropriate geographical factors (input criteria), data organization, data checking, data processing and editing were done. On the other hand, exploratory (experimental) data analysis attribute table design and editing, data cleaning, field verification, digitization, data integration, data validation, data transforming, modeling and algorithms with the goal of discovering useful information, suggesting conclusions, and supporting decision-making was carried out. While in data standardization criteria such as constraints dataset and thematic layers were converted into raster data format and the converted layers were reclassified based on an elaborate literature search, endogenous and expert knowledge have been conducted. However, before analysis and standardization of the raw data, the following main activities have been carried out.

3.4.1.1. Slope of terrain relief

Slope is the inclined surface of a hill, mountain, ridge, or any other part of the earth's land surface. It is the inclination not only of major surface relief features (hills and mountains), but also of minor relief features like ditches, small gullies, mounds, low escarpments, small pinnacles, and sinkholes that generally do not appear on topographical maps. While some of the minor relief features may be considered a factor of roughness rather than slope, they are included in the general slope category because their obstacle value is due to the steepness of their slopes, banks, or faces. Short vertical slopes, or "steps" higher than 0.3 meters of slow wheeled vehicles, and 1.5 meters could stop tanks. The steep slopes commonly make cross-country vehicular movement difficult or impossible in mountainous areas. Existing terrain can channel the movements. Usually the amount of slope is expressed as a percentage which is the number of meters of difference in elevation per 100 meters of horizontal distance. Under optimal conditions, most military vehicles can ascend 60 percent (about 30/35 degrees) slopes. However, that limit is too big to negotiate in military operations. 45 per cent (about 27 degrees) is commonly used as the reasonable upper limit for tanks and 30% (about 17 degrees) for trucks when evaluating terrain for cross-country movement. Wet weather, trees, unfavorable soil conditions, snow, boulders, and the use of obstacles to reinforce can impassable gentle slopes (FM 5-102). The slope was reclassified in to five categories as shown in Figure 3.8, ranked between most suitable for flat to <5 degrees and unsuitable for slopes greater than 25 degrees (Table 3.4).

Table 3.4: Slope gradient and effect on vehicles.

Factors	Criteria value	Effect on tracked vehicle	Effect on wheeled vehicle
Slope	<= 5	Easy	Passable
	5–10	Passable	Passable slowly
	10–20	Passable slowly	Passable very slowly
	20–25	Passable very slowly	Passable very slowly with great difficulty
	>= 25	Passable very with great difficulty (25–30)	Impassable

Source: FDRE Military Topography Officers Handbook (Addis Ababa, 1998), NATO standards.

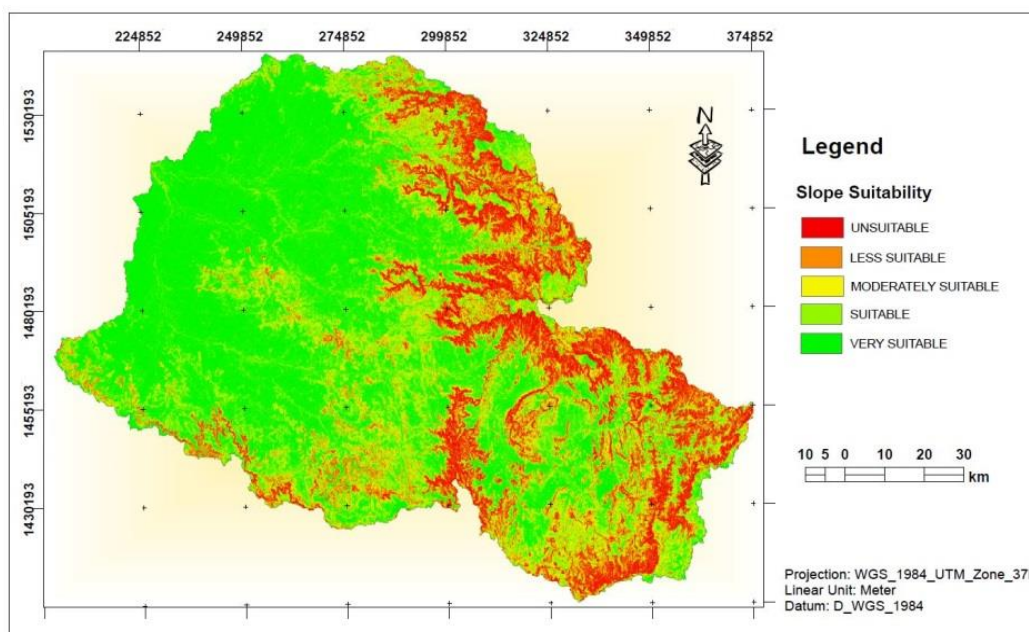


Figure 3. 8: Reclassified slope map

3.4.1.2. Elevation of terrain relief

Elevation data, measured as a relative height above a known datum (sea level), is used to describe the terrain for an area (FM 7-20, 1978). The ALOS PALSAR (12.5 m) DEM of the study area is shown in Figure 3.9 presents the highest elevation of 3067 meters and lowest elevation of 535 meters above mean sea level.

The study area is located within the Dansha Plains which comprises extensive tracts of almost level to gently undulating lightly dissected land, broken in places by groups of rocky hills. The area is divided

into three main relief features: the western zone comprised mainly of plains and lowland areas with 547 m above the sea level as the highest peak, while the central part comprised of upland areas with elevation ranging between 547 m and 1808 m above the sea level. The eastern and southern margins of the areas are more strongly dissected with elevation ranging from 1808 to 3069 m (Figure 3.9). The highest peak in the area is 3069 m which is located at the bottom of Ras Dashen Mountain. Therefore, locations with high elevations were also added to this category considering they slow down wheeled, tracked and foot traffic.

Table 3.5: Criteria for terrain relief

Factors	Criteria value	Classification
Elevation	<=500	Very suitable
	500–900	Suitable
	900–1000	Moderately suitable
	1000–1500	Less suitable
	>=1500	Unsuitable

Source: FDRE Military Topography Officers Handbook (Addis Ababa, 1998), NATO standards and (FM 7-20, 1978).

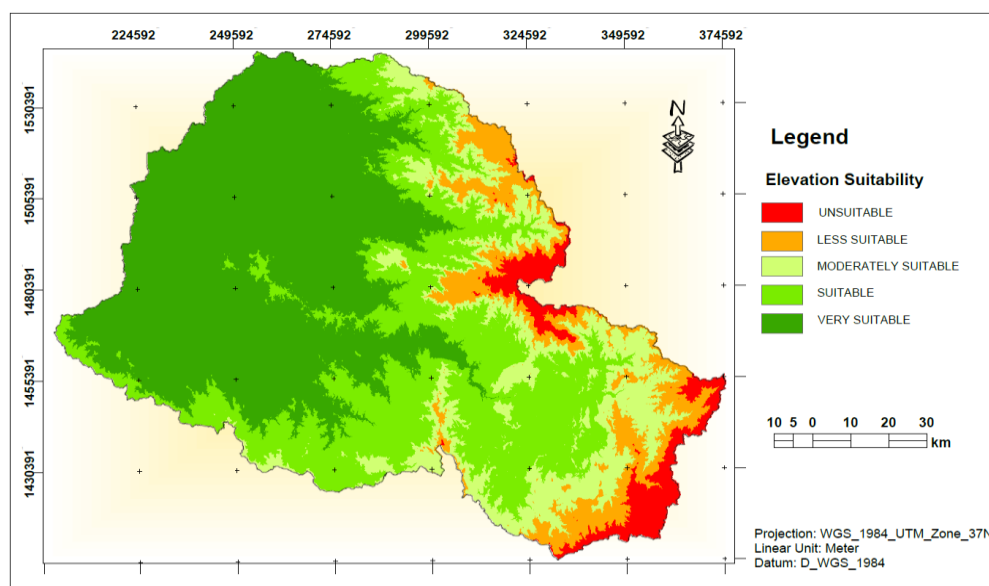


Figure 3. 9: Reclassified elevation map

3.4.1.3. Vegetation

Vegetation includes not only natural, "wild" vegetation, but also cultivated forests and crops. The primary concern of cross-country movement is forest vegetation. Trees are major barriers to movement. While high grass and brush can obstruct vision, in most cases they are of relatively minor significance. However, practically all forests have a slowing effect on movement. Tank obstacles are forests with trees 20 to 25 centimeters (8 to 10 inches) in diameter, and most wheeled vehicles can be stopped by 5 centimeter (2-inch) stands. Fully reliable criteria related to trees size and the significance of species and root systems were not determined. For example, medium tanks pushed up as much as 30 centimeters (12 inches) in diameter over single trees. Complications will also be created by overturning trees within stands; for example, if several trees are pushed over, some will interlocked with other trees to form a better obstacle to motion. Obstacles to vehicles are the protruding root system and trunks of overturned trees. The critical average distance between trees is about 3 to 5 meters (10 t) in forests where trees are too large to be pushed over, depending upon whether the trees are regularly or irregularly planted. Though this distance may be large enough for the vehicle to pass, there is no room for turning in most cases. For two reasons, recognition is particularly important as a source of information about the vegetation. Firstly, two of the trees' size characteristics and the distances between them are rarely recorded. Second, the size and distances frequently are difficult to determine from satellite imagery or aerial photography. Tree blowdown during nuclear attack can present significant mobility problems (FM 5-102, 1985).

In this study the vegetation cover data source was Ethiopian Environment, Forest and Climate change Commission which were collected in 2016. The data were included trunk diameter, average distance between trees and canopy heights as point data format. The thematic map of vegetation cover for the study area was interpolated using Arc GIS 10.4 from available point data by using an Inverse Distance Weighted (IDW) technique. Inverse distance weighted is a deterministic estimation method where values at unmeasured points are determined by a linear combination of values at nearby measured points. Among available parameters, the power parameter can significantly affect the results. As the power parameter increases, IDW acts similarly to the nearest neighbor interpolation method in which the interpolated value is close to the value of the nearest measured value. The advantages of IDW are that it is simple, easy to understand, and efficient but kriging is that it requires substantially more computing time and more input from users, compared to IDW (Yi-Hwa (Eva) Wu *et al.*, 2016).

The vegetation cover was reclassified in to five categories as shown in Figure 3.10 tree spacing or density, Figure 3.11 tree diameter and Figure 3.12 tree height ranked between most suitable to unsuitable (Table 3.6, 3.7 and 3.8).

Table 3.6: Criteria for tree spacing OR (Vegetation density)

Factors	Tree Density (No tree/0.5ha)	Classification
Tree spacing OR (Density)	<=30	Very suitable
	30–40	Suitable
	40–50	Moderately suitable
	50–60	Less suitable
	>=60	Unsuitable

Source: NATO standards classify terrain, (FM 5-102, 1985).

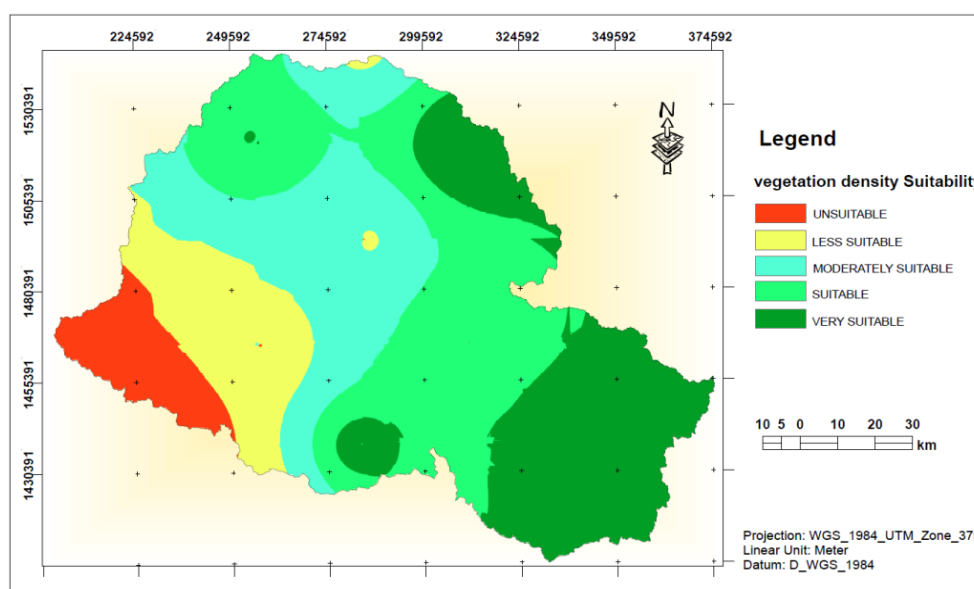


Figure 3.10: Reclassified vegetation density map

Table 3. 7: Criteria for Trunk diameter

Factors	Stem diameter (cm)	Classification
Trunk diameter	<=25	Very suitable
	25–30	Suitable
	30–35	Moderately suitable
	35–40	Less suitable
	>=40	Unsuitable

Source: NATO standards classify terrain, (FM 7-20, 1978).

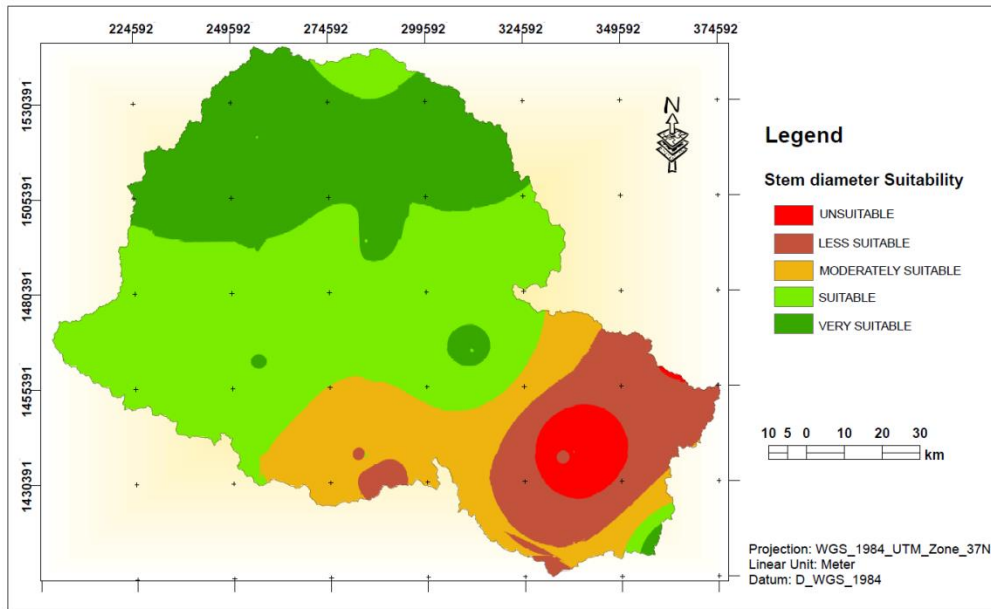


Figure 3.11: Reclassified vegetation (Tree diameter) map

Table 3.8: Criteria for height of vegetation

Factors	Canopy height (m)	Classification
Height of vegetation	<=8	Very suitable
	8-9	Suitable
	9-10	Moderately suitable
	10-11	Less suitable
	>=11	Unsuitable

Source: FM 5-33 (1990), FM 5-102 (1985), FM 7-20 (1978).

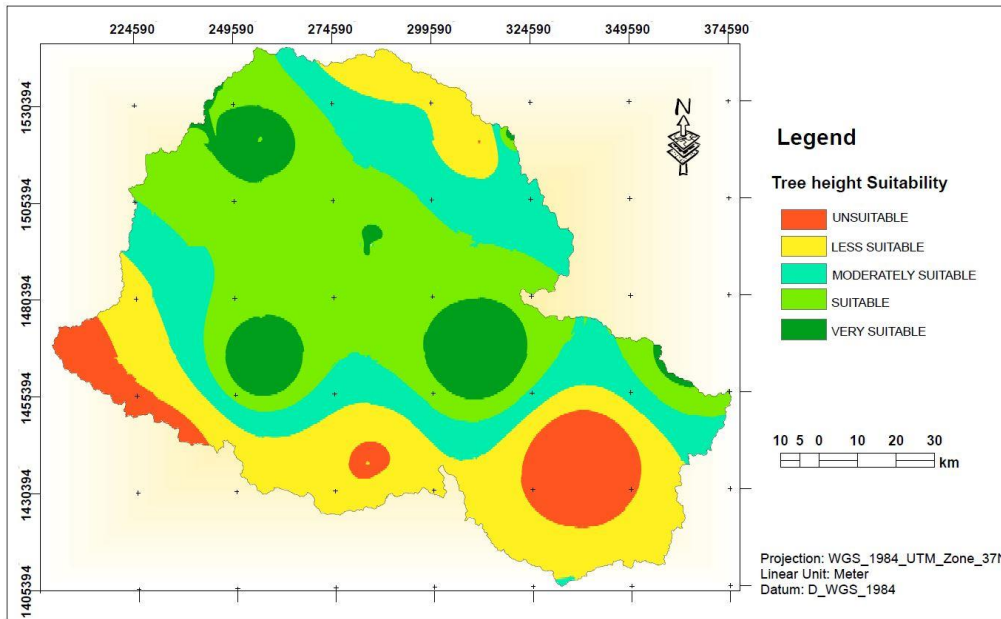


Figure 3.12: Reclassified vegetation (Tree height) map

3.4.1.4. Drainage Features

Features of drainage or surface water include rivers, streams, canals, lakes, ponds, marshes, swamps, and moorings. Such characteristics are obstacles when the water becomes deep or turbulent enough to threaten soldiers' safety and vehicle operations. Large, unfordable rivers are formidable obstacles because they must be crossed by tactical bridging, swimming, ferrying, or special deep-water fording. Ease of crossing these rivers is determined by the width, depth, velocity, turbulence, bank and bottom conditions, and rapid tactical bridging available, and existing bridges. Minor fordable rivers, streams, and canals are much more numerous than major rivers and their tactical value as obstacles should not be overlooked. These features are variable in effectiveness as obstacles. Careful preparation is important to incorporate these into the network of obstacles. Watercourses are often elongated obstacles in the terrain that might otherwise be excellent for movement. Drainage also affects the road net orientation and the direction of movement within an environment. The collapse of a few chosen bridges can cause cross-country or long detours. During floods, minor rivers and streams will become major obstacles. They can cause conditions that extend the obstruction effect for a considerable period by damaging temporary and expedient bridges, and by deepening the river or stream's original channel, making it difficult or impossible to access or egress.

Foldability of a stream expresses how easily it may be crossed without the means of bridging or ferrying. Fordability depends on characteristics of both the vehicle and the stream. Significant features of streams are: channel width, water depth and speed, bottom shape, height, slope, and bank strength. These features may vary independently, so that even the smallest stream fording requires selecting a site where favorable conditions coincide. A stream is a minor hindrance when a ford is available and usable with little or no improvement. A stream is a major obstacle if there is a lack of a suitable ford, or if fording involves significant planning of approaches, bottom protection or the use of special equipment on vehicles. A tank can bridge stream channels that are less than 3 meters long, but wheeled vehicles do not have the ability. Once the capacity of tracked vehicles to self-bridge is exceeded, streams can only be crossed by bridging, ferrying, or fording. Although the width of a stream is significant for bridging, ferrying (provided it is wide enough) and fording are relatively insignificant. The wider the source however, the greater the danger involved. For fording, the maximum permissible water depth for most tanks is between 0.9 and 1.5 meters (3 to 5 feet); and for trucks, roughly 0.9 meters (3 feet). Vehicles can be fitted with deep water fording devices that allow them to traverse water bodies as deep as 5 to 6 meters (17 to 20 feet). The first few vehicles can often negotiate a ford with minor difficulty, but the remaining ones cannot be able to cross because use has deteriorated in the bottom conditions or approaches. For reasonably safe fording the stream speeds should be less than 1.5 meters (5 feet) per second. The stream channels at the bottom must be firm enough to support vehicles. Bottoms made up of fine-grained material can prevent fording even though the water may be only a few inches deep. Suitable bottoms are restricted to those that are sandy, gravelly, or rocky; but even sandy bottoms may give way under the weight of vehicles, or boulders may prevent vehicular movement. The banks also are important. Hard, vertical banks can hinder tanks when bank height exceeds 1.5 meters (4 feet), and trucks when bank height exceeds 0.3 meters (1 foot). Greater heights can be tolerated if the vehicles are able to get adequate traction or if help such as winching is being used. The type of the material that makes up the banks can be significant. Banks formed from fine-grained soils can fail in repeated traffic. Sandy and gravel materials generally provide adequate durability and strength (FM 5-102, 1985).

a) Watershed Delineation and Stream extraction

The high-resolution 12.5 m DEM obtained from open source (<https://search.asf.alaska.edu/#/>) for hydrological modeling (drainage), slope and elevation analysis. Before using the DEM, it was recommended that the data must be processed through three phases. According to Jenson (1991), stated that depressions in the DEM were first filled by raising the values of cells in depressions to the value

of the depression’s spill point. Next, the computation of the flow direction for each cell in the depressionless DEM was performed. The direction water will flow out of each cell is encoded to correspond to the orientation of one of the eight cells that surround the cell. The third conditioning step is that computation of the flow accumulation value for each cell. This is the count for each cell of how many upstream cells would contribute drainage to it based on their flow directions (Mason and Maidment, 2000). Therefore, in DEM processing the above listed three phases were applied and slope, drainage and the watershed boundary were directly derived from filled DEM.

The purpose of filling raw DEM data is, to improve the accuracy of the data by removing peak, pits (sinks) and flat areas to maintain continuity of flow to the catchment outlet. Sinks and peaks in a DEM are often errors due to the resolution of the data or rounding of elevations to the nearest integer value. In ArcGIS, the fill tool uses to locate and fill sinks as well as remove peaks. The tool iterates until all sinks within a specified Z limit are filled and again iterates until all peaks within a specified z limit are removed. The overall hydrological modeling process is shown in (Figure 3.13).

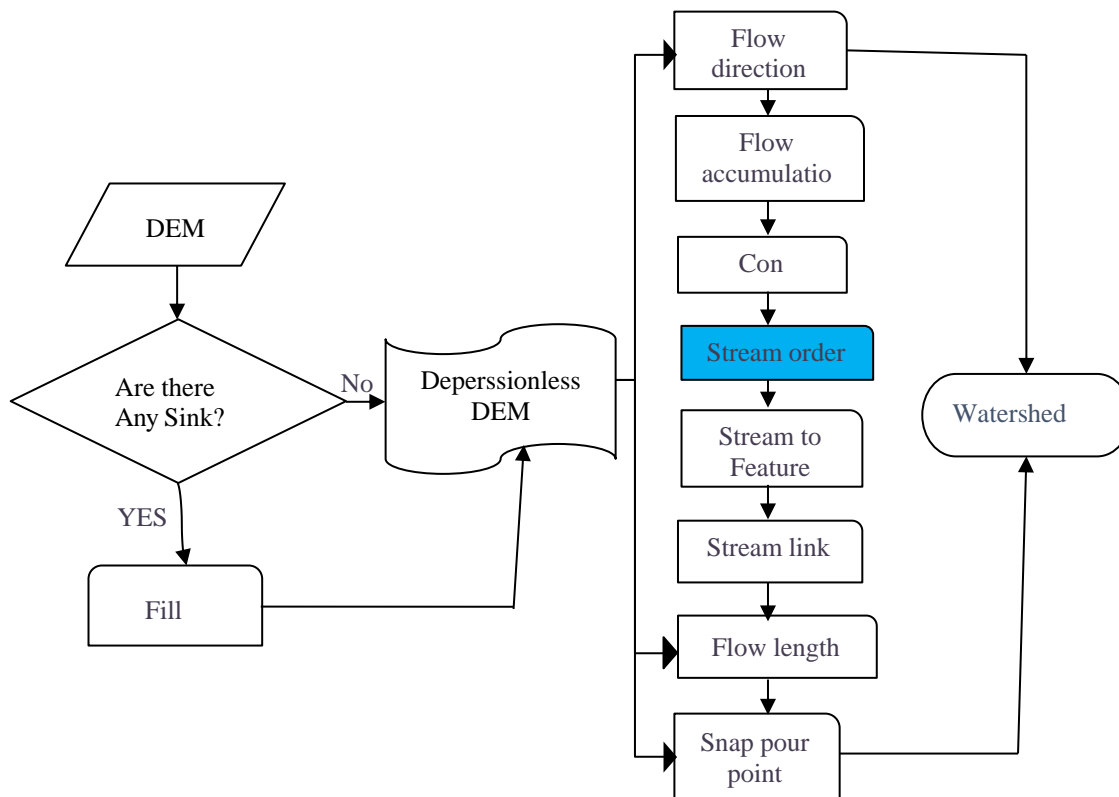


Figure 3.13: Hydrological modeling-stream order extraction flow chart.

Water bodies that flow through a current through the study area and are contained within a narrow channel, and banks are known as rivers, creeks or streams. A tributary is a stream that flows into a main stem river not flowing directly into the biggest river. The Stream Order tool was used to categorize streams in our watershed by size. Stream Order is a common classification system used to study and measure the size of the study area waterways: the further downstream the stream is, the higher the order; the further upstream the stream, the more likely it is to dry up during parts of the year.

When studying stream order, it is important to recognize the pattern associated with the movement of streams up the hierarchy of strength. Because the smallest tributaries are classified as first order, scientists often give them the value of 1. It then takes a joining of the two first order streams to form a second order stream. When two streams of the second order merge, they form a third order stream, and when two streams of the third order join, they form a fourth, and so on (Figure 3.14). However, if two different-order streams join, neither can increase in order. For example, if a second order stream joins a third order stream, the second order stream simply ends by flowing its contents into the third order stream, which then maintains its place in the hierarchy (Land Trust, 2009).

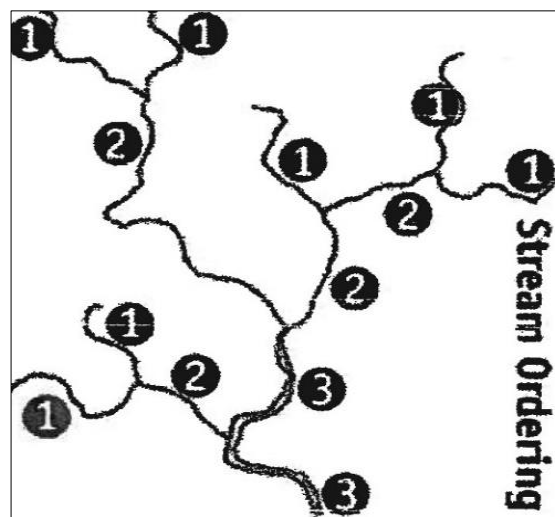


Figure 3.14: Stream-ordering system

The basic property of stream-order numbers is that if two "orders" N be combined [operation denoted by an asterisk (*)] the resulting stream is of order $N+1$.

Hence: $N*N=N+1$ (6)

This relates algebraically the operation of combination and the operation of addition [denoted as usual by plus (+)], with respect to channels of the same order (Adrian, 1965).

In this study the drainage (stream order) was reclassified in to five categories as shown in Table 3.9 and Figure 3.15.

Table 3.9: Criteria for Drainage (Stream order)

Factors	Stream Order	Classification
Drainage	1,2	Very suitable
	3	Suitable
	4	Moderately suitable
	5	Less suitable
	6	Unsuitable

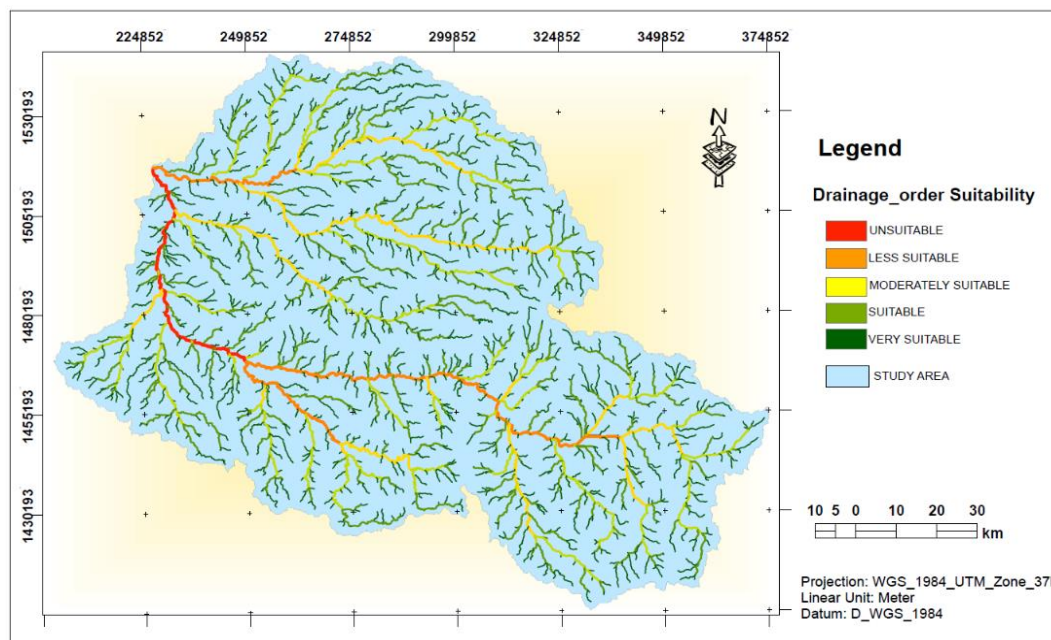


Figure 3.15: Reclassified Drainage order map

3.4.1.5. Land-use and land-cover

According to Gebreslasie (2009), land-use and land cover-cover mapping was used to assess if bypass was enough for a given type of vehicle. Further, expanding the illustration, a region was too vegetated for the cross- country movement if the vegetation was both too closely spaced for the vehicle to drive around and too thick for the vehicle to override. According to the opinion of experts, Shrub and Bushland

are the most suitable ones while forests and water bodies are not possible to traverse. In the study area, the grasslands are found in plain areas where there is seasonal flooding. Agricultural lands are assumed to provide a better traction for the mobility of military vehicles than grasslands.

For the purpose of cross-country trafficability modeling, the land use and land cover of the study area was classified in to twenty-four classes (Figure 3.4). Although land cover can be identified in paper maps, remote sensing data was used in this research to delineate the major land use and land cover of the study area as the topographic maps were outdated and do not include detailed features of the terrain. For the ease of modeling in the WLC, Bare lands are merged with shrub and bush lands as very suitable. On the other hand, Water bodies are merged with Woodland dense, swamp, settlement dense and urban, swamp grassland, Riverine vegetation, river course, grassland wet or undrained, forest, dryland forest, degraded hills and cropland in hill terrain as unsuitable and reclassified accordingly. In the Expert system the Woodland dense, swamp, settlement dense and urban, swamp grassland, Riverine vegetation, river course, grassland wet or undrained, forest, dryland forest, degraded hills, cropland in hill terrain; Woodland open, Bu(settlement), mixed forest, homestead plantation, exposed rock, cropland with tree; Shifting cultivation, plantation forest; Shrub and bush dense, grassland drained, cropland with no tree; Shrub/bush open and Bare land/Open space are assigned with raster values; 1,2,3,4 and 5 respectively. Accordingly, the different classes were reclassified and ranked in to five suitability classes such as unsuitable, less Suitable, moderately suitable, suitable, and very suitable classes with raster values as 1,2,3,4 and 5 (Figure 3.16), respectively for the WLC.

Table 3.10: Criteria for land-use and land-cover

Source: (FM 5-33, 1990, MMWR, 2008 and RM-TEREX, 2012)

Factor	Description	Classification
Land-use and land-cover	Shrub and bush open, Bare land/Open space	Very suitable
	Shrub and bush dense, grassland drained, cropland with no tree, Shifting cultivation, plantation forest	Suitable
	Woodland open, Bu(settlement), mixed forest, homestead plantation, exposed rock, cropland with tree	Moderately Suitable
	Woodland dense, swamp, settlement dense and urban, swamp grassland, riverine vegetation, river course, grassland wet or undrained, forest, dryland forest, degraded hills, cropland in hill terrain	Less suitable
	Woodland dense, swamp, settlement dense and urban, swamp grassland, riverine vegetation, river course, grassland wet or undrained, forest, dryland forest, degraded hills, cropland in hill terrain	Unsuitable

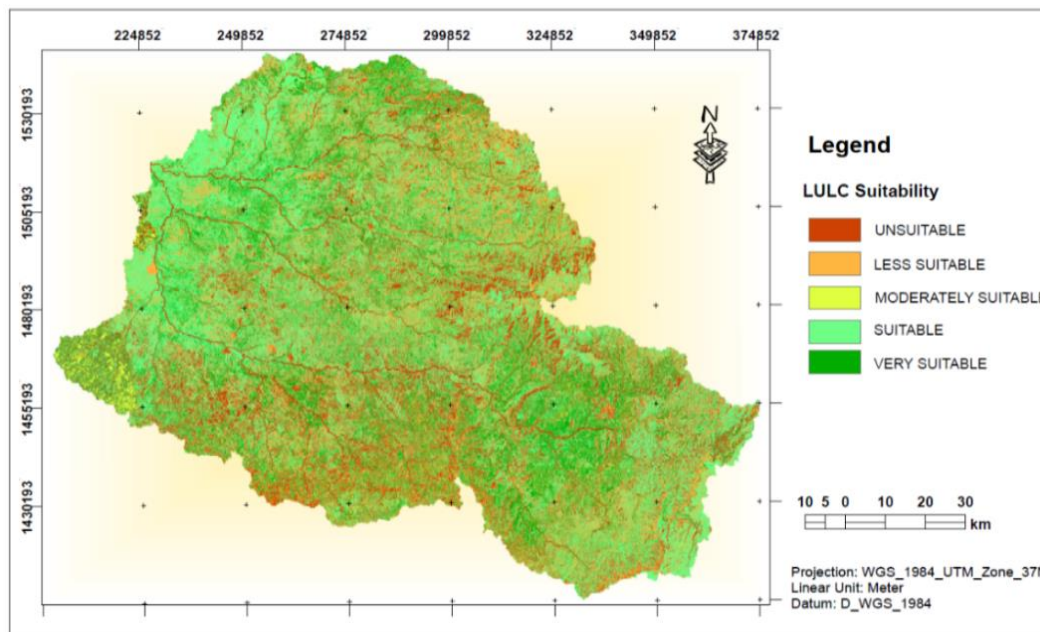


Figure 3.16: Reclassified land-use and land-cover map

3.4.1.6. Soils

Several literatures and knowledge of experts has been used to categorize these soils according to their clay content and depth and their impact for the movement of military vehicles in off-road condition and in a natural soil. High clay content reduces affordability of the soil and raises dust which in turn reduces visibility (FM 5-33, 1990).

According to GlobalSecurity.org, (2000) the slipperiness and stickiness of the soils impact the trafficability of soils and is determined by the bearing capacity of soils. Several literatures and mainly soil experts are used to transfer the agricultural soil classification in to their engineering characteristics and associated with the *FDRE Military Topography Officers Handbook* (Addis Ababa, 1998) which categorizes the impact of soil types on the mobility of vehicles in a generalized manner.

A terrain analysis manual prepared by the United States Department of Army, FM 5-33 (1990) ranked soil types according to their affordability for off-road trafficability by considering their clay content. According to this manual, soil types are ranked in order of decreasing affordability for off-road mobility as grave; sand; silt and clay.

As there is no soil map of the country classified in this respect, the soil of the study area Table 3.11 was ranked according to increasing content of clay in each soil as described by the soil reference base for soil resources prepared by FAO (2006), NATO standards classify and knowledge of experts.

Accordingly, the different classes are reclassified and ranked in to five suitability classes unsuitable, poorly suitable, moderately suitable, suitable, and most suitable classes with raster values as 1,2,3,4 and 5, respectively. Figure 3.17 shows the reclassified soil map of the study area according to their suitability based on clay content and Figure 3.20 soil depth reference base for soil resources prepared by FAO (2006) yields the following characteristics of the soils identified in the study area.

3.4.1.6.1. Soil Types

- i. **Leptosols:** are very shallow soils which are highly gravely and/or stony over dense rock and soils.
- ii. **Cambisols:** Are medium and fine textured materials derived from a wide range of rocks, characterized by slight or moderate weathering of parent material and the absence of significant amounts of illuviated clay.
- iii. **Nitisols:** Are deep, well-drained, red, tropical soils with diffuse horizon boundaries and a subsurface horizon with more than 30 per cent clay and moderate to strong angular blocky structural elements that easily disintegrate into characteristic shiny, polyhydrated (nutty) elements.
- iv. **Luvisols:** Are soils with a higher clay content in the subsoil as a result of pedogenetic processes (especially clay migration) leading to an argic subsoil horizon than in the topsoil. Luvisols are particularly active in the argic horizon and have a high base concentration at some depths.
- v. **Vertisols:** Are heavy, churning clay soils with a high proportion of swelling clays. These soils form deep wide cracks downwards from the surface when they dry out, which occurs in most years.
- vi. **Regosol:** Is one of the 30 soil groupings in the Food and Agriculture Organization (FAO) classification system. Regosols are characterized by shallow, medium to one-texture, unconsolidated parent material of alluvial origin and lack of significant soil horizon (layer) formation due to dry or cold weather conditions. They are usually found under their original natural vegetation or under limited dryland cropping (FAO soil group, 2020).
- vii. **Calcisol:** Is also one of thirty soil groups within the Food and Agriculture Organization (FAO) classification system. Calcisols are distinguished at any depth in the soil profile by a layer of translocated (migrated) calcium carbonate-whether soft and powdery or hard and cemented. They are typically well-drained soils of one to medium texture, and due to their high calcium content they are fairly fertile (FAO soil group, 2020). By consulting experts, the soil classification in the study area is translated into its engineering features. As a result, the soil is reclassified according to clay content and depth in up to five suitability classes. Leptosol soil types are found to be the most appropriate soil types while Vertisols and

Calcisol with the highest clay content are the least appropriate in the suitability class. Figure 3.17 shows the reclassified soil type of the study area according to their suitability based on clay content and soil depth and texture.

Table 3.11: Criteria for Soil Type

Factor	Soil Type	Classification
Soil type	Leptosols	Very suitable
	Cambisols, Regosol	Suitable
	Nitisol	Moderately suitable
	Luvisols	Less suitable
	Vertisols, Calcisol	Unsuitable

Source: FDRE Military Topography Officers Handbook (Addis Ababa, 1998).

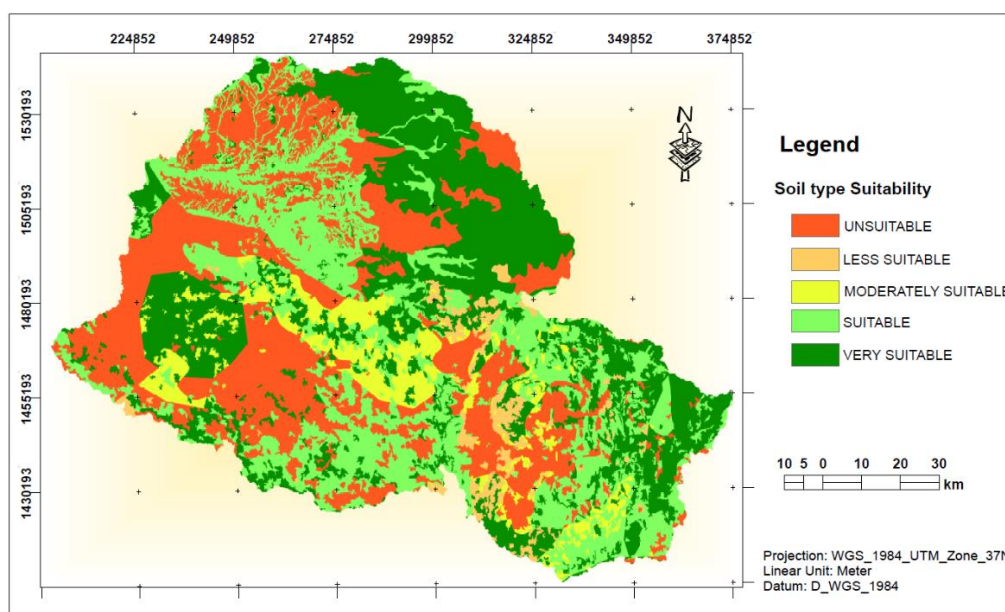


Figure 3.17: Reclassified soil type map

3.4.1.6.2. Soil Drainage

Drainage Class (natural) refers to the frequency and duration of wet periods under conditions similar to those under which the soil formed. Alterations of the water regime by human activities, either through drainage or irrigation, are not a consideration unless they have significantly changed the morphology of the soil. Seven classes of natural soil drainage are recognized-excessively drained, somewhat excessively drained, well drained, moderately well drained, somewhat poorly drained, poorly drained,

and very poorly drained. Drainage classes are from observations of water tables, soil wetness, landscape position and soil morphology. In many soils the depth and duration of wetness relate to the quantity, nature, and pattern of redoximorphic features. Redoximorphic features are soil features associated with wetness. They result from the reduction and oxidation of iron and manganese compounds in the soil after saturation with water and desaturation, respectively (*www.cteco.uconn.edu*).

As a result, the soil drainage was reclassified in to four suitability classes according to drainage characteristics. Well drained (W) are found to be the most suitable soil types while Poorly Drained (P) are the least suitable in the suitability class. Figure 3.18 shows the reclassified drainage of the study area according to their suitability based on organic content and soil depth and texture.

Table 3.12: Criteria for Soil Drainage

Factor	Soil Drainage	Classification
Soil Drainage	Well Drained (W)	Very suitable
	Imperfectly Drained(I)	Suitable
	Imperfectly Poorly Drained (IP)	Moderately suitable
	Poorly Drained (P)	Unsuitable

Source: FDRE Military topography officers’ handbook (Addis Ababa, 1998).

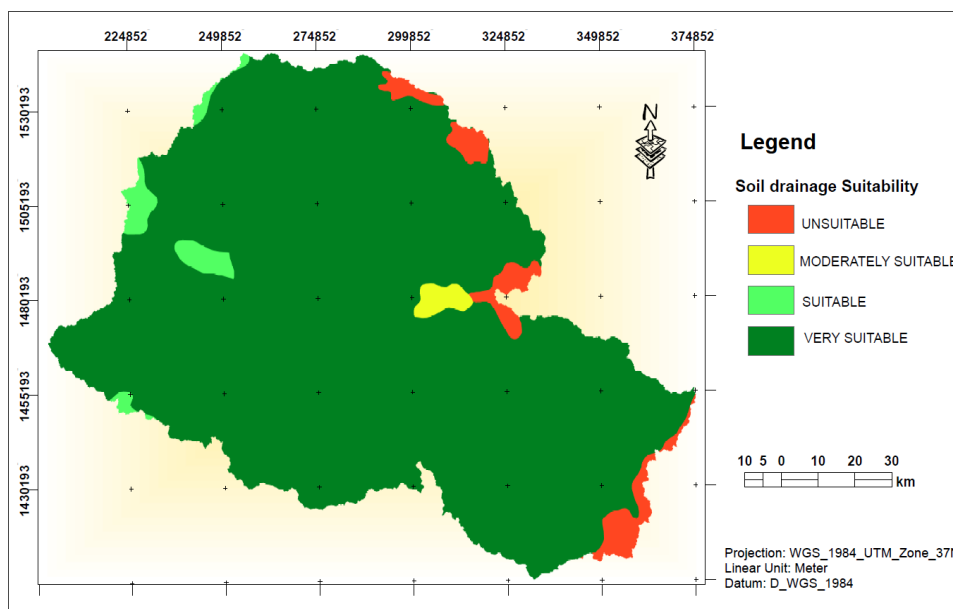


Figure 3.18: Shows the reclassified Soil Drainage map

3.4.1.6.3. Soil Texture

Soil texture describes the proportion of three sizes of soil particles and the fineness or coarseness of a soil. Soil texture may be determined in one of two ways. The percentages of sand, silt, and clay may be tested in the lab. Once tested, the textural class of the soil can be determined by referring to the textural triangle. Soils with different amounts of sand, silt, and clay are given different names. For instance, a soil containing 40 percent sand, 40 percent silt, and 20 percent clay is called loam soil (<http://www.public.iastate.edu/~arossi/page%202.htm>- accessed on 4/9/2020).

In this study area, the soil texture was reclassified in to three suitability classes according to textural size characteristics. Sandy Loams (Coarse silt) are found to be the most suitable soil texture while clays are the least suitable in the suitability class. Figure 3.19 shows the reclassified soil texture of the study area according to their suitability based on their size.

Table 3.13: Soil Textural Classes

Sandy Loam	<ul style="list-style-type: none"> • Dry—Clods easily broken; sand can be seen and felt. • Moist—moderately gritty; forms ball that can stand careful handling; definitely stains fingers. • Sand: 43–85%, Silt: 0–50%, Clay: 0–20%
Loam	<ul style="list-style-type: none"> • Dry—Clods moderately difficult to break; somewhat gritty. • Moist—neither very gritty nor very smooth; forms a ball; stains fingers. • Sand: 23–52%, Silt: 28–50%, Clay: 7–27%
Clay	<ul style="list-style-type: none"> • Dry—Clods cannot be broken with fingers without extreme pressure. • Moist—Quite plastic and usually sticky when wet; stains fingers. (A silty clay feels smooth; a sandy clay feels gritty.) • Sand: 0–45%, Silt: 0–40%, Clay: 40–100%

Table 3.14: Criteria for Soil Texture

Factor	Soil texture type	Classification
Soil Texture	Sandy loam (Coarse silt)	Suitable
	Loam (Silt)	Moderately Suitable
	Clay	Less Suitable

Source: FDRE Military Topography officers’ handbook (Addis Ababa, 1998), NATO standards.

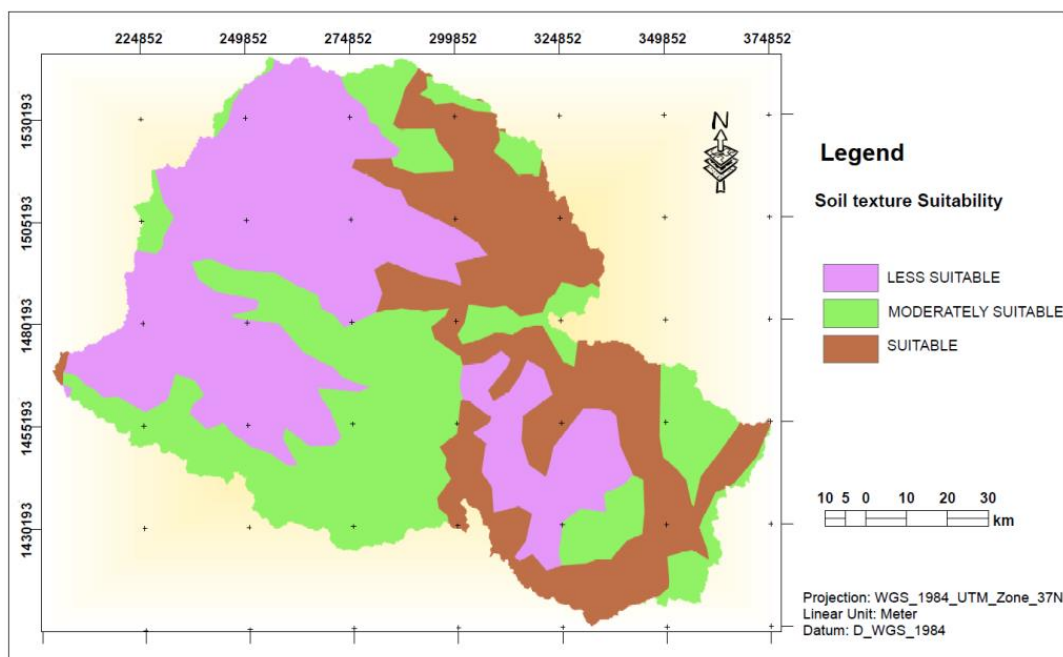


Figure 3.19: Reclassified soil texture map of the study area

3.4.1.6.4. Soil Depth

Soil depth is one of the most important input parameters for hydrological and ecological models. Its spatial pattern, significantly affects soil moisture, runoff generation, and subsurface and groundwater flow (Freer et al., 2002; McNamara et al., 2005; Stieglitz et al., 2003). Consequently, its accurate representation is becoming increasingly important. It is highly variable spatially, and laborious, time consuming and difficult to practically measure even for a modestly sized watershed (Dietrich et al., 1995).

Consequently, the soil depth was reclassified in to five suitability classes according to their distance characteristics. Very Shallow (≤ 30) are found to be the most suitable and Very deep soils (≥ 150) are the least suitable in the suitability class. Figure 3.20 shows the reclassified soil depth of the study area according to their suitability based on distance.

Table 3.15: Criteria for Soil depth

Factor	Soil depth	Depth (Topsoil + subsoil) (cm)	Classification
Soil depth	Very Shallow	<=30	Most suitable
	Shallow	30–50	Suitable
	Moderately deep	50–100	Moderately suitable
	Deep soils	100–150	Less suitable
	Very deep soils	>=150	Poorly suitable

Source: FDRE Military topography officer’s handbook (Addis Ababa, 1998), NATO standards.

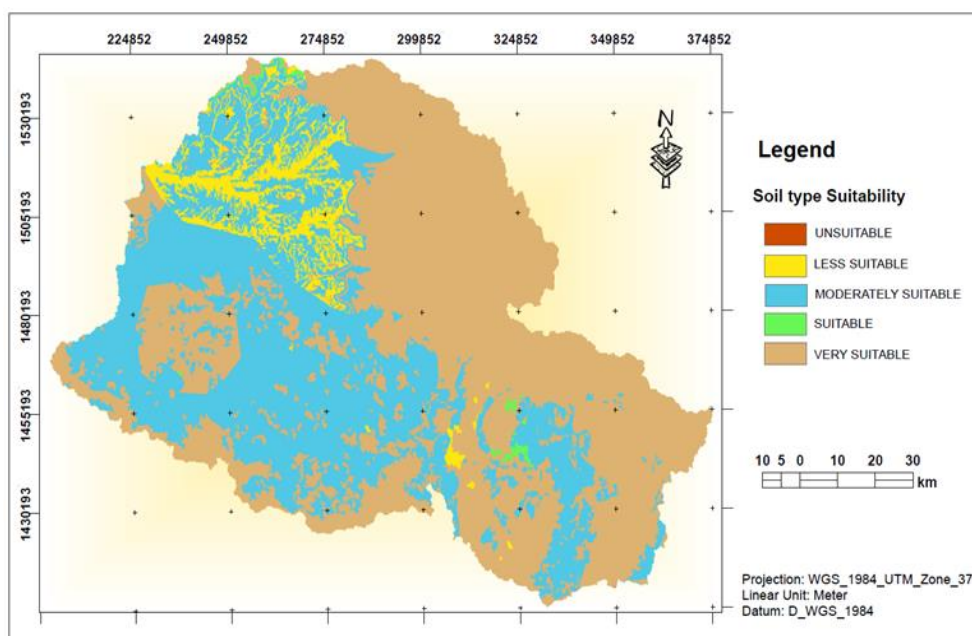


Figure 3.20: Reclassified soil depth map

3.4.1.7. Urban terrain

Depending on a unit’s mission, urban areas could be considered as obstacles. Due to potential collateral damage, civilians on the battlefield, and canalizing terrain, commanders may decide to bypass urban areas during the military decision-making process (MDMP). When considering that obstacles are used to disrupt, fix, turn, or block, it is understandable that an urban environment’s built-up terrain can be used to achieve these effects on air and ground mobility. Urban environment populations could also be considered as obstacles as they have the potential to restrict movement and freedom of action.

Urban environment interior and exterior spaces can present challenges to ground forces as well as to forces using the air domain. These spaces are often canalizing, making direction of movement predictable to opposing forces. City layouts, street patterns, and buildings are designed with ease of mobility in mind. These considerations direct movement and can make the direction of travel predictable during conflicts. They also provide threats likely areas where friendly force movement can likely terminate. For example, if friendly forces are conducting operations in a city with a radial layout, threat forces are more than likely know where to plan ambushes. Urban environments may also contain multiple obstacles to air and ground mobility, including but not limited to areas of civilian concentration, barriers, bridges and overpasses, buildings and streets, built-up areas masked to fires, doorways and hallways, stairways and staircases, subterranean terrain, towers, walls, windows, and wires. Trafficability through the build-up areas is affected by the following factors: *land coverage (a number of towns, cities and villages) of the area involved, location, structure, form and orientation of the urban areas* to the direction of troop’s movement and *width of urban area*, i.e. diameter of an urban area. In determining the cross-country mobility parameters of the urban areas, the GIS data, digital models of terrain and detailed plans of towns and cities can be used (<https://armypubs.army.mil/> accessed on 4/9/2020).

As a result, the urban areas were reclassified in to five suitability classes according to their area width. Areas $\leq 0.5\text{km}^2$) are found to be the most suitable and areas $\geq 3.5\text{km}^2$) are the least suitable in the suitability class. Figure 3.21 illustrates the reclassified urban area of the study area according to their suitability based on their area or width of the town.

Table 3.16: Criteria for urban area

Factor	Urban areas width	Classification
Urban areas	≤ 0.5	Most suitable
	0.5–1	Suitable
	1–1.5	Moderately suitable
	1.5–3	Less suitable
	≥ 3.5	Poorly suitable

Source: FDRE Military topography officer’s handbook (Addis Ababa, 1998), NATO standards.

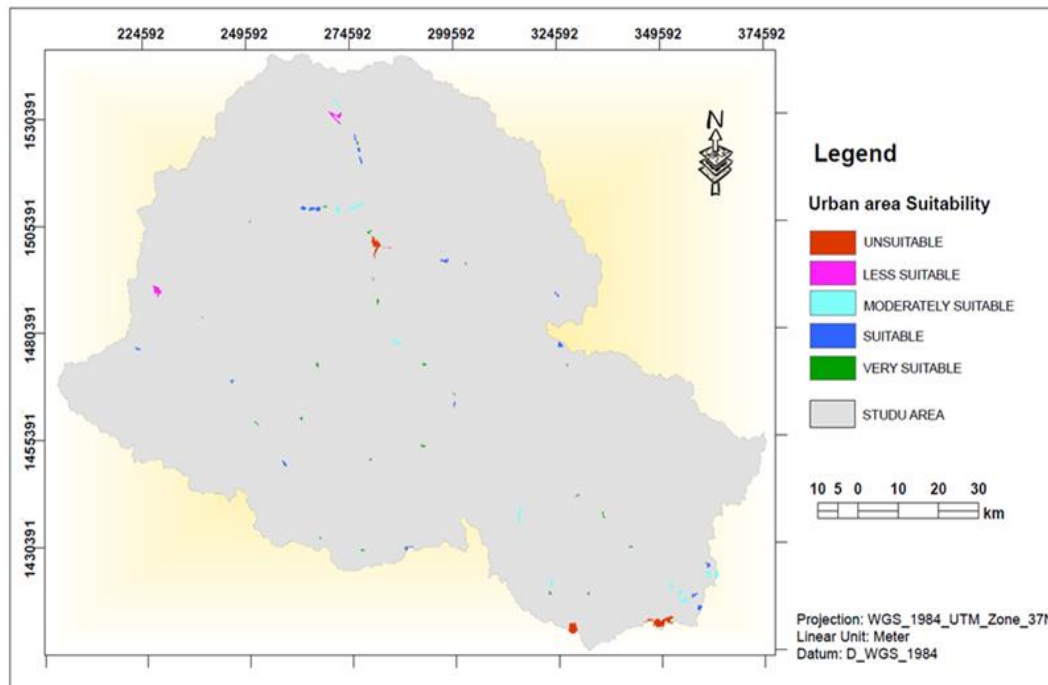


Figure 3.21: Reclassified urban areas map of the study area

3.4.1.8. Roads Network

Roads influence the cross-country mobility either as lines of communication, when they are directed with the axes of movement; objects of obstacles, when they lead across the direction of movement and created on the embankments or dugouts. They have a similar effect on the cross-country mobility as line elements. The cross-country mobility (trafficability) is greatly influenced by the road and railway network. Railway in terms of the cross-country mobility can be classified by: - number of tracks; traction (type of drive); track gauge and transportation significance (railway capacity per period of time). The road net is critical to the movement of the attacker's following echelons. For its logistical support the attacker must have a well-developed road net. Each break in this road net creates an obstacle to the rapid tactical movement of an attacker, the movement of his subsequent echelons and his logistics. If the break is rear or farther back in his division, its effect is prohibition. Corps and division obstacle plans, as well as denial plans, must consider this effect. Further, a highly developed road and/or railroad network with its numerous cuts, fills, and embankments creates obstacles to transverse movement which are comparable in extent to the drainage network (FM 5-102, 1985).

Within the study area, main (asphalt) roads and minor (gravel) roads can be found. Most of the roads are crossing to the town areas. The below classified data were reclassified as two classes. The asphalt

road was most suitable and the gravel road was suitable as shown on the following road class map based on quality of road surface (Figure 3.22).

Table 3.17: Criteria for road classes

Factor	Road class type	Classification
Road class	Asphalt	Most suitable
	Gravel	Suitable

Source: FDRE Military Topography Officers Handbook (Addis Ababa, 1998), (FM 5-102, 1985).

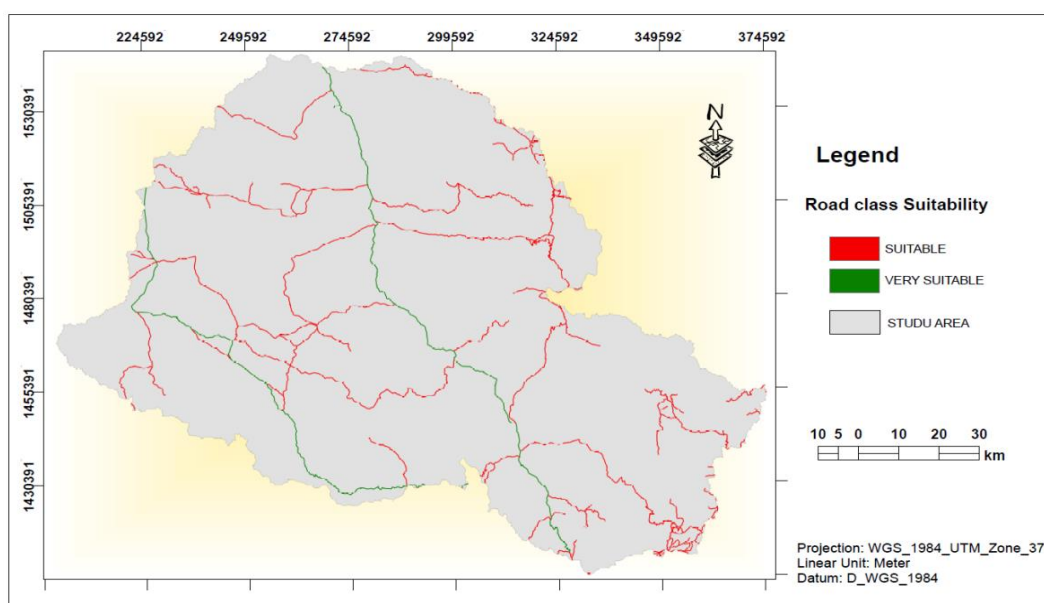


Figure 3.22: Reclassified road classes map

3.4.1.9. Climate Conditions

Climate and weather both significantly affect cross-country movement, although their effects are usually indirect, and their influence is variable in duration and difficult to predict. Climatic influences are usually reflected in the nature of the terrain and obstacles. To a large extent, climate controls soil moisture, and thus soil strengths. It also determines basic river and stream characteristics. Some easily overlooked direct effects of climate are important. Fog and haze, common in some areas, significantly affect weapons employment and can retard or even prevent movement. Dust storms and snowstorms have the

same effect. Seasonal weather patterns are important. An attacker anticipating a quick victory may choose to strike at any time of the year. Existing obstacles should be evaluated on the basis of the seasonal weather conditions to determine their obstacle value. The ability to evaluate terrain and properly assess its obstacle value provides a significant advantage to the commander who does it well. A good analysis enables the commander to determine avenues of approach, key terrain, and best areas for weapons employment. It also provides the commander a beginning for the obstacle plan. Full use of existing obstacles can help in conserving precious manpower and logistical effort necessary to emplace reinforcing obstacles (FM 5-102).

3.4.1.9.1. Temperature

Temperature that affect soil and rock properties, drainage coefficients and thus even the stream depth and velocity, character of precipitations (rain, snow.), slippery ice creation, rivers and streams ford ability especially during winter weather, mechanical properties of transport means. Temperatures are measured in °C (°F) and can be forecast from the weather maps where the temperatures are interpolated mainly from January and to December using ArcGIS 10.4 tool called IDW. According to Ethiopian Metrological Agency, the annual average temperature varies from 15.7 to 18.8-degree Celsius. Figure 3.23 shows the mean monthly temperature of the study area for thirty-two years.

As a result, the temperature was reclassified in to five suitability classes according to the annual average temperature. The temperature $\geq 17.9^{\circ}\text{C}$ were found to be the most suitable and the temperature $\leq 15.7^{\circ}\text{C}$ were the least suitable in the suitability class. Table 3.18 illustrates the reclassified temperature of the study area according to their suitability based on their temperature range.

Table 3.18: Criteria for Temperature

Factor	Temperature (°C)	Classification
Temperature	≤ 15.7	Poorly suitable
	15.7–16.5	Less suitable
	16.5–17.1	Moderately suitable
	17.1–17.9	suitable
	≥ 17.9	Most suitable

Source: FDRE Military topography officer’s handbook (Addis Ababa, 1998), NATO standards.

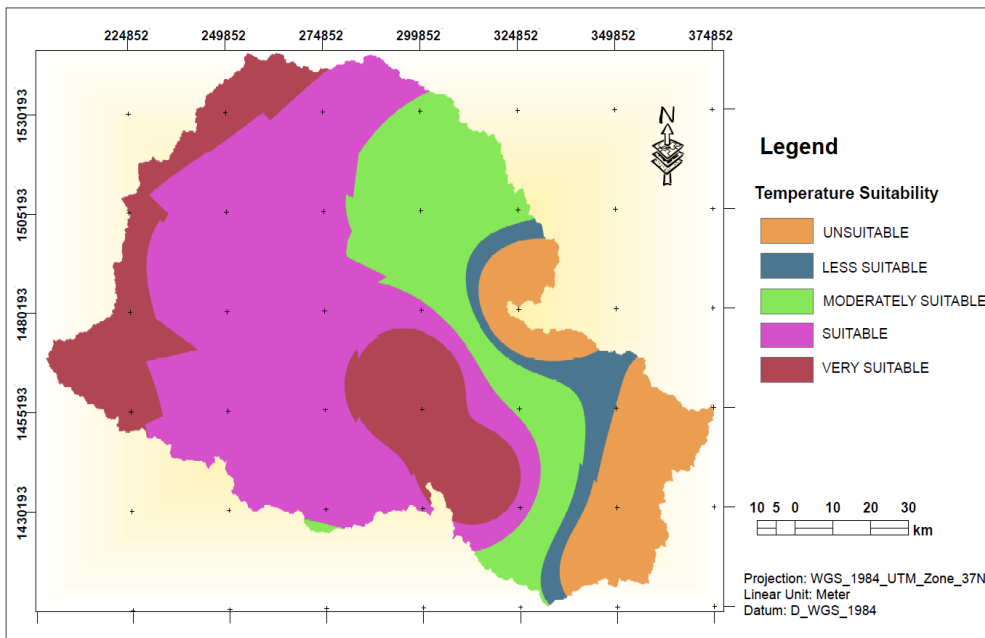


Figure 3.23: Reclassified temperature map of the study area

3.4.1.9.2. Precipitation

Precipitation is very important to trafficability. The effect depends on the type and amount of precipitation, the soil type, surface slope, type and amount of vegetation cover, and soil moisture content before the precipitation fell. Because of this complexity, exact rules are not given. However, the decision to use dry or wet values is, at present, up to the analyst’s judgement. Light showers seldom affect trafficability. They may even improve it over sand. However, moderate or greater rain can be degraded it. *Precipitation that affects especially:* - soil conditions and consequently the slope possibility, roads and terrain trafficability especially in winter season (during slippery ice and deep snow), rivers and streams possibility and especially the depth and velocity of currents. Precipitations are measured in mm/time and they can have a long-term effect on the cross-country mobility. Apart from the amount of rainfall or snowfall, this effect depends especially on drainage coefficients in individual river basins, on soil structure and temperatures. Precipitations can be forecast to a certain extent from the weather maps by interpolation methods from the hypsometric overlay of total precipitations; fogs, humidity and inversion that affect visibility during movement; clouds that affect the air forces flight capabilities (Rybansky, 2003).

According to Ethiopian Metrological Agency, excess rainfall intensity and distribution occur in the summer from July to mid-September, whereas the remaining season is characterized by little or no rain. Figure 3.24 shows the mean monthly rainfall of the study area. The mean monthly rainfall is averaged

for thirty-two years. Consequently, the rainfall was reclassified in to five suitability classes according to their mean distribution in millimeter. Rainfall ≤ 95 mm were found to be the most suitable and rainfall ≥ 200 mm was the least suitable in the suitability class. Table 3.19 shows the reclassified rainfall of the study area according to their suitability mean distribution. The rainfall of the study area is thirty-two years.

Table 3.19: Criteria for rainfall

Factor	Rainfall (mm)	Classification
Rainfall	≤ 95	Most suitable
	95–125	suitable
	125–150	Moderately suitable
	150–200	Less suitable
	≥ 200	Poorly suitable

Source: FDRE Military topography officer’s handbook (Addis Ababa, 1998), NATO standards.

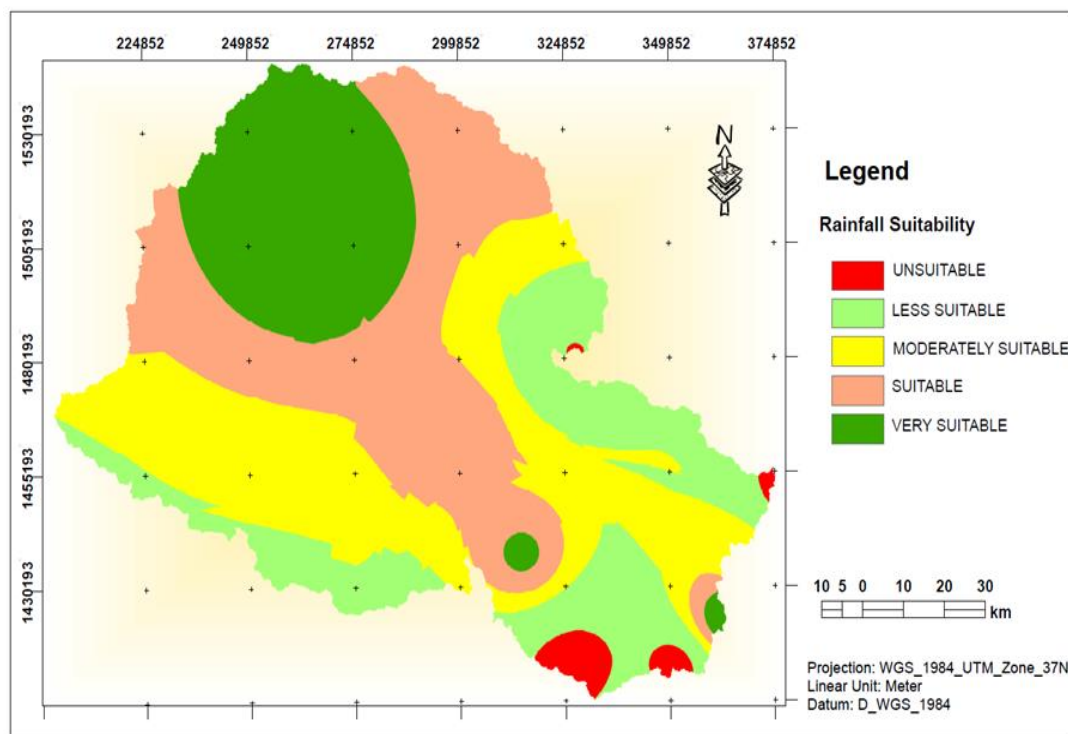


Figure 3.24: Reclassified rainfall map

3.5. The steps of Chang’s fuzzy extent analysis are as follows:

Step 1: Normalized values of row sums, also known as values of *fuzzy synthetic extent* where computed for each of the fuzzy judgment matrices, by making use of fuzzy arithmetic operations of equation 7.

$$\tilde{S} = \sum_{j=1}^n \tilde{a}_{ij} * \left[\sum_{k=1}^n \sum_{j=1}^n \tilde{a}_{kj} \right]^{-1} \tag{7}$$

Where *denotes the extended multiplication of two fuzzy numbers. To obtain $\sum_{j=1}^n \tilde{a}_{ij}$, the fuzzy addition operation was applied to the fuzzy numbers in the fuzzy judgment matrices, such that,

$$\sum_{j=1}^n = \sum_{j=1}^n l_j, \sum_{j=1}^n m_j, \sum_{j=1}^n u_j, \tag{8}$$

To obtain

$$\left[\sum_{k=1}^n \sum_{j=1}^n \tilde{a}_{kj} \right]^{-1}$$

the fuzzy addition operation was applied to column values in the matrix obtained from Equation 8, followed by computation of the inverse of the resulting vector such that,

$$\left[\sum_{k=1}^n \sum_{j=1}^n \tilde{a}_{kj} \right]^{-1} = \left(\frac{1}{\sum_{k=1}^n u_k}, \frac{1}{\sum_{k=1}^n m_k}, \frac{1}{\sum_{k=1}^n l_k} \right) \tag{9}$$

Step 2: This step involved taking two criteria at a time and then using their normalized TFNs obtained from Equation 9, to determine the degree of possibility of one criterion fuzzy number ‘s being greater than or equal to the other criteria fuzzy number’s $\tilde{S}_i \geq \tilde{S}_j$. This can be represented by Equation 10 as follows:

$$V(\tilde{S}_i \geq \tilde{S}_j) = \sup_{y \geq x} \left[\min \left(\tilde{S}_i(x), \tilde{S}_i(y) \right) \right] \tag{10}$$

Where *Sup* is ("supremum"), means basically the largest and **x** and **y** are the values on the axis of membership function of each criterion.

This can be equivalently expressed as,

$$V(\tilde{S}_i \geq \tilde{S}_j) = \begin{cases} 1 & \text{if } m_i \geq m_j \\ \frac{l_j - u_i}{(m_i - u_i) - (m_j - l_j)} & \text{if } m_j \leq u_j \\ 0 & \text{Otherwise} \end{cases} \quad (11)$$

Where $\tilde{S}_i = (l_i, m_i, u_i)$ and $\tilde{S}_j = (l_j, m_j, u_j)$.

In order to compare, \tilde{S}_i and \tilde{S}_j , both the values of $V(\tilde{S}_i \geq \tilde{S}_j)$ and $V(\tilde{S}_j \geq \tilde{S}_i)$ were computed (Figure 3.25).

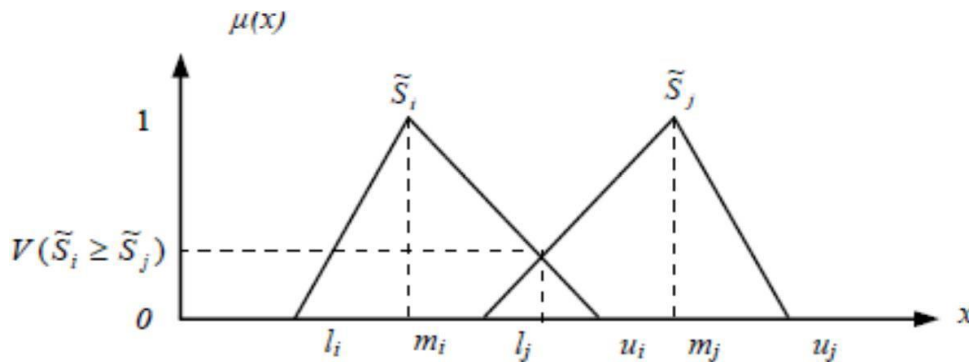


Figure 3.25 : The degree of possibility $(\tilde{S}_i \geq \tilde{S}_j)$

The degree of possibility for a fuzzy number to be greater than n fuzzy numbers $\tilde{S}_i = (1,2,3 \dots j)$ Can be defined by: $V(S \geq \tilde{S}_1, \tilde{S}_{12}, \tilde{S}_{13}, \dots, \tilde{S}_j) = [V(S \geq \tilde{S}_1) \text{ and } V(S \geq \tilde{S}_2) \text{ and } \dots \text{ and } V(S \geq \tilde{S}_j)]$

$$= \min V((S \geq \tilde{S}_i), i=1,2,3 \dots j) \quad (12)$$

Assume that $d(\tilde{A}_n) = \min V((S \geq \tilde{S}_i), j=1,2,3 \dots n, \text{ if } j \neq j \text{ then the weight vector is given by:}$

$$w' = d'(A_1), d'(A_2), d'(A_3), \dots, d'(A_n)^T \quad (13)$$

Where (\tilde{A}_i) are n elements

Via normalization, the normalized weight vectors are:

$$w = d(A_1), d(A_2), d(A_3), \dots, d(A_n)^T$$

Where w is a non-fuzzy number.

Step 3: The normalized weight vectors for each fuzzy comparison matrix, \tilde{A}_i at each level of the hierarchy were then determined by normalizing the weight vector, w. In other literature's this process is

known as defuzzification and involves dividing each value in the weight vector, by their total sum as follows:

$$W_i = \frac{(\tilde{s}_i \geq \tilde{s}_j \mid j=1, \dots, n; j \neq i)}{\sum_{k=1}^n (\tilde{s}_k \geq \tilde{s}_j \mid j=1, \dots, n; j \neq k)}, i = 1 \tag{14}$$

According to reviewed literatures and the expert’s opinions by perception or preference, Table 3.21-3.48 shows the pair comparison matrix of factors. Therefore, by considering the above algorithms, the fuzzy logic approach was used in the study to standardized factors in the range of 0 to 1. The fuzzy membership function tool in ArcGIS 10.4 or IDRISI 17 was used to derive membership functions for factors used to derive spatial suitability levels. The calculated weight (W) for each factor in the hierarchy is shown in the last column for Table 3.50.

In fuzzy AHP, the goal, criteria, and sub-criteria had been arranged into a hierarchical structure and evaluated by an expert. The relative importance of each criterion was determined by using linguistic variables which were represented as triangular fuzzy numbers. In this study, the Center of Gravity defuzzification method was used to convert the fuzzy evaluations into their corresponding crisp values.

3.6. A Case Study on Assessing Suitability of Cross-country Mobility

In this cross-country mobility prioritization problem, the relative importance of different decision criteria involves a high degree of subjective judgment and individual preferences. The linguistic assessment of human feelings and judgments are vague and it is not reasonable to represent them in terms of precise numbers. It feels more confident to give interval judgments. Hence, for taking the priority of one decision variable over another, triangular fuzzy numbers are used. The triangular fuzzy numbers are determined from reviewing literature. Thereafter, synthetic extent analysis method is used to decide the final priority weights based on triangular fuzzy numbers and so-called as fuzzy extended AHP method. In the following sections, the main steps of the method have been explained thoroughly.

Firstly, defines the main attributes (criteria) and alternatives (factors) for cross-country mobility suitability selection to design the fuzzy analytic hierarchy process tree structure. First, the overall objective of the Cross-country Mobility category prioritization problem has been identified which was “prioritization of the best Cross-country Mobility for military vehicles”. In the cross-country mobility, a lot of criteria should be taken into account because the competition is really high. All of the possible important criteria, which could affect the vehicles mobility of the critical part, have been discussed with experts in the operational and intelligence planning department. By combining the attributes that have

been determined by the expert and the attributes that have been used in the literature, the main attributes (criteria) and the alternatives (factors) in the study are determined. Three main attributes (criteria), nine alternatives (factors) and eight sub-alternatives (sub-factors) have been identified. The main determined attributes (criteria) are Physical criteria, Environmental criteria and Socio-economic criteria. The alternatives (factors) attributes are Slope, Soils, Elevation, Climate, Vegetation, Drainages, Roads, urban area and LULC. The sub-alternatives (sub-factors) are Soil type, Soil texture, Soil depth, Temperature, Rainfall, Stem diameter, Vegetation density (tree spacing) and Canopy height. Figure 3.26 shows the decision hierarchy model of Terrain CCM structure.

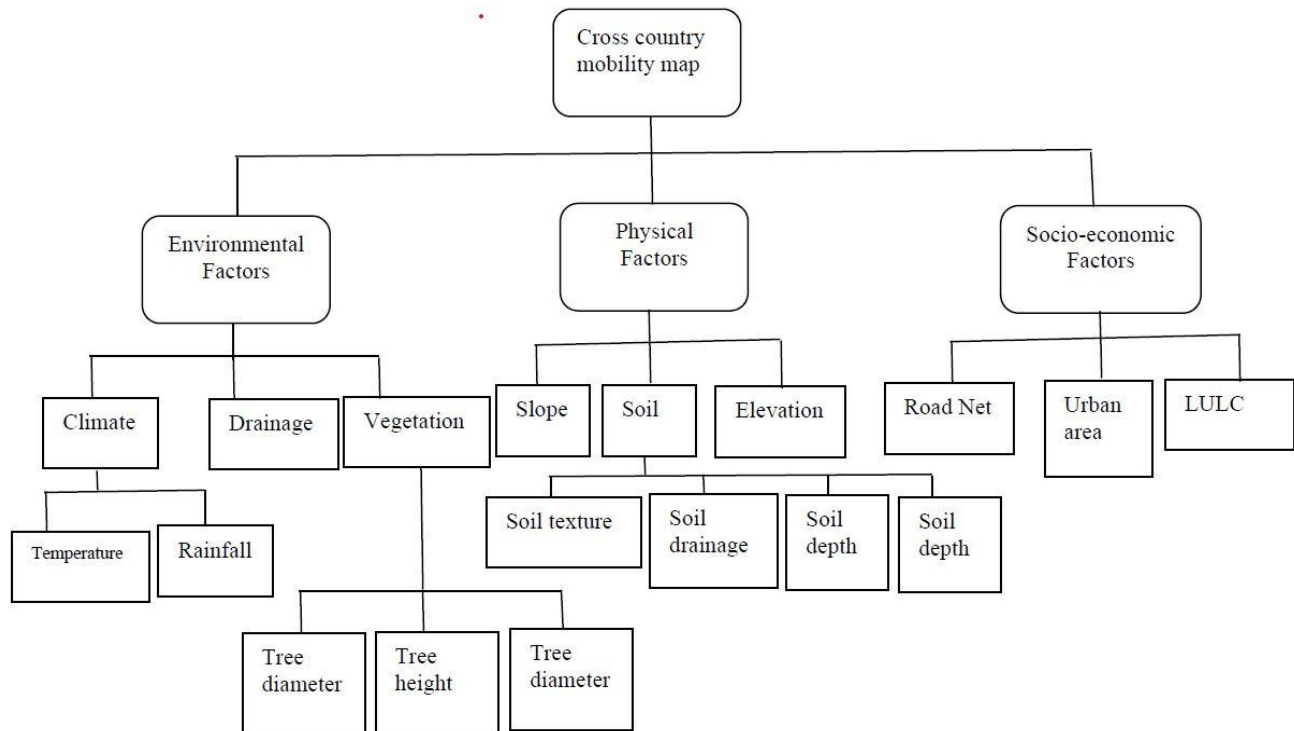


Figure 3.26: Hierarchy model for terrain CCM

Secondly, after forming the pairwise comparison matrices, the consistency of the pairwise judgment of each comparison matrix is checked using the calculation method of consistency index and consistency ratios in crisp AHP. Each triangular fuzzy number, $M = (l, m, u)$ in the pairwise comparison matrix is converted to a crisp number using:

$$M = \text{Crisp } (1+4m+u)/6 \tag{15}$$

After converting the fuzzy comparison matrices into crisp matrices, the consistency of each matrix is checked by the method in crisp AHP. For this, first, multiplying together the entries in each row of the matrix and then taking the n^{th} root of that product. The n^{th} are summed and that sum is used to normalize the Eigen value. The next stage is to calculate, multiply total value of each column to Eigen value. The consistency index for a matrix is calculated from $(\lambda_{\text{max}} - n) / (n-1)$. Some randomly generated consistency index (R.I) values are shown in Table 3.49. Acceptability of alternative or attribute is measured terms of Consistency Ratio (CR).

$$CR = RI / CI \tag{16}$$

Where CR is consistency ratio, RI is randomly generated consistency Index, CI is Consistency Index. After calculation, the consistency ratio of each comparison matrix is found to be under 0.10. Therefore, we can conclude that the consistency of pairwise judgments in all matrices is acceptable.

3.7. Calculating weight for each factors

Using Equation 4, TFNs used to represent vague data were then defined in the order. Linguistic variables, which are variables whose values are expressed in linguistic terms, were also used by the decision makers in situations not well defined to be reasonably described by conventional quantitative expressions. The proposed TFNs and matching linguistic variables related to Saaty’s scale of preference values along with their membership functions are provided in Table 3.20.

Table 3.20: Proposed TFNs, linguistic variables and membership functions.

Crisp-Saaty’s-scale-of relative-importance (Saaty, 1980)	Preference-expressed-in linguistic-variables by (Saaty, 1980)	TFNs.scale (l,m,u)	Reciprocal-of Triangular-Fuzzy numbers
1	Equally strong	(1,1,1)	(1,1,1)
3	Moderate strong	(1,3,5)	(1/5,1/3,1)
5	Strong	(3,5,7)	(1/7,1/5,1/3)
7	Very strong	(5,7,9)	(1/9,1/7,1/5)
9	Extreme strong	(7,9,9)	(1/9,1/9,1/7)
2,4,6,8	Intermediate		

Source: The scale is adopted from (Tsiko et al., 2011).

Table 3. 21: The fuzzy evaluation matrix with respect to goal with triangular fuzzy numbers **A: B1—3**

A(GOAL)	B1	B2	B3
B1	(1,1,1)	(1,3,5)	(3,5,7)
B2	(0.2,0.333,1)	(1,1,1)	(1,3,5)
B3	(0.143,0.2,0.333)	(0.2,0.333,1)	(1,1,1)

Where **A** is CCM, **B1** is Physical criteria, **B2** is Environmental criteria, **B3** is Socio-economic criteria

Table 3.22: Calculating Geometric mean (GM), Eigen value using Crisp AHP method

A(GOAL)	B1	B2	B3	GM	Eigenvalue
B1	1.00	3.00	5.00	2.46	0.61
B2	0.42	1.00	3.00	1.08	0.27
B3	0.21	0.42	1.00	0.43	0.10
Total	1.63	4.42	9.00	3.97	

$\lambda_{max} = (1.63 * 0.61) + (9.00 * 0.10) + (4.42 * 0.27) = 3.08$, $CI = (3.08-3)/3-1 = 0.04$, $RI = 0.58$, $CR = CI/RI = 0.04/0.58 = 0.068 = 6.8\%$.

As $CR \leq 10\%$, the level of consistency of comparison matrix is satisfactory.

In order to find the priority weights of the main attributes, first, the fuzzy synthetic extent values of the attributes are calculated by using Eq. (7). The different values of fuzzy synthetic extent of the three different main attributes are denoted by SB1, SB2, and SB3.

Table 3.23: Priority weights of the main attributes

A(GOAL)	B1	B2	B3	Row Sum
B1	(1,1,1)	(1,3,5)	(3,5,7)	(5,9,13)
B2	(0.2,0.333,1)	(1,1,1)	(1,3,5)	(2.2,4.333,7)
B3	(0.143,0.2,0.333)	(0.2,0.333,1)	(1,1,1)	(1.343,1.533,2.333)
Total sum				(8.543,14.863,22.333)

Inverse the row sum total using equation 10.

$(8.543, 14.863, 22.333) = (1/22.333, 1/14.863, 1/8.543)$

Multiply each row sum with inverse of row sum total.

$$SB1 = (5, 9, 13) \oplus (1/22.333, 1/14.863, 1/8.543) = (0.2239, 0.6054, 0.5217).$$

$$SB2 = (2.2, 4.333, 7) \oplus (1/22.333, 1/14.863, 1/8.543) = (0.0985, 0.2915, 0.8194).$$

$$SB3 = (1.343, 1.533, 2.333) \oplus (1/22.333, 1/14.863, 1/8.543) = (0.0601, 0.1031, 0.2731).$$

After obtaining SB1, SB2, and SB3 from equation 11, these fuzzy values are compared by using equation 12 and the following are obtained.

The degree possibility of Si over Si (i, j) is determined by using equations (13) and (14).

$$V (SB1 \geq SB2) = 1.000, V (SB1 \geq SB3) = 1.0000, V (SB2 \geq SB1) = 0.6548, V (SB2 \geq SB3) = 1.000$$

$$V (SB3 \geq SB1) = 0.0892, V (SB3 \geq SB2) = 0.4810$$

Using this minimum degree of possibility:

$$D' (B1) = V (SB1 \geq SB2, B2) = \min (1.000, 1.000) = 1.000.$$

$$D' (B2) = V (SB2 \geq SB1, B3) = \min (0.6548, 1.000) = 0.6548$$

$$D' (B3) = V (SB3 \geq SB1, B2) \min (0.0892, 0.4810) = 0.0892.$$

$$\text{Weight vector, } W' = (1, 0.6548, 0.0892)$$

Therefore,

$$W' = ((d' (DB1), d' (DB2), d' (DB3))^T = (1, 0.6548, 0.0892)^T$$

The priority weights with respect to main goal are calculated using equation 15 as the normalized weight vectors for the decision criteria DB1, DB2 and DB3 are calculated as follows: $W = (0.57360939, 0.37552001, 0.05087059)^T$

Table 3.24: The fuzzy pairwise comparison matrix of alternatives under decision criteria- **A: B1-B3**

A(GOAL)	B1	B2	B3	Defuzzified normalized weight
B1	(1,1,1)	(1,3,5)	(3,5,7)	0.57360939
B2	(0.2,0.333,1)	(1,1,1)	(1,3,5)	0.37552001
B3	(0.143,0.2,0.333)	(0.2,0.333,1)	(1,1,1)	0.05087059

Therefore, the weight is given as $= (1, 0.6548, 0.0892)^T$. After normalization process, the weight vector of the main attributes(criteria), which are Physical criteria, Environmental criteria and Socio-economic criteria is found to be $W = (0.5733, 0.3754, 0.0511)^T$. We can conclude that the most important attribute (criteria) in the cross-country mobility suitability selection process is Physical criteria, because it has the highest priority weight. Environmental criteria and Socio-economic criteria are the next preferred attribute (criteria).

Table 3.25: The pairwise comparison matrix, **B1:C1—C3**.

B ₁	C ₁	C ₂	C ₃
C ₁	1,1,1	3.0,5.0,7.0	1.0,3.0,5.0
C ₂	0.14,0.2,0.33	1,1,1	0.2,0.33,1.00
C ₃	0.2,0.33,1.00	1.0,3.0,5.0	1,1,1

Where **B1** is Physical Criteria, **C1** is Slope, **C2** is Elevation, **C3** is Soil and **GM** is Geometric Mean is the weight of C1, C2 and C3.

Table 3.26: Calculating Geometric mean (GM), Eigen value using Crisp AHP method

B ₁	C ₁	C ₂	C ₃	GM	Eigenvalue
C ₁	1.00	5.00	3.00	2.46	0.61
C ₂	0.21	1.00	0.42	0.43	0.10
C ₃	0.42	3.00	1.00	1.08	0.27
Sum	1.63	9.00	4.42	3.97	

$\lambda_{max} = (1.63 * 0.61) + (9.00 * 0.10) + (4.42 * 0.27) = 3.08$, $CI = (3.08-3)/3-1 = 0.04$, $RI = 0.58$, $CR = CI/RI = 0.04/0.58 = 0.068 = 6.8\%$.

As **CR** < 10%, the level of consistency of comparison matrix is satisfactory.

In order to find the priority weights of the vegetation criteria (attributes), first, the fuzzy synthetic extent values of the attributes are calculated by using Eq. (8). The different values of fuzzy synthetic extent of the three different vegetation factors (alternatives) are denoted by SC1, SC2 and SC3.

Table 3.27: Priority weights of the physical criteria

B₁	C₁	C₂	C₃	Row sum
C ₁	1,1,1	3.0,5.0,7.0	1.0,3.0,5.0	(5,9,13)
C ₂	0.14,0.2,0.33	1,1,1	0.2,0.33,1.00	(1.343,1.533,2.333)
C ₃	0.2,0.33,1.00	1.0,3.0,5.0	1,1,1	(2.2,4.333,7)
Sum				(8.543,14.866,22.333)

Inverse the row sum total using equation 10.

$$(8.543, 14.866, 22.333) = (1/22.333, 1/14.866, 1/8.543)$$

Multiply each row sum with inverse of row sum total.

$$SC1 = (5, 9, 13) \oplus (1/22.333, 1/14.866, 1/8.543) = (0.2239, 0.6054, 1.5217).$$

$$SC2 = (1.343, 1.533, 2.333) \oplus (1/22.333, 1/14.866, 1/8.543) = (0.0601, 0.1031, 0.2731).$$

$$SC3 = (2.2, 4.333, 7) \oplus (1/22.333, 1/14.866, 1/8.543) = (0.0985, 0.2915, 0.8194).$$

After obtaining SC1, SC2 and SC3 from equation 8, these fuzzy values are compared by using equation 12 and the following are obtained.

The degree possibility of **Si** over **Si** (i j) is determined by using equations (13) and (14).

$$V (SC1 \geq SC2, SC3) = 1.00; V (SC2 \geq SC1, SC3) = 0.0892; V (SC3 \geq SC1, SC2) = 0.6548$$

$$\text{Weight vector, } W' = (1.00, 0.0892, 0.6548)^T$$

Therefore,

$$W' = ((d' (DC1), d' (DC2), d' (DC3)) ^T = (1.00, 0.0892, 0.6548)^T$$

The priority weights with respect to physical attributes (criteria) are calculated using equation 15 as the normalized weight vectors for the decision criteria DC1, DC2 and DC3 are calculated as follows:

$$W = (1.00, 0.0892, 0.6548)^T = 1.00+0.0892+0.6548= 1.744$$

$$(1.00/1.744, 0.0892/1.744, 0.6548/1.744)^T = W = (0.573394495, 0.05114679, 0.37545872)^T$$

Table 3.28: Priority weights of the physical criteria

B ₁	C ₁	C ₂	C ₃	Defuzzified normalized weight
C ₁	1,1,1	3.0,5.0,7.0	1.0,3.0,5.0	0.573394495
C ₂	0.14,0.2,0.33	1,1,1	0.2,0.33,1.00	0.05114679
C ₃	0.2,0.33,1.00	1.0,3.0,5.0	1,1,1	0.37545872

Therefore, the weight is given as $W' = (1.00, 0.0892, 0.6548)^T$. After normalization process, the weight vector of the physical Criteria attributes(criteria), which are Slope, Elevation and Soil is found to be $W = (0.5733944954, 0.05114678899, 0.37545871560)^T$. We can conclude that the most important attribute (criteria) in the cross-country mobility suitability selection process is slope, because it has the highest priority weight. Soil and Elevation are the next preferred attributes (criteria) respectively.

Table 3.29: Pair-wise comparison matrix C2: C5—8.

C2	C5	C6	C7	C8
C5	1,1,1	1.0,3.0,5.0	3.0,5.0,7.0	5.0,7.0,9.0
C6	0.20,0.33,1.0	1,1,1	1.0,3.0,5.0	3.0,5.0,7.0
C7	0.14,0.20,0.33	0.20,0.33,1.0	1,1,1	1.0,3.0,5.0
C8	0.11,0.14,0.20	0.14,0.20,0.33	0.20,0.33,1.0	1,1,1

Where **C2** is Soil criteria, **C5** is Soil type, **C6** is Soil drainage, **C7** is Soil texture, **C8** is Soil depth, **GM** is Geometric Mean is the weight of **C5**, **C6**, **C7** and **C8** to **C3**.

Table 3.30: Calculating Geometric mean (GM), Eigen value using Crisp AHP method

C2	C5	C6	C7	C8	GM	Eigenvalue
C5	1.00	3.00	5.00	7.00	3.20	0.55
C6	0.42	1.00	3.00	5.00	1.58	0.27
C7	0.20	0.42	1.00	3.00	0.70	0.12
C8	0.14	0.21	0.42	1.00	0.31	0.05
Sum	1.76	4.63	9.42	16.00	5.79	

$\lambda_{max} = (1.76 * 0.55) + (4.63 * 0.27) + (9.42 * 0.12) + (16 * 0.05) = 4.14$, $CI = (4.14-4)/4-1 = 0.04$, $RI = 0.90$, $CR = CI/RI = 0.047/0.90 = 0.044 = 4.4\%$.

As $CR < 10\%$, the level of consistency of comparison matrix is satisfactory.

Table 3. 31: Priority weights of the main attributes

C2	C5	C6	C7	C8	Row sum
C5	(1,1,1)	(1.0,3.0,5.0)	(3.0,5.0,7.0)	(5.0,7.0,9.0)	(10,12,22)
C6	(0.20,0.33,1.00)	(1,1,1)	(1.0,3.0,5.0)	(3.0,5.0,7.0)	(5.2,9.33,14)
C7	(0.14,0.20,0.33)	(0.20,0.33,1.0)	(1,1,1)	(1.0,3.0,5.0)	(1.48,1.67,2.53)
C8	(0.11,0.14,0.20)	(0.14,0.20,0.330)	(0.20,0.33,1.0)	(1,1,1)	(2.34,4.53,7.33)
Sum					(18.99,27.53,45.86)

In order to find the priority weights of the main attributes, first, the fuzzy synthetic extent values of the attributes are calculated by using Eq. (8). The different values of fuzzy synthetic extent of the three different main attributes are denoted by SC5, SC6, SC7 and SC8.

Inverse the row sum total using equation 10.

$$(18.99, 27.53, 45.86) = (1/45.86, 1/27.53, 1/18.99)$$

Multiply each row sum with inverse of row sum total.

$$SC1 = (10, 12, 22) \oplus (1/45.86, 1/27.53, 1/18.99) = (0.21, 0.43, 1.15).$$

$$SC2 = (5.2, 9.33, 14) \oplus (1/45.86, 1/27.53, 1/18.99) = (0.11, 0.33, 0.73).$$

$$SC3 = (1.48, 1.67, 2.53) \oplus (1/45.86, 1/27.53, 1/18.99) = (0.05, 0.16, 0.38).$$

$$SC4 = (2.34, 4.53, 7.33) \oplus (1/45.86, 1/27.53, 1/18.99) = (0.03, 0.06, 0.13).$$

After obtaining SC1, SC2, and SC3, these fuzzy values are compared and the following are obtained.

The degree possibility of Si over Si (i j) is determined:

$$V(SC1 \geq SC2, SC3, SC4) = 1; V(SC2 \geq SC1, SC3, SC4) = 0.83; V(SC3 \geq SC1, SC2, SC4) = 0.38; V(SC4 \geq SC1, SC2, SC3) = 0.075$$

$$\text{Weight vector, } W^* = (1.00, 0.83, 0.38, 0.075)$$

Therefore,

$$W' = ((d'(\text{DC1}), d'(\text{DC2}), d'(\text{DC3}))^T = (1.00, 0.83, 0.38, 0.075)^T$$

The priority weights with respect to physical attributes (criteria) are calculated as the normalized weight vectors for the decision criteria DC1, DC2 and DC3 are calculated as follows:

$$W' = (0.47577462, 0.33803709, 0.15026848, 0.03591981)^T$$

Table 3.32: Priority weights of the Soil criteria- C2: C5-C8

C2	C5	C6	C7	C8	Defuzzified normalized weight
C5	1,1,1	1.0,3.0,5.0	3.0,5.0,7.0	5.0,7.0,9.0	0.47577462
C6	0.20,0.33,1.0	1,1,1	1.0,3.0,5.0	3.0,5.0,7.0	0.33803709
C7	0.14,0.20,0.33	0.20,0.33,1.0	1,1,1	1.0,3.0,5.0	0.15026848
C8	0.11,0.14,0.20	0.14,0.20,0.33	0.20,0.33,1.0	1,1,1	0.03591981

Therefore, the weight is given as $= (1, 0.6548, 0.0892)^T$. After normalization process, the weight vector of the soil attributes(criteria), which are Soil type (C5), Soil drainage (C6), Soil texture (C7) and Soil depth (C8) is found to be $W = (0.45, 0.38, 0.17, 0.036)^T$. We can conclude that the most important attribute (criteria) in the cross-country mobility suitability selection process is Soil type, because it has the highest priority weight. Soil drainage, Soil texture and Soil depth criteria are the next preferred attribute (criteria) respectively.

Table 3.33: Priority weights of the environmental criteria

B2	D1	D2	D3
D1	(1,1,1)	(1.0,3.0,5.0)	(3.0,5.0,7.0)
D2	(0.20,0.33,1.0)	(1,1,1)	(1.0,3.0,5.0)
D3	(0.14,0.20,0.33)	(0.20,0.33,1.0)	(1,1,1)

Where, **B2** is Environmental criteria, **D1** is climate, **D2** is vegetation, **D3** is drainage, **GM** is geometric mean is the weight of **D1**, **D2** and **D3**.

Table 3.34: Calculating Geometric mean (GM), Eigen value using crisp AHP method

B ₂	D1	D2	D3	GM	Eigenvalue
D1	1.00	3.00	5.00	2.46	0.61
D2	0.42	1.00	3.00	1.08	0.27
D3	0.21	0.42	1.00	0.43	0.10
Sum	1.63	4.42	9.00	3.97	

$\lambda_{max} = (1.63 * 0.61) + (4.42 * 0.27) + (9.00 * 0.10) + (16 * 0.05) = 3.08$, $CI = (3.08-3)/3-1 = 0.04$, $RI = 0.58$, $CR = CI/RI = 0.04/0.58 = 0.068 = 6.68\%$.

As $CR < 10\%$, the level of consistency of comparison matrix is satisfactory.

Table 3.35: Priority weights of the Environmental criteria

B ₂	D1	D2	D3	Row sum
D1	(1,1,1)	(1.0,3.0,5.0)	(3.0,5.0,7.0)	(5.0,9.0,13.0)
D2	(0.20,0.33,1.0)	(1,1,1)	(1.0,3.0,5.0)	(2.2,4.33,7.0)
D3	(0.14,0.20,0.33)	(0.20,0.33,1.0)	(1,1,1)	(1.34,1.53,2.33)
	Sum			(8.54,14.86,22.33)

Inverse the row sum total:

$$(8.54, 14.86, 22.33) = (1/22.33, 1/14.86, 1/8.54)$$

Multiply each row sum with inverse of row sum total.

$$SD1 = (5.0, 9.0, 3.0) \oplus (1/22.33, 1/14.86, 1/8.54) = (0.2239, 0.6057, 1.5222).$$

$$SD2 = (2.2, 4.33, 7.0) \oplus (1/22.33, 1/14.86, 1/8.54) = (0.0985, 0.2914, 0.8197).$$

$$SD3 = (1.34, 1.53, 2.33) \oplus (1/22.33, 1/14.86, 1/8.54) = (0.0600, 0.1030, 0.2728).$$

After obtaining SD1, SD2, and SD3 from, these fuzzy values are compared and the following are obtained.

The degree possibility of Si over Si (i j) is determined:

$$V (SD1 \geq SD2, SD3) = 1; V (SD2 \geq SD1, SD3) = 0.6547; V (SD3 \geq SD1, SD2) = 0.0887$$

$$\text{Weight vector, } W^p = (1.00, 0.6547, 0.0887)^T$$

Therefore,

$$W' = ((d' (DC1), d' (DC2), d' (DC3))^T = (1.00, 0.6547, 0.0887)^T$$

The priority weights with respect to physical attributes (criteria) are calculated as the normalized weight vectors for the decision criteria DD1, DD2 and DD3 are calculated as follows:

$$W = (0.45, 0.38, 0.17, 0.036)^T = 1.00+0.6547+0.0887= 1.7434$$

$$(1.00/1.7434, 0.6547/1.7434, 0.0887/1.7434)^T = W = (0.573609394, 0.375520014, 0.050870592)^T$$

Table 3.36: The pairwise comparison matrix, **B2—D1—D3.**

B2	D1	D2	D3	Defuzzified normalized weight
D1	(1,1,1)	(1.0,3.0,5.0)	(3.0,5.0,7.0)	0.573609394
D2	(0.20,0.33,1.0)	(1,1,1)	(1.0,3.0,5.0)	0.375520014
D3	(0.14,0.20,0.33)	(0.20,0.33,1.0)	(1,1,1)	0.050870592

Where **D1** is Climate criteria, **D4** is precipitation, **D6** is temperature, and **GM** is geometric mean is the weight of **D4** and **D5**.

Table 3.37: priority weights of the Climate Criteria, **D1—D4, D5.**

D1	D4	D5
D4	(1,1,1)	(0.20,0.33,1.00)
D5	(1.0,3.0,5.0)	(1,1,1)

Table 3.38: Calculating Geometric mean (GM), Eigen value using crisp AHP method

D1	D4	D5	GM	Eigenvalue
D4	(1,1,1)	(1.0,3.0,5.0)	1.73	0.72
D5	(0.20,0.33,1.0)	(1,1,1)	0.64	0.27
Sum	1.42	4.00	2.37	

$$\lambda_{max} = (1.42 * 0.72) + (4.00 * 0.27) = 2.10, CI = (2.10-2)/2-1 = 0.10, RI = 0.00, CR = CI/RI = 0.10/0.00 = 0.000 = 0.000\%$$

As **CR** < 10%, the level of consistency of comparison matrix is satisfactory.

In order to find the priority weights of the environmental criteria (attributes), first, the fuzzy synthetic extent values of the attributes are calculated. The different values of fuzzy synthetic extent of the two different climate factors (alternatives) are denoted by SD4, SD5.

Table 3.39: Priority weights of the climate criteria

D1	D4	D5	Row sum
D4	(1,1,1)	(1.0,3.0,5.0)	(2.00,4.00,6.00)
D5	(0.20,0.33,1.0)	(1,1,1)	(1.200,1.33,2.00)
Sum			(3.20,5.33,8.00)

Inverse of the row sum total are:

$$(3.20, 5.33, 8.00) = (1/8.00, 1/5.33, 1/3.20)$$

Multiply each row sum with inverse of row sum total.

$$SD4 = (2.00, 4.00, 6.00) \oplus (1/8.00, 1/5.33, 1/3.20) = (0.25, 0.7505, 1.875).$$

$$SD5 = (1.200, 1.33, 2.00) \oplus (1/8.00, 1/5.33, 1/3.20) = (0.15, 0.2495, 0.625).$$

After obtaining SD4 and SD5, these fuzzy values are compared and the following are obtained.

The degree possibility of **Si** over **Si** (i j) is determined:

$$V (SD4 \geq SD5) = 1; V (SD5 \geq SD4) = 0.4281$$

$$\text{Weight vector, } W^* = (1.00, 0.4281)^T$$

Therefore,

$$W' = ((d' (DC1), d' (DC2), d' (DC3)) ^T = (1.00, 0.4281)^T$$

The priority weights with respect to physical attributes (criteria) are calculated as the normalized weight vectors for the decision criteria DD4 and DD5 are calculated as follows:

$$W = (1.00, 0.4281)^T = 1.00+0.4281= 1.428$$

$$(1.00/1.428, 0.4281/1.428)^T = W = (0.70022497, 0.29977502)^T$$

Table 3.40: The pair-wise comparison matrix, D1—D4—D5.

D1	D4	D5	Defuzzified normalized weight
D4	1,1,1	1.0,3.0,5.0	0.70022497
D5	0.20,0.33,1.00	1,1,1	0.29977502

Therefore, the weight is given as = $\mathbf{W} = (0.70023, 0.2998)^T$. After normalization process, the weight vector of the climate attributes (criteria), which are precipitation and temperature is found to be $\mathbf{W} = (0.70023, 0.2998)^T$. We can conclude that the most important attribute (criteria) in the cross-country mobility suitability selection process is precipitation, because it has the highest priority weight. Temperature criteria are the next preferred attribute (criteria).

Table 3.41: The pairwise comparison matrix, D2—D6—D8.

D2	D6	D7	D8
D6	1,1,1	3.0,5.0,7.0	1.0,3.0,5.0
D7	0.14,0.2,0.33	1,1,1	0.2,0.33,1.00
D8	0.2,0.33,1.00	1.0,3.0,5.0	1,1,1

Where, **D2** is vegetation criteria, **D6** is stem diameter, **D7** is canopy height, **D8** is tree density, GM is geometric mean is the weight of D6, D7 and D8.

Table 3.42: Calculating Geometric mean (GM), Eigen value using crisp AHP method

D2	D6	D7	D8	GM	Eigenvalue
D6	1.00	5.00	3.00	2.46	0.61
D7	0.21	1.00	0.42	0.43	0.10
D8	0.42	3.00	1.00	1.08	0.27
Sum	1.63	9.00	4.42	3.97	

$\lambda_{max} = (1.63 * 0.61) + (9.00 * 0.10) + (4.42 * 0.27) = 3.08$, $CI = (3.08-3)/3-1 = 0.04$, $RI = 0.58$, $CR = CI/RI = 0.04/0.58 = 0.068 = 6.8\%$.

As $CR < 10\%$, the level of consistency of comparison matrix is satisfactory.

In order to find the priority weights of the vegetation criteria (attributes), first, the fuzzy synthetic extent values of the attributes are calculated. The different values of fuzzy synthetic extent of the three different vegetation factors (alternatives) are denoted by SD6, SD7 and SD8.

Table 3.43: Priority weights of the vegetation criteria

D2	D6	D7	D8	Row sum
D6	1,1,1	3.0,5.0,7.0	1.0,3.0,5.0	(5,9,13)
D7	0.14,0.2,0.33	1,1,1	0.2,0.33,1.00	(1.343,1.533,2.333)
D8	0.2,0.33,1.00	1.0,3.0,5.0	1,1,1	(2.2,4.333,7)
Sum				(8.543,14.866,22.333)

Inverse of the row sum total are:

$$(8.543, 14.866, 22.333) = (1/22.333, 1/14.866, 1/8.543)$$

Multiply each row sum with inverse of row sum total.

$$SD6 = (5, 9, 13) \oplus (1/22.333, 1/14.866, 1/8.543) = (0.2239, 0.6054, 1.5217).$$

$$SD7 = (1.343, 1.533, 2.333) \oplus (1/22.333, 1/14.866, 1/8.543) = (0.0601, 0.1031, 0.2731).$$

$$SD8 = (2.2, 4.333, 7) \oplus (1/22.333, 1/14.866, 1/8.543) = (0.0985, 0.2915, 0.8194).$$

After obtaining SD4 and SD5, these fuzzy values are compared and the following are obtained.

The degree possibility of **Si** over **Si** (i j) is determined:

$$V (SD6 \geq SD7, SD8) = 1.00; V (SD7 \geq SD6, SD8) = 0.0892; V (SD8 \geq SD6, SD7) = 0.6548$$

$$\text{Weight vector, } W' = (1.00, 0.0892, 0.6548)^T$$

Therefore,

$$W' = ((d' (DC1), d' (DC2), d' (DC3)) ^T = (1.00, 0.0892, 0.6548)^T$$

The priority weights with respect to physical attributes (criteria) are calculated as the normalized weight vectors for the decision criteria DD6, DD7 and DD8 are calculated as follows: **W= (1.00,**

$$0.0892, 0.6548)^T = 1.00+0.0892+0.6548= 1.744$$

$$(1.00/1.744, 0.0892/1.744, 0.6548/1.744)^T = \mathbf{W} = (0.57339449, 0.0511467889, 0.3754587156)^T$$

Table 3.44: Priority weights of the vegetation criteria

D2	D6	D7	D8	Defuzzified normalized weight
D6	1,1,1	3.0,5.0,7.0	1.0,3.0,5.0	0.57339449
D7	0.14,0.2,0.33	1,1,1	0.2,0.33,1.00	0.0511467889
D8	0.2,0.33,1.00	1.0,3.0,5.0	1,1,1	0.3754587156

Therefore, the weight is given as $W' = (1.00, 0.0892, 0.6548)^T$. After normalization process, the weight vector of the vegetation attributes(criteria), which are stem diameter, canopy height and tree density is found to be $W = (0.5734, 0.0512, 0.3755)^T$. We can conclude that the most important attribute (criteria) in the cross-country mobility suitability selection process is stem diameter, because it has the highest priority weight. Tree density and canopy height are the next preferred attributes (criteria) respectively.

Table 3.45: The pairwise comparison matrix, B3—E1—3.

B ₃	E1	E2	E3
E1	1,1,1	1.0,3.0,5.0	3.0,5.0,7.0
E2	0.20,0.333,1.0	1,1,1	1.0,3.0,5.0
E3	0.143,0.20,0.33	0.20,0.333,1.0	1,1,1

Where **B₃** is socio-economic criteria, **E1** is road network, **E2** is urban area, **E3** is LULC, and **GM** is geometric mean is the weight of **E1**, **E2** and **E3**.

Table 3.46: Calculating Geometric mean (GM), Eigen value using Crisp AHP method

B ₃	E1	E2	E3	GM	Eigenvalue
E1	1.00	3.00	5.00	2.46	0.61
E2	0.42	1.00	3.00	1.08	0.27
E3	0.21	0.42	1.00	0.43	0.10
Sum	1.63	4.42	9.00	3.97	

$\lambda_{max} = (1.63 * 0.61) + (4.42 * 0.27) + (9.00 * 0.10) + (16 * 0.05) = 3.08$, $CI = (3.08-3)/3-1 = 0.04$, $RI = 0.58$, $CR = CI/RI = 0.04/0.58 = 0.068 = 6.68\%$.

As $CR < 10\%$, the level of consistency of comparison matrix is satisfactory.

In order to find the priority weights of the Socio-economic criteria (attributes), first, the fuzzy synthetic extent values of the attributes are calculated. The different values of fuzzy synthetic extent of the three different Socio-economic factors (alternatives) are denoted by SE1, SE2 SDE3.

Table 3.47: Priority weights of the environmental criteria

B₃	E1	E2	E3	Row sum
E1	1,1,1	1.0,3.0,5.0	3.0,5.0,7.0	(5.0,9.0,13.0)
E2	0.20,0.333,1.0	1,1,1	1.0,3.0,5.0	(2.2,4.333,7.0)
E3	0.143,0.20,0.33	0.20,0.333,1.0	1,1,1	(1.343,1.533,2.333)
Sum				(8.54,14.866,22.333)

Inverse of the row sum total are:

$$(8.54, 14.866, 22.333) = (1/22.333, 1/14.866, 1/8.54)$$

Multiply each row sum with inverse of row sum total.

$$SD1 = (5.0, 9.0, 3.0) \oplus (1/22.333, 1/14.866, 1/8.54) = (0.2239, 0.6054, 1.5222).$$

$$SD2 = (2.2, 4.333, 7.0) \oplus (1/22.333, 1/14.866, 1/8.54) = (0.0985, 0.2915, 0.8197).$$

$$SD3 = (1.343, 1.533, 2.333) \oplus (1/22.333, 1/14.866, 1/8.54) = (0.0601, 0.1031, 0.2732).$$

After obtaining SE1, SE2 SDE3, these fuzzy values are compared and the following are obtained.

The degree possibility of Si over Si (i, j) is determined:

$$V (SE1 \geq SE2, SE3) = 1; V (SE2 \geq SE1, SE3) = 0.6549; V (SE3 \geq SE1, SE2) = 0.0894$$

$$\text{Weight vector, } W' = (1.00, 0.6549, 0.0894)^T$$

Therefore,

$$W' = ((d' (DC1), d' (DC2), d' (DC3))^T = (1.00, 0.6549, 0.0894)^T$$

The priority weights with respect to physical attributes (criteria) are calculated as the normalized weight vectors for the decision criteria DE1, DE2 and DE3 are calculated as follows:

$$W' = (1.00, 0.6549, 0.0894)^T = 1.00+0.6549+0.0894= 1.7443$$

$$(1/1.00, 1/0.6549, 1/0.0894)^T = W = (0.57360939, 0.37552001, 0.05087059)^T$$

Table 3.48: Priority weights of the Socio-economic Criteria

B ₃	E1	E2	E3	Defuzzified normalized weight
E1	1,1,1	1.0,3.0,5.0	3.0,5.0,7.0	0.57360939
E2	0.20,0.333,1.0	1,1,1	1.0,3.0,5.0	0.37552001
E3	0.143,0.20,0.33	0.20,0.333,1.0	1,1,1	0.05087059

Therefore, the weight is given as $W' = (1.00, 0.6549, 0.0894)^T$. After normalization process, the weight vector of the Socio-economic attributes(criteria), which are road network, urban area and LULC is found to be $W = (0.5733, 0.3755, 0.0513)^T$. We can conclude that the most important attribute (criteria) in the cross-country mobility suitability selection process is road network, because it has the highest priority weight. Urban area and LULC are the next preferred attributes (criteria) respectively.

3.7.1. Calculating the Fuzzy Consistency Ratio

To determine if the comparisons are consistent or not in assigning the weights a Consistency Ratio which is known as Fuzzy Consistency Ratio (FCR) was calculated using equation 17 proposed by Modarres et al. (2010). The steps of the algorithm are as follows:

Step 1: A fuzzy matrix \tilde{H} was defined such that:

$$\tilde{h}_{ij} = w_j * \tilde{a}_{ij}, \tag{17}$$

Where, w_j is the weight for the j^{th} criteria or attribute, for, and are the TFN's in the fuzzy judgement matrix.

Step 2: \tilde{h}_{ij} values in each i^{th} row of the matrix \tilde{H} were summed, as follows,

$$\tilde{s}_i = \sum_{j=1}^n \tilde{h}_{ij}, \tag{18}$$

Step 3: $\tilde{\lambda}_i$ for $i = 1$ to n values were then calculated such that

$$\tilde{\lambda}_i = \frac{\tilde{s}_i}{w_i}, \tag{19}$$

Step 4: The Consistency Index (CI) was then calculated as follows:

$$CI = \frac{\frac{1}{n} \sum (\tilde{\lambda}_i - n)}{n-1}, \text{ n is the dimension of the fuzzy judgment matrix} \tag{20}$$

Step 5: The FCR was then calculated using the following formula:

$$FC\tilde{R} = \frac{C\tilde{I}}{RI}, \tag{21}$$

Where RI is the random consistency index, which was obtained from Table 3.49

Table 3.49: Random index for n=15

Random Index (RI)															
<i>n</i>	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48	1.56	1.57	1.58

n is dimension of judgement matrix

In this study, the numbers of criteria are 15 and have the corresponding RI used for this study was 1.58.

Step 6: Because TFNs were used to represent the vagueness in the judgment matrix, the FCR values obtained from Equation 21 were in the form of a set with 3 values. According to Modarres and Sadi-Nezhad (2001), FCR is determined as a preference ratio, which is defined as the percentage of the *i*th fuzzy number within a set being the most preferred one. This ratio is expressed by Equation 22 as follows:

$$R_{(i)} = \frac{|\Omega_i|}{|\Omega|} \tag{22}$$

The preference ratio should be about 10%, or less for the weights to be acceptable, otherwise the decision maker may need to re-examine the judgment process of assigning the weights. Fortunately, the preference ratio values (also known as FCR values in this study) of all comparisons made for the criteria at each hierarchical level (Tables 3.21-3.48) were lower than 10%, which indicated that the weights were acceptable. This procedure sometimes requires several interaction and adjustment until an acceptable consistency ratio is achieved. This could be done by revising the manner in which questions are asked in making the pairwise comparisons. If this should fail to improve consistency then it is likely that the problem should be more accurately structured; that is, grouping similar elements under more meaningful criteria.

3.7.2. Calculating the final weights of each input layer

The weight (Wf) of every last factor to the main objective of the hierarchy (A) was calculated by normalizing the weight (W) of each factor shown in (Tables 3.21-3.48). This was done by multiplying the weight of a factor in the lower level by that of the element/s in the upper level as long as they were

directly related as in the hierarchical structure. For example, to get the final weight of the Soil type input layer (represented by C_5 in the hierarchy), the following formulae was used:

$$Final\ weight\ of\ C_5 = Weight\ of\ C_5\ to\ C_2 * Weight\ of\ C_2\ to\ B_1 * Weight\ of\ B_1\ to\ Goal\ A$$

This was done for all the input layers and the results are shown in Table 3.50.

Table 3.50: Summary of major criteria and minor criteria to identify suitable site

Goal	Main criteria	Weight	Factors (Alternatives)	Weight	Sub-factors (Sub-alternatives)	Weight	Composite weights
Assessing Trafficability for Vehicle mobility use (A)	Physical (B1)	0.57360939	Slope (C1)	0.57339449			0.32890446
			Elevation (C2)	0.05114678			0.02933827
			Soil (C3)	0.37545871	Soil type (C5)	0.47577462	0.10246598
					Soil texture (C6)	0.33803709	0.07280191
					Soil depth (C7)	0.15026848	0.03236282
					Soil drainage (C8)	0.03591981	0.00773593
	Environmental (B2)	0.37552001	Climate (D1)	0.57360939	Precipitation (D4)	0.70022497	0.15082972
					Temperature (D5)	0.29977502	0.06457208
			Vegetation (D2)	0.37552001	Stem diameter (D6)	0.57339449	0.08085738
					Canopy height (D7)	0.051146788	0.00721248
					Tree density (D8)	0.375458715	0.05294542
	Drainage (D3)	0.05087059		0.01910292			
	Socio-economic (B3)	0.05087059	Road network (E1)	0.57360939		0.02917985	
			Urban area (E2)	0.37552001		0.01910292	
			LULC (E3)	0.05087059		0.00258782	

3.7.3. Fuzzy Aggregation

Once the criteria maps (factors) were developed and the associated weights were assigned to each of the input layers, an evaluation (or aggregation) stage was undertaken to combine the information from the various factors. The MCE module in the IDRISI-17 software package offers three methods for the aggregation of multiple criteria, such as Boolean Intersection, Weighted Linear Combination (WLC), and the Ordered Weighted Average (OWA). WLC chosen as the method of aggregation. According to

Baban and Wan-Yusof (2003), this technique is a much better representation of the way major decisions are made in reality and it avoids the hard decisions of defining any particular area as absolutely suitable or not, but rather uses a continuous scale to present suitability. As shown in Equation 23, this method multiplies each standardized factor map by its factor weight and then sums the results as:

$$S = \sum(W_i * X_i) \tag{23}$$

Where

S is suitability,

W_i is weights of factor i , and

X_i is factor i

This process was done on a pixel by pixel basis and yielded a suitability map with the same range of values as the standardized factor maps that were used. Factor maps were converted to byte binary format used in Equation 24 was then multiplied by the constraint map to “mask out” the areas unsuitable for siting a cross-country mobility. The constraint map was a binary coded image showing all areas where siting of trafficability was simply not possible due to drainage factors as zero (0) values whilst the other areas were shown as one (1). Thus, Equation 23 was modified as follows:

$$S = \sum(W_i * X_i) * \prod C_i \tag{24}$$

Where C_i is constraint, \prod is the product and \sum is Somme.

WLC(S): [Slope] * **0.32890446** + [Precipitation] * **0.15082972** + [Soil type] * **0.10246598** + [Stem diameter] * **0.08085738** + [Soil texture] * **0.07280191** + [Temperature] * **0.06457208** + [Tree density] * **0.05294542** + [Soil depth] * **0.03236282** + [Elevation] * **0.02933827** + [Road network] * **0.02917985** + [Drainage/Stream order] * **0.01910292** + [Urban area] * **0.01910292** + [Soil drainage] * **0.00773593** + [Canopy height] * **0.00721248** + [LULC] * **0.00258782**.

Using IDISI 17 software, all factors were given specific weights to manage the tradeoff between factors and the weights. The weighted overlay operation for the off-road trafficability map was operated using model builder in ArcGIS 10.4 Software. By combining all the factors in a spatial analysis, the modeler is an interesting approach of showing the processes that leading to complete trafficability model from the raw data through the links and finally results is included in the ArcGis Spatial Analyst sub-program called the Model Builder. Figure 3.27 shows partially the model builder of the whole process.

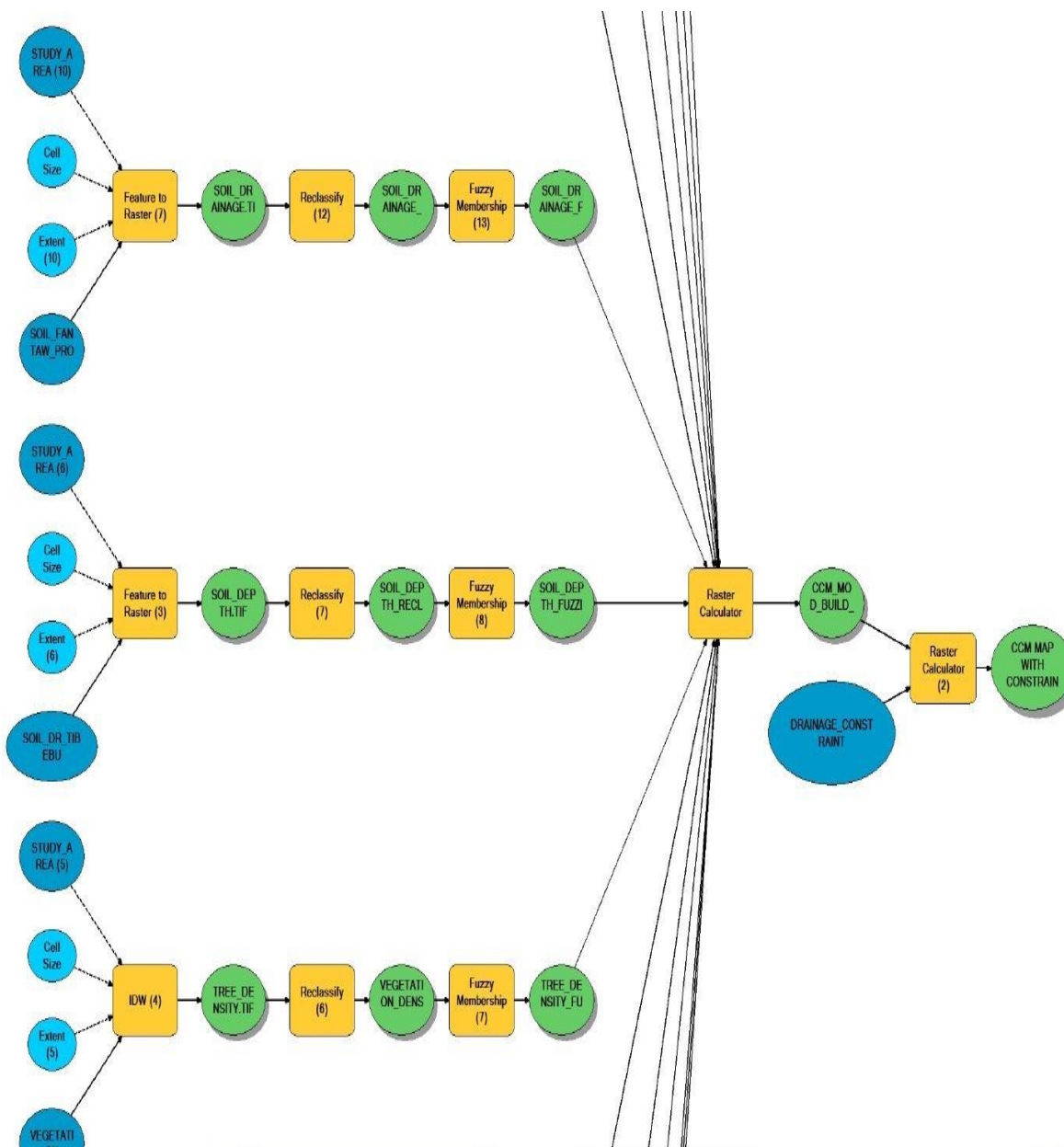


Figure 3.27: Partially schematic visualization of the steps to create CCM model in model builder.

CHAPTER FOUR

4. RESULTS AND DISCUSIONS

4.1. RESULTS

4.1.1. Cross-Country Trafficability Site

This research was carried out to identify candidate sites for locating Off-road Cross-country Trafficability in the administrative district of North West of Ethiopia. Figure 3.1 shows the location of the site and cross-country trafficability without constraints. Results of each suitability class were represented in (Figure 4.1).

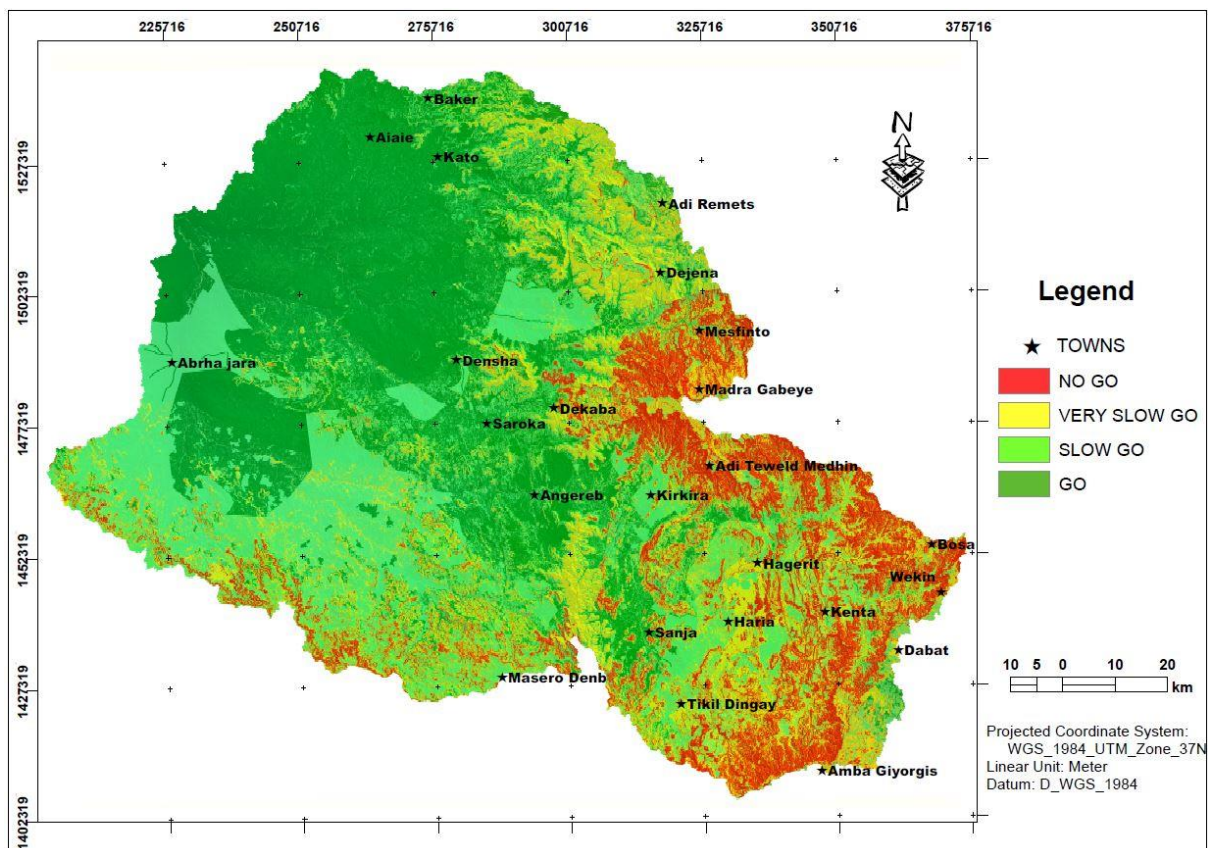


Figure 4.1: Cross-Country trafficability without constraints

Results revealed that from central to northern zones of the investigated region have high vehicles mobility area. Such zones are appropriate for setting up military operation. The total investigated area is equivalent to 1331422.825ha. The GO zones amount to 455585.36 ha with percent of 34% and the SLOW-GO suitable zones amounting to 430366.89 ha having percent of 32%, VERY SLOW-GO

suitable zones amounting to 283602.96 ha having percent of 21% and the NO-GO suitable zones amounting to 161867.61 ha having percent of 12%, respectively.

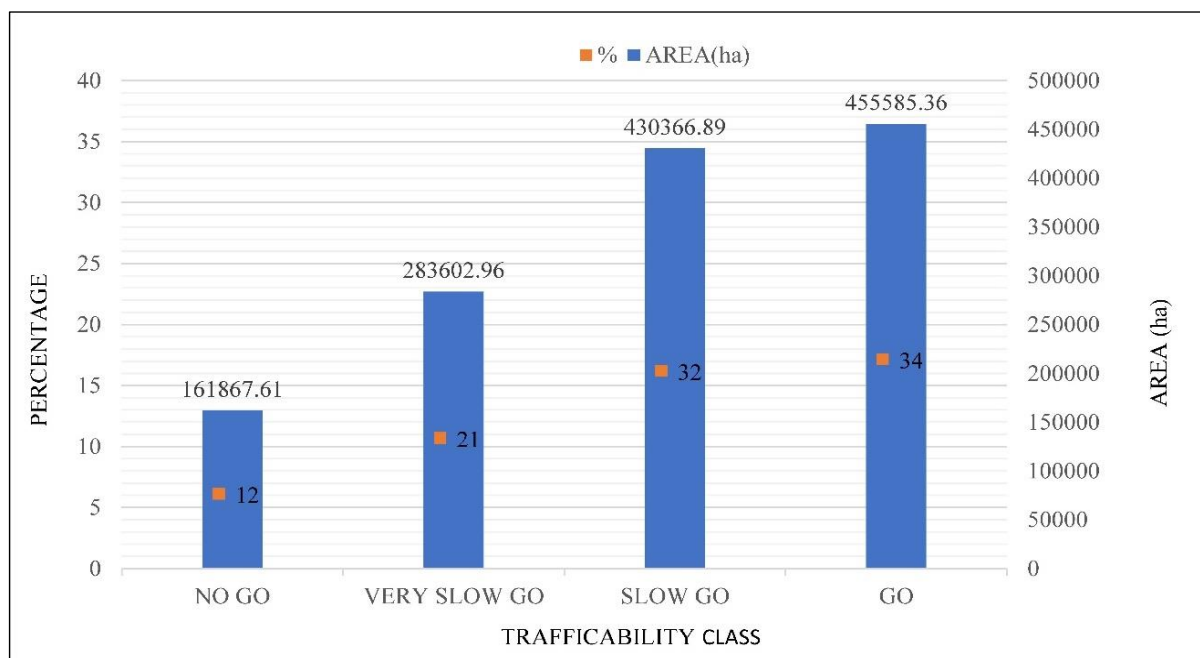


Figure 4.2: Area of cross-country trafficability classes in hectare (before constraint).

4.1.2. Standardized Fuzzy membership

The fuzzy membership function transforms the standardize input data to a 0.0 to 1.0 scale based on the possibility of being a member of a specified set, which indicating a continuous increase from non-membership to complete membership of a pixel in given layer categories. The basic premise of fuzzification is that to address inaccuracies in attribute and spatial data, 0.0 is assigned to the lowest input value and 1.0 or closer to 1.0 assigned to the largest input value. The fuzzified results of each criteria layer of slope, precipitation, soil type, stem diameter, soil texture, temperature, tree density, soil depth, elevation, road network, drainage, urban area, soil drainage, canopy height and LULC were presented based on the suitability rating score of each factor for generating suitable trafficability site selection (Figure 4.1) in section 4.1.1. Each fuzzified input layers for CCM suitability site selection results were presented in (Figures 4.3, 4.4 and 4.5).

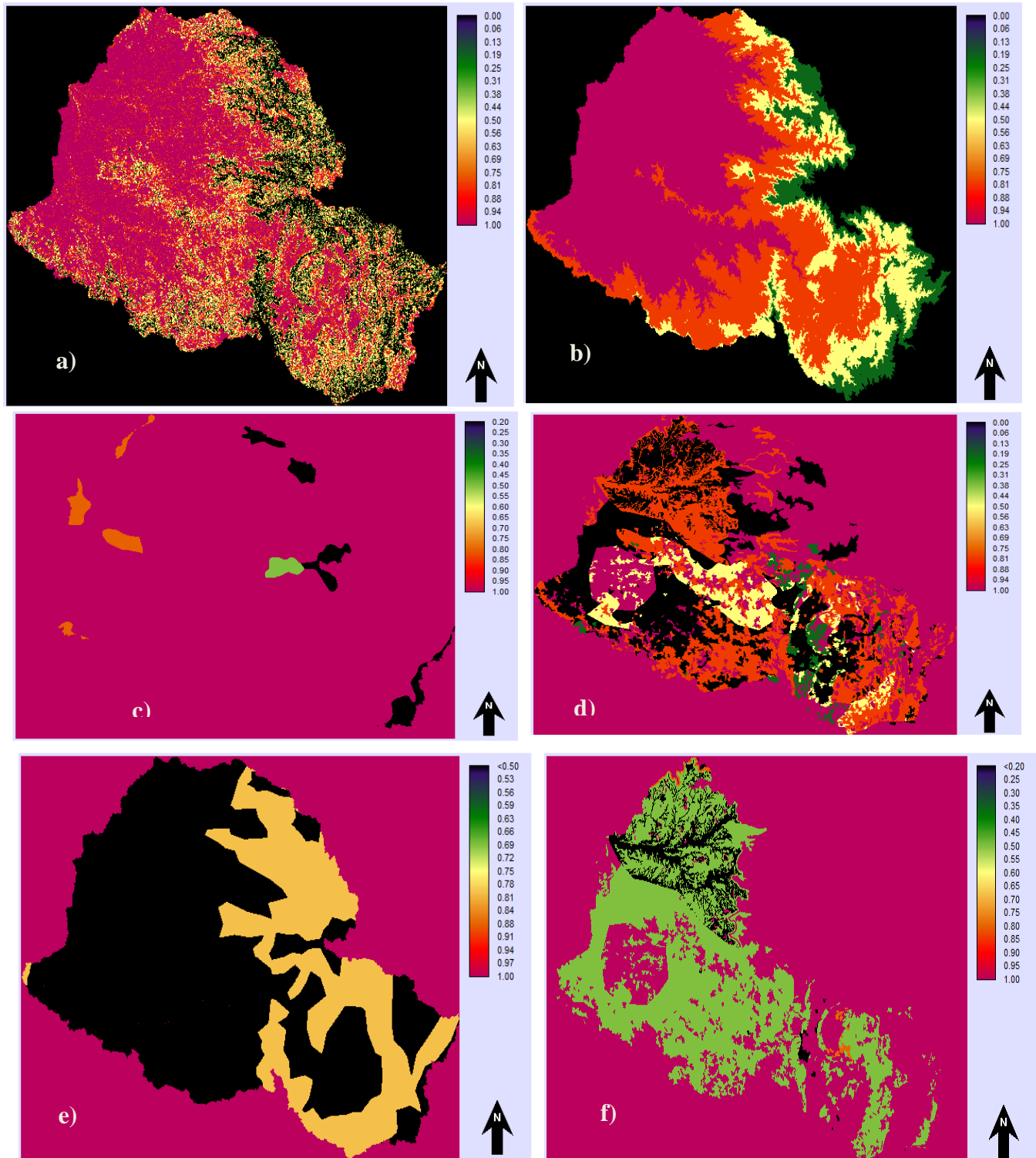


Figure 4.3: The physical criteria: Suitability fuzzy membership attribute maps: slope (a), elevation (b) soil drainage (c), soil type (d), soil texture (e), and soil depth (f).

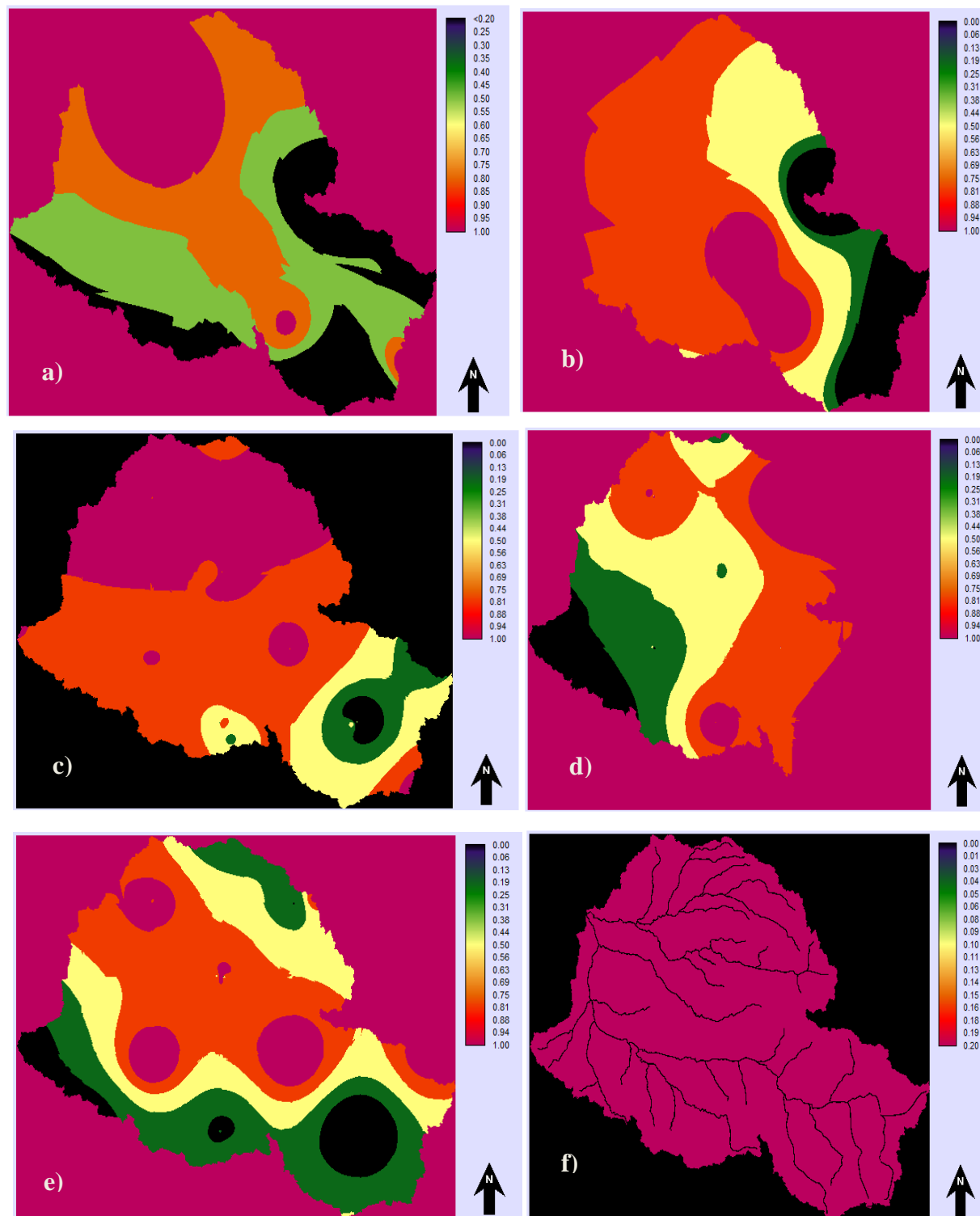


Figure 4.4: The Environmental criteria: Suitability fuzzy membership attribute maps: (a) precipitation, (b) temperature, (c) stem diameter, (d) tree density, (e) canopy height, and (f) stream order.

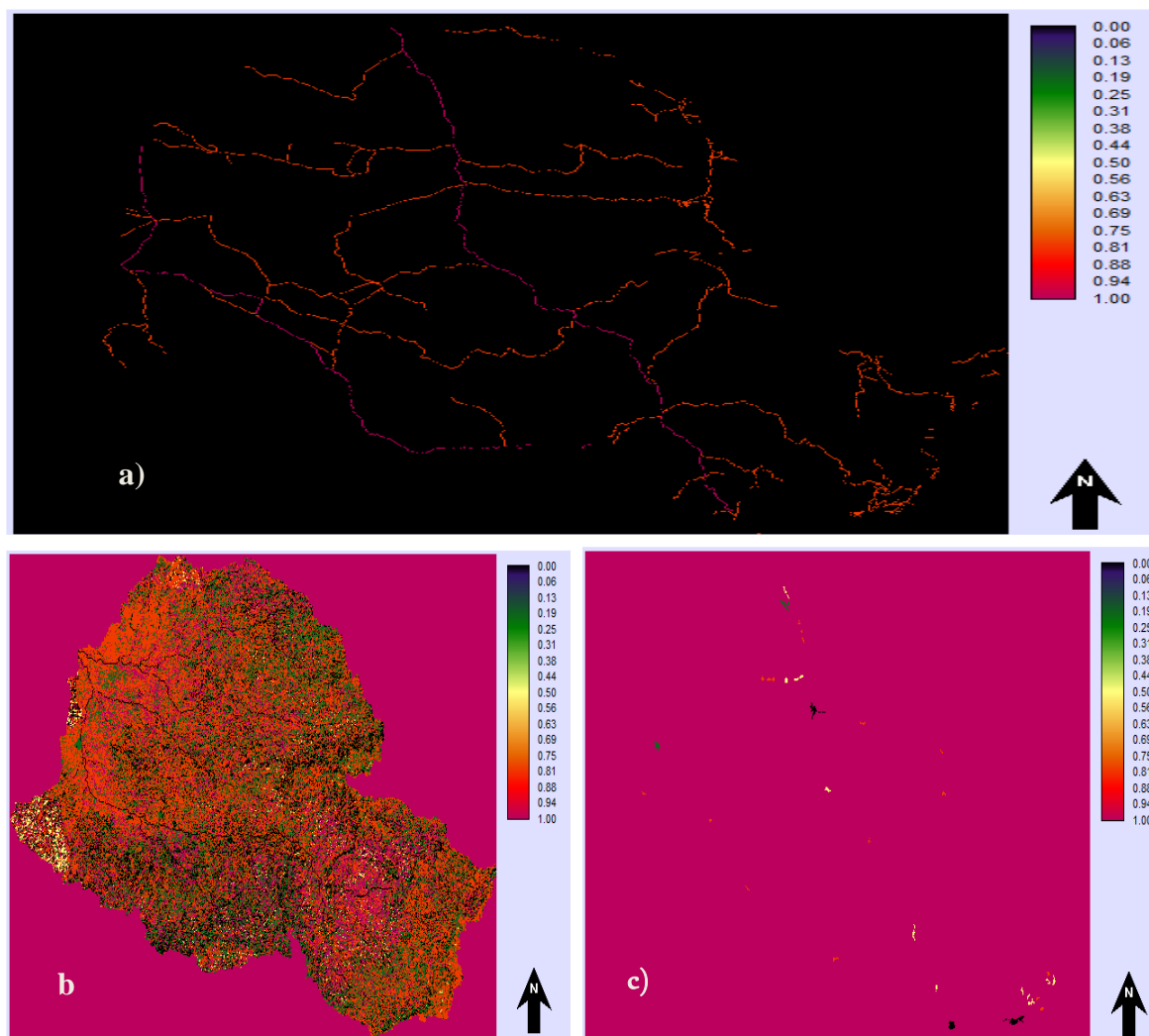


Figure 4.5: The Socio-Economic criteria: Suitability fuzzy membership attribute maps: (a) road, (b) land-use and land-cover, and (c) urban area.

Table 4.1: Attribute values of Fuzzy standardized based on suitability for the CCM site.

Factors	Extremely Suitable	Very suitable	Suitable	Less suitable	Not suitable
Fuzzy Score	1	0.8	0.5	0.2	0
Slope	$\leq 5^\circ$	$5-10^\circ$	Slope $10-20^\circ$	$20-25^\circ$	$\geq 25^\circ$
Precipitation	≤ 95 mm	95–125 mm	125–150 mm	150–200 mm	≥ 200 mm
Soil type	Leptosols	Cambisols, Regosol	Nitisol	Luvisols	Vertisols, Calcisol
Stem diameter	≤ 25 cm	25–30 cm	30–35cm	35–40 cm	≥ 40 cm
Soil texture	-	Sandy loam (Coarse silt)	Loam (Silt)	Clay	-

Temperature	$\geq 17.9\text{C}^\circ$	17.1–17.9C°	16.5–17.1C°	15.7–16.5C°	$\leq 15.7\text{C}^\circ$
Tree density	$\leq 30\text{ cm}$	30–40 cm	40–50 cm	50–60 cm	≥ 60
Soil depth	$\leq 30\text{ cm}$	30–50 cm	50–100 cm	100–150 cm	$\geq 150\text{ cm}$
Elevation	$\leq 500\text{ m}$	500–900 m	900–1000 m	1000–1500 m	$\geq 1500\text{ m}$
Road network	Asphalt	Gravel	-	-	-
Drainage	Stream order (1,2)	Stream order (3)	Stream order(3)	Stream order (5)	Stream order (6)
Urban area	$\leq 0.5\text{ km}^2$	0.5–1 km ²	1–1.5 km ²	$\geq 3.5\text{ km}^2$	$\geq 3.5\text{ km}^2$
Soil drainage	well drained (W)	imperfectly drained(I)	Imperfectly Poorly Drained (IP)	poorly drained (P)	-
Canopy height	≤ 8	8–9 m	9–10 m	10–11 m	$\geq 11\text{ m}$
LULC	Shrub and bush open, Bare land/Open space	Shrub and bush dense, grassland drained, cropland with no tree)	Shifting cultivation, plantation forest	Woodland open, Bu(settlement), mixed forest, homestead plantation, exposed rock, cropland with tree	Woodland dense, swamp, settlement dense and urban, swamp grassland, Riverine vegetation, river course, grassland wet or undrained, forest, dryland forest, degraded hills, cropland in hill terrain

4.1.3. Modeling Fuzzy AHP of influential factors

Weights were assigned to the factors using a series of pair wise comparison judgments to express the relative strength of each of the factor maps. Pair wise comparison allows one to consider two factors at a time, which reduces the complexity of the decision-making process. Assigning weights using pairwise comparison is more suitable than direct assignment of the weights, because one can check the consistency of the weights by calculating the consistency ratio. The study used a pairwise comparison of FAHP to determine the factors weights from judgment set of decision-making experts. The FCI was used in this research to calculate the Fuzzy Consistency Ratio (FCR) and the result was < 0.1 . The assigned weights from applying FAHP were presented in Table 4.2.

Table 4.2: Final result obtained for functional layout

Factors	Composite weights	Percentage of composite weights	Rank
Slope (C1)	0.32890446	32.9	1
Precipitation (D4)	0.15082972	15.1	2
Soil type (C5)	0.10246598	10.2	3
Stem diameter (D6)	0.08085738	8.1	4
Soil texture (C6)	0.07280191	7.3	5
Temperature (D5)	0.06457208	6.5	6
Tree density (D8)	0.05294542	5.3	7
Soil depth (C7)	0.03236282	3.2	8
Elevation (C2)	0.02933827	2.9	9
Road network (E1)	0.02917985	2.9	10
Drainage (D3)	0.01910292	1.9	11
Urban area (E2)	0.01910292	1.9	12
Soil drainage (C8)	0.00773593	0.8	13
Canopy height (D7)	0.00721248	0.7	14
LULC (E3)	0.00258782	0.3	15
Total	1.00	100	

4.1.4. Generation of constraint layer maps

One layer was identified as a constraint. The drainage found in the watershed was considered as a constraint and converted into binary maps. A value of 1 assigned as suitable area while a value of 0 was assigned as a restricted (Unsuitable) area for CCM suitable area (Figure 4.6a). The restricted area means never used for GO area since those areas are more valuable for vehicles mobility for military application. Since, the aim of this study was trafficability for vehicles mobility in Angereb watershed area; drainage is considered as a constraint. Finally, the constraint and cross-country mobility suitability map was aggregated (Figure 4.6b).

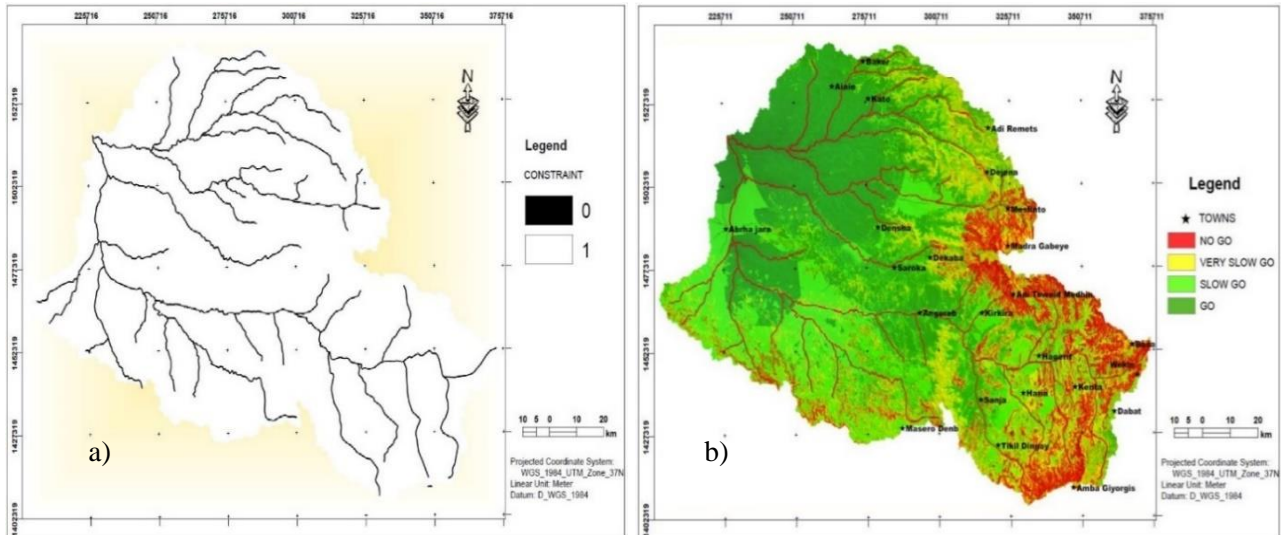


Figure 4.6: Drainage constraint map (a), and combined suitability index map (b)

Results revealed that from central to northern zones of the investigated region have high vehicles mobility area. Such zones are appropriate for setting up military operation. The total investigated area is equivalent to 1,331,379.36ha. The GO zones amount to 437637.2676 ha with percent of 32.87% and the SLOW GO suitable zones amounting to 421584.5088 ha having percent of 31.66%. Results can be explained as follows (Figure 4.7):

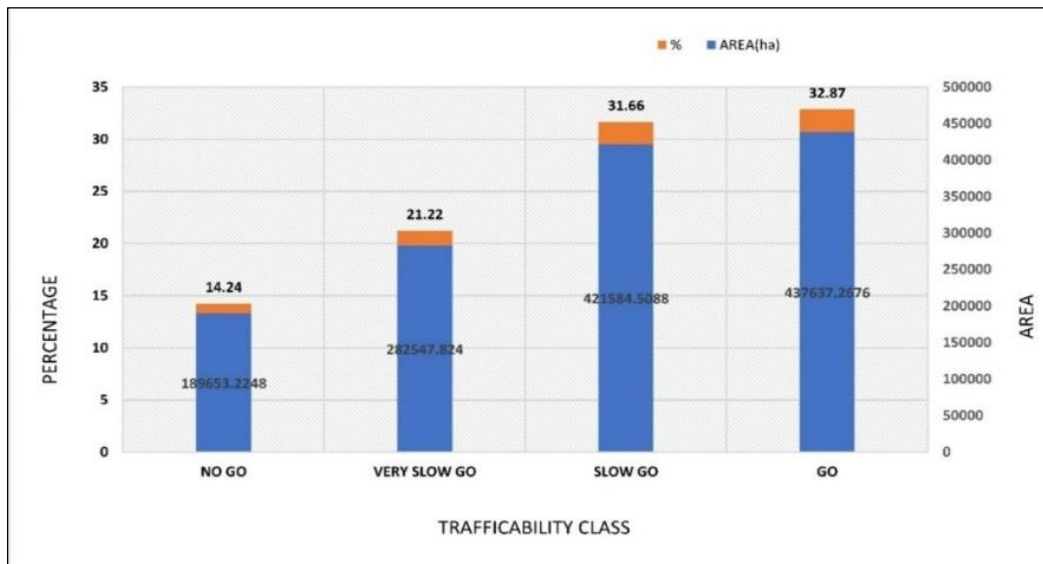


Figure 4.7: Area of Cross-Country Trafficability classes in hectare (after constraint).

As indicated above, the GO terrain conditions are the large trafficability class with an area of 437637.2676ha with percent of 32.87% of the study area. Land-use and land-cover types such as shrub and bush open, bare land/open space, well-drained soil, soil types (Leptosols), soil depth ≤ 30 cm, slope gradient of less than slope $\leq 5^\circ$, built-up area (≤ 0.5), tree spacing/density (≤ 30), tree stem diameter (≤ 25 cm), tree canopy height (≤ 8 m), road classes (asphalt), stream order (1,2), elevation (≤ 500 m), temperature ($\geq 17.9^\circ\text{C}$) and precipitation (≤ 95 mm) are designated as a GO terrain condition.

SLOW-GO terrain condition, the second larger class occupies 421584.5088ha having percent of 31.66% of the study area. These surface condition areas in slope is $5-10^\circ$, imperfectly drained (I) soil, sandy loam (Coarse silt), cambisols and regosol, soil depth (30–50 cm), built-up area (0.5–1 km²), tree spacing/density (30–40), tree stem diameter (25–30 cm), tree canopy height (8–9 m), LULC (shrub and bush dense, grassland drained, cropland with no tree), road classes (Gravel), stream order (3), elevation (500–900 m), temperature (17.1–17.9°C) and precipitation (95–125 mm) are categorized as SLOW-GO because of the relatively steep slope. Mobility over a slope $10-20^\circ$, imperfectly poorly drained (IP) soil, loam (silt), soil types (Nitisol), soil depth (50–100 cm), built-up area (1–1.5 km²), tree spacing/density (40–50), tree stem diameter (30–35 cm), tree canopy height (9–10 m), LULC (shifting cultivation, plantation forest), stream order (3), elevation (900–1000 m), temperature (16.5–17.1°C) and precipitation (125–150 mm) are also categorized in this terrain condition. Moreover, bare grounds, which were the most suitable land cover type, were passable slowly when the slope is greater than 5 and less than 15 degrees. Finally, SLOW-GO is possible over the above indicated terrain conditions if the river sections are affordable throughout.

The other trafficability class was the VERY SLOW-GO surface condition of the trafficability map. This was the third class in the Fuzzy analysis next to the SLOW-GO terrain condition. It is third largest one in area covering only 282547.824 ha (21.22%) of the study area. If the soil poorly drained (P), clay, (Luvisols), depth (100–150 cm) over a slope of between $20-25^\circ$, mobility through tree stem diameter (35–40 cm) and tree canopy height (10–11m) is possible very slowly. LULC (woodland open, (settlement), mixed forest, homestead plantation, exposed rock, cropland with tree) where the slope gradient was steeper (between 20 and 25 degree) is categorized as a VERY SLOW-GO terrain condition. Besides, lightly dense trees over in slope gradient of between 15 and 20 degree are passable very slowly if the soil type is also either clay or Luvisols soil type. If the slope was greater than 25 the result would be NO-GO. The river sections must be affordable for VERY SLOW-GO terrain condition.

The NO-GO terrain condition makes the complex part of the Fuzzy Inference System base with greater number of rules than any other classes. This was because rules of exception increase towards the NO-GO terrain condition. It was the least in terms of area coverage with 189653.2248 hectare (14.24%) of the total area. This class was characterized by extreme cases. The terrain was impassable if the slope is $\geq 25^\circ$ over any soil and land cover type. If the LULC (Woodland dense, swamp, settlement dense and urban, swamp grassland, Riverine vegetation, river course, grassland wet or undrained, forest, dryland forest, degraded hills, cropland in hill terrain) and water bodies the result is a NO-GO terrain condition under any soil type and slope gradient. Tree spacing/density (≥ 60), tree stem diameter (≥ 40 cm), tree canopy height (≥ 11 m) were impassable in any slope range if the soil Vertisols, Calcisol Soil depth (≥ 150 cm). Figure 4.8 shows comparison of CCM suitability class of the study area before and after combined constraints.

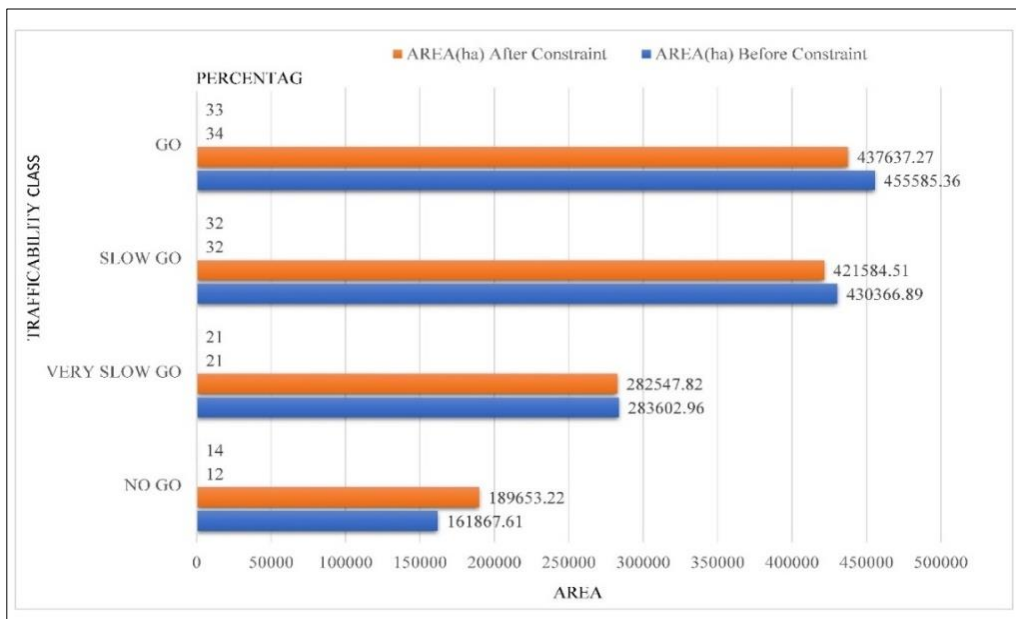


Figure 4.8: Comparison of CCM suitability class of with constraint and without constraint.

4.1.5. CCM Composite least-cost path

The final set of sub-functions to be performed within the CCM spatial analysis model execute the aggregation of the fifteen individual CCM terrain layers into a single composite cost surface with values that reflect the spatially coincidental mobility costs of each terrain layer's characteristics. This is executed using WLC sum function which adds each of layers values together to produce the composite CCM cost surface. Once the aggregate CCM composite cost surface is produced the model runs two passes of focal mean filters, using a neighborhood of 3 x 3 cells, to smooth the continuous surface and produce more subtle transitions between CCM cost impact values.

Since the slope layer in the study area is the influential factor, the vertical factor has been calculated via an extraction of the Z values (height values taken from the centroid points) of the bordering to each other grid cells. A Digital Elevation Model has been used as the vertical factor. In addition, to assign the ‘barrier value’ of the traversing by terrain car (too steep slope), there was available option to determine the cut angle for both upslope and down slope travel situations (the slope vehicle performance was based on the **Shoop’s studies** for the military vehicles).

Figure 4.9 shows the least-cost accumulative path through the compound cost surface raster map. To the right, a map on the start point area and the road pointing out the least-cost path generated by the algorithm. Dijkstra's algorithm is a centralized routing algorithm that maintains information in a central location to find the least-cost path from a specified source node to all other nodes. This algorithm determines least-cost paths from the origin node to a destination node by optimizing the cost in multiple iterations (Sari et al., 2017).

The performance of the imaginative vehicle leads mostly along the existing road structure (the calculated path is represented by the line on the map). Only in the start and at the destination points, the cost path is dealing with some of the cross-country trafficability ground conditions, choosing the optimal path in terms of surface least roughness and shortest distance to these points.

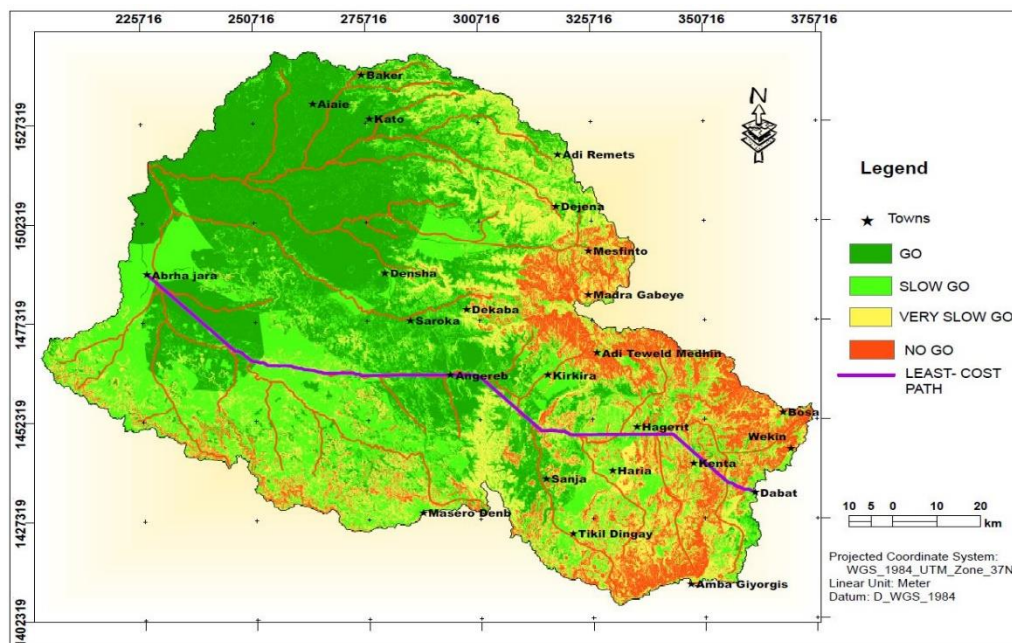


Figure 4.9: Randomly chosen destination path for the cross-country vehicle performance

4.1.6. Suitability of fuzzy approach comparing to crisp for modeling CCM area

Figure 4.10(a) and (b) illustrate the difference between a Boolean approach and fuzzy logic two maps were produced. Figure 4.10(a) all the factor layer maps were created with crisp approach are combined using an OR operator. Figure 4.10(b) all the factor maps were standardized with fuzzy membership were combined by using WLC operator. According to the result, in the Boolean Suitability index map the high-class boundaries of the Fuzzy Suitability index map disappear and replace by a gradual decrease of trafficability areas as a rank decreases from each feature. The result shows that the fuzzy approach is more reasonable and reflects the human perception in better way. As indicate in Figure 4.10(b) suitable CCM area by fuzzy method increased and improved some land classes. This indicates that flexibility is another characteristic of fuzzy logic.

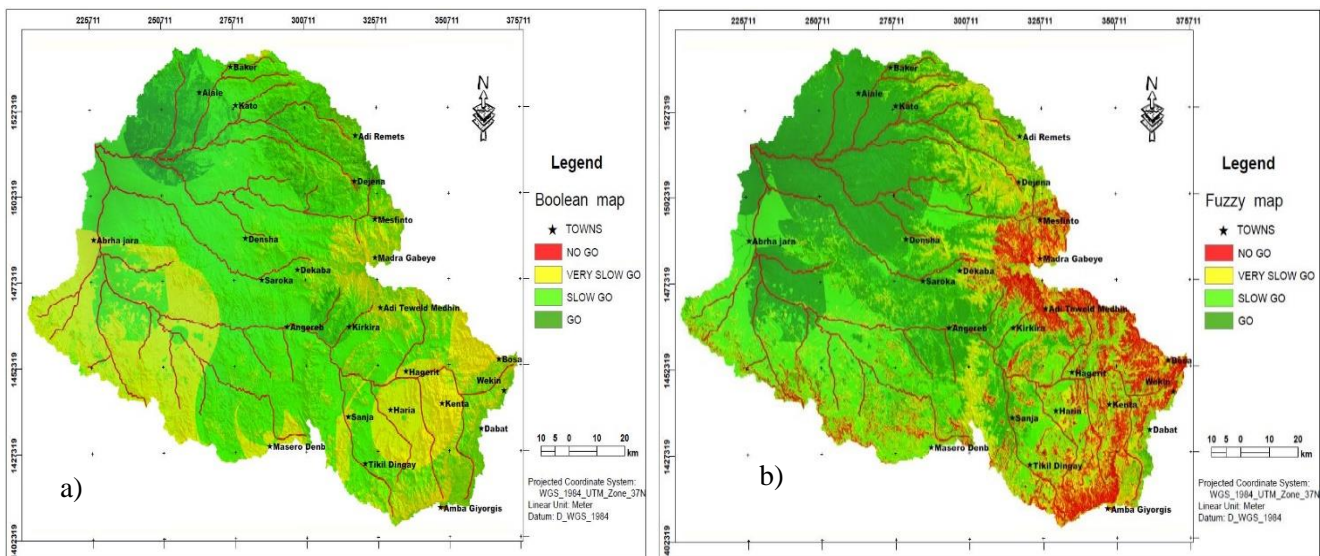


Figure 4.10: Boolean suitability map (a) and Fuzzy suitability map (b)

4.1.7. Validation and Accuracy assessment of CCM sites

To check the applicability of trafficability sites, the locations of suitable CCM identified for military need to be validated with existing area. To check the applicability of terrain trafficability for CCM sites, the suitable map of vehicles which was identified for military decision analysis to be validated with existing terrain. The 40 random sampling points of (latitudes and longitudes) was generated in using ArcGIS 10.4 on the proposed suitability map for CCM map identified in (Figure 4.10b) and converted to kml file. The exported kml file overlaid with Google Earth and validated with the locations of existing terrain by visual interpretation. Figure 4.11 indicates that 90% of existing area were in GO terrain and

80% located in SLOW GO terrain whereas 100% were in the VERY SLOW GO terrain suitable area and 90% located in NO GO (Restricted area) terrain. The total accuracy assessment over four classes is 90%. Therefore, accuracy assessment taken into consideration by overlaying the locations of existing area identified and the suitable trafficability zones which were developed by the model were agreed with the experiences and terrain military knowledge by the military officers. The capacity of existing mobility in the area was not clearly known, and due to this most of the area was not suitable to cross-country trafficability for military operation.

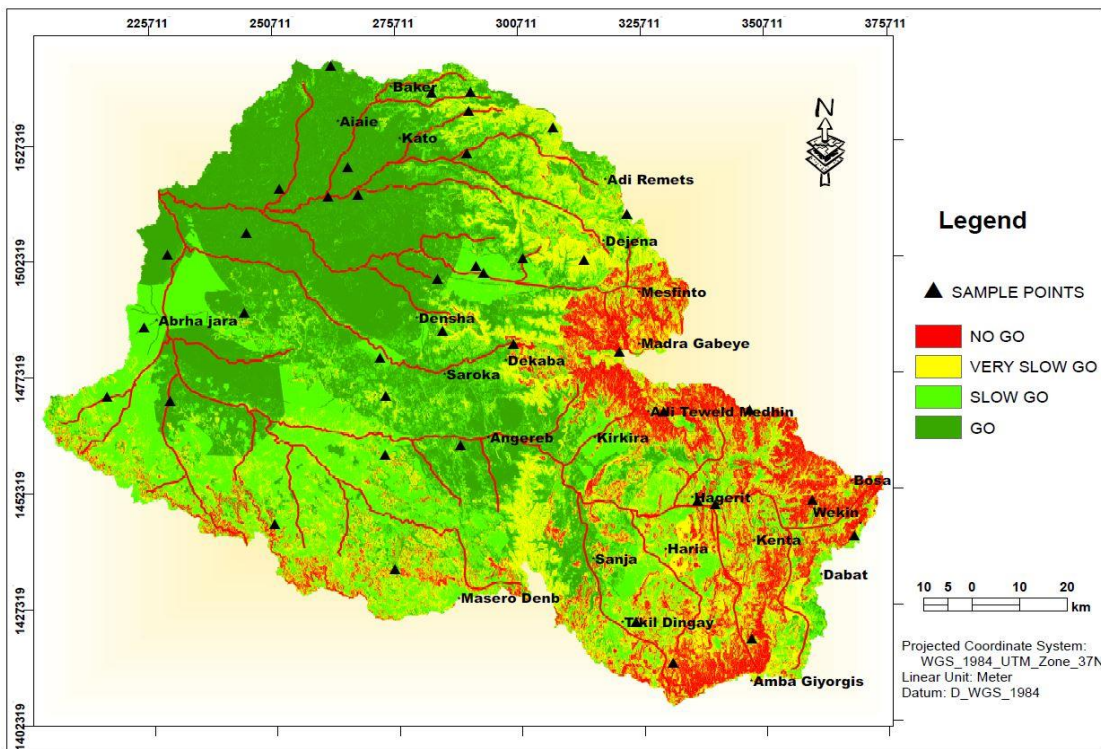


Figure 4.11: GO and NO GO map of trafficability

Cross-Country trafficability performed in the study indicate that: Kato, Angereb, West Dansha and Aiaie districts were found under GO terrain and Abraha jira, Dejena, Adi Ramets, and Baker were found under SLOWGO.

4.1.8. Cross Tabulation of crisp and Fuzzy results

According to Gebreslasie (2009), the area of the resulting maps is cross tabulated using Zonal area tabulation in ArcGIS. Zonal tools take a value raster as input and calculate a function or statistics for each cell using the value for each cell and all cells within the same zone. The Zonal tools are grouped

by the specified zones, a single input value raster or a second zone raster. The Zonal tools where a single input value raster determines the zones either measure statistics or quantify the geometry characteristics of the input zones.

The result obtained from the Crisp (Boolean) system is taken as a dataset that defines the zones. The result from the FUZZY logic method was the dataset that defines the classes that have their areas summarized with in each zone. The resulting table is area in meter square tabulated for each cell value (Table 4.3). The area cover is converted to percent by dividing each class by the row total.

Table 4.3: Cross tabulation of the results’ covers (values in %)

Fuzzy model		Crisp system model			
		GO	SLOW GO	VERY SLOW GO	NO-GO
GO		99.8	0.2	0.0	0.0
SLOW-GO		30.8	22.4	41.1	5.7
VERY SLOW-GO		2.1	24.4	30.9	42.6
NO-GO		0.0	0.0	20.8	79.2

For the ease of analysis, the level of correspondence for each cover summarized with in similar zone in the cross-tabulation table are categorized in to four level of correspondence as Low, Good, Very good and excellent. Table 4.4 shows the level of correspondence of the two methods for each cover summarized with in similar zones.

Table 4.4: Level of correspondence from the cross-tabulation table

Above 75%	Excellent
Covers Summarized with in Similar Zone in %	Level of Correspondence
Below 50 %	Low
50–65%	Good
65–75 %	Very good

Strong agreement in the cross-tabulation table of results lays in the GO class where 99.8 % from the FUZZY logic is summarized in the same class in the crisp (Boolean). Similarly, 79.2% the NO-GO class in the FUZZY logic generalized in the same class in the crisp (Boolean) systems. The less suitable class which is the VERY SLOW-GO surface condition is the other significant relationship where 30.9% is summarized in both results. In this case, 42.6% is classified as a NO-GO terrain condition in the case of crisp (Boolean) system. The disagreement in the results of the two methods seems to be in the SLOW-GO surface condition where only 22.4% of it in the WOA is summarized to be in the same class in the crisp (Boolean) system.

Excellent correspondence between the two outputs is observed in the GO terrain condition where 99.8% of this class in the WOA was identified in the same condition in the crisp (Boolean) system. The SLOW-GO terrain condition implies the case where there is a poor correspondence between the two methods. Only 22.4% is found to be summarized in the same zone in both methods. Rather, 24.4% which is much greater than the diagonal value is allocated to the SLOW-GO terrain condition in the (Boolean) system. The main diagonal of Table 4.3 shows the agreement between the two methods. Generally, most of the suitable terrain conditions for off-road mobility of wheeled and tracked military vehicles and the obstacles which are impassable were similarly classified in both methods except in the SLOW-GO terrain condition.

There is a considerable disagreement in the VERY SLOW GO terrain condition where only 30.9% of the class in FUZZY logic is similarly summarized in the same zone in the crisp (Boolean) system. The main difference between the two results is that the FUZZY logic uses the weight factors to emphasize or deemphasize the different factors of the cross-country trafficability analysis. Whereas in the crisp (Boolean) system method, the experts' opinion is freely exercised assigning weights using single numbers was not an appropriate abstraction of the way humans make judgments in reality. As a result, some of the terrain conditions are overemphasized and some were emphasized or deemphasized in the FUZZY logic to bring a different result from the Boolean AND system approach.

The general spatial relationship of the two approaches is obtained from the Multivariate band collection statistics. This shows how the results spatially correlate to each other. Section 4.8.1. Shows the overall spatial correlation of the results using a multivariate band collection statistic.

4.1.9. Multivariate Band Collection Statistics of Boolean and Fuzzy map Results

The correlation matrix shows the values of the correlation coefficients that depict the relationship between two datasets. In the case of a set of raster layers, the correlation matrix presents the cell values from one raster layer as they relate to the cell values of another layer. The correlation between two layers is a measure of dependency between the layers.

Correlation ranges from +1 to -1. A positive correlation indicates a direct relationship between two maps, such as when the cell values of one map increase, the cell values of another map are also likely to increase. A negative correlation means that one variable change inversely to the other. A correlation of zero means that two maps are independent of one another. The correlation matrix is symmetrical. Its diagonal from the upper left to lower right is 1.0000 since the correlation coefficient of identical maps is +1. A correlation matrix using the multivariate statistics shows how the pixels in each output spatially correlate as a result. (Figure 4.12) revealed the spatial correlation of the results.

# STATISTICS of INDIVIDUAL LAYERS					
# Layer	MIN	MAX	MEAN	STD	
# -----					
1	0.0000	5.0000	3.6178	0.9425	
2	0.0000	4.0000	2.8310	1.0421	
# =====					
# COVARIANCE MATRIX					
# Layer	1	2			
# -----					
1	0.49290	0.30940			
2	0.30940	0.60268			
# =====					
# CORRELATION MATRIX					
# Layer	1	2			
# -----					
1	1.00000	0.56768			
2	0.56768	1.00000			
# =====					

Figure 4.12: Multivariate band collection statistics of maps

According to the results obtained, the correlation of the two maps is 0.57. It is therefore sufficed to deduce that the results spatially correspond to each other, not strongly as the ideal correspondence is +1.

This shows that the results from the methods have less spatial correlation and hence the two methods have less comparable outputs for this particular application.

4.2. DISCUSSIONS

In this study, the final output of the potential for cross-country mobility (CCM) by vehicles has increasingly become an integral part of tactical planning for military operations and depends on a multitude of parameters. A comprehensive trafficability forecast requires the analysis of terrain, including terrain surface, land-use/land-cover and physical soil properties, climate, vegetation, urban area, roads and drainages.

Among other things, procedures in the operational Military Decision process also include military-geographic terrain analysis, where there are always complex analyses of vehicle ground mobility within them. The focus is on exploring the parameters of physical-geographic factors and their interrelation with mobility on the vehicle terrain. Parameters with attributes of relief, water, vegetation, soil and meteorological phenomena were made the factors of multi-criteria analysis. Data quality and accuracy were specifically examined where fuzzy logic methods were introduced within the GIS model that perform vague boundaries between phenomena since the boundaries within soil types or vegetation cover cannot be clearly defined. Fuzzy logic has also been implemented to create vehicle deceleration coefficients for all physical-geographic factors on the ground compared to the maximum possible travel speed of a vehicle. Implemented fuzzy logic methods represent vehicle mobility map, as well as an interactive application for optimized vehicle movement paths with the Cost path function in ESRI ArcGIS program package.

In this study, the final output of cross-country mobility model of fuzzy approach developed through identification and selection of influential factors of trafficability, which are the key determinant for selection of cross-country mobility areas.

Besides managing decisional uncertainty, Fuzzy set theory (Zadeh, 1965) is often used for criteria standardization before it is coupled with the Weighed linear aggregation methods (Gorsevski *et al.*, 2006; Jiang and Eastman, 2000). Different researchers used a fuzzy membership functions for the standardization of raster GIS-based criteria to assign a value between zero and one to each grid cell (Burrough and McDonnell, 1998; Eastman, 1999; Gorsevski *et al.*, 2006). According to Rodney *et al.* (2011), this process expresses the unit of measurement of each factor map as belonging to a set ranging from 0.0 to 1.0 or 1 to 255, indicating a variation from non-belonging to complete-belonging (or NO-

GO terrain (unsuitable) to GO terrain (most suitable). This is important to transform and rescale the original criteria into comparable units.

Figure 4.3, 4.4 and 4.5 represent the all value of input layers scored by fuzzy standardization between 1.0 which is most suitable and 0.0, which is unsuitable. Moreover, the different influential factors identified for the analysis are not equally important to select mobility areas. This difference can be managed by multi factor evaluation of weighted linear aggregation method for Weight calculation to give weight to each criterion to reflect their relative importance. This can be effective because it forces the decision maker/s to give thorough consideration to all elements of a decision problem and also by assigning quantitative weights, it is possible to make important criteria have a greater impact on the outcome than other criteria.

The method that integrates Fuzzy logic and AHP (FAHP) (see equation 24) was adopted to obtain weights to each factor for locating suitable trafficability areas. GIS-based FAHP schemes for suitable trafficability area analysis have been reported by a few numbers of studies. This approach allows decision makers to give interval judgments, which can capture a human's appraisal of ambiguity when complex multi-attribute decision making problems such as CCM siting are considered. Different researchers use FAHP, according to Akbari et al. (2008) and Ocalir et al. (2010), integrating fuzzy logic into the AHP process give a much better and more exact representation between criteria and alternatives. The calculated FCR from equation 21 was less than 0.1 which indicates that a reasonable level of consistency in the pair-wise comparisons and the weights were accepted. The results of the AHP method were compatible with our field observations.

Hence, in this study, the weight obtained from FAHP shows that weight of slope (32.9%), precipitation (15.1%), soil type (10.2%), stem diameter (8.1%), soil texture (7.3%), temperature (6.5%), tree density (5.3%), soil depth (3.2%), elevation (2.9%), road network (2.9%), drainage, (1.9%), urban area (1.9%), soil drainage (0.8%), canopy height (0.7%), LULC (0.3%) as presented in Table 4.2, the identified sites strongly reflect the influence of the slope data layer, which was one of the fifteen factors used in this study. The extremely suitable, class 5 and 4 areas were found in high GO terrain zone which shows flat areas. This is corresponding with best suitable map to the vehicle's mobility of military terrain.

Moreover, utilizing exclusionary criteria in preliminary screening is important to exclude unacceptable areas for siting a cross-country mobility. In this research as shown in Figure 4.6(b), different areas were identified as exclusionary to prevent effects on military equipment in the combat area; economic

conditions in the regions; transportation conditions; terrain improvement, construction and destruction of objects; environmental factors and accomplishment of tasks related to natural disaster; conditions for logistic and medical support of troops (Rybansky, 2003). The distance from drainages at less than 200 m was considered as ‘restriction zones’. Further, areas were in greater than 25° of slope to be NO-GO or impassable zone and Stream Order has in six values are impassable terrain, elevation greater than 500m are become ‘Poorly suitable zones’, temperature less than 15.7°C are unsuitable due to increasing soil moisture and that can be influenced trafficability especially of the stagnant waters in winter season soil and rock properties, drainage coefficients and thus even the stream depth and velocity, rivers and streams fordability, especially during winter weather. Mechanical properties of transport means can make the cross-country movement easier or it can make it difficult. Similarly, precipitation greater than 200 mm is unsuitable that affect especially soil conditions and consequently the slope passability, roads and terrain trafficability during in winter season (during slippery ice and deep snow), rivers and streams passability and mainly the depth and velocity of currents. The effect of vegetation (tree spacing, stem diameters and canopy heights) are slow down the vehicles velocity, width of urban area, i.e. the area greater than 1 km² are NO GO because it can affect vehicles speed. Soil conditions are considering the cross-country mobility, there exist various types or groups of soil that to be a various extent of influence the troops mobility which depending on a current structure of transport means and weather conditions are given by total amount of precipitation in a given territory. According to percentage content of clay particles which noted in Table 3.12 and 3.13, in texture size and depth can be influence of the level of roughness of the soil on mobility (average speed of movement), it is possible at individual types of transport means to identify the multiple coefficients of speed deteriorating groups. The land-use and land-cover natural and man-made objects affecting the cross-country mobility like woodland dense, swamp, settlement dense and urban, swamp grassland, Riverine vegetation, river course, grassland wet or undrained, forest, dryland forest, degraded hills, cropland in hill terrain (NATO standards classify).

Once the factors maps were developed and the associated weights assigned to each input layer, an aggregation stage was undertaken to combine the information from the various factors. The candidate sites have identified (Figure 4.1) on a continuous dimensionless scale which ranging from 1 to 5, it indicating a variation from NO GO (impassable) to GO (most suitable) site. This is one of the characteristics of the Weighted Linear Combination (WLC) technique that used to aggregate the factor maps in this study.

According to Baban and Wan-Yusof (2003) noted that this technique is a much better representation of the way major decisions are made in reality and it avoids the hard decisions of defining any particular area as absolutely suitable or not, but rather uses a continuous scale to represent suitability. This is also aided by the fact that the WLC method allows weights to be assigned to factors.

The result of fuzzy analysis in Figure 4.6(b) shows a gradual suitability for a vehicles trafficability site. The results of the Boolean logic (Figure 4.6(a)) and the fuzzy analysis (Figure 4.6(b)) also compared that in order to avoid the uncertainty. Flexibility is another characteristic of fuzzy logic. By using a fuzzy map and decision-makers are considering with regarding to the social, economic and environmental aspects may first select areas with a high suitability membership value and field investigations. When the site deemed inappropriate, they can proceed either to another site with the same membership value or to another membership value of lower suitability. This is the benefit that they do not need to conduct a new analysis, or change the rules, or the criteria, saving time and effort.

CHAPTER FIVE

5. CONCLUSION AND RECOMMENDATIONS

5.1. Conclusion

GIS and Remote sensing techniques were commonly used in spatial assessments and spatial decision-making, and were found to perform well in spatial data modeling. However, the arbitrary choice of weights in spatial site suitability assessments has made the universal acceptance of results from geospatial techniques difficult.

To overcome the weight allocation problem MCE has been incorporated into these techniques. AHP, which is a comprehensive, logical and structured multi-criteria decision making technique, has been widely used in suitability evaluations including CCM assessments. In spite of its conceptual simplicity and computational efficiency in structuring the problem in a systematic manner and in calculating weights, the traditional AHP suffers some shortcomings. The major shortcoming is its inability to handle impression and attitude of the decision maker in deciding the criteria. The current study proposed and demonstrated the use of Fuzzy AHP to deal with ambiguity in CCM assessments. Fuzzy AHP, with embedded techniques such as fuzzy numbers and fuzzy extent analysis can adequately handle the inherent uncertainty and imprecision of the human decision making process and provide the flexibility and robustness needed for the decision maker to better understand the decision problem and their decision behaviors. Using FAHP, a hierarchy model was proposed to incorporate information from physical, environmental and socio-economic factors, are offer a reference for vehicle mobility site selection in the area. Because this study took into account criteria representing the views and values of different military applications, the process by which the model selected trafficability site is suitable for other case studies, which require multi-military applications engagement and troop's participation. Participatory approaches are complimentary, not oppositional, to decision support tools such as the AHP. A total of 15 criteria were used as input into the AHP. Weights were assigned to each criterion to reflect their relative importance. By assigning quantitative weights it was possible to make important criteria have a greater impact on the outcome than other criteria. With fuzzy logic, it was possible to adequately handle the inherent uncertainty and imprecision associated with the decision-making process of assigning weights. The fuzzy approach allowed judgments to be made as a set of intervals in order to capture a human's appraisal of ambiguity when faced with complex multi-attribute decisions. Weights

were assigned to the factors using a series of pairwise comparison judgment matrices. By allowing decision makers to explicitly state and weight their decision criteria through a structured process, and making it possible to identify areas of agreement or disagreement, the fuzzy AHP achieved transparency.

Classes 5 and 4 were then grouped together and considered to be the best or best sites, whilst those in classes 2 and 3 were considered as the good or back-up sites. But class 1 considered as the poorly suitable or impassable sites. The result was the map shown in the Figure 4.6(b), with sites divided into 4 discrete categories: GO-sites, SLOWGO-site, VERYSLOWGO-site and NO GO-site or RESTRICTED trafficable sites. However, selection of suitable cross-country sites is also affected by the type of vehicles for military application. The methodology described was adopted in the least cost path to avoid the high cost but if it is evenly distributed across the AOI, it will have an equal penalty to cross. The field observation could not be carried out, but the process was conducted by GIS techniques systematically.

The similarity pointed out from both methods of Boolean (Crisp) and Fuzzy have very good correspondence with 79.2% summarized in same zone for the NO-GO trafficability class, which is relevant when the models are used to select only areas where trafficability is restricted. Besides, the two methods have excellent correspondence in the GO terrain trafficability class with 99.8% summarized in the same zone as shown in cross tabulation table. For the VERY SLOW GO trafficability class, the two methods have good correspondence value in the cross tabulation result where 30.9% is summarized within the same zone. Low correspondence occurs in the SLOW-GO trafficability class, where only 22.4% is summarized in the same region. The disagreement in between the two methods is mainly due to the use of factor weights (W_i) used in the WOA method which cannot be employed in the Expert systems and the detail knowledge of experts in the Expert system which can't be entertained in the Boolean (Crisp) method. However, the spatial correlation result obtained from the multivariate band correlation statistics (0.57) showed that an overall less spatial correlation between the results obtained from the two methods. It is therefore sufficed to conclude that the FUZZY logic method allowed judgments to be made as a set of intervals in order to capture a human's appraisal of ambiguity when faced with complex multi-attribute decisions based approach to model cross-country trafficability analysis for military vehicles.

The accurate and precise of modeling is very important in military operation planning, especially during the course of movement of armed force during war times. The Boolean (crisp) is computationally easier and faster as compared to the FUZZU logic system which demands complex computation and the

development of the knowledge base is complex and time taking task. But the FUZZY logic can therefore be effective for accuracy for Combined Obstacle Overlay (COO), which is usually manually done using paper maps.

Generally, the FUZZY logic system was more powerful tool that provides detailed accurate performance and decision-making process than the very much generalized method in the Boolean (Crisp) which prerequisites factors measured in ordinal scale.

Finally, it is worth mentioning that speed and accuracy in military operations planning is important to evaluate a battle area for successful operations. In this reason, the GIS and remote sensing techniques are very important for the Ethiopian Army to transform the manual combination of terrain-based knowledge with state-of-the-art technology in order to have successful military operations planning. The results of present research indicated that the methodology applied is an effective and simple approach for Army. In addition, the described methodology is user friendly and can employed by military authorities in developing countries to lower both time and cost.

5.2. Recommendations

- Although the fact that, Geoinformatics and its enormous application in military have gone hand in hand throughout the course of history, the military sector has been remained to be the most un-researched area in Ethiopia. It can therefore be a good research area in this field where there are several directions that should be explored.
- Military planners should encourage GIS and remote sensing techniques in making terrain-based decisions, rather than relying on inflexible paper maps and lacking up-to - date knowledge.
- The Fuzzy logic system used in this research is designed for general applications in GIS and remote sensing. A capable of answering questions like what type of vehicle to use in what type of weather and terrain conditions need to be designed.
- In this research is conducted by considering fifteen factors. However, in reality, other important factors like geological parameters, cover and concealment, line of sight, and location of enemy forces have to be included for real world applications and further researches are necessary to assess all terrain-based tasks in military operations planning. It would be highly interesting to might have prepared and performed simulation over the Earth surface of the studied area. There are many possibilities to provide realistic models of vehicles, slope vegetation, soil, buildings etc., all of which

can be verified the movements of the vehicles over the modeled paths in the terrain to rehearse military operations.

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Appendices

Annex 1: Soil physical parameters for the ground condition trafficability classes (depth, type)

FID	SoilDepth_	SoilUnit_1	SoilU_Code	SoilGroup	SoilUnit
100	100-150	Eutric Cambisols	CMeu	Cambisols	Fibric Cambisols
101	50-100	Haplic Vertisols	VRha	Vertisols	Haplic Vertisols
102	50-100	Calcaric Cambisols	CMca	Cambisols	Calcaric Cambisols
103	50-100	Haplic Vertisols	VRha	Vertisols	Haplic Vertisols
104	<30	Haplic Vertisols	VRha	Vertisols	Haplic Vertisols
105	<30	Lithic Leptosols	LPLi	Leptosols	Lithic Leptosols
106	<30	Calcaric Cambisols	CMca	Cambisols	Calcaric Cambisols
107	50-100	Haplic Vertisols	VRha	Vertisols	Haplic Vertisols
108	100-150	Calcaric Cambisols	CMca	Cambisols	Calcaric Cambisols
109	50-100	Haplic Vertisols	VRha	Vertisols	Haplic Vertisols
110	<30	Eutric Cambisols	CMeu	Cambisols	Fibric Cambisols
111	<30	Lithic Leptosols	LPLi	Leptosols	Lithic Leptosols
112	<30	Lithic Leptosols	LPLi	Leptosols	Lithic Leptosols
113	<30	Lithic Leptosols	LPLi	Leptosols	Lithic Leptosols
114	50-100	Haplic Vertisols	VRha	Vertisols	Haplic Vertisols
115	50-100	Haplic Vertisols	VRha	Vertisols	Haplic Vertisols
116	50-100	Haplic Vertisols	VRha	Vertisols	Haplic Vertisols
117	50-100	Haplic Vertisols	VRha	Vertisols	Haplic Vertisols
118	50-100	Haplic Vertisols	VRha	Vertisols	Haplic Vertisols
119	50-100	Haplic Vertisols	VRha	Vertisols	Haplic Vertisols
120	50-100	Haplic Vertisols	VRha	Vertisols	Haplic Vertisols
121	50-100	Haplic Vertisols	VRha	Vertisols	Haplic Vertisols

Annex 2: Soil physical parameters for the ground condition trafficability classes (Texture)

FID	SYMBOL	SOIL_TYPE	SOL_ZMX	ANION_EXCL	TEXTURE	SOL_Z1
0	LPq	Lithic Leptosols	100	0.5	Sandy loam	10
1	LPe	Eutric Leptosols	300	0.5	Sandy loam	30
2	CMc	Calcaric Cambisols	1000	0.5	Sandy loam	100
3	CMc	Calcaric Cambisols	1000	0.5	Sandy loam	100
4	LPe	Eutric Leptosols	300	0.5	Sandy loam	30
5	LPe	Eutric Leptosols	300	0.5	Sandy loam	30
6	LPq	Lithic Leptosols	100	0.5	Sandy loam	10
7	NTu	Humic Nitisols	1000	0.5	loam	100
8	LVh	Haplic Luvisols	1000	0.5	loam	100
9	LPe	Eutric Leptosols	300	0.5	Sandy loam	30
10	LVx	Chromic Luvisols	1000	0.5	loam	100
11	VRe	Eutric Vertisols	1000	0.5	Clay	100
12	LVx	Chromic Luvisols	1000	0.5	loam	100
13	VRe	Eutric Vertisols	1000	0.5	Clay	100
14	NTu	Humic Nitisols	1000	0.5	loam	100
15	LVh	Haplic Luvisols	1000	0.5	loam	100
16	NTu	Humic Nitisols	1000	0.5	loam	100
17	LVx	Chromic Luvisols	1000	0.5	loam	100
18	NTu	Humic Nitisols	1000	0.5	loam	100
19	LVh	Haplic Luvisols	1000	0.5	loam	100
20	VRe	Eutric Vertisols	1000	0.5	Clay	100
21	LPe	Eutric Leptosols	300	0.5	Sandy loam	30
22	LVh	Haplic Luvisols	1000	0.5	loam	100
23	VRe	Eutric Vertisols	1000	0.5	Clay	100
24	LPd	Dystric Leptosols	300	0.5	Sandy loam	30
25	LVx	Chromic Luvisols	1000	0.5	loam	100
26	VRe	Eutric Vertisols	1000	0.5	Clay	100
27	VRe	Eutric Vertisols	1000	0.5	Clay	100

Annex 3: Soil physical parameters for the ground condition trafficability classes (drainage)

Fid	Dom1	Reliab	Geology	Vegetation	Edepthhig1	Faoclass1	Parentmat2	Drainage
0	LPe	H	B/P	BC	50	LPe.cm	X	W
1	LVx	H	P/X	C	100	LVx.ni	CX	I
2	LVh	H	B/P	BCG	100	LVh.or	C	W
3	VRe	H	B	BG	150	VRe.ch	X	W
4	NTu	H	B/P	C	150	NTu.mo	X	P
5	LPd	H	B/P	B	50	LPd.cm	X	W
6	NTu	H	B/P	C	150	NTu.mo	X	P
7	LVx	H	P/X	C	100	LVx.ni	CX	I
8	LVh	H	B/P	BC	100	LVh.or	X	W
9	LVh	H	B/P	C	150	LVh.or	CX	I
10	LVh	H	B/P	BCG	100	LVh.or	C	W
11	NTu	H	B/P	C	150	NTu.mo	X	P
12	LVx	H	B/P	C	100	LVx.or	C	IP
13	LVh	H	B/P	BCG	100	LVh.or	C	W
14	CMv	M	B	BG	50	CMv.or	CX	W
15	VRe	H	B/P	C	150	VRe.pe	CX	W
16	LPq	H	B/P	BG	10	LPq	C	W
17	LPd	H	B/P	B	50	LPd.cm	X	W
18	NTu	H	B/P	C	150	NTu.mo	X	P
19	LVh	H	B/P	C	150	LVh.or	CX	I
20	LVh	H	B/P	BCG	100	LVh.or	C	W
21	LPe	H	B/P	BC	50	LPe.cm	X	W

Annex 4: Vegetation parameters for the ground condition trafficability classes (vegetation density, tree diameter, tree height)

sampling_ unite no	x	y	plot_no	tree no	Vegetation Density (no/0.5ha)	diameter_30_at0.3m(cm)	tree height(m)
29	396158	1487542	1	29	58	16	6
29	391821	1492688	2	16	32	60	14
29	392071	1492938	3	41	82	30	8
29	392321	1492688	4	23	46	56	15
35	199040	1471706	1	60	120	24	12
35	201744	1466224	2	27	54	25	11
35	201994	1466474	3	26	52	41	10
35	202244	1466224	4	88	176	27	15
36	256428	1463502	1	26	52	34	6
36	256230	1465461	2	27	54	40	13
36	256428	1463502	3	46	92	32	12
36	256780	1465211	4	44	88	33	7
37	310998	1465222	1	28	56		1
37	310548	1465472	2	19	38	55	10
37	311048	1465412	3	16	32		1
38	375739	1472635	1	20	40	28	8
38	364164	1465485	2	23	46	45	10
38	364414	1465735	3	5	10	47	8
38	364664	1465485	4	16	32	42	6
39	419251	1464959	3	7	14	13	13
43	229213	1439581	1	28	56	48	11
43	228659	1438435	2	53	106	31	13
43	228909	1438685	3	95	190	25	10
43	229159	1438435	4	61	122	27	13
44	287365	1431792	1	17	34	57	14
44	283138	1437591	2	2	4	32	8
44	283155	1437838	3	21	42	56	9
44	283638	1437591	4	17	34	22	13
45	335153	1437086	1	13	26	49	8
45	337298	1438082	2	15	30	50	23
45	337548	1438332	3	10	20	98	7
46	392218	1436968	4	10	20	17	8
54	200791	1411980	1	18	36	63	16
54	200743	1410845	2	34	68	29	13
54	200993	1411095	3	68	136	11	7

Annex 6: Climate parameters for the ground condition trafficability (Daily Temperature/Station)

NAME	GEOG	ELEV	Element	YEAR	MO	TIME	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29				
Adi_Arkey	13.5	37.1	1548	TMPMAX	2013	2	0.75	35	32	33	34	35.5	30.5	27.5	35	35	30.5	30.5	35.5	37.5	38.5	37.5	36.5	37.5	35.5	37.5	33.5	34.5	35	37.5	37.5	35	36.5						
Adi_Arkey	13.5	37.1	1548	TMPMAX	2014	2	0.75	33.5	33.7	34.2	34.4	34.6	33.6	33.2	33	33.1	30.9	31.7	32.1	32.2	33.2	32.9	33.1	33.2	33.6	32.8	33.4	34.1	34.2	33.6	33.8	34.9	34.7	33.9	35.6				
Adi_Arkey	13.5	37.1	1548	TMPMAX	2015	2	0.75	35.5	35.4	35	34.5	35	34.8	34.9	35	35.2	34.8	35.5	34.9	34.5	35	35.5	33.5	34.8	35.5	35.3	35.1	34.9	36	36.8	37	35.5	36	36	36.3				
Adi_Arkey	13.5	37.1	1548	TMPMIN	2014	2	0.38	16.9	16.7	16.3	15.2	17.6	17.5	15.6	15.4	15.2	14.9	15.4	15.7	15.6	16.6	16.2	16.6	15.9	15.7	16.5	16.1	15.7	15.9	15.2	15.3	15.6	15.3	16.2	15.2				
Adi_Arkey	13.5	37.1	1548	TMPMIN	2015	2	0.38	17	16.5	17.2	18	18.2	17.4	17.8	16.9	19.1	19.4	19	19.4	18.5	17.2	18.2	19	20	21	20.1	20.9	18.6	16.7	17.5	16.8	17.5	20.3	20	19.5				
Ambagiorgis	12.8	37.6	2900	TMPMAX	1982	2	0.75	18	17	18.5	18.2	18.5	16.9	17.5	18.2	15.9	16.5	17.8	18.1	18.5	17.8	18	18.1	17.6	18.7	18.2	17.5	19	18.8	17.5	18	17.5	18	18.4	19				
Ambagiorgis	12.8	37.6	2900	TMPMAX	1983	2	0.75	16.5	17.5	17.5	18	18.5	19	19	20	19	17.5	17.5	18.5	18.5	19	20.4	20	17.5	17	18.5	19	20	21	21	21.5	22	21.5	18.5	19				
Ambagiorgis	12.8	37.6	2900	TMPMAX	1984	2	0.75	19	19	20	21	21	20.5	20.5	20	20.5	21	22.5	21	22	22	21	20.5	21.5	22	20.5	20	21.5	21	22.5	22.5	21.5	22	22.5	22	22.5	21.5		
Ambagiorgis	12.8	37.6	2900	TMPMAX	1985	2	0.75	21.5	20.5	18	19	20.5	18	19	15	17.5	19	19.5	18	18	17.5	16.5	17	19	19.5	19.5	19.5	20	21	19.5	20.5	19.5	19	20	21				
Ambagiorgis	12.8	37.6	2900	TMPMAX	1986	2	0.75	18.5	18.5	18.5	18.3	19.5	20.5	19.5	20.5	22.5	21	20.5	21.2	21.5	18.5	19.5	19.4	19.5	19.5	18.5	19.5	18.5	19.5	20.5	20.5	19.4	20	20.5	22.5				
Ambagiorgis	12.8	37.6	2900	TMPMAX	1987	2	0.75	20	19.2	19.5	18.5	19.5	20.5	19.5	20.5	18.5	19.5	19	18.5	19.2	22.5	21.5	20.5	21.5	20.5	21.5	22.5	21	20.5	21	20.5	20	21	20.5	20.5				
Ambagiorgis	12.8	37.6	2900	TMPMAX	1988	2	0.75	19.5	19.5	19.5	18.5	19.5	18	19	20.2	18.5	19	18.3	19.5	18.5	17.6	18.5	17.5	19.6	19.5	19.2	14.5	16.5	18	19.5	19.5	21.5	20.5	20	19.5	20.5			
Ambagiorgis	12.8	37.6	2900	TMPMAX	1989	2	0.75	19.5	20	20.5	18.5	16.5	17.5	16.5	17.5	17.5	17.5	17.5	17.5	20.1	19.5	20.7	19.5	20.7	19.5	19.1	16	16.1	16.1	18.5	19	19.5	19	20	20.5				
Ambagiorgis	12.8	37.6	2900	TMPMAX	1990	2	0.75	18	17	17	17.5	16.5	17.5	17.6	17	19	16.7	19	19.2	19.5	20	19.2	19	19.3	19.5	19	18	20	19	17	17	16.5	15.5	16	17.1				
Ambagiorgis	12.8	37.6	2900	TMPMAX	1991	2	0.75	21	21.1	19.5	22	21.5	20.5	19.5	19	17.2	17.5	18	17.5	17.5	17.5	18	20	21	20.5	19.5	18	20.1	20.5	18.7	19	21.5	20	19.5	18.5				
Ambagiorgis	12.8	37.6	2900	TMPMAX	1992	2	0.75				20.5	19	19.5	19	26	23	22.5	22.6	24	24.5	20	20	18.5	17.5	16.5	18.5	20.5	22	21.9	22.5	21	24	21.5	22.5	23	23.5			
Ambagiorgis	12.8	37.6	2900	TMPMAX	1993	2	0.75	17	16.5	19	18.5	17.5	16.5	16	14.5	16.5	17	17.5	17.5	18	20.1	22	21.5	22.5															
Ambagiorgis	12.8	37.6	2900	TMPMAX	1994	2	0.75	18	17	17.5	19	20.5	19.5	20.5	18.5	17.5	20.5	18.5	20.5	16.5	20.5	19.5	19	18	20.5	17.5	18.5	19	18	20.5	17.5	18.5	15.5	20.5					
Ambagiorgis	12.8	37.6	2900	TMPMAX	1995	2	0.75	18.5	19.5	20.5	22.5	20	18.5	18	16	17	18	19.5	17	18.5	17.5	20	17	18	20.5	18.5	18.5	20.5	19.5	21.5	21	19.5	18.5	20	20				
Ambagiorgis	12.8	37.6	2900	TMPMAX	1996	2	0.75	18	19	19.5	19	18	18.5	19	20	20.5	20.5	21	21.5	21	20	20.5	21	20	19.5	19.5	21	21.5	22	21.5	21.5	20.6	20	21	21.5	21			
Ambagiorgis	12.8	37.6	2900	TMPMAX	1997	2	0.75	18	17.4	17.4	18.1	18	18.4	19	19	19.5	20	19.5	19	19.5	19.1	19.2	19.5	18	18.1	18.5	19	19.1	20	19.5	20	19.5	20	19.5	19.1				
Ambagiorgis	12.8	37.6	2900	TMPMAX	1998	2	0.75	19.3	19	19.2	20	20.4	20.1	19.1	18.4	18	16.2	15.2	19.3	19.4	20.1	18	19.1	20.1	19.1	18.3	19.4	19.1	19.3	20.4	21	20.4	21	19.2	19.4				
Ambagiorgis	12.8	37.6	2900	TMPMAX	1999	2	0.75	23.1	22.4	21.4	22.2	19.3	18.3	19.1	20.4	20.2	18.4	18.4	20.3	23.4	24	22.2	22.2	23.1	24.1	22	19.4	21.3	23.3	22.1	22	21	21.4	23.1					
Ambagiorgis	12.8	37.6	2900	TMPMAX	2000	2	0.75	19.2	18.2	20.2	20.1	20	20	19.2	19	19.3	21	20.2	19.3	19.2	19.4	21	19	20	19.4	20.1	19.2	20.1	19.3	18.2	20	19.1	18	19	19.1	18	20.1		
Ambagiorgis	12.8	37.6	2900	TMPMAX	2001	2	0.75	16.1	17	18.1	17.2	19	18.3	20.1	19.2	14.4	19	18.1	17.2	18	19.4	20.3	21.1	21.2	20.4	21.2	19.4	19.1	20.4	20.3	21.4	20.2	19	18.2	20				
Ambagiorgis	12.8	37.6	2900	TMPMAX	2002	2	0.75	20	19.2	19	19	18.3	18.4	19.2	19.3	20	19.1	18.3	18	18.2	19.3	20.1	18.3	19.4	20.3	21.1	19.2	20.1	21	20.4	22	23.3	23.2	21					
Ambagiorgis	12.8	37.6	2900	TMPMAX	2003	2	0.75	21.1	22	22.2	21.4	21.2	21	21.3	21.1	21.4	20.3	20.4	21	21.2	22	21.4	21	21.3	20.4	20.1	19.3	19.1	18.2	19	19.3	20.4	21	22.2	22				
Ambagiorgis	12.8	37.6	2900	TMPMAX	2004	2	0.75	18.1	19	18	19	18.1	17	19	19.1	20	21	22.1	21	21.1	22	20.1	19.1	21	20.1	19	18	19	19.1	18	19	19.1	18	17	19	18.1			
Ambagiorgis	12.8	37.6	2900	TMPMAX	2005	2	0.75	21.1	21	20.1	19.1	21	22.1	22	21	21	22.1	22	21	21	20.1	20	22	20	21	22.1	20.1	23	25.1	25	24.1	23	24	23.1	23				
Ambagiorgis	12.8	37.6	2900	TMPMAX	2006	2	0.75	18.1	20	21.1	21	19	20.1	20	22	23	21.1	22.1	22	23	21	19.1	22	20.1	19	21	22.1	20	21.1	19.1	20	18.1	20.1	22					
Ambagiorgis	12.8	37.6	2900	TMPMAX	2007	2	0.75	18	17	18.1	18	18	20	19	19.1	18	20	19	20.1	18	20.1	18	20.1	20	18.1	17	19.1	21	21	19.1	18.1	18	21	22.1	19.1				
Ambagiorgis	12.8	37.6	2900	TMPMAX	2008	2	0.75	20	22.1	22	19	21	20	18.1	18.1	20	18	18.1	20	20	22	21.1	19	18.1	18	21	19.1	22	21.1	21	22	22	19.1	18	20	21.1			
Ambagiorgis	12.8	37.6	2900	TMPMAX	2009	2	0.75	19.1	22	22.1	21	20.1	19	19.1	22	20	19.1	19	21	23	22.1	20	20.1	21	22.1	22	22.1	20	21.1	22	21.1	23	21	23	21				
Ambagiorgis	12.8	37.6	2900	TMPMAX	2010	2	0.75	22	23.1	23	22.4	20	21	19.1	22	21.1	21	20.1	20	22.1	21.1	23	23.1	22	22	22.1	23	21	22	23.1	23								

Signed Declaration

This thesis is my original work and has not been presented for a degree in any other university, and that all sources of material used for the thesis have been dully acknowledged.

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Place and date of Submission:

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