MODELLING MULTI-CRITERIA LAND EVALUATION USING GIS-MCDA (MULTI-CRITERIA DECISION ANALYSIS) BASED ON FUZZY LOGIC: CASE STUDY FOR IDENTIFYING SUITABLE LANDS FOR HUMAN REHABILITATION IN SOUTHERN BHUTAN.

CHOKILA -

A Thesis Submitted to the Graduate School of Naresuan University
in Partial Fulfillment of the Requirements
for the Master of Science in (Geographic Information Science)
2019

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Thesis entitled "Modelling multi-criteria land evaluation using GIS-MCDA (Multi-Criteria Decision Analysis) based on fuzzy logic: Case study for identifying suitable lands for human rehabilitation in Southern Bhutan."

By CHOKILA -

has been approved by the Graduate School as partial fulfillment of the requirements for the Master of Science in Geographic Information Science of Naresuan University

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ABSTRACT

Systematic and effective land suitability evaluation is an indispensable prerequisite to achieving sustainable and optimum utilization of land resources. However, the land evaluation is a complex multi-criteria and objective decision-making process that is often confronted with conflicting views, ambiguity and consequential risk.

This study attempts to develop a model framework for multi-criteria land evaluation using an integrated Geographic Information System and Multi-Criteria Decision Analysis (GIS-MCDA) technique based on fuzzy logic. The land evaluation model is used in a case study for identifying suitable land for human rehabilitation in two Districts of Southern Bhutan that covers with an area of 2294 km^2.

The human rehabilitation program encompasses two objectives viz. evaluating land for residential and agriculture purpose. Based on the requirement of the National Rehabilitation strategy documents, a total of seven main-criteria and twenty sub-criteria considering social, economic, climate, environments and topography are identified, and their relative importance evaluated by a group of

relevant experts. The suitability maps are then generated by the GIS-MCDA model.

The model included sensitivity analysis to validate the robustness of the land evaluation model and the stability of criteria against the subjectivity of the expert's judgements. The suitability class has a minimum change of areal values ranging from 0.2% to 36.0% and the spatial pattern has minimal variation under the changed criterion weight percentage.

It is observed that over 50% and 47% of the study cannot be considered for residential and agriculture land use respectively. This primarily due to the existence of large parks and biological corridors zones which enforce the reservation and protection. The highly suitable (S1) area for future residential and agriculture is only 5.01 km^2 (0.2%) and 18 km2 (0.8%) respectively. Under the best scenario, this can be recommended for planning human rehabilitation in future.

There exists conflict between the two objectives. The identified residential land is in full conflict with agriculture land. The conflict is resolved using Multi-Objective Land Allocation (MOLA) tool.

The suitability maps with six different levels of risks and tradeoffs are generated using OWA method which helps decision-maker(s) understand how the suitability values change depending upon the level of risk and tradeoff one wish to assume.

To date, there is no record of any scientific based method like GIS-MCDA used for land suitability analysis in Bhutan. It is positioned that this land evaluation model can significantly enhance the land evaluation for human rehabilitation. In general, this will also serve as a useful tool in achieving the sustainable and optimum use of a limited land resource and ultimately contribute to effective land management and planning in the country.

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ABBREVATIONS

AHP	:	Analytical Hierarchy Process
BHU	:	Basic Health Unit
CI	:	Consistency Index
CR	:	Consistency Ratio
DEM	:	Digital Elevation Model
FAHP	:	Fuzzy Analytical Hierarchy Process
FAO	:	Food and Agriculture Organization
GIS	:	Geographic Information System
HQ	:	Headquarter
IDW	:	Inverse Distance Weighting
MADM	:	Multi-Attribute Decision Making
MCDA	:	Multi-Criteria Decision Analysis
MCDM	:	Multi-Criteria Decision Making
MCE	:	Multi-Criteria Evaluation
MODM	:	Multi-Objective Decision Making
MOLA	:	Multi Objective Land Allocation
NCHM	:	National Center for Hydrology and Metrology
NFE	:	Non-Formal Education
NLCS	:	National Land Commission
NRP	:	National Rehabilitation Programme
NSB	:	National Statistical Bureau
ORC	:	Out-Reach Clinic
OWA	:	Ordered Weighted Averaging
RNR	:	Renewable and Natural Resource
TFAHP	:	Triangular Fuzzy AHP
WLC	:	Weighted Linear Combination

CHAPTER I

INTRODUCTION

1.1 Background and significance of the study

Land is a pervasive issue that underpins all the socio-economic development activities. The ever-growing aspiration for the standard of living, population growth and rapid economic activities continues to exacerbate pressure on the limited land and natural resources in the country. Every year significant chunks of land are allocated to various new socio-economic activities like hydropower construction, infrastructure setup, urban expansion, human settlements and rehabilitation, etc.

The stakeholders competing for the limited land resource are on the rise. The effective and systematic management and planning with extra prudence have become very indispensable for the ever-dwindling land resources.

However, the land evaluation for suitability forms an integral key component for effective land management and planning. As the landscape is characterized by a varying set of features which forms suitable for certain land use, land evaluation for suitability is a very important activity. It is a prerequisite to achieving optimum utilization of the available land resources. The land evaluation for suitability is the process of determining the fitness of a land type for defined land use and provides useful information on constraints and opportunities for the use of land thereby guides the decision-makers on the optimal utilization of the land resources (FAO, 1976).

Generally, any decision on the use of land and its allocation encompasses multi-objectives, multicriteria, multi-views, and preferences in the decision-making process. For example, the human rehabilitation is not simply about identifying and providing the piece of land to the beneficiary or moving people from one place to identified place. It involves very complex spatial decision-making process that requires considering multiple criteria including policies, legalities, sustainability, environment, politics, social and economic issues that influence the decision. The decision-making process is often confronted with conflicting views and interest, uncertainty, and consequential risk.

Such complexity necessitates a systematic and comprehensive approach to the decision-making process to accommodate the multiplicity and multi dimensionalities of the problem for effective decision (Laskar, 2003) associated with land use and allocation.

With the emergence of a new Geographic Information System (GIS) technologies, GIS is recognized as a decision support system that involves the integration of spatially referenced data in a problem-solving environment (Cowen, 1988). GIS is widely used for many land-related evaluations and suitability analysis.

However, on its own, it lacks the analytical capabilities to handle preferences, judgments, arguments and opinions involved in the decision-making process (Malczewski, 1999). The spatial analytical functionality of GIS is limited to performing only deterministic overlay and buffer operations, thus limiting its use when multiple and conflicting criteria and objectives are encountered (Carver, 1991).

On the other hand, multi-criteria Decision Making Analysis (MCDA), provides numerous techniques and procedures for decision problems in structuring, designing, and evaluating and prioritizing alternatives (Malczewski, 2006a). However, the conventional MCDA technique lacks the spatial component and treats that the area under consideration as spatially homogenous. Such an assumption is unrealistic as in many cases the evaluation criteria vary across space (Laskar, 2003).

Due to the synergetic capabilities and complimentary benefits, many authors have suggested the integration of MCDA and GIS for the spatial decision-making process (Carver, 1991; Malczewski, 1999). Thus, hybrid GIS-MCDA has greatly improved the conventional GIS-based multi-criteria land evaluation.

The most common approach for MCDA technique for multi-criteria land evaluation is the Analytical Hierarchy Process (AHP) which is primarily used to determine the criterion weights through pairwise comparisons. However, the AHP has the limitation of uncertainty or fuzzy due to the subjectivity issue of the decision-makers in the decision making. Also, the conventional methods assume that the criterion weights are given in a numerical form and therefore, cannot express the weights of importance through linguistics statement (Malczewski, 2004). Many MCDA techniques are using fuzzy logic, but many are found quite complex not widely used.

Therefore, there should be simple and effective MCDA techniques to address the fuzzy problems and determine the value-based information based on the decision maker's preferences for multiple factors.

The conventional GIS technique for land evaluation is mostly based on a Boolean approach which operates on the assumption of the input data as crisp or precise. Such an assumption is unrealistic since it is almost impossible to provide precise numerical information given the fuzzy boundaries between the suitable and unsuitable features. The precise boundaries may be an exception in the case of legal requirement. With Boolean analysis approach, the set is included only upon completely satisfying the specified thresholds and rejects the sets that are even very close to the specified thresholds. Such operations are not realistic as it does not represent the complete information for decision making.

The issues related to vagueness, imprecision and ambiguity of conventional techniques of land-use suitability analysis can be addressed by applying fuzzy logic (Zoccali et al., 2017). The concept of fuzzy logic is flexible and more suitable for data modelling where there is a lack of sharp boundaries of the element belonging to the set (Zadeh, 1965).

Through a review of literature, it is observed that several multi-criteria land evaluation studies have been conducted using myriads of GIS-MCDA methods and techniques. However, most of the techniques and methods adopted are not easy to understand. Some techniques are more complex than the problem itself thereby limiting its applications only to the advanced GIS experts and programming experts. Moreover, the issue of uncertainty and ambiguity in multi-criteria decision-making are very common due to its complexities. Such issues underscore the importance of adopting simple and effective GIS-MCDA techniques which can be implemented easily.

In Bhutan, among others, the ongoing human rehabilitation and resettlement program in Bhutan involves significant land resource allocation and utilization. The program is primarily targeted for poverty alleviation through the provision of adequate land and basic infrastructures that supports the livelihood of the economically disadvantaged section of the society. The problem is complex and multi-criteria in nature where social, economic, climate, topography and soil aspects have to be considered. The National Land Commission Secretariat (NLCS) as a responsible agency for the program lacks scientific methods of land evaluation.

Recognizing the increasing land use and allocation for various socio-economic activities resulting rapid depletion of land resources and lack of effective and systematic land evaluation techniques underscore the importance of adopting GIS-MCDA based on fuzzy logic as the solution for the multi-criteria land evaluation. This can be a helpful tool in achieving the sustainable and optimum use of a limited land resource and ultimately contribute to effective land management and planning in the country.

Therefore, the main objective of the study is to develop the simple, effective and comprehensive modelling framework for multi-criteria land evaluation using GIS-MCDA based on simple fuzzy logic. The evaluation model is explained and demonstrated simultaneously in a case study for identifying suitable land for human rehabilitation and resettlement in Bhutan.

1.2 Research Problem

The importance of sustainable land resource management is recognized globally (Laskar, 2003). The ever-increasing competition for a limited land resource by various stakeholders for numerous socio-economic activities only emphasizes the sustainability and optimization of the land resource. To this end, the evaluation of suitability of land uses is prerequisite and forms the important component of sustainable land use and planning.

Land evaluation for suitability is the process of determining the most appropriate land for future uses according to the specified requirement and preferences. The area identified for the chosen purpose should fulfil its requirement. The land use and its allocation process should be preceded by the land evaluation for its suitability.

Human rehabilitation and resettlement require a lot of land allocation. The National Rehabilitation and Resettlement program is initiated by the government of Bhutan as a strategic intervention to reduce the poverty in the country where the lands are allotted to the landless and economically disadvantaged people. The land evaluation should be performed for the feasibility of residential for human settlement and agricultural to support their livelihood an important activity.

Such suitability analysis should be based on a comprehensive and quantified assessment of potentials and development possibilities of the land resources with due consideration accorded to the biophysical, environmental and socio-economic factors, as well as space and time dimension of sustained land use (Laskar, 2003).

Given the very scarce land resource in the country amidst the competing needs of various stakeholder, the under-utilization and under-optimizations of the land resource is an unsustainable and costly affair.

Currently, given the multi-criteria and complex nature of the decision-making process for human rehabilitation, the use of conventional techniques for land evaluation and allocation process inevitably leads to ineffective land management and planning. The traditional technique lacks an effective scientific tool to handle multi-criteria decisions problems.

Some of the problems associated with the traditional approach of land evaluation are:

1. Susceptible to overlapping issues such as land allocation from the prohibited area or allocation from already earmarked for other purposes.
2. Frequent occurrence of land-use conflicts in the absence of information on land suitability, resulting from whether land should be used for agriculture, residential or industrial use.
3. No authoritative and convincing statistics on land suitability for rehabilitation in the country, thereby coercing managers and decision-makers to ponder if the lands allocated are best suitable for full optimization.
4. Often there is an incidence where the land allotted to the people are abandoned failing to meet certain amenities or allotted land found not productive or useful.
5. Involves field intensive works costing huge manpower, time and resources.

The systematic approach of decision making is necessary to address the complexities and multi dimensionalities of the problem. To date there is no scientific-based design and selection model to perform the land evaluation for human rehabilitation in Bhutan.

1.3 Research Questions

1. How to integrate fuzzy logic in GIS-MCDA model?
2. Which method is used to generate scenario of land use suitability maps with varying degrees of risk and tradeoff values?
3. How to resolve the conflict of suitable lands between the two or more competing objectives?

1.4 Objectives of the Research

The study explores the potential GIS-MCDA for multi-criteria land evaluation. The main aim of the study is to develop a comprehensive framework for multi-criteria land evaluation model using GIS-MCDA based on fuzzy logic. A case study to be conducted for identifying suitable land for human rehabilitation in Southern Bhutan. The specific objectives are:

- To integrate fuzzy logic in the GIS-MCDA model.
- To generate suitability map for human rehabilitation.
- To generate scenario maps of land suitability under varying degrees of risk and tradeoffs
- To resolve conflicts between Residential and Agriculture land use.

1.5 Study area

Location and area:

The location of the study area is shown in Figure 1. The study area lies in the Southern part of the country sharing its border with India. It is geographically located between 26°43’ to 27°13’ latitude and 90°00’ to 90°46’ longitude. It consist of two districts: Tsirang and Sarpang and has a total area of 2293 km^2.

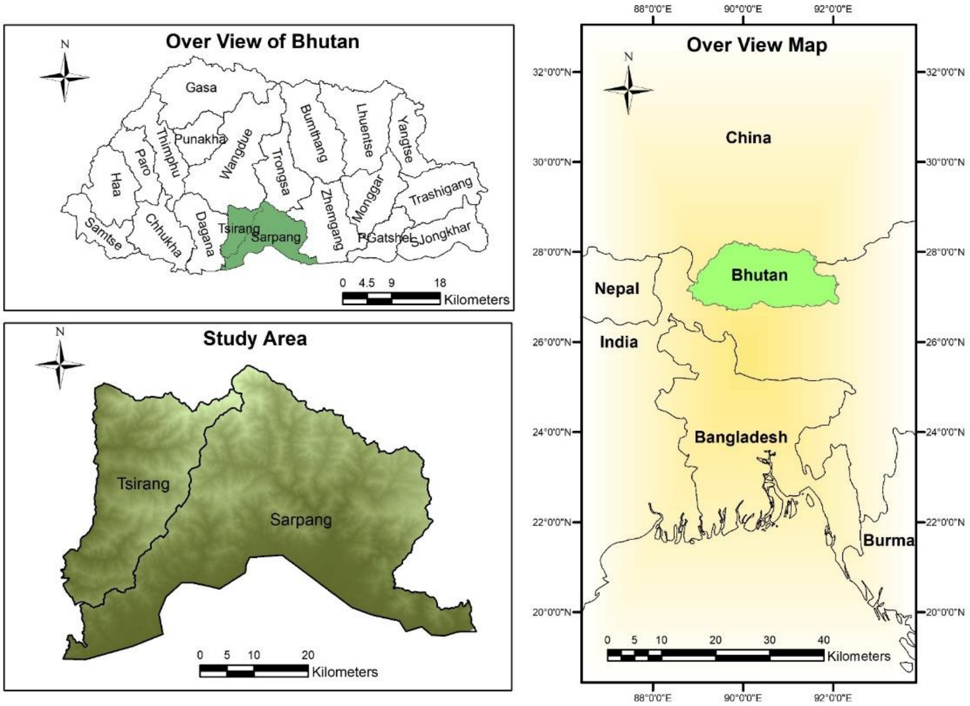


Figure 1 Location of the study area.

In the study, the part of Southern Bhutan (Tsirang and Sarpang district) is chosen as study area primarily due to the following reasons:

- Southern region is topographically and climatically more suitable for conducting socio-economic activities than the regions. These factors have significant support human rehabilitation.
- The region has updated and comprehensive spatial data on 1:25,000 scale.
- The human resettlement along the Sothern boarder can strengthen the security of the country which shares its border with India, its neighboring country.

Climate:

The elevation ranges from 200 m to 4200 m above sea level. The summer condition is hot and humid while the winter is dry and warm or moderately warm. The average annual rainfall ranges from 1000 mm to 5000 mm per year.

Land cover and land use:

About 90 % of the total area of Sarpang district is under forest cover. Around 657 km^2 of its land falls under the protected area which comprises of the Royal Manas and, Jigme Singye Wangchuck National Park and Phibsoo Wildlife Sanctuary Reserve. Dryland is most dominant agriculture land use type followed by the wetland. The crops like maize, rice, mustard and millet are some of the major annual crops; orange, cardamom areca nut, ginger, and banana are some of the cash crops grown in the District. As per the National Statistical Bureau 2017 (NSB2017) records, it has population of 45,636 people and the district has established major Infrastructures facilities like education (39 schools, 71 NFEs), health (15 hospitals & BHUs, 13 ORCs), roads (480 km) and electricity.

Tsirang District has forest cover of 87.50%. Part of its area (about 33 km^2) falls under Jigme Singye Wangchuk National Park. About 9.03% of the total area is under agriculture cultivation where the dryland is dominant use followed by the wetland. The crops like maize, rice, potatoes and other vegetables are grown. The cultivation of orange serves as the major source of the cash income.

The National Statistical Bureau 2017 (NSB2017) records total population of 22,386 people and the district has established Infrastructures like education (27 schools, 18 NFEs), health (9 hospitals & BHUs, 20 ORCs), roads (260.27 km) and electricity (100 % electrified).

1.6 Expected Outcome

- Suitability map for Residential and Agriculture for human rehabilitation.
- Map of area of conflicts between Residential and Agriculture objectives.
- Scenario maps of agriculture and rehabilitation at varying level of risk and tradeoffs values

CHAPER II

LITERATURE REVIEW

2.1 Land Evaluation and suitability

2.1.1 Concepts on Land evaluation and suitability analysis

As the landscape is characterized by a varying set of features which forms suitable for certain land use, the evaluation for land-use suitability is very important activity (Musakwa et al., 2017). It is a prerequisite to achieving optimum utilization of the available land resources (Dengiz & Usul, 2018). The land suitability analysis is performed for selecting the desired land, impact studies and land management and planning (J. Kaiser Edward et al., 2010) . There is every risk associated with land utilization without having suitability information. The suitability should justify the utilization of land for any specific purpose.

The suitability analysis is the process of determining the appropriateness of land for a particular use (Jahangeer et al., 2018). In other words, the land evaluation is a systematic process to see how well the land characteristics match with the land according to the specified requirement and preferences of its desired use. It is an assessment of the degrees of the appropriateness of land for certain use (Ritung S, 2007). The land evaluation for suitability is key to the success of sustainable land resource management which involves multicriteria analysis of the land or parcel with the particular land use under consideration. In GIS land suitability model, a variety of factors such as social, economic, cultural and physical are included and the suitability maps are displayed highlighting the areas from high to low suitability. (Jahangeer et al., 2018).

Nowadays, GIS-based land suitability analysis techniques are extensively applied in diverse field of studies like agriculture, environment, urban growth, waste management etc. (Malczewski, 2004) pointed out an important distinction between the site selection and site search. The site selection analysis deals in identifying the best site for some activity given the set of potential sites. All the characteristics such as location, size and relevant attributes of the candidate sites are predetermined and known. The best site is chosen by ranking the alternatives based on their characteristics. On the other hand, the site search analysis involves mainly in identifying the boundary of the best site, since it lacks the predetermined set of candidate sites or alternatives, which requires solving the problem.

However, both the analysis works under the assumption that the study area is divided into a set of a basic unit of observations such as polygons or raster (Malczewski, 2004). The suitability analysis classifies the unit of observation according to their suitability of specific purpose, and site search analysis determines not only suitability but its spatial characteristics such as size and contiguity based on some criteria.

2.1.2 Basic principles of land evaluation

Recognizing the importance of land evaluation, an approach by FAO was presented for an expert consultation meeting in The Netherland in 1972 and later published under the title “A Framework for Land Evaluation"(FAO, 1976). FAO framework is a collection of concepts, principles and procedures for evaluation systems.

Following are the summary of basics principles that are fundamental for the land evaluations (FAO, 1991; W.Verheye et al., 2008):

- Matching the requirement of land use against the quality of the land where the suitability of land is assessed against the specific kind of land use. The evaluation is always for a specific use and applies at all scales and levels of management.
- The suitability of each land use is deduced by comparing the required inputs with yields or other benefits.
- It is a multidisciplinary approach where the land evaluation must be made in relevance to the physical environment, economic and the social context of the area concerned.
- Suitability should be considered on a sustained basis. Short term gain should be disregarded if it has an adverse effect like environmental degradation.

The FAO concept of land suitability or evaluation is of plant or crop-specific where the potential to produce crops is determined by the combined effect of biophysical, human and capital resources (W.Verheye et al., 2008).

The literature review has observed that many suitability or land evaluation studies pertaining to agriculture have followed the FAO framework. Refer to agriculture-related studies by (Elsheikh et al., 2013; Kazemi & Akinci, 2018; Mohamed et al., 2016; Yalew et al., 2016).

2.1.3 Land suitability classification

The guideline provided by (FAO, 1976) has divided the suitability classification into Order, Class, Sub-class, and Unit. The Order is a global suitability group and divided into S (Suitable) and N (Not suitable). Class is a suitable group within order level and divided into Highly suitable (S1), Moderately suitable (S2), and Marginally suitable (S3).

It is observed that the FAO framework for land evaluations are mostly adopted for suitability analysis related to agriculture farming and production. Numerous agriculture-related studies have followed this framework of suitability classification. For example, an assessment of crop-specific land suitability and capability by (Mohamed et al., 2016; Yalew et al., 2016), agriculture suitability for Mango by (Elsheikh et al., 2013) and, agriculture suitability by (Kazemi & Akinci, 2018; Yalew et al., 2016) have followed FAO framework of land suitability classification.

However, there are also several suitability studies related to agriculture where the above classification conventions are not adopted but demonstrated similar effectiveness.

2.2 Rehabilitation and Resettlement

The rehabilitation and resettlement are the global phenomena where the people get displaced from their original habitats, mainly due to various natural and man-made reasons. Therefore, clear and effective national policies are required to address such issues.

As such, in Bhutan, the National Rehabilitation Strategy was developed in 2013 and it also complements certain provisions of the Land Act 2007 of Bhutan. However, most developing countries do not have separate policies on addressing human rehabilitation until the problem becomes the national issue. Even India brought out its first National Policy Rehabilitation and Resettlement (NPRR) for project affected families (PAFs) or families affected by the developments in the country only in 2004 (Guha, 2005).

2.2.1 Cause of human displacement

Inter alia, the following factors are attributed to the cause of human displacement in Bhutan.

Natural Reasons:

The exploitation of natural resources leads to climate change. As a result, the natural calamity such as floods, drought, landslides and soil erosions become rampant. Earthquakes and forest fires also aggravate the problems. Such natural calamities affect lives of the people by forcing to evict the area and look for a new place for rehabilitation.

Acquisition of registered land:

The rising socio-economic activities such as the construction of hydropower, industries, factories, expansion of towns and cities, setting up of infrastructures like roads, institutional buildings, water, transmission lines etc., require large areas of state land allocation. Also, the lands under human occupation are acquired for such activities wherever and whenever deemed necessary. Land acquisition is legally permitted under the provisions of the Land Act of Bhutan 2007 in the country. Such land acquisition also result in people becoming landless or near landless and forcing them to look for alternative land for rehabilitation and resettlement.

Economic disadvantage or poverty:

The landless and near-landless people are on the rise primarily due to increasing population over the fixed and limited land resource. The landless people are more vulnerable to fall under poverty groups. The Bhutan Poverty Analysis Report 2017 has estimated 8.2 % of the population under poverty. In poverty estimation, the food is considered as one of the main components (NSB, 2017). Since agriculture is an important source of food, there is a direct link between land and poverty. However, the statistics show that only 2.75% of the total geographical area of the country is found cultivated, serving as the source of food for the people (FRMD, 2017). Rehabilitation and resettlement program work to provide adequate land to poor sections of society which is one of the efficient and sustainable means to address poverty (NRP, 2014).

However, referring few sources on Rehabilitation and Resettlement documents (Bugalski & Pred, 2013; Guha, 2005; IRS, 2004; RF, 2014), unlike in Bhutan, the aspects of poverty or economic disadvantage are never considered for rehabilitation and resettlement in other countries. The rehabilitation and resettlement are considered only for the project affected families or people affected by the developments.

2.2.2 National Rehabilitation Programme in Bhutan

Human rehabilitation in Bhutan is continuation of resettlement program which was initiated in 1997 to grant land to the landless and near landless (NRP, 2014). This initiative was in recognition of the connection between land and poverty. The nature of land ownership and utilization has a direct bearing on the poverty of the people.

The program is implemented through the adoption of a strategy document titled “National Rehabilitation Strategy” which provides a framework for the implementation of the rehabilitation programme for landless farmers and socio-economically disadvantaged communities (NRP, 2014). The main objective is to address the poverty in the country through providing adequate land with access to necessary socio-economic facilities and services to improve and sustain their livelihoods. The programme mainly consists of two broad activities:

Beneficiary identification and site selection. However, this study is targeted to assist in site selection component. The implementation process is depicted in Figure 2.

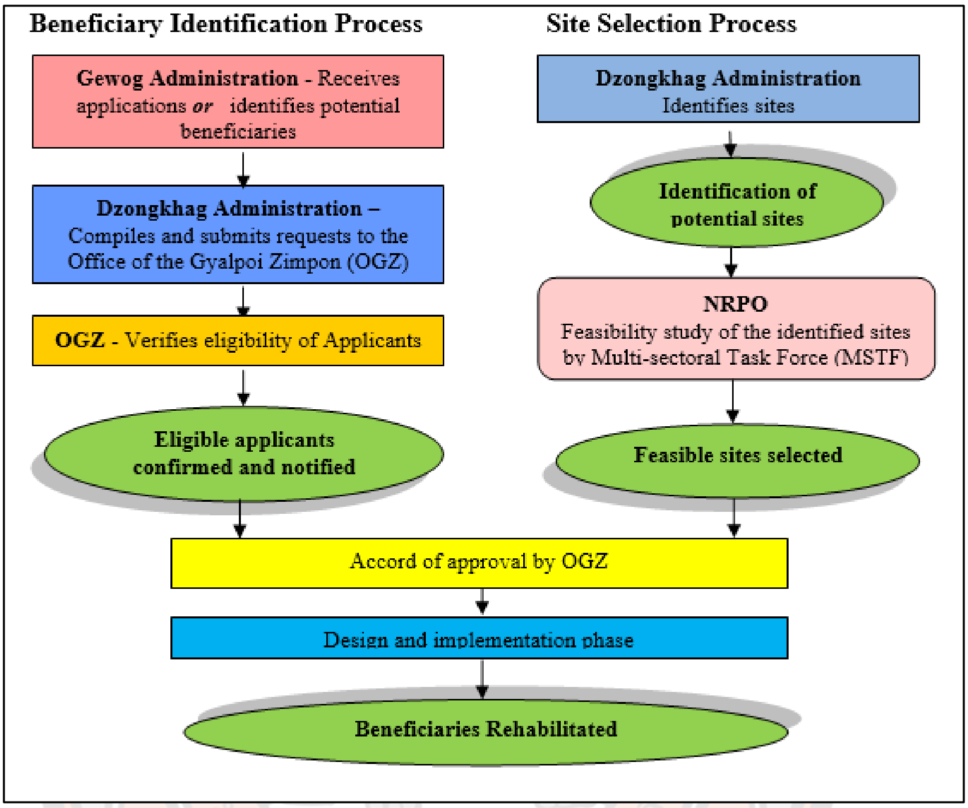


Figure 2 Flowchart for the human rehabilitation in Bhutan

Source: (NRP, 2014)

The beneficiary identification process involves receiving and verifications of applications submitted by the applicants. Approval is granted only for genuine cases. The site selection process involves, identification of potential land for rehabilitation through the involvement of multi-sectoral taskforce. The suitable lands with alternatives are submitted for approval. The approved lands are then allotted to the beneficiary for rehabilitation.

Records (NRP, 2014) show that from 2011 to 2011, 300 households were rehabilitated in 790 acres of land located in five districts viz. Pema Gatshel, Lhuntse, Samdrup Jongkhar, Haa and Dagana. Figure 3 shows the detail of household numbers, area of residential and dry land allotted for human rehabilitation in the five districts.

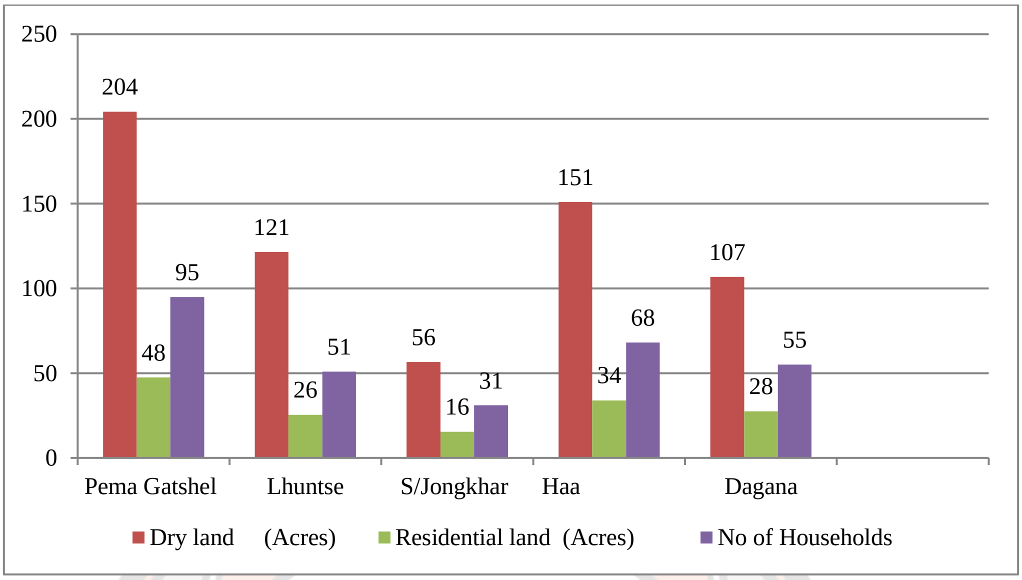


Figure 3 Number of households rehabilitated from 2011 to 2019

Source: (NRP, 2014)

2.3 GIS-MCDM

2.3.1 Introduction to GIS-MCDM

The evaluation for land-use suitability is a spatial decision-making process that involves a set of alternatives, conflicting and incommensurate multi-criteria evaluation. The conventional Multi-Criteria Decision Analysis (MCDM) technique lacks the spatial component and considers that the area under consideration as spatially homogenous. Such an assumption is unrealistic, as in many cases the evaluation criteria vary across space (Laskar, 2003). The presence of spatial component distinguishes between the conventional MCDA and spatial MCDA technique.

On one hand, the Geographic Information System (GIS) is recognized as a decision support system that involves the integration of spatially referenced data in a problem-solving environment (Cowen, 1988). On the other hand, MCDA support numerous techniques and procedures for decision problems in structuring, designing and evaluating and prioritizing alternatives (Malczewski, 2006a).

The GIS and MCDA techniques play a very important role, especially for multi-criteria land evaluation and allocation. Conventionally, the GIS-MCDA can be explained as the process of transforming and combining spatial data and value judgment (preference of decision-makers) to obtain the information for the decision making (Jacek Malczewski & Claus Rinner, 2015; Malczewski, 2006a).

Given its importance and greater relevance in spatial decision-making process GIS-MCDA has well-established body of literature. For instance the authors (Afshari, 2012; Bhushan N., 2004; Carver, 1991; Chakhar & Mousseau, 2015; Eastman, 1995; Eastman et al., 1998; Eastman et al., 1993; Estoque, 2011; Ishizaka & Nemery, 2013; Jacek Malczewski & Claus Rinner, 2015; Janssen & Rietveld, 1990; Leung LC & Cao, 2001; Malczewski, 1999; Roy, 1996; Voogd, 1982) has contribution to the established body of literature.

Numerous studies have used GIS-MCDA technique for a range of purpose. GIS-MCDA technique for land evaluation is applied in various field such as suitability for waste management (Cheng & Thompson, 2016; F.D. Emmanuel, 2017; Feo & Gisi, 2014; Hariz et al., 2017), urban growth and planning (Jahangeer et al., 2018; Parry et al., 2018; Peng & Peng, 2018), environment conservation and impact assessment (Jelokhani-Niaraki et al., 2018; Jeong & Ramírez-Gómez, 2017), human settlement (Çetinkaya et al., 2016; Rusdi et al., 2015), exploring ecotourism potentials (Gigović et al., 2016; Jeong et al., 2016), agriculture productions (Kazemi & Akinci, 2018; Mohamed et al., 2016; Yalew et al., 2016) and selection of best site for public facilities (Dell'Ovo et al., 2018; Rusek et al., 2018).

2.3.2 How GIS supports Decision Making

GIS tools are applied in a wide range of areas to support the spatial decision-making process. There are numerous frameworks for analysis of decision making and the one introduced by (Simon, 1960) is widely accepted generalization. Simon suggested that any decision-making process can be structured into three phases: Intelligence phase, design Phase and Choice Phase. GIS tool can be used to assist in all these three phases of the decision-making process. This is well explained by (Malczewski, 1999) as follows.

In the intelligence phase, the decision-making process begins with the identification of the problem. The decision problem is the 'Gap' between the desired and existing states as viewed by the decision-maker. This phase of decision making involves the collection of raw data and processing to obtain information for the identification of problem or opportunities. The capability and efficiency of GIS in large data collection, storage, processing and analyzing can adequately support the intelligence phase of the decision-making process (Siddiqui, 2006). Besides managing to integrate information and data from a different source, GIS can efficiently analyze large volumes of data which are beyond the human cognitive ability and obtain very comprehensive information for the decision- making.

The design phase involves developing a set of solutions or alternatives for the identified problem in the intelligence phase. GIS has the capability of deriving the spatial alternatives by processing and analyzing the spatial data and information based on the spatial relationship principles of connectivity, contiguity, proximity and overlay method.

The Choice phase consists of evaluating all the possible solutions or alternatives identified in the design phase and select the most favourable course of action. The most critical use of GIS in this phase is it's capability to incorporate the decision maker's preferences in the decision-making process. Since most of the GIS packages have the spatial analytical functionalities to mainly perform deterministic and buffer operation, this has limited use when multiple and conflicting criteria and objective are concerned (Carver, 1991).

2.3.3 Integration of GIS-MCDA

Why do we need to integrate GIS and MCDA? GIS is widely known as a decision support system due to its capabilities like effective data management, processing, analysis and visualization functionalities for geographic data. Such capability of GIS for supporting the decision-making process is of great importance for the land use and suitability mapping and modelling (Malczewski, 2004).

However, on its own, it lacks the analytical capabilities to handle preferences, judgments, multiple and conflicting arguments (criteria) and opinions involved in the decision-making process (Lidouh, 2013; Malczewski, 1999). The spatial analytical functionality of GIS is limited to performing only deterministic overlay and buffer operations, thus limiting its use when multiple and conflicting criteria and objectives are encountered (Carver, 1991)

On the other hand, MCDA provides a mechanism for revealing and integrating multiple preferences and opinions of the decision-makers for identifying and exploring compromise alternatives, thus it improves communication and building the consensus among multiple decision-makers to reach the policy compromise (Malczewski, 2006a).

Due to the synergetic capabilities and complimentary benefits, many authors have suggested the integration of MCDA and GIS for the spatial decision-making process (Carver, 1991; Chakhar & Mousseau, 2015; Malczewski, 1999). Thus, hybrid GIS-MCDA has greatly improved the conventional GIS-based multi-criteria evaluation for land-use suitability analysis.

2.3.4 Classification of MCDM / MCDA problems

As in the case of many literature, MCDM and MCDA are used interchangeable. MCDM problems are classified based on the following two major dichotomies viz. Multi-Attribute Decision Making (MADM) and Multi-Objective Decision Making (MODM) by (Jacek Malczewski & Claus Rinner, 2015; Malczewski, 1999, 2006a). The Figure 4 shows the classification of MCDM.

Broadly, the MCDM can be categorized as MADM and MODM based on the evaluation criteria and objectives (Eastman, 2012b; Jacek Malczewski & Claus Rinner, 2015; Malczewski, 1999, 2006a).

MADM problems are assumed to have a predetermined and limited number of alternatives (Malczewski, 2006a). Therefore, it is sometimes referred to as discrete decision problems. MADM is also alternatively referred to as Multi-Criteria Evaluation (MCE) where it deals with specific single objective (Estoque, 2011).

MODM problems are assumed to have continues meaning that the best alternatives or solution can be found anywhere within region of feasible solutions (Malczewski, 2006a). Therefore, it is sometimes referred to as continuous decision problems. MODM also sometimes referred to as Multi-Objective Evaluation (MOE) deals with multiple objectives (Estoque, 2011). It provides a framework for designing a set of alternatives. Example, analysis of best land uses (residential, forestry, agriculture, etc.). Table 1 provides a clear and comprehensive comparison of MODM and MADM.

MODM and MADM approaches are further divided into Individual and Group category depending upon the goal preference by the decision-maker(s). The degree of consensus is a major determinant of the nature of the decision-making process and it is considered to be an individual decision for single goal, preferences and belief structure despite there are a number of decision-makers (Jacek Malczewski & Claus Rinner, 2015). The literature survey of MCDA conducted by (Malczewski, 2006a) from 1900 to 2004 has observed the majority of the GIS-MCDA articles represented the individual decision-making approach.

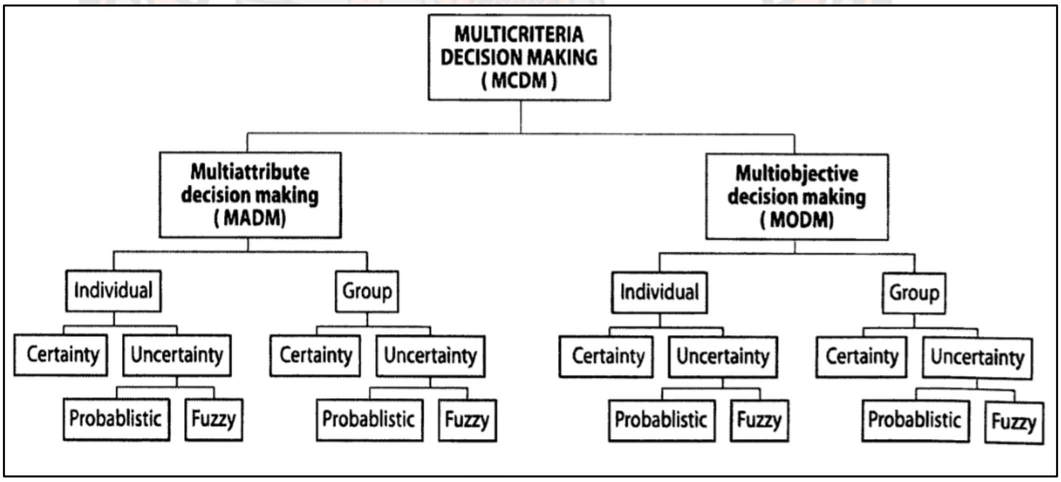


Figure 4 Classification of Multi-Criteria Decision Making (MCDM)

Source: (Malczewski, 1999, 2006a)

Individual and Group approaches are further categorized into decision under Certainty and Uncertainty depending upon the decision-maker's knowledge about the decision under consideration or the amount of information available on the decision. The decision made with the clear and complete information of the environment is said to be the decisions under certainty or deterministic decision making.

But in the real world, the decisions often involve the aspects that are unknown and uncertain. Such decision making is said to be a decision under uncertainty. Further depending upon the sources of uncertainty, the decision can be either probabilistic (limited information about the decision situation) and fuzzy or imprecise description of phenomena or events. These sub-division of decision-making is applied to both MADM and MODM approaches.

Table 1 Comparison of MODM and MADM Approaches

	MODM	**MADM**
Criteria defined by:	Objectives	Attributes
Objectives defined:	Explicitly	Implicitly
Attributes defined:	Implicitly	Explicitly
Constraints defined:	Explicitly	Implicitly
Alternatives defined:	Implicitly	Explicitly
Number of alternatives	Infinite (large)	Finite (small)
Decision maker's control	Significant	Limited
Decision modeling paradigm	Process-oriented	Outcome-oriented
Relevant to:	Design/search	Evaluation/choice
Relevance of geographical data structure	Vector-based GIS	Raster-based GIS

Source: (Malczewski, 1999)

2.3.5 GIS-MCDM framework

The simple decision framework of GIS-MCDM is explained using Figure 5 by (Malczewski, 1999) consisting of three phases as follows:

Intelligence Phase: Any decision-making process begins with the definition of decision objects or problem. The decision problem is defined as a gap between the desired and the existing states as viewed by a decision-maker. The intelligence phase involves in setting the right environment for decision making wherein the raw data are obtained, processed and examined for clues that may identify opportunities or problems. The GIS can provide major support in the problem definition due to its capabilities for data storage, management, and analysis.

After the decision problem is identified, MCDM involves specifying comprehensive sets of evaluation criteria and constraints. The criteria and constraints are mostly associated with geographical entities and their relationships which can be represented by maps. The evaluation criterion map (referred to as attribute map) is used to evaluate the performance of the alternatives, constraints map represents the limitations on the values that attribute, and decision variables may assume.

Design Phase: The decision maker's preferences with respect to the evaluation criteria are incorporated into the decision matrix or model. The preferences are expressed in terms of the weights of the relative importance of each criterion to other criteria. The determination of weights are central step for realizing the decision maker's preferences. Then, the unidimensional measurements (geographic data layers) and judgements preferences and uncertainty must be integrated to provide the overall assessment of the alternatives. This is achieved by appropriate decision rules or aggregation function. The decision rules dictate how best to rank alternatives to decide which alternative is preferred to another. Accordingly, the set of ranked decision alternatives are produced.

Choice Phase: the sensitivity analysis is performed to test the robustness. It is defined as a procedure for determining how the recommended course of action is affected by the changes in the input of the analysis. It aims at identifying the effects of changes in the inputs (geographical data and decision-maker's preference) on the outputs (ranking alternatives). If the changes do not significantly affect the outputs, the ranking is considered robust. If not, information about the output may be used to return to the problem definitions step.

Recommendation is the end-result of a decision-making process for future action which is based on the ranking of alternatives and sensitivity analysis. It may include description of the best alternatives or group of alternatives considered for implementation. In this phase the support is offered by GIS and MCDM for making spatial decision.

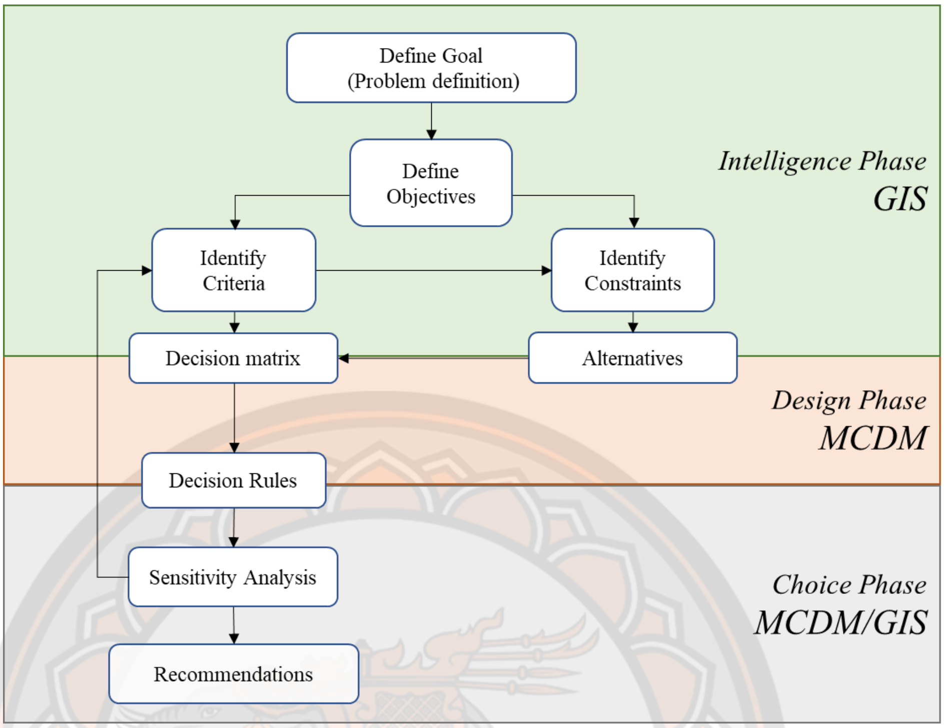


Figure 5 Framework for GIS based MCDM.

Source: Adopted from (Malczewski, 1999)

2.3.6 Identification of evaluation criteria

The spatial multi-criteria decision making requires the decision-makers to explicitly specify the objectives and identify its attributes (criteria) to measure the objectives. The objectives and attributes/criteria should adequately represent the nature of the decision problem and are hierarchically structured.

The construction of a hierarchical structure of objectives and attributes can help to simplify the complex decision problems. In multiple objectives, the most general objectives are at the highest level which is defined in terms of more specific objectives at the lower levels (Jacek Malczewski & Claus Rinner, 2015). In context of land use suitability analysis, the concept of attributes and objectives in hierarchical structure can be represented as shown in Figure 6.

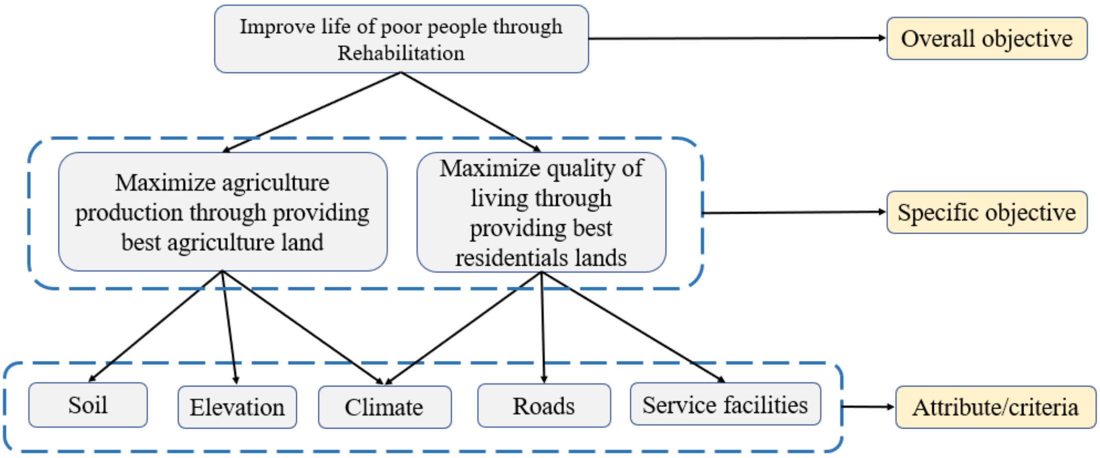


Figure 6 Hierarchical structure of the objectives and associated attributes

Source: Concept adopted from (Malczewski, 1999).

In the given example, the overall goal is to improve the life of poor people through rehabilitation. To achieve this objective, the problem is divided into more specific objectives: maximize agriculture production through providing best agricultural land and the quality of their living through providing best residential lands. Accordingly, the criteria or attributes are identified based on which the performance of the respective objectives are assessed. The performance of agriculture is evaluated based on the criteria such as soil, elevation and climate attributes, and the performance of quality of living is assessed based on roads, service facilities and climate attributes.

The objectives are defined more specifically at the lower level of the hierarchy. The attributes are at the lowest level to which the associated objectives are realized. The hierarchical structure depicts the main element of the decision problems; goal (overall objective) at the top, then descends to objectives (general to more specific) and ultimately at the attribute level.

The set of criteria should be comprehensive, complete (cover all aspects of decision problem), measurable, operational (able to use meaningfully in the analysis), decomposable (can be simplified by breaking further into parts), non-redundant (avoid duplication problems) and minimal (keep small number as possible)

(Jacek Malczewski & Claus Rinner, 2015). However, sometimes the choice of selecting the criteria is also subject to the availability and quality of the required data.

As per (Eastman, 2012b), the criterion can be of two types: Factors and Constraints.

Factor: is a criterion that enhances or detracts from the suitability of a specific alternative for the activity under consideration. It is most commonly measured on a continuous scale. In general, the factor is used synonymously to criteria in the land suitability analysis. Identification of factor is one of the important tasks in any MCDA. The types and numbers of factor identification and selection depend on the type of goal and objectives of the problem. For example, (Yalew et al., 2016) performed web-based GIS-MCDA for evaluation of land suitability for agriculture at a regional scale by considering soil (soil depth, soil water stress), land cover, topography (slope, elevation) and proximity to infrastructures (roads, water, towns) as the factors.

(Çetinkaya et al., 2016) conducted suitability analysis to identify suitable sites for the establishment of a refugee camp which is analogous to finding suitable land for human rehabilitation in Bhutan. The factors such as geographical (proximity to water source, forest), infrastructure (proximity to roads, drainage, airports, railways, etc.), social criteria (proximity to local communities, poverty density, tourist sites) and disaster (flood, landslide, warzone etc.) are identified based on the expert's knowledge and literature review of similar case studies.

Similar land suitability study for human settlement in South Africa was carried out by (Musakwa et al., 2017). The GIS-MCDA is used to provide and support a spatial decision. The decision analysis was based on factors such as infrastructure proximity (schools, road networks, etc.), social (place of worship, open space) economic opportunities as the bedrock for sustainable human settlement.

Constraints: impose the restriction on the decision alternatives under consideration. An alternative is feasible only if it satisfies all the constraints, otherwise, it is referred to as infeasible or unacceptable alternative (Jacek Malczewski & Claus Rinner, 2015).

Generally, in GIS-MCDA, constraints are mostly expressed as a Boolean (logical) map where the excluded areas are coded with 0 and those included for consideration is coded with 1 (Carver, 1991; Chakhar & Mousseau, 2015; Eastman, 1995; Eastman, 2012b; Eastman & Jiang, 1996; Jacek Malczewski & Claus Rinner, 2015; Malczewski, 1999).

A case study about the expansion of the carpet industry in the Kathmandu Valley area in Nepal was carried out using GIS-MCDA (Eastman et al., 1998). It is a multi-criteria/multi-objective land allocation process. In the study, three constraints were identified such as the exclusion of the forested areas and existing urban areas, restriction of slope gradients greater than 100% and exclusion of the carpet industry from its development within the ring road surrounding Kathmandu.

It is also important to note that although the factors and constraints are criteria opposed to each other, it can demonstrate as a continuum of varying degrees of risks that one wishes to introduce and tradeoffs in their influence over the solution (Eastman, 2012b). In the multi-criteria evaluation, it is demonstrated using Weighted Linear combination and Ordered Weighted Averaging methods.

2.3.7 Criterion maps

After establishing a set of criteria for evaluating alternative decisions, every criterion should be represented as a map layer in GIS. The map layer representing the criteria is known as criterion map. Criterion map can consist of two types: Factor map and Constraints map ((Eastman et al., 1993). The term Criterion map is used instead of factor map since it represents the spatial distribution of an attribute that measures the degree to which its associated objective is achieved (Malczewski, 1999).

The attributes of criterion maps can be a measure of either qualitative or quantitative scale. Accordingly, the criterion map can be classified as a qualitative or quantitative map. For example, categorical maps such as soil, vegetation types, settlement types are qualitative data, and maps based on distance, rainfall distribution, etc. are quantitative data layers.

Due to varying scales on which the attributes are measured, GIS-MCDM requires that the criterion values be standardized to the common scale (Eastman, 2012b; Malczewski, 1999). There exists variety of approaches for criterion standardization such as linear scale transformation, value/utility function approach, probability approach, fuzzy set membership approach. However, in the context of the current study, which is based on fuzzy logic, the section below shall discuss on standardizing criterion map values using fuzzy membership function approach.

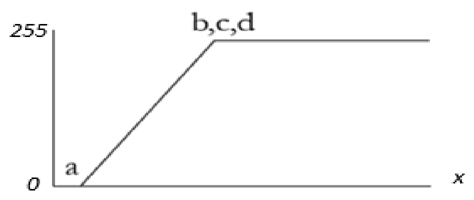
2.3.8 Fuzzy set membership and functions

The concept of fuzzy logic is explained in Section 2.6. Here, the focus is on the use of fuzzy membership functions in standardizing the criterion maps. A fuzzy set is a class of elements or objectives that do not have clear boundaries of their belongings to the defined class. The belongingness of the element to the set is defined based on the degree of membership of a particular function and the choice of the membership functions depend on the nature of data, decisions and experiences of experts (Gigović et al., 2016; Jamali et al., 2018; Jeong et al., 2016). Therefore, careful selection of the membership function is very critical while applying the fuzzy logic.

Following fuzzy membership functions are widely used in Various land-use suitability analysis study:

1. Linear fuzzy membership function:

This membership function takes an original range of continuous data and performs a simple linear stretch. Depending upon the nature of suitability problems, we can use increasing or decreasing functions.



$$\mu_A(X) = \begin{cases} 0 & \text{if} \quad x < a \\ \dfrac{x-a}{b-a} & \text{if } a \le x \le b \\ 255 & \text{if } \ b < x < c \end{cases}$$

Figure 7 A Graph representing a monotonically increasing function.

Source: Adopted from (Eastman, 2012b)

Where a, b, c and d are the control points and x value represents pixel value of the criteria. The functions of control points are:

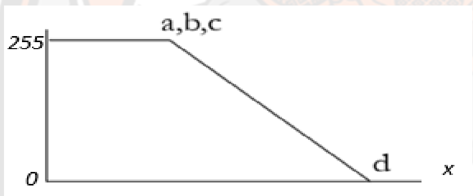
a= the value at which the suitability begins to rise sharply above zero

b= value at which the suitability begins to level off and approach a maximum of 255.

c and d = identical to b value.

The monotonically increasing function is used to produce increasing suitable values (membership values) for increasing criteria value. The criterion value is represented along the x-axis and membership value along the y-axis. This applies to all subsequent functions.

In Monotonically decreasing function the membership values decrease as the criterion value increases. For example, a closer to the road, more suitable the location of residential is.



$$\mu_A(X) = \begin{cases} 0 & \text{if} \quad x > d \\ \dfrac{d-x}{d-c} & \text{if} \quad c \le x \le d \\ 255 & \text{if} \quad b < x < c \end{cases}$$

Figure 8 A Graph representing a monotonically decreasing function.

Source: Adopted from (Eastman, 2012b)

The functions of control points are:

c= the value at which the suitability begins to fall sharply below 255

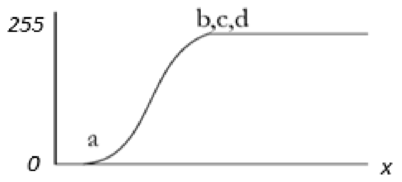
d= value at which the suitability approaches to 0

a and b = identical to value of c

2. Sigmoidal fuzzy membership function:

A sigmoidal function is used in the situation when there is an absence of constant increase or decrease in the suitability for the given criterion values. Such situation cannot be described by linear functions. Therefore, sigmoidal fuzzy membership function is used. It can be monotonically increasing or decreasing depending on the problem situation.

Monotonically increasing function is represented as below:



$$\mu_A(X) = \begin{cases} 0 & \text{if} \quad x < a \\ \frac{1}{2}\left(1 - \cos\left(\pi \frac{x-a}{b-a}\right)\right) & \text{if} \quad a \le x \le b \\ 255 & \text{if} \quad b < x < c \end{cases}$$

Figure 9 A Graph representing a monotonically increasing function.

Source: Adopted from (Eastman, 2012b)

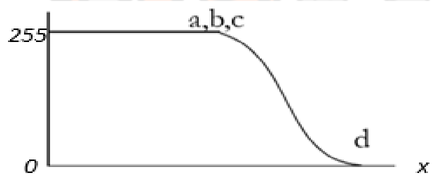
The functions of control points are:

a= the value at which the suitability begins to rise sharply above zero

b= the suitability value begins to level off and approach a maximum of 255

c and d = identical to b value.

Monotonically decreasing function:



$$\mu_A(X) = \begin{cases} 0 & \text{if} \quad x > d \\ \frac{1}{2}\left(1 + \cos\left(\pi \frac{x-c}{d-c}\right)\right) & \text{if} \quad c \le x \le d \\ 255 & \text{if} \quad b < x < c \end{cases}$$

Figure 10 A Graph representing a monotonically decreasing function.

Source: Adopted from (Eastman, 2012b)

The functions of control points are:

c= the value at which the suitability begins to fall sharply below 255

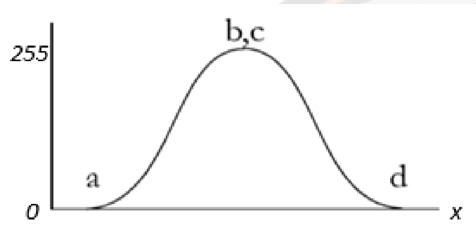
d= value at which the suitability approaches to 0

a and b = identical to value of c

3. Symmetric fuzzy membership function:

There is rise and fall in the suitability value. It can be of linear or sigmoidal. Sigmoidal Symmetric function: In case where the function rises and falls immediately, point b and c can be taken as same value. In a case where it rises and stays at 255 for a while and then falls, all a, b, c and d must have distinct values. This same concept of control points can be applied to the linear symmetric function.

Sigmoidal Symmetric function:

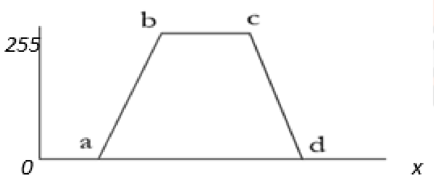


$$\mu_A(X) = \begin{cases} 0 & \text{if } a > x > d \\ \frac{1}{2}\left(1 - \cos\left(\pi \frac{x-a}{b-a}\right)\right) & \text{if } a \le x \le b \\ \frac{1}{2}\left(1 + \cos\left(\pi \frac{x-c}{d-c}\right)\right) & \text{if } c \le x \le d \\ 255 & \text{if } b < x < c \end{cases}$$

Figure 11 A Graph representing a Sigmoidal symmetric function.

Source: Adopted from (Eastman, 2012b)

Linear Symmetric function:



$$\mu_A(X) = \begin{cases} 0 & \text{if } a > x > d \\ \frac{x-a}{b-a} & \text{if } a \le x \le b \\ \frac{d-x}{d-c} & \text{if } c \le x \le d \\ 255 & \text{if } b < x < c \end{cases}$$

Figure 12 A Graph representing a linear symmetric function.

Source: Adopted from (Eastman, 2012b)

The Linear symmetric function: Numerous site suitability studies have used the Linear symmetric membership functions to standardize the criterion. Examples, a land evaluation model of a site selection for ecotourism development by Gigovic and others have used Sigmoidal and linear fuzzy membership to standardize the criterion (Gigović et al., 2016).

2.3.9 Alternatives and decision variables

At the rudimentary level, the GIS-MCDM problems involve selection of one or more alternatives from a set of geographically defined alternatives through systematic ordering with respect to a given set of evaluation criteria (Carver, 1991; Malczewski, 1999). In the context of GIS, the alternatives are collection of spatial objects like points, lines and polygon to which the criterion values are attached.

The alternatives are generated based on the set of evaluation criteria. The decision variable (attribute) is assigned to each alternative so that the performance of the alternative is measured using the decision variables by the decision makers. (Jacek Malczewski & Claus Rinner, 2015) has classified the decision variables into three categories:

Binary: decision is defined by 0 (no) and 1(yes) which are binary values.

Discrete: variables that take finite number of values (gap exist between specified values) and restricted to the integer values.

Continuous: variables that has infinite number of possible values (laying within the specified range). Also, depending on the problem situation, the decision variables may be deterministic, probabilistic or linguistics (Jacek Malczewski & Claus Rinner, 2015; Malczewski, 1999).

2.3.10 Criterion Weighting

The main purpose of criterion weighting is to express the relative importance of each criterion. Several criterion weighting techniques have been proposed for the multi-criteria decision making. Under this section, the concepts of most commonly used methods for determining the criterion weights are discussed.

2.3.10.1 Analytic Hierarchy Process (AHP)

The Analytic Hierarchy Process (AHP) introduced by Saaty is an effective tool for dealing with complex decision making where it helps the decision-makers to set realistic priorities and make the best decision (Elaalem et al., 2011; Malczewski, 1999; Ocalir et al., 2010; Saaty, 1980). It was developed in response to the absence of simple and easy-to-implement methodology for solving the complex decisions while directing the research project in US Arms Control and Disarmament Agency. Since then, there is widespread use of AHP in various field of social, government, business, defense, research and development across the world simply due to its power of simplicity and effectiveness. Besides, being simple and easy to use, AHP helps to structure the decision maker's thought whereby the problem can be well organized that is simple to follow and analyze. The AHP proved to be accepted methodology capable of producing results that agree with perceptions and expectations, and it is universally adopted as a new paradigm for decision-making (Bhushan N., 2004).

Principle:

(Malczewski, 1999) notes that the AHP is based on three principles: decomposition, comparative judgement and synthesis of priorities. In decomposition, the decision problems are further decomposed into a hierarchical structure that captures essential elements of the problem and any criteria or sub-criteria that have an impact on the given problem, and the relevant alternatives are presented in the hierarchy in one go (Saaty, 1980).

Typically, the hierarchical structure consists of four levels: goal, objectives, attributes, and alternatives (Malczewski, 1999) as shown in Figure 13. The top of the level is the goal of the decision. The hierarchy then trickles down from more general to more specific until the level of an attribute is reached. This is the lowest level against which the decision alternatives of the lowest level of the hierarchy area evaluated.

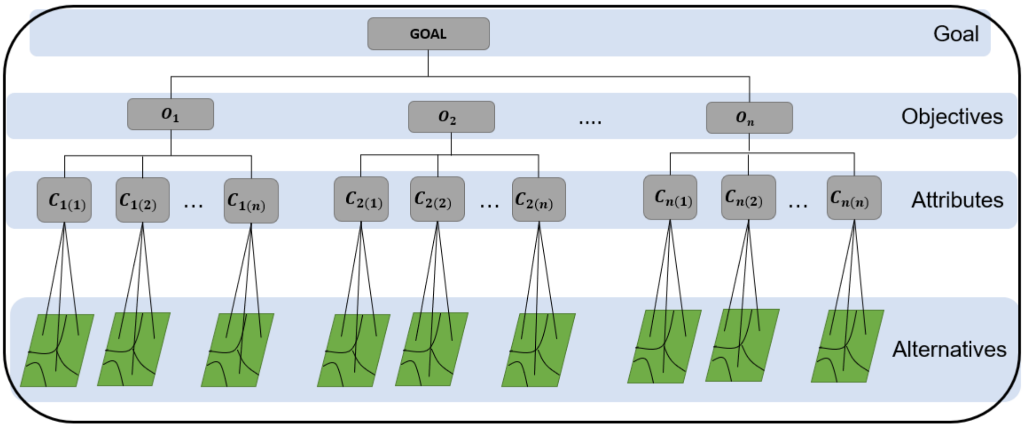


Figure 13 The hierarchical structure of AHP decision making process

Source: (Kordi & Brandt, 2012)

The comparative judgement requires assessment of pairwise comparisons of the elements within the given level of the hierarchical structure; The decision-maker can conduct paired comparisons a_{ij} of two alternatives i and j corresponding to a criterion/sub-criterion on a ratio scale which is reciprocal ,i.e. $a_{ij} = \frac{1}{a_{ij}}$ and it is impossible to judge one alternative to be infinitely better than another criterion, i.e. $a_{ij} \neq \infty$ (Saaty, 1980).

Since only two components are considered for comparison at any given time, this procedure effectively reduces the conceptual complexity of the decision making. The pairwise comparisons are conducted to estimate the relative importance of each element at a particular level with respect to the higher-level components (Malczewski, 1999).

One important element of AHP is that it allows gauging the consistency of judgements in the evaluation process (Banai-Kashani, 1989). For example, given three alternatives A1, A2 and A3, the order of preference by the experts/decision-maker may be arranged as A1 is preferred to A2 and A2 is preferred to A3. Logically the A1 should be always preferred to A3 in this case. The preference judgement is then said to be consistent. However, due to various reasons such as multicriteria in nature, limited information, uncertainty, etc., achieving the ideal consistency cannot be the case always. Therefore, there should be a mechanism to check and gauge such inconsistencies (if any) so that decision can be improved by incorporating better information and greater scrutiny of the behavioural and contextual environment of decision making (Banai-Kashani, 1989).

The synthesis principle takes each of the derived ratio-scale local priorities in the various levels of the hierarchy and constructs a composite set of priorities for the elements at the lowest level of hierarchy (alternatives). This is the final steps where the relative weights obtained in the second step is aggregated to produce the composite weights where this represents the ratings of the alternatives with respect to the overall goal (Malczewski, 1999). The decision is made based on these weights which can also be as decision alternative scores.

Like any other models and methods, AHP has its strengths and weakness, and it is subject to debate among the MCA specialists. Few prominent points are reviewed with respect to MCDA.

Strengths:

- The important advantage of the AHP lies in its ability to rank choices in the order of their effectiveness in meeting conflicting objectives (Coyle, 2004).
- The advantage of AHP in MCDA is its flexibility and its ability is check inconsistences (Ramanathan, 2001).
- AHP decomposes a decision problems into its sub parts and constructs hierarchies of criteria leading to clear importance of each criterion (Macharis, 2004).

Weakness (Pitfalls):

Despite its popularity and wide range of applications, AHP has been criticized by several authors on different grounds of applications.

- The first problem is that of rank reversal where in many scenarios, the rankings of alternatives obtained by AHP may change when a new alternative is added (Bhushan N., 2004).
- As the decision problems are being decomposed into layers of sub-criteria the number of pairwise comparisons can grow very large and become lengthy task (Macharis, 2004).

- It cannot account for the fuzziness and vagueness inherently existing in many decision-making problems (Aşkın ÖZDAĞOĞLU, 2007; Bouyssou, 2000). Such uncertainty in the preference of judgement can give rise uncertainty in the ranking of alternatives as well as difficulty in determining the consistency of preferences (Leung, 2000).

2.3.10.2 Fuzzy Analytical Hierarchy Process (FAHP)

In most of the suitability analysis concerning the MCDA, AHP is primarily used to determine the criterion weights through pairwise comparisons. However, the AHP has the limitation of uncertainty in the decision making. To address the problem of uncertainty and vagueness of human thinking, Zadeh has proposed a new theory called "Set Theory" in 1965 which operates based on the membership function. Fuzzy logic is applied to improve the accuracy and reduce the uncertainty of human thinking (Samphutthanon et al., 2014).

Numerous studies have attempted to address the fuzzy and uncertainty problem of AHP using variety of approaches such as integrated constrained fuzzy stochastic analytic hierarchy process (IC-FSAHP) by (Sitorus et al., 2019), Fuzzy Decision Making Trail and Evaluation Laboratory (FDEMATEL) by (Gigović et al., 2016; Jamali et al., 2018; Jeong et al., 2016), Fuzzy Inference System (FIS) by (Vema et al., 2019) and many others techniques. However, such techniques are found not used widely.

The most common and widely used approach is Fuzzy AHP (FAHP) which uses linguistic expression. Fuzzy AHP (FAHP) based on (Chang, 1996)'s extent analysis has been used for land-use suitability quite extensively. However, (Wang et al., 2008) have critically investigated the method on its application for weight determination and criticized it for failing to estimate the true weights from the comparison matrix and has led to erroneous application. They have cautioned on the use of this method on the basis that priority vectors determined by the extent analysis method do not represent the relative importance of the decision criteria or alternatives and may lead to wrong decisions to be made.

Another Fuzzy AHP (FAHP) method used for determining criterion weight is based on a geometric mean. It was proposed by (Buckley, 1985). It works on triangular fuzzy membership function. The method is simple and accounts well for fuzzy and uncertainty problems. The method is proposed to be used in the study. The detail procedure is discussed in Section 3.5.1.

2.3.10.3 Other methods

Ranking methods:

This is the simplest form of weighting the criteria. Every criterion under consideration is ranked in the order of the decision maker's preferences. It uses ranking like 1 for extreme important, 2 for medium important and 3 for low important or in reverse order. After ranking the set of criteria, the numerical weights are then generated using certain procedures like rank-sum, rank reciprocal and rank exponent methods (Malczewski, 1999). Such methods are found rarely used for land-use suitability analysis.

Rating methods:

The criterion weights can be estimated by the decision-maker(s) based on a predetermined scale. For example, a scale of 1 to 100 can be used. Then the rating methods like point allocation is to allocate the points. For example, in the context of land-use suitability analysis for Residential, the scale can be from 0 to 100. The decision-maker then may allocate 40 points for topography, 50 points for infrastructure and 10 for recreational criteria. Then the weights for the criteria under consideration are 0.4 for topography, 0.5 for infrastructure and 0.1 for recreational facilities. This rating method is rarely used in the studies related to MCDAM.

Trade-off analysis:

This method makes use of direct assessment of trade-offs that the decision-maker is willing to make between pairs of alternatives. In this study, the trade-off analysis using OWA is applied for generating the different scenarios of land-use suitability under different risk and trade-off values.

2.3.11 Decision Rules and Combination methods

Decision rules are the procedure for ordering decision alternatives to choose the most preferred alternatives (Malczewski, 1999). They provide systematic ways of combining the criterion, alternatives and preference of the decision-maker.

The methods here are in the context of the algorithm or combination (decision) rules for GIS-MCDA. A decision rule can also be stated as a procedure for combining criteria into a single composite index to arrive at a particular evaluation thereby allowing the decision-makers to select preferred alternatives among the set of available alternatives. Such process is also referred to as Multicriteria Evaluation (MCE) methods where several criteria are evaluated to meet the specific objective (Carver, 1991; Voogd, 1982).

Considerable number of GIS-MCDA methods have been proposed for various field of application. However, the discussion here is limited to few GIS-MCDA methods and their basic comparisons in the context of land-use suitability analysis. Some of the widely used GIS-MCDA methods are explained by Malczewski as highlighted in Table 2 (Jacek Malczewski & Claus Rinner, 2015; Malczewski, 1999).

Table 2 Basic comparisons among the commonly used GIS-MCDA methods.

Sl No	Method	Principles	Disadvantage	Advantage	Software support
1	WLC	>> Multiplies each standardized factor map by its factor weight and then sums the results.	>> Has to carefully consider many underlying assumptions while solving the MCDM problems (Malczewski, 2004)	>>Easy implementation and intuitive process. >>Intuitive to decision makers.	IDRISI, ILWIS, Common GIS ArcGIS

Table 2 (Cont.)

Sl No	Method	Principles	Disadvantage	Advantage	Software support
2	OWA developed by Yager in 1988	>> Extension of WLC >> Use Order weights in combination procedure		>> Flexibility of tradeoff and risk >>Range of possibilities between the two extremes of decisions	IDRISI, ArcView /ArcGIS, web GIS system
3	AHP by Saaty in 1980	>> Pairwise comparison of the criteria with respect to its objective	>> Too many comparisons for larger problems >> Problem of rank reversal	>> Captures all important elements of decision. Simple and easy to implement	IDRISI, ILWIS-SMCE
4	Ideal Point Methods (eg TOPSIS)	>> Decision alternative is evaluated with reference to some specific target or goal (Zeleny, 1982)	>> Some difficulties associated with the assumption underlying WLC	>> Does not assume preference independence of attributes	
5	Outranking Methods (ELECTRE, PROMETHEE)	>> Decision maker's preference can be represented by outranking relations	>> Very large number of pairwise comparison alternative with respect to each evaluation criteria	>> Mathematically simple and transparent >> Ability to consider both quality and quantity criteria for pairwise comparison of alternatives	PROMCALC,DIVISION LAB2000

Source: Summarized from (Jacek Malczewski & Claus Rinner, 2015)

These GIS-MCDA methods are mostly applied for land-use suitability analysis. Malczewski, in his survey of the literature (surveyed 300 articles from 1990 to 2004) on GIS-MCDA, noted that the weighted summation or Boolean approach was most popular among other approaches for GIS-MCDA (Malczewski, 2006a). Similarly, (Eastman, 1995; Eastman, 2012a) mentioned Boolean overlay and Weighted Linear Combination (WLC) as the two most commonly used methods to achieve the Multi-Criteria Evaluation.

2.3.11.1 Boolean overlay

Boolean overlay techniques form an important component of GIS-based land-use suitability analysis. However, it has its limitations depending on the decision problems.

The Boolean operations can be expressed with ordinary operations of arithmetic, or by the minimum (AND) or maximum (OR) functions (Jamali et al., 2018). In the Boolean overlay, firstly all the criteria are converted to logical statements of suitability and then aggregated using one or more logical operators such as intersection (AND) or union (OR).

This evaluation method is a very extreme form of decision making (Eastman, 2012b). Using AND operator, the factors must meet all the specified criteria without which it will not be included in the analysis. As a result, the decision constitutes full risk aversion. On the contrary, the OR operator allows the factors to be included in the analysis even if only one specified criterion is fulfilled thereby resulting in a full risk-taking decision.

Nevertheless, the Boolean overlay method is adopted in the suitability analysis studies depending on the context of the problem. For example, (F.D. Emmanuel, 2017) used Boolean overlay method for Site suitability analysis and route optimization for solid waste disposal. This method is generally used in conjunction with other GIS-MCDA approach (Malczewski, 2006a). Similarly, (Jamali et al., 2018) has applied Boolean logic for the constraints and fuzzy logic for standardizing the factors in Site Suitability Analysis for Subsurface.

2.3.11.2 Simple Additive Weighting methods (WLC)

WLC is a multi-attribute decision making (MADM) and it is widely used for land-use suitability analysis, site search and resource evaluation (Malczewski, 2000). The approach is based on the concept of a weighted average. The WLC method can be operationalized using any GIS system having overlay capabilities where the overlay techniques allow the criterion map layers to be aggregated in order to determine the composite output map layer (Malczewski, 2004). In WLC all the criteria are considered continuous (factors) which is firstly standardized to a common numeric range and then aggregated by means of weighted average. Firstly, the criterion weight of relative importance is assigned to each criterion map (standardized) layer. The criterion weight is then multiplied with standardized criterion value and then aggregated all the products to get the total score for each alternative. The result is then masked out by the Boolean constraints to produce the final decision.

The method has some limitations. (Malczewski, 2000, 2004) has highlighted the importance of carefully considering the underlying assumption of the WLC method which can result in dubious results if ignored. The evaluation method allows tradeoff the qualities of the criteria (Eastman, 2012a). As such a factor with high weightage can tradeoff or compensate for lows weights on other factors, even if the suitability score for that highly weighted factor is unsuitable in a particular pixel location. On the contrary, a factor with low weightage can weakly compensate for factors with high weightage even the low weighted factor is of highly suitable.

The method is extensively used for land suitability analysis (Aydi et al., 2016; Eskandari, 2017). The popularity of this technique is attributed mainly due to easy implementation within a GIS using map algebra operation and cartographic modelling (Malczewski, 2000). Due to its capability of offering full tradeoff or compensation between the factors, it avoids the hard-Boolean decision (absolutely suitable or not) and instead uses the soft or fuzzy concepts. The operator represents neither AND nor OR – lying in mid, therefore indicating neither risk aversion nor risk-taking. The degree of tradeoffs is determined by a set of Factor Weights (Eastman, 2012b)

In this study, the WLC method is used for aggregating the criterion maps to produce the composite map of land suitability for human rehabilitation.

2.3.11.3 Ordered Weighted Average (OWA)

(Yager, 1988) introduced an aggregation technique based on Ordered Weighted Average (OWA) and it is a generalization of the three aggregation fuzzy functions (intersection, union and averaging operators). This has formed as the third option for Multi-Criteria Evaluation (MCE) called Ordered Weighted Average (OWA). It allows the decision-makers to define the decision strategy on a continuum between two extreme ends of pessimistic risk-averse and optimistic risk-taking depending upon the level of risk the decision-makers wish to assume in their MCE (Eldrandaly, 2013).

Unlike the WLC method, the second set of weight called the order weights controls aggregation of the weighted factors (Eastman & Jiang, 1996). Unlike factor weights, order weights do not apply to any specific criteria. They are applied on a pixel-by-pixel basis to criteria scores at each location (pixel). The order weights permit factors to be aggregated anywhere along the risk continuum between the two extremes – AND and OR operations. After ranking, the order weight 1 (lowest score) is assigned to the lowest-ranked factor for that pixel, 2 for next higher-ranking factor, and so forth.

To examine how order weights change the aggregated results by controlling degrees of tradeoffs and risk, (Eastman, 1995) has provided the example below:

Consider decision making that consists of three factors. Order weights (1 0 0) is an equivalent of logical AND operation which produce a risk-averse (pessimistic) solution, the factors cannot compensate and select only factor with a minimum score. On the contrary, Order weights (0, 0, 1) will produce an equivalent of logical OR operation which is a risk-taking (optimistic) solution, the factors cannot compensate and only select factor with maximum score. Order weights (0.33, 0.33, 0.33) is an equivalent of WLC which produces an intermediate solution (risk-neutral). It allows full tradeoff so that the relatively poor factor can be compensated for by the higher scores of good factors.

The order weights in OWA can take on any combination of values that sums to one. This results in the decision rule which can be represented by a triangular decision strategy space (shown in Figure 14) that defines the dimensions of risk attitude and tradeoff (Eastman et al., 1998).

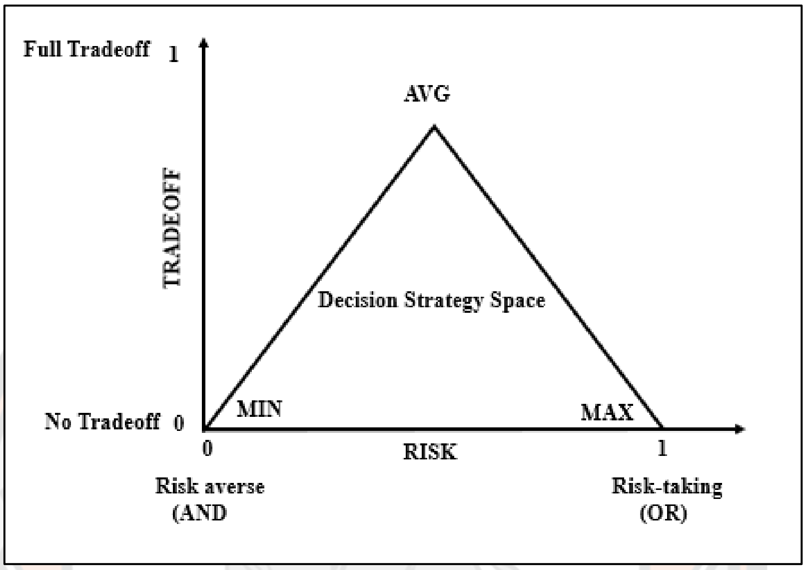


Figure 14 Decision strategy of OWA

Source: Modified from (Eastman et al., 1998)

In this strategy, the skewness of the order weights determines the ANDness, while the relative spread of weights between the ranked factors determines the degree of TRADEOFF. The three measures (ORness, ANDness, and Tradeoffs associated with any set of order weights can be calculated as follows (Malczewski, 1999):

$$ORness = 1 - ANDness$$

$$ANDness = \frac{1}{n-1}\sum((n-i)W_{order-i})$$

$$TRADEOFF = 1 - \sqrt{\frac{n.\sum(W_{order-i} - 1/n)^2}{n-1}}$$

Where:

n = total number of factors,

i= order of factors,

$W_{order-i}$= *weight for the factor of the i-th order.*

Since OWA method can generate scenarios of various suitability maps depending on different level of risk and tradeoff values, this method can help understand how the suitability changes with change in risk and tradeoff level by the decision-maker(s). The two jargons Tradeoff and Risk have to be understood clearly in the context of OWA method for land suitability.

The tradeoff: is the degree of compensation or substitutability between the factor(s) (Jacek Malczewski & Claus Rinner, 2015) depending on the set of factor weights which is sometimes called tradeoff weights (Eastman, 2012b). Factor weight applies to the specific factor or criteria and it determines how it will tradeoff with other factors. For instance, the factor with high factor weight can tradeoff or compensate with poor criterion values (suitability score) on other factors even if that highly weighted factor has low suitability score or particularly not good. On the contrary, a factor with high suitability score but small factor weight can only weakly compensate for poor scores on other factors (Eastman, 2012b)

Risk: in reality, there are decision-makers with optimistic (or risk-taking) attitudes who emphasize good properties of alternatives while pessimistic (risk aversion) decision-makers tend to focus on bad properties of the alternatives (Jacek Malczewski & Claus Rinner, 2015).

Therefore, GIS-MCDA land evaluation is also characterized by a certain level of risk that will strongly influence the final suitability map. Boolean logic provides very extreme solutions of either risk-averse when the AND operator is used or risk-taking solution when OR operator is used. AND operator allows suitability aggregation only if all the other factors have high scores while the OR operators allow even if one of the factors has low suitability score. The extent degree of risk is AND (minimum) and OR (maximum).

2.4 Sensitivity Analysis

In spatial multi-criteria decision analysis the sensitivity analysis is generally recommended to perform on the suitability output to verify its stability against the subjectivity of decision-makers (Çetinkaya et al., 2016; Gigović et al., 2016). It is very useful where there exists uncertainty in the determination of the importance of weights by the decision-maker (Chen et al., 2013).

The sensitive analysis is commonly performed by changing the input criterion weights and see its effect on the output (Çetinkaya et al., 2016). Therefore, in this study, criterion weights are changed to check the stability of the suitability classes of agriculture and residential map.

In land-use suitability analysis, the sensitivity analysis is performed after obtaining the ranked orders of suitable alternatives to determine the robustness of the decision made for the ranking of the alternatives. It identifies the effect of changes in the inputs (decision maker's preference) on the outputs (ranking of alternatives), whereby the decision can be considered robust if there is no significant effect on the ranking of the suitable alternative despite making changes to the input (Malczewski, 1999). The ranking orders of the suitable alternatives can be affected by the uncertainty in the decision weights or criteria values (Mosadeghi, 2013).

Though not many have applied the sensitivity analysis in the evaluation of their land-use suitability analysis, it is important to systematically check uncertainties and provide effective solution supported by the majority of stakeholders.

2.5 Conflict Resolution of competing objectives

Multi-objective decision making is expected when there is more than one objective in decision-making. Such objectives can be either complementary or conflicting (Carver, 1991). In the complementary objectives, the land areas may satisfy more than one objective (i.e belong to more than one decision set) while in the conflicting objectives, there is competition among objectives for the available land since it can be allotted to only one objective. For example, a piece of land allocated for the combined environment and wildlife sanctuary protection can be complementary objectives. In such objectives, the optimal area fulfils both the objectives at the maximum degree possible. An example of conflicting objective could be between the two objectives of suitable land for residential and agriculture, where a piece of land can be allotted only for one objective.

Although the conflicts between the objectives in the multi-objective decision-making process are quite rampant, especially in the multi-criteria land evaluation process, there are no easy and effective decision tools available in most of the GIS. Instead, the mathematical programming tools outside the GIS were used as an extension of MCE (Eastman et al., 1998).

(Malczewski, 2006a) has noted that the traditional approaches to multi-objective decision-making process using goal programming has certain limitations. Firstly, it is only possible to formulate decision problems in terms of mathematical programming models. Secondly, the ability of such methods are limited and not applicable for large and complex problems. Thirdly, it cannot find important decision solutions. Given these limitations, several heuristics approaches such as MOLA have been proposed.

IDRISI has included a specific tool called MOLA (Multi-Objective Land Allocation) for multi-objective decision making. The possible solution using MOLA for conflict resolutions through prioritization or compromise of objectives is illustrated below by (Eastman, 2012a; Eastman et al., 1998).

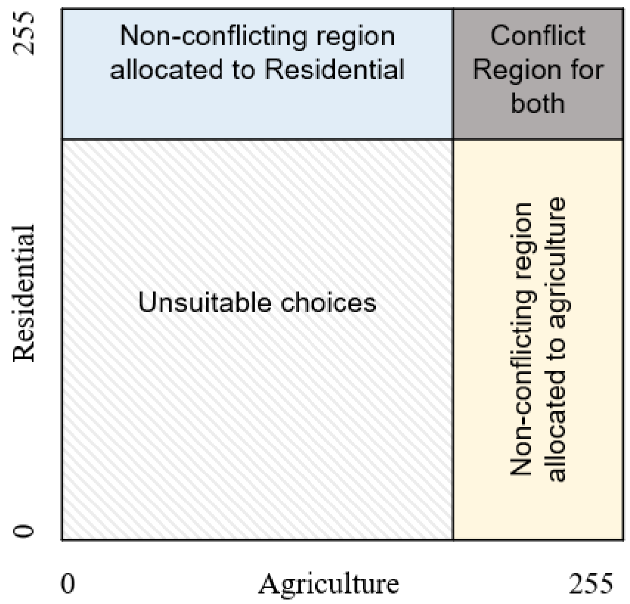


Figure 15 Division of the decision space for MOLA.

Source: Adopted from (Eastman et al., 1998)

Figure 15 represents the division of decision space for MOLA. The decision space is divided into four regions:

1. Area best suitable for cultivation and not suitable for residential
2. Area best suitable for residential and not suitable for cultivation
3. Area not suitable for both
4. Area best suitable for both (this is the area of conflict)

To resolve area of conflict, the portioning techniques of the affected cells is used where the decision space is further partitioned into two regions as shown in Figure 16.

The ideal point represents the best possibility of a suitable case - a cell that has maximum suitability for one objective and minimum suitability for anything else (Eastman, 2012a).

To resolve this conflict zones, MOLA reclassifies the ranked suitability maps to perform a first stage allocation, checks for conflicts and then allocates conflicts based on a minimum-distance-to-ideal-point rule using the weighted ranks (Eastman et al., 1998). The weights of the objectives can be specified which is represented by the 45-degree line between the objectives. The conflict resolution is a means of achieving the maximum optimization of the land-use.

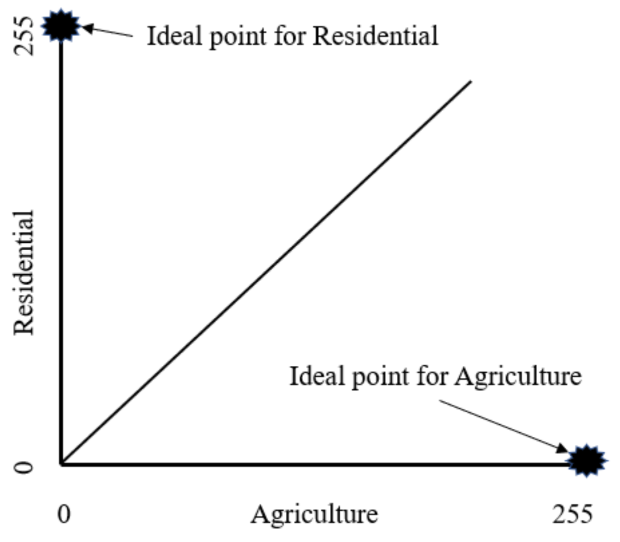


Figure 16 Ideal point region in the decision space MOLA.

Source: Adopted from (Eastman et al., 1998)

Several approaches including the traditional methods such as linear integer programming, goal programming, reference point algorithm, etc and heuristic search methods are used for multi-objective land evaluation to achieve the maximum optimization of land-use. For instance, a land-use optimization in the form of a linear programming model is used to explore a range of smart agriculture development with climate adaptation (Dunnett et al., 2018). MOLA based on a heuristic approach is used for resolving conflicting objectives between the expansion of carpet industry and protection of traditional agriculture land in Kathmandu valley, Nepal (Eastman et al., 1998). MOLA is used for zoning the protected area of Ghamishloo wildlife sanctuary in Iran to avoid conflicts due to the possible use of land (Hajehforooshnia et al., 2011).

Also, simulated annealing (SA) algorithm is used for the optimization of multi-objective land resource allocation (Li & Ma, 2018).

2.6 Fuzzy logic in land-use suitability analysis.

One of the serious drawbacks of conventional methods of land-use suitability analysis is the assumption of the input data as crisp or precise (Malczewski, 2004). Such an assumption is unrealistic as it is almost impossible to provide precise numerical information where there is a lack of clear boundaries between the suitable and unsuitable features. The existence of precise boundaries may be an exception in the case of legal requirement. However, in many circumstances, there are no distinct natural cut-offs boundaries associated with the land-use. In the conventional approach, the cut-offs are generally defined using the linguistics term such as within, close to, nearby, etc.

For example, a suitable site must be within 5 km of a health centre. The problem of such specification is that it considers precisely up to 5 km only. It categorizes 4.99 km as suitable but 5.01 km as unsuitable, though they are very close to each other. Defining such cut-off results in ambiguity and imprecision in the analysis output. Similarly, the decision criteria for a suitable site to construct a house would be expressed by linguistic concepts such as having *a* moderate slope, favourable aspect, warm temperature, close to town, and not near crime area. We can see that the linguistics expressions of the condition are very vague. There are no clear class values for these linguistic terms such moderate, favourable, etc. as it lacks clear boundaries or the classification of a feature into a class is not obvious (M.S. Mesgari et al., 2008).

The conventional Boolean approach can be used to convert the above expressions into crisp set as Slope less the 10 per cent to be moderate, aspects between 120 degrees to 150 degrees to be favourable, temperature between 21 degree Celsius to 25 degree Celsius to warm, within 1 km from town to be close, 20 km from crime area to be far away from crime.

In many cases, the conventional overlay functions that rely on the crisp set Theory (Boolean logic) are used in GIS to integrate the criteria to produce the useful information for the decision-makers (M.S. Mesgari et al., 2008).

However, with such an analysis approach, the set would be included only if it completely meets the specified thresholds. It rejects the sets that are even very close to the specified thresholds. Such operations are not realistic and may not accurately represent the decisions. Moreover, in the land-use suitability analysis, the criterion weights are given in the numerical.

On the contrary, the experts accord the weights of importance using linguistic terms such as least important to extremely important. Therefore, it is very important to deal with the related issues of uncertainty, vagueness, imprecision and ambiguity in the land-use suitability analysis. This can be addressed by fuzzy set theory and fuzzy logic (Malczewski, 2004; Zadeh, 1965).

The concept of fuzzy logic is flexible and more suitable for data modelling where there is a lack of sharp boundaries of the element belonging to the set (Zadeh, 1965). Fuzzy using embership functions were first introduced by Zadeh in 1965 who proposed using the membership range from 0 to 1 (Jamali et al., 2018).

The main concept of fuzzy logic is the membership function, which represents the degree to which a given element belongs to the set. It provides a good framework for representing and treating uncertainty in the sense of vagueness, imprecision, lack of information, and partial truth (Malczewski, 2004). Using the fuzzy membership functions, instead of excluding or rejecting from the analysis, it will assign a very low degree of membership value depending on how close it is to the threshold value and still include in the analysis.

There are several advantages of applying fuzzy logic over the conventional methods of spatial problems in general and land-use suitability in particular. The application of fuzzy set methods can help to retain complete information of partial memberships giving due consideration to the uncertainty and ambiguity involved (Malczewski, 2004).

From the discussion in the above section, we can say that the fuzzy approach of land-use suitability has fewer limitation compared to conventional methods. However, it has its own share of limitation. The main problem while applying fuzzy logic to land-use suitability modelling is the lack of a definite method for determining the membership function (Malczewski, 2004).

2.6.1 Fuzzy sets

The fuzzy sets are classes without sharp boundaries i.e. the gradual transition between membership and non-membership values in the decision set (Schmucker, 1982; Zadeh, 1965). The fuzzy set theory renders a rich mathematical basis for understanding decision problems and for constructing decision rules in criteria evaluation and combination (Eastman, 2012a).

The simple mathematical definition and explanation is provided by (Kainz) as below:

A fuzzy set A of a universe X is defined by a membership function $\mu_A : X \rightarrow [0,1]$ where $\mu_A(x)$ is the membership value of x in A. If the universe is a finite $X = \{x_1, x_2, x_3, x_4, ...x_n\}$ then the fuzzy set A on X is expressed as

$$A = \frac{\mu_A(x_1)}{x_1} + \frac{\mu_A(x_2)}{x_2} + \cdots + \frac{\mu_A(x_n)}{x_n} = \sum_{i=1}^{n} \frac{\mu_A(x_i)}{x_i}$$

The term $\frac{\mu_A(x_i)}{x_i}$ indicates the membership value to the fuzzy set A on for x_i. The symbol "___" is called separator, Σ and "+" function as aggregation and connection of terms. If the universe is an infinite set $X = \{x_1, x_2, x_3, x_4, ...x_n\}$ then fuzzy A on X is expressed as $A = \int_X \frac{\mu_A(x)}{x}$. The symbol $\int$ and "___" function as aggregation and separator. The empty fuzzy set Ø is defined as $\forall x \in X, \mu_X(x) = 1$, i.e the universe is always crisp.

For example, assume that $X = \{x1, x2, x3\}$, and $A = \left\{\frac{0.2}{x1}, \frac{0.4}{x2}, \frac{0.3}{x3}\right\}$ is a fuzzy subset of X. The numerical values denote the membership value of x. Therefore, 0.2, 0.4 and 0.3 are the membership values for $x1, x2$ and $x3$ respectively in the fuzzy subset A.

A fuzzy set is specified by the membership function. A membership function assigns a degree of membership value to every element of the universe in a fuzzy set. This membership value must be between zero (no membership) and one (full membership). All other values between zero and one indicate to which degrees an element belongs to the fuzzy set. This is illustrated in Figure 17.

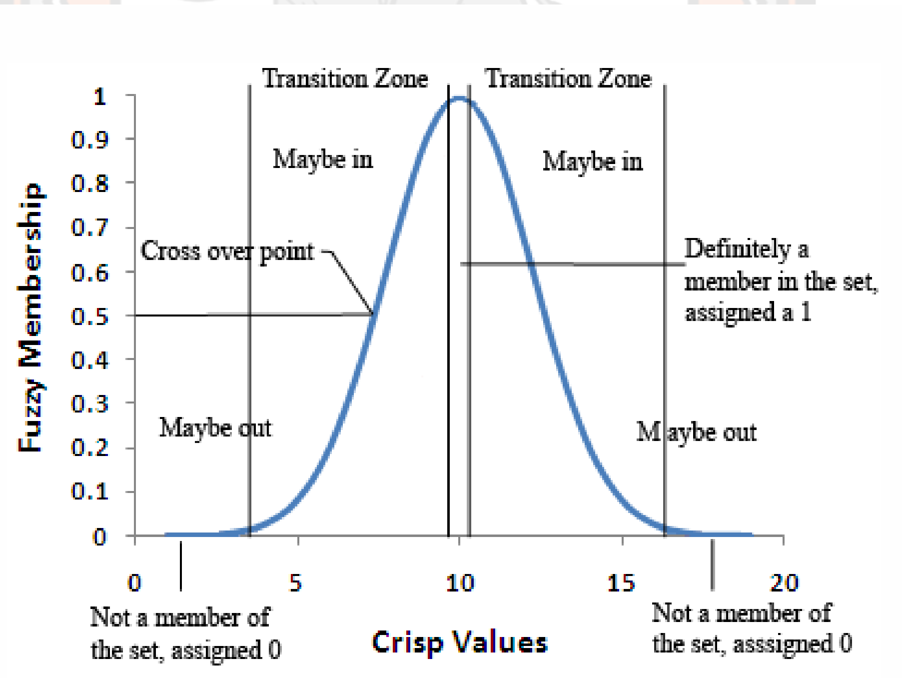


Figure 17 Fuzzy membership function diagram.

Source: desktop.arcgis.com

2.6.2 Fuzzy logic in GIS

The concept of fuzzy membership function has been used in several GIS-based studies focusing on land evaluation and classification (Malczewski, 2004). For instance, (Malczewski, 2006b) has incorporated the concept of fuzzy (linguistic) quantifiers in conjunction with GIS-based land suitability analysis via ordered weighted averaging (OWA).

The fundamental premise behind fuzzy logic is that there are uncertainties in attribute and the geometry of the spatial data. In GIS, the fuzzy sets can be used to represent the geographical entities with imprecisely defined boundaries as fuzzy objects or regions (Malczewski, 1999).

Malczewski explained using the Figure 18 below. The set of pixels of the spatial data (raster format) can be considered as a fuzzy region. The central point is interpreting the degree to which these cells fall inside or form part of some entity that has a fuzzy boundary.

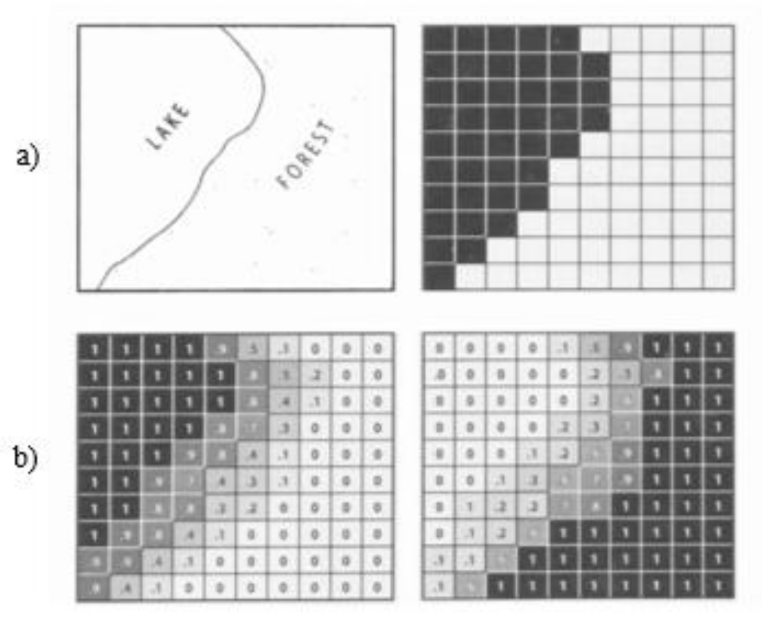


Figure 18 Crisp and Fuzzy representation.

a) Crip representation b) Fuzzy representation (left: lake, right: Forest).

Source: (Malczewski, 1999)

The figure shows that the cells are interpreted as the degree to which the point is inside or part of a forest or lake entity. The crisp region represents the sharp boundaries with a discrete binary value of 1 for present or 0 for absent at each location. The attribute has homogenous concentration over the region.

On the other hand, the fuzzy represents varying concentration over the region. The concentration is expressed as the membership value (from 1 for the highest concentration to 0 for the lowest concentration) at each pixel location.

Unlike the crisp sets, the fuzzy is based on the membership function where it defines the likelihood of phenomena being the membership of the set or class. In GIS-based multi-criteria evaluation, fuzzy set membership is used in the standardization of the criteria (Eastman, 2012b).

CHAPTER III

RESEARCH METHODOLOGY

3.1 Introduction

Multi-Criteria Decision Making (MCDM) for land suitability analysis involves developing a decision model which requires specifying goals, objectives and all the criteria that influence the decision-making process. In the study, the overall model framework was designed and used the model for finding suitable land for human rehabilitation which is based on the requirement of the Rehabilitation strategy document, other relevant sources of information through literature review and available datasets. This section includes the overall conceptual model framework and it's detailed components and process.

3.2 Model framework and process

The main objective of this study is to develop a land evaluation model using a hybrid of GIS and MCDA technique of land evaluation for site suitability. The GIS-MCDA involves evaluation of spatial events based on the criterion values and the decision maker's preferences with respect to a set of evaluation criteria (Malczewski, 1999). The overall model framework for multi-criteria evaluation model is presented in Figure 19.

The model framework consists of four phases viz. 1. A preliminary study, 2. Data collection and preparation, 3. GIS-MCDA based land evaluation and 4. Validation and recommendation.

Each phase is described separately in the following pages. Phase 3 (GIS-MCDA based land evaluation) forms the main component of the model framework and consist two processes, GIS and MCDA.

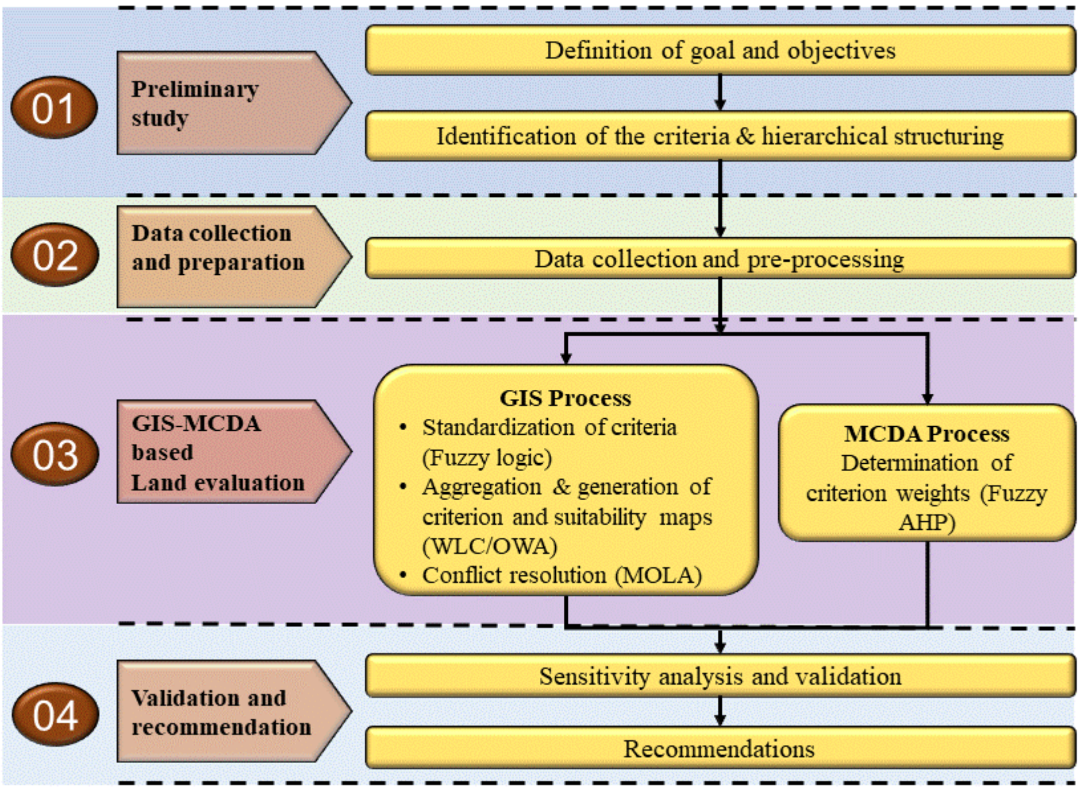


Figure 19 Overall land evaluation model framework

MCDA has higher analytical capability in developing a decision model, the technique is used to define the objectives or goal, identify the criteria and construction of the hierarchical structure to simplify the complexity of multicriteria, and determine the relative importance of the criterion identified. The GIS technique involves mainly to process the spatial data input using certain methods. The GIS input data represents the factor or criteria identified by the MCDA model. This input is then standardized to produce the criterion map which is then aggregated to produce the output representing the objectives. The final outputs are then validated in the fields.

Based on the model framework, the land evaluation procedural model for human rehabilitation is developed as shown in Figure 20. The ultimate goal (land suitability for human rehabilitation) is divided into two specific objectives (suitability for Agriculture and Residential).

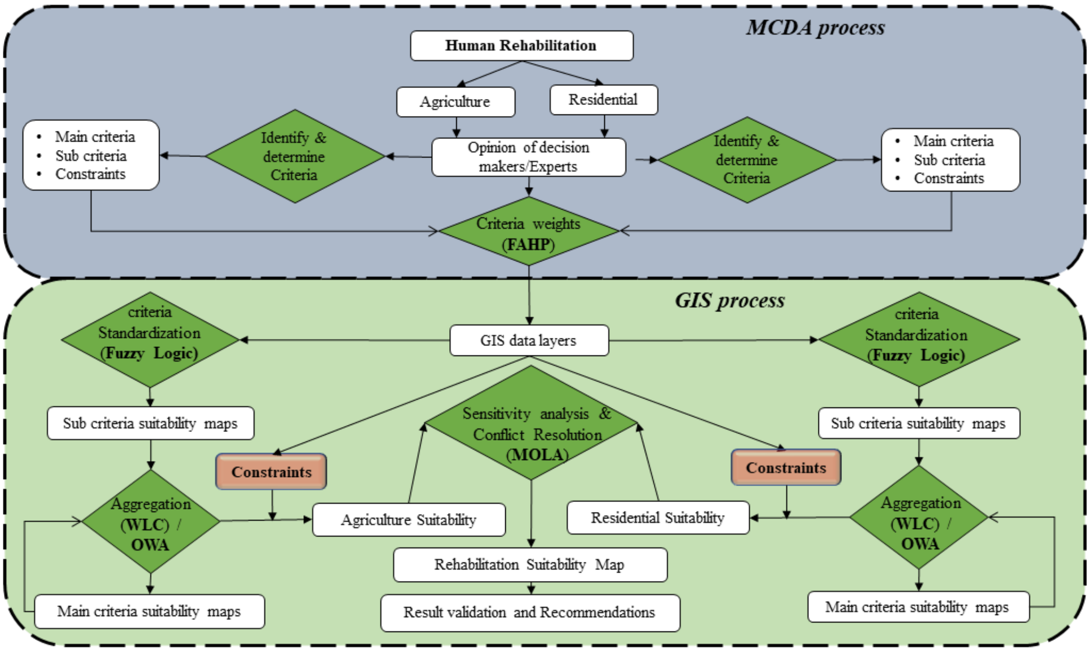


Figure 20 Land evaluation procedural model for human rehabilitation

The expert/decision maker identifies all the criteria based on which the performance of suitability of respective objective is evaluated. The weightage of the criterion is based on the expert's knowledge using fuzzy AHP method. After the identification of criteria, the spatial data (GIS data layers) that represents the specific criteria are collected. These data are then standardized using fuzzy membership functions to produced sub-criterion maps. The number of sub-criterion maps are then aggregated using WLC method and applying appropriate constraints and weightage to produce the suitability maps (for agriculture and residential) for the respective objectives. Then the sensitivity analysis is performed to ensure that the processing model is robust, and the results are without anomalies of expert's subjectivity on the criterion weights.

Since there are two suitability maps for the same area with different objectives, the conflict of area is expected which needs to be resolved. The final suitability map for rehabilitation is produced after performing conflict resolution between the two objectives. The results are validated and then recommended accordingly.

The components of model framework and process are elucidated in the following sections.

3.3 Phase 1: Preliminary studies

Preliminary studies consist of firstly defining problem statements of the study area with clear goal and objectives and, then identifying the criteria and its hierarchical structuring. The goal and objective form the perspectives of the decision-makers and guides in structuring the decision rules including the number of alternatives to be considered (Eastman, 2012b). Based on the objectives or goal, relevant criteria should be identified and then construct in hierarchical order to simplify the relationship between the objectives and respective attributes.

3.3.1 Problem statement and definition of goal and objective

In the context of performing a GIS-MDA land evaluation for human rehabilitation, the overall goal is to identify the suitable land for human rehabilitation in Bhutan. The allocation of adequate suitable land to improve the lives of people under the poverty is the ultimate goal. The goal is divided into two specific objectives as per the strategy documents: Suitable land for Agriculture and suitable land for Residential. Agriculture suitability is considered primarily for the source of livelihood through agriculture farming and suitable residential site is considered for construction of residential buildings for living. Multiple criteria such are socio-economic, topography, climatic and soil factors have to be evaluated to achieve this goal or objective.

3.3.2 Identification and definition of criteria and hierarchical structuring

To achieve the goal and its objectives, it is important to identify its determinant criteria (factors and constraints) based on which the land evaluation is assessed. In the study, criteria are identified based on the requirement of the rehabilitation strategy documents (NRP, 2014) where social, economic, climate and topographical factors are considered. The literature reviews on similar case studies were made and ideas incorporated. The constraints are identified based on legal obligations, safety and security aspects.

Hierarchical structuring of criteria and sub-criteria of the respective objectives simplifies the multi-criteria complexities. Table 3 shows the hierarchical structure of land evaluation for human rehabilitation. There are seven main criteria, twenty sub-criteria and, six constraints identified.

Table 3 The hierarchical structure of criteria for human rehabilitation.

Objectives	Criteria		
	Factors		Constraints
	Main Criteria	**Sub Criteria**	
Residential	RC-1: Topography	RC1-a: Slope	C1: Protected area C2: Registered land C3: Hazard risk zone C4: Road Buffer C5: River Buffer C6: Biological corridor
		RC1-b: Aspect	
	RC-2: Proximity to economic infrastructures	RC2-a: Road	
		RC2-b: Electricity	
		RC2-c: Drinking Water	
		RC2-d: Urban points	
	RC-3: Proximity to social service centers	RC3-a: Education	
		RC3-b: RNR/Sub District center	
		RC3-c: Health	
		RC3-d: District HQ	
		RC3-e: Religious center	
Agriculture	AC-1: Topography	AC1-a: Slope	
		AC1-b: Aspect	
		AC1-c: Elevation	
	AC-2: Soil	AC2-a: Thickness	
		AC2-b: Sediments	
	AC-3: Climate	AC3-a: Temperature	
		AC3-b: Rainfall	
	AC-4: Accessibility	AC4-a: Irrigation water	
		AC4-b: Road	

Table 4 Criteria for Residential

Cluster Criteria	Sub-criteria and rationale
R-C1: Topography	**RC1-a: Slope:** The construction regulation for residential restricts the slope above 30^0. Flatter the terrain, more the suitable it is. **RC1-b: Aspect:** The Aspects for the residential is preferable in the South and West and least preferred in other orientations. Those are more suitable due to slope, vegetation and temperature for rural housings development.(Jeong et al., 2016)
R-C2: Access to the infrastructure	**RC2-a: Roads:** Access to roads for transportation is very important consideration for achieving economic development. Settlements closer to the roads are most suitable. **RC2-b: Electricity:** Electricity is required for general lighting and powering machinery, factories etc. It is useful for convenience and generating income. Therefore, proximity to electricity is an important consideration. **RC2-c: Drinking water:** Drinking water is a basic need for any being’s survival. There cannot be a human settlement where there is no water for drinking. The suitability of human settlement increase with decreasing distance from the water source. **RC2-d: Urban points:** Access to urban points can be helpful in two ways. People can buy their basic commodities from the nearest town and export or sale their local produce (if any) to the nearest markets. The closer the market point, more suitable the site is.

Table 4 (Cont.)

Cluster Criteria	Sub-criteria and rationale
R-C3: Access to public service center	**RC3-a: Education:** Settlement located far from education center finds difficulty while sending their children to the school. Includes schools, colleges and Non formal education (NFE). Easy access to the School and NFEs is more important for the rural communities. **RC3-b: RNR:** The Renewable and Natural Resource (RNR) center provides support to the rural communities in their agriculture fields. **RC3-c: Health:** Access to health services are very important for people's good health. Includes Hospitals and Out Reach Clinic (ORC) which are very important source of health service for the rural communities. **RC3-d: Administration and management:** District Head Quarter (Dzongkhag HQ) and sub district head office (Gewog) play vital role for management and administration of any developmental and socio-economic issues in the communities. Therefore, the access to such service center should be considered. **RC3-e: Religious center:** The proximity to the religious centers like monasteries and temples improves the spiritual well-being of the people and community vitality.

Table 5 Criteria for Agriculture

Cluster Criteria	Sub-criteria and rationale
AC-1: Topography	**AC1-a: Slope:** The allotment of land is considered only for gradient less than 45^0 or 100% (FNCRR, 2017), (LRR, 2007). Flatter the terrain more the suitability is. **AC1-b: Aspect:** The Aspect of agriculture is preferable in the South and West and least preferred in other orientations. Those are more suitable due to slope, vegetation and temperature for rural housings development.(Jeong et al., 2016). **AC1-c: Elevation:** Suitable elevation is an important factor for agriculture farming. It is impossible to do agriculture farming in extreme altitudes. The study area falls under the major agro-ecological zones of humid subtropical and wet-subtropical (Katwal, 2010). Therefore, the elevation between 150 meters to 3000 meter above sea level is considered favorable for general agriculture farming.
AC-2: land capability	**AC2-a: Soil thickness:** Soil depths can influence the growth of plants (crops), deeper soil provides more water and soil nutrients than shallow soils (Rajakaruna & Boyd, 2019) as shallow soil depths can limit the root penetration of plants (Abd-Elmabod et al., 2017). **AC2-b: Soil sediments: S**oil erosion and deposition occur simultaneously. Sediments finer than sand can form fertile soil. Therefore, the area with higher sentiments is preferred for agriculture.

Table 5 (Cont.)

Cluster Criteria	Sub-criteria and rationale
AC-3: Climate	**AC3-a: Temperature:** Crops cannot be grown in the extreme temperature. Based on the agro-ecological zones of the area the mean annual temperature between 17.2^0 C to 23.6^0 C is more favourable. **AC3-b: Rainfall:** Most of agriculture farming are rainfed. Based on the agro-ecological zones of the area the annual rainfall between 650 mm to 5500 mm per year is favourable for general crop production.
AC-4: Accessibility	**AC4-a: Irrigation water:** Due to unpredictable climate change, rainfall sometimes proves to be very uncertain. Access to the irrigation water source can be very useful for good crop production. **AC4-b: Roads:** The farmlands can be made accessible by the roads. It helps with transportation and market access. Farmland close to the roads is preferred.

Table 6 defines six constraints used in the study viz. protected zone, registered land, hazard zones, road buffer zones, river buffer zones and biological corridor zone.

Table 6 Constraints and buffer values

Constraints	Buffer distance (m)	Description and rationale
C1: Protected zone	100	The allotment of land from protected zone like nature reserves including parks are restricted (FNCRR, 2017). Buffer distance of 100 m is applied to ensure no encroachment in the protected zones.
C2: Registered land	0	The registered lands are under the legitimate right of the landowner and allotment of land is restricted (LA, 2007).
C3: Hazards zone	500	Areas prone to natural hazards like landslides are avoided for land allotment (LRR, 2007). The buffer distance of 500m is applied to ensure safety.
C4: Roads buffer	180	Buffer distance of 180 m is maintained for the National High Ways(FNCRR, 2017) and 50 ft for other types of roads(2013).
C5: River buffer	30	The land allotment is restricted within 30 meters of the bank or edge of any river and 15 meters of stream or water source shall not be considered (FNCRR, 2017)
C6: Biological corridor zone	0	The allotment of land falling in this zone is restricted from the human settlement with permanent structures. However, the use of cultivation is allowed. In the study, this constraint is applied for residential objective only.

Table 7 Data source and description

Data Types	Year	Scale/resolution	Geoprocessing	Source	Output criteria generated
Topographical Contour	2016 – 2018	10 m contour interval	Surface Analysis tools	NLCS	Slope, Aspect, Elevation
Topographical, cadastral & urban data	2016 – 2018	1:25,000	Euclidean distance tools	NLCS, NSB, Municipal office	Proximity to: Roads (National Highways, Paved, Unpaved, Footpath), electricity, Drinking water, Urban Points, irrigation sources.
Topographical,cadastral & urban data	2016 – 2018	1:25,000		NLCS, NSB, Municipal office	Proximity to: Education, RNR, Gewog (sub-district center), Health, District, Schools, Religious center, ORC
Climate data	2009-2018	1:25,000	IWD	NCHM	Precipitation, Temperature
Soil data	2016 – 2019	1 km grid	Raster extraction	https://doi.org/10.3334/ORNLDAAC/1304	Soil thickness and sediments.
Hazard maps	2016 – 2018	1:25,000	Buffer analysis and Boolean tools	National Land Commission	Landslide zones
Protected area maps	2010-2018	1:50,000		Ministry of Agriculture	National Parks, wildlife sanctuary, biological corridors

3.4 Phase 2: Data collection and preparation

Based on the objective of the problem, the spatial data representing the criteria and constraints are collected from various sources and are entered in the geodatabase and processed in ArcGIS 10.6.14 ESRI software. Table 7 shows spatial data sources, their description geoprocessing and output criteria generated. All the criteria identified for land-use suitability analysis should have its spatial data representing the attributes of criteria with respect to its objective. The spatial data collections are made from various sources based on its relevancy, quality, use, and availability. The spatial resolution for input raster is set at 30 m.

The quantitative information for criterion weights are collected from experts through set of questionnaires (see APPENDEX I).

3.5 Phase 3: GIS-MCDA based land evaluation

This phase is the main decision-making process of GIS-MCDA based land evaluation. This phase includes three processes viz. determination of the criterion weights using fuzzy AHP, generating criterion maps using fuzzy membership function, generating suitability maps using Weighted linear combination (WLC & OWA methods) and conflict resolution of competing objectives. The components of this phase are explained and demonstrated in the following sections.

3.5.1 Determination of the criterion weight

Having identified complete set of criteria and sub-criteria against each objective, the next task is to assign the weights of relative importance to each criterion. Since the information on criterion weight is sourced from the relevant experts, the questionnaire consisting of pair wise comparison of each criteria and sub-criteria with respect to the specific objective is designed. The questionnaire is designed using the linguistics terms such as “Equally important”,” Moderately important”, etc. instead of using crisp number for the evaluating the relative importance.

The designed questionnaire is then presented to the group of six experts for evaluation. The expertise includes the following:

- ✓ Agriculture experts: include people who have knowledge relevant to agriculture related, example, agriculture extension officers, soil specialist, etc.
- ✓ Residential Experts: include people who have knowledge relevant to residential building related, examples, civil engineers, survey engineers, people who have prior knowledge and information, etc.

Checking of Consistency Ratio:

After the having evaluated by the experts, it is important to test the consistency of the pairwise comparison matrix to ensure that the expert's judgements are consistent. Inconsistent judgements are not considered for subsequent calculation of criterion weight determination. Such judgments are reviewed and re-evaluated by the experts.

For checking the consistency, firstly the Consistency Index (CI) needs to be estimated which provided by adding the columns in the judgment matrix and multiply the resulting vector by the vector of priorities (i.e., the approximated eigenvector) (Evangelos Triantaphyllou & Mann, 1995) . This results an approximation of the maximum eigen value $\lambda_{\max}$. Then the (CI) is calculated by equation given below.

$$CI = \frac{\lambda_{\max} - n}{n - 1}$$

Where:

$$\lambda_{\max} = \frac{CV}{n}$$

$$CV = \frac{1}{n}\left[\frac{1}{w_i}\left[\sum_{j=1}^{m}\left(\left(\sum_{j=1}^{m}\left(\frac{x_{ij}}{\sum_{i=1}^{n} x_{ij}}\right)\right) \times x_{ij}\right)\right]\right]$$

x_{ij} is pairwise comparison value of dimension i factor to j where $i, j \in \{1, 2, 3, \ldots n\}$. The CR coefficient is calculated by dividing the CI value by the Random Consistency index (RCI) $for\ i = 1, 2, \ldots .n$ as provided in Table 8.

$$CR = \frac{CI}{RIC}$$

The judgment matrix of the pairwise comparisons are considered to be consistent if the consistency ratio (CR) is less than 10 % and if the CR value is greater than 0.10, it is cautioned to re-evaluate the pairwise comparisons (Evangelos Triantaphyllou & Mann, 1995), (Samphutthanon et al., 2014).

Table 8 Random Inconsistency Index

n	1	2	3	4	5	6	7	8	9	10	11	12
RCI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48

Source: (Saaty, 1980)

Calculation of weights using Fuzzy AHP:

The final criterion weight is determined using fuzzy concepts in AHP. The fuzzy logic is an approach to counter the data uncertainties and imprecision of human knowledge. The fuzzy set eliminates the stark boundaries between the members and non-members that exists in a crisp set by providing the range of change values between the full membership and non-membership (Leung LC & Cao, 2001). There are many Fuzzy AHP methods proposed by various authors (Mosadeghi, 2013). In this study, Triangular Fuzzy Analytic Hierarchy Process (TAHP) based on geometric mean developed by Buckley in 1985 is used for determining the criterion weights.

The fuzzy triangular membership function shown in Figure 21 is used to express the uncertainty of the judgement of the experts for this method.

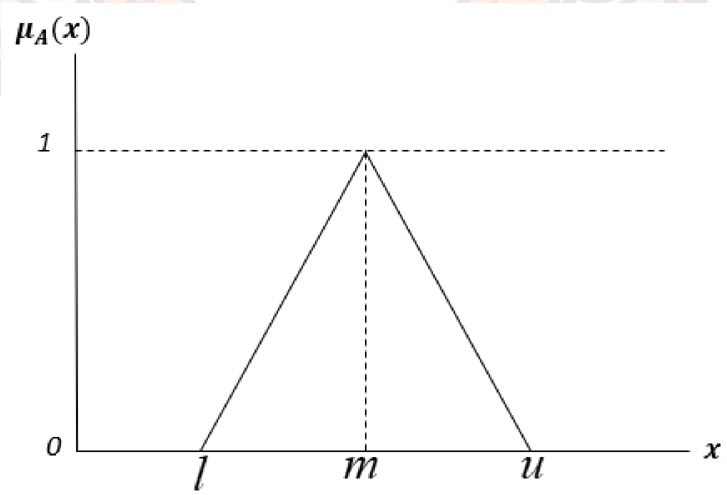


Figure 21 Membership functions of triangular fuzzy number

Where R is the set of real numbers $l \leq m \geq u$; l, m, u are lower, middle and upper values i. e (l, m, u) is the triangular fuzzy number values along the x-axis and the corresponding degree of fuzzy membership values are represented in the range of 0 to 1 along the y-axis.

The expert's preference or judgment on the relative importance of factors are expressed linguistically based on the scale of importance shown in the Table 9 below:

Table 9 Membership values of Triangular fuzzy AHP

Fuzzy Number	Linguistics (meaning)	Triangular Membership number
$\tilde{1}$	Equally important	(1,1,1)
$\tilde{2}$	*Intermediate value*	(1,2,3)
$\tilde{3}$	Moderately important	(2,3,4)
$\tilde{4}$	*Intermediate value*	(3,4,5)
$\tilde{5}$	Strongly important	(4,5,6)
$\tilde{6}$	*Intermediate value*	(5,6,7)
$\tilde{7}$	Very strongly important	(6,7,8)
$\tilde{8}$	*Intermediate value*	(7,8,9)
$\tilde{9}$	Extremely important	(8,9,10)

Source: Adopted from (Gumus, 2009)

Steps in fuzzy AHP:

Suppose if there are two triangular fuzzy numbers $\tilde{s}_1$ and $\tilde{s}_2$, the following algebraic laws of operations like addition $(\tilde{s}_1 + \tilde{s}_2)$, subtraction $(\tilde{s}_1 - \tilde{s}_2)$, multiplication $(\tilde{s}_1 \otimes \tilde{s}_2)$, division $(\tilde{s}_1 \div \tilde{s}_2)$, and reciprocal s^{-1} for $l_1, l_2 > 0;\ m_1, m_2 > 0;\ u_1, u_2 > 0$ are applied as follows:

$$(\tilde{s}_1 + \tilde{s}_2) = (l_1, m_1, u_1) + (l_2, m_2, u_2) = (l_1 + l_1, m_1 + m_2, u_1 + u_2)$$

$$(\tilde{s}_1 - \tilde{s}_2) = (l_1, m_1, u_1) - (l_2, m_2, u_2) = (l_1 - l_1, m_1 - m_2, u_1 - u_2)$$

$$(\tilde{s}_1 \otimes \tilde{s}_2) = (l_1, m_1, u_1) \otimes (l_2, m_2, u_2) = (l_1 \otimes l_1, m_1 \otimes m_2, u_1 \otimes u_2)$$

$$(\tilde{s}_1 \div \tilde{s}_2) = (l_1, m_1, u_1) \div (l_2, m_2, u_2) = (l_1 \div l_1, m_1 \div m_2, u_1 \div u_2)$$

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

Following are steps are involved in determining the criterion weights using Fuzzy AHP (FAHP) based on the Geometric mean (Modified from Buckley in 1985).

Step 1: Construction of pairwise comparison matrix based on a triangular fuzzy number. The judgement of the experts can be expressed as the triangular fuzzy number and the pairwise comparison matrix can be expressed as $\tilde{A}$. See the result of the expert's pairwise comparison used in the study in the Table 4.1-4.9 of Appendix II.

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

Where $\tilde{a}_{ij} = (i_{ij}, m_{ij}, u_{ij})$ and $(\tilde{a}_{ij})^{-1} = \left(\frac{1}{i_{ij}}, \frac{1}{m_{ij}}, \frac{1}{u_{ij}}\right)$

For $i = 1, 2, 3, ...n$ and i ≠ j, $n = number\ of\ criteria$

Step 2: Calculate the geometric mean of fuzzy comparison matrix

$$\tilde{x}_{ij} = (\tilde{a}_{ij}{}^{1} \otimes \tilde{a}_{ij}{}^{2} \otimes \cdots \otimes \tilde{a}_{ij}{}^{b} \otimes \cdots \tilde{a}_{ij}{}^{n})^{\frac{1}{n}}$$

Where $\tilde{x}_{ij}$ is a geometric mean of fuzzy comparison matrix value of dimension $i \times j$ for all expert $i, j \in \{1, 2, 3, ...n\}$

Step 3: Calculate Fuzzy weights $(\tilde{w}_i)$ using the given formula

$$\tilde{W}_{ij} = \tilde{x}_{ij} \otimes (\tilde{a}_{ij}{}^{1} \otimes \tilde{a}_{ij}{}^{2} \otimes \cdots \otimes \tilde{a}_{ij}{}^{b} \otimes \cdots \tilde{a}_{ij}{}^{n})^{\frac{1}{n}}$$

Where $\tilde{x}_{ij}$ is a geometric mean of fuzzy comparison matrix value of dimension $i \times j$ for all expert $i, j \in \{1, 2, 3, ...n\}$

Step 4: The weights are converted to the crisp value by using the center of area (COA). This process is called de-fuzzification of weights

$$Centre\ of\ Area\ (COA)\ W_i = \frac{l + m + u}{3}$$

where W_i is the De-fuzzified weight and l, m, u are the lower, middle and upper fuzzy value respectively.

Step 5: The final weights are calculated by dividing each de-fuzzified weights by total de-fuzzified weights. This is called the Normalization.

3.5.2 Generating criterion maps

This step deals with GIS process and working with spatial data input that represents the criteria to assess the fulfilment of a specific objective. After establishing a set of criteria, every criterion should be represented as a map layer in GIS. The map layer representing the criteria is known as criterion map. Sub-criterion maps are generated by standardization of criteria and main-criterion maps are generated by aggregation of multiple sub-criterion maps.

3.5.2.1 Standardization of factors

Multiple criteria gathered from different sources and scales need to be standardized to a common scale. Since the spatial phenomena inherently possess the fuzzy boundaries, the criteria are standardized using the fuzzy membership functions. The element belonging to the set is defined based on the degree of membership of particular fuzzy functions (Gigović et al., 2016).

The data standardization is processed in IDRISI software using the FUZZY tools. It requires to provide the value of control points (a, b, c & d) and specify the type of fuzzy membership function. This is described in Table 10.

Generally, the range value for criteria standardization can be either 0 to 1 or 0 to 100 real number scale depending upon the choice of the operator or user. However, a 0 to 255 byte scale is used in the study. This is because, the MCE module in IDRISI has been optimized for processing speed using a 0 – 255 level standardization (Eastman, 2012b). The principle idea is that the higher value of the standardized values must represent the case of being more likely to belong to the decision set.

There are variety of fuzzy membership functions available (Refer Section 2.3.8). The linear fuzzy membership function takes an original range of criterion values and performs simple linear stretch. The function is generally applied for criteria with linear proximity attributes. Therefore, in the study, are all criteria / factor that consist of proximity attributes such as roads, electricity, urban points, education centers, etc. used linear fuzzy membership functions.

A sigmoidal function is used in the situation where there is absence of constant increase or decrease of criterion values. In the study, all criteria that has natural factors like slope, aspect, soil, rainfall and temperature used Sigmoidal fuzzy membership functions. Similarly, sigmoidal symmetry is used where there is both rise and fall of criterion values.

The function of the fuzzy membership function can be explained by a simple example. Consider a map that displays the slope gradient in degrees. The slope map can be converted to standardized form using linear fuzzy membership function. The objective here is that we prefer slope value of 0 to 20 degrees to be the most suitable. The suitability should gradually decrease after crossing the slope value of 20 degrees till reaches 45 degrees. The slope gradient beyond 45 degrees is unsuitable. Therefore, here the control value should be a=20 degree and b=45 degree.

The output of standardization shows that all the gradient value below 20 degrees are assigned full membership value of 255 indicating the most suitable. The gradient value between 20 and 45 degrees are assigned membership values in decreasing order from 255. The gradient value of 50 degrees is assigned no membership value indicating unsuitability.

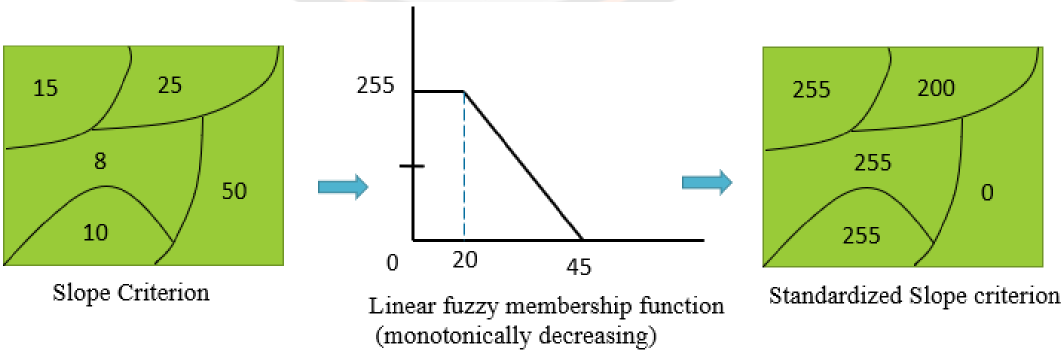


Figure 22 Criterion map by fuzzy membership function approach.

Source: Adopted from (Malczewski, 1999).

3.5.2.2 Defining control point or inflection point values.

Proper specification of control point values for criteria standardization is very important as it has great influence on the determination of the final suitability output.

Table 10 Control points values for fuzzy membership function

Objectives	Criteria	Control Point				Fuzzy Membership Function
		a	b	c	d	
Residential	RC1-a: Slope			0	30	Sigmoidal-monotonically Decreasing
	RC1-b: Aspect	22.5	157.5	202.5	337.5	Sigmoidal Symmetric
	RC2-a: Roads			100	15000	Linear-monotonically Decreasing
	RC2-b: Electricity			100	20000	
	RC2-c: Drinking Water			100	2000	
	RC2-d: Urban points			500	20000	
	RC3-a: Education centers			3000	20000	
	RC3-b: RNR_sub-District center			1000	10000	
	RC3-c: Health centers			1000	15000	
	RC3-d: District Centers			5000	30000	
	RC3-e: Religious centers			1000	15000	
Agriculture	AC1-a: Slope			0	45	Sigmoidal-monotonically Decreasing
	AC1-b: Aspect	22.5	157.5	202.5	337.5	Sigmoidal Symmetric
	AC1-c: Elevation			150	3000	Sigmoidal decreasing
	AC2-a: Soil thickness	0	2.33			Sigmoidal increasing
	AC2-b: Soil sediments	0	50			Sigmoidal increasing
	AC3-a: Temperature	9.9	23.6			
	AC3-b: Rainfall	650	5500			
	AC4-a: Irrigation water			100	5000	
	AC4-b: Road			100	5000	Linear-monotonically Decreasing

However, in the context of the current study, except for legal requirements such as constraints, there is no established rule or basis available for determining specific values. For instance, there is no exact suitable and unsuitable distances for the criteria that have proximity attributes. Table 10 shows the control pint values and the type of fuzzy membership functions used for human rehabilitation.

The specification and definition of control values is based on a literature review where similar case studies are undertaken and the expert's view. Another choice could be using the minimum and maximum extent of Euclidian distance value of the given criterion map.

3.5.3 Generating land suitability maps

The standardized criterion maps are aggregated to produce the composite map of suitability. It is very important to mention that the process of standardization and aggregation follows the bottom-up approach. That is the aggregation of criterion maps begins at the lowest level, and the output composite map of suitability serves as the input for next aggregation at next higher level.

In the context of this study, Figure 23 exemplifies the bottom-up approach for criterion standardization and aggregation.

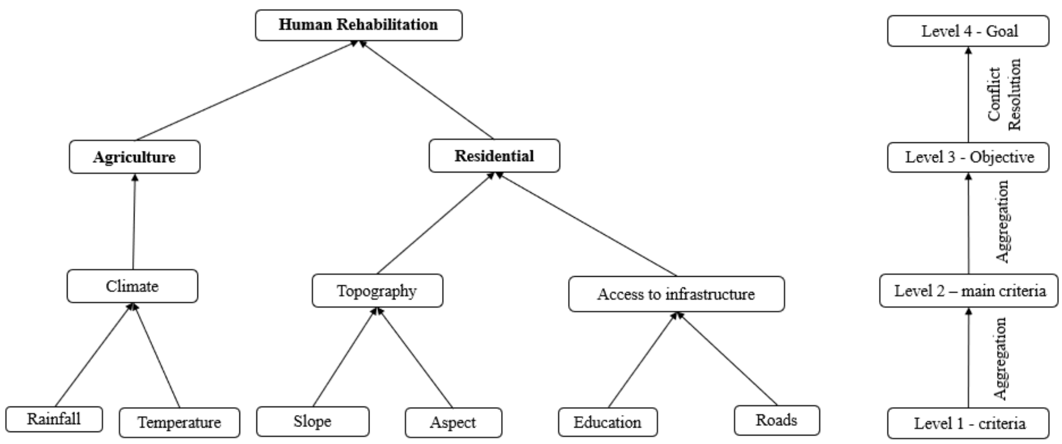


Figure 23 Flow diagram for criteria aggregation – Bottom-up approach.

In the study, the aggregation takes place at two levels following the bottom-up approach. The aggregation begins from the sub-criteria level to produce the composite criterion map of main criteria which is then used as input to generate the final suitability map for respective objectives. The aggregation method adopted for the study is discussed in the following section.

3.5.3.1 Weighted Linear Combination (WLC)

Weighted Linear Combination (WLC) method is used for aggregating the criterion maps to produce composite maps of suitability. The WLC method operates by multiplying each standardized factor map by its factor weight and then sums the results. This output is then multiplied by the constraint inputs (if any) to exclude the undesirable areas. The mathematical formula for this method can be expressed as.

$$s = \sum w_i x_i * \prod c_j$$

Where:

s – the composite suitability score

w_i - weights assigned to each factor

x_i – factor scores (pixel value)

c_j – constraints (Boolean factors)

$\sum$ - sum of weighted factors

$\prod$ - product of constraints (1- suitable, 0 unsuitable)

IDRISI provides the specific and comprehensive WLC tool under the Multi-criteria Evaluation (MCE) for criterion map combination. The tool requires to specify the standardized criterion input and value of criterion weight.

Following the bottom-up approach, the constraints are applied only at level 2 to produce the final suitably map of Residential and Agriculture.

Higher the cell values, higher the suitable or potential of the area is. Using the geostatistical tool and the suitability degree of score range provided in Table 11, the map is zoned into five levels of suitable class.

Table 11 Defining the score range for suitability class

Suitability Class	Score range/ Degree of suitability	Description
Highly Suitable (S1)	205 – 255	Has the highest degree of suitability. As it satisfies maximum criteria the land can be considered to have no significant limitations to the proposed land use type.
Moderately Suitable (S2)	154 – 204	The overall degree of suitability is less than class S1 land. It satisfies most of the criteria and the land has moderate limitations to land use type under consideration.
Low Suitable (S3)	103 – 153	The overall degree of land suitability is less than S1 and S2 class. It satisfies few criteria and has significant limitations to sustained land use type under consideration.
Very Low Suitable (S4)	52 – 102	The overall degree of suitability is less than class S1, S2 and S3. The land has severe limitations to sustained land use type as it satisfies very few criteria.
Not suitable (NS)	0 – 51	Satisfies the least or no criteria. The land is not suitable for the type of land use under consideration. It also includes all the constraints area.

3.5.3.2 Ordered Weighted Average (OWA)

In the study, OWA method is used to produce different scenarios of suitability maps for Residential and Agriculture with varying levels of tradeoff and risk. Refer Section 2.3.11.3 for more detail.

The method is similar to that of WLC. However, in addition to the factor and constraints, the set of order weights are introduced depending on the level of risk one wish to assume. The risk and tradeoff can be controlled through a set of order weights for varying levels of rank order positions of factors at every pixel location. After the factor weights are applied, the factor with the lowest suitability score is given 1^{st} order weight and the factor with the next lowest suitability score is given the 2^{nd} order weight, and so on. IDRISI provides the OWA tools which require to execute the following two steps in sequence:

1. Specify the set of factors with its respective criterion weights and the constraints
2. The following order weights are specified depending on the risk and tradeoff one wish to assume.

Table 12 and 13 shows the order weights used for residential and agriculture in the study.

Table 12 Order weights for residential

1. Average Risk and Full Tradeoff (ARFT)			
Order weight	0.33	0.33	0.33
Rank order	1	2	3
2. Low Risk and No Tradeoff (LRNT)			
Order weight	1	0	0
Rank order	1	2	3
3. High Risk and No Tradeoff (HRNT)			
Order weight	0	0	1
Rank order	1	2	3
4. Low Risk and Middle Tradeoff (LRMT)			
Order weight	0.80	0.20	0
Rank order	1	2	3
5. High Risk and Middle Tradeoff (HRMT)			
Order weight	0	0.20	0.80
Rank order	1	2	3
6. Middle Risk and No Tradeoff (MRNT)			
Weight	0	1	0
Rank order	1	2	3

Table 13 Order Weights for agriculture

1. Average Risk and Full Tradeoff (ARFT)				
Order weight	0.25	0.25	0.25	0.25
Rank order	1	2	3	4
2. Low Risk and No Tradeoff (LRNT)				
Order weight	1	0	0	0
Rank order	1	2	3	
3. High Risk and No Tradeoff (HRNT)				
Order weight	0	0	0	1
Rank order	1	2	3	4
4. Low Risk and Middle Tradeoff (LRMT)				
Order weight	0.70	0.20	0.10	0
Rank order	1	2	3	4
5. High Risk and Middle Tradeoff (HRMT)				
Order weight	0	0.10	0.20	0.70
Rank order	1	2	3	4
6. Middle Risk and No Tradeoff (MRNT)				
Weight	0	0.5	0.5	0
Rank order	1	2	3	4

Following mathematical formula given by (Yager, 1988) is used for computation while performing the above process.

Given the set of criterion weights, $w_1, w_2, ...w_n$, and set of order weights $\lambda_1, \lambda_2, ..., \lambda_n (o \le \lambda_k \le 1, \text{ and } \sum_{j=1}^{n} \lambda_j = 1)$ and set of attribute values $a_{i1}, a_{i2}, ..., a_{in}$ at the i^{th} location $(i = 1, 2, ..., m)$, OWA can be define as:

$$V(A_i^0) = \sum_{k=1}^{n} \frac{\lambda_k u_k z_{ik}}{\sum_{k=1}^{n} \lambda_k u_k} ,$$

Where:

$V(A_i^0)$ is the overall value of the i^{th} decision alternative location.

u_k is the criterion weight reordered according to the attribute value z_{ik}

The below example is in the context of Agriculture suitability used in the study.

Table 14 Calculation of order weights for Agriculture

k	Criterion values $v_k(a_i)$	Criterion weights w_k	Ordered criterion values z_{ik}	Ordered criterion weights u_k	Order weights λ_k	$\lambda_k u_k$	$\lambda_k u_k z_{ik}$	$V(A_i^0)$
AC-1	60	0.32	90	0.32	0.25	0.080	7.200	28.8
AC-2	30	0.295	60	0.295	0.25	0.074	4.425	17.7
AC-3	20	0.263	30	0.263	0.25	0.066	1.973	7.89
AC-4	90	0.122	20	0.122	0.25	0.030	0.610	2.44
$\sum$		1.0			1.0	0.250		56.83

It has the main criterion or factor AC-1, AC-2, AC-3 and AC-4 with criterion weights of 0.32, 0.295, 0.263 and 0.122 respectively. Considering at i^{th} pixel location, let's say the criterion values for AC-1, AC-2, AC-3 and AC-4 are 60, 30, 20 and 90 respectively. Therefore, the over-all OWA value at that pixel location is calculated as 56.83 in the output suitability map.

Similarly, the Table 15 provides example for calculating order weights for Residential suitability.

Table 15 Calculation of order weights for Residential

k	Criterion values $v_k(a_i)$	Criterion weights w_k	Ordered criterion values z_{ik}	Ordered criterion weights u_k	Order weights λ_k	$\lambda_k u_k$	$\lambda_k u_k z_{ik}$	$V(A_i^0)$
RC-1	150	0.405	200	0.405	0.33	0.134	26.7	81.0
RC-2	200	0.272	150	0.323	0.33	0.107	16.0	48.5
RC-3	50	0.323	50	0.272	0.33	0.090	4.5	13.6
$\sum$		1.0			1.0	0.330		143.1

RC-1, RC-2 and RC-3 are the main criterion with weight of 0.405, 0.272 and 0.323 respectively. In the example, at i^{th} pixel location, the hypothetical criterion values for RC-1, RC-2 and RC-3 are 150, 200 and 50 respectively. Using the given mathematical formula, the overall OWA value at the i^{th} pixel location is 143.1 in the output scenario suitability map.

Using OWA, the land suitability maps under varying risk and tradeoff levels are generated for both the objectives using the set of order weights given in Table 12 and 13. See the results in Figure 37 and 38.

3.5.4 Conflict Resolution of competing objectives

Since there are two different objectives (residential and agriculture) in the same study area, there is bound to have the area of suitability overlap or conflict area which needs to be resolved. As mentioned in Section 2.5, the conflict resolution works on the principle of resolving conflicted lands among the competing objectives. The same piece of land cannot be allocated to both the objective. The possible solution is through prioritization or compromise of objectives (Eastman, 2012a).

IDRISI has a specific tool called MOLA (Multi-Objective Land Allocation) to address the issue of conflicts among multiple objectives in the land-use suitability analysis which forms part of the multi-objective decision making.

Following are steps involved in conflict resolution using MOLA tool in IDRISI.

1. Convert the suitability map (byte map) into the rank suitability map using the RANK tool, the rank should be output in descending order (rank 1= best).
2. Enter the number of objectives. In this study, we have two objectives: Agriculture and residential.
3. Give proper caption for the objective, enter the weight for each objective. In this study, the two objectives are treated with equal weightage.
4. Select the suitability file (the rank suitability map) and specify the area requirement (in a number of pixels). In the study, we have a pixel size of 30 X 30 meter which is equivalent to 0.22 acres. Therefore, for instance, for an area of 100 acres of agriculture, we can specify 455 cells and for 50 acres of residential, we can specify 228 cells.
5. Enter the output name and specify the total areal tolerance to be used. This areal tolerance is a point at which MOLA will decide that it has come close

enough to satisfying the area requirements of the objective to stop its iterations. In the study, we use the areal tolerance value of 10.

6. Enter the title for the output and click OK

3.6 Phase 4: Validation and Recommendation

This phase consists of conducting sensitivity analysis and validation of final suitability results and then making the appropriate recommendations.

3.6.1 Sensitivity analysis

The sensitivity analysis is performed on the suitability output to verify its stability against the subjectivity of decision-makers. Refer to Section 2.4 for more 78etail.

To assess the sensitivity, the following formula is used to create the variation in the weight at a certain percentage change

$$W_i = W_{i0} \pm W_{i0} \times PC$$

Where:

$W_i =$ new weight of main criterion at the base after applying percent change

$W_{i0} =$ weight of main changing criterion at the base

$PC =$ Percent Change

Then the corresponding change of other criterion weight can be produced by

$$W_j = \frac{(1 - W_i) \times W_{j0}}{(1 - W_{i0})}$$

Where:

$W_j =$ new weight of *j*th criterion

$W_i =$ new weight of main criterion at the base

$W_{j0} =$ weight of *j*th criterion

The sum of new weights should be always 1 or 100 per cent ($W_i + W_j = 1$). Generally, factor weights are changed within the range of 0 % to $\pm$20% for all the factors. In the study, the percentage change of ± 10% and ± 20% are applied to the factor having the maximum weight. Accordingly, the changed weights applied are shown in Table 16 and 17 for Agriculture and Residential objectives respectively.

Table 16 New criterion weight after applying the change on AC-1 factor

Main	Percentage of criterion change				
criteria	**20%**	**10%**	**0%**	**-10%**	**-20%**
AC-1	38.40%	35.20%	32.00%	28.80%	25.60%
AC-2	26.72%	28.11%	29.50%	30.89%	32.28%
AC-3	23.82%	25.06%	26.30%	27.54%	28.78%
AC-4	11.05%	11.63%	12.20%	12.77%	13.35%
Total	100.00%	100.00%	100.00%	100.00%	100.00%

Table 17 New criterion weight after applying the change on RC-1 factor

Main	Percentage of criterion change				
criteria	**20%**	**10%**	**0%**	**-10%**	**-20%**
RC-1	48.60%	44.55%	40.50%	36.45%	32.40%
RC-2	23.50%	25.35%	27.20%	29.05%	30.90%
RC-3	27.90%	30.10%	32.30%	34.50%	36.70%
Total	100.00%	100.00%	100.00%	100.00%	100.00%

The scenario maps generated after subjecting to the sensitivity analysis by applying a certain percentage change in the criterion weight are shown in Figure 7. This can be illustrated by the following example. Suppose Topography has three criteria with the following weights.

Criteria	Weights
Slope	0.20
Aspect	0.30
Elevation	0.50

Now we apply 20 % increase on Slope criteria

Criteria	Weights	Weight variation (new weights)
Slope	0.20	$W_i = W_{i0} \pm W_{i0}\ X\ PC$
		W_i=0.20+0.20 X 0.20=0.24
Aspect	0.30	$W_j = \frac{(1 - W_i)\ \mathrm{X}\ W_{j0}}{(1 - W_{i0})}$
		$W_j = \frac{(1 - 0.24)\ \mathrm{X}\ 0.30}{(1 - 0.20)} = 0.285$
Elevation	0.50	$W_j = \frac{(1 - W_i)\ \mathrm{X}\ W_{j0}}{(1 - W_{i0})}$
		$W_j = \frac{(1 - 0.24)\ \mathrm{X}\ 0.50}{(1 - 0.20)} = 0.475$
Sum	1.0	0.24+.285+0.475=1.0

Similarly, the other criterion (Aspect or Elevation) can be taken as the base criterion weight and corresponding new criterion weight can be generated. Generally, the per cent change within the range of 20% is applied in some studies.

The new weight values are then applied to the respective criteria in the GIS to produce new spatial pattern under the change of criteria. The change of area with new criterion weight can be compared at each suitable class level.

3.6.2 Validation with existing cadastral data

Cross-validation of the land suitability results (generated by the land evaluation model) with existing residential and agricultural land under occupation is performed using Intersection Tools of the overlay analysis in ArcGIS.

It is based on the premise that the existing land under occupation for residential and agricultural use is maximum in the most suitable lands and minimum (or least) in the low or not suitable area. A separate validation is performed for residential and agriculture objective.

The area of intersection of existing cadastral land with suitability results are generated separately for both the objectives and area analyzed to see if the above premise is fulfilled or not. See the validation result in Section 4.6.

3.7.3 Recommendation

The recommendation for future action is the end-result of the spatial multicriteria decision-making process which should be based on the suitability ranking of alternatives and sensitivity analysis (Malczewski, 1999). The confidence of the recommendation comes from how reliable the final result is. There is no point making recommendation using the inaccurate or unreliable output.

In the study, the general recommendation on the model and its outputs based on the sensitivity analysis test and cross validation with existing cadastral records.

CHAPTER IV

RESULTS

This chapter presents the results of the third and fourth phase of GIS-MCDA model and its validation for residential and agriculture objectives.

4.1 Criterion weights by FHAP

Using the theoretical concept of the fuzzy set theory described in Section 2.6 and FAHP steps under section 3.5.1, the criterion weights are determined using the inputs of the experts through questionnaires. The results of the criterion weights are presented in Table 18- 19 and Figure 24 – 25 for Residential and Agriculture respectively.

Table 18 Priority weights of main and sub-criteria for Residential

Main Criteria	Fuzzy Weights	De-fuzzified Weights	CR	Sub Criteria	Fuzzy Weights	De-fuzzified Weights	CR
RC-1: Topography	(0.291,0.412,0.535)	0.405	0.056	RC1-a: Slope	(0.366,0.666,1.098)	0.644	0
				RC1-b: Aspect	(0.211,0.333,0.634)	0.356	
RC-2: Proximity to economic infrastructures	(0.202,0.26,0.371)	0.272		RC2-a: Road	(0.155,0.256,0.461)	0.254	0.044
				RC2-b: Electricity	(0.13,0.231,0.429)	0.23	
				RC2-c: Water source	(0.171,0.388,0.743)	0.38	
				RC2-d: Urban points	(0.07,0.124,0.274)	0.136	
RC-3: Proximity to social service centres	(0.291,0.327,0.371)	0.323		RC3-a: Education	(0.071,0.128,0.223)	0.219	0.049
				RC3-b: RNR_gewog center	(0.088,0.168,0.278)	0.278	
				RC3-c: Health	(0.071,0.128,0.223)	0.219	
				RC3-d: District HQ	(0.046,0.073,0.144)	0.136	
				RC3-e: Religious center	(0.057,0.084,0.144)	0.148	

Table 19 Priority weights of main and sub-criteria for Agriculture

Main Criteria	Fuzzy Weights	De-fuzzified Weights	CR	Sub Criteria	Fuzzy Weights	De-fuzzified Weights	CR
AC-1: Topography	(0.19,0.327,0.499)	0.32	0.043	AC1-a: Slope	(0.309,0.572,0.959)	0.512	0.056
				AC1-b: Aspect	(0.214,0.361,0.665)	0.345	
				AC1-c: Elevation	(0.097,0.151,0.264)	0.143	
AC-2: Soil	(0.226,0.304,0.407)	0.295		AC2-a: Soil thickness	(0.366,0.471,0.634)	0.5	0
				AC2-b: Soil sediments	(0.366,0.471,0.634)	0.5	
AC-3: Climate	(0.172,0.256,0.407)	0.263		AC3-a: Temperature	(0.211,0.333,0.634)	0.356	0
				AC3-b: Rainfall	(0.366,0.666,1.098)	0.644	
AC-4: Accessibility	(0.072,0.112,0.204)	0.122		AC4-a: Road	(0.211,0.333,0.634)	0.356	0
				AC4-b: Irrigation water	(0.366,0.666,1.098)	0.644	

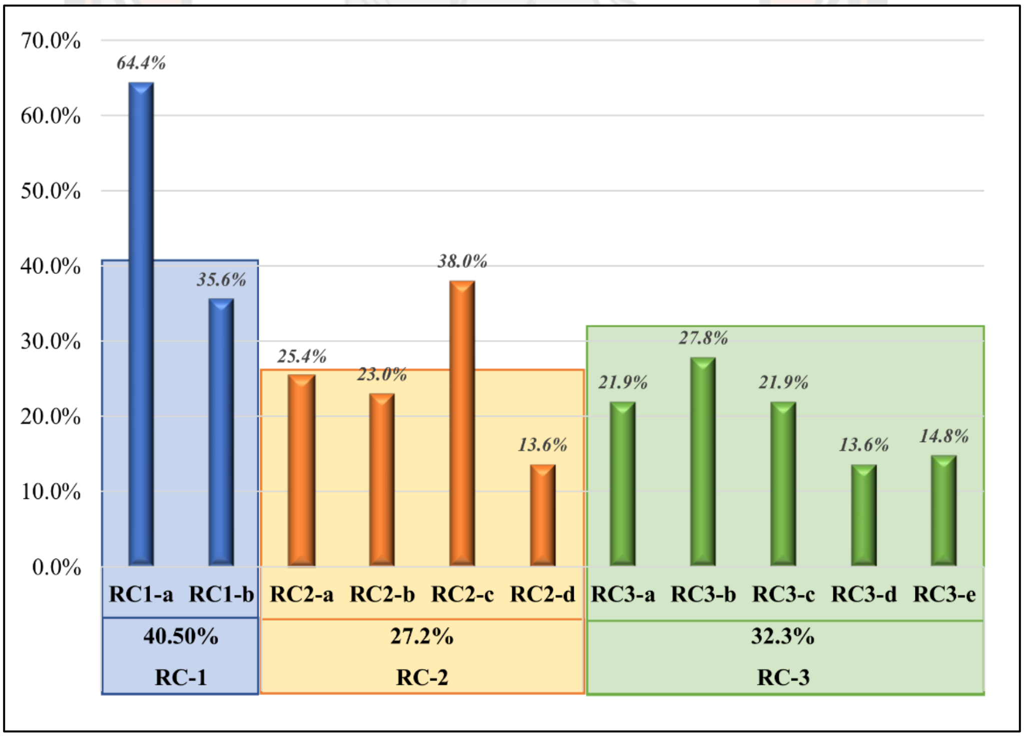


Figure 24 Graph of Priority weights of main and sub-criteria for Residential

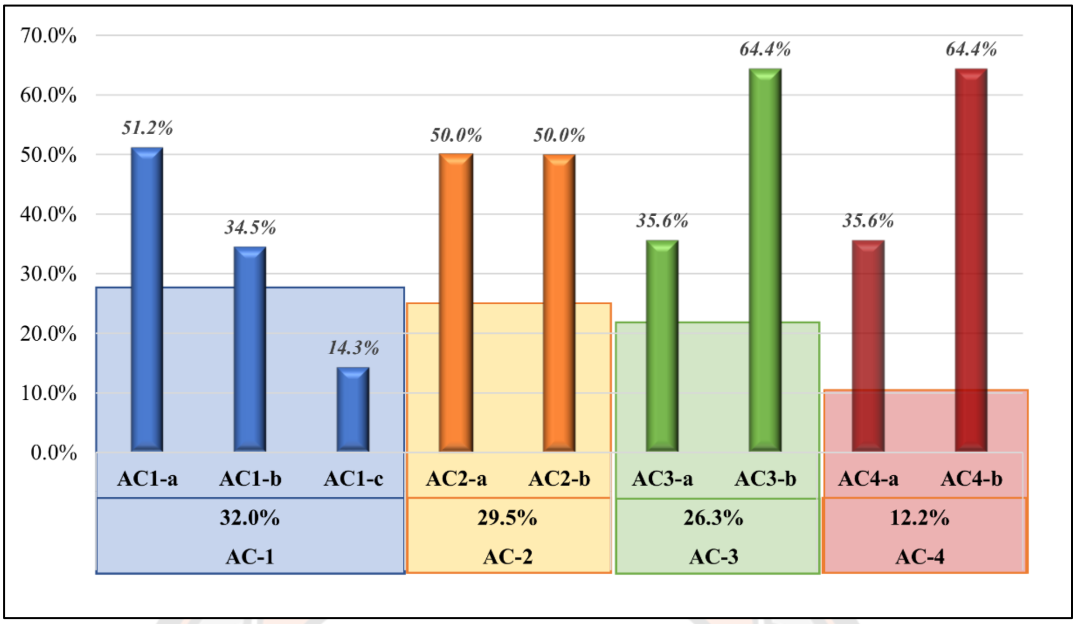


Figure 25 Graph of priority weights of main and sub-criteria for Agriculture

In Table 18 and Figure 24, we can see that topography (RC-1) factor has been accorded the highest preference with 40.5% followed by proximity to social service centres (RC-3) and economic infrastructure (RC-2) with 32.3% and 27.2 % respectively in the main criteria of land suitable for the residential. This substantiates the fact that the rugged topography is an opposing factor for developing many socio-economic infrastructures in the country. The consistency ratio (CR) for the main criteria evaluation is 5.6% which is far below 10%.

Looking at the sub-criteria, slope (RC1-a) factor has high importance compared to the aspect (RC1-b) in determining the topography suitability for residential land.

Among the sub-criteria of the proximity of economic infrastructures (RC-2), access to the drinking water source (RC2-c) is considered the highest importance with 38% followed by access to road (RC2-a) with 25.4% and electricity (RC2-b) with 23%. The access to urban point (RC2-d) is considered the least important with only 13.6 %. This could be mainly due to many existing markets points which are located within the accessible range in the study area. The consistency ratio (RC) of 4.4% is achieved.

Similarly, among the five sub-criteria of proximity to social/public service (RC-3), the accessibility to the sub-district administration centre (RC3-b) is considered the most important factor with 27.8%. The access to education centre (RC3-a) and health centre (RC3-c) has equal importance with 21.9%. The access to district HQ (RC3-d) and religious centres (RC3-e) are accorded with only 13.6 % and 14.8% respectively.

Table 19 and Figure 25 show the priority criterion weights preferred by experts for evaluating and identifying suitable lands for agriculture. The topography (AC-1) criteria are considered more important with 32.0% which is closely followed by soil (AC-2) and climate (AC-3) with 29.5%, and 26.3%. The accessibility (AC-4) factor is rated the lowest with 12.2%.

In the sub-criteria evaluations of topographic suitability for residential land, the slope (AC1-a) factor is considered the most important with 51.2% followed by aspect (AC1-b) and elevation (AC1-c) with 34.5% and 14.3% respectively.

Due to unavailability of soil data and information, only two sub-criteria of soil viz. soil thickness (AC2-a) and soil sediments (AC2-b) are considered by evaluating soil suitability. They are considered equally important.

The temperature (AC3-a) is considered the highest influencing factor with 64.4% compared to rainfall (AC3-b) with only 35.6% in determining the climate suitable land for residential.

For access suitability land for residential, the proximity to the irrigation source (AC4-b) has accorded with priority weight of 64.4% while accessibility to roads has priority weight of only 35.6%.

4.2 Criterion maps

The sub-criterion maps or attribute maps are generated using fuzzy standardization process and specified control point values given in Table 10. The degree of membership of the criterion values using specified fuzzy membership functions are represented by the scale bar legend with values ranging from low of 0 to high of 255. Higher the values higher the suitable and vice versa. The result of the sub-criterion maps are presented in Appendix III and are self-explanatory.

The main criterion maps are the product of aggregating sub-criterion maps. Following the bottom-up approach, the main criterion maps form the input for generating final suitability maps.

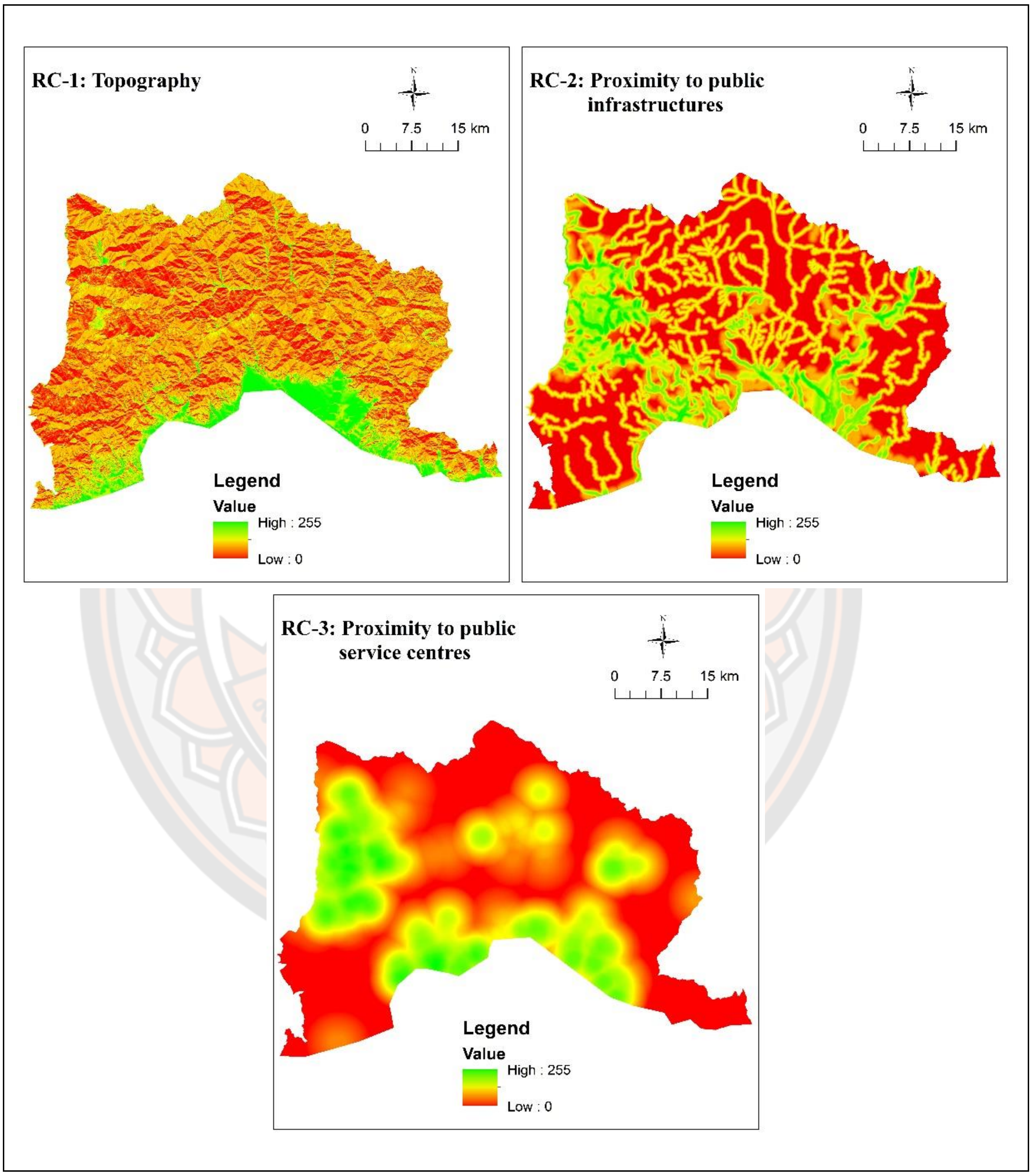


Figure 26 Main criteria maps for Residential

Figure 26 shows the main criterion maps for residential. It can be seen that the topography criterion map (RC-1) indicates that the degrees of membership values fulfilling the topographic conditions are located along the southern border. In other words, the suitable topography for residential is highly clustered along the southern region of the study area. This is due to low and gentle slopes of the southern region.

Criterion map of economic infrastructure (RC-2) shows that the high degree of suitability is located within the existing public infrastructure or economic like roads, electricity, drinking water source and urban points.

Similarly, the proximity to social infrastructure (RC-3) map shows the highest suitable lands within the specified buffer zones of the existing infrastructures like education, health, religious, district and sub-district administration centres. The degree of land suitability decreases with increasing buffer distance from the public infrastructure.

Figure 27 shows the main criterion maps for agriculture. The topography (AC-1) criterion map of agriculture is spatially similar to that of topography (RC-1) criterion maps of residential. The controlling value for membership is specified as 0^0 to 45^0 for slope (see Table 10). Therefore, the highest suitable topography is located along the southern borders. The degree of suitability decreases as the slope values increases along the northern region.

The soil (AC-2) criterion map shows a higher degree of suitable soils in the Gelephu region which has large agricultural farming land compared to other locations. It must be mentioned that the soil suitability map may not be accurately represented since it is determined using only two sub-criteria viz. soil thickness and sediment.

The climate (AC-3) criterion map is prepared using sub-criterion rainfall (AC3-a) and temperature (RC3-b) as input in the WLC model. The rainfall and temperatures input data are prepared through IWD interpolation of 20 primary data distributed across the country. Since the spatial resolution of rainfall and temperature data are very low, the main criterion map of climate is quite homogeneous in the study area. The highest degree of climate suitability is located in the Gelephu region. The suitability decreases with increasing distance from the Gelephu region.

The accessibility (AC-4) is aggregated product of two sub-criterion maps viz. proximity to road and irrigation water source. The proximity to the irrigation water source has assigned the weightage of 64.4% against proximity to roads with 34.6%. Both the sub-criterion are standardized using linear decreasing membership function with control point value to 0.1 km and 5 km. Therefore, criterion map indicates the highest degree of suitability along the existing roads and irrigation water source.

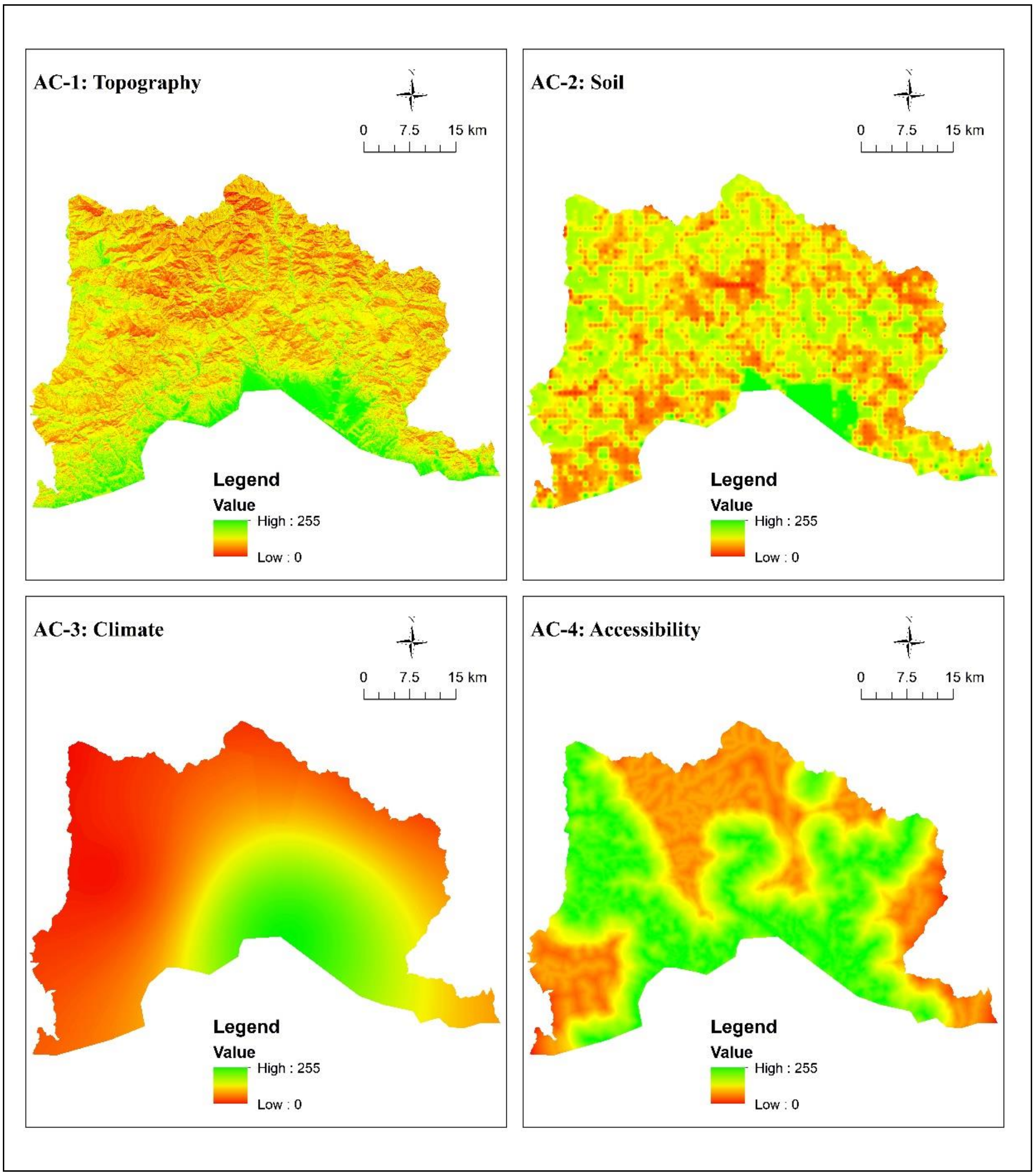


Figure 27 Main Criteria map for Agriculture

Figure 28 shows the constraints used in land evaluation for human rehabilitation. Certain buffer distances specified in Table 6 are applied. The constraint maps are generated using binary logic where 0 represents not suitable and 1 represents suitable.

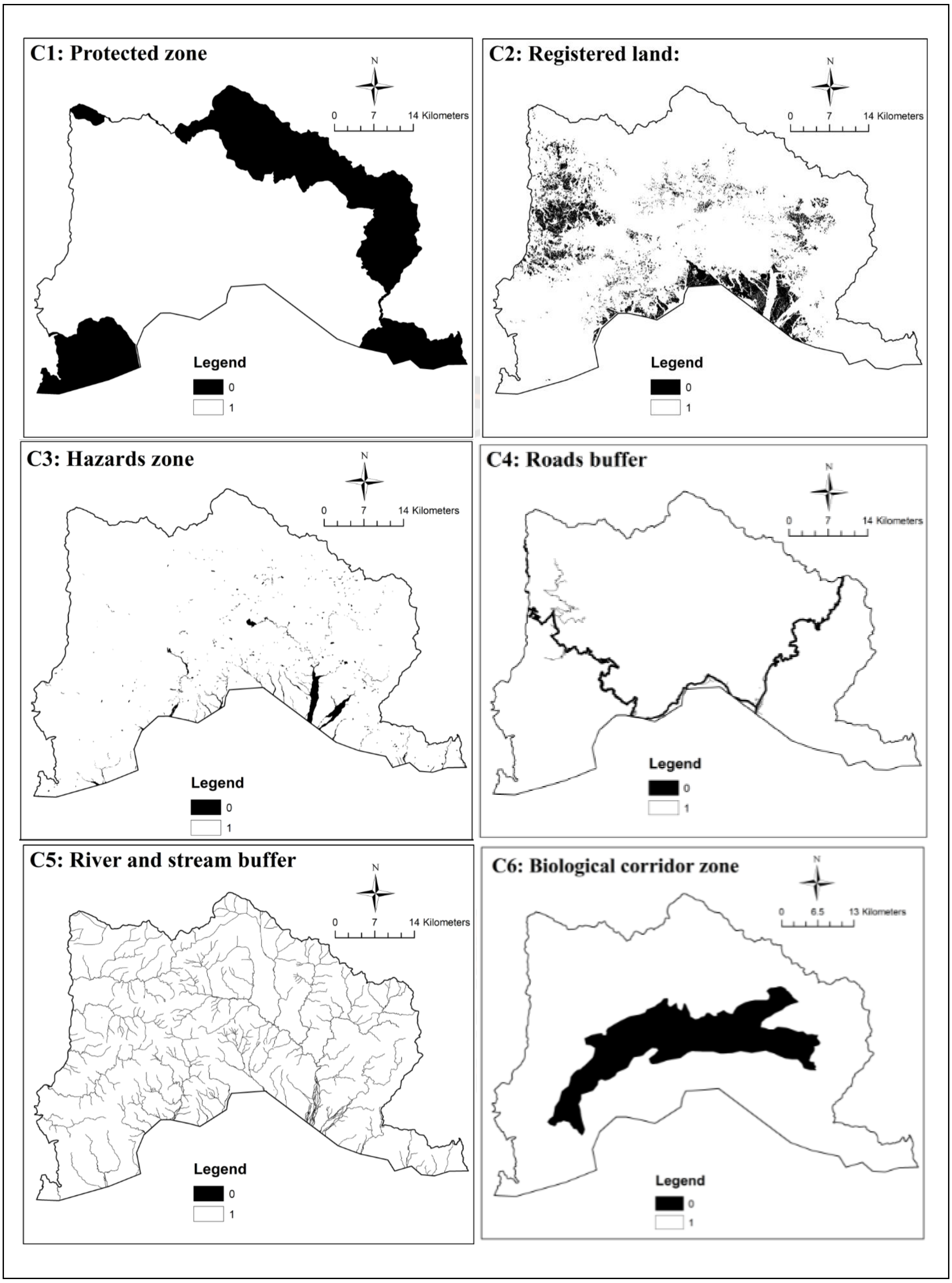


Figure 28 Constraint maps

Table 20 shows the coverage area of the respective constraints in the study area. The protected zone (C1) has an area of 705.7 km^2 which comprise 30.8% of the study area which is the highest. Biological corridor zone (C6) has the second most coverage with an area of 376.5 km^2 (16.40% of the total study area).

It must be noted that constraints C3 and C5 are common to both the agriculture and residential objectives, and forms 'Not suitable' (NS) class since its membership function value is 0. The allocation of land is legally prohibited from areas falling in the protected zone(C1), registered land (C2), buffer roads (C4) and biological corridor zone (C6) and are completely excluded from consideration. Such areas are classified as 'Not Considered' (NC). The biological corridor zone (C6) constraint is applied only to the Residential objective since the human settlement is not allowed in the biological corridor.

Table 20 Coverage area of the constraints

Constraints	**Km^2**	**% coverage of study area**
C1: Protected zone	705.70	30.80%
C2: Registered land	206.57	9.00%
C3: Hazards zone	40.64	1.80%
C4: Roads buffer	60.29	2.60%
C5: River buffer	90.69	4.00%
C6: Biological corridor zone	376.56	16.40%
Total	**1480.45**	**64.50%**

In general, it is observed that 64.5% which is more than half of the study area is either legally restricted or completely not suitable for any human rehabilitation.

4.3 Suitability Maps

Using GIS-MCDA based multi-criteria land evaluation model (Phase 3 of the model), the land-use suitability map of residential and agriculture for human rehabilitation are generated and shown in Figure 29. Figure 30 shows the class-wise area of the land suitability for both the objectives.

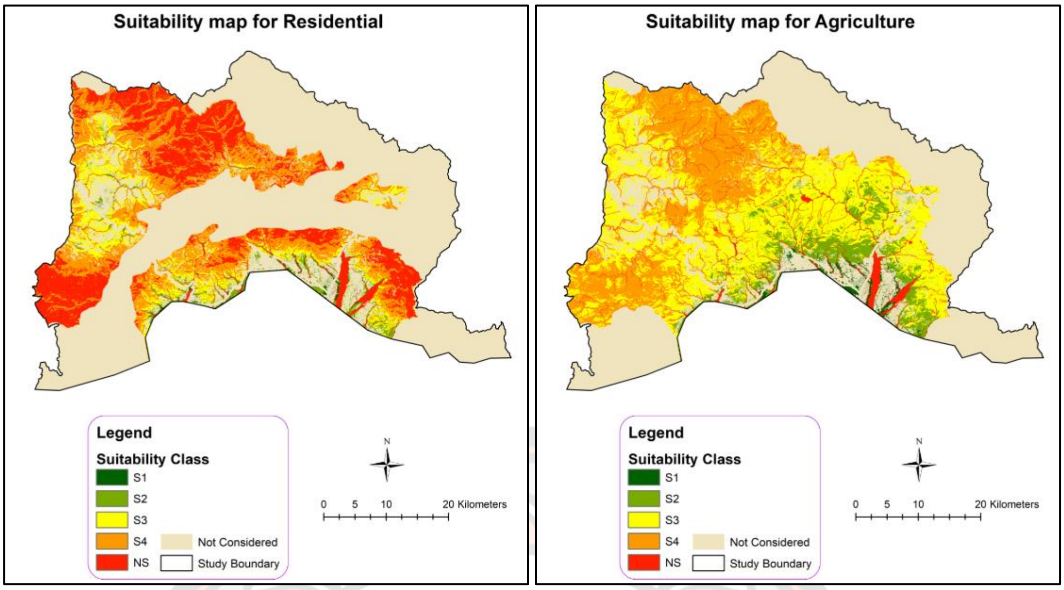


Figure 29 Suitability map of agriculture and residential

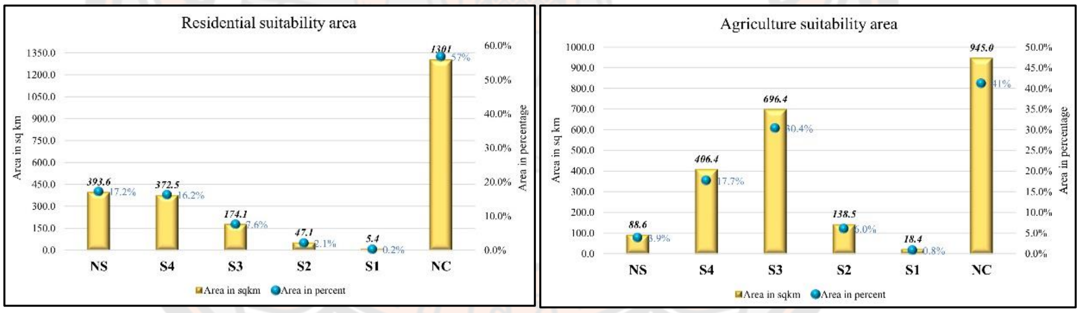


Figure 30 Bar graph showing an area of land suitability class.

The suitability maps are obtained using WLC method and are classified into five classes using the class interval defined in Table 11. The suitability maps in Figure 29 shows that, high suitable (S1 class) land is mostly located in the Southern region. In general, the degree of land suitability decreases from low foothills from South to high foothills in the North.

In Figure 30, for Residential the general trend of land suitability exponentially increases from ‘Highly suitable’ (S1) class to ‘Not Suitable’ (NS) class. S1 class has only 5.4 km^2 and accounts for 0.2% of the study area. The ‘Not Suitable’ class occupies an area of 393.6 km^2 and accounts for 17.2% of the total study area. It has the least degree of suitability due to its failure to meet most or none of the specified criteria. This is followed by 'Very Low Suitable' (S4) with 372.5 km^2 (16.2%), 'Low Suitable' (S3) with 174.1 km^2 (7.6%) and 'Moderately Suitable' (S2) with 47.1 km^2 (2.1%). 'Not Considered' class occupies an area of 1031 km^2 and accounts for 57% of the total study area. The 'Not Considered' class consist of protected zone(C1), registered land (C2), buffer roads (C4) and biological corridor zone (C6) where human settlement is prohibited by law. Given the best scenario, 5.4 km^2 can be recommended for Residential planning.

For Agriculture, a total of 18.4 km^2 which accounts for only 0.8% of the study area is classified under S1 class. This indicates that this class has satisfied the highest degree of suitability criteria. The S3 class has a maximum area with 696.4 km^2 or 30.4% followed by S4 class with 404.4 km^2 (17.7%), S2 class with 138.5 km^2 (6.0%) and NS class with 86.6 km^2 (3.9%). The Not considered (NC) class has an area of 945 km^2 comprising 41% of the total study area. The NC class here consists of protected zone(C1), registered land (C2) and buffer roads (C4).

Considering the best scenario, 18.4 km^2 can be recommended for Agriculture planning and management.

4.4 Validation and sensitivity analysis result

The sensitivity test is performed on both the outputs of residential and agriculture suitability map. The results in Figure 31 and Figure 33 shows the Sensitivity of suitability class in terms of areal change when the percentage change of $\pm$10% and $\pm$20% are applied to the criterion weights of agriculture and residential respectively. Figure 34 and Figure 35 shows the sensitivity in terms of spatial extent when the percentage change of $\pm$10% and $\pm$20% are applied on the criterion weights of agriculture and residential respectively.

For Agriculture, the change is applied to the Topography (AC-1) criteria since it has the maximum priority weight for the agriculture objective. The baseline for calculating the actual variation in the suitability class area is at 0% which is without any change. It is seen that all the suitability class has very minimum change with overall change values ranging from 0.2% to 6.0% only.

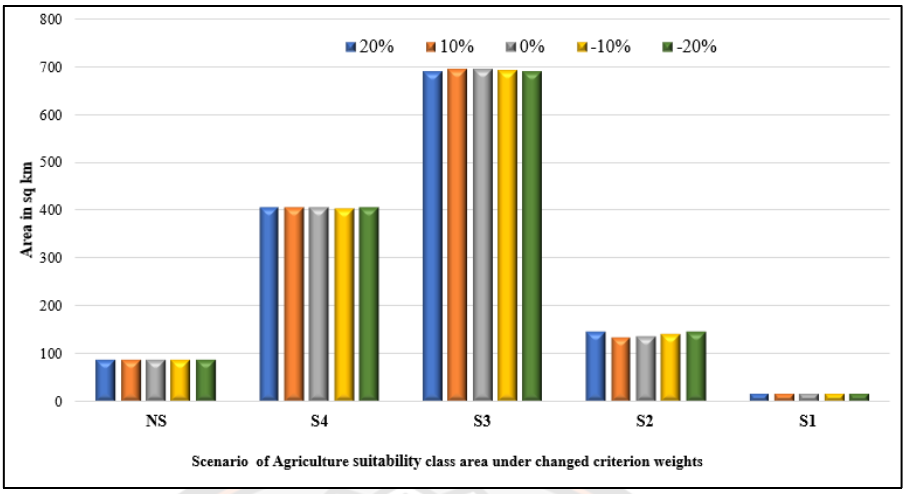


Figure 31 Sensitivity of Agriculture suitability class under ±10% and ± 20% change.

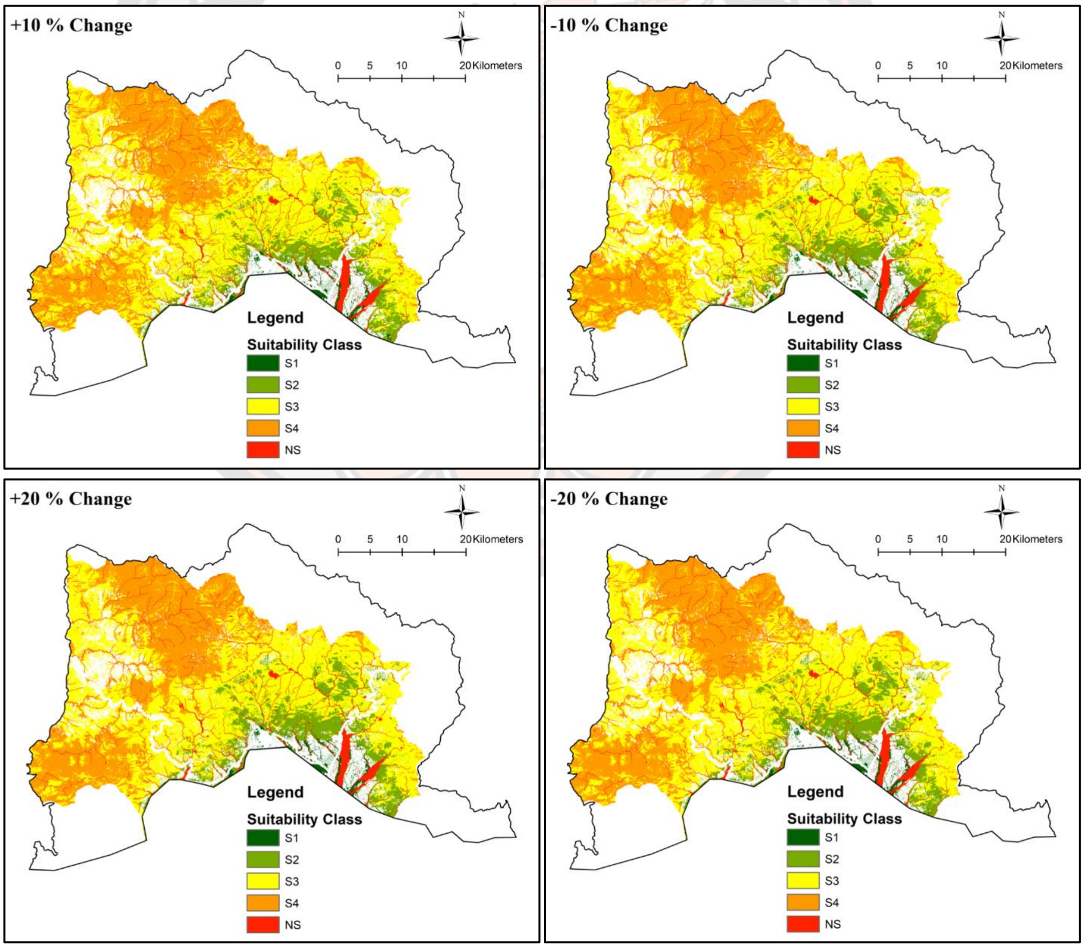


Figure 32 Scenario of Agriculture suitability maps under sensitivity test between ±10% and ±20% of criterion weights.

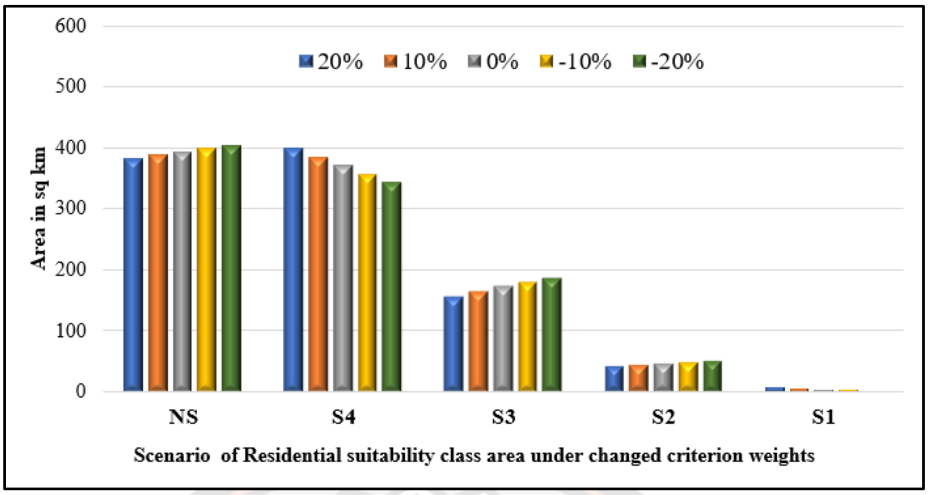


Figure 33 Sensitivity of Residential suitability class under ± 10% and ± 20% change.

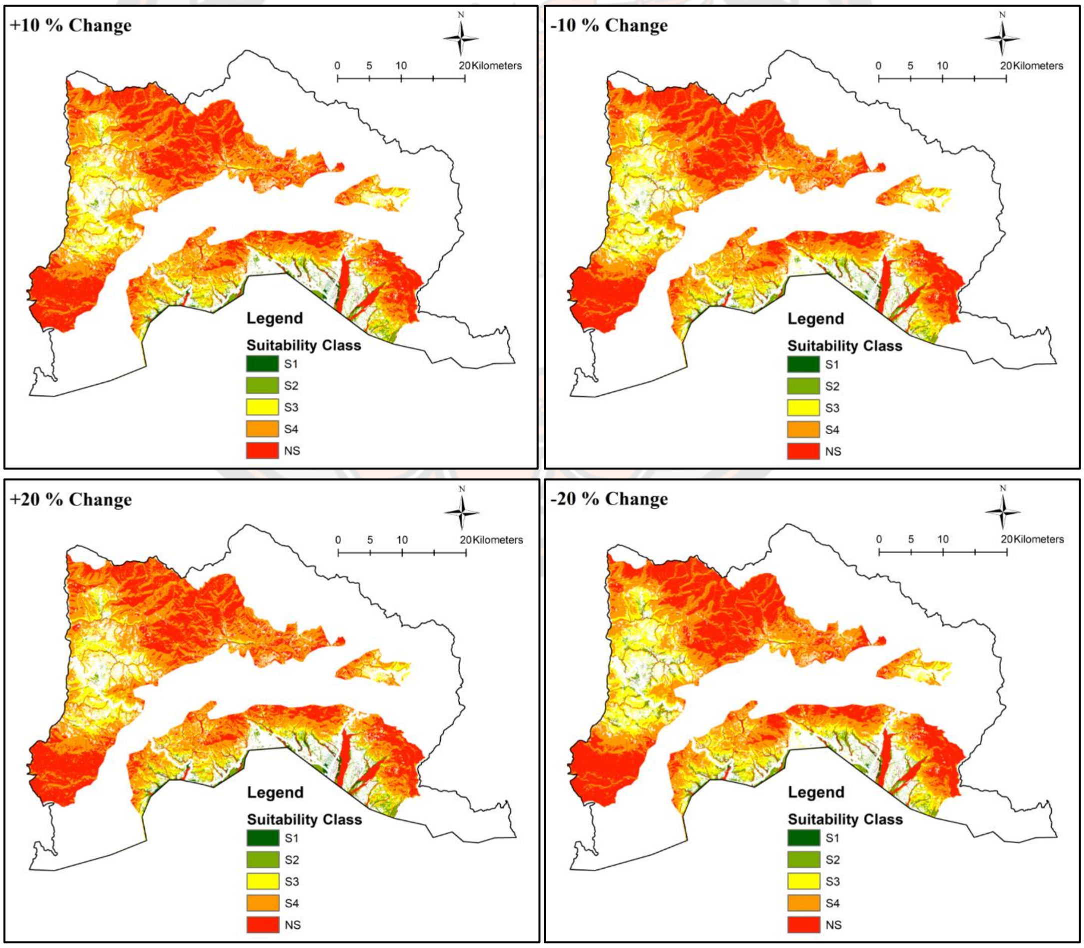


Figure 34 Scenario of Residential suitability maps under sensitivity test between ± 10% and ± 20% of criterion weights.

There is very minimal variation in the spatial pattern of the output suitability class under different changed criterion weight percentage. Therefore, the model proved to be robust for evaluating and generating agriculture suitability map. This also indicates that the stability against the subjectivity on the preference of criterion by the decision-makers is stable.

In the case of residential objective, the change is applied to the Topography (RC-1) criteria since it has the maximum priority weight. the changed criterion weights used in the sensitivity test provided in Table 17.

The baseline for calculating the actual variation in the suitability class area is at 0% which is without applying the change. Figure 33 shows the pattern of suitability class area variations. It is seen that the overall variation ranges from 1.3% to 36% Nevertheless, there is no change in the rank order of the suitability class area category. Therefore, the model is robust for evaluating and generating residential suitability map. Hence, also the stability against the subjectivity on the preference of criterion by the decision-makers is stable.

4.5 Suitability maps with Varying level of Risk and tradeoff

Following the theoretical concepts described in Section 2.3.11.3 and using the methods outlined in Section 3.5.3.2, the six scenarios of suitability maps with varying degrees of risk and tradeoffs are produced for agriculture and residential objectives as shown in Figure 35 - 38. The six scenarios are: (1) Average Risk and Full Tradeoff (ARFT), (2) Low Risk and No Tradeoff (LRNT), (3) High Risk and No Tradeoff (HRNT), (4) Low Risk and Middle Tradeoff (LRMT), (5) High Risk and Middle Tradeoff (HRMT) and (6) Middle Risk and No Tradeoff (MRNT).

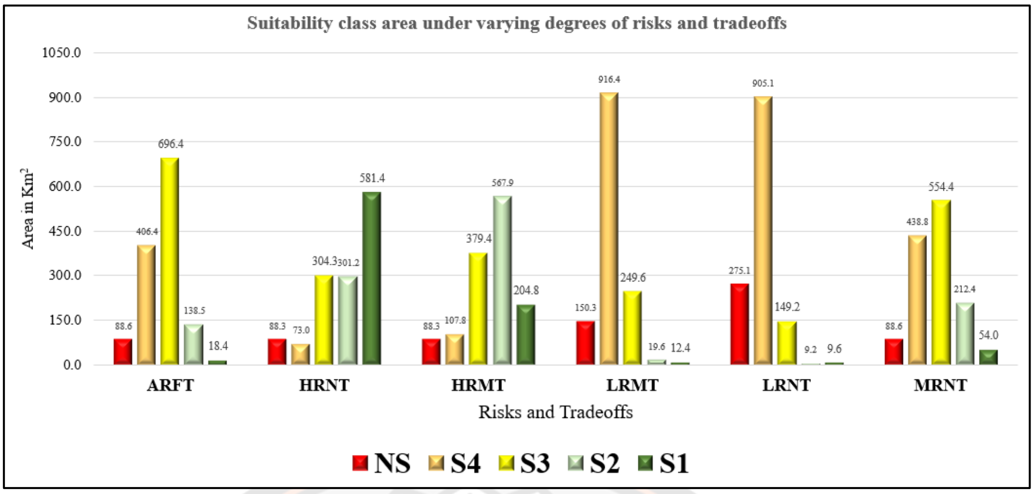


Figure 35 Graph showing the comparative suitability class area of agriculture under different level of risk and tradeoff values.

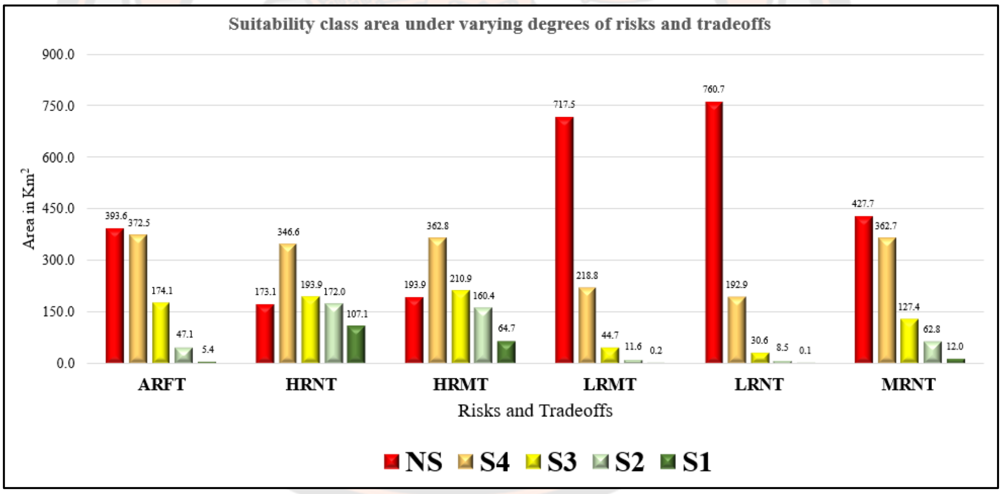


Figure 36 Graph showing the comparative suitability class area of Residential under different level of risk and tradeoff values.

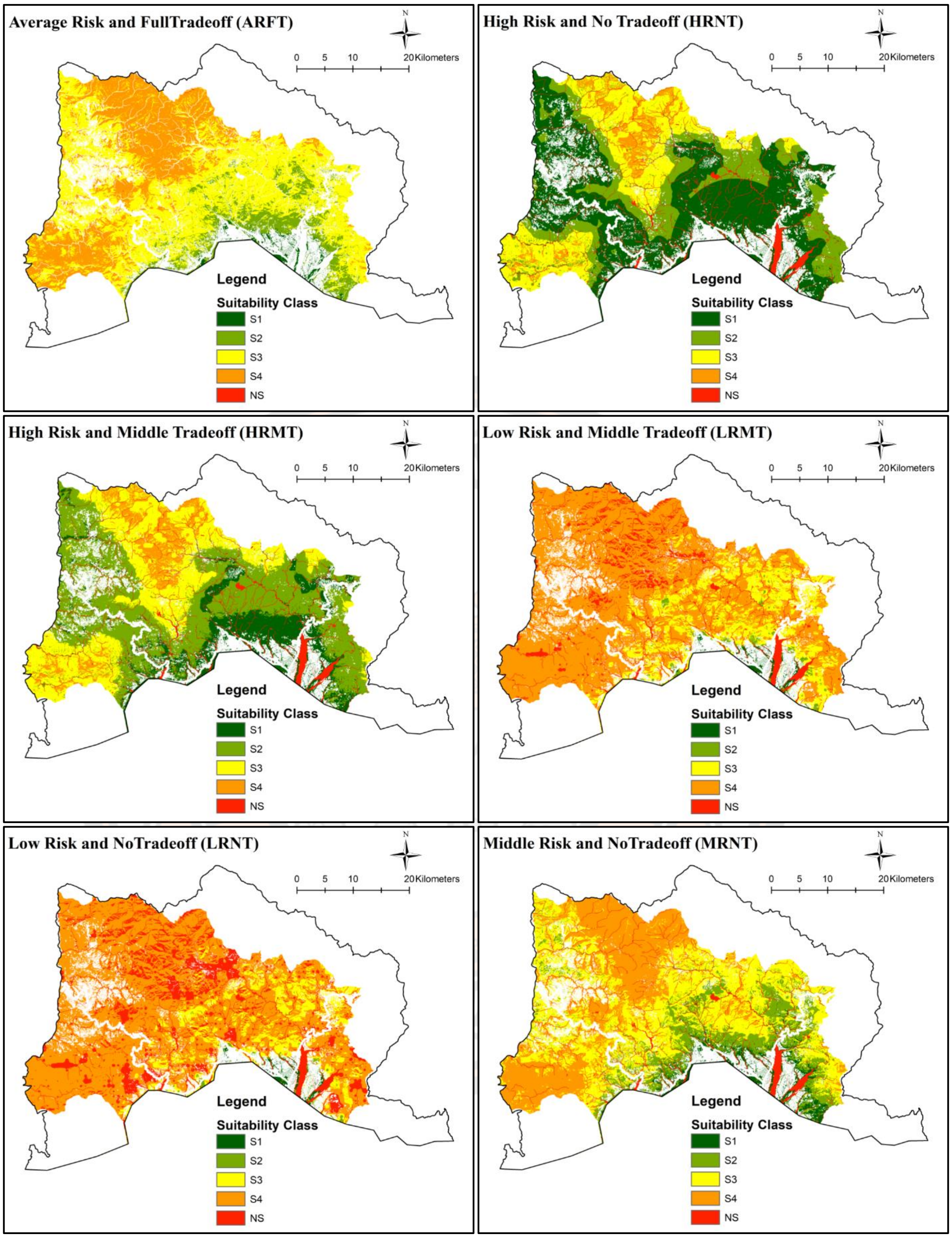


Figure 37 Scenario of suitability maps of agriculture under different level of risk and tradeoff values.

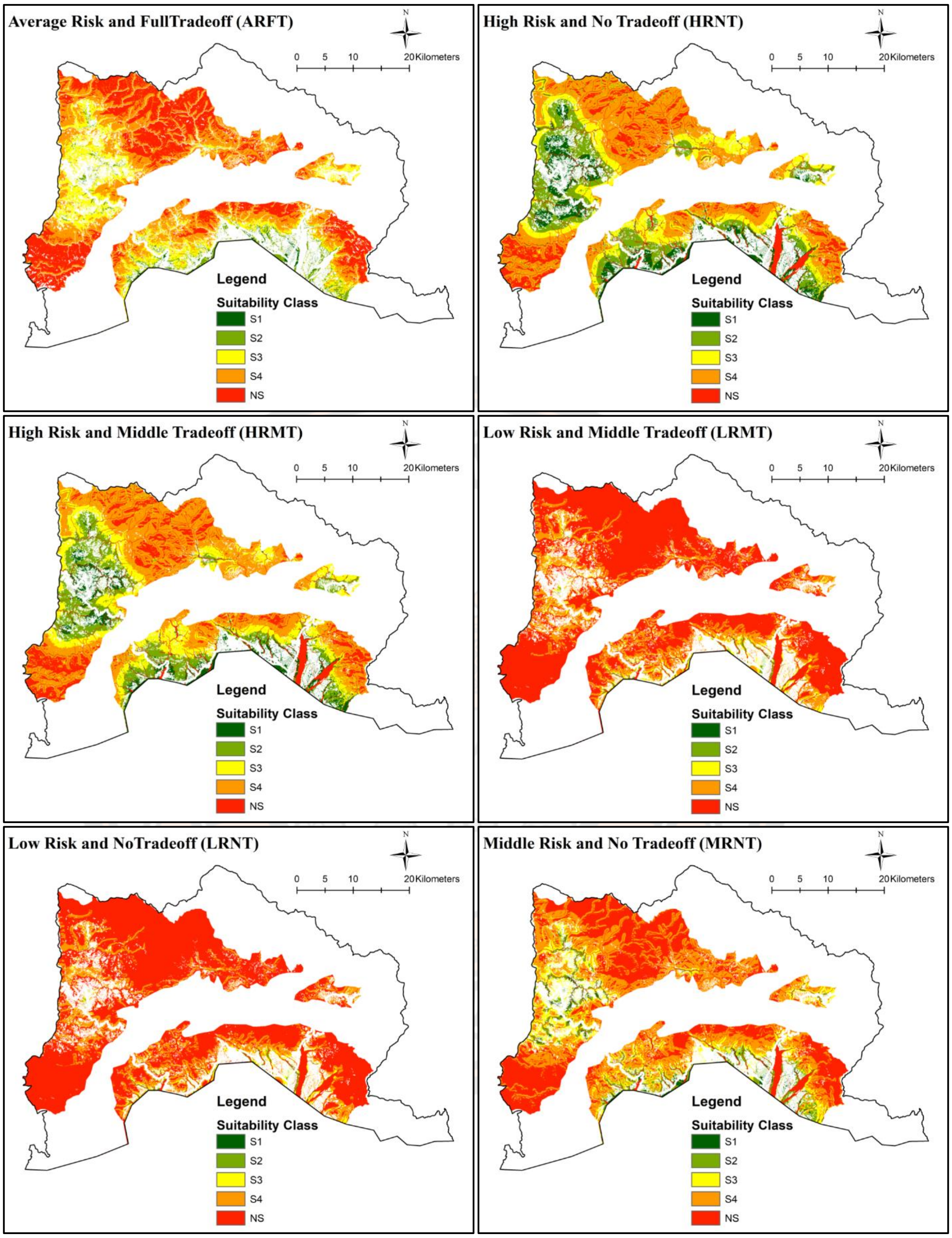


Figure 38 Scenario of suitability maps of residential under different level of risk and tradeoff values.

Unlike the Boolean approach which operates on two extreme functions that result in risk-averse solution when the AND operator is used or risk-taking solution when OR operator is used, the OWA provides solutions that fall anywhere between the OR and AND risk continuum. It provides user the flexibility of choice depending on what level of risk and tradeoff he can afford to take it.

It is general accepted principle that the degree and area of land suitability decreases when choosing the risk values in the order of Low Risk (LR), Middle Risk (MR) and High Risk (HR) and tradeoff values in the order of High Tradeoff (HT), Middle Tradeoff (MT) and Low Tradeoff (LT). The different combination of risk and tradeoff values can give different scenarios of land suitability.

This principle is elucidated by the areal Graphs and maps. Figure 35 and 36 are Graphs showing the suitability class area under different level of risk and tradeoff values for agriculture and residential objective respectively.

Similarly, Figure 37 and 38 are Scenario of suitability maps under different level of risk and tradeoff values for agriculture and residential objective respectively. The map legend indicates that the order of degree of land suitability decreases from S1 to NS in each map.

In the comparative analysis of areal Graphs and six visual scenario maps, it is seen the land suitability decreases in the order of HRNT, HRMT, ARFT, MRNT, LRMT, LRNT.

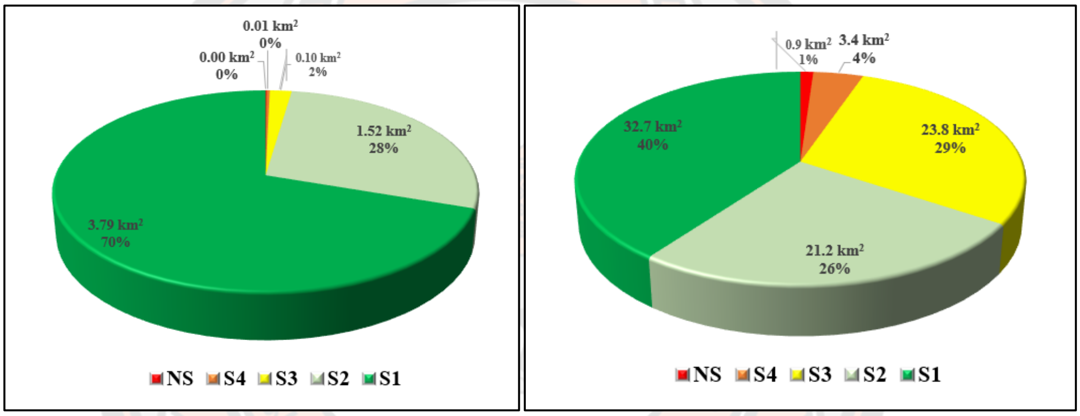
4.6 Validation with existing cadastral data

As described in Section 3.6.2 the results of suitability maps generated by the GIS-MCDA model are validated by overlaying with the existing cadastral data of Residential and Agriculture lands. For residential output validation, a total of 3784 number of existing residential parcels consisting of 5.43 km^2 is used. Similarly, 22817 agriculture land parcels with a total area of 82.05 km^2 are used for validating the agriculture land suitability output of the model. The cross-overlay validation results are shown in Figure 39.

The results of Figure 39 (a) shows that no residential parcels fall in the Not Suitable (NS) class. The 70% of the plots fall under the Highly Suitable (S1) which is the highest with the total area of 3.79 km^2. This is followed by 25% (with a total area of 1.52 km^2) of plots falling in Moderately Suitable (S2) class. Only 0% (0.01 km^2) and 2% (0.10 km2) of residential plots fall under Very Low Suitable (S4) class and

Low Suitable (S3) class respectively. This indicates that in general, the areal extent of the existing residential parcels decreases with the decreasing order of the land suitability.

Similarly, for Agriculture, shown in Figure 39 (b), the maximum 40% (32.7 km^2) area of current agriculture lands fall in the S1 class and only 1% (0.9 km^2) of parcels fall in NS class which is the least. About 29% (23.8 km^2) of parcels fall under S3 class. This is mainly attributed to the fact that appreciable agriculture lands have less slope suitability. 26% (21.2 km^2) and 4% (3.4 km^2) of parcels fall under S2 and S4 class respectively.



a) Residential **b) Agriculture**

Figure 39 A Pie chart showing the area of intersection of the model result and existing cadastral data (currently under occupation)

4.7 Conflict resolution

Since there are two objectives (land suitability for Residential and Agriculture), it constitutes a multi-objective decision-making process. The objectives are conflicting in nature as they compete for suitable land from the same area and the same piece of land cannot be allocated for both the objectives. Thus, it is important to resolve these conflicted areas. Using the principles of Multi-Objective Land Allocation (MOLA) described in Section 2.5 and procedures of MOLA tools specified in Section 3.5.4**,** the results are generated as follows.

In the study, with the objectives of identifying the most suitable land for human rehabilitation, the conflict resolution is performed only for S1 (Highly suitable) and S2 (Moderately suitable).

Conflict resolution at S1 suitability level:

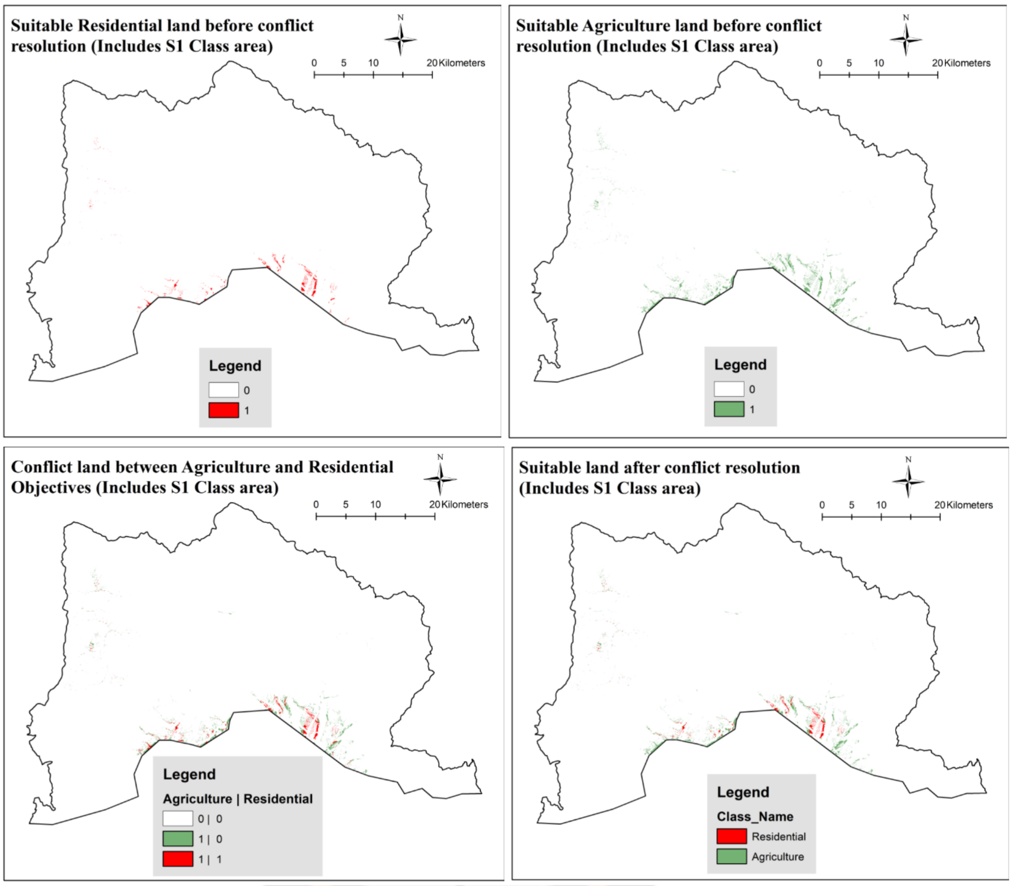


Figure 40 Maps of Conflict resolution between Residential and Agriculture objectives at S1 suitability class area

The area of suitable residential and agricultural land is 5.4 km^2 and 18.4 km^2 respectively at S1 (Highly Suitable) class category. (see Figure 40). The map below (Top right and top left) of Figure 40 shows the S1(Highly Suitable) for Residential and Agriculture. The map on the bottom left of Figure 40 shows the conflicted area between the two objectives. It is observed that all the land identified as S1(Highly suitable) for Residential objective also qualifies as S1(Highly suitable) for Agriculture objective. Therefore, there is a complete conflict of suitable land between the two objectives. This exactly matches the ground reality in Bhutan, because most of the land suitable for Residential can also be used for Agriculture with few exceptional cases. The map on the bottom right of Figure 40 shows the result after resolving the conflicted areas. The new area for Residential is 4.5 km^2 and agriculture has 13.9 km^2. From the map, we can also see how the allocation of land for each objective change after the resolution of conflict by MOLA.

Conflict resolution at S1 and S2 suitability level:

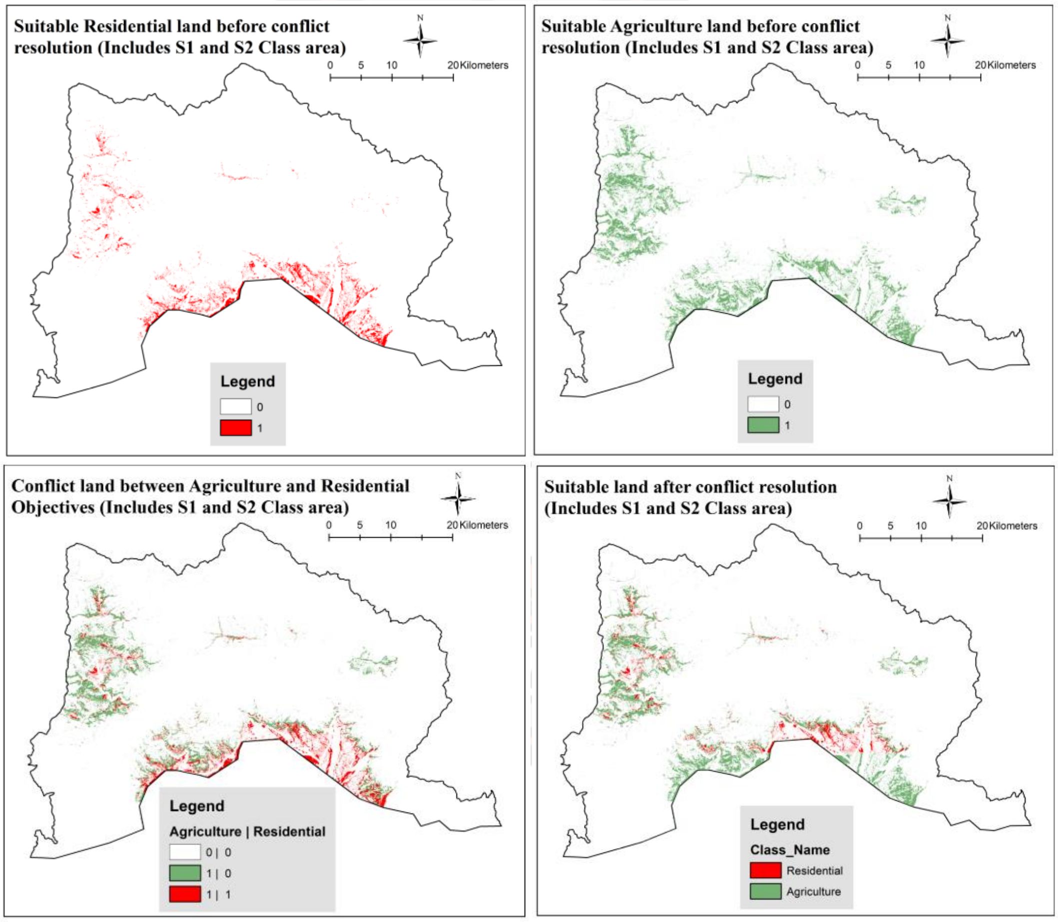


Figure 41 Maps of Conflict resolution between Residential and Agriculture objectives at S2 suitability class area

Same logic of case above is applied here except with different input area. The S2 (Moderately suitable) area is added to the S1 (Highly Suitable) area to increase the area and see how the results changes after resolving the conflict area. The area of suitable residential and agricultural land is 5.4 km^2 and 18.4 km^2 respectively at S1 (Highly Suitable) class category and 52.5 km^2 and 156.9 km^2 respectively at S2 (Moderately Suitable). See Figure 29 and Figure 30. The map (Top right and top left) of Figure 41 shows suitable land of S1 and S2 class for Residential and Agriculture. The map on the bottom left of Figure 41 shows the conflict area between the two objectives. Residential land is in complete conflict with agriculture land. The map on the bottom right of Figure 41 shows the result after resolving the conflicted areas. The new area for Residential is 27.3 km^2 and agriculture has 129.5 km^2.

CHAPTER V

DISCUSSION AND CONCLUSION

5.1 Discussion

Criterion weights: Inter alia, the criterion or factor weights largely influence and dictate the outcome of the final suitability maps based on the degree of each factor weights. Therefore, the flexibility of MCDA provides the analytical capability to evaluate the criterion weights and plays a critical role in the land evaluation process when integrated with GIS.

In the study, twenty sub-criteria and seven main criteria are identified for the residential and agriculture objectives and, weights calculated based on the expert's opinion.

It is noted that from the expert's evaluation, the criteria weight for topographic has the highest weightage in both the objectives of residential and agricultural land evaluation. As such it is evident from the final suitability maps that high suitable areas are mostly located in the Southern region of Sarpang District where it has more public infrastructures, service centres and gentle topography compared to other area.

It can be concluded that the identification and weighting of the criteria are subjective to the expert or user's knowledge on the problem under consideration. This is well corroborated by many similar approaches in studies like landfill suitability by (Alanbari et al., 2014), site suitability for ecotourism by (Gigović et al., 2016), land evaluation for urban growth by (Aburas et al., 2017), etc. The fuzzy logic is used as an extension of AHP in the study to calculate the weights evaluated by the experts to manage the extreme judgement of the experts. However, as stated by (Mosadeghi, 2013) such techniques may not have a significant impact on the overall result than by AHP as it also depends on the level of detail, spatial extent and model uncertainty. Therefore, further comparative analysis with other techniques is required.

Risk and tradeoffs maps: OWA method is used to generate various suitability maps with varying level of risk and tradeoff values. Its helps decision-maker(s) understand how the degree of suitability values change with change in the level of risk and tradeoff the decision-maker wants to assume to achieve the objective under consideration. The six scenarios of suitability maps with varying degrees of risk and tradeoffs are produced for agriculture and residential objectives. The result of the suitability map under Average Risk and Full Tradeoff (ARFT) is same as WLC generated suitability map. This indicates the WLC method is sub-set of OWA method. average combination of the criterion of WLC method.

As expected, it is observed that the area consisting of a high degree of suitability increases in the order from HRNT, HRMT, ARFT, MRNT, LRMT and LRNT for both the objectives. The results also substantiate the fact that in low risk, the area considered most suitable in the final result is minimized since it must be of highly suitable in all factors. On the contrary, in high risk, the area considered most suitable in the final result is maximized since any area that is highly suitable for any factors are considered highly suitable in the result.

GIS-based land suitability by (Malczewski, 2006b) used OWA to generate a wide range of suitability scenarios for decision strategies by changing the input parameter. The difference is that the input parameters used are linguistics (like all, almost all, most, half, few, etc). However, in general, the working principle and results are the same in both the case.

Sensitivity & validation: The sensitivity analysis explores the influence of the criterion weights as parameters on the suitability map as the model output. Sensitivity analysis lets one understand the final model output can be influenced by the input parameters. This test also validates the robustness of the land evaluation model for human rehabilitation. If a change of one criterion weight results in a significant change in the final suitability output, the land evaluation model can be considered sensitive and this changed criterion weight is said to have a significant influence on the final output. On the other hand, if the changed criterion weight input parameter results in little change or no change in the final output, the model is considered robust.

In the study the percentage change of ± 10% and ± 20% are applied to the factor having the maximum criterion weight because, the model is expected to produce more variation in the output for criteria parameter with higher weightage. The sensitivity test is performed on both the outputs of residential and agriculture suitability map. It is observed that there is minimum variation of 0.2% to 6.0% for

Agriculture and 1.3% to 36% for Residential objective. Also, the spatial pattern of the output suitability class under different changed criterion weight percentage is very minimum for both the objectives. Therefore, the model proved to be robust for evaluating and generating suitability map. This also indicates that the stability against the subjectivity on the preference of criterion by the decision-makers is stable.

This technique of sensitivity analysis is well-substantiated in land use suitability study for refugee camp sitting by (Çetinkaya et al., 2016) where similar results are produced. The increment of 5% is applied within the range of ± 5% to ± 20% to the criterion weights. The overall variation of suitability class area is between 3.88% to 30.33% for his study.

In the study, also, the suitability results are validated using the existing cadastral data. For residential output validation, 3784 number of existing residential parcels with a total area of 5.43 km^2 is used. Similarly, 22817 agriculture land parcels with a total area of 82.05 km^2 are used for validating the agriculture land suitability output of the model. The cross-validation results indicate that in general, the areal extent of the existing residential parcels decreases with the decreasing order of the land suitability. For Agriculture, 29% (23.8 km^2) of parcels fall under S3 class. Which is greater than S2 class with 26% (21.2 km^2). This is mainly attributed to the fact that appreciable agriculture lands have less slope suitability.

From the cross validation and observation, it is concluded that the suitable output of the model result confirms the general premise that existing lands under occupation are maximum in the most suitable land and minimum in the low or not suitable land. However, the quantitative assessment and validation of the model result may be necessary for the future. This would entail making field visits.

Conflicts resolution: It is observed that there is complete conflict between the two objectives viz: Residential and Agriculture land. That is all land parcels suitable for Residential is equally suitable for Agriculture. This supports the fact that in general most of the criteria satisfying the objective of finding suitable Residential land also satisfy objective of finding suitable agriculture land and vice versa. However, the land cannot not be allocated for both the objectives. This require effective methods address the conflicts. The MOLA tools in IDRISI are used to solve the conflict based on the prioritization of objectives. This tool proved to be very easy and effective since it has intuitive appeal and handles larger datasets for conflict resolution of multi-objective.

The other solutions to resolving the conflicts in multi-objectives are compromise solution using mathematical programming (such as linear or integer) tools outside GIS (Eastman, 2012b). Such methods, however, works only for smaller number of alternatives and cannot handle massive raster data. Moreover, the programming is not approachable for many decision makers.

The effectiveness of using MOLA for resolving the conflict among the multi-objectives are well demonstrated by (Eastman et al., 1993) where they have used it in resolving the conflicts between the two competing objectives viz. suitable land Agriculture and Industry. It has effectively allocated 1500 hectares for industrial uses and 6000 hectares for agriculture. The only difference is that instead of using the suitability class area (S1 and S2) in the study, he has predefined area based on the objective. This proves that MOLA is very flexible and effective tool for resolving the conflicts in multi-objective decision-making.

5.2 Conclusion

There is a growing global concern for the sustainable planning and management of dwindling land resources. Effective land evaluation is indispensable and pre-requisite for achieving sustainable and optimum utilization of the limited land resources in the country.

Against the backdrop of increasing land use and allocation for various socio-economic activities and lack of effective and systematic land evaluation techniques underscore the importance of adopting GIS-MCDA as the solution for the multi-criteria land evaluation.

Therefore, the main objective of the study is to develop the simple, effective and comprehensive modelling framework for multi-criteria land evaluation using GIS-MCDA based on fuzzy logic. The study comprises of four specific objectives and it is summarized in the following on addressing the objectives.

The land evaluation model is explained and demonstrated simultaneously in a case study for identifying suitable land for human rehabilitation in Southern Bhutan where multiple factors based on social, economic, climate, environments and topography are identified as the input and the suitability maps generated by the model.

The spatial and statistical results are generated with five suitability class ranging from high to not suitable class. Such information on the land-use suitability can be very important for future planning of human rehabilitation in the two districts.

The robustness of the land evaluation model and stability of criteria preferences against the subjectivity of the experts are validated using sensitivity analysis test and the results proved to be robust and stable.

To conclude, it is positioned that the proposed GIS-MCDA model can be the basis for the scientific approach for general land evaluation and suitability analysis. In particular, the model is expected to ameliorate many existing problems faced by conventional methods while allocating land for human rehabilitation in particular. In general, implementing such a model can of immense help to the planers and the decision-makers in formulating appropriate land use and allocation plans and policies. This will contribute towards the sustainable and optimized use of a limited land resource which ultimately can enhance and strengthen the policy of sustainable land-use planning and management in the country.

5.3 Addressing Research Objectives

Objective 1: To integrate the fuzzy logic in the GIS-MCDA model:

The conventional GIS technique for land evaluation is mostly based on a Boolean approach which operates on the assumption of the input data as crisp or precise. Such an assumption is unrealistic since it is almost impossible to provide precise numerical information given the fuzzy boundaries between the suitable and unsuitable features. The precise boundaries may be an exception in the case of legal requirement. With Boolean analysis approach, the set is included only upon completely satisfying the specified thresholds and rejects the sets that are even very close to the specified thresholds. Such operations are not realistic as it does not represent the complete information for decision making.

For the MCDA part, the conventional methods assume that the criterion weights are given in a numerical form and therefore, cannot express the weights of importance through linguistics statement. In most of the conventional GIS-MCDA model fuzzy logic is not adopted or it is restricted either GIS or MCDA technique only. Various literature reviews point out that the issues related to vagueness, imprecision and ambiguity can be addressed by applying fuzzy logic.

Fuzzy logic is integrated in the land evaluation model where fuzzy membership functions are used for criteria standardization (in GIS) and fuzzy AHP for in MCDA for determining the criterion weights. Therefore, the objective of integrating the fuzzy logic in the GIS-MCDA is well achieved.

Objective 2: To generate the suitability map for human rehabilitation:

The human rehabilitation program encompasses two objectives viz. evaluating land for residential and agriculture. Using GIS-MCDA based land evaluation model, the land-use suitability map for each objective is generated in the study area that covers an area of 2294 km^2.

Using the geostatistical tool and the suitability degree of score range, the maps are zoned into five suitable classes.

It is observed that more than 50% of the study cannot be considered for residential development and 47% of the area cannot be considered for agriculture land. This is mainly due to the environmental protection such as parks and biological corridors reserve zones where the land allocation for human rehabilitation is legally not permitted. The highly suitable (S1) area for future residential and agriculture is only 5.01 km^2 (0.2%) and 18 km^2 (0.8%) respectively. For optimum and sustainable land-use under the best scenario, highly suitable (S1) and moderately suitable (S2) class can be recommended for consideration for human rehabilitation in future.

Objective 3: To generate scenario maps of land suitability under varying degrees of risk and tradeoffs:

OWA is used to generate scenario maps of land suitability with different levels of risks and tradeoffs are generated OWA method.

Total of six different scenarios maps are generated: (1) Average Risk and Full Tradeoff (ARFT), (2) Low Risk and No Tradeoff (LRNT), (3) High Risk and No

Tradeoff (HRNT), (4) Low Risk and Middle Tradeoff (LRMT), (5) High Risk and Middle Tradeoff (HRMT) and (6) Middle Risk and No Tradeoff (MRNT).

The area of output suitability maps depends on the degree of risk and tradeoff that the decision-maker(s) can afford to assume. Thus, it helps decision-maker(s) understand how the degree of suitability values change with change in the level of risk and tradeoff the decision-maker wants to assume to achieve the objective under consideration.

Thus, the objective of generating scenario maps of land suitability under varying degrees of risk and tradeoff is successfully achieved in the study. OWA method can be recommended for multi-criteria land evaluation which involves studying and analyzing varying degrees of the risk and tradeoff analysis.

Objective 4: To resolve the conflicts between Residential and Agriculture land use:

One of the problems stated in this research problem is the frequent occurrence of land-use conflicts among various stakeholders with different objectives competing for the same land. The existing conventional land evaluation method acutely lacks the capability to handle such conflicting issues. Therefore, conflict resolution between the competing objectives of either complementary or conflicting is very important and necessary.

In the study, the residential and agriculture are the two conflicting objectives competing for land from the same study area. It is observed that the S1 class area of residential land is in complete conflict with the S1 class area of agriculture objective. However, the land cannot be allotted for both the objectives. To resolve this conflict, Multi-Objective Land Allocation (MOLA) is used. In the analysis, the areal suitability maps before and after conflict resolutions are presented. These conflicts are effectively resolved based on the desired area for the respective objectives.

The model can be very effective in the case of multi-objectives more than two objectives. The objective of resolving conflicts between residential and agriculture objective is achieved.

5.4 Recommendations and further research

Recommendations:

It is acknowledged that there are some limitations or problems in any research work. Following are few pertinent recommendations against the problems encountered in the study which may be considered or implemented in similar studies in future:

1. The successful application of the MCDA is contingent on identification of comprehensive criteria and experts who has prior knowledge on the subject and accurately prioritize and rank the criteria without subjective bias. However, finding relevant experts are difficult given the limited number of experts available and time constraints. Also, there is lack willingness of the experts to participate in the academic research. Therefore, exploring effective means and alternatives to attract maximum participation of relevant experts should be given priority.

2. To have a realistic result, identification of comprehensive criteria that represent the overall goal and objectives are very important. However, its consideration is subjective to the availability of spatial data that represents it. For instance, comprehensive soil, climate and irrigation data are not available in the country. Obtaining such data always involve cost and time. In the study, only thickness and sediments of soil at coarser resolution available from satellites are used. For climates, the temperature and rainfall data from 20 primary stations are interpolated in the country (only two in the study area). The perineal streams are used as the source of irrigation and drinking water.

With the advancement of the global space technology, many complicated and powerful earth observation satellites are added in space system every year. Therefore, it is recommended to explore the use of data available from satellites. Of course, the data relevancy and accuracy must be investigated before its use in the study. Other alternative is to conduct field survey using appropriate surveying technologies and machines.

3. Another area that can influence the result of the land evaluation is defining the control point values for criteria standardization. There are no standard set of

values. Expert's views and literature reviews on similar studies are based wherever applicable in the study.

Therefore, to further enhance the capability of GIS-MCDA based land evaluation, it is highly recommended that appropriate ameliorative measures to tackle above-cited limitations should be given due consideration.

Further research:

1. Since there is lack of clear spatial boundaries between the suitable and not-suitable features and uncertainty and ambiguity involved in the expert’s preference over the criterion, the fuzzy logic is applied to both the GIS and MCDA technique to tackle such problems in the decision-making process. However, further research is necessary to quantitatively assess the effectiveness of applying fuzzy logic in the multi-criteria decision-making model.

2. The study has demonstrated the application of fuzzy AHP of MCDA can produce a good result. However, it also depends on the magnitude of details, degree of uncertainties of input and the evaluation model and spatial extent. Therefore, comparative analysis with other advanced MCDA techniques is necessary.

3. Another research area would be to make this GIS-MCDA land evaluation model available and accessible to the decision-makers and public use via internet leveraging the web technologies for effective implementation. This can be a very open approach to public information and participation in the complex decision-making process of evaluating and identifying suitable public land.

It can be noted that the MCDA approach has the flexibility of public or stakeholder participation and provides very good analytical support for the decision-making process. The mass participation of the relevant stakeholders should be given due importance. The panel on the group decision making must be considered to incorporate diverse views of different stakeholders and, make a realistic, inclusive and bias-less decision. In the event when the group decision making is impossible, the application of MCDA may be avoided.

APPENDIX I

Survey Questionnaire Design

Research topic:

Modelling multicriteria land evaluation using GIS-MCDA (Multi-Criteria Decision Analysis) based on Fuzzy logic: A case study for identifying suitable sites for human rehabilitation in Southern Bhutan

Background:

This survey questionnaire is designed to determine the relative importance of the factors that influence the evaluation and identification of suitable land for human rehabilitation in Bhutan. The specific study area includes Tsirang and Sarpang Districts.

The questionnaire has two sections A and section B. Section A pertains to evaluating the criteria for identifying suitable residential land (where people can construct a house to live) and Section B is about evaluating the criteria for identifying suitable Agriculture land (where people can grow crops for their livelihoods).

Based on the requirement of the National Rehabilitation Programme 2014 (NRP2014) strategy document main factors like social, economic, topography, climatic are considered for the suitability analysis for rehabilitation.

The task requires the experts to determine the relative importance of each criterion based on its respective objective.

Methods:

The evaluation of criteria shall be performed by the experts through group discussion. The Fuzzy Analytical Hierarchy Process (FAHP) model shall be used to determine the final criterion weights.

Scope:

- The survey shall be limited only to evaluating the criteria included in the survey questionnaire.

- Experts (agriculture): shall include people who have who knowledge relevant to agriculture-related,e.g, agriculture extension officers, soil specialist, etc.
- Experts (Residential): shall include people who have knowledge relevant to residential building related, examples, civil engineers, survey engineers, etc.
- The number of experts: each group shall consist of a minimum of three experts.

Survey Questionnaire

Respondent / Expert's Information

1. Name		
2. Designation		
3. Expertise relevance	Residential	Agriculture

Example of evaluation:

1. Topography
Which criteria with respect to Topography is more important and state the level of its importance.

Sl No	Which criteria is important?				1. Equally important	2. *Intermediate*	3.Moderately important	4. *Intermediate*	5. Strongly important	6. *Intermediate*	7. Very Strongly important	8. *Intermediate*	9.Extremely important
1	Slope	✓	Aspect						✓				
2	Slope		Elevation				✓						
3	Aspect	✓	Elevation										✓

→Importance level→

1. Slope is strongly more important than Aspect.
2. Elevation is moderately important then Slope
3. Aspect is extremely important than Elevation

Section A

Land suitability for Residential

The primary objective here is to evaluate the relative importance of factors, and or subfactors that that can influence the decision making in evaluating and identifying lands suitable for residential building. Following factors are identified for evaluating the land suitable for residential development.

Objectives	Criteria/Criteria	
	Main Criteria	**Sub Criteria**
Residential	RC-1: Topography	RC1-a: Slope RC1-b: Aspect
	RC-2: Proximity to economic infrastructures	RC2-a: Road RC2-b: Electricity RC2-c: Drinking Water RC2-d: Urban points
	RC-3: Proximity to social service centres	RC3-a: Education RC3-b: RNR_gewog centre RC3-c: Health RC3-d: Dzongkhag HQ RC3-e: Religious centre

Q1. *Which criteria with respect to **topography** is more important? State the level of its importance.*

					→Importance level→								
Sl No	**Which criteria is important?**				1. Equally important	*2. Intermediate*	3.Moderately important	*4. Intermediate*	5. Strongly important	*6. Intermediate*	7. Very Strongly important	*8. Intermediate*	9.Extremely important
1	Slope		Aspect										

Q2. *Which criteria with respect to* ***Proximity to economic Infrastructure*** *is more important? State the level of its importance.*

					→Importance level→								
Sl No	**Which criteria is important?**				1. Equally important	2. *Intermediate*	3.Moderately important	4. *Intermediate*	5. Strongly important	6. *Intermediate*	7. Very Strongly important	8. *Intermediate*	9.Extremely important
1	Roads		Electricity										
2	Roads		Drinking water										
3	Roads		Urban points										
4	Electricity		Drinking water										
5	Electricity		Urban points										
6	Drinking water		Urban points										

Q3. *Which criteria with respect to* ***Proximity to social/public service centre*** *is more important? State the level of its importance.*

					→Importance level→								
Sl No	**Which criteria is important?**				1. Equally important	2. *Intermediate*	3.Moderately important	4. *Intermediate*	5. Strongly important	6. *Intermediate*	7. Very Strongly important	8. *Intermediate*	9.Extremely important
1	Education		RNR/Gewog										
2	Education		Health centre										
3	Education		District HQ										
4	Education		Religious centre										
5	RNR/Gewog		Health centre										
6	RNR/Gewog		District HQ										
7	RNR/Gewog		Religious centre										
8	Health centre		District HQ										
9	Health centre		Religious centre										
10	District HQ		Religious centre										

Q4. *Which criteria with respect to* ***Residential*** *is more important? State the level of its importance.*

Sl No	Which criteria is important?				→Importance level→ 1. Equally important	*2. Intermediate*	3.Moderately important	*4. Intermediate*	5. Strongly important	*6. Intermediate*	7. Very Strongly important	*8. Intermediate*	9.Extremely important
1	Topography		Economic Infrastructures										
2	Topography		Social service centres										
3	Economic Infrastructures		Social service centres										

SECTION B

Land suitability for Agriculture

The main objective of this section is to evaluate the relative importance of main criteria, and or sub-criteria that that can influence the decision making in identifying lands suitable for agriculture farming. Following are factors are identified for evaluating land suitability for residential.

Objectives	Criteria/Factors	
	Main Criteria	**Sub Criteria**
Agriculture	AC-1: Topography	AC1-a: Slope AC1-b: Aspect AC1-c: Elevation
	AC-2: Soil	AC2-a: Soil thickness AC2-b: Soil sediments
	AC-3: Climate	AC3-a: Temperature AC3-b: Rainfall
	AC-4: Accessibility	AC4-a: Irrigation water AC4-b: Road

Q1. *Which criteria with respect to* ***topography*** *is more important? State the level of its importance.*

					→Importance level→								
Sl No	**Which criteria is important?**				1. Equally important	*2. Intermediate*	3.Moderately important	*4. Intermediate*	5. Strongly important	*6. Intermediate*	7. Very Strongly important	*8. Intermediate*	9.Extremely important
1	Slope		Aspect										
2	Slope		Elevation										
3	Aspect		Elevation										

Q2. *Which criteria with respect to* ***soil*** *is more important? State the level of its importance.*

					→Importance level→								
Sl No	**Which criteria is important?**				1. Equally important	*2. Intermediate*	3.Moderately important	*4. Intermediate*	5. Strongly important	*6. Intermediate*	7. Very Strongly important	*8. Intermediate*	9.Extremely important
1	Soil Thickness		Sediments										

Q3. *Which criteria with respect to* ***climate*** *is more important? State the level of its importance.*

					→Importance level→								
Sl No	**Which criteria is important?**				1. Equally important	*2. Intermediate*	3.Moderately important	*4. Intermediate*	5. Strongly important	*6. Intermediate*	7. Very Strongly important	*8. Intermediate*	9.Extremely important
1	Temperature		Rainfall										

Q4. *Which criteria with respect to **accessibility** is more important? State the level of its importance.*

Sl No	Which criteria is important?				1. Equally important	*2. Intermediate*	3.Moderately important	*4. Intermediate*	5. Strongly important	*6. Intermediate*	7. Very Strongly important	*8. Intermediate*	9.Extremely important
					→Importance level→								
1	Irrigation source		Roads										

Q5. *Which criteria with respect to **Agriculture** is more important? State the level of its importance.*

Sl No	Which criteria is important?				1. Equally important	*2. Intermediate*	3.Moderately important	*4. Intermediate*	5. Strongly important	*6. Intermediate*	7. Very Strongly important	*8. Intermediate*	9.Extremely important
					→Importance level→								
1	Topography		Soil										
2	Topography		Climate										
3	Topography		Accessibility										
4	Soil		Climate										
5	Soil		Accessibility										
6	Climate		Accessibility										

APPENDIX II

The following Tables show fuzzy pairwise comparison matrixes and geometric mean constructed from expert's questionnaires using FAHP method.

Residential (RC) sub-criteria

Table 4.1 Fuzzy pairwise comparison matrix of topography (RC-1)

Criteria	RC1-a	RC1-b	Geometric mean
RC1-a	(1,1,1)	(1,2,3)	(1, 1.414, 1.732)
RC1-b	(0.333,0.5,1)	(1,1,1)	(0.577, 0.707, 1)

Table 4.2 Fuzzy pairwise comparison matrix of proximity to economic infrastructure (RC-2)

Criteria	RC2-a	RC2-b	RC2-c	RC2-d	Geometric mean
RC2-a	(1,1,1)	(1,1,1)	(0.333, 0.5, 1)	(2,3,4)	(0.904, 1.107, 1.414)
RC2-b	(1,1,1)	(1,1,1)	(0.333, 0.5, 1)	(1,2,3)	(0.76, 1, 1.316)
RC2-c	(1,2,3)	(1,2,3)	(1,1,1)	(1,2,3)	(1, 1.682, 2.28)
RC2-d	(0.25,0.333,0.5)	(0.333,0.5,1)	(0.333, 0.5, 1)	(1,1,1)	(0.408, 0.537, 0.841)

Table 4.3 Fuzzy pairwise comparison matrix of proximity to social service centres (RC-3)

Criteria	RC3-a	RC3-b	RC3-c	RC3-d	RC3-e	Geometric mean
RC3-a	(1,1,1)	(1,1,1)	(0.333, 0.5, 1)	(1,2,3)	(1,2,3)	(0.803, 1.149, 1.552)
RC3-b	(1,1,1)	(1,1,1)	(1,2,3)	(1,2,3)	(1,2,3)	(1, 1.516, 1.933)
RC3-c	(1,2,3)	(0.333, 0.5, 1)	(1,1,1)	(1,2,3)	(1,1,1)	(0.803, 1.149, 1.552)
RC3-d	(0.333, 0.5, 1)	(0.333, 0.5, 1)	(0.333, 0.5, 1)	(1,1,1)	(1,1,1)	(0.517, 0.66, 1)
RC3-e	(0.333, 0.5, 1)	(0.333, 0.5, 1)	(1,1,1)	(1,1,1)	(1,1,1)	(0.644, 0.758, 1)

Residential (RC) main criteria

Table 4.4 Fuzzy pairwise comparison matrix of Residential

Criteria	RC-1	RC-2	RC-3	Geometric mean
RC-1	(1,1,1)	(1,2,3)	(1,1,1)	(1,1.26,1.442)
RC-2	(0.333,0.5,1)	(1,1,1)	(1,1,1)	(0.693,0.794,1)
RC-3	(1,1,1)	(1,1,1)	(1,1,1)	(1,1,1)

Agriculture (AC) sub-criteria

Table 4.5 Fuzzy pairwise comparison matrix of topography (AC-1)

Criteria	AC1-a	AC1-b	AC1-c	Geometric mean
AC1-a	(1,1,1)	(1,2,3)	(2,3,4)	(1.26,1.817,2.289)
AC1-b	(0.333,0.5,1)	(1,1,1)	(2,3,4)	(0.874,1.145,1.587)
AC1-c	(0.25,0.333,0.5)	(0.25,0.333,0.5)	(1,1,1)	(0.397,0.481,0.63)

Table 4.6 Fuzzy pairwise comparison matrix soil (AC-2)

Criteria	AC2-a	AC2-b	Geometric mean
AC2-a	(1,1,1)	(1,1,1)	(1,1,1)
AC2-b	(1,1,1)	(1,1,1)	(1,1,1)

Table 4.7 Fuzzy pairwise comparison matrix of climate (AC-3)

Criteria	AC3-b	AC3-a	Geometric mean
AC3-a	(1,1,1)	(0.333, 0.5, 1)	(0.577, 0.707, 1)
AC3-b	(1,2,3)	(1,1,1)	(1, 1.414, 1.732)

Table 4.8 Fuzzy pairwise comparison matrix of accessibility (AC-4)

Criteria	AC4-b	AC4-a	Geometric mean
AC4-a	(1,1,1)	(0.333, 0.5, 1)	(0.577, 0.707, 1)
AC4-b	(1,2,3)	(1,1,1)	(1, 1.414, 1.732)

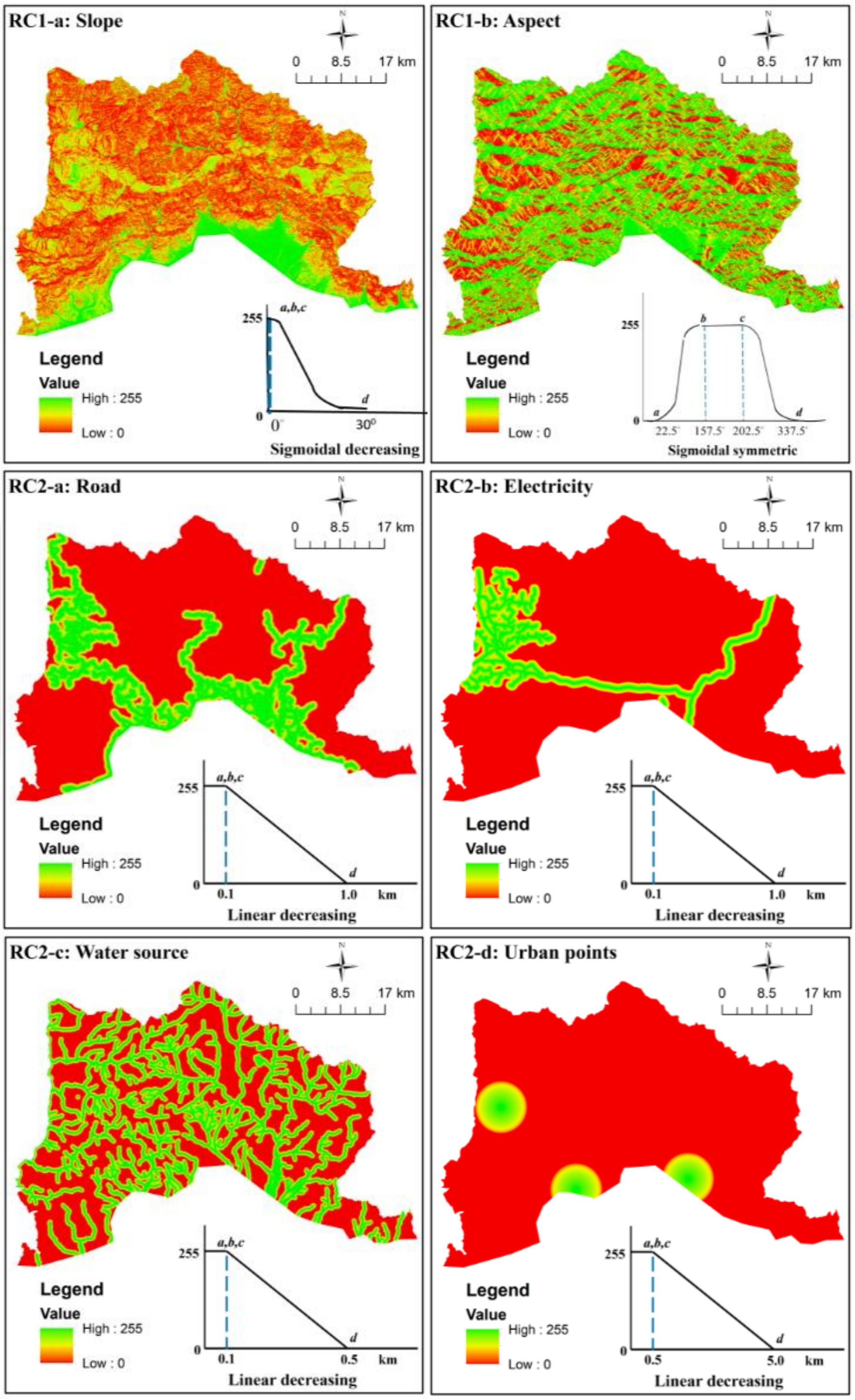
Agriculture main criteria

Table 4.9 Fuzzy pairwise comparison matrix of Agriculture

Criteria	AC-1	AC-2	AC-3	AC-4	Geometric mean
AC-1	(1,1,1)	(1,1,1)	(1,2,3)	(1,2,3)	(1, 1.414, 1.732)
AC-2	(1,1,1)	(1,1,1)	(1,1,1)	(2,3,4)	(1.189, 1.316, 1.414)
AC-3	(0.333, 0.5, 1)	(1,1,1)	(1,1,1)	(2,3,4)	(0.904, 1.107, 1.414)
AC-4	(0.333, 0.5, 1)	(0.25, 0.333, 0.5)	(0.25, 0.333, 0.5)	(1,1,1)	(0.38, 0.485, 0.707)

APPENDIX III

Residential: Sub-criterion maps



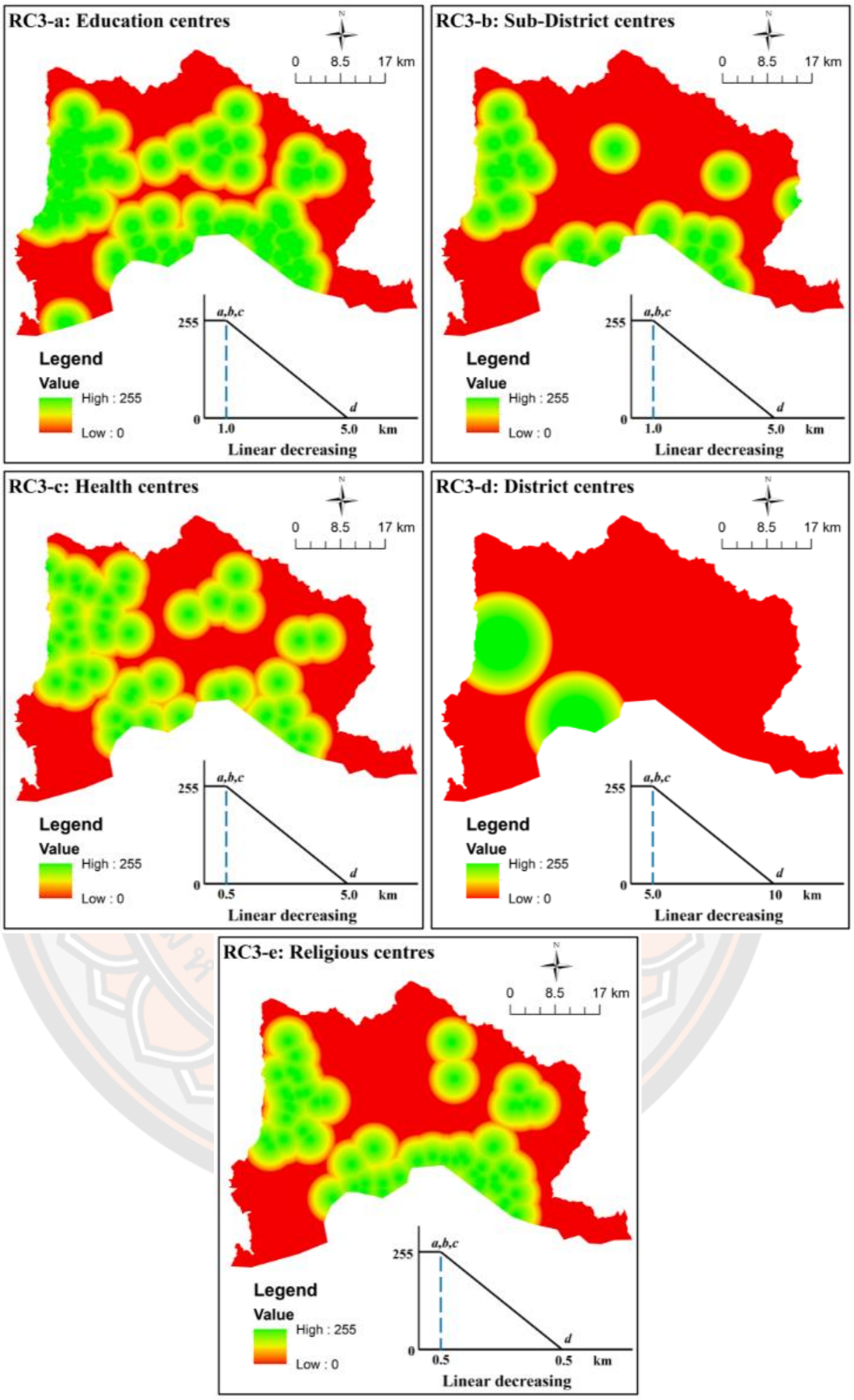
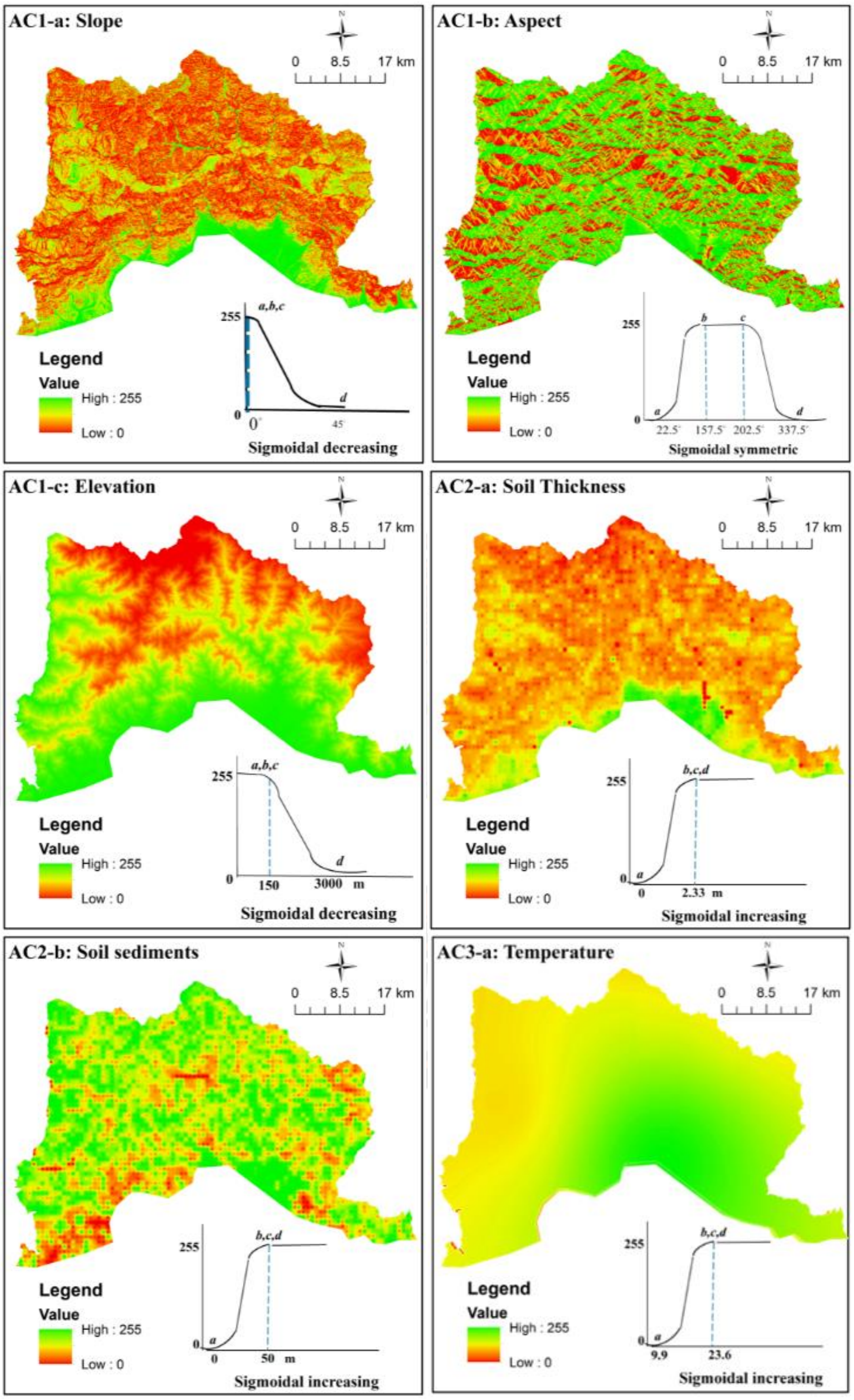


Figure 4.3 Sub-criterion or attribute maps for Residential

Agriculture: Sub-criterion maps



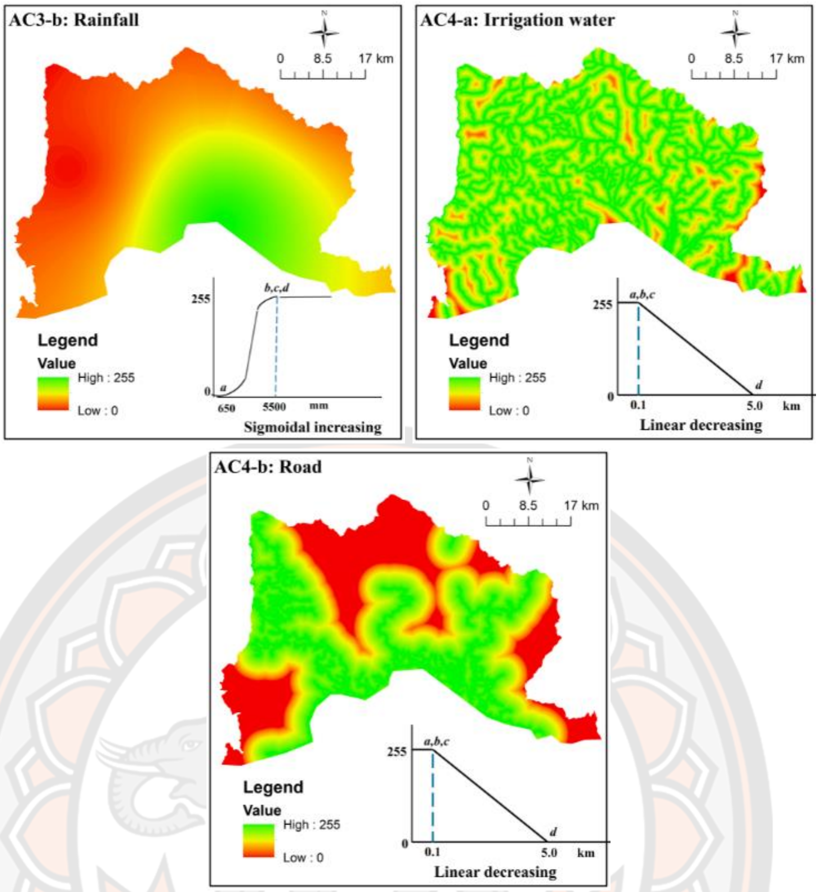


Figure 4.4: Sub-criterion or attribute maps for Agriculture

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