The Application of Land Evaluation Techniques in Jeffara Plain in Libya using Fuzzy Methods

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by

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ABSTRACT

This research compares three approaches to land suitability evaluation, Boolean, Fuzzy AHP and Ideal Point, for barley, wheat and maize crops in the north-western region of Jeffara Plain in Libya. A number of soil and landscape criteria were identified to accommodate the three cash crops under irrigation conditions and their weights specified as a result of discussions with local experts. The findings emphasised that soil factors represented the most sensitive criteria affecting all the crops considered. In contrast, erosion and slope were found to be less important in the study area.

Using Boolean logic the results indicated only four suitability classes (highly suitable, moderately suitable, marginally suitable and currently not suitable) for all crops. In contrast, the results obtained by adopting the Fuzzy AHP and Ideal Point approaches revealed that the area of study has a greater degree of subdivision in land suitability classes. Overall, the results of the three approaches indicated that the area under consideration has a good potential to produce barley, wheat and maize under irrigation provided that the water and drainage requirements are met.

Comparing the three models showed that each suitability class derived from the Boolean approach is associated with low and high values for joint membership functions when derived from Fuzzy AHP and Ideal Point approaches respectively. In other words, the two fuzzy approaches have shown their ability to explore the uncertainties associated with describing the land properties. The richer overall picture provides an alternative type of land suitability evaluation to Boolean approaches and allows subtle variations in land suitability to be explored. The Fuzzy

AHP approach was found to be better than the Ideal Point approach; the latter was biased towards positive and negative ideal values. In the future, field trial plots will be needed to evaluate and validate the results further.

Keywords: Land suitability evaluation, Boolean, Fuzzy AHP, Ideal Point, irrigation, north-western region of Jeffara Plain in Libya.

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LIST OF ABBREVIATIONS

MAAFF: Ministry of Agriculture, Fisheries and Food

USDA: United States Development Agency

USBR: United States Bureau of Reclamation

NLP: Land Care Programme

LCA: Land Capability for Agriculture

FAO: Food Agricultural Organization

LUTs: Land Utilizations Types

LQs: Land Qualities

LCs: Land Characteristics

ALES: Automated Land Evaluation System

Micro LEIS: Microcomputer Land Evaluation Information System

LECS: Land Evaluation Computer System

ISLE: Intelligent System for Land Evaluation

LEIGIS: Land Evaluation Implementation Geographic Information System

LUCIE: Land Use Capability Investigation and Evaluation

FAO AEZ: FAO Agro-Ecological Zoning

ARC: Agricultural Research Center

GMPR: Great Man-Made River

GIS: Geographic Information System

DEM: Digital Elevation Model

MCDM: Multicriteria Decision Making

MADM: Multiattribute Decision Method

MODA: Multiobjective Decision Analysis

AHP: Analytical Hierarchy Process

PCs: Matrix Pairwise comparison

CR: Consistency Ratio

WLC: Weighted Liner Combination

Fuzzy AHP: Fuzzy Analytical Hierarchy Process

OWA: Ordered Weighted Averaging

TOPSIS: Technique for Ordered Performance by Similarity to Ideal Solution

CROSSTAB: Cross Tabulation

MFs: Membership functions

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LIST OF PUBLICATIONS

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- Elaalem, M., Comber, A., and Fisher, P. (2010). 'Land Evaluation Techniques Comparing Fuzzy AHP with Ideal Point methods'. Paper 60 in Proceedings of the GIS Research UK (GISRUK) 18th Annual Conference, 14-16 April 2010, University College London.
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CHAPTER 1

INTRODUCTION

1.1 Problem Description

Land resources are gradually becoming scarce as increases in population put pressure on natural resources. Population increases and urbanisation have resulted in increased pressure on agricultural resources (Orhan et al., 2003). The challenge in the next decades is to ensure that global and regional food security increases food production for the survival of the growing population. However, this puts increased pressure on land resources, which may result in land degradation, particularly in countries with restricted water and other natural resources. Therefore, increases in food production are urgently required to tackle poverty and land degradation problems in developing countries (Fredrick and Julie, 1997). As a result, food security is one of the top agricultural policies in developing countries, and arable land in these countries needs to be evaluated for current and future agricultural uses.

Libya is one of these developing countries that are searching for alternatives in order to increase food production. This is due to the rapidly increasing population, particularly in the Jeffara Plain region. This region is under considerable land use pressures from increased industrial and residential developments. The Jeffara Plain region has significant resources, such as soil, water, vegetation, climate and human resources (Ben Mahmoud et al., 2000; Selkhozpromexport, 1980). Within this region, there is a current danger of underestimating the importance of having land use policies to sustain agricultural productivity, and as a result, this region requires special attention.

The Libyan government is concerned to be self-sufficient in the main cash crops which provide most of the diet of the majority of the country's population. For this reason, a project called the Great Man-Made River (GMPR) was designed in 1984 to pipe water from the south of the country to the north of the country. The main purpose of this water is to invest in the arable lands and in particular the Jeffara Plain region to produce a number of agricultural crops such as barley, wheat and maize (GMPR, 1990; 2008). The GMPR project (which is responsible for agricultural development in Libya) is interested in using the traditional land evaluation approach (i.e. the Boolean approach with the FAO framework for land suitability evaluation) which developed within a study that was conducted in the north-east of Libya by Nwer (2005) in the Jeffara Plain region. It has stated that the use of the Boolean method with the FAO framework has provided the Libyan planners with information to identify scarce land in suitable areas, so as to design farming systems suitable to local environmental conditions (GMPR, 2008).

Traditional land evaluation has been criticized by many authors (e.g. Burrough et al., 1987; Burrough, 1989; Hall et al., 1992; Davidson et al., 1994; McBratney and Odeh 1997; Baja et al., 2001; G. Delgado et al., 2008), because of its Boolean representations, which ignore the continuous nature of soil and landscape variation, and uncertainties in measurement, each of which can result in areas that just fail to match strictly defined requirements being identified in the set of 'suitable'. The implicit assumption in Boolean approaches is the absence of any uncertainty or vagueness associated with the suitability model, measurement, vagueness in the concepts that are specified. In reality these assumptions may be invalid. Fuzzy set methodologies have been proposed as a method for overcoming problems related to vagueness in definition and other uncertainties. The use of fuzzy set methodologies in land suitability evaluation allows imprecise representations of vague, incomplete and uncertain information. Fuzzy set methodologies have the potential to provide better land evaluations compared to Boolean approaches because they are able to accommodate attributed values and properties which are close to category boundaries. Fuzzy land evaluations define continuous suitability classes rather than ‘true’ or ‘false’ categories as in the Boolean model (Keshavarzi, 2010).

A range of fuzzy Multi-Criteria Decision Analysis (MCDA) approaches have been developed. These include Fuzzy Analytical Hierarchy Process (Fuzzy AHP), introduced by Xiang et al. (1992), and TOPSIS (Technique for Order Preference by Similarity to Ideal Solutions), proposed by Hwang and Yoon 1981 (Malczewski, 1999). The Fuzzy AHP and TOPSIS methods have the ability to address and explore the uncertainties associated with land resources, especially if they are integrated with fuzzy set models. According to Prakash (2003) and Chaddad et al. (2007), the use of the Fuzzy AHP and TOPSIS approaches is successful in land suitability evaluation, because they are able to handle uncertainty in land suitability evaluations. The use of the fuzzy MCDA methods is still new to land suitability evaluations. This research considers the use of Fuzzy AHP and Ideal Point approaches as methods that suit Libyan conditions. These techniques are used to develop land evaluation and suitability models that will identify areas for selected cash crops to be grown successfully.

1.2 Research Objectives and Questions

1.2.1 General Objective

The main aim of this research is **"**to explore the added benefits of modelling land suitability evaluations using Fuzzy Analytical Hierarchy Process and Ideal Point approaches compared to using traditional Boolean ones in the context of the need for increased food production in the north-western region of Jeffara Plain in Libya**"**.

1.2.2 Specific Objectives

The specific objectives to be achieved in this study are:

1. To identify from local knowledge the land factors that define land utilization types, land qualities and land characteristics that affect agricultural land suitability analysis in the study area.

2. To determine the importance of each factor from local experts in order to assign differential weights to factors for different agricultural crops.

3. To explore how fuzzy representations using Fuzzy Analytical Hierarchy Process (Fuzzy AHP) and Ideal Point can extend existing Boolean land evaluation techniques.

4. To generate different land suitability models for a number of cash crops using Boolean, Fuzzy AHP and Ideal Point methods.

5. To compare and assess the results derived from Fuzzy AHP and Ideal Point methods with those from the Boolean model.

1.2.3 Research Questions

For this study six main research questions are considered:

1. Which land evaluation methods are suitable for generating land suitability mapping sensitive to Libyan environmental conditions?
2. Which evaluation criteria should be taken into account for designing land suitability models for agricultural crops under irrigation conditions in the study area?
3. How can Fuzzy AHP and Ideal Point methods develop the process compared to Boolean methods?
4. How can local experts and land evaluators develop land suitability models in the study area?
5. Do the results obtained with the FAO framework and the Fuzzy AHP and Ideal Point methods correspond to the model outputs created from the FAO framework and the Boolean land evaluation method in the study area? Which results are more realistic?

1.2.4 Thesis Structure

This thesis is arranged in ten chapters.

1. Chapter 1 deals with the research problem, research objectives and research questions.
2. Chapter 2 shows the research context and selected study area for applying the methodology thus developed.
3. Chapter 3 provides a critical overview of land evaluation methods.
4. Chapter 4 reviews the Multicriteria Decision Analysis methods.
5. Chapter 5 presents the Boolean, Fuzzy AHP, and Ideal Point methods and their applications in land suitability analysis and land evaluation studies.
6. Chapter 6 introduces the selected methods employed in the research.
7. Chapter 7 presents the methodologies developed and applied in this research.
8. Chapter 8 presents and compares the results derived from the different land suitability models according to the methodology presented in Chapter 7.
9. Chapter 9 discusses the results presented in Chapter 8.
10. Chapter 10 provides the general conclusions and recommendations from the analysis done in Chapters 7 and 8 in relation to the research questions.

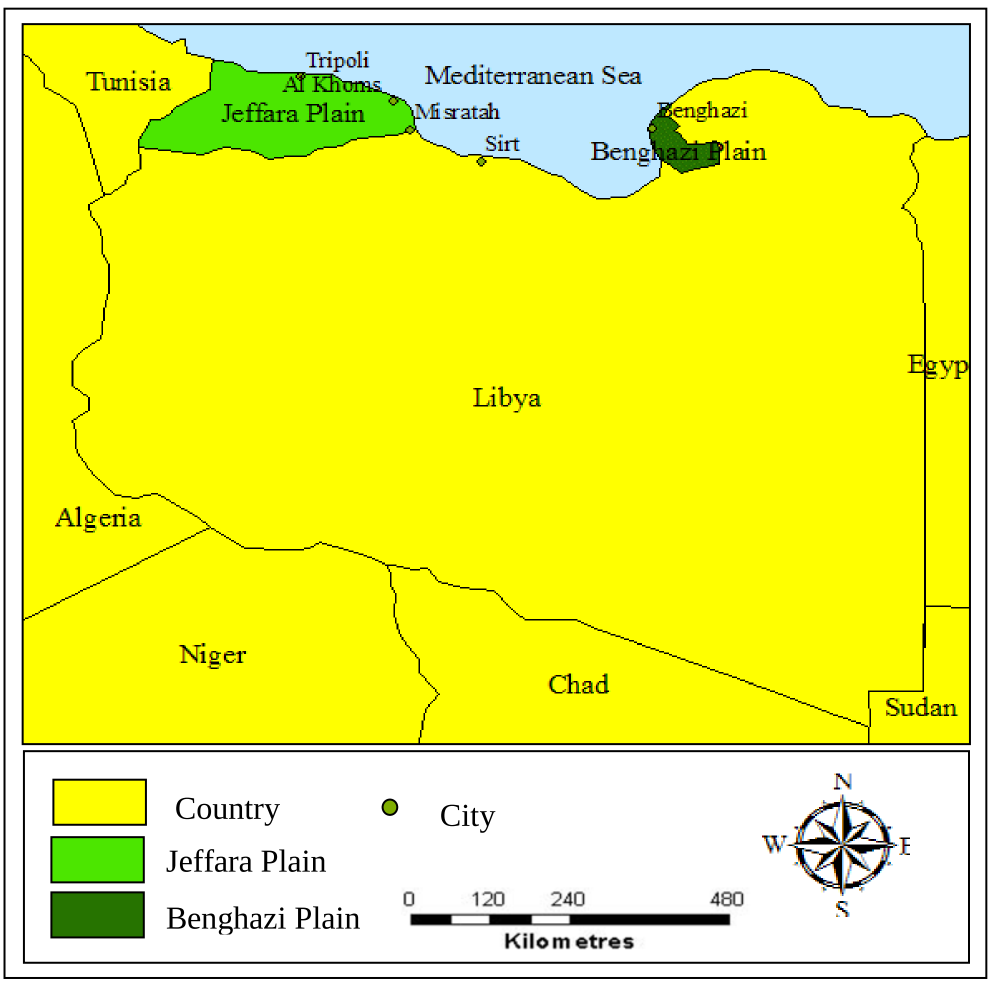
CHAPTER 2

RESEARCH CONTEXT

2.1 Introduction

Libya is sited in the north of Africa, from 20 to 34° N and 10 to 25° E. It occupies 176 million hectares. It is bordered in the east by Egypt and in the west by Tunisia, Algeria and Niger; by Chad and Sudan in the south and by the Mediterranean Sea in the north. It has an important physical asset in its strategic site at the centre of Africa's northern rim (figure 2.1).

Figure 2.1: Map of Libya.



The fertile lands are located in the north of Libya in two main regions: Benghazi and the Jeffara Plain. These regions are economically the most important lands.

2.2 Description of Land Forms

In Libya, two main land systems were identified, based essentially on geographic location and geomorphological patterns: the barren plains are in the north part and the plateaus are in the south part of the country. The Mediterranean coastal lands stretch from west to east, from the Tunisian border to the Egyptian border, over about 2000 km, ranging between 15 and 100 km in width (Ben Mahmoud et al., 2000); these lands in the north and the Sahara desert in the south are the most dominant natural features.

The main parts of the northern region are the low-lying areas. In the northern region of Libya, the coastal plain consists of coastal lowlands (Jeffara Plain, Sirt Plain and Benghazi Plain) in addition to lagoons, salt marshes, swamps and coastal sand dunes. The coastal lowlands are separated from each other by pre-desert zones and backed by plateaus with steep north-facing scarps.

The topography of the Jeffara Plain region is almost flat and is categorized into three main parts: the coastal strip (in the north), the central parts, and the foot of Jabal Naffusah (mountain) in the south. This region is covered by quaternary deposits with occasional outcrops of limestone hills belonging to the Aziziyah formation.

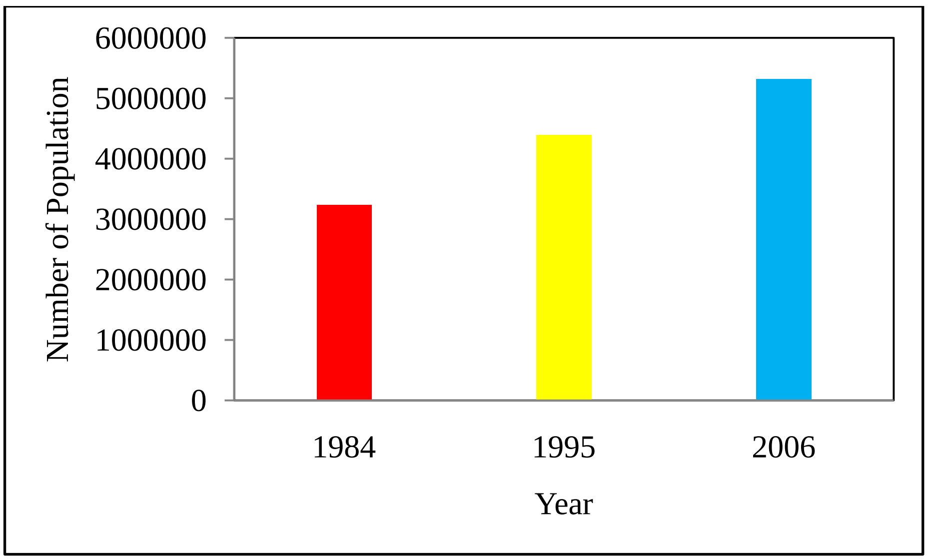
The central locations of this region are mainly covered by poorly consolidated Aeolian deposits mixed with brownish silts, while some southern locations in Jeffara

Plain are covered by coarser fluvial sediments. Landforms in the Jeffara Plain region are subjected to wind erosion, due to restricted vegetation cover and human activity.

2.3 Population

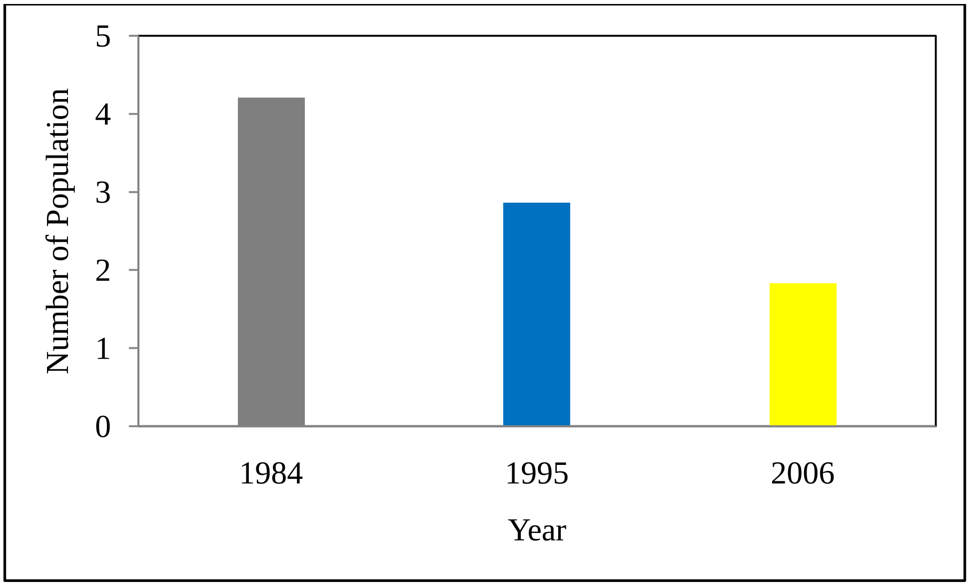
Libya’s total population was 3.23 million in 1984 and 4.38 million in 1995, and increased to about 5.5 million in 2006 (figure 2.2 and 2.3).

Figure 2.2: The Number of Libyan Population in the Censuses ‘1984, 1995 and 2006’.



Source: *Libyan Statistics Book 2007*

Figure 2.3: Total population, 1984, 1995 & 2006 censuses.



Source: *Libyan Statistics Book 2007*

Libyan people inhabit two regions: the Jeffara Plain, where about 58 per cent of Libyan citizens live, and the Benghazi Plain. The main reasons for this concentration are significant resources such as soil, water, vegetation and climate. According to the General Authority for Information elementary census of 2006, the population of Libya will be more than 10 million in 2025. Approximately 90 per cent of the Libyan people will be living in the urban areas and 10 per cent of them will be residing in the rural areas. As a result, increased supplies of food are needed to match this growth. Population growth plus the absence of control and planning policies has resulted in some serious problems in Libya. One of these problems is the increase competition between urban and agricultural lands (Libyan Statistics Book 2007).

2.4 Water Resources

Libya is an arid country, with an average yearly rainfall of less than 100 mm over 91 per cent of its land surface (Al-Ghariani, 1996). Water resources are divided into surface water, groundwater, and desalinated and treated water

2.4.1 Surface Water

The surface water resources are very limited, and contribute less than 3 per cent of the current water resources in use. The total mean annual runoff measured at the entrance of the wadis in the plains is estimated at 200 million m^3 per year, but part of it either evaporates or contributes to the recharge of the aquifers (Al-Ghariani, 1996). Therefore, the surface water resources are roughly estimated at only 100 million m^3 per year.

2.4.2 Desalinated and Treated Water

A number of desalination plants have been established near large municipal centers and industrial complexes. The total quantity of desalinated water was approximately 160 million m^3 in 2006. A number of sewage treatment water plants are already in operation; for instance, El-Khadra plant was created in 1971 in the south of Tripoli city. The treated water was estimated at 91 million m^3 in 1990 and then increased to 250 million m^3 in 2006 (ARC, 2000).

2.4.3 Ground Water

The groundwater accounts for more than 97 per cent of the water resources in use. Starting from the early sixties, groundwater extraction rates accelerated rapidly to meet the growing water demand in the coastal zone where most of the population is concentrated. Currently, aquifers are recharged only in this zone (namely in Jeffara

Plain, Jabel Nefusa and Jabel Akhdar). Renewable groundwater resources are estimated at 800 to 1000 million m^3 per year. Since not all the renewable groundwater can be abstracted without affecting the environment, the safe yield was estimated in this zone at only 500 million m^3 per year. Over-extraction of groundwater in the coastal zone (particularly in the eastern Jeffara plain) is leading to a continuing decline in the groundwater level, and to seawater intrusion which is estimated to be advancing at a rate of 100 to 250 m per year. If this over-extraction is not stopped or reversed, it is expected that these intrusions will lead to the contamination of all productive aquifers in the near future. Conversely, most of the groundwater potential is located to the south in the desert area (Al-Ghariani, 1996). Through the Great Man-Made River Project, about 2 cubic kilometers per year of fossil water is transported from the main reservoirs of underground water to the coastal zone, mainly for irrigation and partly for water supply to the major cities. More detail regarding the Great Man-Made River project is discussed in the next section.

2.5 The Great Man-Made River Project

At the beginning of the sixties, when oil drilling penetrated south inside the Libyan Desert, a tremendous store of fresh underground water was discovered. The most important rock strata carrying water were formed in the geological era when the Mediterranean Sea waters used to flow south till they reached the Tibisti Mountains. In addition, the sea water level changed occasionally, and this led to the formation of sedimentary rocks of different kinds. These geological activities resulted in the emergence of Nafusah Mountain and Jebal Akhdar and the formation of the underground aquifers. These aquifers are porous sedimentary rocks in which water accumulates and which are surrounded by non-porous rocks. About 14,000 to 38,000 years ago, the climate of North Africa was mild.

Libya used to have high precipitation; therefore, rainwater leaked inside the porous rocky strata and was stored there, forming fresh underground water. There are five main reservoirs of underground water. These are Al-Kufrah, Sirt, Murzuq, Al-Hamadah and Jeffara Plain. These huge stores of underground water provide the coastal areas with great quantities of water (GMPR, 2008).

2.5.1 The Importance of the Great Man-Made River project

As is shown from the water balance in Libya (Tables 2.1 and 2.2), there is a huge surplus of underground fresh water in the south of Libya which still awaits utilization. This surplus amounts to about 90 per cent of the underground storage of Al-Kufrah reservoir, and 84 per cent of the surplus of Sarir reservoir can be used in compensating for the severe shortage of water in the coastal cities. More alternative methods were studied and discussed for dealing with underground water in Libya. However, this was prevented by the poor soil in the southern desert areas and the difficulty of transferring the agricultural products to consumption areas, especially vegetables and fruits which spoil in a short time, in addition to the lack of sufficient manpower to cultivate the desert land.

Table 2.1: Population increases and the consequent needs for water for different applications, based on present growth rates (million m^3 per year)

Year	2000	2005	2010	2015	2020	2025
Population (million capita)	5.7	6.7	7.8	9	10.3	11.7
Agricultural needs	4800	5060	5325	5590	5850	6640
Human needs	647	830	1015	1260	1512	1759
Industrial needs	132	185	236	330	422	566
Total needs	5579	6075	6576	7180	7784	8965

Source: (Al-Ghariani, 1996)

Table 2.2: The expected water balance in Libya (million m^3 per year)

Year	2000	2005	2010	2015	2020	2025
Underground water	3430	3430	3430	3430	3430	3430
Surface water	120	120	120	120	120	120
Desalinated water	130	135	140	145	150	160
Treated water	220	250	300	400	450	520
Total available	3900	3935	3990	4095	4150	4230
Total needs	5579	6075	6576	7180	7784	8965
Shortage	1679	2140	2586	3085	3634	4735

Source: (Al-Ghariani, 1996)

The alternative of transporting humans from sites in coastal areas with an increasing demand for water to places in the middle of the desert with underground reservoirs was suggested; however, the idea did not receive any response or approval from the inhabitants of coastal cities, who had lived in those cities for a long time. Moreover, it was not accepted because many oil industries, which the Libyan economy depends on, exist near northern coastal cities.

Many studies in Libya concluded that it was necessary to transfer underground water from the south to the coastal consumption areas in the north. This was supported by the economic feasibility studies which proved that the cost of extracting a cubic meter of underground water from the reservoirs and transporting it to the coastal cities through pipelines underground does not exceed 100 dirham (0.35$), compared to 1.271 dirham (3.75$), which is the cost of desalinization of a cubic meter of salt water, and 950 dirham (2.80$), which is the cost of transferring a cubic meter of water by marine carriers from neighboring countries to Libyan Arab Jamahiriya (GMPR,1990;2008).

2.5.2 Objectives of the Great Man-Made River project

The project aspires through the agricultural investment programmers to achieve the following objectives:

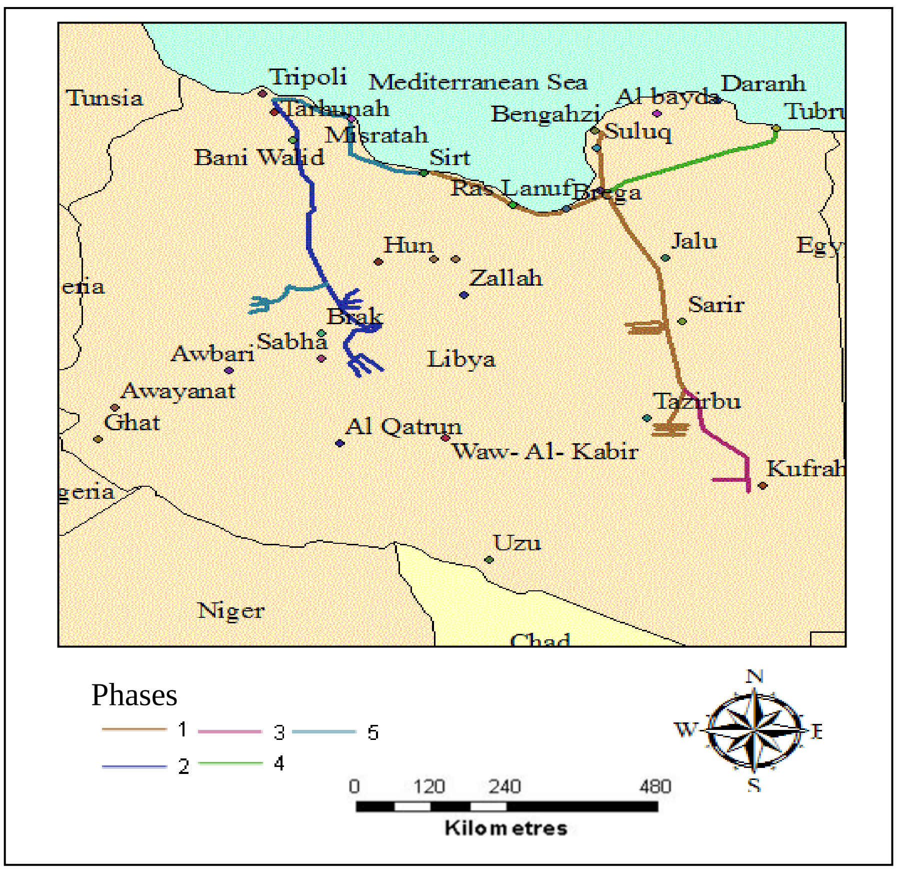
- **Objective 1**: achieving food security and increasing self-sufficiency in different strategic commodities
- **Objective 2:** increasing the contribution of the agricultural sector to the total local product, and expanding the production base, increasing income and providing an alternative source for oil in the national income.
- **Objective 3:** achieving social development in the targeted areas by investing through increasing income and providing work opportunities and stability.
- **Objective 4:** maintaining the environment and protecting natural resources in the investment areas by soil and vegetation cover

conservation programmes and by growing windbreaks and establishing check dams to prevent soil erosion.

2.5.3 Stages of the Great Man-Made River Project

The GMPR project is a civil engineering project and it is considered as a new conquest of the desert's secret areas in order to use its hidden resources of fresh water. This project was created in 1984 and is represented through extending an enormous system to transfer water from the desert to the fertile areas through huge buried pipes at a depth of approximately seven meters with an interior diameter of four meters (GMPR, 1990; 2008). This project has been divided into five phases, are shown in Figure 2.4.

Figure 2.4: The main phases of the Great Man-Made River Project.



2.5.4 Crop Pattern for Investment Projects

Targeted crops were selected either in small farms or in large farms, in order to make an adequate crop pattern that can achieve a good economic result from using the Great Man-Made River water, and can match the general food strategy of the Libyan Arab Jamahiriya on the basis of achieving a high rate of self-sufficiency in agricultural production, especially in grains and fodder. Furthermore, it puts into consideration simplifying the necessary agricultural activity, particularly in small farms. There was a focus in the proposed crop pattern on field crops to produce grain and necessary to provide fodder for sheep, besides guaranteeing a local market for them when there is a surplus.

A limited area inside every small farm was allocated to the production of fruit and vegetables to cover the needs of the family when these crops are locally marketed (GMPR, 1990). These crops have been selected for investment projects on the Jeffara Plain region for the following technical reasons:

- **Barley** is an essential crop in small farms because it is the traditional winter grain for all farmers, and it is the most easily acclimatized of all crops.
- **Wheat** is a strategic crop targeted in the general plan of the Libyan Arab Jamahiriya to achieve food security through achieving self-sufficiency in it. Therefore, it is the principal grain among these crops.
- **Alfalfa** is a highly productive fodder crop and it reliably gives a high quantity of protein and energy to livestock throughout the whole year. In addition to this, it has great economic value in the local market, where it makes a good income for the farmer when he sells the surplus.

- **Maize and Oat Mixture:** These are considered as seasonal fodder when the growth of alfalfa is slow; the chick ling vetch and oat mixture plays that role in winter, while sorghum and maize play that role in summer. Oat mixture and sorghum may not be familiar to a farmer, but they do not differ from other fodder crops in the way they are cultivated they are cut while they are green before they become.
- **Fruit trees and Vegetables:** Crops of small farms include limited areas specified for producing vegetables and fruits that are most suitable to irrigated agriculture under the local environmental conditions, such as tomatoes, beans, marrows, okra, grapes, figs, pomegranates and olives.

2.6 Climate

The Libyan climate is situated in the Mediterranean climatic zone, in the belt of the subtropical alternate atmospheric circulation. The climate in Libya is characterized as following: cold weather is scarce; summers are hot, with two to three dry months, and cool rainy winters; rainfall comes with hurricanes and strong winds; low total amounts of rainfall in winter and high temperatures in summer are common (*Tripoli Metrological Report, 2005*). The main climate elements are discussed below:

- **Temperature**: The distribution of mean annual temperatures in Libya increases gradually from the north to the south of the country in winter and summer seasons. The highest temperatures in the coastal zone occur in August, while the lowest temperatures in the coastal zone occur in December and January. The mean annual temperature is low in the north, while it is high in the south of the country.

- **Rainfall**: Rainfall is the most important climatic element. The mean annual rainfall in Libya ranges from 0 mm in the south to more than 500 mm in the north. Most of the rainfall in Libya comes during the winter season, mainly from November to March, and there is a variation from year to year and from one place to another. The most important two regions, Jeffara Plain and Benghazi, receive an annual yearly rainfall of 100 to 500 mm whilst the rest of the country receives less than 50 mm.
- **Relative air humidity**: Relative air humidity is generally low in the south and high in the north. Mean annual relative air humidity drops from 65-75 per cent in the north to less than 35 per cent in the south. The relative air humidity differs in winter and summer seasons. In the north, summer values are higher than winter values, while in the south, winter values are mostly higher. It also varies during the day. In the early morning in the north it drops from 80-90 per cent to 40 per cent or less in January and to 20-30 per cent and less in July. In January and July alike, the air in the afternoon is very dry in the north, and humidity then may also fall to 5-30 per cent.

2.7 Soil Information

The main soil classification system used in Libya is the Soviet soil classification system. Soils in the north of the country were investigated using the Soviet soil pedology system. This study was conducted by the Soil-Ecological Expedition of v/o "Selkhozpromexport", the Agricultural Research Centre (ARC), Al Fateh University and the Ministry of Agriculture. The taxonomy of the Soviet soil pedology system was adopted for elaboration of the soil classification, and the soil nomenclature generally applied to characterize the soil mantle of the Mediterranean countries was also partially used. Classes and subclasses have been singled out on the basis of the classification structure for the tropics and sub-tropics given by Zonn (1974). The definitions of the Russian terminology system used in this chapter are summarized below:

- **Class**: A class unites soils of similar mineral part composition, the similarity being caused by the nature and direction of soil formation, as well as by peculiarities of origin and age of parent materials (weathering crusts).
- **Subclass:** A subclass unites soil types with similar combinations of the conditions of their formation connected with the development processes which are conditioned by the composition and properties of the soil-forming rock, as well as peculiarities of climatic regimes.
- **Type:** A type unites soils which develop under similar (typical) biological, climatic and hydrological conditions, and which have a similar soil profile structure and, generally, similar properties. Soils of a single type are characterized by common origin, migration, transformation and accumulation of substances. Their genesis is connected with a distinct manifestation of the soil formation processes, with possible combinations with other processes.

- **Subtype:** A subtype embraces soils within a type, varying in quality as far as the intensity of manifestation of the main and secondary elementary processes of soil formation is concerned. Subtypes represent stages of an evolutionary transition of one type into another. While reflecting the peculiarities of soil development, subtypes preserve a general typical structure of the profile, but, at the same time, possess some specific features of their own.
- **Genera:** A genus includes soil groups within a subtype. A genus reflects soil properties connected with the influence of local factors, manifestation of the features caused by a peculiar character of parent material influence, chemical composition of groundwater. The given classification distinguishes soils into genera according to their calcareousness, leachedness, solonetzicity, and salinity, as well as to the combination of these properties.

In addition, non-soil formations, represented by maritime and continental sands, rock outcrops and coarse-texture stony alluvial and proluvial deposits were also delineated on the soil maps. Most of the soils in Libya have transition between aridic and xeric moisture regimes and thermic and hyperthermic temperature regimes. The classification distinguished 2 soil classes, 4 soil subclasses, and 6 soil types, including 15 subtypes. Further on, the soils are subdivided into genera, series and categories (table 2.3).

Table 2.3: The scheme of soil division into classes, types, subtypes and genera in Jeffara Plain region.

Russian Classification			**USDA Classification**
Soil type	**Soil Subtype**	**Soil Genus**	**Soil Groups**
Siallitic cinnamon	Typical	Carbonate, carbonate saline, leached	Calcic Xerochrepts, Typic Xerochrepts
	Crust		
Reddish brown arid	Differentiated	Carbonate, carbonate saline, carbonate solonetzic saline and carbonate gypsic	Typic Cambrthids, Typic Calciorthids, Typic Gypsiorthids, Typic Torripsamments
	Differentiated crust	Carbonate and carbonate saline	
	Slightly differentiated	Carbonate, carbonate saline, carbonate solonetzic saline, carbonate gypsic and leached	
Reddish brown arid	Slightly differentiated crust	Carbonate, carbonate saline, carbonate gypsic and leached	Typic Cambrthids, Typic Calciorthids, Typic Gypsiorthids, Typic Torripsamments, Lithic Camborthids, Lithic Torriorthents
	Non-differentiated	Carbonate, carbonate saline, leached and non-carbonate	
	Non-differentiated crust	Carbonate, carbonate saline and leached	

Table 2.3 continued:

Russian Classification			**USDA Classification**
Soil Groups	**Soil Subtype**	**Soil Genus**	**Soil Groups**
Alluvial	Slightly differentiated	Carbonate	Typic Torrifluvents
Lithosols	Cinnamonic	Carbonate, carbonate saline and carbonate gypsic	Lithic Torriorthents , Lithic Torripsamments, Typic Torriorthents, Typic Torripsamments
	Reddish brown		
Crusts	Non-monolithic		
Solonchaks	Hydromorphic, hydromorphic crust and hydromorphic Sebkha		Aquic Salorthids, Typic Salorthids

Source: Selkhozpromexport, 1980; Ben Mahmoud, 1995

2.8 Soil Erosion

Most soils in Libya are subjected to erosion processes. A study conducted in 1980 showed that there are two types of soil erosion distinguished in Libya: water erosion and wind erosion. Wind erosion was found in the form of deflation within the Jeffara Plain, while water erosion is very common in the form of sheet washing and rill forms, occurring mainly within the Jebel Nefusa upland and the Benghazi region (Selkhozpromexport, 1980). Table 2.4 shows the classification of water and wind erosion in Libya.

Table 2.4: The classification of wind and water erosion in Libya.

Type of erosion	Category of erosion
Wind erosion (Deflation)	None
	Slight
	Moderate
	Severe
Water erosion (Sheet and Gully erosion)	None
	Slight
	Moderate
	Severe

Source: Selkhozpromexport, 1980

2.9 Description of Agricultural Conditions

In Libya, most arable lands are owned by the farmers, while the remaining arable lands are owned by the Great Man-Made River Project (GMPR) and the Agricultural Research Centre (ARC). In the arable lands owned by the government, two irrigation systems, overhead sprinkler and drip irrigation systems are employed, and fertilizers and pesticides are used. The labour is manual on most land owned by farmers, while the labour is mostly by machinery in lands owned by GMPR and ARC (GMPR, 2008). The main agricultural products in Libya are vegetables, cereals, fruits, meat, legumes and dairy products (Table 2.5).

Table 2.5: Total agricultural production in Libya in 2006.

Products	**Productions (1000 tones)**
Vegetables	420,000
Cereals	650,000
Fruits	350,000
Meat	16,000
Legumes	22,000
Dairy products	90,061

Source: *Libyan Statistics Book 2007*

All these crops are grown for domestic consumption. The usual market for most of these products is the local market, where these products are transferred from the farmers to the consumers (Libyan Statistics Book 2007).

2.10 Summary

Population growth has led to more need for food security in Libya, particularly in the northern regions where approximately 70 per cent of Libyan people live. Due to the low amount of rainfall and because groundwater resources are used in agricultural development, the Libyan government generated the GMPR project, a project designed in 1984 to bring water from southern aquifers to the northern regions. Most of this water is intended for agricultural development. The Jeffara Plain and Benghazi regions of northern Libya were both selected by the Libyan government for agricultural development. These locations are planned to accommodate a number of cash crops such as barley, wheat, maize and sorghum. In these regions, some agricultural projects have been designed to produce some irrigated cereal crops. Consequently, evaluation of the suitability of lands for these crops is a very important and necessary task for land use planning and management and agricultural development in the north region of Libya.

The analytical methods for land evaluation in the Benghazi region were developed by taking Libyan agricultural policy into consideration (Nwer, 2005), but this has not yet been done in the Jeffara Plain region. The aim of this research is to develop the analytical methods for a land evaluation system for a number of cash crops using different GIS models. The north-western region of Jeffara Plain in Libya has been selected as a case study for this research.

This research develops novel analytical methods for a land evaluation system for a number of cash crops using fuzzy GIS models. These methods have the potential to provide more spatially nuanced models of suitability as they will include some areas in the set of ‘suitable’ that are excluded by traditional Boolean methods. Such models have the potential to support land planning decisions better by providing richer information about the extent of land suitable for different crops that explicitly includes some of the uncertainty associated with suitability models.

CHAPTER 3

A CRITICAL OVERVIEW OF LAND EVALUATION METHODS

3.1 Land Resources

Sustainability is a process in which the exploitation of resources, the direction of investment, the orientation of technological development and institutional change are made consistent with future, as well as present, needs (World Commission on Environment and Development, 1987). Moreover, sustainable land management has been defined as "a system of technologies and/or planning that aims to integrate ecological with socio-economic and political principles in the management of the land for agricultural and other purposes to achieve inter-generational equity" (Dumanski, 1994). The integrated approach to planning the use and management of land resources is to make optimal and informed choices on the future uses of the land. This will be done on the basis of efficient, comprehensive data gathering and processing in an appropriate storage and retrieval system, through a network of nodal institutions (FAO, 1995). For this purpose, there is a great need for a holistic approach, especially for environmental applications, by using modern technology, such as the Geographic Information System and computerised models for land evaluation, to handle and manipulate the data.

3.2 Land Evaluation Definition

Land evaluation is defined by Stewart (1968) as "the evaluation of land suitability for man's use in agriculture, forestry, engineering, hydrology, and regional planning". According to the FAO (1976), land evaluation is defined as "a part of the process of land use planning". Some authors, however, have differentiated land suitability from land capability. According to Florence (2002: 39), "Land capability refers to general land use that takes the limiting factors into account, such as soil salinity and slope, while the term 'land suitability' refers to specific agricultural use."

To Dent and Young (1981: 385, 386) land evaluation can be applied to different purposes: land assessment as a single-purpose classification; land evaluation as multiple-purpose classification; land evaluation as a general-purpose classification; current land suitability classification; qualitative land evaluation system; quantitative land evaluation system and economic land evaluation.

3.3 Land Evaluation Methodologies

Different methodologies have been developed for land suitability evaluation. Several of these methods were developed before the FAO Framework for Land Evaluation (1976), such as Land Capability - the American method **(**USDA) (Klingebiel and Montgomery, 1966), and the USBR Land Suitability for Irrigation (U.S. Department of the Interior, 1951). The differences among land evaluation systems are given by the particular use to be considered, the factors regarded as relevant for that use, and the scale of analysis. The next sections focus on reviewing the most widely applied land evaluation methodologies.

3.3.1 Land Capability- the American method (USDA)

The USDA approach is a qualitative land classification system developed and adopted in 1949 mainly for farm planning, soil erosion control and conservation (Klingebiel and Montgomery, 1961). The USDA land capability classification was evaluated by taking land properties and the limiting factors for each land unit into consideration. The USDA land capability classification is considered a negative technique, because it depends on the limiting factor rather than positive potential (Davidson, 1992). The method uses a single scale to categorize land based on a scale of productivity from the 'best' to the 'worst'. This scale includes classes I, II, III and IV as suitable for cultivation; classes V and VI are suitable for grazing, class VII is suitable for forestry and class VIII is suitable for wildlife and recreation. This method considers the extent and quality of good arable land and areas with erosion, drainage and salinity problems. Morgan (1995) argued that the USDA land capability system needs to adopt specific biophysical and cultural properties when used outside the United States. Davidson (1992) concluded that the USDA land capability classes have shown an obvious lack of quantitative criteria and do not take crop requirements into consideration. Davidson mentioned that "Phrases such as gentle slopes, moderate susceptibility to wind or water erosion or less than ideal slope clearly lack precision of definition, thus making them liable to diversity of interpretation". To Dent and Young (1981) the main weakness of this method was the failure to classify the land sufficiently for alternative uses other than arable. The classification has not distinguished between the soils for general arable use and those suitable for specific kinds of land use.

3.3.2 Land Capability - the British System

This system classifies the land according to the whole relationship between crop yield and land management, soil parameters, topography and climatic data. In the British method, climatic restriction was given more consideration then other factors. Soil surveys of Scotland, England and Wales applied the USDA land capability classification after some modification (Bibby and Mackney, 1969). The eight land capability classes in the American method were reduced to seven land capability classes in the British land capability classification. Classes 1 and 2 are suitable for agricultural use. Classes 3 and 4 are suitable for agriculture and pasture. Class 5 is suitable for pasture and forestry. Class 6 is suitable for recreation and forestry, and class 7 is not suitable for any agricultural production. As Davidson (1992) reported, the British method has many disadvantages. For example, it is unable to match all land characteristics used for assessing sites to specific land capability classes. Also, all upland and hill areas were covered by the two lowest classes, class 4 and 5. For that reason, this system was modified and revised by the Ministry of Agriculture, Fisheries and Food (MAAFF) and the Welsh Office of Agricultural Department in 1988.

The Land Capability for Agriculture (LCA) system is very similar to the USDA land capability classification. The seven land capability classes in Scotland (1988) are: Class 1: lands are able to produce a very wide range of agricultural crops. Class 2: lands are able to produce a wide range of agricultural crops. Class 3: lands are able to produce a moderate range of agricultural crops. Class 4: lands are capable of producing a narrow range of agricultural crops. Class 5: lands are suitable for grassland. Class 6: lands are more suitable for grazing. Class 7: lands are less suitable for agricultural production. The main limiting factors that have been used in developing the LCA are climate, site, soil wetness and droughtiness. Classes 5, 6 and 7 in the old system correspond to class 5 in Land Capability for Agriculture.

3.3.3 The United States Bureau of Reclamation (USBR) Land Suitability for Irrigation

The USBR classifies the lands according to their suitability for irrigation. The suitability criterion is the payment capacity of the land and the financial circumstances of the farmer as a measure of overall productivity. It divides the land into six land suitability classes (USBR, 1951):

- Class 1: arable land which is highly suitable for irrigated agriculture
- Class 2: arable land which is moderately suitable for farming
- Class 3: arable land which is marginally suitable for irrigated agriculture
- Class 4: special land use: is only for specific uses, e.g. fruit or rice
- Class 5: non-arable land: land is assessed as unsuitable for arable farming on the basis of particular problems, e.g. salinity or flooding
- Class 6: non-arable land: land is unsuitable for any irrigation development as a result of steep slopes, inadequate drainage etc.

These classes were divided into subclasses. These subclasses were indicated by letters to show the particular restrictions. The FAO framework (1985) is the closest approach to the USBR classification of land suitability for irrigation. The disadvantage of using this system is that it does not take suitability of crops into account, and ignores some factors that can affect crop yield, e.g. climate, thus disregarding bio-physical relationships between crops and land management units. The USBR classification is considered not to be a comprehensive land evaluation system because it ignores other land uses (Young, 1976). This method is based on economic principles. Although the Jeffara region is to be irrigated, the project was a deliberate government policy to make Libya self-sufficient in food production, so the USBR method may not meet local needs for this study (GMPR, 2008).

3.3.4 Land Capability - the Canadian Method

The Canadian land capability classification was introduced by the Canada Land Inventory (CLI) in 1963 as a result of the Agricultural Rehabilitation and Development (*The Canada Land Inventory Report*, 1967). It was designed to give basic information for land resources and land use planning. It was designed to apply at regional, provincial and national scales. This system is inappropriate to use at the local scale, because the data collected by the CLI are very general. As Davidson (1992) described it, this approach was modelled on the USDA land capability classification. The Canadian method has a wider range of restrictions than the USDA method. This method is based on the physical parameters, which could then be used as inputs to economic and social analysis. The Canadian land capability system classifies the land into seven land capability categories instead of eight. In the first category, soils are suitable for agricultural use. In the second category, soils have moderate restrictions on the range of crops for which they can be used. In the third category, soils have moderately severe restrictions on the range of agricultural crops. In the fourth category, soils have severe restrictions on the range of agricultural crops. In the fifth category, soils have very severe restrictions and are most suitable for producing perennial forage crops. In the sixth category, soils are able only to produce perennial forage crops. In the seventh category, soils are unable to produce any type of agricultural crops. Category O contains the organic soils and not cited in land capability classes.

3.3.5 Land Capability - a Dutch Method

The Dutch land capability classification is known for its intensity of use and land is always under increasing pressure. Not only is the Dutch landscape important for preserving the soil most appropriate for farming, which plays a most important role in the Dutch economy, but space is also needed for different land uses, such as industrial sites, new houses, forestry and roads. In the Netherlands land evaluation was applied in the 1950s, when soil surveys were interpreted for agricultural crop production, land reclamation and improvement. Much attention has been given to soil surveys in relation to town and country planning, with the major contribution in the Netherlands being the preservation of soil particularly appropriate for horticulture (Davidson, 1992).

The term ‘suitability’ has been used more than ‘capability’ in the Dutch method. The Dutch method is based on soil limitations rather than any other parameters. This system is divided into two main classes: arable and grasslands activities. Davidson (1992) summarized it as follows:

- Major Category BG (arable land and grassland soils): soils commonly divided to arable land and grassland; subdivided into seven classes (BG1 to BG7).
- Major Category GB (grassland and arable soils): soils commonly divided to grassland and arable land; subdivided into three classes (GB1 to GB3).
- Major Category B (arable land soils): commonly divided to arable land, but mostly poorly or not divided to grassland; subdivided into three categories (B1 to B3).
- Major Category G (grassland soils): soils commonly are sited to grassland, but mostly poorly or not sited to arable land; subdivided into five classes (G1 to G5).
- Major Category (O): inappropriate soils predominantly poorly divided to arable and grasslands subdivided into two classes (O1 to O2).

3.3.6 Parametric Methods

The parametric systems incorporate land characteristics that influence agricultural production by using mathematical equations. Many parametric approaches have been used for land evaluation. Some of these approaches are simple, while others are more complicated. These approaches vary in the specific parameters they include and in their mathematical manipulation (McRae and Burnham, 1980). Davidson (1992) and Nwer (2005) report the main problem in the use of the parametric systems for models of land evaluation. They mentioned that if parameter scores are assigned as very high or low, they will have a considerable impact on the overall index. The parametric systems have been developed to be used in less developed countries such as Libya. In Libya, the parametric land evaluation system was applied to land suitability classification for many agricultural crops (Ben Mahmoud, 1995). Ben Mahmoud has identified eleven land attributes to calculate the productivity index rating (Equation 3.1).

Productivity Rating (PR) =

$$\left(A_1 \times A_2 \times A_3 \times A_4 \times A_5 \times A_6 \times A_7 \times A_8 \times A_9 \times A_{10} \times A_{11}\right) \qquad 3.1$$

where A1 = soil texture, A2 = soil calcium carbonate, A3 = soil depth, A4 = soil reaction, A5 = soil organic matter, A6 = soil salinity, A7 = soil slope, A8 = soil erosion, A9 = internal soil drainage, A10 = water table, A11 = exchangeable sodium percentage. Land variables in this system are given scores from 0 to 1, depending on the effect of the parameter on agricultural production in Libya. This system has been criticized by Nwer (2005). Nwer claimed that the parametric land evaluation system is not suitable for agricultural development in Libya, because it only gives useful results in a localized area. Nwer added that the parametric land evaluation system in Libya failed to take the mean temperature for crops into consideration.

3.3.7 The FAO Agro-Ecological Zoning (FAO AEZ)

The FAO AEZ is a system of quantitative land evaluation of plant adaptability to some locations. The FAO AEZ takes the length of growing season, precipitation and temperature regime, and soil and landscape requirements for the crops into consideration. The FAO AEZ map outputs are maps of land suitability classes (S1, S2, S3, N1 and N2). Many land resource applications have been employed within the process of the FAO AEZ methodologies. These applications are: land resource inventory, inventory of land utilization categories and production systems, potential yield calculation, land suitability and land productivity evaluation, mapping agro-climatic zones, land degradation evaluation, evaluating and mapping flood and drought damage to crops, evaluation of impact of climate change, and monitoring of land resources development. In the FAO AEZ methodologies, various databases need to be incorporated as layers of spatial information into the GIS environment: these data include topography, geology, soil, land form, climate data, land use or land cover data and roads/communication. The FAO Agro-Ecological Zoning has been applied in Bangladesh, Philippines, Indonesia, Malaysia, China, Sri Lanka, Thailand and Kenya (FAO, 2007).

3.3.8 The FAO Framework for Land Evaluation

The FAO framework for land evaluation is considered as a set of methodological guidelines rather than a land classification system. It was mainly designed to fit any kind of environment and at any scale, and to be utilized especially in regions with restricted basic data (FAO, 1976). Land mapping unit, major kind of use, land utilization type, land characteristics, land qualities, diagnostic parameters, land use requirement and land improvement are ranked as key concepts for the FAO framework (FAO, 1976). It is necessary to clarify some important definitions that will be used in the FAO framework. All of these definitions were set out by FAO (1976).

- "**Land**: Land comprises the physical environment, including climate, relief, soils, hydrology and vegetation, to the extent that these influence potential for land use. It includes the results of past and present human activity, e.g. reclamation from the sea, vegetation clearance, and also adverse results, e.g. soil salinization. Purely economic and social characteristics, however, are not included in the concept of land; these form part of the economic and social context."
- "**Land mapping unit:** A land mapping unit is a mapped area of land with specified characteristics. Land mapping units are defined and mapped by natural resource surveys, e.g. soil survey, forest inventory. Their degree of homogeneity or of internal variation varies with the scale and intensity of the study. In some cases a single land mapping unit may include two or more distinct types of land, with different suitabilities, e.g. a river flood plain, mapped as a single unit but known to contain both well-drained alluvial areas and swampy depressions."
- **"Land utilization type**: a kind of land use described or defined in a degree of detail greater than that of a major kind of land use. In detailed or quantitative land evaluation studies, the kinds of land use considered will usually consist of land utilization types. They are described with as much detail and precision as the purpose requires. Thus land utilization types are

not a categorical level in a classification of land use, but refer to any defined use below the level of the major kind of land use".

- "**Land suitability**: the fitness of a given type of land for a defined use. The land may be considered in its present condition or after improvements. The process of land suitability classification is the appraisal and grouping of specific areas of land in terms of their suitability for defined uses."
- **"A land characteristic** is an attribute of land that can be measured or estimated. Examples are slope angle, rainfall, soil texture, available water capacity, and biomass of the vegetation". Land mapping units, as determined by resource surveys, are normally described in terms of land characteristics.
- **"A land quality** is a complex attribute of land which acts in a distinct manner in its influence on the suitability of land for a specific kind of use. Land qualities may be expressed in a positive or negative way. Examples are moisture availability, erosion resistance, flooding hazard, nutritive value of pastures, and accessibility. Where data are available, aggregate land qualities may also be employed, e.g. crop yields, or mean annual increments of timber species".
- "**Qualitative land suitability classification**: a land suitability classification in which the distinctions between classes are made in terms which do not meet the requirements of a quantitative land suitability classification."
- "**Quantitative land suitability classification**: a land suitability classification in which the distinctions between classes are defined in common numerical terms, usually economic, which permit objective comparison between classes relating to different kinds of land use."

Davidson (1992, p.81; FAO 1976, p.2) indicated that the FAO framework was designed to answer a number of questions. These questions are:

- "How are lands currently managed, and what will happen if present practices are not changed?
- What improvements in management practices, within the present use, are possible?
- What other uses of land are physically possible and economically and socially relevant?
- Which of these uses offer possibilities of sustained production or other benefits?
- What adverse effects, physical, economic or social, are associated with each use?
- What recurrent inputs are necessary to bring about the desired production and minimize the adverse effects?
- What are the benefits of each form of land use?"

The FAO framework is based on the following six principles (Davidson 1992, p.80-81; FAO 1976, p.3):

- "Land suitability is assessed and classified in relation to particular land uses;
- Evaluation requires a comparison of the land inputs and outputs needed on different types of land**;**
- A multi-disciplinary approach is required**;**
- The evaluation is made with careful reference to the physical, economic and social context of the area under investigation**;**
- Suitability refers to use on a sustained basis**;** and
- Different kinds of land use are compared on a simple economic basis."

The FAO framework evaluates the suitability of land for specific land use rather than general use (as land capability). The FAO framework has three levels of land utilization description: summary, intermediate and detailed (FAO, 1983). Description at one of these levels is based upon the purposes of the evaluation and the type of the study (e.g. reconnaissance and low-intensity study). In land evaluation studies, a land use type should be described using the following set of management-related characteristics and socio-economic settings that together define land utilization types (LUTs): level of inputs, produce, market orientation, capital intensity, labour intensity, mechanization, and infrastructure and land tenure. A brief description of this set is listed below (FAO, 1983, 1985):

- **Level of Inputs**: represents the amount of inputs such as seeds and fertilizers used for a particular produce. Level of inputs can be low, intermediate or high.
- **Produce**: a description of the cropping patterns.
- **Market Orientation**: destination of products (subsistence and commercial).
- **Capital Intensity**: cost of hand tools and fertilizers.
- **Labour Intensity**: the estimated required number of man-months per hectare per year.
- **Mechanization**: refers to the level of mechanization of the field or farm. Three categories can be defined: mechanized farming, farms moderately mechanized and non-mechanized farming.
- **Infrastructure**: plays an essential role in the development plans. LUTs require a number of very important factors such as right of entry to markets and distribution centers.
- **Land Tenure**: refers to the ownership of the land or the correct use of the land.

The FAO framework also takes the biophysical land requirements and socio-economic requirements into account, with assumptions on the level of management, location and type of farming. Land components in the FAO framework which have direct effect on land use are described as land qualities (LQs). “Land quality “is a complex attribute of the land resulting from land characteristics which emphasizes the combination of land characteristics that affect crop growth (Dent and Young, 1980 and Davidson, 1992). The FAO framework depends on the matching between land utilization types and land use requirements for the land mapping unit. For this reason, the FAO framework recommends a description of land in terms of land qualities or land characteristics. Furthermore, this framework classifies the land into four categories: land suitability orders, land suitability classes, land suitability sub-classes and land suitability units. Orders indicate lands suitable for crops (S) or not suitable for crops (N). Classes show the degree of land suitability, such as (S1) highly suitable, (S2) moderately suitable, (S3) marginally not suitable, (N1) currently not suitable and (N2) permanently not suitable. Subclasses indicate the type of limitation.

The FAO framework has three different guidelines. These guidelines are land evaluation for rainfed agriculture (FAO, 1983), land evaluation for irrigated agriculture (FAO, 1985) and land evaluation for extensive grazing (1991). These guidelines are designed to assess crop, management, environmental and conservation requirements. The FAO framework has taken some concepts from the USDA land capability classification and the USBR system of land suitability for irrigation. Class, sub-class and land unit terms have the same meanings in the USDA system ,while the FAO land suitability classes S1, S2, S3 and N2 correspond to the USBR land suitability classes 1, 2, 3 and 6 (Young, 1976).

The FAO framework for land evaluation has been widely applied in many developing countries, such as Zimbabwe, Jordan and the north-east of Libya (Kanyanda, 1988; Nagowi & Stocking, 1989; Nwer, 2005). For the north-east of Libya, Nwer defined twelve land qualities relevant to determining suitability for barley, wheat, maize and sorghum. These qualities are temperature regime, rooting conditions, moisture availability, excess of salts, nutrient availability, nutrient retention, soil toxicities, infiltration, oxygen availability, conditions for germination, erosion hazard and potential for mechanization. Following the FAO (1976) framework for land evaluation, fifteen land characteristics were defined in order to evaluate these qualities.

3.3.9 Computerized Land Evaluation Methodologies

Since the FAO framework for land evaluation was published, a number of computer systems have been used to develop land evaluation methods. In the next sections, computerized land evaluation methods are assessed:

3.3.9.1 Automated Land Evaluation System (ALES)

ALES is a microcomputer programme developed in 1989 by Rossiter and Van Wambeke (1989) and refined in 1990 by Rossiter and Van Wambeke to evaluate the land according to the FAO framework and taking local socio-economic evaluation into consideration. It was intended for application at a regional scale and the evaluation had no defined list of land qualities for evaluation. Local conditions and objectives are taken into account in the regional-scale land evaluation (Rossiter, 1990). ALES offer the integration of local knowledge by allowing the user to insert his expertise in land evaluation. ALES has seven components: knowledge base; a database describing the land areas; an inference mechanism; a consultation mode; a report generator and an import and export module. This framework is not GIS but can analyze and support geographic land characteristics and reclassification of IDRISI or Arc Info maps when used with the framework database.

3.3.9.2 Land Evaluation Computer System (LECS)

LECS was considered a very simple model of computerised evaluation (Wood and Dent, 1983). Basic economic data and crop requirement data for each land unit are taken into account and analyzed in two steps. The first step involves the potential productivity of the land by evaluating management input and the type and level of technology used to model soil degradation. This measurement is based on soil loss estimates from the Universal Soil Loss Equation (USLE). The second step evaluates productivity and improved management on an economic basis (costing various conservation options).

3.3.9.3 Microcomputer Land Evaluation Information System (MicroLEIS)

This system uses interactive software designed for comprehensive evaluation of rural resources, particularly sustainable use of soils in the Mediterranean region. The Micro LEIS was described as a complete land evaluation model. This system is suitable to use in agro-forestry land use because it incorporates climate, soil, land, site and management conditions. It consists of four modules: information and knowledge database, productivity and ecosystem modelling, erosion and contamination modelling, and impact and response simulation for identifying the optimal use of agriculture and forestry land systems under Mediterranean conditions (De la Rosa et al., 1992). De la Rosa added two components in order to comply with increasing environmental concerns: prediction of global change impacts via generating hypothetical scenarios; and integration of the land use sustainability concept through a set of tools to compute present state, potentiality and risks, impacts, and responses.

3.3.9.4 The Intelligent System for Land Evaluation (ISLE)

The ISLE was designed to evaluate the land automatically and display results graphically in digital maps. ISLE has three components: input, geographical database and digital representation of the study area in maps. The system displays the results in maps based on the selected land units and this system has been used with the FAO methodology for land evaluation (FAO, 2007).

3.3.9.5 Land Evaluation Implementation GIS (LEIGIS)

LEIGIS is a software application modelled in 2002 in Greece (Kalogirou, 2002). This system takes the physical and economic evaluation into account. The LEIGIS system has a function to display maps in GIS environment. It comprises two models: a general cultivation model and a model for particular crops (e.g. wheat, maize, cotton, barley and sugar beet). Some physical conditions which affect crop production, such as climate, were ignored. LEIGIS was originally designed to classify land suitability for general cultivation and for certain crops by adopting the FAO framework. This system use bio-physical land evaluation as a basis for different economic evaluations of agricultural land. Scores are assigned to individual land characteristics in hierarchical importance of land qualities.

3.4 Summary

This chapter has reviewed the most widely applied land evaluation methodologies, such as the USDA land capability classification, the United States Bureau of Reclamation (USBR) land classification for irrigated land suitability, the FAO framework for land evaluation, parametric land suitability system, the FAO agro-ecological zoning and computerized land evaluation systems. Land evaluation methodologies described in this chapter are assessed and compared in Table 3.1.

Table 3.1: Characteristics of the major land evaluation methods

Land evaluation system	**Purpose**	**Land uses**	**Data required**	**Model outputs**
USDA	Capability	General land uses	Physical	8 classes
British	Capability	General land uses	Physical	7classes
USBR	Capability	Irrigation uses	Physical and economic	6 classes
Canadian	Capability	General land uses	Physical	7classes
Dutch	Capability	General land uses	Physical	3 classes
Parametric	Suitability	Specific land uses	Physical	Continuous capability
FAO-AEZ	Suitability	Specific land uses	Physical	5 classes
FAO	Suitability	Specific land uses	Physical and socioeconomic	5 classes
Fuzzy	Suitability	Specific land uses	Variables	Continuous suitability

The FAO framework for land evaluation is becoming increasingly popular and has become the main point of reference for land evaluation in many developing countries. In the FAO framework, land suitability is evaluated individually for each land utilization type, which is a specific manner of using the area of land, with precise management approaches and levels. The FAO framework is based on the concept of land use requirement, which refers to the main conditions of the land for successful and sustained use. While the land utilization type is defined by a number of land use requirements, the land provides land qualities; are measured as classified factor ratings, and express the capability of land to fulfil detailed requirements for a specific land use (Rossiter, 1990; Nwer, 2005).

The FAO framework for land evaluation has been selected to be applied in this study. The selection of the FAO framework in the study area was based on a decision made by the GMPR project. The GMPR states that the implementation of the FAO framework for land suitability evaluation, which uses Boolean models developed by Nwer (2005) in the north-east region of Libya, can be used for the model of land evaluation in the Jeffara Plain of Libya (GMPR, 2008).

The selection of the FAO framework for land evaluation in Jeffara Plain in Libya will allow the matching of land characteristics against crop needs and the assessment of a suitability rating for each selected land characteristic. This is particularly the key concept of land evaluation, because, as Nwer (2005) concludes, “The matching is very much a requirement in Libya, where the land suitability for certain crops is required to meet the national policy.”

The main disadvantage with the current implementation of the FAO framework for land evaluation in Libya is that it was tested with the Boolean approach, in which the suitability class of the area is defined by the less-favoured land quality. The Boolean model involves an abrupt division of the region into suitability classes (i.e. S1, S2, S3 and NS), which in turn leads to the loss of much more information; Burrough (1989) therefore suggested a fuzzy-logic method, according to which an area is described by its membership grade in each suitability class, so that the loss of information decreases and a greater degree of subdivision between areas is achieved.

This study will develop analytical methods in a land suitability evaluation system for a number of cash crops using fuzzy GIS approaches under Libyan conditions. These fuzzy approaches (i.e. Fuzzy AHP and Ideal Point approaches) have the potential to give more spatially nuanced models of suitability as they will include some locations in the set of 'suitable' that are excluded by traditional Boolean models.

The definition of Boolean, Fuzzy AHP and Ideal Point methods will be covered and assessed in Chapter 4, while the use of these approaches to the model of land evaluation will be reviewed and discussed in Chapter 5.

CHAPTER 4

Multi-Criteria Decision Analysis

4.1 Introduction

Multi-criteria Decision Analysis (MCDA) was designed in the 1960s to assist decision-makers to incorporate many options, reflecting the opinions of the actors concerned, into a potential or retrospective framework. MCDA in general includes a set of alternatives which are assessed on the basis of conflicting and incommensurable factors which are quantitative and/or qualitative in nature. It has been divided into two main groups of methods: Multi-Attribute Decision Analysis (MADA) and Multi-Objective Decision Analysis (MODA). If the problem is to assess a finite feasible set of alternatives and to choose the best one according to the scores of a set of criteria, it is a MADA problem. MODA deals with the choice of the best alternative based on a series of conflicting objectives. Both the MADA and MODA problems have been classified as single-decision-maker problems or group decision problems (Massam, 1988; Malczewski, 1999).

Multi-criteria decision analysis is a field of theory that analyses problems on the basis of a number of criteria or attributes and can be used with both vector and raster data (Pereira and Duckstein, 1993). The MCDA approaches can also be classified according to the level of cognitive processing demanded of the decision maker and the approach of aggregating criterion scores (Jankowski, 1995).

Traditional multi-criteria decision analysis approaches such as the Boolean approach are subjected to the hypothesis that the location under consideration is completely homogenous and ranked as non-spatial in nature. This hypothesis has made the traditional approaches impractical as in many cases evaluation factors differ across the space.

The main difference between traditional Multi-criteria decision analysis such as Boolean analysis and spatial multi-criterion decision analysis is the explicit presence of a spatial element and therefore the need for data on the geographic sites of alternatives or geographical data defining criterion values (Phua and Minowa, 2005).

4.2 Why use Multi- Criteria Decision Analysis in the process of decision making?

Multi- criteria decision analysis approaches tackle real world problems that are multi-dimensional in nature. MCDA is used to combine qualitative and quantitative criteria and to specify the degree and nature of the relationships between those criteria in order to support spatial decision-making. In a GIS context MCDA is used to combine layers of spatial data representing the criteria in the model. The model specifies how the layers are combined, for example the relative weighting given to each individual criterion, and how the data are combined (Jiang and Eastman, 2000). It is argued that the combination between GIS and MCDA gives the decision makers support in all steps of decision making (Tkach and Simonovic, 1997).

The major advantages of the use of MCDA methods are summarized by Malczewski (1999, p.259) as follows:

- **“**The MCDA methods facilitate the analysis of several conflicting, incommensurate criteria**;**

- The MCDA methods allow the decision maker to analyze problems involving a large number of alternatives and to reduce the set of alternatives to meaningful size**;**
- They are flexible in terms of combining objective information into the spatial decision-making process**;**
- The models can be used to find good or acceptable solutions, compromise solutions, or high-confidence solutions**;**
- They can be used as formal methods for preference elucidation and preference aggregation in both individual and group decision situations**;** and
- The MCDA approaches allow the decision maker to evaluate alternatives by many procedures.**"**

4.3 Multi-Attribute Decision Analysis methods (MADA)

As mentioned above, the MCDA approaches are categorized into two types: spatial MADA and spatial MODA. This research will be dealing with spatial MADA and so this chapter will review the most widely used MADA approaches. Multi-attribute decision methods are defined as techniques where elements are serving as both decision variables and decision objectives and it is assumed that there are restricted numbers of alternatives (Zhu and Dale, 2001).

4.4 Boolean Logic Theory

Boolean logic was introduced by the English mathematician and logician, George Boole. It has been mostly used where the attribute of any cell can only be an integer, 1 (True) or 0 (False), and the boundaries between these integers or classes are clearly defined (figure 4).

Figure 4.1: Representing Boolean classes.

0	0	0	0	0	1	1	1	1	1
0	0	0	0	0	0	1	1	1	1
0	0	0	0	0	0	1	1	1	1
0	0	0	0	0	0	1	1	1	1
0	0	0	0	0	1	1	1	1	1
0	0	0	0	1	1	1	1	1	1
0	0	0	0	1	1	1	1	1	1
0	0	0	1	1	1	1	1	1	1
0	0	1	1	1	1	1	1	1	1
0	1	1	1	1	1	1	1	1	1

Boolean logic has three basic operators: Intersection (the logical term AND), Union (the logical term OR) and Complement (the logical term NOT). These Boolean operators use integers (True and False) as input rasters on a cell-by-cell basis. Output values of True are (1) and those of False are (0). An example of these operators is given below:

Input layer 1		
1	1	0
2	3	3
	0	1

Input layer 2		
1	2	0
2	3	3
1	1	1

Output layer		
1	1	0
1	1	1
	0	1

- **Intersection:** The values are true (non-zero) in the cells in input layer 1 and input layer 2.
- **Union:** The non-zero values are present in the cells of one or both input layers.

- **Complement:** The non-zero values are not present in the cells of a single input layer.

All these operations can be undertaken in IDRISI and ArcGIS softwares (Boolean Analysis for use with IDRISI 15.0; Spatial Analysis for use with ArcGIS 9.2).

4.5 Fuzzy Logic Theory

The term fuzziness was introduced by Lotfi Zadeh in 1965. Zadeh used the term 'fuzziness' to model the ambiguity of natural language, and this term has been applied to modeling many processes that are complex and not well-defined. As mentioned in Boolean logic, the boundaries between classes are clearly distinct (1 and 0 or True and False), but in fuzzy logic there is a transition zone where each class has a lower membership grade in relation to the other (figure 4.2).

Figure 4.2: Comparison between Boolean and fuzzy mapping.

S	S	S	S	S	N	N	N	N
S	S	S	S	S	S	N	N	N
S	S	S	S	S	S	N	N	N
S	S	S	S	S	S	N	N	N
S	S	S	S	S	N	N	N	N
S	S	S	S	N	N	N	N	N
S	S	S	S	N	N	N	N	N
S	S	S	N	N	N	N	N	N
S	S	N	N	N	N	N	N	N
S	N	N	N	N	N	N	N	N

1	1	1	1	.7	.4	0	0	0
1	1	1	1	1	.9	0	0	0
1	1	1	1	1	.7	0	0	0
1	1	1	1	.7	.7	0	0	0
1	1	1	.9	.9	0	0	0	0
1	1	.9	.9	.4	0	0	0	0
1	1	.9	.8	.4	0	0	0	0
1	.9	.5	.4	0	0	0	0	0
.9	.9	.5	0	0	0	0	0	0
.8	.7	.6	0	0	0	0	0	0

0	0	0	0	0	0	.9	1	
0	0	0	0	0	0	.9	.8	1
0	0	0	0	.9	.8	.9	1	1
0	0	0	0	.6	.7	.9	1	1
0	0	0	0	.8	.6	.8	1	1
0	0	.7	.7	.7	.6	.8	1	1
0	0	.4	.3	.5	.5	1	1	1
0	0	.7	.6	1	1	1	1	1
0	0	.5	1	1	1	1	1	1
0	.7	1	1	1	1	1	1	1

In fuzzy logic, the map for S shows membership values closer to 1 when the set falls within S class, while the values are close to 0; the same applies for class N. According to McBratney and Odeh (1997), the fuzzy set can be mathematically defined as follows:

$$A = \{\chi, \mu_A(x)\} \quad \text{for each } x \in X \qquad 4.1$$

Where μ_A is the membership function (MFs) that defines the grade of MFs of x in A. The MFs $\mu_A(x)$ takes values between 1 and 0 inclusive for all A. If $X = \{x_{1,}x_2, x_3, x_n\}$ the previous equation can written as following:

$$A = x_{1,}\mu_A(x_1) + x_2\mu_A(x_2) + x_{3,}\mu_A(x_3) + x_{n1,}\mu_n(x_n) \qquad 4.2$$

In plain words equations 4.2 and 4.3 mean that for every x belongs to the set X, there is a membership function MFs μA that describe the degree of ownership of x in A is.

McBratney and Odeh (1997) expressed that the fuzzy membership function as $\mu_{A(x)} \rightarrow [0,1]$ with each element x belonging to X with a grade of membership$\mu_{A(x)} \in [0,1]$. In this way $\mu_{A(x)} = 0$ represents that the value of x does not belong to A and $\mu_{A(x)} = 1$ means that the value belongs completely to A. On the other hand, $0 < \mu_A(x) < 1$ means x belongs in a definite degree to A.

4.5.1 Fuzzy Sets Membership Functions

Fuzzy Sets are classes without sharp boundaries; that is, the transition between membership and non-membership of a location in the class is gradual (Zadeh, 1965). A fuzzy set is described by fuzzy membership functions (MFs) that range from 0.0 to

1.0, representing a continuous increase from non-membership to complete membership. Examples of fuzzy set membership functions are given in figures 4.3, 4.4 and 4.5.

Figure 4.3: Triangular fuzzy membership function model.

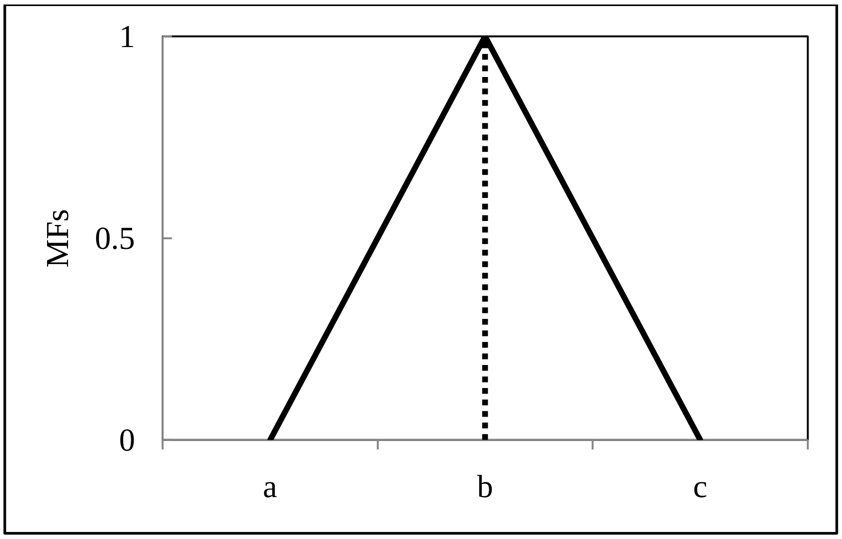


Figure 4.4: Gaussian fuzzy membership functions model.

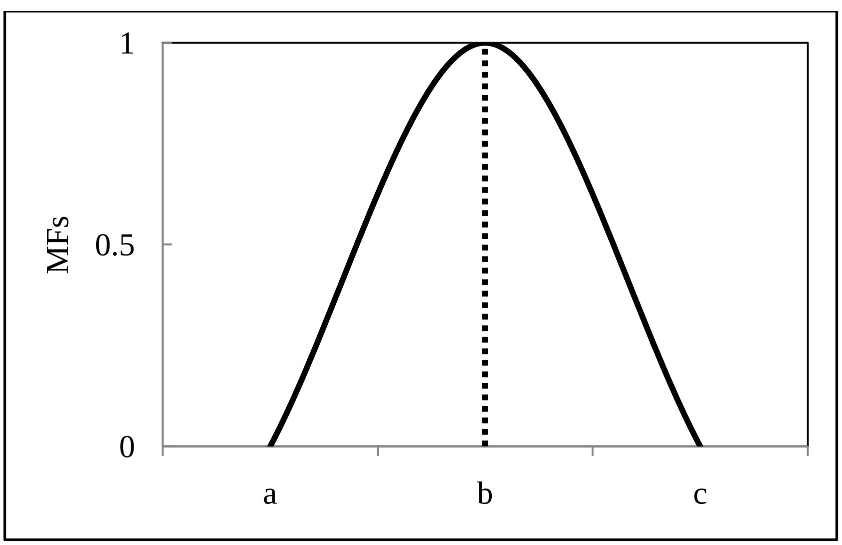
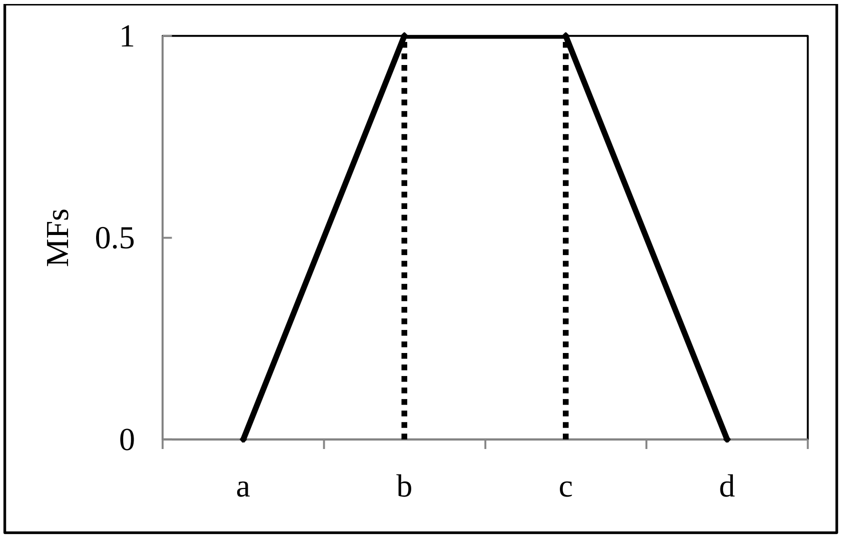


Figure 4.5: Trapezoidal fuzzy membership functions model.



4.5.2 Fuzzy logic operations

The main operations that can be performed utilizing fuzzy sets are a generalization of those that can take place with crisp sets (Zadeh, 1965). For defining these operations, McBratney and Odeh (1997) assumed two fuzzy sets, A and B, each of which belongs to finite sets X of real numbers $\Re$.

- **Inclusion:** Fuzzy set A is integrated in fuzzy set B if

  $$\mu_A(\chi) \leq \mu_B(\chi), \chi \in X \qquad 4.3$$

  , and it can be referred as $A \subset B$

- **Intersection:** Defined as the maximum fuzzy subset of objects from A and B, $A \cap B$, with $\mu_A \cap B(X) = (\mu_A(X) \wedge \mu_B(X)) = \min(\mu_A(X), \mu_B(X)), \chi \in X$ 4.4

  It is equal to the operator of AND.

- **Union:** This operator was defined as the smallest subset with objects from both A and B. It refers to the OR.

  $A \cup B$ is $\mu_A \cup B(\chi) = \big(\mu_A\,(X) \vee \mu_B(X)\big) = \max\,(\mu_A\,(X),\, \mu_B\,(X), \chi \in X$ 4.5

- **Equality:** **A** and **B** are both equal if and only if:

  $\mu_A\,(X) = \mu_B\,(X), \chi \in X$ 4.6

  , and it can be referred as $A = B$.

- **Product:** Two fuzzy subsets based on the product operator are defined as follows:

  $AB = \mu_{A(\text{-})}B^{Z} = \vee\big(\mu_A\,(X)\big)^{\wedge}\ \mu(B(y)) = \max(\mu A\,), \mu B\,(X)), \chi, y, z\,)\ \in X$ 4.7

  Where $z = X - y$

- **Complementation:** Both of the fuzzy sets A and B are complementary if

  $\mu B\,(X) = 1\text{-}\mu_A\,(X), \chi \in X$ 4.8

  , and refers as $B = \overline{A}$ or $\overline{A} = B$. And the complement of A is A. The complement equal to the operator of NOT.

According to McBratney and Odeh (1997), fuzzy logic is also a generalization of Boolean theory that in place of utilizing the binary True and False values uses “soft” criteria such as very deep, moderately deep soils and so on. These criteria are given a range from 0 to 1 and this allows a continuous range of values to be created.

4.6 Weighted Linear Combination (WLC)

Weighted linear combination or simple additive weighting is usually used where continuous parameters have been normalized to a common numeric scale, and after that combined via means of a weighted average. It is considered the most extensive technique for resolving spatial multi-attribute decision-making problems. In this technique decision-makers straightforwardly allocate weights of “relative importance” to each attribute. After that the total scores can be obtained for each attribute by multiplying important weights; are assigned for all attributes by the scaled values which have been given to alternatives on those attributes and by summing the product’s overall attributes. When the overall scores are computed for each alternative, the alternative with the maximum overall score is selected as the best alternative. The weighted linear combination (WLC) as described by Voogd (1983) provides a refinement to Boolean approaches. Overall suitability is calculated from the sum of the weighted normalized data layers representing factors in the model:

$$S_i = \sum_{j=1}^{n} w_j \quad x_{i,j} \text{ where } \sum_{j=1}^{n} w_j = 1 \qquad 4.9$$

and where S_i is the suitability score for site i, w_j is the weight of criteria j, x_{ij} is the value of site i under criterion j, and n is the total number of criteria. Unlike Boolean approaches WLC allows low values in one criterion to be compensated for by high values in another (trade-off as described by Jiang and Eastman, 2000). In addition to this, the weighted linear combination approach requires GIS technology with overlay techniques. This function allows attribute maps to be combined to produce the composite map layers. This function can be employed in many GIS environments such as Arc GIS and Idrisi softwares. The WLC approach is appropriate for use in both raster and vector environments (Heywood et al., 1995). The main advantage of using weighted linear combination is that it is considered to be more flexible than a Boolean approach and it is a suitable method for weighting and combining continuous parameters to produce land suitability maps (Eastman, 1993).

The weighted linear combination (WLC) approach was applied to the parametric land evaluation system. Davidson (1992) showed how the additive, multiplicative and deductive approaches can be applied to the parametric land evaluation system. The use of the WLC approach in land evaluation was widely modified and applied in many countries such as Libya, India, New Zealand and the USA.

According to McRae and Burnham (1981) and Davidson (1992), the main issue with a land evaluation approach based on WLC is that if component scores are very small or very large, they have a considerable effect on the overall suitability. Another critical issue is that the results will not necessarily be appropriate to other crops and other locations. A critical problem with the parametric land evaluation is interaction of parameters or factors and how combinations affect land use or crops yield.

4.7 Analytical Hierarchy Process (AHP)

The Analytical Hierarchy Process **(**AHP) method was developed by Saaty (1977). It is an extension to WLC. AHP is a procedure that seeks to consider the context of the spatial planning decision, identifying and arranging the criteria into different groups (Vogel, 2008; Abdi et al., 2009). AHP is based on three principles: decomposition, comparative judgment, and synthesis of priorities (Eldrandaly et al., 2005). The decomposition principle is to improve the understanding of complex decisions by decomposing the problem into a hierarchy, whilst comparative judgment needs evaluation of parameters by pairwise comparison at each level in the hierarchy. The synthesis principle takes each of the produced ratio-scales in the different levels of the hierarchy and constructs a composite group of priorities for each parameter at the lowest level of the hierarchy (Lai and Hopkins, 1995; Siddiqui et al., 1996; Wu, 1998; Mendoza et al., 1999). AHP can be employed in two ways. First, it can be used to disaggregate problems into a hierarchical structure, the branches of which can be considered individually. In a GIS context these branches are generally criteria or factors represented by data layers. Second, it can be used to generate the criterion weights associated with, for example, the data layers in land suitability map analysis, using a pairwise comparison of factors (Eastman et al., 1993). The analytical hierarchy process procedure has three major stages:

Stage 1: Develop the analytical hierarchy process procedure: At this stage the most and least important elements of the decision problem should be defined and entered into the AHP procedure. At the top level of the hierarchy, the main goal of this decision problem should be defined, and below that the hierarchy descends from the general to the more specific until a level of attributes is reached. Each level must link to the next-highest level in the hierarchy. In general, the hierarchy involves four levels: goal, objectives, attributes and alternatives. These alternatives can be represented in a geographic information system database. Map layers comprise the element values assigned to alternatives and then alternatives are linked to the higher-level attributes.

Stage 2: Perform a pairwise comparison of decision elements: The matrix pairwise comparison (PCs) is considered the fundamental input for the AHP method. The pairwise comparisons matrix was developed by Thomas Saaty in 1980 in the context of the AHP procedure. It is based on forming judgments between two particular criteria rather than attempting to prioritize an entire list of parameters (Saaty, 1980), and is designed to determine the weights of criteria for the parameters of a composite suitability map layers. It includes three main steps (Lai and Hopkins, 1995; Siddiqui et al., 1996):

- The first stage is developing the pairwise comparison matrix by using scale ranges from 1 to 9: equal importance, equal to moderate importance, moderate importance, and moderate to strong importance, strong importance, strong to very strong importance, very strong importance, very to extremely strong importance and extreme importance. This scale was designed by Saaty to define how important A is relative to B.
- The second stage includes three main operations: (1) add the values in columns of the PCs matrix; (2) divide each element in the PCs matrix by its column total; and (3) calculate the average of the elements in each row of the standardized matrix: i.e., divide the sum of standardized scores for each row by the number of variables.
- The final stage includes the determining of the Consistency Ratio (CR) of the pairwise comparison matrix. The CR is a measure of how much difference is acceptable and must be less than or equal to 0.1. If the Consistency Ratio is greater than 10 %, the pairwise comparisons matrix should be recalculated.

The calculation of the consistency index (CI) is based on the observation that λ is always larger than or equivalent to the number of criteria or parameters (n) under consideration for positive, reciprocal matrixes, and λ = n if the pairwise comparison matrix is consist matrix. Consequently, λ – n is considered as a measure of the degree of inconsistency. This measure can be standardized as follows:

$$\mathrm{CI} = \frac{\lambda - \mathrm{n}}{\mathrm{n} - 1} \qquad 4.10$$

where CI refers to the consistency index; this gives measures of departure from consistency. Also, the consistency ratio (CR) can be computed from the pairwise comparison matrix as follows:

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}} \qquad 4.11$$

where RI is the random index; this gives the consistency index of a randomly created pairwise comparison matrix (Malczewski, 1999).

Stage 3: Construct an overall priority rating: At this stage the composite weights are created. The composite weights are derived by multiplying the relative weights matrix at each level of the hierarchy. The composite weights show the rating of alternatives with respect to the overall goal and also represent decision alternatives scores. The overall score of the alternative can be computed by using equation 4.9 described in the section on weighted linear combination.

The main advantage derived from the application of the AHP method to the model of land suitability analysis is that the AHP allows the decision-makers to know the relationship between the goals, criteria, sub-objectives and alternatives. The disadvantage of the use of the AHP is that the scale range 1 to 9 is considered an unbalanced scale, because the parameters in the AHP can be organized at the same level. The difficulty in using the AHP method is to compare attributes. For too many criteria the pairwise comparisons analysis must be run a number of times (Malczewski, 1999; Prakash, 2003).

4.8 Ideal Point methods

The Ideal Point approach uses a group of separation metrics to derive the best alternatives from a range of factors by ordering them according to their distance from the ideal point. The distance is calculated as follows:

$$S_{i+} = [\sum_i w_i^P \left(X_{ij} - X_{+i}\right)^P]^{\frac{1}{P}} \qquad 4.12$$

where S_{i+} is the separation of the alternative from the ideal point, w_i is a weight assigned to the criteria, X_{ij} is the normalized criterion value of the alternative, X_{+i} is ideal value for the criterion, and p is the power factor rating from 1 to ∞.

The separation of the negative and positive ideal points is needed to derive the optimal weightings. The assumption is that the most suitable alternatives have the shortest distance from the positive ideal solution, and the longest distance from the negative ideal solution. The most popular Ideal Point approach is the Technique for Order Performance by Similarity to the Ideal Solution (TOPSIS). TOPSIS considers alternatives which are closest to the ideal point to be the most suitable alternatives (Hwang and Yoon, 1981). Data in this method are standardized and then weighted to generate the most suitable alternatives. The positive ideal point is the minimum weighted standardized criteria score, while the negative ideal point is defined as the maximum weighted standardized criteria score (Malczewski, 1996). The Ideal Point method is like the analytical hierarchy process method, because it can be applied in both raster and vector GIS (Carver, 1991).

The advantage of the application of the Ideal Point approach to the models of land suitability problems is that it generates complete sets of weights and ranks for each attribute. It has the capability to overcome some of the disadvantages that are associated with the hypothesis of interdependence between criteria which underlies approaches such as AHP and Weighted Linear Combination (Zeleny, 1982; Pereira and Duckstein, 1993).

4.9 Summary

The need for the multi-criterion decision analysis methods in decision making has been shown in this chapter. The multi-criterion decision analysis methods are applicable for use in resolving land suitability problems such as land suitability evaluation and land use planning. Land suitability evaluation involves incorporating information from different sources, and also involves defining a number of criteria or parameters which are grouped to assess the land for specific use so that each parameter is contributing towards the suitability of land for a defined purpose. The parameters in land suitability evaluation can contribute much better towards the assessment of suitability if these parameters or criteria are grouped and organized in the hierarchy. In land suitability evaluation, decisions should be taken into consideration at different levels, from choosing the land utilization types relevant to the area under consideration, to the selection of the land qualities and land characteristics for each selected land utilization type. This means land suitability evaluation is a multi-criterion decision analysis process. In this chapter also, traditional multi-criterion decision analysis (i.e. the Boolean approach) and spatial multi-criterion decision analysis (i.e. AHP, fuzzy and Ideal Point approaches) have been defined.

This research uses the AHP and Ideal Point methods with fuzzy set models in a land suitability evaluation system for a number of cash crops. These approaches have the possibility of giving more spatially nuanced models of suitability than Boolean ones. Therefore, the Fuzzy AHP and Ideal Point approaches developed in this research will be compared with some areas in the set of ‘suitable’ that are excluded by a conventional Boolean model.

CHAPTER 5

APPLICATIONS OF GIS FOR LAND EVALUATION

5.1 Introduction

Geographic data have been conventionally shown in map form. Land analysis historically was derived with map overlay technique and was usually done manually. McHarg (1969) described how utilizing manual map overlaying can be done systematically. As the use of computer technology has developed, the more efficient digital form has increasingly replaced manual mapping. This rapidly evolving technology is known as Geographic Information System (GIS). A Geographic Information System has been defined as a computer-based system for input, storage, management, analysis and display of geographic data according to user-defined specifications (Laurini and Thompson, 1992). It becomes an effective technology for scientists, managers and decision makers in addressing multidisciplinary and complex programmes for environmental monitoring, assessment and management. A GIS gives better information to support complex decision-making. With the rapid advancements taking place in computer hardware and GIS software, more complex models have been developed. These models help decision makers and researchers to simplify a complex problem such as land use planning and land suitability. Land suitability maps derived from using GIS tools provide useful databases not only for decision makers but also to help farmers in selecting the best crops for their land (Nwer, 2005).

In recent years, many GIS approaches have been employed to improve the analytical methods for land evaluation systems and defining land suitability problems. There are a considerable number of studies demonstrating the use of GIS in land evaluation.

This chapter reviews many empirical studies that have used Boolean, fuzzy set, analytical hierarchy process, fuzzy analytical hierarchy process (Fuzzy AHP) and Ideal Point approaches to land evaluation methodology.

5.2 Boolean Modeling and its Applications to Land Evaluation

As mentioned in the previous chapter**,** Boolean logic theory is mostly employed as a technique when parameter maps have been classified into Boolean suitable (Yes) and Boolean unsuitable (No) categories. Boolean logic refers to only True (suitable) or False (unsuitable) in the classification procedures. The main weakness encountered is that a membership function (MF) value (i.e. membership to the set of 'suitable') is expressed only as being full or empty, or as 1 or 0. The Boolean method takes no account of measurement errors or uncertainties, because it is inflexible for estimating real ambiguity (Burrough et al., 1992). Boolean mapping refers to a clearly defined boundary and only two possibilities are represented in the Boolean procedure: an object is either 0 or 1 in a set. Boolean logic takes no account of partial membership of an object in a set (Banai, 1993). Banai added that, traditionally, thematic layers are shown with discrete characteristics based on Boolean memberships, such as lines, points and polygons. These types of data may have or may not have values; an intermediate option is not possible.

According to Malczewski (1999), Boolean mapping has three basic operators: Intersection (the logical term AND), Union (the logical term OR) and Complement (the logical term NOT). All these operations can be undertaken in IDRISI and

ArcGIS softwares. Boolean methodology tends to represent reality in a discrete way.

The use of the Boolean method for land suitability evaluation has taken root over the last twenty-five years or so and many researchers have made progress in developing land evaluation methods using Boolean technique (Table 5.1).

Table 5.1: Some studies which have used Boolean mapping in land evaluation for agricultural crops.

Author and date	**Country of Application**
Kanyanda, 1988	Zimbabwe
Nagowi and Stocking, 1989	Jordan
Florence, 2000	Morocco
Florence, 2000	Bolivia
Florence, 2002	Tunisia
Hoobler et al., 2003	East Park County, Wyoming, USA
Nwer ,2005	North-east Libya
Wahba et al., 2007	Sahal Baraka, Farafra Oasis, Egypt
Shahbazi et al.,2009	Ahar area, north-west Iran

As shown in Table 5.1, many researchers have made progress in developing land evaluation methods using a Boolean classification. All these researchers have used the FAO (1976) framework for land evaluation with Boolean logic to derive land suitability maps for agricultural crops.

Most of the studies shown in Table 5.1 use a straightforward process, which means that no weights have been assigned to land properties which have a major effect on results. Only one study, that conducted by Nwer (2005), was not straightforward, which means that different weights were given to different land properties to derive the overall land suitability maps. These studies reported that, for the 'highly suitable' class, all the selected land characteristics affecting the suitability should have a value S1 (highly suitable). This means that if one factor was assigned as S2 or moderately suitable, the overall suitability will be moderately suitable. In addition to this, most of these studies showed that the results in the Boolean classification are based upon the rules that are applied to derive overall land suitability maps. Davidson et al. (1994) stated that the results from the Boolean approach are based upon the rules that are employed, and which can be simply changed in GIS environment. For example, Boolean intersection results in a very hard AND; an area will be excluded from the result if any single parameter has failed to meet its threshold values. In contrast, the Boolean union operator employs a very liberal model of aggregation: an area will be selected in the result as long as a single parameter meets its threshold values.

These studies concluded that the use of a Boolean approach to land evaluation analysis is very simple to apply and it is possible to manage and trace simply which parameters are affecting the suitability of land. On the other hand, the application of Boolean logic to land evaluation has many critical issues and has become invalid. These disadvantages have been explained by Burrough (1989). As an alternative to Boolean logic, fuzzy set theory has been proposed by Burrough for use in land evaluation and soil studies. Fuzzy modelling and its application to land evaluation are discussed in the next section.

5.3 Fuzzy Modelling and its Applications to Land Evaluation

As mentioned in Chapter 4, fuzzy logic is used as an alternative to the concept of 'True or False', and it is considered as a generalization of the Boolean method (Zadeh, 1965). Fuzzy set theory is an extension of the ordinary (crisp or Boolean) set theory which assigns to each element partial and/or multiple membership of the set (i.e. degree of membership, uncertainty, or truth, depending on its application). This grade can be any real number between 0 and 1, where 0 indicates absence (no membership) and 1 indicates complete membership. In addition to this, fuzzy logic uses a soft type of linguistic data (e.g. clay, very deep, saline) which are defined by a continuous range scale or membership values (MFs) ranging from 0 to 1.

Fuzzy logic has been applied to many different topics. This research has focused on reviewing the application of fuzzy logic to land evaluation. The use of fuzzy logic in land evaluation and soil studies was first explained by Burrough (1989). He showed how soil data which are required for land evaluation need to use fuzzy logic. Burrough has given a good justification regarding the application of fuzzy logic and fuzzy set models to land evaluation and soil studies. Burrough mentioned that soil information gathered from soil survey studies which is then used in land evaluation models is mainly defined by seemingly imprecise terms such as ‘slightly susceptible to soil erosion’ or ‘poorly drained’. Not even when these types of data are identified exactly is the qualitative vagueness removed. Burrough (1989) added that the aim of most land evaluators is to create a number of clearly defined boundaries between land suitability classes (FAO, 1976). Consequently, Burrough considered fuzzy logic and fuzzy set models as good tools that can be applied to land evaluation and soil studies in order to cope with such uncertainty and imprecision, and to handle vagueness.

The strong point of the fuzzy set approach in land evaluation is that it starts from the premise that the environment may be inherently imprecise or vague, and does not try to imagine that the real world (Burrough, 1989).

In the last twenty years, fuzzy logic has become an attractive method for many land evaluators. Many land evaluation studies which have applied fuzzy sets and fuzzy logic to land evaluation methodology have been reviewed and are listed in Table 5.2.

Table 5.2: Shows studies used fuzzy mapping to land evaluation for agricultural crops.

Author and date	**Country of Application**
Chang and Burrough, 1987	Northeast of China
Burrough, 1989	Venezuela and Kenya
Wang et al., 1990	Northwest Java, Indonesia
McBratney and Gruijter, 1992	Wesepe, Netherlands
Hall et al., 1992	Northwest Java, Indonesia
Burrough et al., 1992	Alberta
Davidson et al., 1994	Greece
Van Ranst et al., 1996	Thailand
McBratney and Odeh, 1997	New South Wales, Australia
Van Ranst and Tang, 1999	Haichen county and Anshan county, China
Baja et al., 2001	The Hawkesbury-Nepean River catchment, Sydney, Australia
Stomas et al., 2002	City of Merced, California, USA
Braimoh et al., 2004	Northern Ghana
Sicat et al.,2005	Lao PDR
Ziadat, 2007	Jordan

Table 5.2 continued

Author and date	Country of Application
Moreno , 2007	Provence of Luang Pabang, Laos
G. Delgado et al., 2008	Southern Spain
Hartati and Sitanggang, 2010	Indonesia

As shown in Table 5.2 many researchers have adapted fuzzy systems, including fuzzy logic and fuzzy set theory to land evaluation studies. All these researchers have used fuzzy logic in order to cope with such uncertainty and imprecision, and to handle vagueness in land evaluation. All these studies have criticized the use of Boolean logic in land evaluation. These studies concluded that the main critical issue in the application of Boolean logic to land evaluation is that the boundaries between land suitability classes or land units are sharply defined and this does not always reflect the reality, because many elements are not sharply defined. Boolean logic tends to show the reality in a discrete way and this is mostly untrue in many cases in nature. With Boolean logic, a single low criterion is sufficient to decrease the suitability of land from 'highly suitable' to 'moderately suitable' or less, even if the importance of this criterion is low compared to other criteria. These studies concluded that the application of fuzzy methods is much better and more accurate in land evaluation than Boolean logic, because the loss of information is reduced when the fuzzy approaches are applied to the model of land evaluation. The use of fuzzy methods gives more satisfactory results than the traditional method (i.e. Boolean logic), because a greater discrimination among locations or land units is achieved. Instead of deriving land suitability classes as crisp sets by the use of Boolean logic, a fuzzy logic approach results in continuous value classes, which are more realistic in nature. Fuzzy mapping has improved the quality and the quantity of information in land suitability evaluation. Fuzzy logic has the ability to define the degree of uncertainty associated with the measurement and describe the phenomenon as well. Most of these studies have reported that the application of fuzzy set methodology to land evaluation systems requires accurate data about soil and crop requirements, which are the only evaluation parameters that should be considered, and also requires a number of weights to be assigned to the selected land characteristics which have a major effect on results. In addition to this, fuzzy logic requires knowledge from local experts to be taken into account to obtain results with good quality.

Different fuzzy set models have been used to derive membership functions values (MFs). Burrough (1989) presented two types of fuzzy set models, symmetric and asymmetric, which can be applied to convert land characteristics to common membership grades (i.e. from 0 to 1). The symmetric model is employed where the attribute of land has two ideal points, such as soil pH, while the asymmetric fuzzy set model (i.e. asymmetric left or asymmetric right model) has been employed where only the lower and upper boundaries of a category have practical importance. Examples of using different fuzzy set models to generate MFs for different land characteristics can be seen in Burrough (1989), Burrough et al. (1992), Davidson (1992), Davidson et al. (1994), McBratney and Odeh (1997), Baja et al. (2001), Van Ranst and Tang (1999) and Moreno (2007). For example, Burrough (1989), Burrough et al. (1992) and Moreno (2007) used an asymmetrical second grade function model to generate MFs for soil depth. Davidson et al. (1994) and Baja et al. (2001) successfully applied an asymmetrical left model to convert soil cation exchange capacity (CEC) to a range of membership functions from 0 to 1. McBratney and Odeh (1997) generated MFs for soil depth by using a combination of symmetrical Gaussian functions.

Most of these studies reported that the main critical issues in the application of fuzzy logic to land evaluation are the task of selecting membership functions values (MFs) and the task of choosing weights which clearly have a major effect on the model outputs. Davidson et al. (1994) added that applying fuzzy logic to land evaluation is subject to knowledge and data restrictions as is Boolean logic, but stated that 'it is easier to take into consideration such difficulties if a fuzzy set is adopted rather than a Boolean one'.

5.4 The MCDA and its Applications to Land Evaluation

As many authors (e.g. Malczewski 1999; Jiang and Eastman, 2000) reported, MCDA has been ranked as an applicable method in GIS-based land suitability analysis and to address spatial decision making. There are many MCDA methods which have been reviewed in Chapter 4.

Saaty's Analytical Hierarchy Process is the most popular method for describing the model of a land suitability problem (Saaty, 1977). The analytical hierarchy process is a multi-criterion decision analysis method that employs hierarchical structures for defining a problem and then develops priorities for alternatives based on the judgment of the user (Saaty 1980; 2008). Saaty has shown that weighting activities in MCDA approaches can be effectively dealt with by hierarchical structuring and pairwise comparisons. Pairwise comparison analysis (PCs) is the basic requirement for the AHP methods. The PCs involves three main stages to derive the weights for the selected criterion, and all the three pairwise comparison stages have been covered in Chapter 4.

The AHP method can be used as a set of tools for deriving weights of criteria and as a whole method for decision making. The AHP has the ability to deal with inconsistent judgments and offers a measure of the inconsistency of the judgment of the respondents. The AHP method can cope with the real world problems that are multi-dimensional (Saaty, 1980; Voogd 1983; Malczewski 1999).

According to Nisar Ahamed et al. (2000) and Prakash (2003), the AHP approach failed to address the uncertainty through the pairwise comparison analysis and this was the path for the integration of fuzzy set models in the AHP approach. The integration of the AHP with a group of fuzzy set models was first introduced by Xiang et al. (1992). Xiang et al. (1992) applied the AHP with a group of fuzzy set models for land use planning. The Fuzzy AHP method was much better for addressing uncertainty than the AHP method (Deng, 1999). Triantaphyllou and Lin (1996) stated that the Fuzzy AHP is much better for defining land suitability problems than Fuzzy-TOPSIS (technique for ordered performance by similarity to ideal solution), Fuzzy weighted sum model, and Fuzzy weighted product model.

In recent years, there has been increasing interest in integrating GIS capability with multi-criterion decision analysis methods for spatial planning and management (Sekitani and Yamaki, 1999; Chen et al, 2009; Coulter et al., 2003; Chakhar and Mousseau, 2008). The MCDA methods have managed to achieve many applications in land suitability problems and the evaluation of land suitability for agricultural crops. Table 5.3 shows some of the studies that have used the MCDA methods to evaluate land suitability for agricultural crops.

Table 5.3: Some studies which have used the MCDA methods in land evaluation for agricultural crops.

Author and date	Country of application	MADA
Ceballos-Silva and Lopez-Blanco, 2003	Central Mexico	AHP
Prakash, 2003	Dehradun, India.	Fuzzy AHP,AHP and TOPSIS
Duc, 2006	Vietnam	AHP
Chaddad et al., 2007	Mountains area in Syria	Fuzzy AHP and TOPSIS
Moreno, 2007	Provence of Luang Parbang, Laos	AHP
Chuong, 2008	Thuy Bang commune in Thua Thien Hue province, central Vietnam	AHP
Keshavarzi, 2010	Ziaran Region, Iran	Fuzzy AHP

As shown in Table 5.3, different MADA methods have been used in land evaluation for agricultural crops. The AHP method was used by Duc (2006), Moreno (2007) and Keshavarzi (2010) only for deriving criteria weights, whilst Ceballos-Silva and Lopez-Blanco (2003), Prakash (2003), Chaddad et al. (2007) and Chuong (2008) used a complete AHP approach to support decision making, incorporating AHP with fuzzy set models to evaluate land suitability for agricultural crops. Prakash (2003) compared different methods of MCDA such as AHP, Fuzzy AHP, and TOPSIS in land evaluation for agricultural land suitability, and Chaddad et al. (2007) compared Fuzzy AHP and TOPSIS. They reported that the use of the Fuzzy AHP method in land evaluation has a number of advantages: it is able to fit a number of parameters into the decision-making framework; it can incorporate knowledge from different sources; it deals perfectly with land suitability evaluation models by assigning different weights to the parameters according to their importance for overall suitability; it can deal with both quantitative and qualitative data; and it can be used to specify use priorities and in the planning process. The TOPSIS model by contrast was reported to have a bias towards negative and positive ideal values (Chaddad et al., 2007).

5.5 Summary

In this chapter, land evaluation studies based on using GIS approaches have been reviewed and discussed. From the literature survey it can be summarized that the Geographic Information System has been found to be a technique that offers greater flexibility and accuracy for the decision makers in land evaluation studies. This survey has shown that most of the researchers have focused on using Boolean and fuzzy set approaches to land suitability evaluation, while a few researchers have used the MCDA methods such as Fuzzy AHP, AHP, Ideal Point or TOPSIS for land suitability evaluation studies.

The use of the MCDA methods is still a new task in land suitability evaluation. The AHP and TOPSIS methods have the capacity for addressing and exploring the uncertainties associated with land resources, especially if they are integrated with fuzzy set models (Prakash, 2003; Chaddad et al., 2007; Keshavarzi, 2010).

According to the literature survey, further research is needed into using the fuzzy logic approach with the analytical hierarchy process (AHP) in spatial decision making. This research will explore the possibilities of the Boolean, Fuzzy AHP and Ideal Point methods for addressing the uncertainties in the process of land suitability evaluation for a number of agricultural crops. The Fuzzy AHP and Ideal Point methods in this study will be compared with Boolean logic, and the north-western region of Jeffara Plain in Libya is the case study for this research. The Fuzzy AHP and Ideal Point approaches have not yet been used with the FAO framework (1976) for land suitability evaluation in Libya. Consequently, this research is considered to be the first study using Fuzzy AHP and Ideal Point methods in Libya.

CHAPTER 6

RESEARCH METHODS FOR LAND EVALUATION TECHNIQUES IN THE STUDY AREA

6.1 Introduction

This chapter describes the methods selected to conduct this research in the study area. This selection was based on an extensive overview of different land evaluation models, a review of some empirical studies applying GIS technique to the modeling of land evaluation systems, and a literature review for the study area selected. The first part of this chapter deals with the need for land evaluation in the study area, the second part gives a brief review of the selected land evaluation approach in the study area, the third part explains the need to apply Boolean logic to land evaluation in the study area, and sections 6.5 to 6.9 give a brief description of the newly developed model that uses multi-attribute decision analysis methods, Fuzzy AHP and Ideal Point methods in the study area.

6.2 Why Land Evaluation in the Jeffara Plain region of Libya?

The GMPR project is interested in knowing how much yield it will obtain when cultivating cash crops in the Jeffara Plain region of Libya, and the GMPR also plans to improve the living conditions in the Jeffara Plain region of Libya by introducing cash crops such as barley, wheat, maize and sorghum under irrigation conditions. These questions can be answered by assessing the condition of the land in the Jeffara Plain region of Libya for each of the proposed land uses.

6.3 Land Evaluation Approach

As mentioned in Chapters 1 and 3, the GMPR project aims to apply the FAO framework for land evaluation which was adapted by Nwer (2005) in the north-east of Libya to the study area selected in this research. This decision was made after Nwer's study (2005) provided promising results (GMPR, 2008). The FAO framework for land evaluation was selected as being most suitable for Libyan conditions for the following reasons (Nwer, 2005; GMPR, 2008):

- The FAO framework uses a large array of natural resources databases and integrates them to obtain comprehensive land classes. This is very important because the framework requires a comprehensive integration and compilation of different data in a natural resource database.
- The FAO system is considered a positive methodology, because it concentrates on the optimal land use of each area of land.
- The FAO framework allows for the consideration of physical and social factors that influence land suitability.
- This process allows for the validation of results in the field since the ratings of land qualities are based on individual judgment and understanding of the study area.

According to the GMPR (2008), for the Jeffara Plain region of Libya there are eleven land qualities relevant to determining suitability of land for cash crops under irrigation conditions. These qualities are: rooting condition, moisture availability, nutrient availability, nutrient retention, excess of salts, soil toxicities, condition for germination, oxygen availability, infiltration rate, potential for mechanisation and erosion hazard.

Following the FAO framework (1976) for land evaluation, fourteen land characteristics were defined in order to evaluate these qualities, and most of the land qualities selected by the GMPR were adapted by Nwer (2005). These qualities (LQs) and the selected land characteristics (LCs) and their threshold values will be covered in the research methodology (Chapter 7).

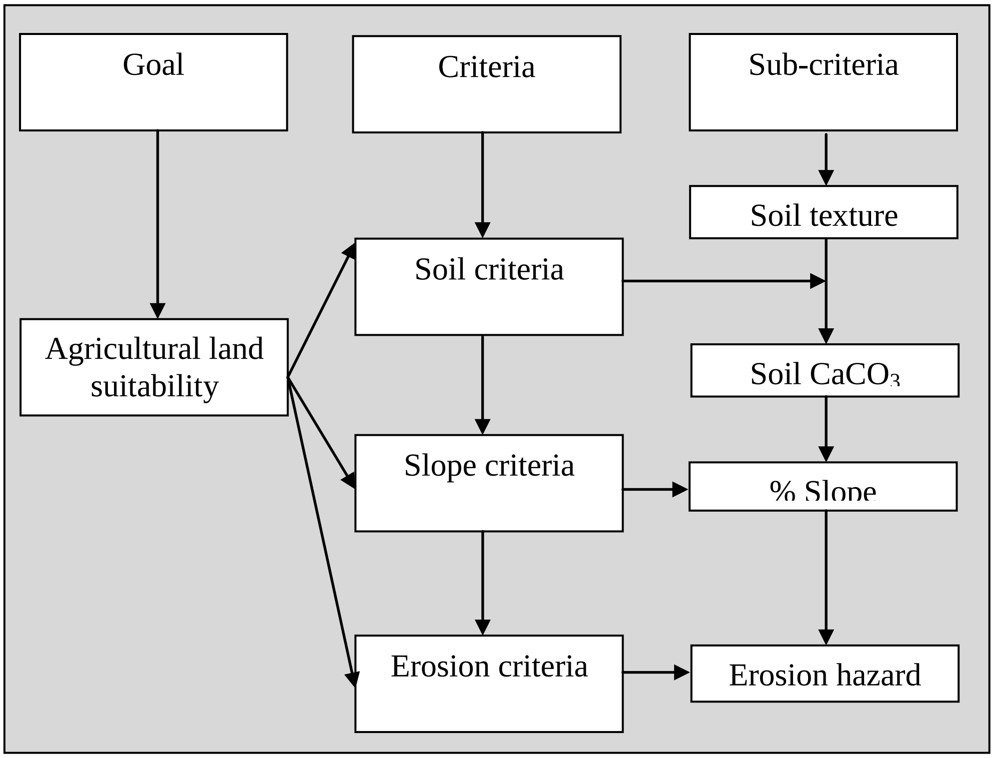
6.4 Boolean

Boolean logic as stated in Chapter 4 has only two possible suitability classes only true or false in the classification procedures. A class in Boolean procedures is expressed only as being full or none, or 1 or 0. The GMBR project plans to use Boolean logic with the FAO framework for land evaluation in the Jeffara Plain region of Libya (GMPR, 2008). Consequently, the FAO framework for land evaluation for the selected crops, using Boolean logic, will be established for the GMPR project in this study. The deficiencies of traditional Boolean logic for designing land suitability evaluation have been recognized by many authors such as Burrough (1986; 1989); therefore the analytical method for land suitability evaluation in the study area needs to be developed.

6.5 Analytical Hierarchy Process (AHP)

As pointed out in Chapter 4, the analytical hierarchy process (AHP) was introduced and developed by Saaty (1980), and the AHP mapping is extensively used in decision making. The principle used in AHP to resolve difficulties is to create hierarchies, and includes three main stages (figure 6.1).

Figure 6.1: Agricultural land suitability analysis hierarchy.



Stage 1: Define the main overall goal from the hierarchy (e.g. agricultural land suitability) and determine the number of criteria and sub-criteria.

Stage 2: Assess the relative importance of the members of each pair of criteria or factors according to the contribution they make to the overall goal. Table 6.1 shows how this can be done using a scale from 1 to 9.

Table 6.1: An example of a pairwise comparisons scale (from Saaty 1980).

Intensity of Importance	Definition
1	Equal importance
2	Equal to moderate importance
3	Moderate importance
4	Moderate to strong importance
5	Strong importance
6	Strong to very strong importance
7	Very strong importance
8	Very to extremely strong
9	Extreme importance

For example, if comparing the criterion ‘soil’ to the criterion ‘percentage slope’, a score of 1 indicates that they are equally relevant to the assessment of land suitability, and a score of 9 indicates that soil is of little significance relative to percentage slope. This comparison is built and defined using a pairwise comparisons (PCs) matrix in Idrisi environment or an Excel spreadsheet model. The PCs created for the levels of the hierarchy include expert local knowledge about the relative importance of parameters.

Stage 3: Assess the pairwise comparisons. A normalized eigenvector is extracted from the pairwise comparisons matrix to assign weights to criteria and then the consistency ratio (CR) is calculated. The CR is calculated from

$$CR = \frac{CI}{RI} \tag{6.1}$$

and where CI is referring to the consistency index and RI is the random index. The CR determines the internal consistency of the weights relative to the overall solution - it is a measurement that reveals how much difference is allowed (Malczewski, 1999). Malczewski states that for good decisions it must be ≤ 0.1, because a consistency ratio ≤ 0.1 shows that the comparisons of criteria or factors were perfectly consistent, and the relative weights are appropriate for applying in AHP approaches.

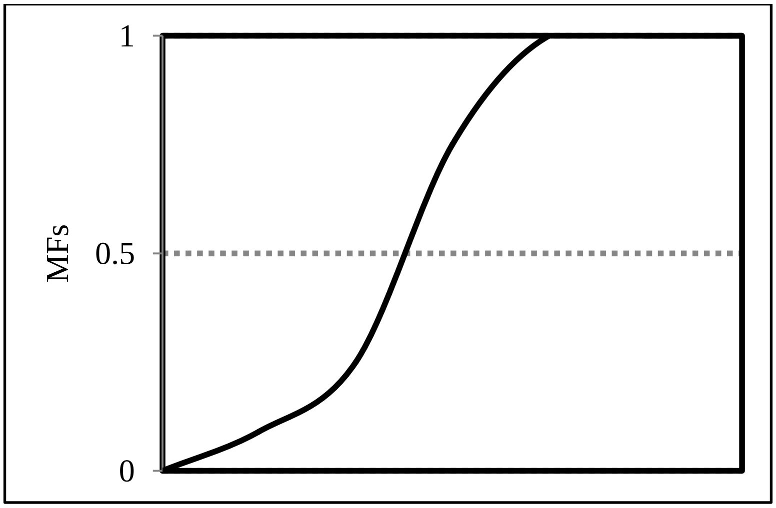
6.6 Fuzzy Decision Making

As discussed in Chapter 4, Boolean methodology tends to represent reality in a discrete way, whereas in nature we find that few elements are discrete, while others are continuous. As Burrough (1989) reported, fuzzy logic is considered as an alternative way to cope with the disadvantages that are found in the application of Boolean logic to land evaluation. The application of fuzzy logic to the model of land suitability evaluation can develop the analysis of parameters that are analyzed from using Boolean approach. Fuzzy methodologies (i.e. fuzzy, Fuzzy AHP and Ideal Point) require definition of the type of fuzzy set models. From the literature survey (e.g. Burrough, 1989; Davidson et al., 1994; McBratney and Odeh, 1997; Baja et al., 2001; Moreno, 2007), asymmetrical and symmetrical models are the fuzzy set models most often applied to generate grades of membership functions (MFs). These asymmetrical and symmetrical models were used to convert the selected land properties to a range of membership functions values. These models are defined below:

Asymmetrical models: The asymmetrical function is divided into two models:

An asymmetrical left model is appropriate when the quality function of the land is appropriate when the characteristic of the land increases (figure 6.2).

Figure 6.2: Asymmetrical left model



The asymmetrical left model is calculated using:

$$MF_{(xi)} = [1/\{1 + 1/d^2(\chi - b)^2\}] \qquad 6.2$$

An asymmetrical right model is suitable when the quality function of the land performs better as the characteristic of the land decreases (figures 6.3a and 6.3b).

Figure 6.3a: Asymmetrical right models

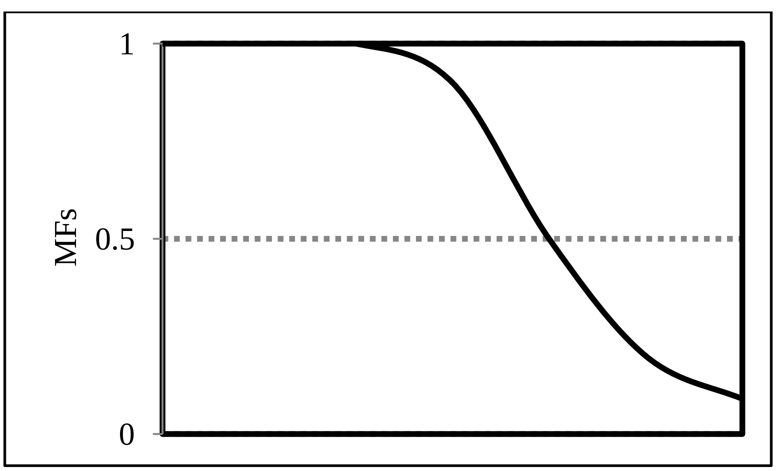
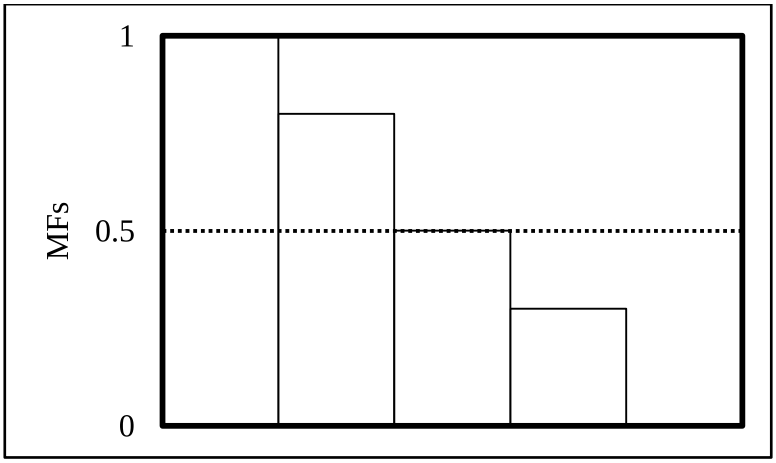


Figure 6.3b: Asymmetrical right models



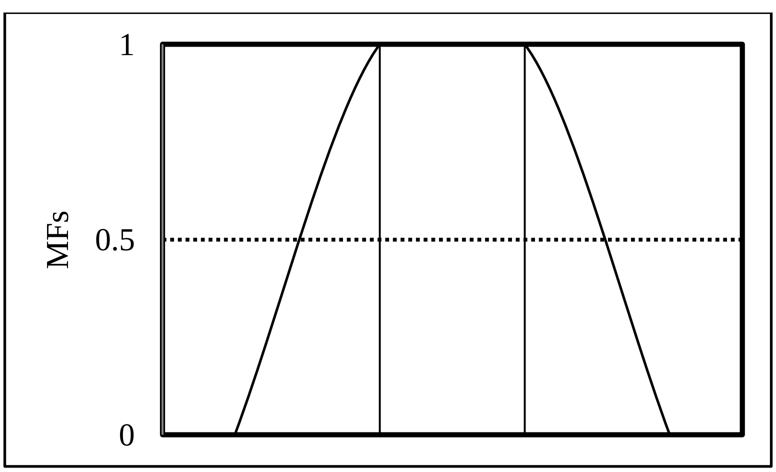
The asymmetrical right model is calculated using:

$$MF_{(xi)} = [1/\{1 + 1/d^2(\chi + b)^2\}] \quad 6.3$$

where is d is the width of the transition zone, while b is for an ideal point level and is the value of land characteristics.

Symmetrical model: This model is also called an optimum range and it uses two ideal point values (figure 6.4).

Figure 6.4: symmetrical fuzzy model



The symmetrical model is calculated using:

$$\mathrm{MF}_{(\mathrm{xi})} = 1 \text{ if } (\mathrm{b}_1 + \mathrm{d}_1) \leq \mathrm{xi} \leq (\mathrm{b}_2 - \mathrm{d}_2) \qquad 6.4$$

where is d is the width of the transition zone, while b_1 and b_2 are for an ideal point level and are the value of land characteristics.

These asymmetrical and symmetrical models are based on defining the lower and upper crossover point (LCP and UCP).

6.7 The Ideal Point Methods

As mentioned in Chapter 4, the Ideal Point technique is selected to be used in this research because it orders a number of alternatives on the basis of their separation from the ideal point, and it employs a number of distance metrics equations to produce the best alternatives. The technique for order preference by similarity to the ideal solution (TOPSIS) is the most popular Ideal Point method for dealing with problem decisions.

6.8 Expert Knowledge for Land Evaluation Models

Land suitability evaluation for agricultural crops is an interdisciplinary technique, and determination of any land for any crop requires incorporation of knowledge from different sources such as soil science, agronomy, social science, meteorology and management science. The application of local knowledge to land evaluation methodologies can improve the quality of the results, as Davidson et al. (1994: p.383) state: **'**As with the Boolean approach, it is important to seek reaction from local staff on the quality of the results of land evaluation.**'** Therefore, to obtain promising results from this research, local staffs in Libya have used their experience to assign different weights to the selected land criteria that affect the production of selected crops.

6.9 Map Agreement

Map agreement is considered one of the most important stages that should be employed to check the validation and understanding of the results. Overall agreement measures between land suitability maps created using different approaches have not been used in previous work reviewed above in Chapter 5. Only the study by Moreno (2007) derived the overall agreement between the Boolean and fuzzy maps. Moreno failed to select the appropriate technique to compare the results, because he employed a hard classification approach to compare the results, based on transferring the fuzzy results to four crisp classes (S1, S2, S3, and N1). This used alpha cuts to partition the fuzzy memberships and without justifications for the threshold values for the fuzzy numbers.

To overcome this problem, this research used cross tabulation analysis based on a soft classification analysis to derive the overall agreement between the maps. The results of deriving the overall agreement between the maps could in fact be incorrect and for that reason field trial plots will be needed to evaluate and validate the results.

The soft cross tabulation allows all pixels to have simultaneous partial membership of more than one class (IDRISI 15.0 help, Clarks Labs, 1987-2006). It has three different operators: multiplication, minimum and composite. The composite operator guarantees that the matrix's entries sum to 100%, which the minimum operator fails to do. These operators were defined by Pontius and Cheuk (2006, p.1-30) as follows:

- **Multiplication operator:** "The contemporary ontology envisions the classes of a pixel as located at points distributed randomly within the pixel. The randomization of points within each pixel is independent of the randomization of the points within any other pixel". For calculating the agreement and disagreement for the maps that are cross tabulated using multiplication operator the following equation is used:

$$Pnij = Pni\bullet \times Pn\bullet j \tag{6.5}$$

According to Pontius and Cheuk (2006), the multiplication operator has many disadvantages. The main critical issue is that when a pixel is not hard-classified, the agreement between a pixel and itself is less than unity. Therefore, if the multiplication operator evaluates a map to itself, the resulting cross-tabulation matrix is not a diagonal matrix. Furthermore, it is possible to find a counter-intuitive result that the agreement between a pixel and itself is less than the agreement between the pixel and a dissimilar pixel.

- **Minimum operator**: "The fuzzy ontology calls for a Minimum operator to compute both the diagonal and off-diagonal entries according to the equation." The equation 6.2 can be used for agreement and disagreement for the maps cross-tabulated using the minimum operator:

$$Pnij = MIN(Pni\bullet, Pn\bullet j) \tag{6.6}$$

The minimum operator is helpful in situations where the category membership is uncertain, although it has problematic features regarding its use for multiple-resolution analysis. Consequently, if the minimum operator compares a soft-classified map layer to itself, the resulting cross-tabulation matrix is not necessarily a diagonal matrix (Pontius and Cheuk, 2006).

- **Composite operator**: "The multiple-resolution ontology calls for a two-step process in computing diagonal entries (i.e. agreement) and off-diagonal entries (i.e. disagreement). The composite rule has many attractive characteristics that the other rules lack, the most important being that it produces the identity matrix when a soft-classified image is compared to itself." For agreement the equation 6.6 can be used, while for the disagreement for the maps that are cross-tabulated using the composite operator, equation 6.7 is employed:

$$Pnij = (Pni\bullet - Pnii) \times \left[\frac{(Pn\bullet j - Pnjj)}{\sum_{J=1}^{J}(Pn\bullet - Pnjj)}\right] \quad \text{For } i \neq j \qquad 6.7$$

where is n, the pixel in the map, $Pni\bullet$ - $Pnii$, since the total membership function is $Pni\bullet$ and the agreement is $Pnii$. For disagreement, n is the pixel in the reference map for the class j is $Pni\bullet$ - $Pnjj$.

According to Pontius and Cheuk (2006), the composite operator, with a different scale of resolution, is better for comparing the maps because it resolves the difficulties of computing the cross-tabulation matrix derived from the use of the multiplication and minimum operators. The composite operator is also helpful in illustrating how well two layers or maps agree in terms of how the categories are clustered spatially.

6.10 Summary

This chapter shows the methods that have been selected for this research. The analytical hierarchy process, Ideal Point methods and fuzzy set models have been selected to develop the analytical methods for a land evaluation technique that uses Boolean logic.

The AHP methods will be used in this research to create the weights through the pairwise comparison analysis and then to aggregate the priority for each level of the hierarchy structure. Local staff from Libya will use their knowledge to assign a number of weights to land characteristics that affect the production of selected crops.

This chapter has also given brief descriptions for the selected fuzzy set models that will be used to convert the raw data to fuzzy numbers. These models have been obtained from an extensive overview of the fuzzy set models that are applied to land evaluation.

Three land evaluation models, Boolean, Fuzzy AHP and Ideal Point methods, will be modelled in this research, with the FAO framework for land evaluation. The aim of designing these three models is to explore their possibilities for addressing the uncertainties in the study area selected in the process of land suitability evaluation.

A comparison of results from using Boolean, Fuzzy AHP and Ideal Point methods will be made. The composite operator with a different scale of resolution will be applied to derive the overall agreement among the resulting maps.

CHAPTER 7

LAND SUITABILITY MODELS FOR THE STUDY AREA

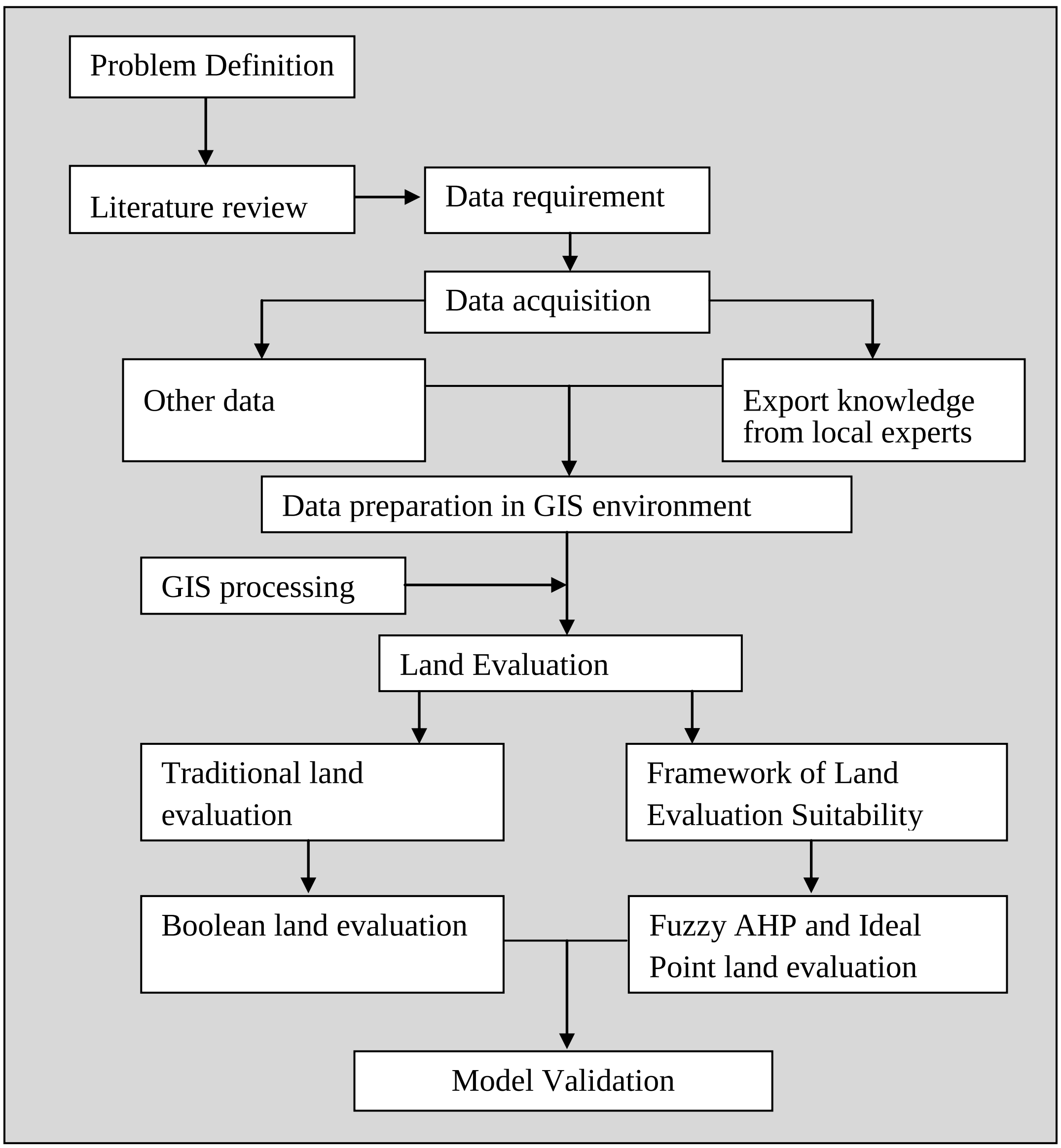
7.1 Introduction

According to the FAO (1975) land evaluation is “the process of assessment of land performance when used for specified purposes”. In other words, land evaluation is defined as the process of estimating the possible behaviour of the land when utilized for a particular purpose; this use could be the current one or a potential one. In this sense, land evaluation could be regarded as a tool to make decisions about the land.

Land suitability “is the fitness of a given area of land for specific land use” (FAO, 1976). Different methodologies have been used to develop land evaluation models in many developing countries including Libya. In Libya, the Boolean method with the FAO framework for land evaluation was employed in the north-east to derive land suitability maps for barley, wheat, maize and sorghum (Nwer, 2005). This model is intended by the GMPR project to be used for the study area selected. The deficiencies of Boolean logic for the land suitability evaluation have been recognized by many researchers such as Burrough (1989) and Davidson et al. (1994). This research aims to compare the input of different methods – Boolean, Fuzzy AHP and Ideal Point – for land suitability evaluation under irrigation conditions for the study area selected.

This chapter shows the research methodology followed during the research process. The research methodology has been divided into six sections. The first section deals with the factors determining the FAO framework for land evaluation for agricultural crops. The second part deals with the weighting of parameters using the pairwise comparison analysis. The third section describes the database scheme for land evaluation techniques in the study area; the fourth section shows the application of the Boolean, Fuzzy AHP and Ideal Point methods to land evaluation in the study area. The final part deals with comparison of the results based on soft classification analysis. Figure 7.1 summarizes the research methodology employed in this study.

Figure 7.1: Research Methodology



7.2 Data Collection

A land evaluation system requires the availability of suitable data. The data used in this research were collected from different sources during a visit to Libya as shown in Table 7.1.

Table 7.1: Data requirement for the research and sources.

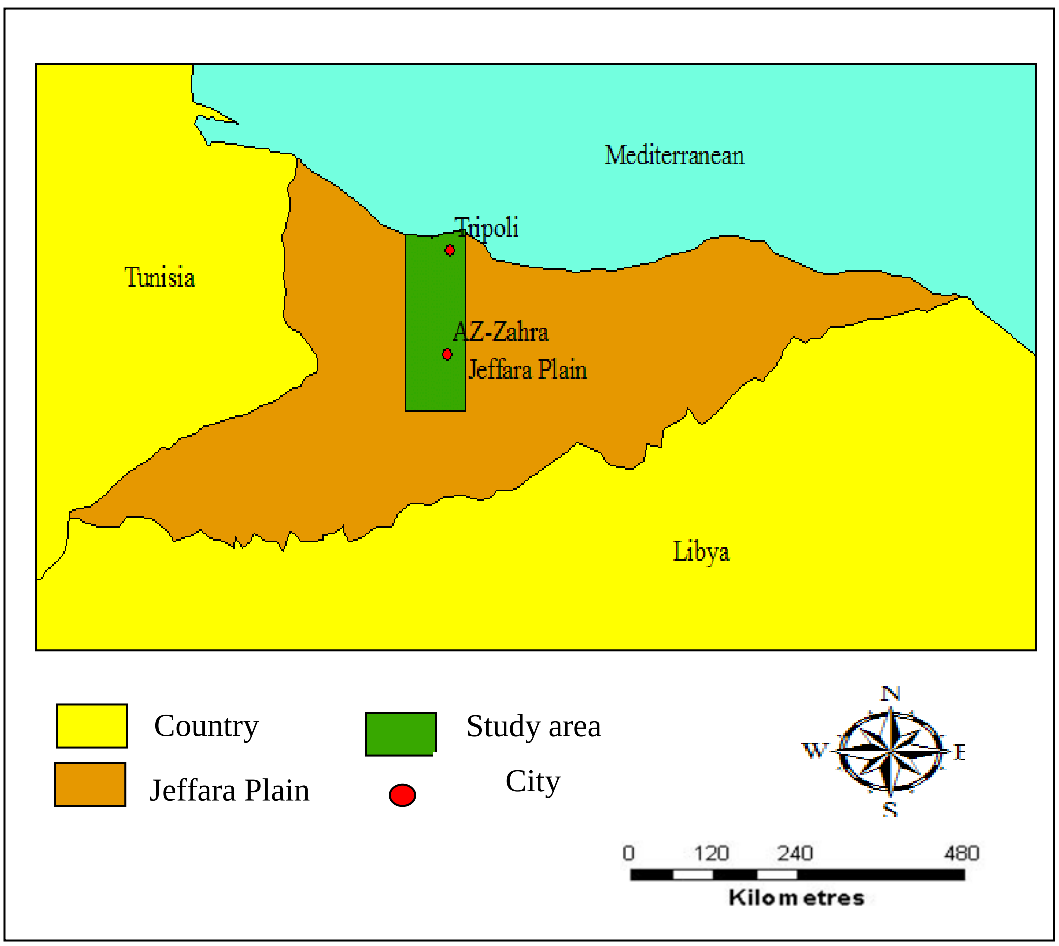
Data	Description	Sources
Topographic data	1. Topographic maps available at a scale of 1:50,000 2. Digital Elevation Model (DEM)	Libyan Natural Resource Center (LY004)
Soil data	1. Soil maps available at a scale of 1: 50,000, 2. Soil sample location map 3. Soil report: physical and chemical soil properties for soil samples	
Soil erosion data	Soil erosion maps also available at a scale of 1: 50000	
Infrastructure	Road maps: main roads and tracks	
Climatic data	1. Rainfall 2. Temperature 3. Humidity	Tripoli Meteorological Station
GMPR report	1. Land utilization types (LUTs) 2. Land qualities (LQ) 3. Land characteristics(LC)	The Great Man-Made River Project (2008)
Field trip	Weighting land characteristics for the selected crops	Local staff (2009) (i.e. discussion with local staff during visits to Tripoli in 2009)

7.3 The Study Area

7.3.1 The Study Area Location

The Jeffara Plain region is triangular in shape and extends from the west of Al Khoms city in Libya to the Tunisian border, and it covers an area of about 1.8 million hectares (Ben Mahmoud, 1995). The selected land investigated in this research is located within the northwest of the Jeffara Plain region and is situated between Tripoli and AZ-Zahra city, between longitudes 12° 45' and 13° 15' east and latitudes 31° 52' and 32° 52' north; it has an area of about 309,396 hectares (Figure 7.2).

Figure 7.2: Study area location.



7.3.2 Soils in the Study Area

The soil studies in the study area were carried out by the Soil-Ecological Expedition of v/o Selkhozpromexport, Agricultural Research Centre (ARC), Al-fateh University and the Ministry of Agriculture. The maps were produced for the Jeffara Plain district using physiographic maps and aerial photographs. In the field, soil units were delineated according to morphological characteristics. Soil samples were taken from depths with different genetic horizons, and auger sampling was carried out at a density of one for every 60 ha; the same density was employed for the depths samples.

The system of soil classification has four categories, i.e. soil subclass, soil type, soil subtype and soil genus. The classification was based on soil properties and diagnosis was observed in the field or implied from observation or based on laboratory measurements. Soil maps were available for this research at a scale of 1:50,000. Five soil types, eleven soil subtypes and twenty-eight soil genera have been recognized in the study area (Table 7.2 and figure 7.3). In addition to this a brief description of the soils in the area of study is given in Appendix (A).

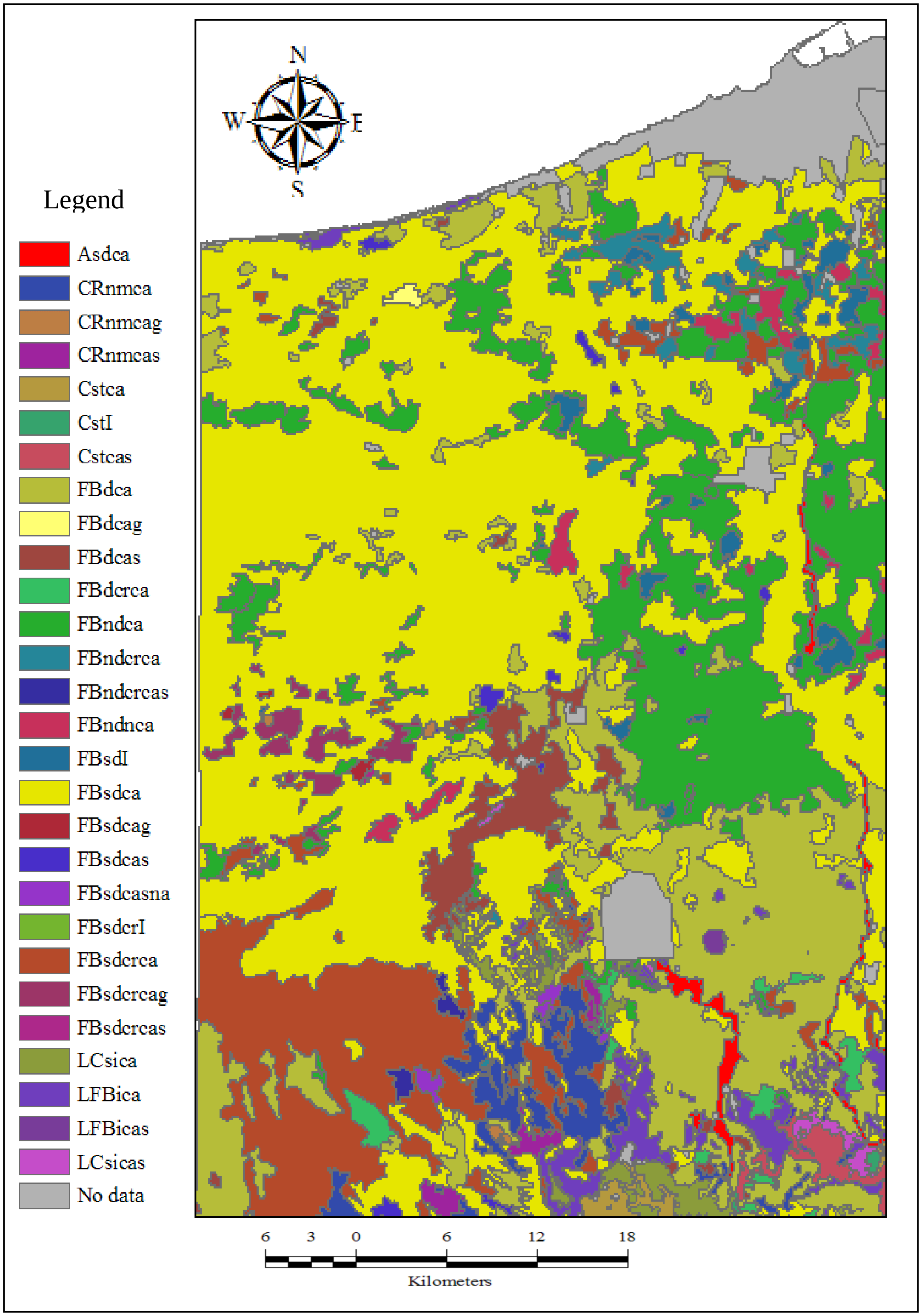
The physical and chemical soil properties which are available in the study area are: soil texture, soil rootable depth, infiltration rate, soil drainage, percentage stones at surface, available water holding capacity, specific density, bulk density, total porosity, minimum moisture capacity, aeration porosity, wilting moisture, organic matter, electric conductivity, exchangeable sodium percentage, percentage of soil calcium carbonate, cation exchange capacity, total nitrogen and percentage of gypsum.

Table: 7.2 Soils in the study area using Russian soil classification.

Soil type	Soil Subtype	Soil Genus	Soil Genus Code
Siallitic cinnamon	Typical	Carbonate, carbonate saline and leached	Cst ca, Cstcas, CstI
Reddish brown arid	Differentiated	Carbonate, carbonate saline and carbonate gypsic	FBdca, FBd cas, FBd cag
	Differentiated crust	Carbonate	FBd crca
	Slightly differentiated	Carbonate, carbonate saline, carbonate solonetzic saline carbonate gypsic and leached	FBsd ca, FBsd cas, FBsd casna, FBsd cag , FBsd I
	Slightly differentiated crust	Carbonate, carbonate saline, carbonate gypsic and leached	FBsd crca, FBsdcr cas, FBsdcr cag, FBsd crI
	Non- differentiated	Carbonate and non-carbonate	FBnd ca, FBnd nca
	Non- differentiated crust	Carbonate and carbonate saline	FBnd crca, FBnd crcas
Alluvial	Slightly differentiated	Carbonate	Asd ca
Lithosols	Cinnamonic	Carbonate and carbonate saline	LCsica, LCsicas
	Reddish brown		LFBi ca, LFBicas
Crusts	Non-monolithic	Carbonate, carbonate saline and carbonate gypsic	CRnm ca, CRnm cas, CRnm cag

Source: Selkhozpromexport, 1980

Figure 7.3: Soil map at soil genus level for the study area.

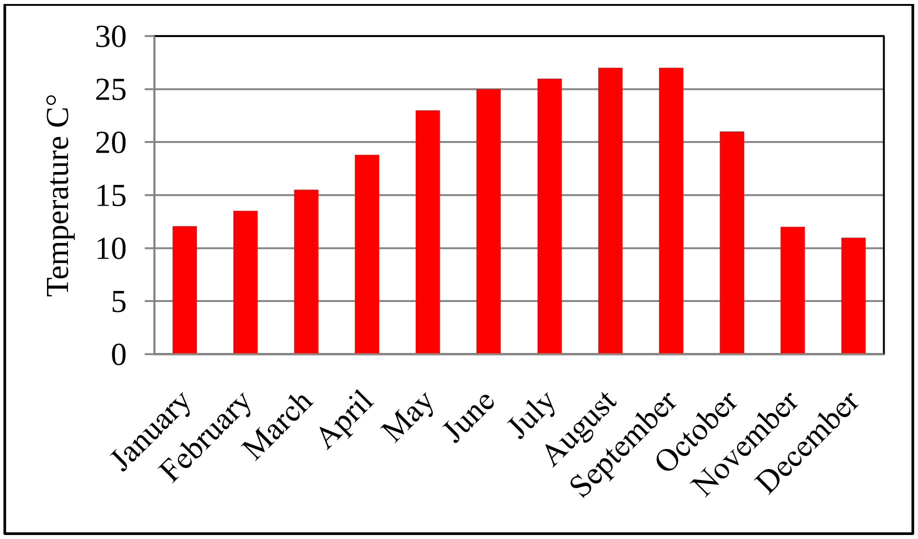


Soil data for the study area selected showed that each polygon area has more than one soil sample, but in this research only one soil sample for each polygon area was chosen to derive soil suitability data or classes for the selected crops. This is mainly because each polygon area has only one representative soil profile and one or more than one control soil profile (Selkhozpromexport, 1980). Incomplete soil data found in a control soil profile made it impossible to include that piece of information in the models of land suitability evaluation. The limitations of using a single soil sample per polygon are noted.

7.3.3 Climate in the Study Area

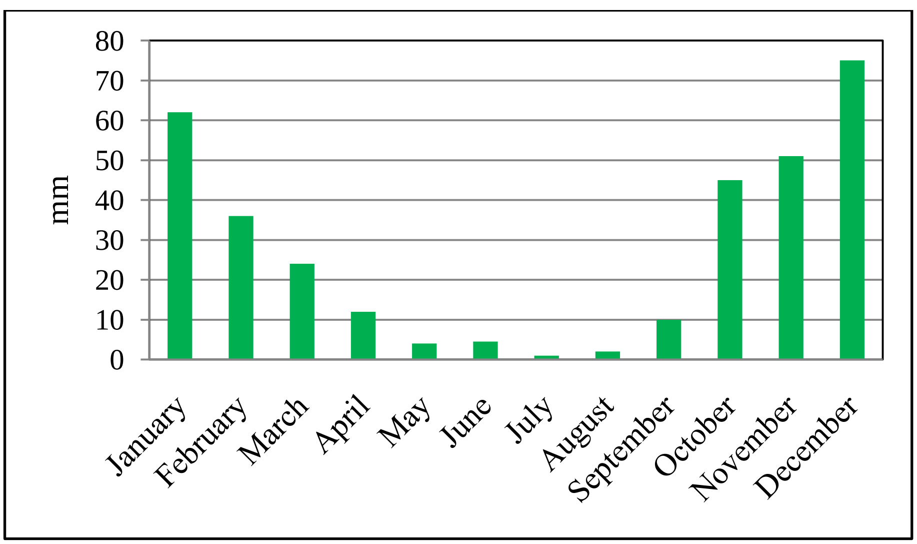
The study area selected is sited in the Mediterranean climate zone. Between October and March the climate is wet and between March and September the climate is dry. In the summer the study area is dominated by the stable high pressure zone situated over the Mediterranean Sea, i.e. by the Azores spur of peak pressure with descending tropical air currents, while in autumn, winter and spring the climatic conditions are determined by the cyclonic activity of ascending air masses of the temperate zone. The mean annual precipitation is 326.5 mm (figure 7.4), the mean annual temperature is 19.33 C° (figure 7.5) and the mean annual relative air humidity is 61.93 per cent (figure 7.6) (Tripoli Meteorological Report, 2005).

Figure 7.4: The mean monthly temperature (C°) from Tripoli Meteorological Stations (Years 1980-2005)



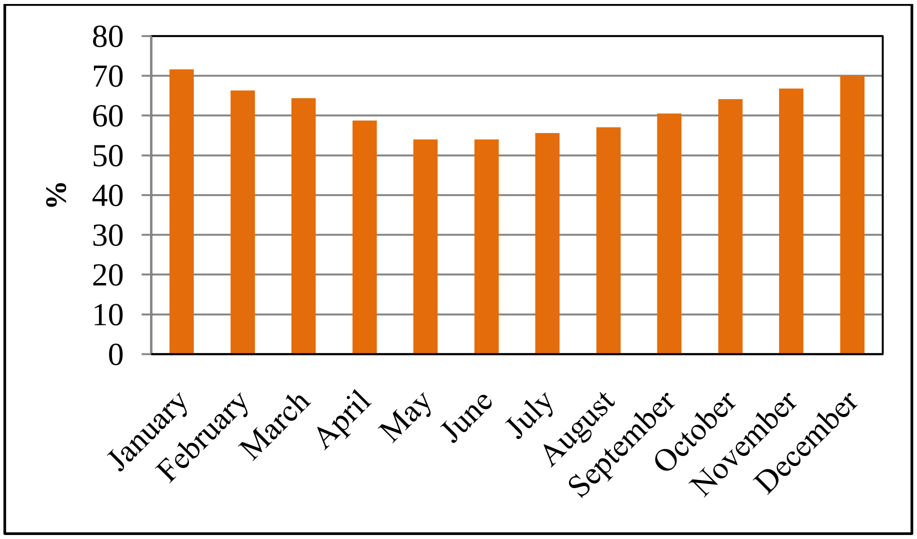
Source: *Tripoli Meteorological Report, 2005*

Figure 7.5: The mean monthly precipitation (mm) from Tripoli Meteorological Stations (Years 1980-2005)



Source: *Tripoli Meteorological Report, 2005*

Figure 7.6: The mean monthly relative air humidity (%) from Tripoli Meteorological Stations (Years 1980-2005)



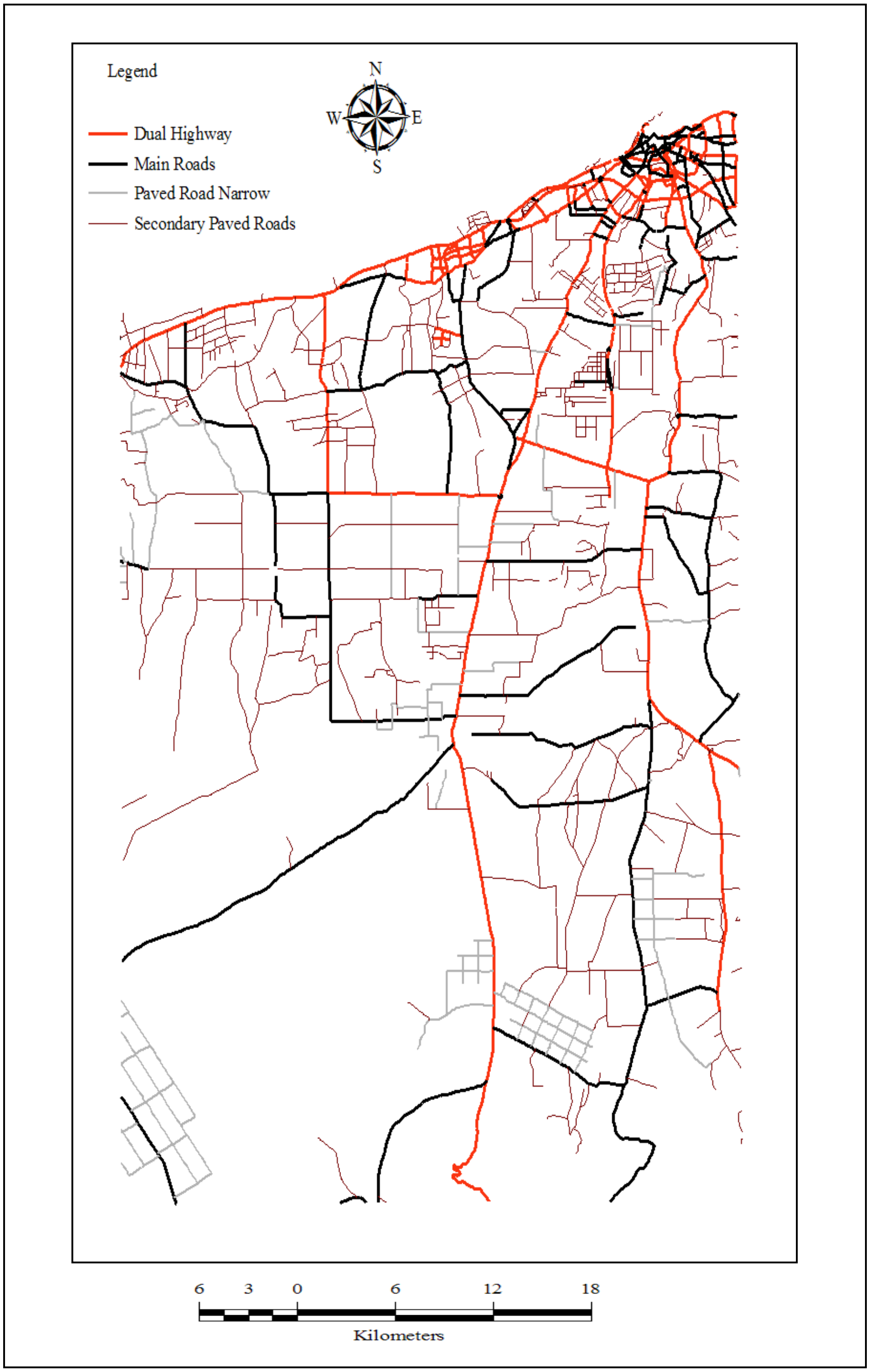
Source: *Tripoli Meteorological Report, 2005*

According to the GMPR (2008), the mean temperature in the growing season is considered an important factor affecting land suitability for many agricultural crops, but this factor doesn't influence barley, wheat and maize production for the study area selected. This is mainly because the mean temperature in the growing season for the study area is quite homogenous. Therefore, it is not included in the models.

7.3.4 Infrastructure in the Study Area

Many roads cross the study area. These roads are: dual highways, main roads, paved roads (narrow) and secondary paved roads (figure 7.7).

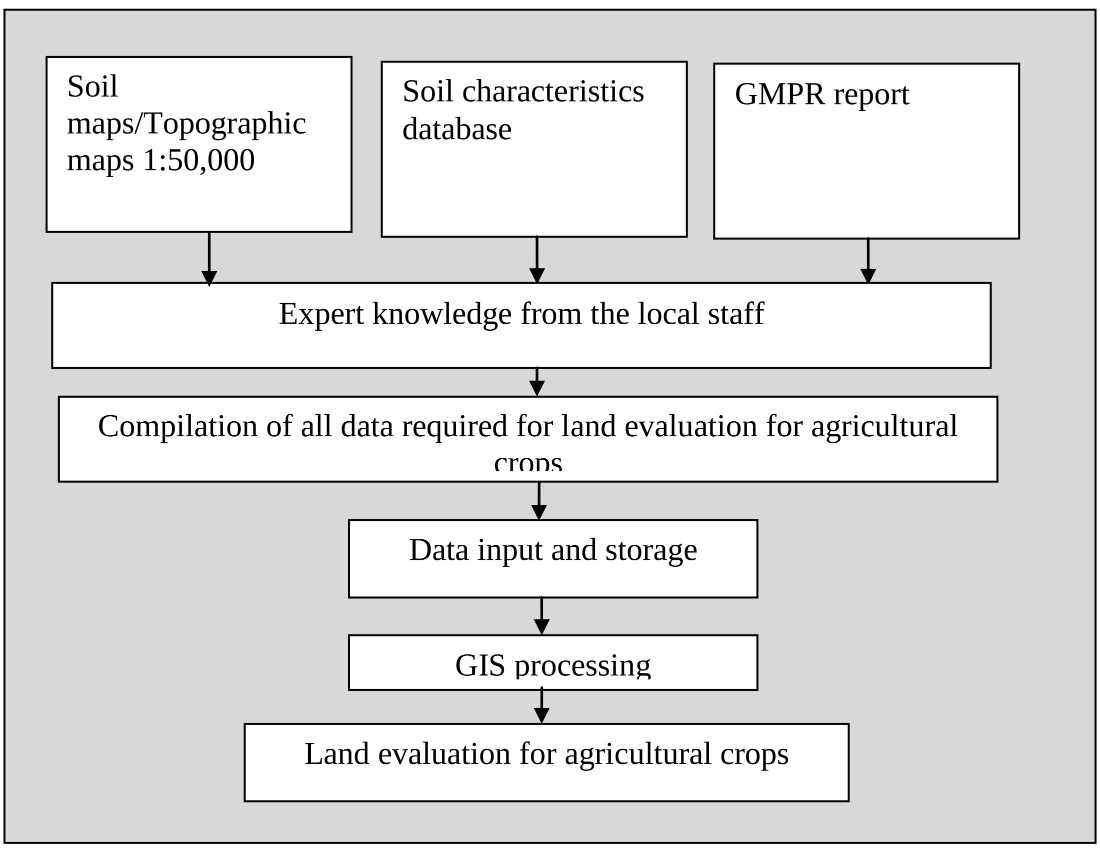
Figure 7.7: Roads in the study area.



7.4 Database Scheme for Land Evaluation in the Study Area

All the required data for modeling a land evaluation system in the study area were constructed by using a number of GIS functions. Two GIS systems (ArcGIS and IDRISI) together with data handling in GIS spreadsheet model were used to construct a land evaluation system for agricultural crops for the study area selected. Soil classification, topographic and soil erosion maps and their interpretation were in digital formats. In addition to this, to obtain promising results from this study, local experts have used their expertise in the models designed in this study. Figure 7.8 describes the database scheme for land evaluation techniques in the study area.

Figure 7.8: Database scheme for agricultural crops in the study area.



7.5 Land Suitability Evaluation in the Study Area

7.6 Factors Determining Land Evaluation in the Study Area

As mentioned in Chapter 3, the GMPR (2008) has successfully identified the main land characteristics affecting barley, wheat and maize growth in the Jeffara Plain region of Libya. But the GMPR has not yet produced land suitability maps for these crops. According to the GMPR (2008) there is no plan to conduct any economic evaluation in the study area using the FAO framework for land evaluation. The main reasons for selecting a land evaluation system in the study area based on using physical conditions are:

- There are rapid changes in the market in Libya - several times a month. Consequently, any economic evaluation in Libya will become outdated.
- Authorization is needed from the Libyan government before conducting any economic evaluation and this authorization in some cases will take time to obtain.
- Carrying out any economic evaluation requires data availability. There is no economic database in Libya; therefore conducting any economic evaluation is not possible for this research.

The procedures of the FAO framework (1976) comprise a number of concepts. The GMPR project adapted the LUTs, and land qualities (LQs) and land characteristics (LCs) in the Jeffara Plain region from the study conducted by Nwer (2005) in the north-east of Libya. Factors defining the land suitability evaluation system in the study area were summarized from the GMPR report and discussion with local staff (Appendix A), and these factors are discussed in the following sections.

7.6.1 Land Utilization Types (LUTs)

Land utilization types (LUTs) refer to land use with more detail than general land use classes. The selection of the LUTs is the essential requirement of the application of the FAO framework, and it has a number of parameters that should be determined within the classification of LUTs: physical, economic and social factors (FAO, 1976). According to the GMPR (2008), the plan is for the study area to accommodate three cash crops, barley, wheat and maize, and these crops are designed to be grown in large and small farms under irrigation conditions. The irrigation scheme will be designed for the study area selected to meet local requirements for these strategic commodities. The main aims for the irrigation scheme in Jeffara Plain region is:

- To give a good chance for the coastal aquifers to recover part of the groundwater lost over the previous years.
- Cultivation and development of large areas of land which remain currently ideal through lack of adequate irrigation water.
- Agricultural expansion to persuade people in the rural areas in the Jeffara Plain region to stay on their lands or farms, thus relieving the population pressure in big cites such as Tripoli (GMBR, 2008).

The irrigation scheme for the study area will be divided into two levels of distribution. In the Jeffara Plain region, the primary networks take the water from the main pipeline system at the end of the reservoirs to the agricultural reservoirs. From the agricultural reservoirs, water is to be pumped to the proposed farms at the pressures required for the irrigation equipment (GMBR, 2008). The centre-pivot system was chosen by the GMPR project to irrigate all the selected lands in the Jeffara Plain region of Libya. The center – pivot system was chosen by the GMPR project to irrigate all the selected lands in the Jeffara Plain region of Libya.

Brief descriptions of the selected LUTs in the study area are shown in Table 7.3, 7.4 and 7.5.

Table 7.3: Definition and description of LUT1 in the study area

Characteristic	**Description of LUT1**
Level of inputs	High
Produce & production	Irrigated barley
Market orientation	Commercial production
Capital intensity	High
Labour intensity	Medium
Mechanization	Mechanized farming
Infrastructure	Market accessibility and distribution centre should be improved
Land tenure	Farms findings by the GMPR and ARC
Water inputs	Carefully controlled irrigation with water pumped from the agricultural reserves to the area under consideration

Source: Nwer, 2005; GMBR, 2008

Table 7.4: Definition and description of LUT2 in the study area

Characteristic	**Description of LUT2**
Level of inputs	High
Produce & production	Irrigated wheat
Market orientation	Commercial production
Capital intensity	High
Labour intensity	Medium
Mechanization	Mechanized farming
Infrastructure	Market accessibility and distribution centre should be improved
Land tenure	Farms findings by the GMPR and ARC
Water inputs	Carefully controlled irrigation with water pumped from the agricultural reserves to the area under consideration

Source: Nwer, 2005; GMBR, 2008

Table 7.5: Definition and description of LUT3 in the study area

Characteristic	Description of LUT3
Level of inputs	High
Produce & production	Irrigated wheat
Market orientation	Commercial production
Capital intensity	High
Labour intensity	Medium
Mechanization	Mechanized farming
Infrastructure	Market accessibility and distribution centre should be improved
Land tenure	Farms findings by the GMPR and ARC
Water inputs	Carefully controlled irrigation with water pumped from the agricultural reserves to the area under consideration

Source: Nwer, 2005; GMBR, 2008

7.6.2 Land Qualities and Land Characteristics in the Study Area

Land qualities (LQs) are estimated or measured by means of land characteristics (LCs). Land characteristics, as described in Chapter 3, refer to an element of land that can be measured and estimated. According to the GMPR report (2008), the following land qualities and land characteristics (Table 7.6) have a major effect on land suitability evaluation for cash crops in the study area.

Table 7.6: The selected land qualities and land characteristics in the study area.

Land Qualities	**Land Characteristics**	**Unit**
Rooting condition	Rootable depth	cm
	Soil texture	Class
Moisture availability	Available-water-holding capacity (AWHC)	mm/m
Nutrient availability	Soil reaction	pH
Nutrient retention	Organic matter	%
	Cation Exchange Capacity	me/100g soil
Excess of salts	Soil salinity (EC)	dS/cm
	Soil Alkalinity (ESP)	%
Calcium carbonate	$CaCO_3$ in root zones	%
Condition for germination	Stones at surface	%
Oxygen availability	Soil drainage classes	(mm/h)
Infiltration	Infiltration rate	(mm/h)
Potential for mechanisation	Slope steepness	%
Erosion hazard	Soil erosion	Class

Source: Sys et al., 1993; Nwer, 2005; GMBR, 2008

The GMPR reported that the selection of land qualities and land characteristics was made according to local conditions. These choices were based on an extensive overview of the literature and on trials from the local study area.

7.6.2.1 Rooting conditions: This land quality was assessed using the combination of two land characteristics:

- **Soil texture**: Soil texture is considered one of the most important soil criteria affecting soil behaviour and land management, and it influences a number of physical and chemical soil characteristics, such as total porosity, wilting moisture, aeration porosity and soil fertility (Brady, 1984; Brady and Wile, 1999).
- **Rootable depth:** Rootable depth is an essential requirement in land suitability classification. It is identified as a key for many soil characteristics, such as soil drainage, irrigation conditions and yields for all crops (Engelstad et al., 1961; Mayaki et al., 1976). Each crop has an optimum soil depth and this depth differs from crop to crop.

7.6.2.2 Moisture availability: One land characteristic was employed to evaluate this land quality:

- **Available water holding capacity (AWHC)**: AWHC is considered an important soil criterion in land suitability classification and planning for irrigation. It is defined as the amount of water that can be stored in soils for plants to utilize during periods without rain or irrigation, and therefore this property of soil is used as an indication of soil droughtiness and wetness (ILACO, 1989; Landon, 1984).

7.6.2.3 Nutrient availability: To assess nutrient availability for the selected crops, only one land characteristics was used:

- **Soil reaction (Soil pH)**: Soil pH is the most important soil criterion in land suitability classification and it controls many chemical soil characteristics and some physical soil properties. Soil reaction controls the solubility of most soil minerals; for example, high soil pH leads to low micronutrient availability and decreases the availability of macronutrients such as calcium, magnesium and phosphorus (Brady and Weil, 1984; 1999). The majority of plants prefer to grow in pH between 5 and 7.5 (Donahue et al., 1971).

7.6.2.4 Nutrient retention: Two land characteristics were taken into consideration to evaluate this land quality:

- **Soil organic matter:** This is a very important soil criterion and is considered the main source for many elements in soil. Soil organic matter supplies soils with nitrogen, phosphorus and sulphur, and helps to maintain the aggregates of soils and increase resistance to erosion. Increasing organic matter in soils will increase the amount of water for plant growth (Brady and Weil, 1984).
- **Cation exchange capacity (CEC)**: The cation exchange capacity (CEC) is used as one way of estimating soil fertility. Soils with a high value of CEC are considered fertile, and soils with a low value of CEC are considered infertile (London, 1984). The cation exchange capacity is used as a parameter for the buffering capacity for fertilizers. The natural fertility level and the buffering capacity do not strongly interact in their influence on the crop and are treated as separate components of the land quality (FAO, 1976).

7.6.2.5 Excess of salts: To assess this land quality, combinations of two land characteristics were used:

- **Soil salinity**: Saline soils are those soils which have an electric conductivity (EC mmohs/cm) of more than 2; salinity refers to the total concentration of all salts in the soils. Soil salinity is a really serious problem for the majority of arid zone soils. A high quantity of salts in soils leads to a decrease in crop production. Plants differ in their resistance and responses to salts (Tanji, 1996).
- **Soil alkalinity**: Solonetzic soils are those soils that have an exchangeable sodium percentage (% ESP) of more than 15 and also have a high value of soil pH (mostly in the range of 8.5 to 10). Soils vary in their quantity of sodium, and plants have different responses to being grown in solonetzic soils; most plants cannot resist the high value of the ESP (Ben Mahmoud, 1995).

7.6.2.6 Soil toxicities: his land quality was evaluated using:

- **Soil calcium carbonate:** Soil $CaCO_3$ is also identified as an important soil criterion for agricultural crops in Libya. This criterion affects soil moisture regime and availability of nutrients to plants (FAO, 2002).

7.6.2.7 Condition for germination: This was evaluated by taking into account the following land characteristics:

- **Stones at surface**: Stones at the surface have different effects on agricultural functions such as crop cultivation, crop harvesting and seed germination. Increasing stones at the surface may limit the use of mechanization (Nwer, 2005).

7.6.2.8 Oxygen availability: This land equality was assessed using:

- **Soil drainage**: Soil drainage is an important soil criterion in land suitability classification, and is also considered one of the most important requirements that should be taken into account in designing agricultural lands under irrigation conditions (FAO, 1979). It refers to oxygen availability to the roots and in some cases could lead to reduced plant growth and yields.

7.6.2.9 Infiltration: This land quality has been evaluated using:

- **Infiltration rate**: This refers to the entry of water into the soils. Infiltration rate is affected by many physical soil characteristics such as soil texture and structure (Diamond and Shanley, 2003).

7.6.2.10 Erosion hazard: This has been evaluated using:

- **Soil erosion:** Erosion is also an important land characteristic in land suitability classification. The effect of erosion hazard is to decrease soil quality and agricultural productivity. Soil erosion degrades the soil fertility and also leads to a loss of vegetation cover (Bakker et al., 2004).

7.6.2.11 Potential for mechanization: This has been assessed on the basis of slope steepness:

- **Slope steepness:** This is considering an important factor in land suitability classification and irrigation assessment. It affects on the irrigation methods, irrigation efficiency, soil drainage, soil erosion, labour requirements and mechanization type (FAO, 1979; Nwer, 2005).

All land qualities and land characteristics that have a major affect on crop growth and production in the study area have been defined. The selected land characteristics and their threshold values are shown in Tables 7.7, 7.8 and 7.9.

Table 7.7: Land suitability classes and their threshold values for barley.

	Suitability classes*			
Land Characteristics	**S1**	**S2**	**S3**	**N1**
Rootable depth(cm)	>80	80-50	>50-30	<30
Soil texture class	1	2	3	4
AWHC (mm/m)	>150	110-150	110-75	<75
Soil pH	8-6.5	6.5-5.3	5.3-5	<5, > 8
% organic matter	>1.5	1.5-1	<1-0.5	<0.5
CEC (me/100g soil)	>16	>8-16	5-8	<5
soil salinity (EC)	0-8	>8-10	>10-13	>13
% ESP	0-15	>15-25	>25-50	>50
% $CaCO_3$ in root zones	0-20	>20-30	>30-40	>40
% stones at surface	0-3	>3-9	>9-20	>20
Soil drainage classes (mm/h)	>125	>42-125	17-42	<17
Infiltration rate (mm/h)	>12	>8-12	6-8	<6
% slope steepness	0-2	> 2-4	>4-8	> 8
Soil erosion (classes)	N	S	M	H

Source: Sys et al., 1993; Nwer, 2005; GMBR, 2008

Table 7.8: Land suitability classes and their threshold values for wheat.

	Suitability classes*			
Land Characteristics	**S1**	**S2**	**S3**	**N1**
Rootable depth(cm)	>120	120-100	>100-50	<30
Soil texture class	1	2	3	4
AWHC (mm/m)	>150	110-150	110-75	<75
Soil pH	7.5-6.5	6.5-5.5	5.5-5	<5,>8
% organic matter	>1.5	1.5-1	<1-0.5	<0.5
CEC (me/100g soil)	>24	16-<24	8-16	<8
soil salinity (EC)	0-6	>6-7.4	>7.4-9.5	>9.5
% ESP	0-10	>10-25	>25-35	>35
% $CaCO_3$ in root zones	0-20	>20-30	>30-40	>40
% stones at surface	0-3	>3-9	>9-20	>20
Soil drainage classes (mm/h)	>125	>42-125	42-17	<17
Infiltration rate (mm/h)	>12	>8-12	6-8	<6
% slope steepness	0-2	> 2-4	>4-8	> 8
Soil erosion (classes)	N	S	M	H

Source: Sys et al., 1993; Nwer, 2005; GMBR, 2008

Table 7.9: Land suitability classes and their threshold values for maize.

	Suitability classes*			
Land Characteristics	**S1**	**S2**	**S3**	**N1**
Rootable depth(cm)	>120	120-100	>100-50	<30
Soil texture class	1	2	3	4
AWHC (mm/m)	>150	110-150	110-75	<75
Soil pH	6-7	5.5-6	5-5.5	<5->8.5
% organic matter	>1.5	1.5-1	<1-0.5	>0.5
CEC(me/100g soil)	>24	16->24	8-16	<8
soil salinity (EC)	0-1.7	>1.7-2.5	>2.5-3.7	>3.7
% ESP	0-8	8-15	15-25	>25
% $CaCO_3$ in root zones	0-15	15-20	20-35	>35
% stones at surface	0-3	>3-9	>9-20	>20
Soil drainage classes (mm/h)	>125	>42-125	42-17	<17
Infiltration rate (mm/h)	>12	>8-12	6-8	<6
% slope steepness	0-2	> 2-4	>4-8	> 8
Soil erosion (classes)	N	S	M	H

Source: Sys et al., 1993; Nwer, 2005; GMBR, 2008

Suitability classes*: highly suitable (S1), moderately suitable (S2), marginally suitable (S3) and currently not suitable (N1). **Soil texture classes*:** (1) silt, silty clay loam, clay, loam, clay loam; (2) sand clay, sandy, clay loam; (3) loamy sand; (4) sand. **Soil Erosion classes***: (N) no erosion, (L) low or slight erosion, (M) moderate erosion, (H) high or severe erosion.

The selected land qualities and land characteristics (Tables 7.7, 7.8 and 7.9) will be included in land suitability evaluation models in this research under irrigation conditions, and, therefore, the irrigation scheme which is to be designed in the near future in the study could lead to alterations in the land qualities and land characteristics and their parameters.

7.7 Weighting Factors

Weighting the model criteria provides relative measures of the interaction and importance of the criteria. Weights for the model criteria have been obtained through the pairwise comparison analysis, the main requirement for the application of the analytical hierarchy process (AHP). The pairwise comparison analysis was chosen because it allows the decision makers to assign different levels of importance to the different factors involved in land suitability. Different weights were assigned to different land properties that need to be considered for the land suitability classification for barley, wheat and maize.

Four local experts who are interested in this field of study (i.e. land evaluation and land resources) were selected to use their experience to assign different weights to the selected land characteristics for barley, wheat and maize, and this task was done during a visit to the study area in 2009 (Appendix B). The local experts played an important role in the process of land suitability and in the iterative adjustment of weights to improve the consistency ratio to ≤ 0.1. The weights that must be used for the pairwise comparison analysis should have a consistency ratio (CR) ≤ 0.1. The CR ≤ 0.1 shows that the comparisons of land characteristics were perfectly consistent, and the relative weights are appropriate for use in land suitability evaluation. The calculation of the CR for the selected land characteristics for barley, wheat and maize was made. The pairwise comparison 9-point continuous scale (i.e. 1/9, 1/7, 1/5, 1/3, 1, 3, 5, 7 and 9) was tested in the matrices on the basis of discussion with local experts to derive the CR for the selected land attributes within the established acceptable limits (0.1). For example, 1/3 was assigned if the land attribute in the column (e.g. % calcium carbonate) is less important than the land attribute in the row (e.g. soil texture), 1 was assigned if the land attribute in the column is equal to the land attribute in the row, and 3 means that the land attribute in the column (e.g. soil texture) is more important than a land attribute in the row (e.g. slope).

Figure 7.9: An example of a pairwise comparison matrix for barley.

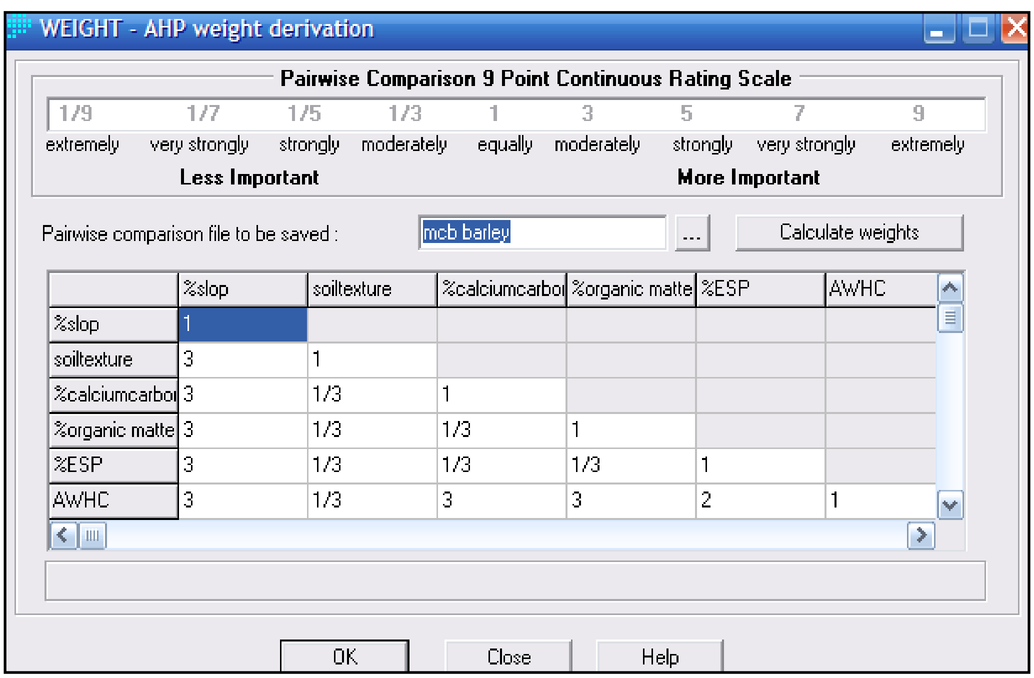


Figure 7.10: An example of a pairwise comparison matrix for wheat.

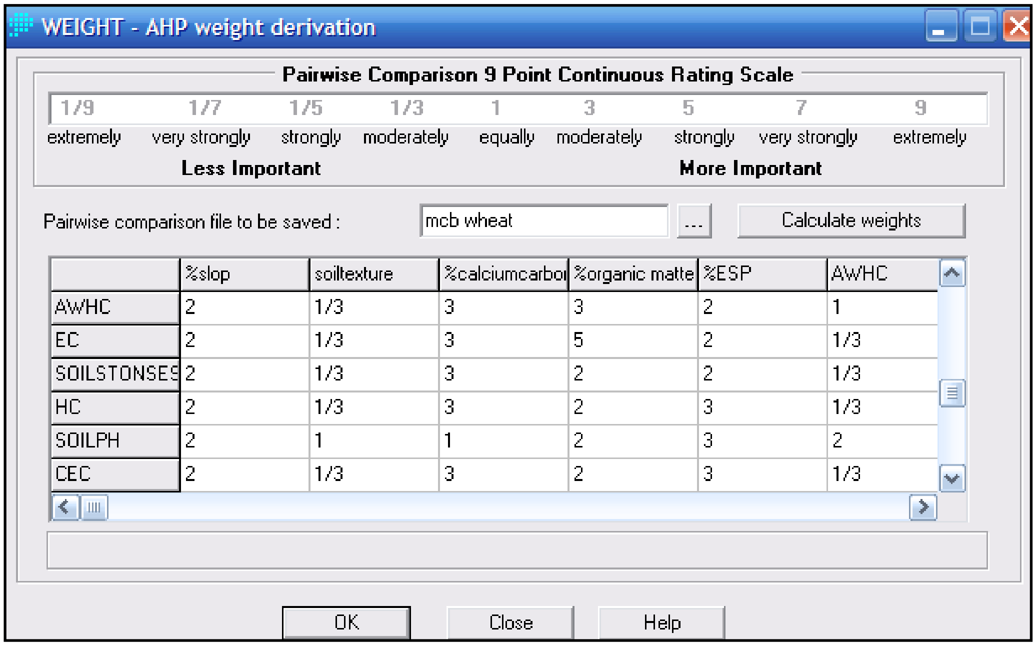
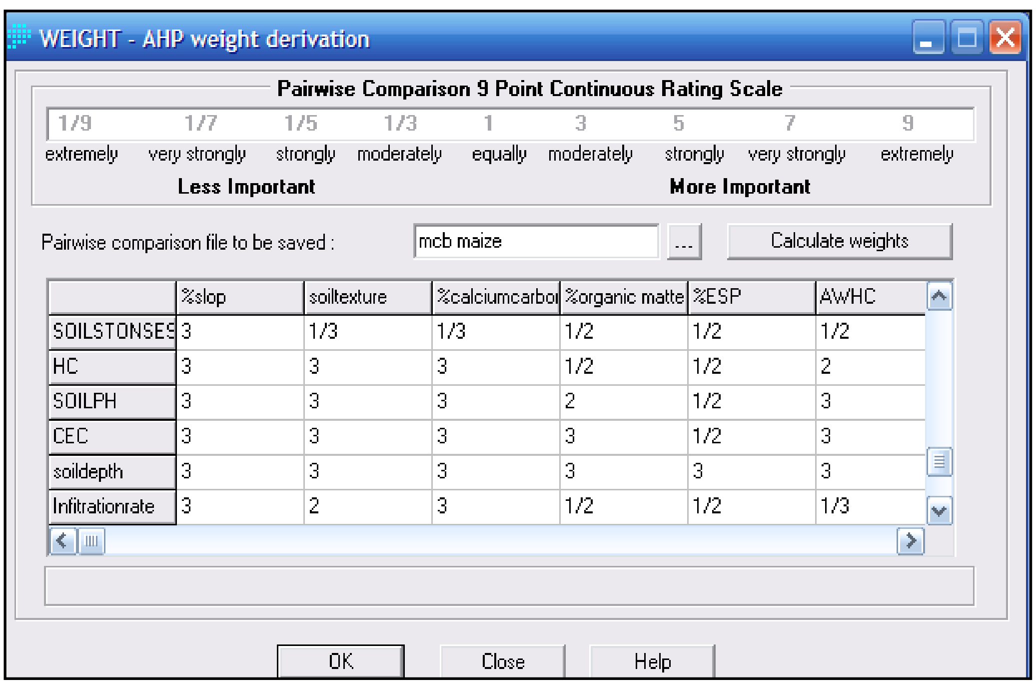


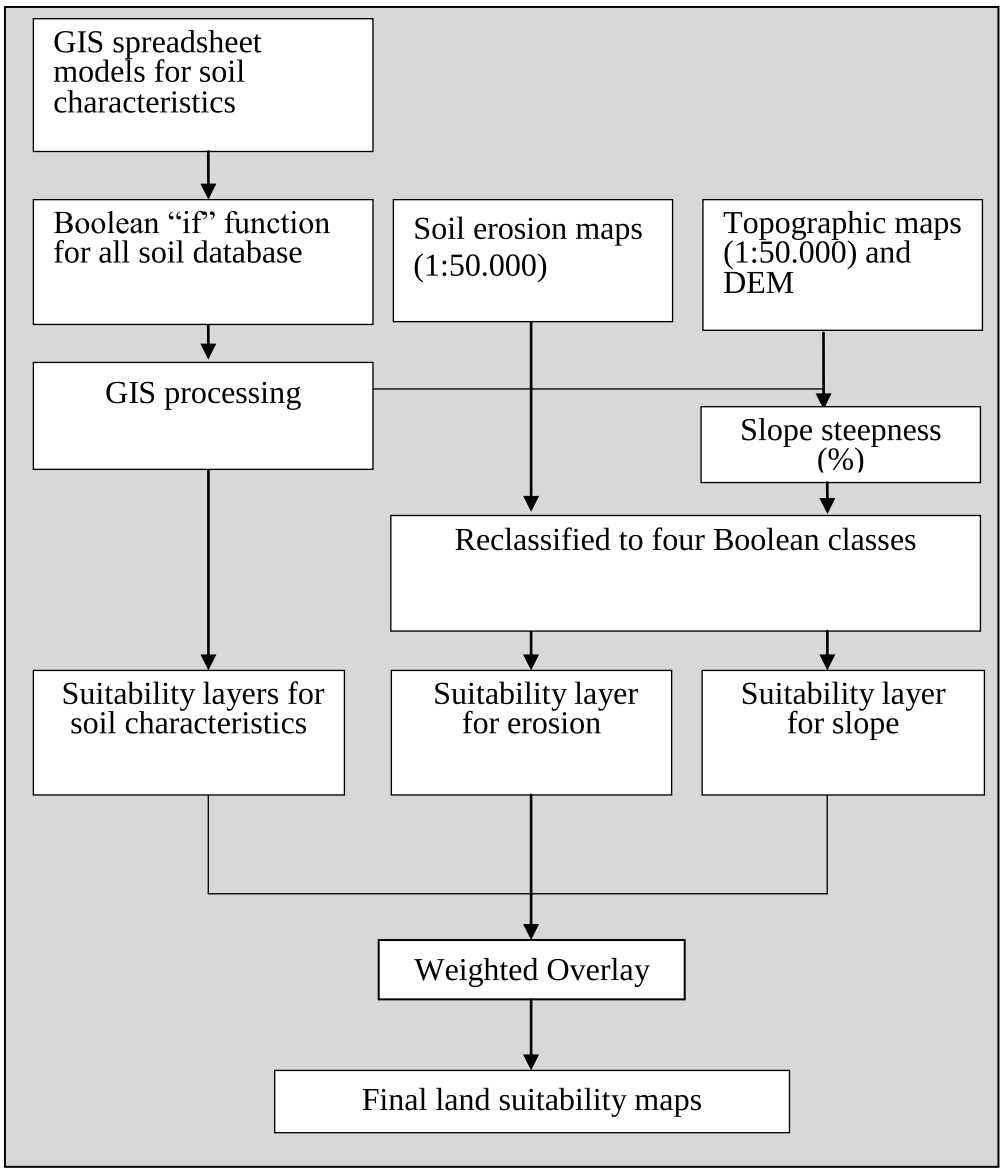
Figure 7.11: An example of a pairwise comparison matrix for maize.



7.8 Boolean Modelling for Land Suitability Evaluation

The FAO framework for land evaluation based on Boolean logic for the study area selected under irrigation conditions has been divided into four main stages in this research (figure 7.12). These stages are:

Figure 7.12: Land suitability evaluation model using Boolean mapping.



Stage 1: **Generation of soil characteristics thematic maps**

At this stage, soil characteristics defined in Tables 7.7, 7.8 and 7.9 were formulated in GIS spreadsheet models to derive the suitability of land for the selected crops. Physical and chemical soil characteristics were stored in spreadsheet models, then the Boolean "if" functions for all soil properties were written to set the limits between land suitability classes for each land area. The overall soil suitability classes for the selected crops were determined and then exported to a GIS database to create soil suitability classes as map layers.

Stage 2: Generation of suitability map for topography

The percentage of slope for the study area selected was created from the Digital Elevation Model (DEM).

Stage 3: Generation of suitability map for soil erosion

Soil erosion maps for the study area selected were reclassified to four Boolean suitability classes using Tables 7.7, 7.8 and 7.9, and then the final soil erosion map was created.

Stage 4: Using weighted overlay technique to produce the final land suitability maps

Once all land characteristics affecting barley, wheat and maize production in the study area have been assessed to produce Boolean maps, the weights computed from the pairwise comparison analysis are multiplied with each map layer to obtain the overall land suitability maps for the selected crops.

7.9 Framework of Land Evaluation Suitability Decision Making

The decision-making problem of land evaluation suitability for agricultural crops under irrigation conditions is analyzed in this research using two decision-making models: fuzzy analytical hierarchy process (Fuzzy AHP) and Ideal Point. The framework of land evaluation decision making was divided into 3 stages. The stages are:

- Selection of land utilization types- barley, wheat and maize.

  Barley, wheat and maize crops have been selected for the framework of land suitability decision making. The aim of the selection of these crops has been discussed in section 7.6.1.

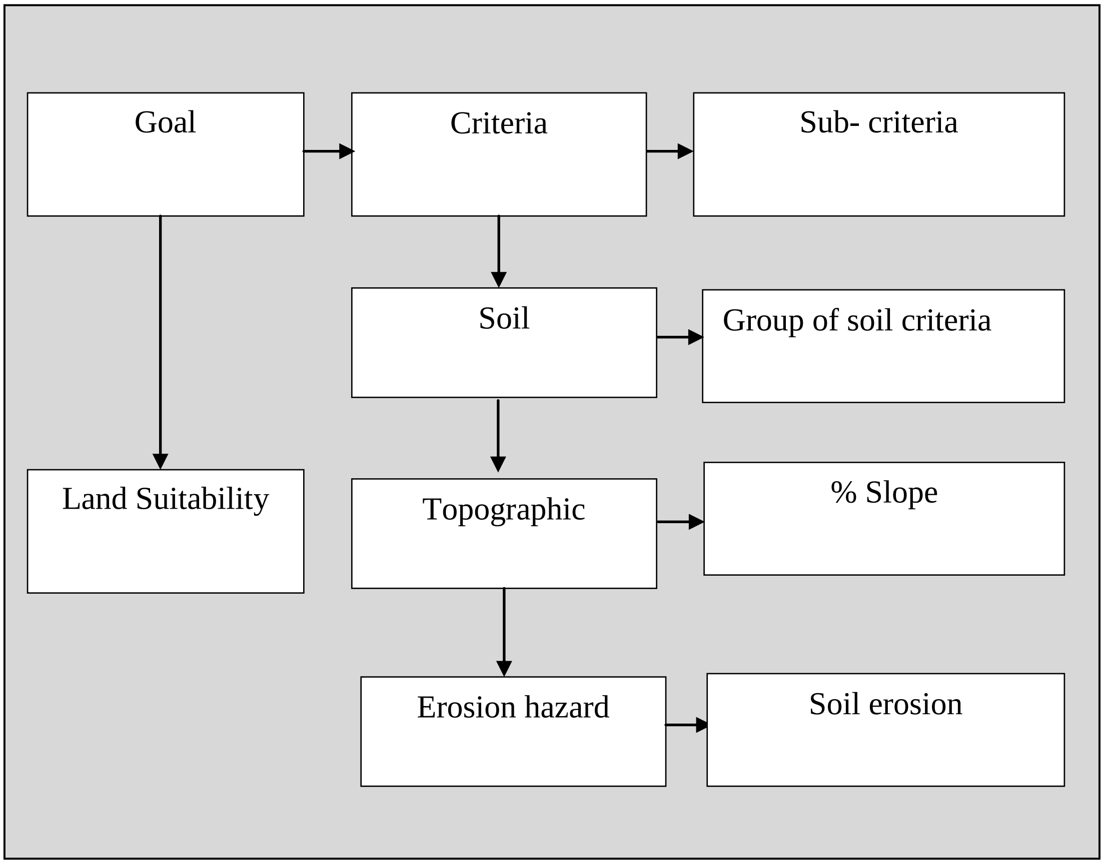
- Selection of the Evaluation Criteria:

  A set of criteria was identified on the basis of discussions with local experts and a literature survey for the study area. The selected criteria for land suitability for barley, wheat and maize are: soil texture, rootable depth, available water holding capacity (AWHC), soil reaction (soil pH), soil organic matter (percentage OM), cation exchange capacity (CEC), soil salinity (EC), soil alkalinity (EC), soil calcium carbonate (percentage $CaCO_3$), stones at surface, soil drainage, infiltration rate, soil erosion and slope steepness (GMPR, 2008).

- Hierarchical organization of criteria

  The relationships amongst the goal, criteria and sub-criteria have a hierarchical structure, with the highest level having the overall goal and the lowest level the decomposed sub-criteria (figure 7.10).

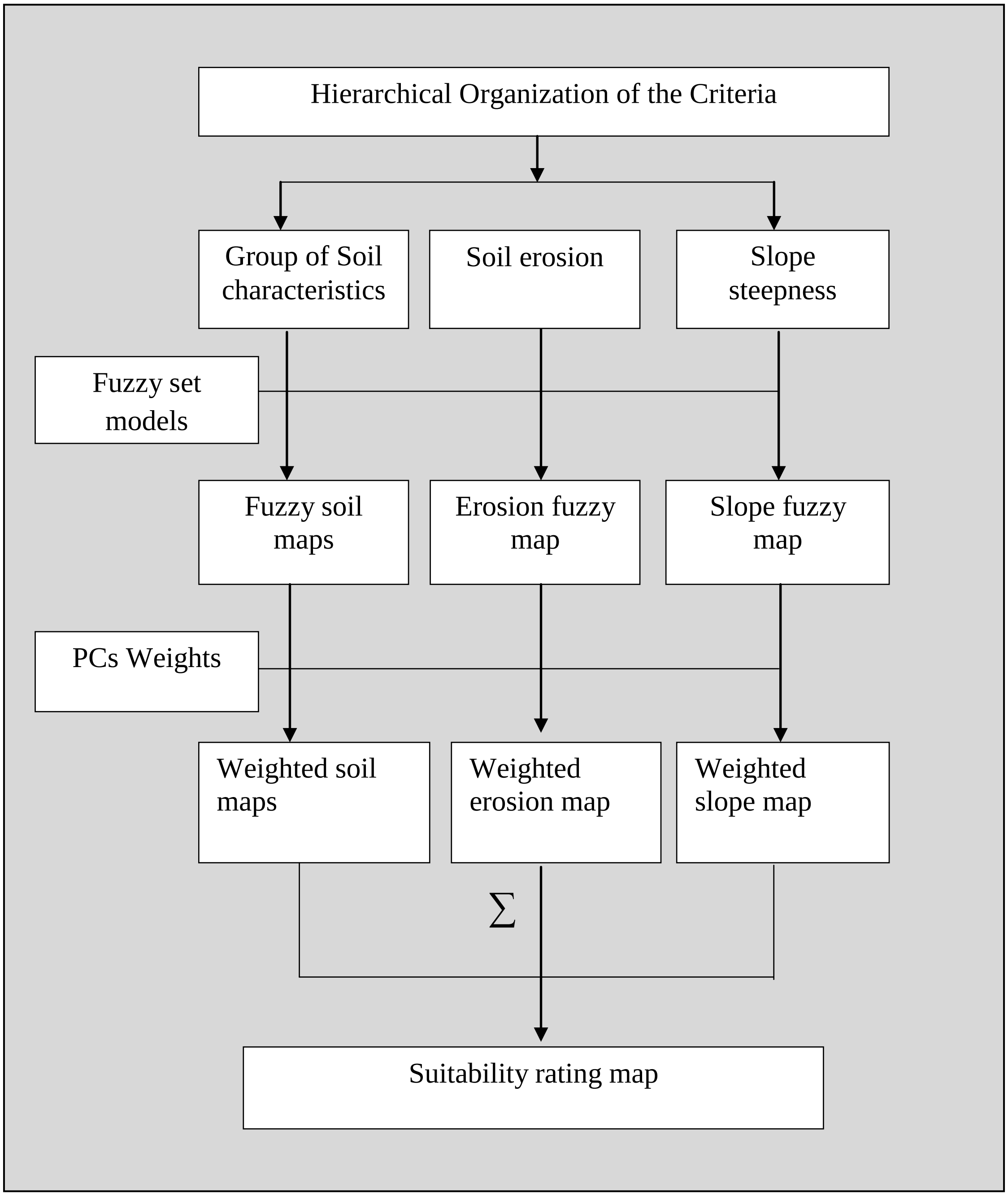
Figure 7.13: Hierarchical organization of the criteria in the study area.



7.9.1 Fuzzy AHP Modelling for Land Suitability Evaluation

In order to make comparisons between Boolean and Fuzzy AHP methods for land suitability, the same land qualities and land characteristics were applied. The Fuzzy AHP approach for land suitability evaluation under irrigation conditions was divided into four stages and is shown in figure 7.14.

Figure 7.14: Land evaluation model using Fuzzy AHP approach.



Stage 1: Defining the parameters affecting the suitability of land for crops

As stated earlier, fourteen criteria of land quality affecting the suitability of land for barley, wheat and maize crops in the study area have been identified, and these parameters were covered in section 7.6.2.

Stage 2: Standardizing land characteristics

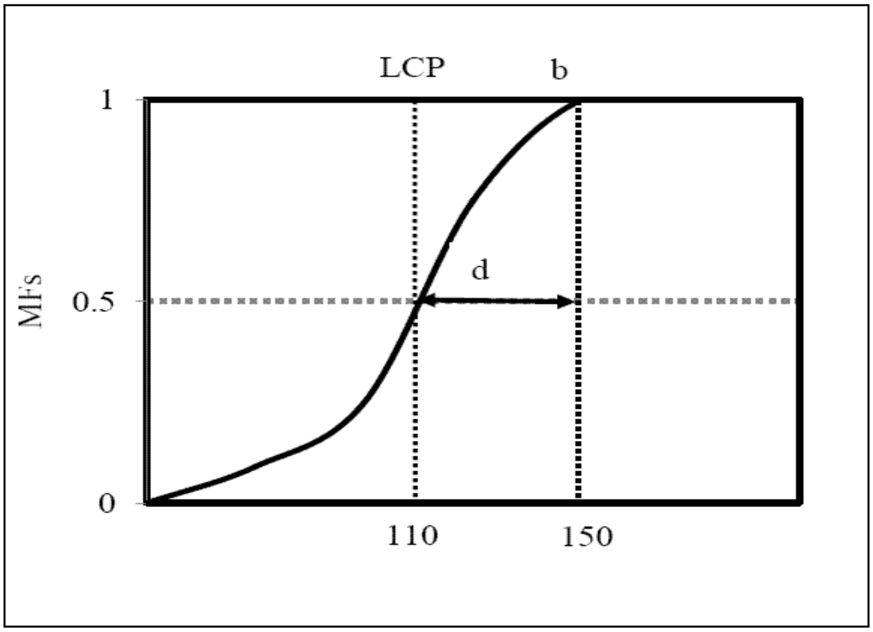
As mentioned in Chapter 6, the asymmetrical and symmetrical models were used to convert the selected land properties to a range of membership function values (Burrough, 1989; Davidson et al., 1994; McBratney and Odeh, 1997; Baja et al., 2001; Moreno, 2007). Table 7.10 shows fuzzy set models used to convert the selected criteria to the fuzzy numbers in the study area.

Table 7.10: Fuzzy set models for the selected land characteristics in the study area.

Land characteristics	Fuzzy set models
Rootable depth (cm)	Asymmetrical left
AWHC (mm/m)	
% organic matter	
CEC (me/100g soil)	
Soil drainage classes (mm/h)	
Infiltration rate (mm/h)	
soil salinity (EC)	Asymmetrical right
% ESP	
% $CaCO_3$ in root zones	
% stones at surface	
% slope	
Soil texture (class)	
Soil erosion (class)	
Soil pH	Symmetrical model

An example of the conversion of a soil characteristic (AWHC) with a continuous scale into a membership function is shown in figure 7.15.

Figure 7.15: Membership functions for available water holding capacity (AWHC) for the selected crops.



For the AWHC, the ideal point (b) was set at 150 mm/m while LCP (i.e. marginal or S3) was set at 110 mm/m and d = b –LCP (150-110 = 40).

The membership functions are:

$MF_{(AWHC)} = [1/\{1 + 1/40^2(\chi - 150)^2\}]$ 7.1

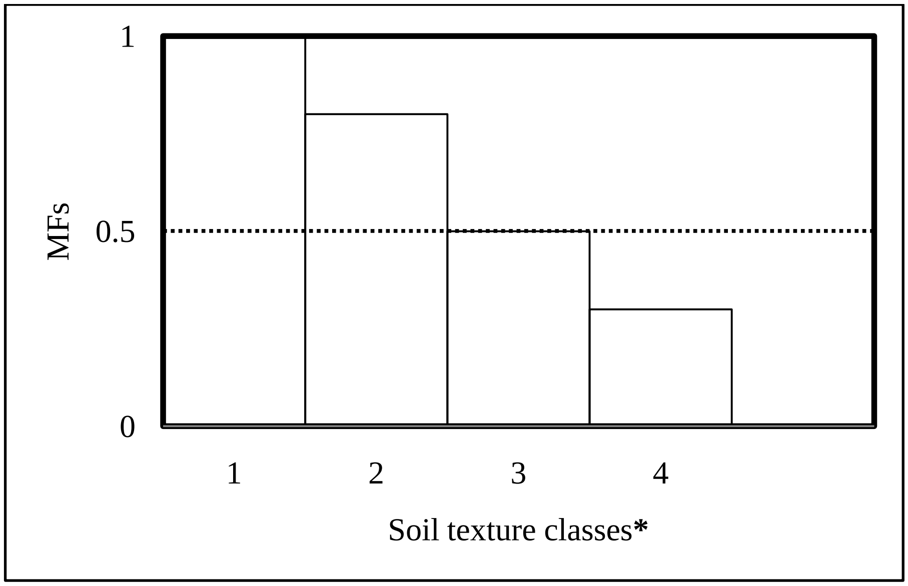
$\mathrm{MF}_{(\mathrm{AWHC})} = 1 \text{ for } \chi > 150$ 7.2

$\mathrm{MF}_{(\mathrm{AWHC})} = 1 \text{ for missing values}$ 7.3

where (χ) , is the value of AWHC: mm/m

Land properties which were given in classes such as soil texture and soil erosion have been converted to fuzzy numbers, based on the value of the characteristics. For example, in the case of soil texture for the crops, where data are ordinal consisting of four categorical classes, 1, 2, 3 and 4, the model shown in figure 7.16 was employed.

Figure 7.16: The membership functions of soil texture classes for the crops.



Source: Baja et al., 2001

Soil texture classes*: (1) silt, silty clay loam, clay, loam, clay loam; (2) sand clay, sandy, clay loam; (3) loamy sand; (4) sand.

In this stage, fuzzy maps for all land characteristics for the three crops have been produced. The fuzzy maps have a continuous scale between 0 and 1, where 1 is highly suitable classes and 0 not suitable classes.

Stage 3: Derivation of the weighted criterion map layers

The weighted criterion layers are generated using the following function:

$$\mathrm{WF_{kn}} = \mathrm{W_i} \times \mathrm{MF_i} \qquad 7.4$$

where is W_i is weight of the land property from the pairwise comparison and MF_i is the membership function for the land property.

Stage 4: Derivation of the overall land suitability map layers

The suitability is calculated by combining the weighted criterion layers. This function sums the weighted maps of the different land properties to obtain land suitability maps at final level:

$$R_i = WF_{K1} + WF_{K2} + WF_{K3} + \dots \dots \dots \dots \dots \dots WF_{Kn} \qquad 7.5$$

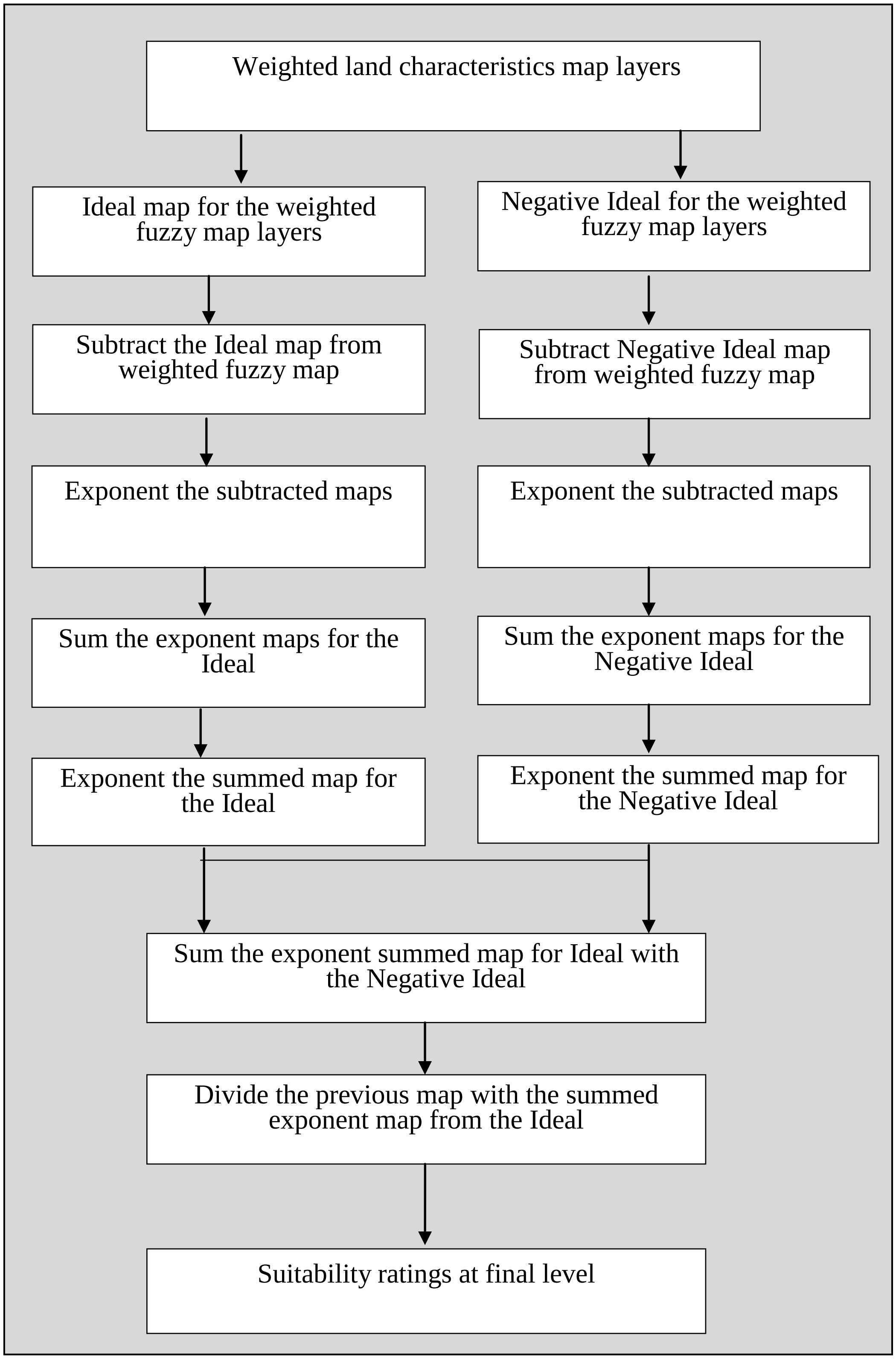
Where R_i , is the overall rating score for the suitability of land and WF_{Kn} is the weighted fuzzy value for the different land properties.

The overall land suitability maps show the overall land suitability classes with a continuous scale ranging from 0 to 1.

7.9.2 Land Suitability Evaluation Model Using Ideal Point Method

To derive land suitability maps for the selected crops on the basis of Ideal Point mapping, the weighted map layers for the selected crops created by previous methods are the input data. The stages of land suitability evaluation under irrigation conditions using the Ideal Point method are given in figure 7.17.

Figure 7.17: Land evaluation model using an Ideal Point method.



Stage 1: Determine the maximum and the minimum values

In this stage the maximum values (the values determining the ideal point) and minimum values (the values determining the negative ideal point) form the weighted map layer for each land characteristic.

Stage 2: Apply a separation measure to the positive ideal point

The distance between the ideal point and each alternative was calculated using the following equation:

$$si_{+} = [\sum_{j}(a_{ij} - a_{+j})^{2}]^{0.5} \tag{7.6}$$

where si_{+} is the separation of the alternative, a_{ij} is the weighted fuzzy map, and a_{+j} is the maximum value for the weighted fuzzy map.

Stage 3: Apply a separation measure to the negative ideal point

The distance between the negative ideal point and each alternative is determined using:

$$s_{i-} = [\sum_{j}(a_{ij} - a_{-j})^{2}]^{0.5} \tag{7.7}$$

where s_{i-} is the separation of the alternative, and a_{ij} is the weighted fuzzy map, a_{-j} is the minimum values for the weighted fuzzy map.

Stage 4: Create maps from compute the relative closeness to the ideal point

At this stage, the closeness between the ideal point and the alternatives was computed and created as map layers for crops using:

$$C_{i+} = \frac{s_{i-}}{si_{+} + s_{i-}} \tag{7.8}$$

where si_{+} and s_{i-} is the separation of the alternative and C_{i+} is closeness between the ideal point and the alternative.

Stage 5: Derive the final rating land suitability map layers

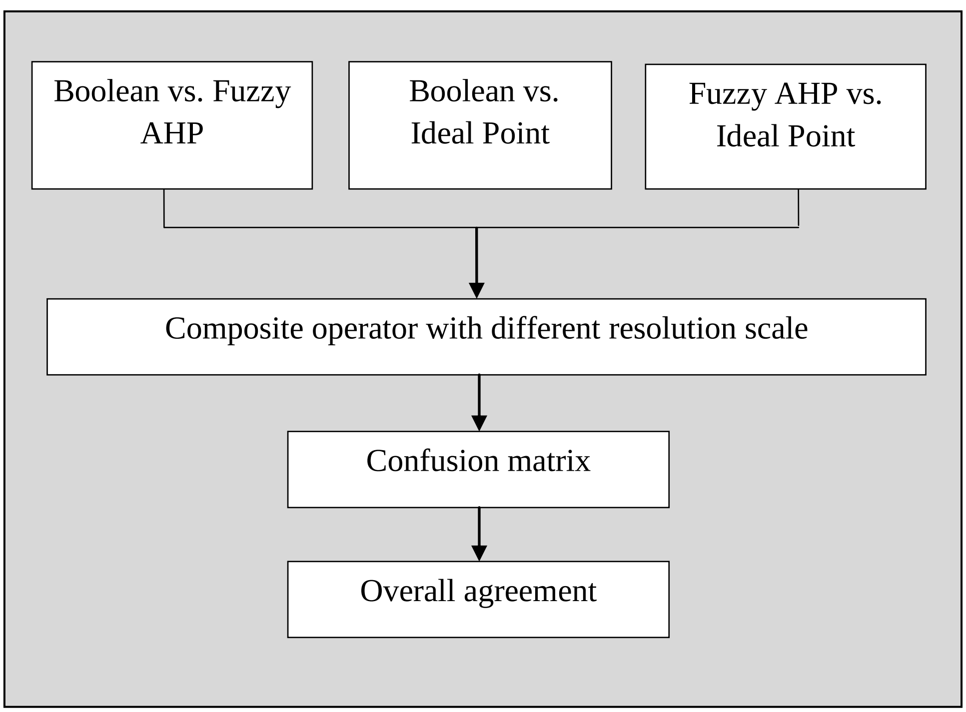
Land suitability maps for each crop were created as a continuous scale ranging from 0 to 1.

7.10 Model Validation/ Map Agreement

The resulting maps from the Boolean, Fuzzy AHP and Ideal Point methods were cross-tabulated with each other using soft classification with a multi-resolution analysis. The 256 (i.e. 48640× 4864) multiples of base resolution analysis was used to derive and check the overall agreements between the resulting maps.

The confusion matrix for each comparison was computed, and once the matrices from the comparisons were obtained, the overall agreements or kappa agreements were derived (figure 7.18).

Figure 7.18: showing validation of the results.



7.11 Summary

In this chapter, methods incorporating local knowledge from local experts and a literature review were used to define land utilization types, land qualities, land characteristics, and their threshold values.

According to the GMPR report, the main land characteristics affecting cash crop production in the study area are: rootable depth; AWHC; soil pH; percentage organic matter; electric conductivity; CEC; percentage ESP; percentage $CaCO_3$; percentage stones at surface; soil drainage; infiltration rate; soil texture; percentage slope; and soil erosion risk. These characteristics have been weighted using the pairwise comparison analysis, and furthermore local staff in Libya used their knowledge to assign different weights to the selected land characteristics for each crop. These weights are the basic requirement for deriving the overall land suitability maps for the selected crops.

Three models – Boolean, Fuzzy AHP and Ideal Point methods with the FAO framework for land evaluation – have been established for the selected cash crops in the study area. The Boolean model for land evaluation has been developed by taking into consideration the weights resulting from the pairwise comparison analysis after discussion with local staff. Furthermore, the Fuzzy AHP and Ideal Point methods have been used to explore and address the uncertainty associated with the traditional methods. All three land evaluation models are compared using Composite operator with different scale resolution. The overall agreement and disagreement between the maps has been computed.

One of the most important developments made in this chapter is the integration of different GIS approaches, functions and local knowledge within the process of land evaluation techniques in GIS environment for the study area selected.

CHAPTER 8

RESEARCH RESULTS

8.1 Introduction

In this research, Boolean mapping, Fuzzy Analytical Hierarchy Process (Fuzzy AHP) and Ideal Point methods were applied to derive land suitability maps for barley, wheat and maize. Land characteristics affecting the growth of selected crops were defined on the basis of literature reviews and discussions with relevant experts. The results of the weighting factors and all the three methodologies are put together here.

8.2 Results of Weighting Factors

As mentioned in Chapter 7, four local staff used their knowledge to assign different weights to the selected land characteristics for each crop. But only one set of results from the four local staff was accepted for use in land evaluation models in this research, because the consistency ratios which were obtained were within the established acceptable limits (0.1). The CR $\leq$ 0.1 shows that the comparisons of land characteristics were perfectly consistent, and the relative weights are appropriate for applying in land suitability evaluation models. The consistency ratios also show any inconsistencies that may have arisen through the pairwise comparison analysis. The results indicate that, for both barley and wheat, the eigenvalues or the weights of soil texture, available water holding capacity and soil reaction are higher than those of other criteria, while for maize the results reveal that the eigenvalues of rootable depth, soil salinity, soil reaction and soil alkalinity are higher than those of other criteria. In addition to this, the results show that the weights for the barley are similar to the weight for the wheat. The weights or eigenvalues resulting from the pairwise comparison analysis are shown in Table 8.1.

Table 8.1: The weights (Eigen-values) for the crops

Land characteristic	**Weights / eigenvalues for the crops**		
	Barley	**Wheat**	**Maize**
Soil texture	0.160	0.150	0.053
Available water holding capacity	0.124	0.123	0.061
Stones at surface	0.046	0.043	0.033
Rootable depth	0.079	0.080	0.147
Infiltration rate	0.058	0.059	0.057
Soil drainage	0.051	0.051	0.062
Calcium carbonate	0.043	0.042	0.035
Organic matter	0.036	0.035	0.060
Soil alkalinity	0.033	0.028	0.101
Soil reaction	0.124	0.132	0.102
Cation exchange capacity	0.062	0.062	0.097
Soil salinity	0.070	0.069	0.138
Slope steepness	0.021	0.032	0.021
Soil erosion	0.093	0.094	0.025

8.3 Summary of Weighting Factors Results

Fourteen land characteristics have been weighted through the pairwise comparison analysis. These characteristics are: physical soil properties (soil texture, available water holding capacity, stones at surface, rootable depth and infiltration rate); chemical soil properties (soil calcium carbonate, soil pH, soil organic matter, exchangeable sodium percentage and electric conductivity); and the percentage of slope and soil erosion.

The results in table 8.1 are expected to be changed when the water requirements for the selected crops are met in the study area, because as mentioned in the previous chapter land evaluation models in this study were designed under irrigation conditions.

The pairwise comparison method was used to weight these characteristics, because it allows the decision makers in the study area to assign different levels of importance to the different factors involved in land suitability evaluation. The derivation of weights for land evaluation suitability models was a central stage in defining the decision maker's preferences, and therefore the local experts played an important role in the process of land suitability and in the iterative adjustment of weights to improve the consistency ratio ≤ 0.1.

As mentioned in the research methodology, four local experts have used their experience to derive the weights for the selected land properties for each crop. Most local experts found some difficulties in using the pairwise comparison analysis and deriving weights with consistency ratios ≤ 0.1. One of the four local experts (i.e. Dr Bashir Nwer) used the pairwise comparison analysis perfectly and derived weights or measures of relative importance for the selected crops with CR ≤ 0. The weights derived from this local expert through the pairwise comparison analysis were acceptable for use in deriving land suitability maps for the selected crops in the study area, because they have consistency ratios equal to 0.1.

According to these eigenvalues, the results indicated that the most important parameters affecting the growth of barley and wheat crops under irrigation condition in the study area were soil texture, available water holding capacity and soil reaction, while the results showed that the most important variables affecting the growth of maize in the area under consideration were rootable depth, soil salinity, soil reaction and soil alkalinity.

8.4 Boolean Technique Results

The model outputs of land evaluation for barley, wheat and maize in the study area derived from the use of Boolean logic are shown below:

8.4.1 Barley Suitability Results

Figures 8.1 and 8.2 showed the results of land evaluation for barley derived by the Boolean method. The Boolean model shows that nearly 36 % of the total study area is highly suitable (S1) for barley; 39 % of the total study area is moderately suitable (S2) for barley production; 10 % of the total study area is marginally suitable (S3); 11 % of the total study area is currently not suitable (N1) for barley production.

Figure 8.1: Barley suitability under Boolean theory: Suitability in percentage of the total area.

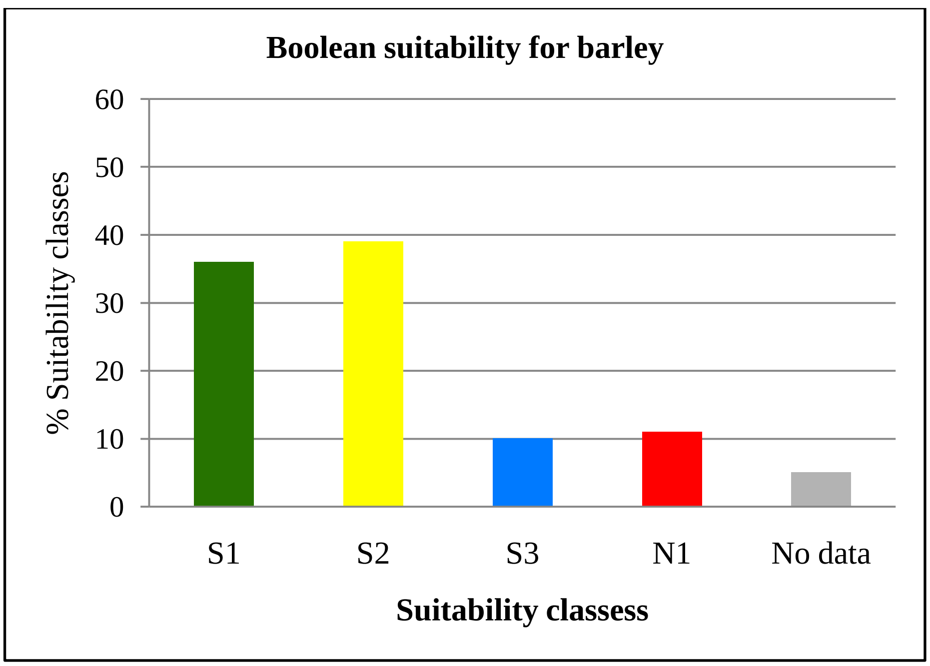
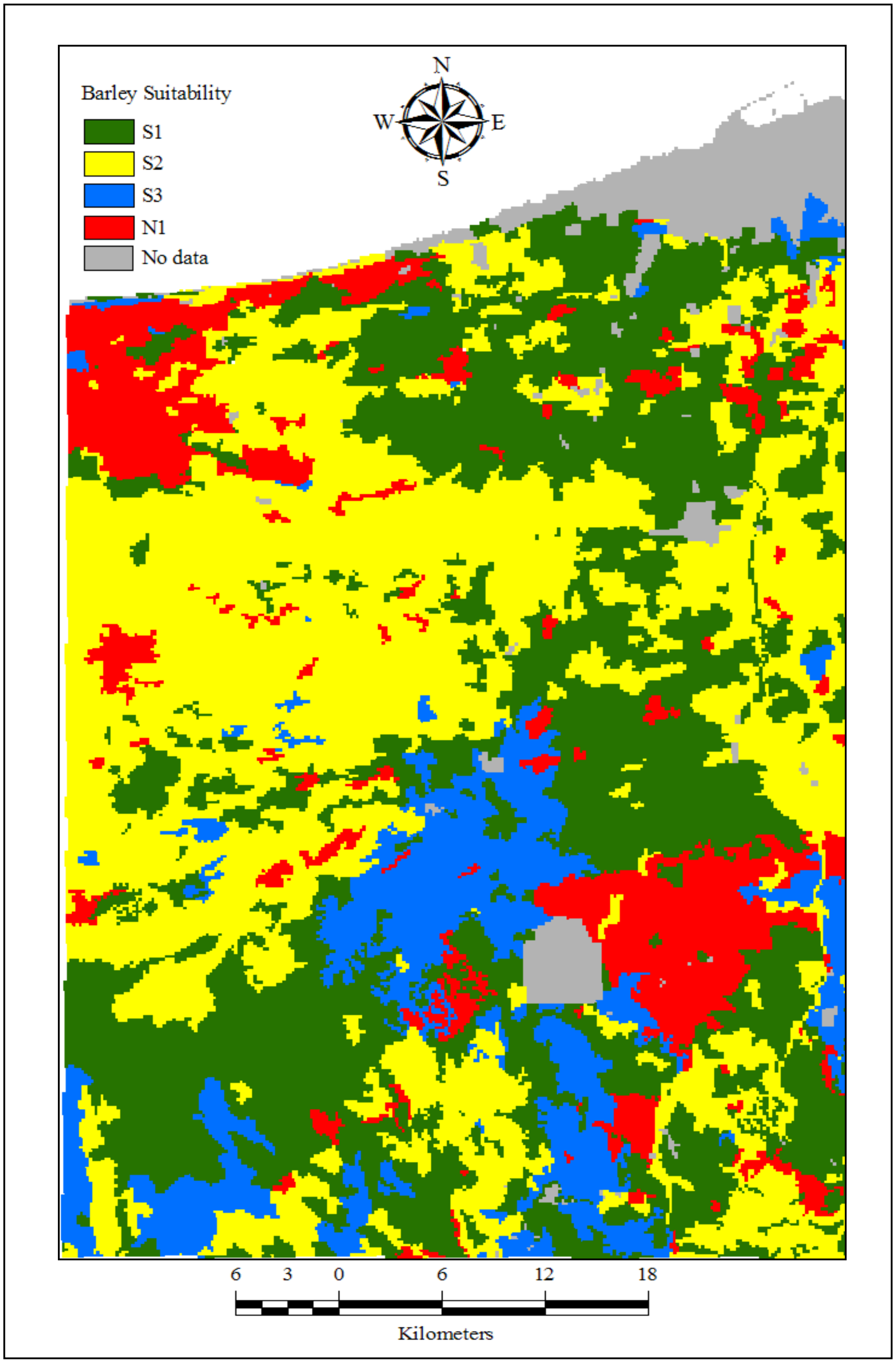


Figure 8.2: Land suitability map for barley based on Boolean mapping.



8.4.2 Wheat Suitability Results

Figures 8.3 and 8.4 present the model outputs of land evaluation for wheat obtained by using the Boolean method. The results show that 48 % of the total study area is highly suitable (S1) for wheat; 30% of the total study area is moderately suitable (S2) for wheat; 3 % of the total study area is marginally suitable (S3); 14 % of the total study area is currently not suitable (N1) for wheat.

Figure 8.3: Wheat suitability under Boolean theory: Suitability in percentage of the total area.

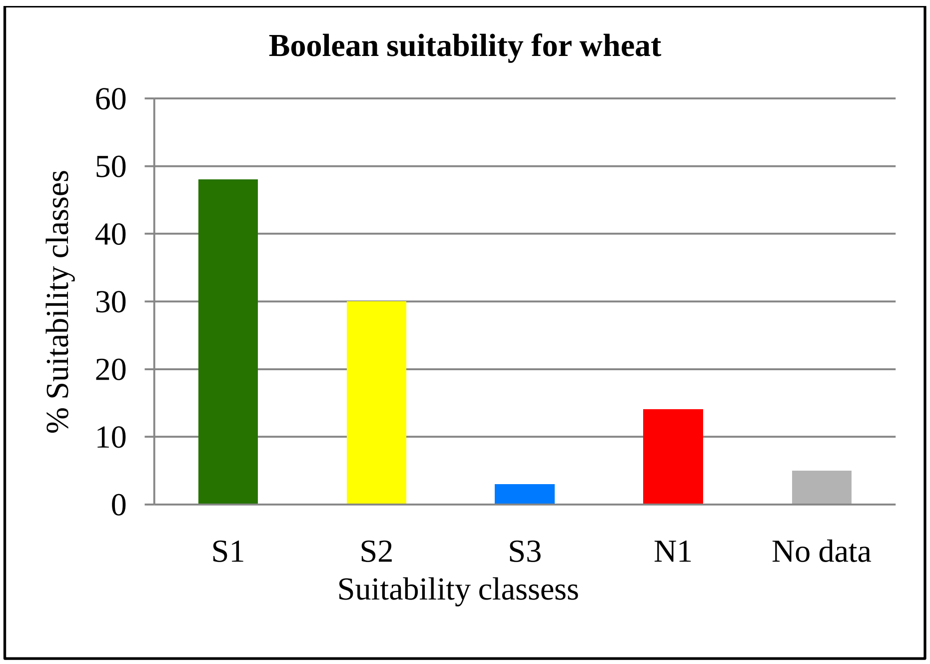
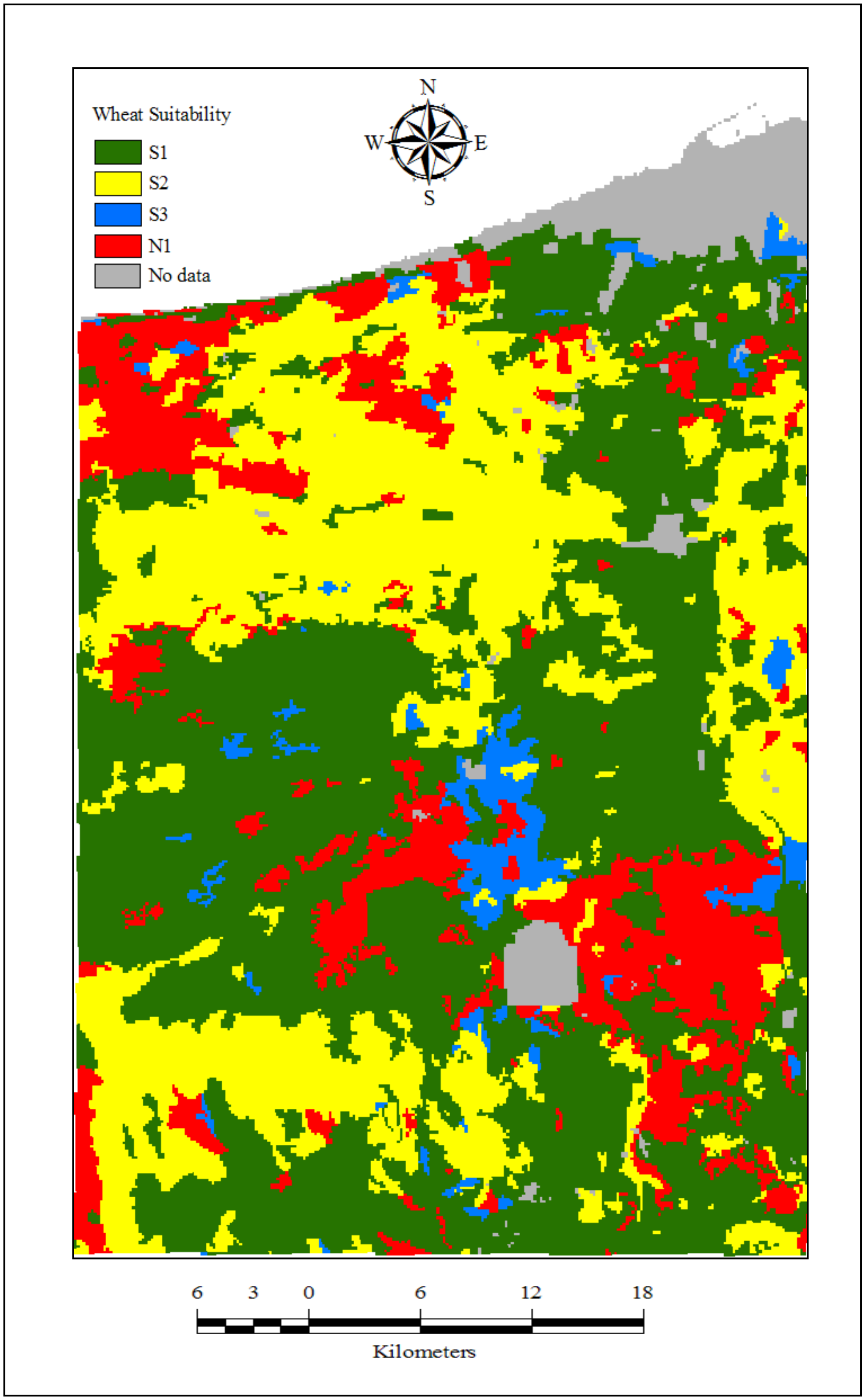


Figure 8.4: Land suitability map for wheat based on Boolean mapping.



8.4.3 Maize Suitability Results

Figures 8.5 and 8.6 showed the results of land evaluation for maize obtained by using Boolean theory. The results reveal that 46 % of the total study area is highly suitable (S1) for maize; 35 % is moderately suitable (S2) for maize; 9% of the study area is marginally suitable (S3) for maize; 6 % of the total study area is currently not suitable (N1) for maize production.

Figure 8.5: Maize suitability under Boolean theory: Suitability in percentage of the total area.

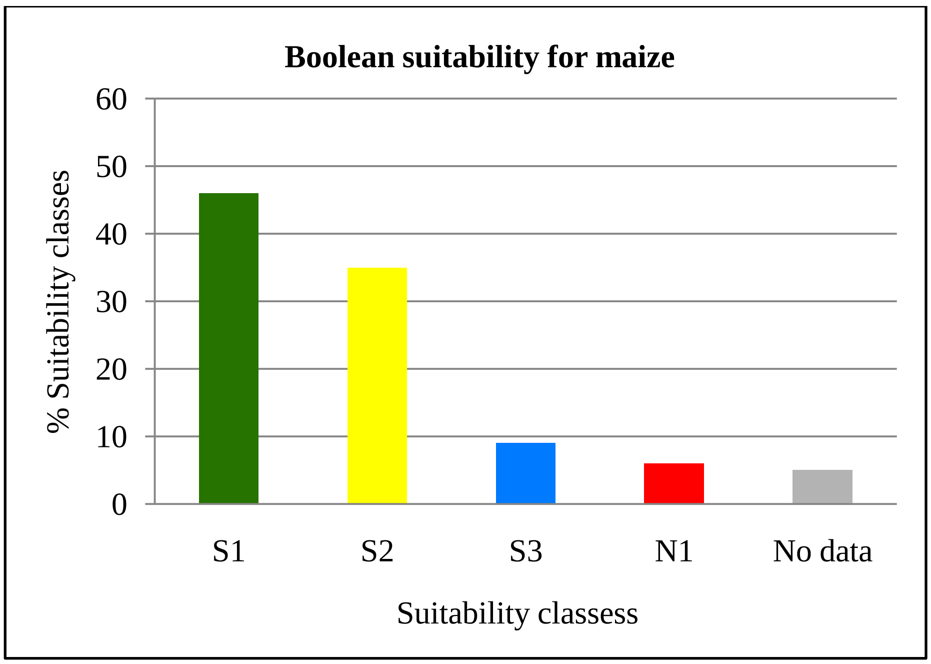
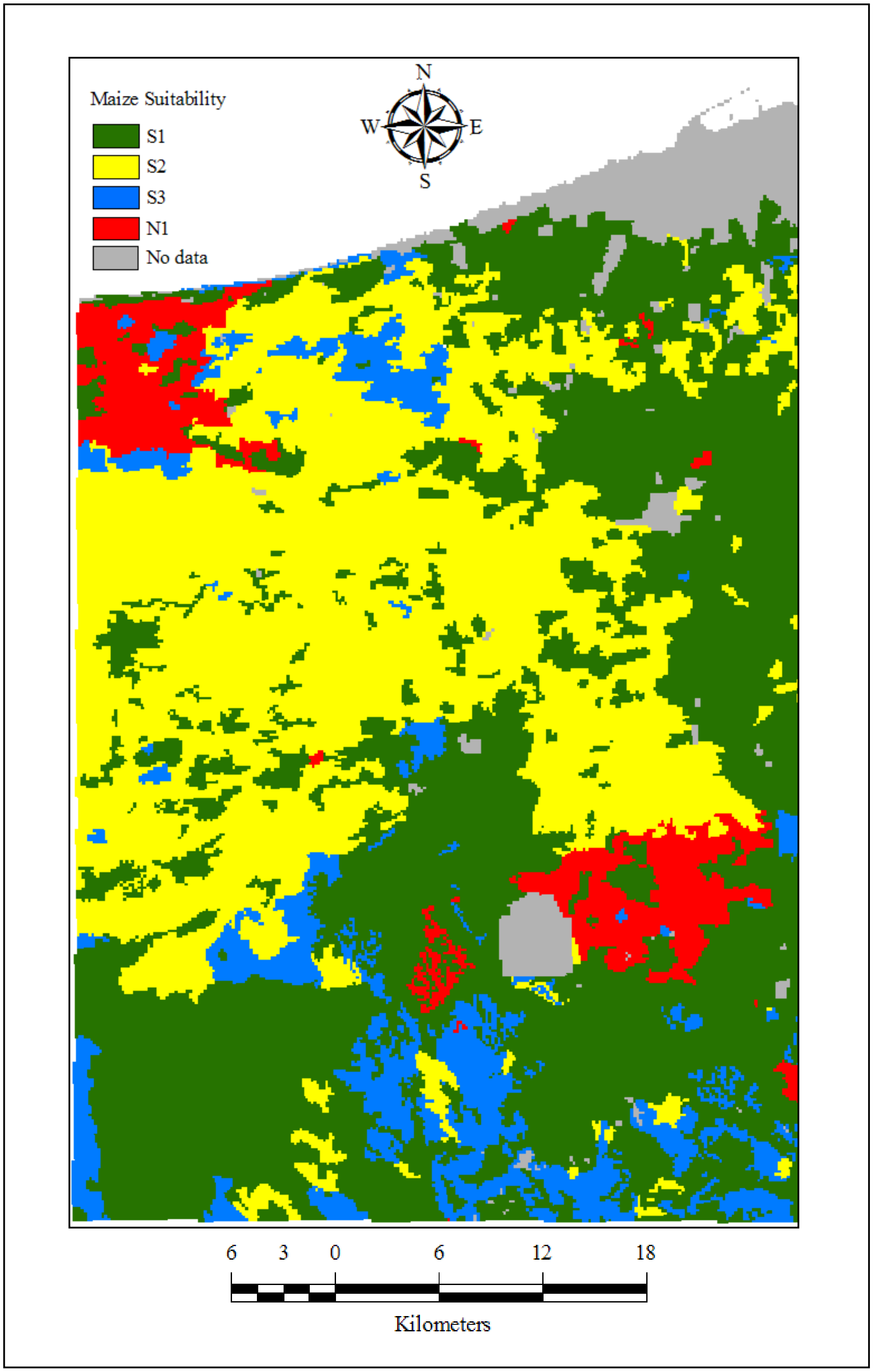


Figure 8.6: Land suitability map for maize based on Boolean mapping.



8.4.4 Summary of Boolean Results

Table 8.2 summarizes the results of suitability for barley, wheat and maize for the Boolean models.

Table 8.2: Suitability results for crops**:**

	Crops: overall suitability (Hectare)		
Suitability Class	**Barley**	**Wheat**	**Maize**
S1 (Highly suitable)	110022	147417	141650
S2 (Moderately suitable)	119139	92900	108579
S3 (Marginally suitable)	32134	9412	26413
N1(currently not suitable)	32577	44143	17230
No data	15524	15524	15524

The results indicate that the area under consideration has good potential to produce barley, wheat and maize under irrigation, provided that the water requirements are met. They show that 48% of the total study area is highly suitable for wheat, 46% is highly suitable for maize and 36% of the study area is highly suitable for barley.

According to the overall suitability, the study area is suitable for wheat, maize and barley. It is evident from the results that most locations within the study area which are highly suitable (S1) and moderately suitable (S2) for barley, wheat and maize production have been mapped. In addition, the results reveal that few locations within the study area which are not suitable or currently not suitable (N1) for the selected crops have been found.

The overall suitability maps for barley, wheat and maize were produced by using the weighted overlay technique, a technique that allows different weights to be applied to different thematic map layers. To generate the overall suitability maps for the selected crops, the weights or measures of relative importance shown in Table 8.1, which were derived from the statistical analysis based on discussion with local experts, were multiplied by 100, because the weighted overlay technique requires the weights to add up to 100.

To produce the overall suitability map for barley, the soil suitability map was weighted to 89%, the erosion suitability map was weighted to 9% and the slope suitability layer was weighted to 2% to produce the overall land suitability map. The soil suitability map was weighted to 88%, the erosion suitability map was weighted to 9% and the slope map was weighted to 3% to produce the suitability of land for wheat. The weighting values of the suitability criteria to produce the overall land suitability map for maize are 95% for the soil suitability map, 3% for erosion suitability and 2% for the slope map layer.

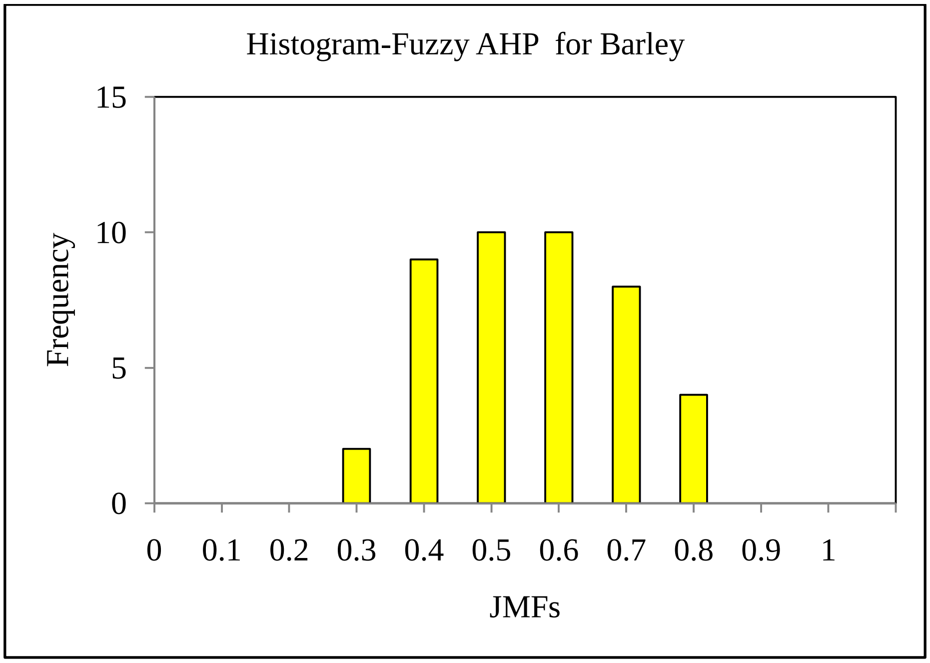
8.5 Fuzzy AHP Technique Results

The results of the FAO framework for land evaluation in the study area based on using Fuzzy AHP are given in the next sections:

8.5.1 Barley Suitability Results

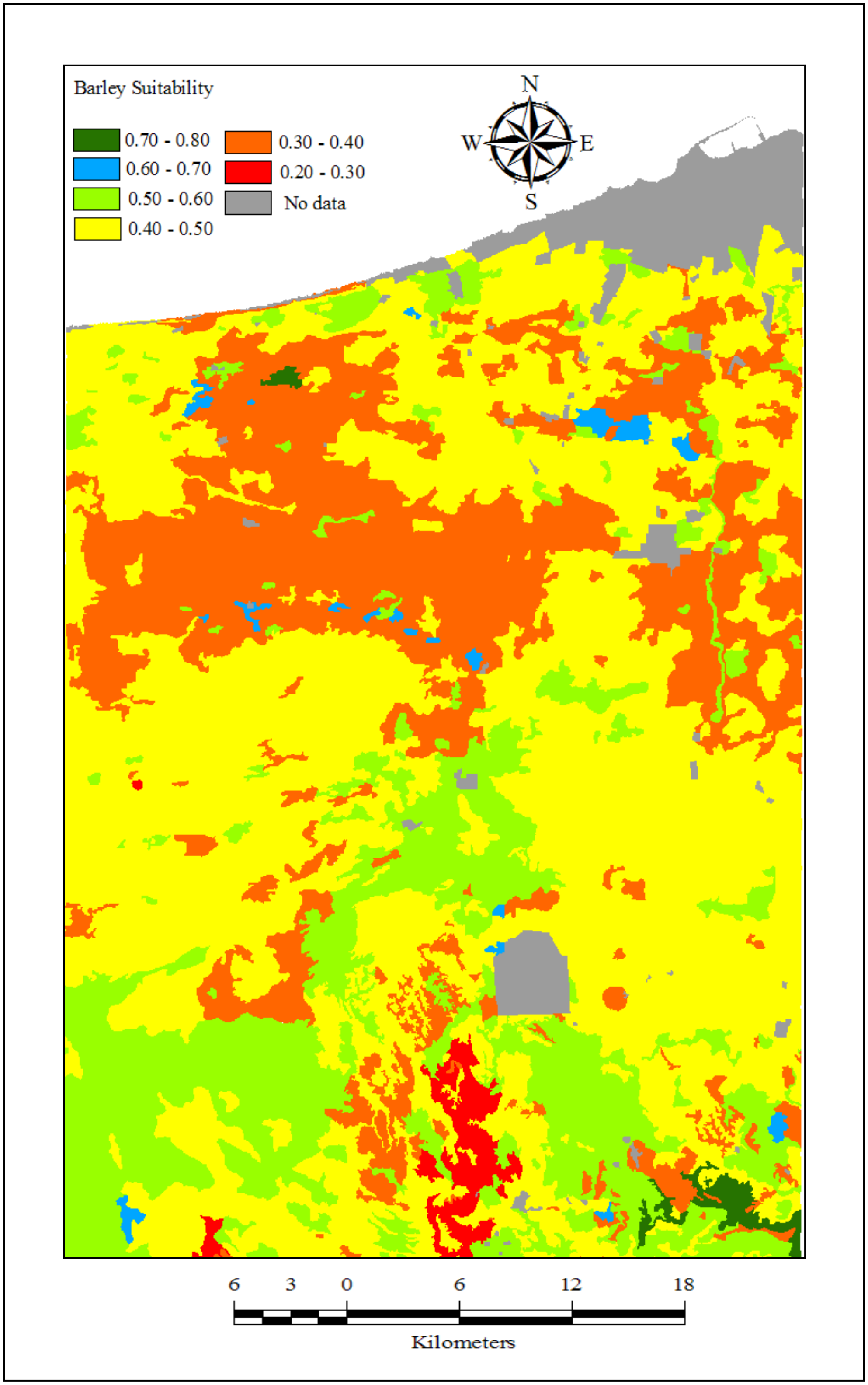
The Fuzzy AHP approach shows that the study area has a greater degree of subdivision in suitability for barley, ranging between 0.29 and 0.79 (figure 8.7).

Figure 8.7: Histogram of the overall suitability values under the use of Fuzzy AHP for barley.



The land suitability map for barley under the use of Fuzzy AHP is shown in figure 8.8. The results show that most locations of the study area were mapped with degrees of suitability of 0.40–0.50, 0.30–0.40 and 0.50–0.60 respectively, while a few locations in the study area were classified with degrees of suitability of 0.20–0.30, 0.70–0.80 and 0.60–0.70.

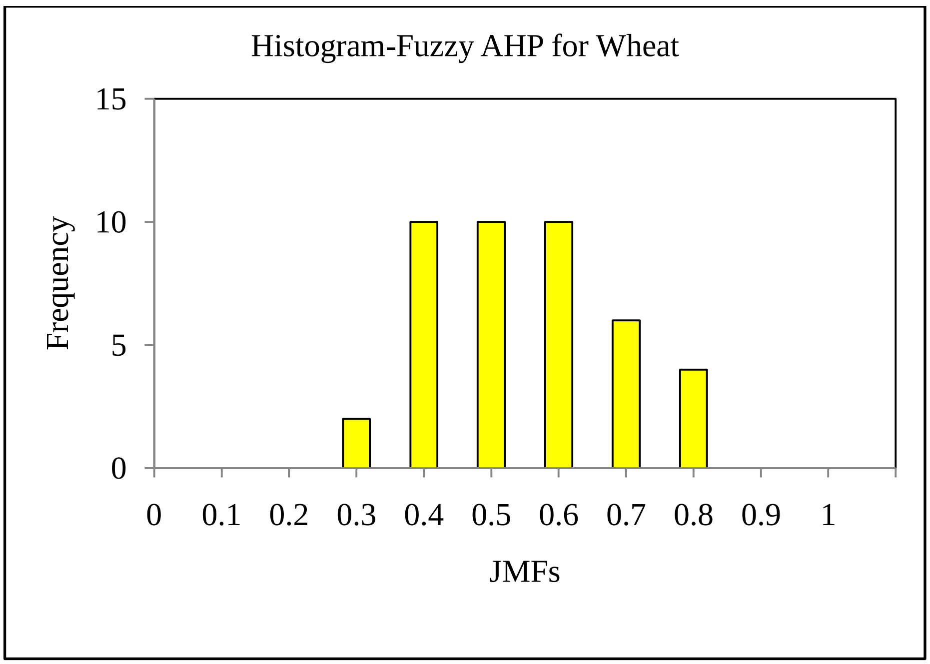
Figure 8.8: Land suitability map for barley based on Fuzzy AHP mapping.



8.5.2 Wheat Suitability Results

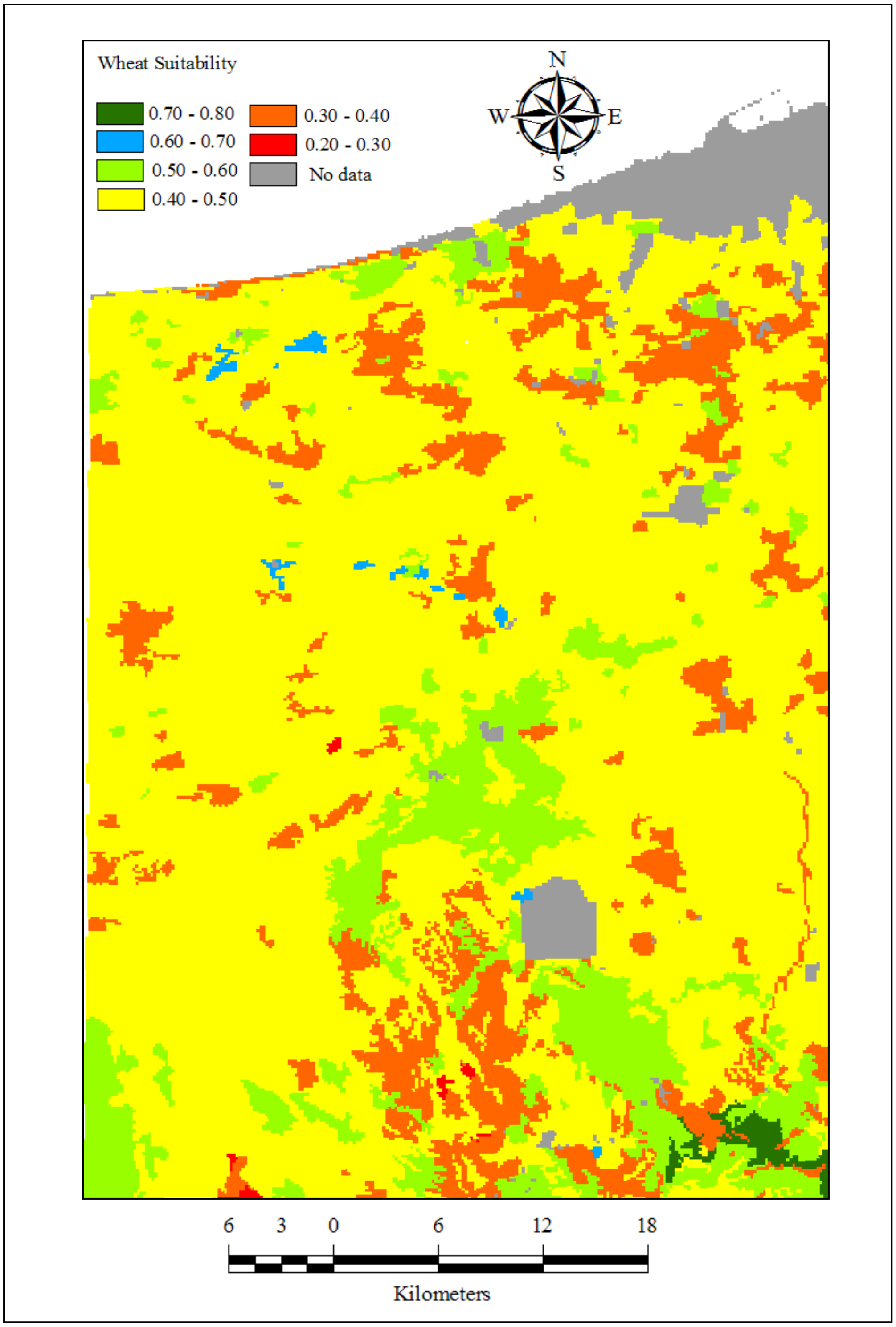
The results obtained from the use of Fuzzy AHP indicates that the study area has different degrees of suitability values for wheat, ranging from 0.29 to 0.78 (figure 8.9).

Figure 8.9: Histogram of the overall suitability values under the use of the Fuzzy AHP for wheat.



In addition to this, the land suitability map for wheat under the use of Fuzzy AHP is given in figure 8.10. The results (figure 8.10) indicate that most sites in the area of study were classified with degrees of suitability of 0.40–0.50, 0.30–0.40 and 0.50–0.6 respectively, while a few locations of the study area were mapped with degrees of suitability of 0.20–0.30, 0.60–0.70 and 0.70–0.80.

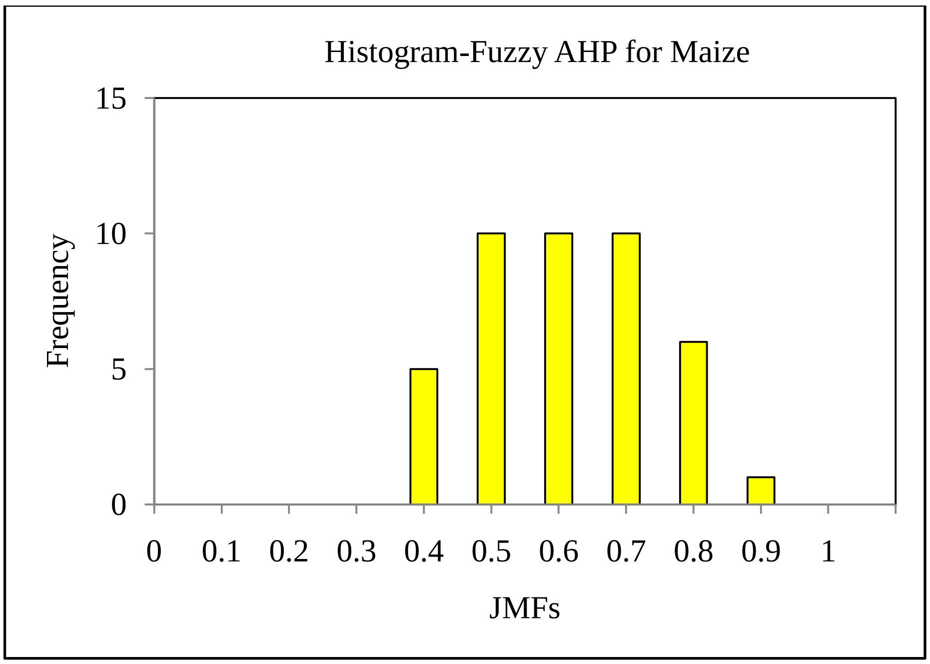
Figure 8.10: Land suitability map for wheat based on Fuzzy AHP mapping.



8.5.3 Maize Suitability Results

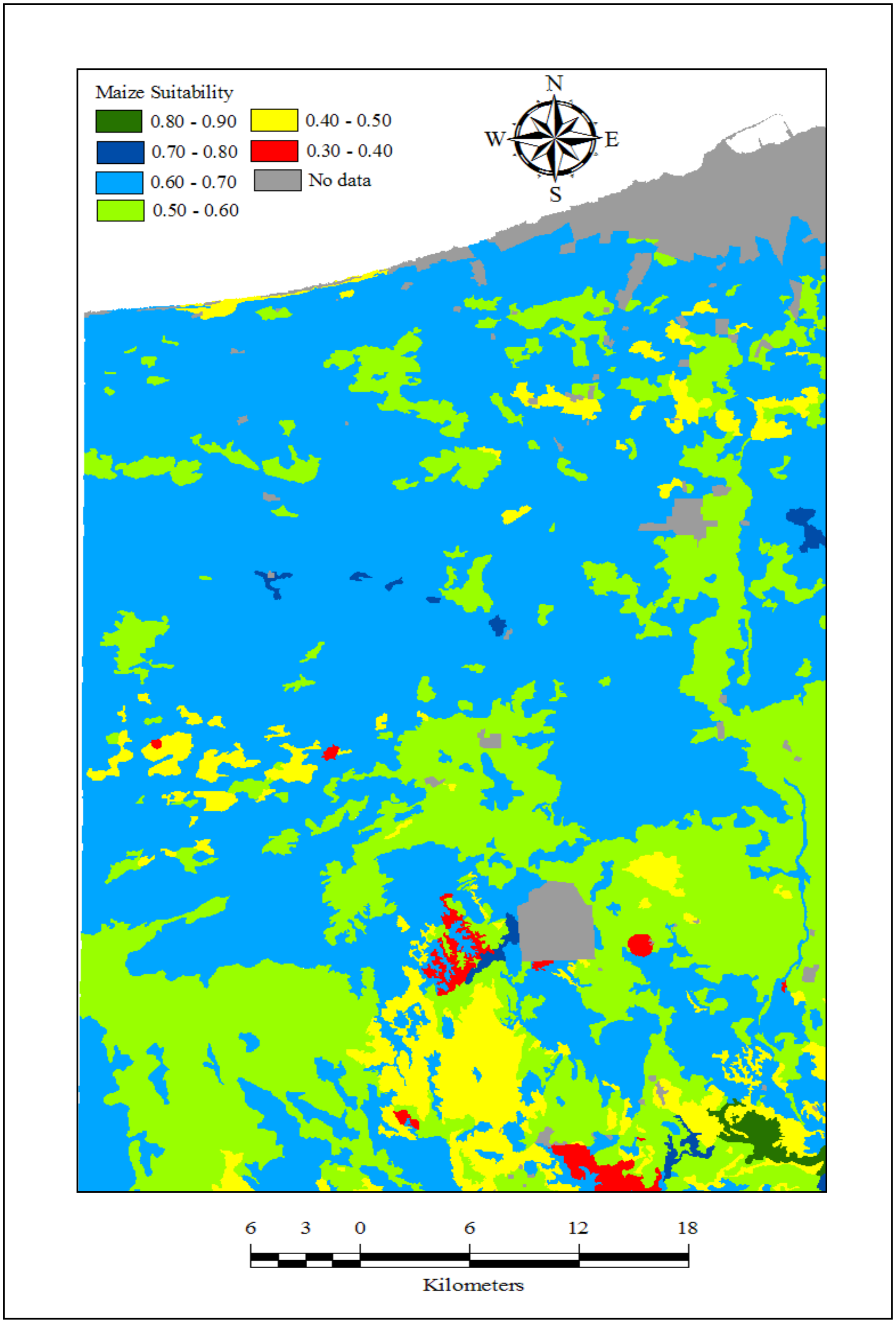
The Fuzzy AHP approach revealed that the overall suitability for maize in the study area ranges between 0.35 and 0.81 (figure 8.11).

Figure 8.11: Histogram of the overall suitability values under the use of the Fuzzy AHP for maize.



The land suitability map for maize under the use of Fuzzy AHP is shown in figure 8.12. It is evident from the results (figure 8.12) that most locations in the study area were mapped with degrees of suitability of 0.60–0.70 and 0.50–0.60 respectively, while small parts in the area of study were classified with degrees of suitability of 0.30–0.40, 0.40–0.50, 0.70–0.80 and 0.80–0.90.

Figure 8.12: Land suitability map for maize based on Fuzzy AHP mapping.



8.5.4 Summary of the Fuzzy AHP Results

The result of the FAO framework for land evaluation based on using Fuzzy AHP methods for the selected cash crops has been derived for the study area selected. The derivation of land suitability maps under the use of Fuzzy AHP comprised three main tasks: conversion of the selected land properties into a continuous scale or fuzzy numbers; derivation of the weighted fuzzy maps for the selected land characteristics by taking the weights obtained from local expertise into account; and derivation of the overall suitability evaluation on the basis of joint membership functions obtained with the weights provided by local experts.

The overall suitability of land from the use of the Fuzzy AHP approach was assigned between 0 and 1, where 1 was a highly suitable location and 0 an unsuitable one. Figures 8.7 and 8.9 showed that the subdivisions of the degrees of suitability for barley and wheat are almost comparable. This may explain the similarity of crop requirements and weights values for these crops.

The results show that the study area has a greater degree of subdivision in land suitability for the selected crops (i.e. high and low values of Joint Membership Function) under irrigation provided that the water requirements are met. The results revealed that certain locations in the study area have been mapped with a high degree of suitability: 0.70–0.80 for barley and wheat, and 0.80–0.90 for maize. Table 8.3 summarizes the overall suitability classes as a continuous scale for the selected crops.

Table 8.3: Suitability results for crops.

	Crops overall suitability (Ha)		
Continuous Classification	**Barley**	**Wheat**	**Maize**
0.0 – 0.10	0.0	0.0	0.0
0.10 – 0.20	0.0	0.0	0.0
0.20 – 0.30	4112	388	0.0
0.30 – 0.40	71972	36825	2340
0.40 – 0.50	158009	218124	20093
0.50 – 0.60	55839	35918	85999
0.60 – 0.70	2082	980	182717
0.70 – 0.80	1858	1637	1529
0.80 -0.90	0.0	0.0	1194
0.90 – 1.0	0.0	0.0	0.0
No data	15524	15524	15524

In addition to this, the results indicated that no locations in the study area have been mapped with JMFs values equal to 1. The results revealed that locations which were classified with a degree of suitability between 0.60 and 0.70 for maize have been mapped with JMFs between 0.40 and 0.50 for wheat and between 0.30 and 0.40 for barley. The variability in the JMFs between the crops is mainly due to the variability between the membership function values (MFs) and the weights which are given to land properties.

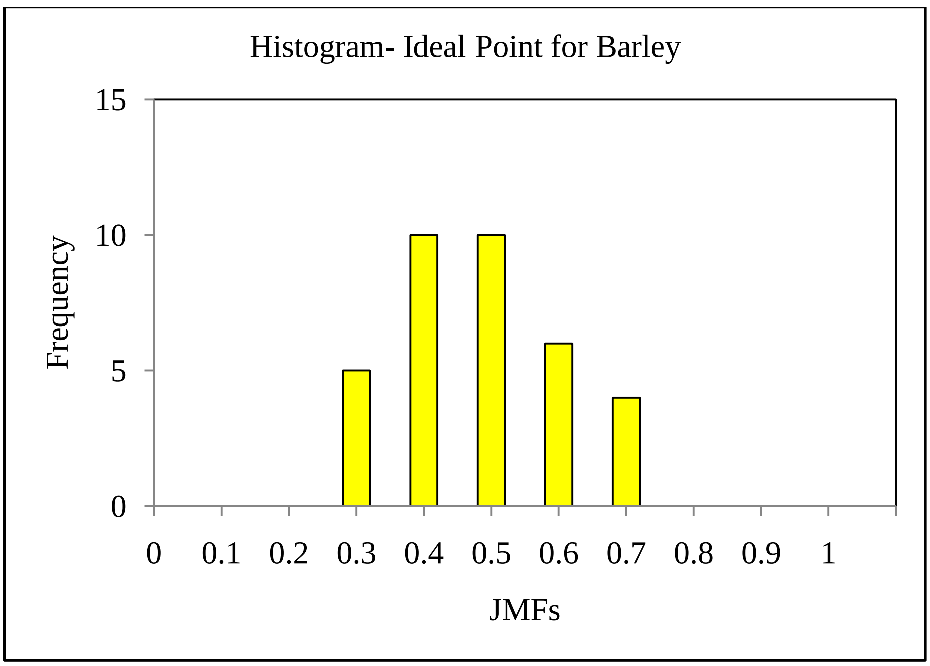
8.6 Ideal Point Techniques Results

The model outputs of the land suitability evaluation in the study area based on the application of an Ideal Point approach are shown in the next sections:

8.6.1 Barley Suitability Results

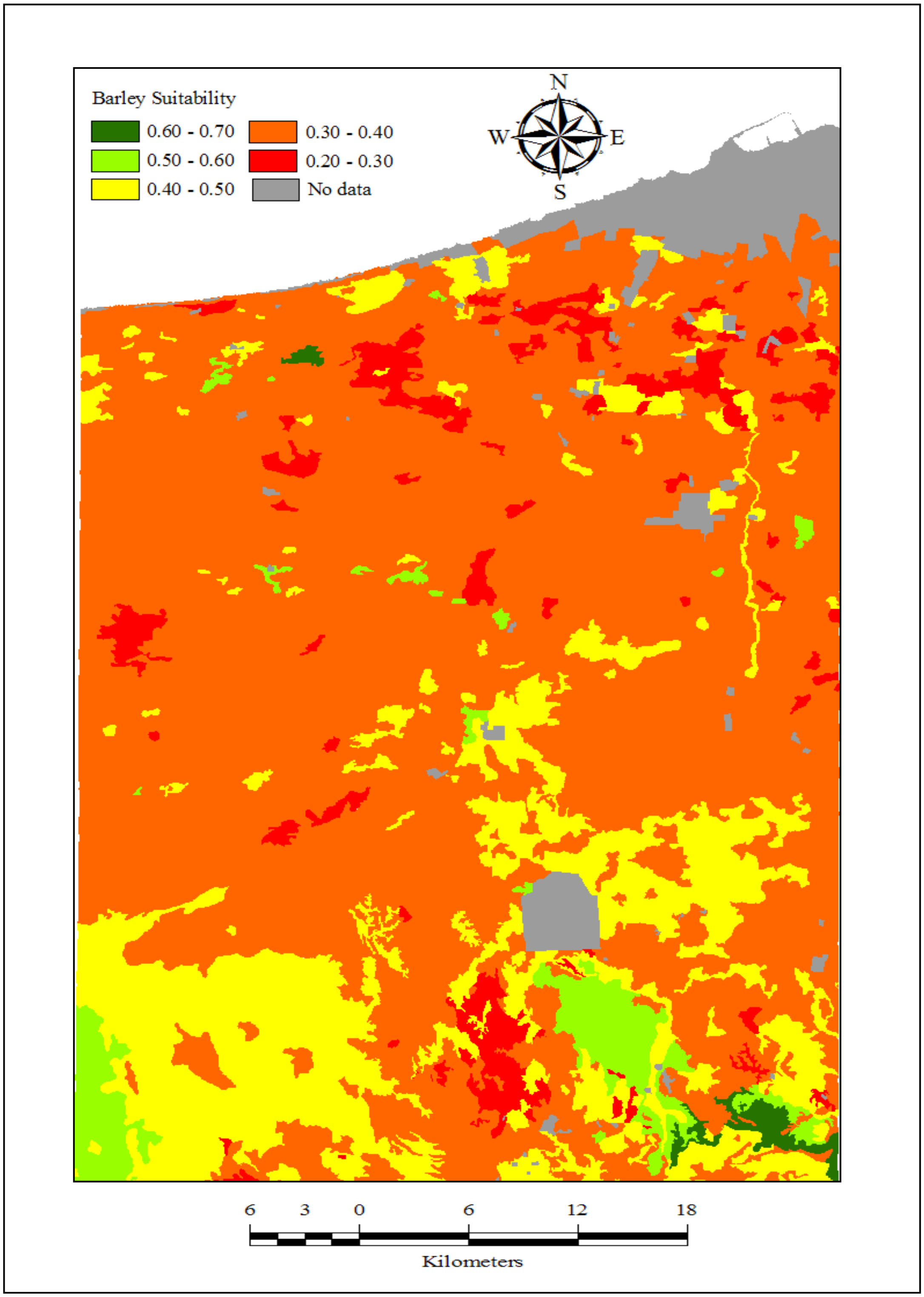
Application of the Ideal Point approach for land suitability for barley reveals that the study area has a wide range of suitability values ranging between 0.24 and 0.66 (figure 8.13).

Figure 8.13: Histogram of the overall suitability values under the use of the Ideal Point approach for barley.



The land suitability map derived under the use of the Ideal Point method is shown in figure 8.14. It is evident from the results (figure 8.14) that most locations of the study area have been mapped with degrees of suitability of 0.30–0.40 and 0.40–0.50 respectively, while a few locations of the area of study were classified with degrees of suitability of 0.20–0.30, 0.50–0.60 and 0.60–0.70.

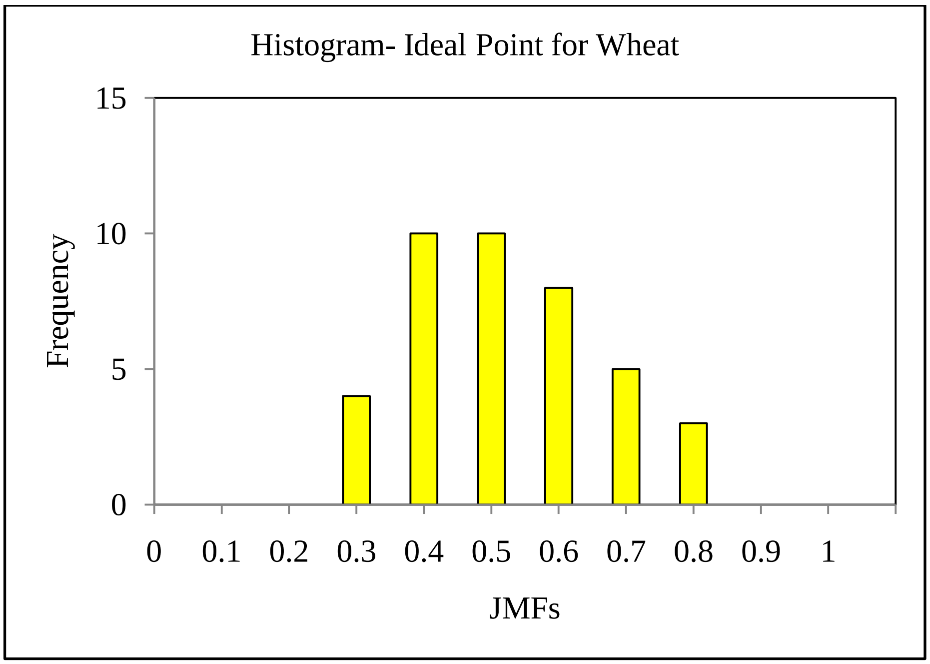
Figure 8.14: Land suitability map for barley based on Ideal Point mapping.



8.6.2 Wheat Suitability Results

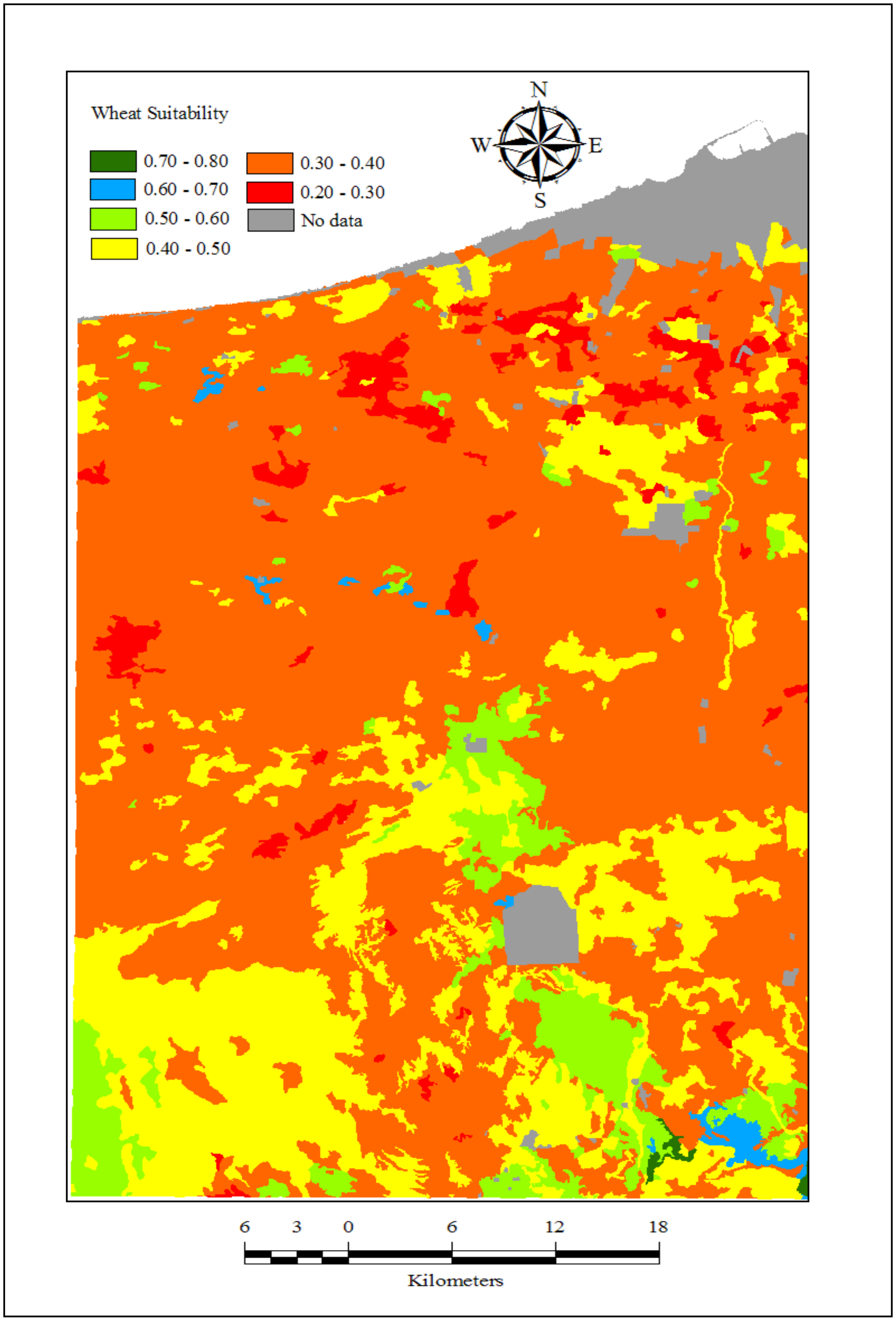
The use of the Ideal Point method for land suitability evaluation for wheat reveals that the study area has a greater subdivision in suitability values, and these values range from 0.27 to 0.77 (figure 8.15).

Figure 8.15: Histogram of the overall suitability values under the use of the Ideal Point approach for wheat.



A land suitability map for wheat using the Ideal Point method is presented in figure 8.16. Figure 8.16 shows that most locations in the study area were mapped with degrees of suitability of 0.3–0.40 and 0.40–0.50 respectively, while the rest of the study area was categorized with degrees of suitability of 0.20–0.30, 0.50–0.60, 0.60–0.70 and 0.70–0.80.

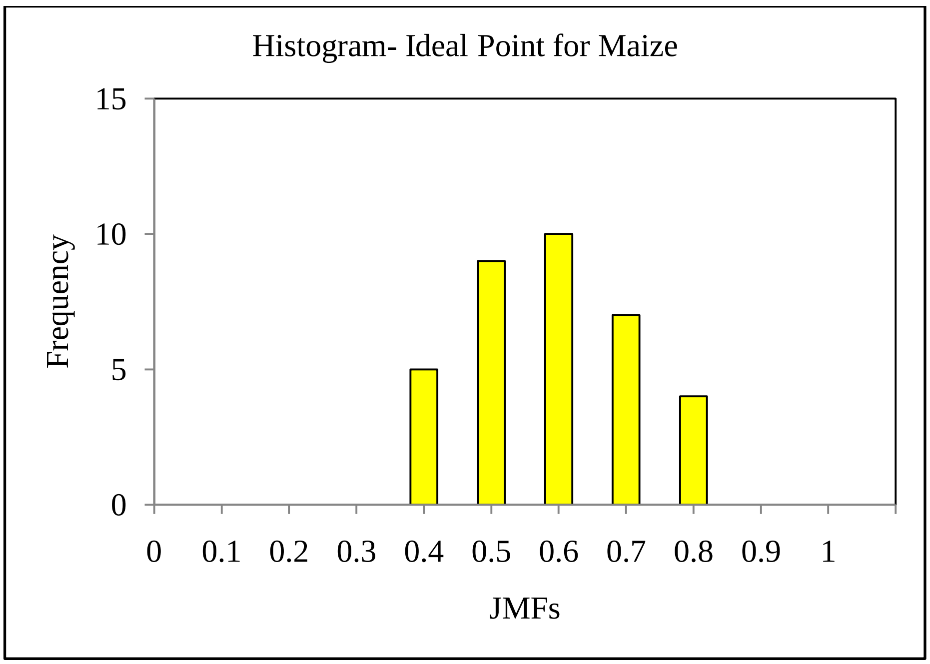
Figure 8.16: Land suitability map for wheat based on Ideal Point mapping.



8.6.3 Maize Suitability Results

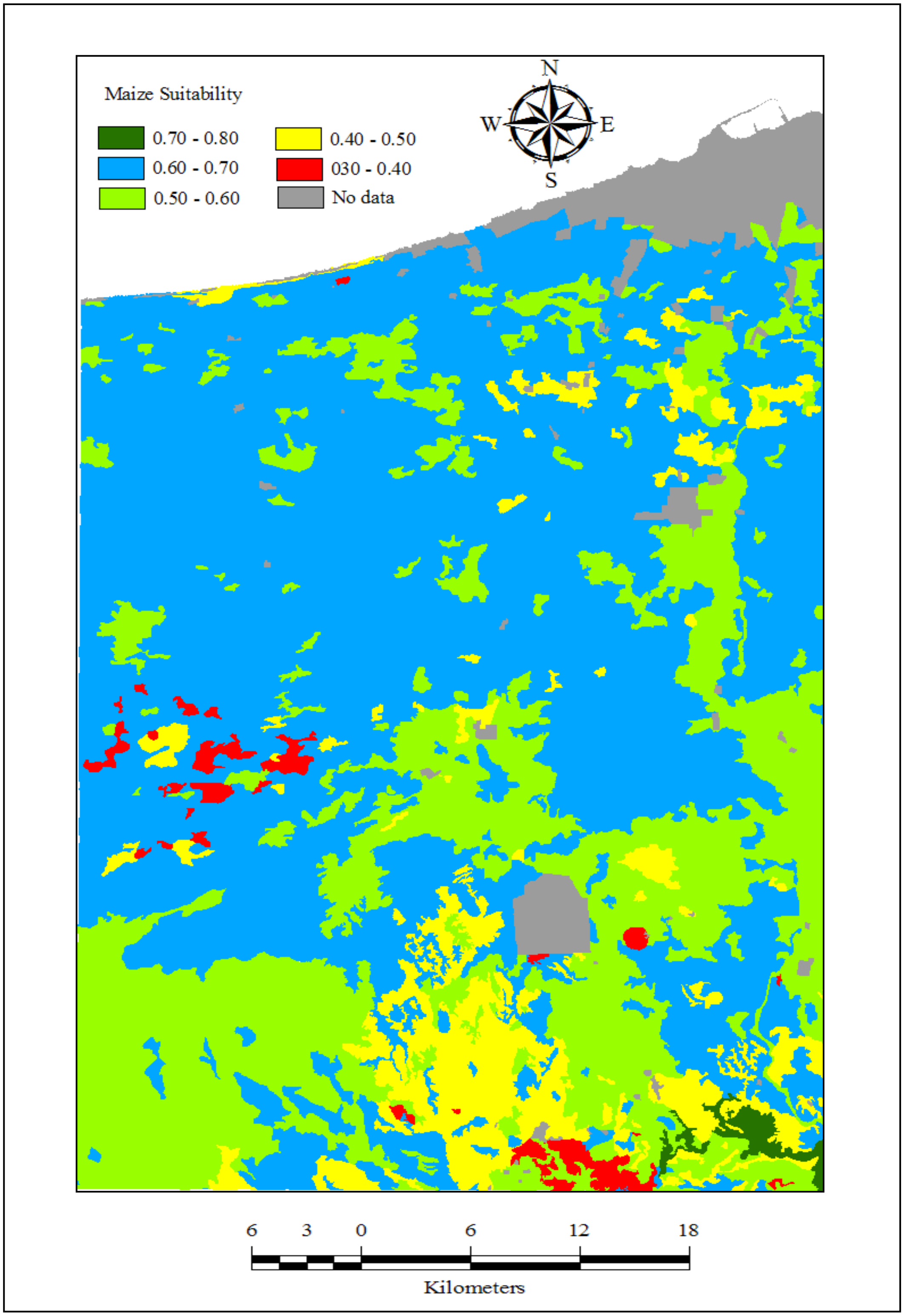
The results derived from the use of the Ideal Point approach for land suability evaluation for maize show that the study area has a different degree of suitability values. The values of suitability for maize under the use of the Ideal Point approach range between 0.32 and 0.80 (figure 8.17).

Figure 8.17: Histogram of the overall suitability values under the use of the Ideal Point approach for maize.



Furthermore, a land suitability map for maize under the use of the Ideal Point method was derived and is shown in figure 8.18. It is evident from the results (figure 8.18) that most locations of the study area were categorized with degrees of suitability of 0.60–0.70 and 0.50–0.60 respectively, whilst small areas were mapped with degrees of suitability of 0.30–0.40, 0.40–0.50 and 0.70–0.80.

Figure 8.18: Land suitability map for maize based on an Ideal Point mapping.



8.6.4 Summary of Ideal Point Results

The results of the FAO framework for land evaluation based on the application of the Ideal Point approach for barley, wheat and maize were obtained on the basis of three main tasks: using the fuzzy weighted maps derived from the use of the Fuzzy AHP approach as the input data, applying a separation measure to the positive and negative ideal points, and computing the relative closeness to the ideal point.

In the Ideal Point approach, like the Fuzzy AHP approach, the suitability of land for the selected crops was given values between 0 and 1, where 1 is a highly suitable location and 0 an unsuitable one. Figures 8.13 and 8.15 indicate that the subdivisions of the degree of suitability for barley and wheat are almost comparable, and, as mentioned under Fuzzy AHP, this may explain the similarity of crop requirements and weights values for these crops.

The results illustrate that the study area has a wide range of values for degree of suitability for the selected crops under irrigation provided that the water requirements are met. Where 1 is a highly suitable location and 0 an unsuitable one, a small number of sites in the study area have been mapped with high degrees of suitability, between 0.60 and 0.70 for barley, and between 0.70 and 0.80 for wheat and maize. Table 8.4 summarizes the overall suitability classes for the selected crops under the use of the Ideal Point approach.

Table 8.4: Suitability results for crops.

	Crops overall suitability (Ha)		
Continuous Classification	**Barley**	**Wheat**	**Maize**
0.0 – 0.10	0.0	0.0	0.0
0.10 – 0.20	0.0	0.0	0.0
0.20 – 0.30	14296	10601	0.0
0.30 – 0.40	210432	195595	4463
0.40 – 0.50	57138	67141	24444
0.50 – 0.60	10148	18186	85369
0.60 – 0.70	1858	1937	177959
0.70 – 0.80	0.0	412	1637
0.80 -0.90	0.0	0.0	0.0
0.90 – 1.0	0.0	0.0	0.0
No data	15524	15524	15524

The results also demonstrate that no areas with JMFs equal to 1 have been found. They reveal that locations which are classified with JMFs between 0.50 and 0.60 for barley and wheat have been assigned with JMFs between 0.60 and 0.70 for maize. The variability in the JMFs values between the crops, as in the Fuzzy AHP approach, is mainly due to the variability of the membership function values (MFs) and their weights, and to the positive and negative ideal values derived from weighted fuzzy maps for each crop.

8.7 Results Comparison

As mentioned in the research problem in Chapter 1, the GMPR project is interested in applying the traditional land evaluation system (i.e. a Boolean approach) to the suitability classification of land for barley, wheat and maize in the Jeffara Plain region of Libya, but the use of the Boolean representations for land evaluation systems has been criticized by many authors (e.g. Burrough, 1989; Wang et al., 1990; Hall et al., 1992; Tang et al., 1991; Davidson et al., 1994; McBratney and Odeh, 1997), as discussed in Chapter 5, because when using a Boolean approach it is impossible to model uncertainties and vagueness in land suitability evaluation. For this reason, fuzzy approaches, such as Fuzzy AHP and Ideal Point, have been adapted and then compared with traditional land evaluation systems that use a Boolean approach in the study area. The comparisons between the three approaches are shown below.

8.7.1 Boolean vs. Fuzzy AHP

A comparison has been made between the maps derived from Boolean and Fuzzy AHP approaches. It showed that the area under consideration has good potential for barley, wheat and maize production when the Boolean model is applied, while the Fuzzy AHP approach indicated that a limited area is highly suitable; areas which are highly suitable (1) and less suitable (0) for the production of selected crops have been mapped (Table 8.5).

Table 8.5: Highly suitable area, as determined by Boolean and Fuzzy AHP approaches

	Highly suitable area (Ha) for the crops					
Model	**Class**	**Barley**	**Class**	**Wheat**	**Class**	**Maize**
Boolean	S1	110022	S1	147417	S1	141650
Fuzzy AHP	0.70-0.80	1858	0.70-0.80	1637	0.80-0.90	1194

Furthermore, a comparison has been made between less suitable areas, as determined by Fuzzy AHP, and currently not suitable areas, as classified by the Boolean approach. This comparison indicates that currently not suitable areas derived from the use of the Boolean approach are higher than the less suitable areas derived from the use of the Fuzzy AHP approach (Table 8.6).

Table 8.6: Currently not suitable area as determined by the Boolean approach and less suitable area as determined by the Fuzzy AHP approach.

	Currently not suitable and less suitable area (Ha) for the crops					
Model	**Class**	**Barley**	**Class**	**Wheat**	**Class**	**Maize**
Boolean	N1	32577	N1	44143	N1	17230
Fuzzy AHP	0.20-0.30	4112	0.20-0.30	388	0.30-0.40	2340

The comparison between the Fuzzy AHP and Boolean approaches also reveals that each suitability class from the Boolean model is associated with high and low joint membership function (JMFs) values respectively. The range of the joint membership function values derived from the use of the Fuzzy AHP approach is given in figures 8.19, 8.20 and 8.21 for each suitability class as determined by the Boolean approach.

Figure 8.19: The range of the overall suitability from the use of the Fuzzy AHP approach for barley, classified for each suitability class (S1, S2, S3 and N1) as determined by the Boolean model.

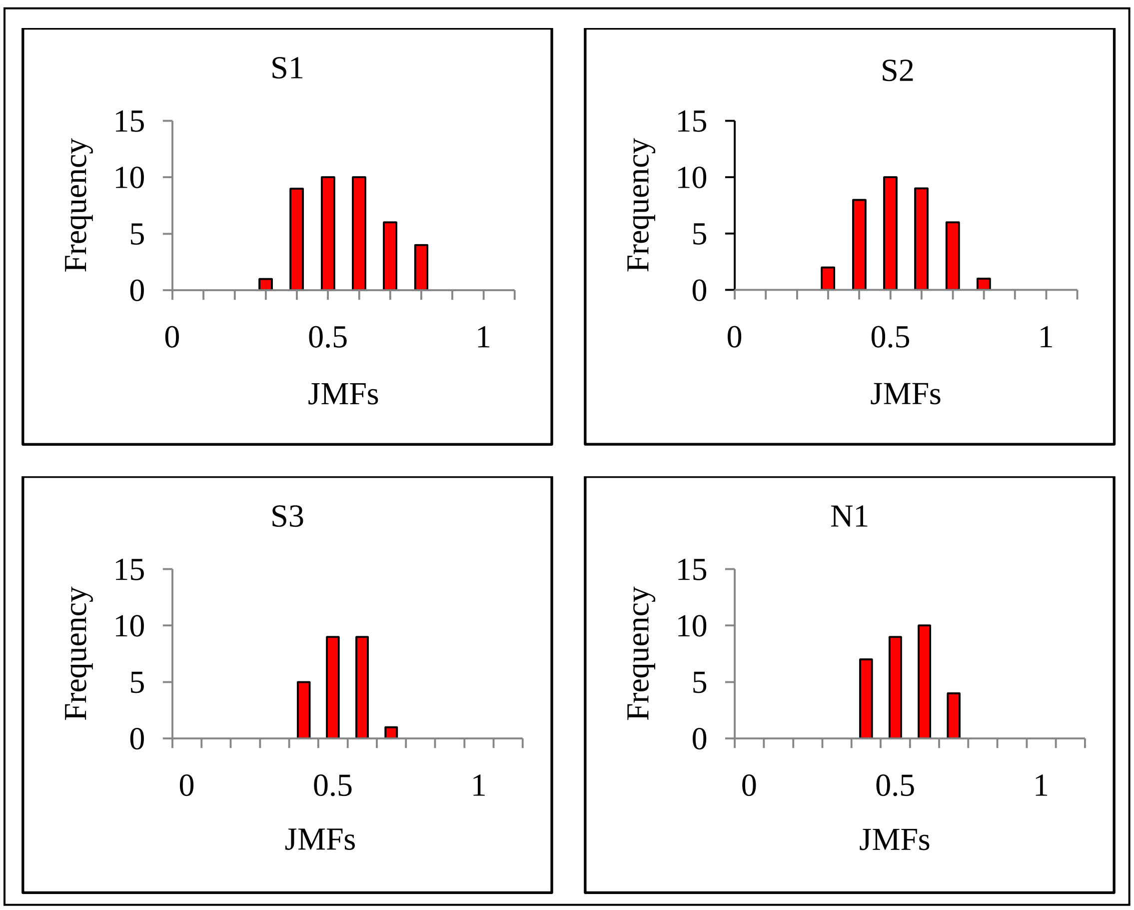


Figure 8.20: The range of the overall suitability from the use of the Fuzzy AHP approach for wheat, classified for each suitability class (S1, S2, S3 and N1) as determined by the Boolean model.

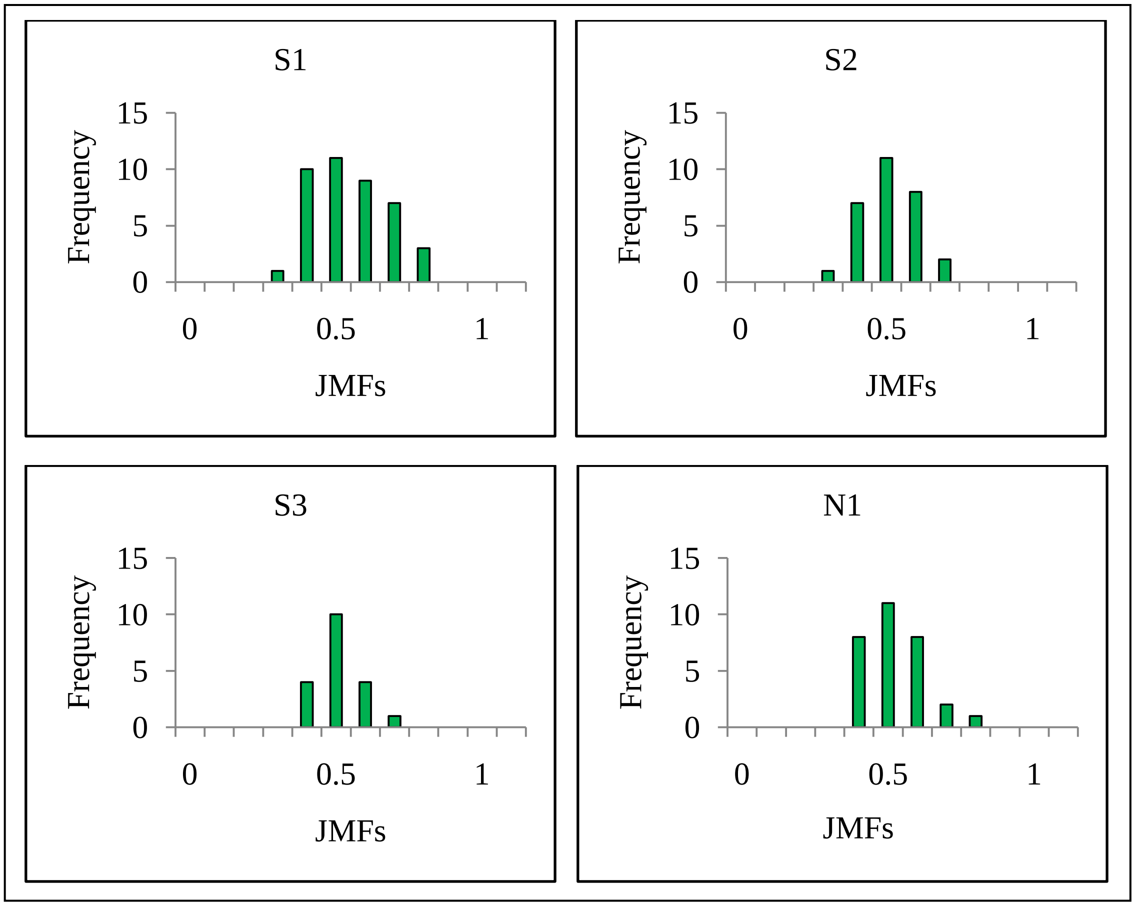
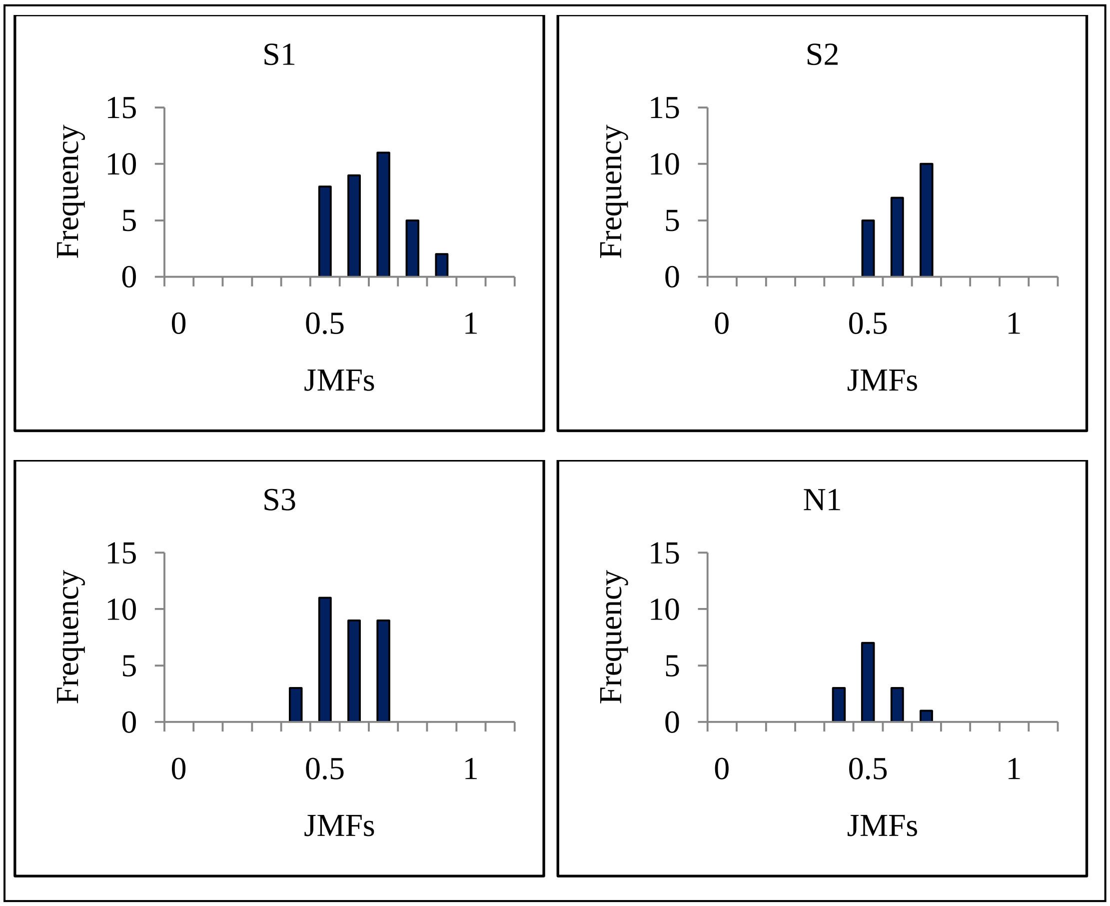


Figure 8.21: The range of the overall suitability from the use of the Fuzzy AHP approach for maize, classified for each suitability class (S1, S2, S3 and N1) as determined by the Boolean model.



According to these figures (8.19, 8.20 and 8.21) the range of the JMFs associated with the suitability classes from the use of the Boolean approach differs from class to class and from one crop to another. For example, in case of land suitability for barley, the JMFs values associated with class S1 and class S2 range between 0.20 and 0.80, while the JMFs values associated with class S3 and class N1 range between 0.40 and 0.70. The variability of the range of the JMFs has resulted from the difference in the membership function values (MFs) and the weights that were given and assigned to the land properties for the crops.

8.7.2 Boolean vs. Ideal Point

A comparison has also been made between the Boolean and Ideal Point approaches and it indicated that the study area has good potential for barley, wheat and maize production under the use of the Boolean model, while it has a limited highly suitable area when the Ideal Point approach is applied (Table 8.7).

Table 8.7: Highly suitable area as determined by Boolean and Ideal Point approaches.

	Highly suitable area (Ha) for the crops					
Model	**Class**	**Barley**	**Class**	**Wheat**	**Class**	**Maize**
Boolean	S1	110022	S1	147417	S1	141650
Ideal Point	0.60-0.70	1858	0.70-0.80	412	0.70-0.80	1637

In addition to this, less suitable areas as determined by the Ideal Point approach have been compared with currently not suitable areas as derived from using the Boolean approach. The comparison has shown that currently not suitable areas derived from the use of the Boolean approach are higher than the less suitable areas derived from the use of an Ideal Point approach (Table 8.8).

Table 8.8: Currently not suitable as determined by Boolean and less suitable area as determined by Ideal Point approach.

	Currently not suitable and Less suitable area (Ha) for the crops					
Model	**Class**	**Barley**	**Class**	**Wheat**	**Class**	**Maize**
Boolean	N1	32577	N1	44143	N1	17230
Ideal Point	0.20-0.30	14296	0.20-0.30	10601	0.30-0.40	4463

The comparison has shown that each Boolean suitability class (i.e. highly suitable, moderate suitable, marginally suitable and currently not suitable) is associated with high and low JMFs values .The range of the joint membership function values derived from the use of the Ideal Point approach is shown in figures 8.22, 8.23 and 8.24 for each suitability class as classified by the Boolean approach.

Figure 8.22: The range of the overall suitability derived from the use the of Ideal Point approach for barley, classified for each suitability class (S1, S2, S3 and N1) as determined by the Boolean model.

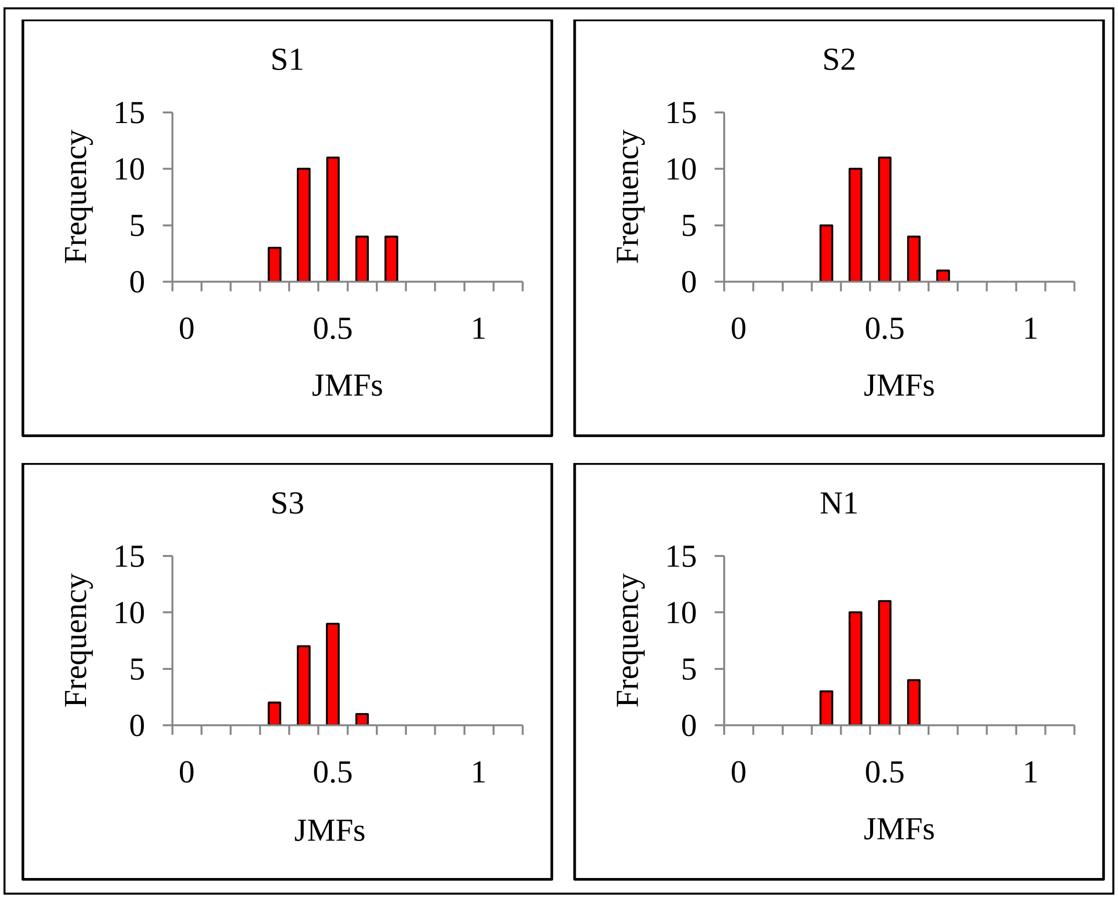


Figure 8.23: The range of the overall suitability derived from the use of the Ideal Point approach for wheat, classified for each suitability class (S1, S2, S3 and N1) as determined by the Boolean model.

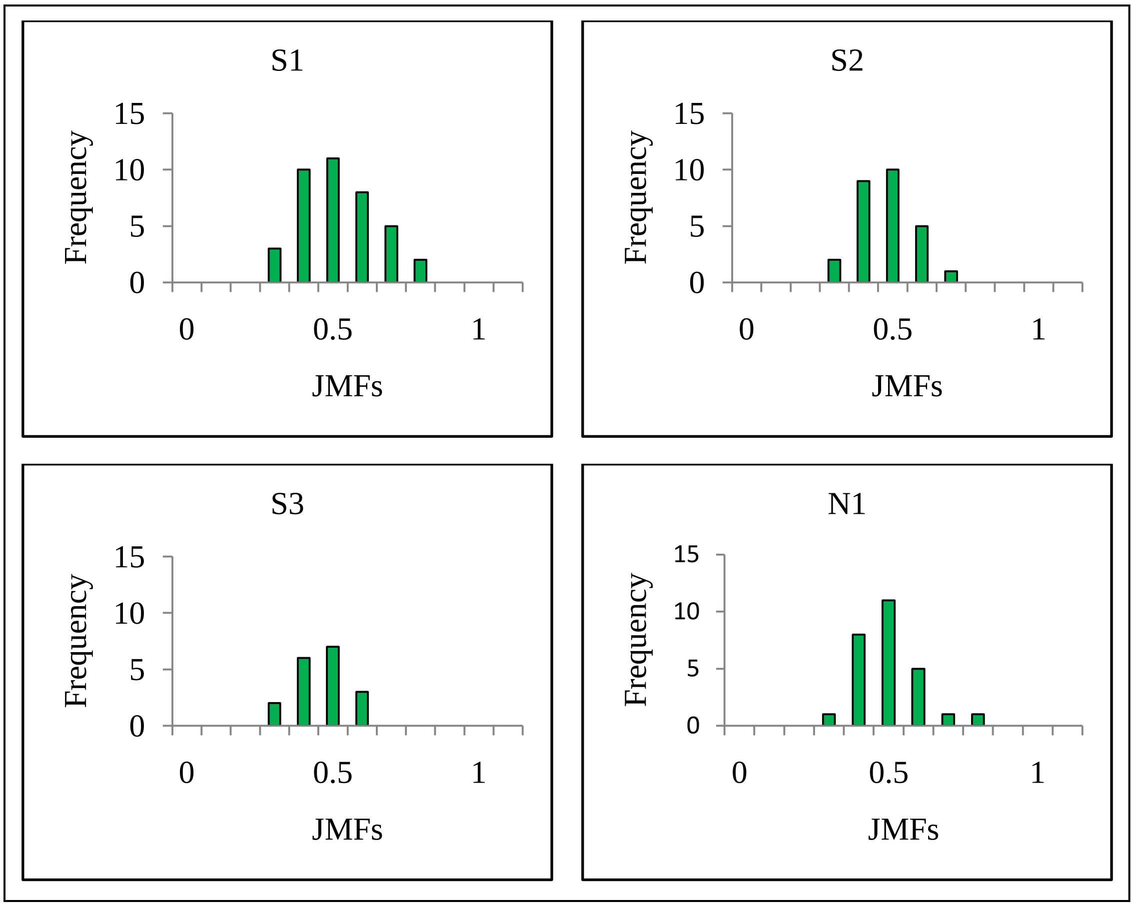
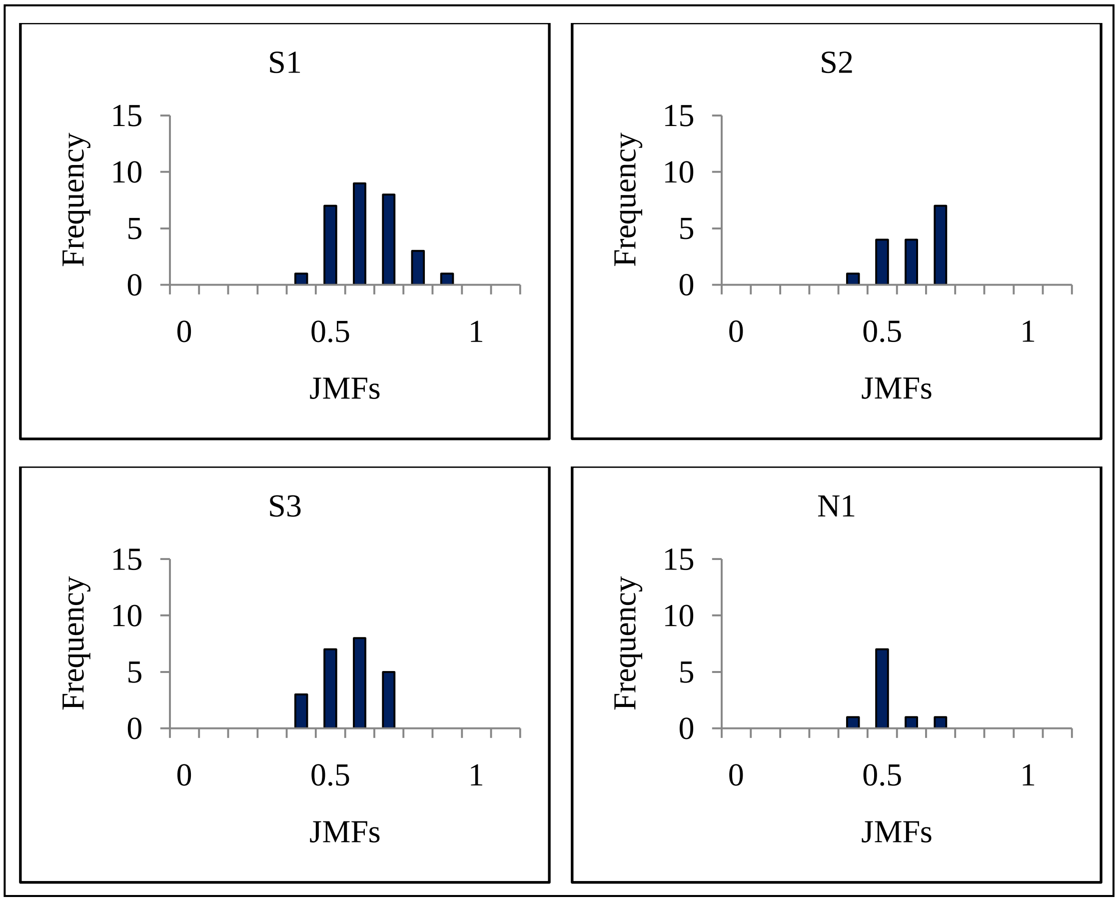


Figure 8.24: The range of the overall suitability derived from the use of the Ideal Point approach for maize, classified for each suitability class (S1, S2, S3 and N1) as determined by the Boolean model.



The results (figures 8.22, 8.23 and 8.24) show that the range of the JMFs associated with the Boolean suitability classes differs from class to class and also from crop to crop. For example, in the case of land suitability for maize, the JMFs values associated with class S1 range between 0.40 and 0.90 while the JMFs values associated with classes S2, S3 and N1 range from 0.40 to 0.70. The variability of the range of the JMFs comes from the variation of the membership function values and their weights and also from the positive and negative ideal values derived from the weighted fuzzy maps for each crop.

8.7.3 Fuzzy AHP vs. Ideal Point

A comparison between the results derived from the use of the Fuzzy AHP approach and those derived from the use of the Ideal Point approach has been made, and the results of the comparison are given in Tables 8.9, 8.10 and 8.11. These tables summarize the comparison of the results of the Fuzzy AHP and Ideal Point approaches for barley, wheat and maize.

Table 8.9: Comparison of the results of the Fuzzy AHP and Ideal Point approaches for barley.

	Overall suitability for barley (Ha)	
Continuous Classification	**Fuzzy AHP**	**Ideal Point**
0.0 – 0.10	0.0	0.0
0.10 – 0.20	0.0	0.0
0.20 – 0.30	4112	14296
0.30 – 0.40	71972	210432
0.40 – 0.50	158009	57138
0.50 – 0.60	55839	10148
0.60 – 0.70	2082	1858
0.70 – 0.80	1858	0.0
0.80 -0.90	0.0	0.0
0.90 – 1.0	0.0	0.0
No data	15524	15524

Table 8.10: Comparison of the results of the Fuzzy AHP and Ideal Point approaches for wheat.

	Overall suitability for wheat (ha)	
Continuous Classification	**Fuzzy AHP**	**Ideal Point**
0.0 – 0.10	0.0	0.0
0.10 – 0.20	0.0	0.0
0.20 – 0.30	388	10601
0.30 – 0.40	36825	195595
0.40 – 0.50	218124	67141
0.50 – 0.60	35918	18186
0.60 – 0.70	980	1937
0.70 – 0.80	1637	412
0.80 -0.90	0.0	0.0
0.90 – 1.0	0.0	0.0
No data	15524	15524

Table 8.11: Comparison of the results of the Fuzzy AHP and Ideal Point approaches for maize.

	Overall suitability for maize (ha)	
Continuous Classification	**Fuzzy AHP**	**Ideal Point**
0.0 – 0.10	0.0	0.0
0.10 – 0.20	0.0	0.0
0.20 – 0.30	0.0	0.0
0.30 – 0.40	2340	4463
0.40 – 0.50	20093	24444
0.50 – 0.60	85999	85369
0.60 – 0.70	182717	177959
0.70 – 0.80	1529	1637
0.80 -0.90	1194	0.0
0.90 – 1.0	0.0	0.0
No data	15524	15524

The comparison showed that most locations in the study area have been mapped with the JMFs between 0.40 and 0.50 for barley and wheat when using the Fuzzy AHP approach, while most sites in the study area were classified with the JMFs between 0.30 and 0.40 for barley and wheat using the Ideal Point approach. For maize, both the Fuzzy AHP and Ideal Point approaches indicated that the majority of the study area has been mapped with JMFs between 0.60 and 0.70. The Fuzzy AHP and Ideal Point approaches illustrate that no locations in the study area have been mapped with joint membership function values equal to 1. In addition to this, both of the fuzzy approaches showed that the study area has better potential for maize production than barley and wheat production, because, for maize, most locations in the study area have been mapped with high values of JMFs between 0.60 and 0.70.

8.8 Summary of the Comparison Results

In this research, all three models were compared and then evaluated for their ability to explore the uncertainties associated with land properties in the process of land suitability evaluation in the north-western region of Jeffara Plain in Libya.

The differences in land suitability evaluation as determined by Boolean and fuzzy approaches were obvious. A comparison between fuzzy approaches (i.e. Fuzzy AHP and Ideal Point approaches) and the Boolean approach was made, and it showed that each suitability class (i.e. S1, S2, S3 and N1) derived from the traditional land evaluation system is associated with high and low values of JMFs when compared with the results derived under the use of the Fuzzy AHP and Ideal Point approaches.

The ranges of the JMFs associated with Boolean suitability differ from class to class and from one crop to another. The variability in the range of the JMFs for crops derived from the use of the Fuzzy AHP has resulted from the variation of the membership function values (MFs) and their weights, while the variation in the JMFs for crops derived from the Ideal Point approach is like that of the Fuzzy AHP, and also to the variability of the negative and positive ideal point values for each crop.

The comparisons illustrate that the results of the Fuzzy AHP approach are more comparable to the Ideal Point results than those derived from the use of the Boolean approach. For example, both of the fuzzy approaches reveal that the study area is more suitable for maize production under irrigation conditions than barley and wheat production while the results from the use of the Boolean approach show that the study area has good potentiality to produce all three selected crops under irrigation conditions. The fuzzy approaches show that no locations in the study area are assigned with JMFs equal to one – i.e. highly suitable classes (where 1 is highly suitable and 0 not suitable).

The comparison revealed that the Fuzzy AHP and Ideal Point approaches are like the fuzzy set methodologies in that it showed their ability to address and accommodate the uncertainties that are associated with boundary conditions in criteria, taking into account the effects of properties which happen to have values close to category boundaries. This means that the Fuzzy AHP and Ideal Point approaches have succeeded in overcoming the problems found from the application of the Boolean model to land suitability evaluation in the study area.

8.9 Map Agreement/ Map Validation Results

To assess the agreement between the maps, the maps resulting from the use of the Fuzzy AHP, Ideal Point and Boolean approaches were cross-tabulated using Composite operator with multiple-resolution scale. To derive the overall agreement between the maps, twenty-seven confusion matrixes have been obtained for each crop and these matrixes are given in Appendix B. The twenty-seven confusion matrices come from using nine resolution scales for three comparisons (i.e. Boolean vs. Fuzzy AHP, Boolean vs. Ideal Point and Fuzzy AHP vs. Ideal Point) for each crop. An example of using the Composite operator analysis with nine multiple-resolutions is given in Table 8.12.

Table 8.12: The cross-tabulation matrix based on using the Composite operator for the Fuzzy AHP and Ideal Point approaches for barley.

Scale		1	2	3	Total	Overall agreement
1 x 1	1	0.1396	0.0000	0.0000	0.1396	0.8634
	2	0.0000	0.6919	0.1349	0.8269	
	3	0.0000	0.0017	0.0318	0.0335	
	Total	0.1396	0.6936	0.1668	1.0000	
2 x 2		1	2	3	Total	Overall agreement
	1	0.1396	0.0000	0.0000	0.1396	0.8638
	2	0.0000	0.6922	0.1347	0.8269	
	3	0.0000	0.0015	0.0320	0.0335	
	Total	0.1396	0.6936	0.1668	1.0000	
4 x 4		1	2	3	Total	Overall agreement
	1	0.1396	0.000	0.000	0.1396	0.8643
	2	0.000	0.6924	0.1345	0.8269	
	3	0.000	0.0012	0.0323	0.0335	
	Total	0.1396	0.6936	0.1668	1.0000	

Table 8.12 continued:

Scale		1	2	3	Total	Overall agreement
8 x 8	1	0.1396	0.000	0.000	0.1396	0.8648
	2	0.000	0.6926	0.1342	0.826	
	3	0.000	0.0010	0.0325	0.0335	
	Total	0.1396	0.6936	0.1668	1.0000	
16 x 16	1	0.1396	0.000	0.000	0.1396	0.8659
	2	0.0000	0.6932	0.1336	0.8269	
	3	0.0000	0.0000	0.033	0.0335	
	Total	0.1396	0.6936	0.1668	1.0000	
32x 32		1	2	3	Total	Overall agreement
	1	0.1396	0.000	0.000	0.1396	0.8668
	2	0.000	0.6936	0.1332	0.8269	
	3	0.000	0.000	0.0335	0.0335	
	Total	0.1396	0.6936	0.1668	1.0000	
64 x64		1	2	3	Total	Overall agreement
	1	0.1396	0.000	0.000	0.1396	0.8668
	2	0.000	0.6936	0.1332	0.8269	
	3	0.000	0.000	0.000	0.0335	
	Total	0.1396	0.6936	0.1668	1.0000	
128x 128		1	2	3	Total	Overall agreement
	1	0.1396	0.000	0.000	0.1396	0.8668
	2	0.000	0.6936	0.1332	0.8269	
	3	0.000	0.000	0.000	0.0335	
	Total	0.1396	0.6936	0.1668	1.0000	
256x 256		1	2	3	Total	Overall agreement
	1	0.1396	0.000	0.000	0.1396	0.8668
	2	0.000	0.6936	0.1332	0.8269	
	3	0.000	0.000	0.000	0.0335	
	Total	0.1396	0.6936	0.1668	1.0000	

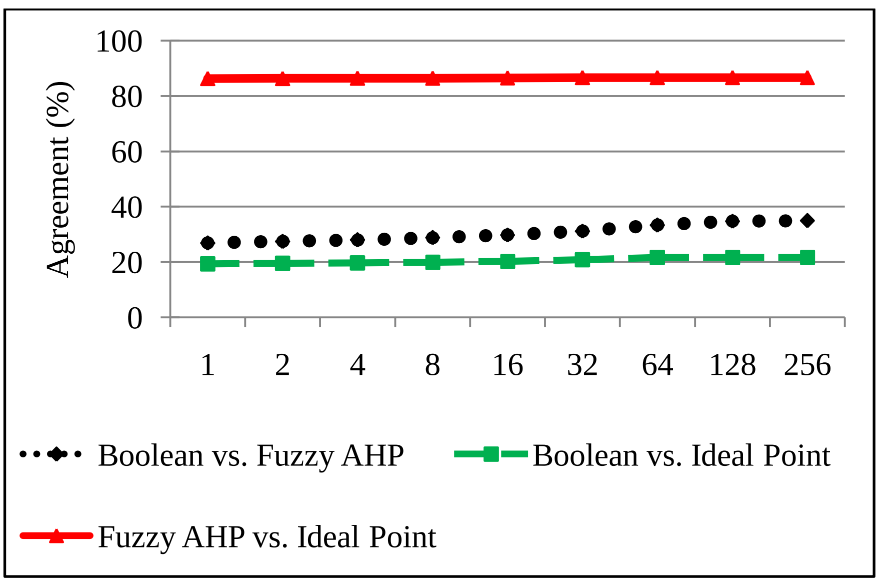
Table 8.12 illustrates that the overall agreement between the Fuzzy AHP and Ideal Point maps ranges from 0.8634 to 0.8668. It shows that the agreement between the Fuzzy AHP and Ideal Point maps increases when the resolution scale increases. The

results of using the Composite operator for deriving the overall agreements and disagreements between the maps for the crops are summarized below:

8.9.1 Map Agreement for Barley

The Composite operator based on multiple-resolution scale analysis has been applied to land suitability maps for barley derived from all three models: Fuzzy AHP, Boolean and Ideal Point. The results show that the overall agreement between the maps was high when the fuzzy maps (i.e. Fuzzy AHP and Ideal Point maps) were cross-tabulated with each other, while the overall agreement was very low when maps derived from fuzzy approaches were cross-tabulated with the map produced from the Boolean approach (figure 8.25).

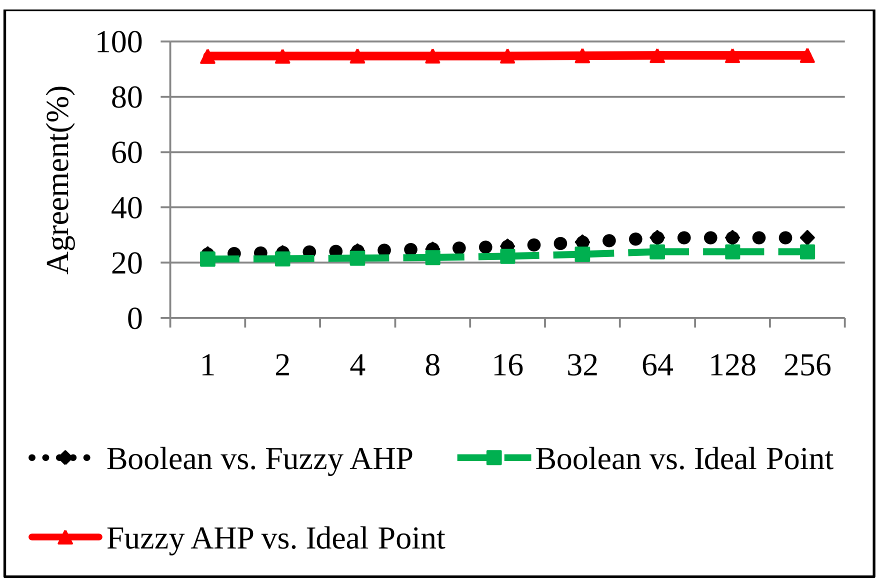
Figure 8.25: The percentages of overall agreement for land suitability maps for barley by using composite operator with multiple-resolution scale analysis.



8.9.2 Map Agreement for Wheat

The comparison between the land suitability maps for wheat was made based on composite operator with multiple-resolution scale analysis. The results illustrate that the overall agreement between land suitability maps for wheat was very high when the maps derived from the use of the fuzzy approaches were cross-tabulated with each other, while the overall agreement was low when the maps produced from the use of the Boolean approach were cross-tabulated with maps created from the use of the fuzzy approaches (figure 8.26).

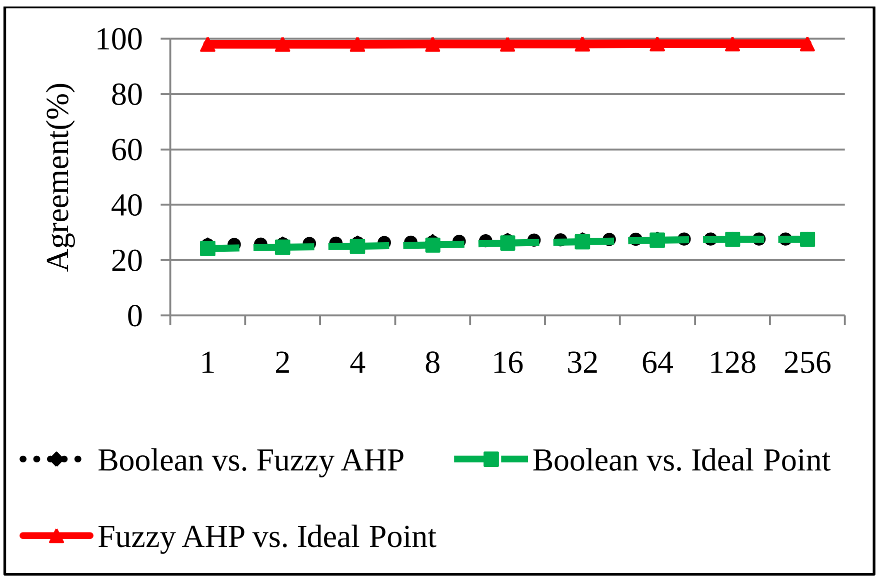
Figure 8.26: The percentages of overall agreement for land suitability maps for wheat by using composite operator with multiple-resolution scale analysis.



8.9.3 Map Agreement for Maize

The overall agreements between land suitability maps for maize based on the composite operator reveal that the overall agreement was high when the comparison between the Fuzzy AHP and Ideal Point maps was made whilst the overall agreement was much lower when the comparisons between the Boolean and Fuzzy AHP maps and between the Boolean and Ideal Point maps were made (figure 8.27).

Figure 8.27: The percentages of agreement for land suitability maps for maize by using Composite operator with multiple-resolution scale analysis.



8.10 Summary of Map Agreement/ Map Validation

The results indicated that the overall agreements obtained from comparing the Fuzzy AHP and Ideal Point maps are higher than the overall agreements obtained from comparing the Boolean and Fuzzy AHP maps and the Boolean and Ideal Point maps. This means the overall disagreements between the Boolean and Fuzzy AHP maps and between the Boolean and Ideal Point maps are always higher than the overall disagreements from comparing the Fuzzy AHP and Ideal Point maps.

It is evident from the results that the overall agreement between the models always increases when the resolution scale moves from low to high while the overall disagreement between the models decreases when the resolution scale increases. The low agreement between the maps is mainly due to the lack of correspondence between the pixels in the classes while the high agreement between the maps may be explained by the good correspondence between the pixels in the classes.

The results show that the overall agreement obtained from comparing the Fuzzy AHP and Ideal Point approaches for maize is higher than the overall agreement obtained from the comparison of the Fuzzy AHP and Ideal Point approaches for barley and wheat. It is clear from the results that using Boolean maps in the comparison process leads to more disagreement than agreement between the maps. The results illustrate that to obtain less disagreement between the maps it is necessary to go to the high resolution scale.

CHAPTER 9

DISCUSSION OF RESULTS

9.1 Introduction

In Chapter 8, all the results derived from the three land evaluation suitability models – Boolean mapping, Fuzzy Analytical Hierarchy Process (Fuzzy AHP) and Ideal Point – were shown. The results of the three models were based on the opinions of local staff, literature reviews for the study area selected, and an extensive overview of many land evaluation studies using different modelling. The results of the three land evaluation models are discussed here and organized as in the previous chapter.

9.2 Discussion of Weighting Factors Results

The choice of weights for land criteria in land suitability evaluation is not a simple task, as Davidson et al. (1994) state: 'One of the critical issues in fuzzy set methodology is the choice of weights which clearly have a major effect on results.' Selection of suitable weights for the model of land evaluation has made the assessment of suitability of land for the crops realistic, because it is essential to know how each factor can affect crop growth and production.

In this study, fourteen land properties were weighted through the pairwise comparison analysis; these properties were: soil texture, available water holding capacity, stones at surface, rootable depth, infiltration rate, soil calcium carbonate, soil pH, soil organic matter, exchangeable sodium percentage, soil salinity, soil alkalinity , cation exchange capacity, the percentage of slope and soil erosion.

As stated in Chapter 8, four local experts in Libya have used their knowledge to assign weights for the selected land characteristics for each crop. The weighting factors of three local experts were ignored because the consistency ratios obtained were not within the established acceptable limits (0.1).

The weights given in Table 8.1 were obtained from discussion with Dr Bashir Nwer, who adapted the FAO framework for land suitability evaluation in the north-east of Libya (Nwer, 2005). The weights obtained from this local expert were suitable for use in land suitability evaluation models, because the consistency ratios obtained were within the established acceptable limits (0.1). The weights used in this study were specifically chosen according to the study area conditions, but if these weights are to be used somewhere else in Libya, further analysis will be needed to explore the suitable weighting scores for land criteria.

According to the opinion of this local expert, soil properties are the most sensitive criteria in the land suitability classification for barley, wheat and maize in the study area. Therefore, this local expert has given bigger weights to soil criteria than the other criteria. In addition to this, most of the study area is sited in the plain region, which has few limitations due to slope and erosion, so these criteria were given smaller weights. Nonetheless, the accuracy of the results from this research is dependent on the designated weights given by this local expert to different land characteristics.

This study revealed that soil criteria such as soil texture, available-water-holding capacity and soil reaction are the most important criteria in the suitability classification for barley and wheat while rootable depth, soil salinity, soil reaction and soil alkalinity are the most important criteria in the suitability classification for maize. The implication of these findings is that soil criteria have to be given bigger weights than the other criteria.

It has to be noted that land qualities and land characteristics which were included in land evaluation models in this research were designated under existing conditions, but assumed an irrigation management regime would be put in place. The consequent irrigation process could in fact lead to change in the land qualities and land characteristics and their parameters. For example, soil salinity could be increased in the study area, especially if an inappropriate drainage system has been designed. To avoid this, it is possible to allow up to 20 per cent of the irrigation water to be leached through a suitable drainage system.

The results discussed above are in agreement with the results found by Nwer (2005). This study emphasizes that bigger weights should be given to soil criteria than to other criteria in Libyan conditions, because they are considered highly sensitive in the suitability classification for barley, wheat and maize production.

This study is also in agreement with some studies (e.g. Malczewski, 1999; Keshavarzi, 2010) that have reported some of the critical issues in the use of pairwise comparison analysis for weighting criteria. This study emphasizes that increasing the number of land properties increases the number of pairwise comparisons that will be employed, because the weights must be consistent, and this means that the consistency ratio for land properties must be ≤ 0.1 to be acceptable. To explain further, in this study, as mentioned earlier, fourteen land properties have been weighted, so the pairwise comparison matrix was run many times to derive weights with suitable consistency ratios (i.e. ≤ 0.1), and this is not a simple task, because decisions have to be made to assign weights according to their relative importance for each selected crop.

9.3 Discussion of the Boolean Results

As stated at the beginning of this research, the Great Man-Made River Project (i.e. the body responsible for agricultural development in Libya) is interested in using the traditional land evaluation system (i.e. the FAO framework for land suitability evaluation with Boolean logic) to derive suitability maps for barley, wheat and maize in the Jeffara Plain region of Libya. Consequently, this research has adapted the traditional FAO framework for land suitability evaluation (i.e. Boolean land suitability evaluation) to derive land suitability maps for the selected cash crops under irrigation conditions in the study area.

It is evident from the results that the study area has good potential to produce wheat (48 per cent), maize (46 per cent) and barley (36 per cent) respectively, according to the Boolean approach. The difference in the results is mainly due to the variability of the threshold values for each suitability class for each land characteristic for crops, as described in Tables 7.7, 7.8 and 7.9, and also to the weights given in Table 8.1.

The results of the Boolean approach depend on the functions and rules which can easily be employed in GIS environment, in the opinion of Davidson et al. (1994). Therefore, weights given in Table 8.1, which have been assigned to each thematic map layer on the basis of the weighted overlay technique, were used to derive the overall land suitability maps for the selected crops. This means that the Boolean land evaluation model which was used in this study is not a straightforward process. The problem that land properties under the use of the Boolean approach may have the same weights, as many authors reported (e.g. Moreno, 2007), can be resolved by assigning different weights based on local experts' judgment to different thematic map layers.

9.4 Discussion of the Fuzzy AHP Results

The use of the FAO framework for land evaluation based on Fuzzy AHP methods for the selected crops under irrigation conditions was one of the research objectives. The objective of applying Fuzzy AHP mapping to the model of land evaluation in the study area was to explore the possibilities of determining land suitability for the selected crops and to resolve the problems that found when using the Boolean approach.

The problem of the properties of land under the Boolean model having the same weight is simple to overcome, as discussed earlier, but the main critical issue in the use of the Boolean approach, as many researchers stated (e.g. Burrough, 1989; Burrough et al., 1992; Hall et al., 1992; Davidson et al., 1994; McBratney and Odeh, 1997; Baja et al., 2001), is that it failed to define the values close to class boundaries. Therefore, this research adapts the Fuzzy AHP approach to the model of land evaluation in the study area.

The overall suitability of land from the use of the Fuzzy AHP approach was assigned values between 0 and 1, where 1 is a highly suitable location and 0 an unsuitable one. The results demonstrated that the land suitability map for barley is more similar to the land suitability map for wheat than the land suitability map for maize. This may explain why the crop requirements for barley and wheat as shown in Tables 7.7 and 7.8 are very similar and why the most important factors affecting barley and wheat production as shown in Table 8.1 are also very similar.

The results of the Fuzzy AHP showed that no locations in the study area were mapped with a degree of suitability or JMFs values equal to 1 for barley, wheat and maize classifications. This does not mean the selected land properties in the suitability classification for barley, wheat and maize were not assigned with membership function values equal to one in the study area. In the Fuzzy AHP model for the suitability classification for barley, wheat and maize, a number of land properties have been given fuzzy numbers equal to one, and this was based on the quality function of land performs. The derivation of the overall suitability under the use of Fuzzy AHP was not only based on the fuzzy membership function values assigned to land properties, but also took weighting values as shown in Table 8.1 into account for deriving the overall suitability or the low and high JMFs. This means that land suitability maps from the use of the Fuzzy AHP approach show the interaction between the fuzzy membership function values and the weights for the selected land properties, and does not only show the fuzzy membership function values for crops.

This study also found that the same locations which were mapped with high JMFs for maize have been mapped with low JMFs for wheat and barley, and therefore, since the high JMFs values refer to highly suitable classes and the low JMFs values refer to less suitable classes; these locations are more suitable for maize production than wheat and barley production.

The derivations of the low and high JMFs values for barley, wheat and maize were mainly due to the fact that land variables affecting production of these crops have different fuzzy membership function values and different weighting values as given in Table 8.1, and therefore the results of the Fuzzy AHP for barley, wheat and maize classifications vary.

The implication of these findings is that locations which were mapped with low JMFs values for wheat and barley and high JMFs for maize should be designated for maize production, while locations which were mapped with low JMFs for maize and high JMFs for wheat and barley should be designated for wheat and barley production. But this will require designating some small farms or small agricultural projects within these locations for trial plots for crops in the study area. This implication will help the GMPR project and the decision makers in Libya towards improving the management of the arable lands in the study area and planning agricultural development in the study area.

The main advantages derived from applying the Fuzzy AHP approach to land suitability evaluation in the study area, as with the fuzzy set methodology, are the ability to define the uncertainties associated with describing the phenomenon itself and the ability to take into consideration the effect of land properties which happen to have values close to category boundaries. Another advantage found in this study is that all land characteristics that affect barley, wheat and maize production are very well-organized in the hierarchy, and this has facilitated the integration of expert knowledge into the framework of decision making. The most important advantage obtained from the use of Fuzzy AHP in the study area was that the results were presented as a continuous scale, which is considered a more realistic classification in nature (Burrough, 1989; Davidson et al., 1994; McBratney and Odeh, 1997; Baja et al., 2001).

The disadvantages of the use of the Fuzzy AHP approach in this study are the selection of the fuzzy membership functions values and the definition of the parameters of membership function values for the land properties affecting the production of selected crops; these disadvantages are in agreement with those found from the application of fuzzy set methodology to land suitability evaluation, as mentioned by many authors (e.g. Burrough, 1989; Keshavarzi, 2010). Another critical issue is that the use of the Fuzzy AHP approach is a very complicated process, particularly if too many parameters have been organized into the hierarchy.

9.5 Discussion of the Ideal Point Results

As stated at the beginning of this research, using the FAO framework for land evaluation based on the Ideal Point method was one of the research objectives. The main aim of the application of the Ideal Point approach to the model of land evaluation in the study area, as with the Fuzzy AHP approach, was to explore what degree of suitability for the selected crops can be obtained and how the Ideal Point method deals with addressing the uncertainty in land suitability evaluation in the study area.

It has to be noticed that the Ideal Point method is an extension of the Fuzzy AHP approach in this research, because the inputs of the Ideal Point approach in this study are the weighted fuzzy maps of land criteria produced in the Fuzzy AHP approach.

The application of the Ideal Point to the model of land evaluation showed that the study area has a wide range of classes for the suitability classification for barley, wheat and maize, and these classes range from 0 (full non-membership function) to 1 (full membership function), where 1 is highly suitable classes and 0 not suitable classes. This range resulted from the differences between the positive ideal and negative ideal values for the criteria and from the weighted fuzzy values produced by applying the Fuzzy AHP approach.

The model outputs also showed that the land suitability map for barley is more similar to the land suitability map for wheat than the land suitability map for maize; this is like the results obtained by applying Fuzzy AHP to the suitability classification for these crops. The similarity between the land suitability maps for barley and wheat as discussed in the section on Fuzzy AHP was explained by the similarity of crop requirements; the weights or measures of relative importance for these crops are very similar, and furthermore the maximum values (the values determining the ideal point) and minimum values (the values determining the negative ideal point) for the weighted fuzzy maps (i.e. the inputs for the Ideal Point approach) for barley and wheat are very similar to each other.

The results from the use of the Ideal Point approach showed that the same locations which were given low JMFs values for barley and wheat have been classified with high JMFs values for maize. The implication of these results is that these locations are more suitable for maize production than barley and wheat production, and this, as discussed in the section on the Fuzzy AHP approach, requires further work including the development of trial plots to ground truth the suitability measures.

The variability in overall suitability resulting from the use of the Ideal Point approach, as with the Fuzzy AHP approach, is mainly due to the variability of the MFs values and their weights and furthermore to the difference between the positive and negative ideal point values (i.e. maximum and minimum values).

The main advantage in using the Ideal Point approach to land suitability evaluation, as with the Fuzzy AHP approach, is the ability to address and explore the uncertainties associated with describing land properties. The Ideal Point approach has the ability to take into consideration the effect of land properties which happen to have values close to category boundaries. The Ideal Point approach has facilitated the incorporation of expert knowledge into the model of land suitability evaluation. The Ideal Point approach presents suitability classes as a continuous scale, which is preferred in the process of land suitability evaluation; this is in agreement with the findings of Prakash (2003) and Chaddad et al. (2007).

The main critical issue in the application of the Ideal Point approach to land suitability evaluation is like that of the Fuzzy AHP approach; furthermore, the Ideal Point approach, according to Malczewski (1999), Prakash (2003) and Chaddad et al. (2007), was found to be biased towards positive and negative ideal values. The use of the Ideal Point approach is a very complicated process, particularly if too many parameters have been organized into the hierarchy.

9.6 Discussion of the Results Comparison

As stated at the beginning of this research, the main aim of this study was to explore the added benefits for land suitability evaluation of using a framework of land evaluation decision making with Fuzzy AHP and Ideal Point approaches, compared to traditional land evaluation using a Boolean approach.

The comparison of the results from these three models was one of the most fundamental stages in this research, and there were many reasons for evaluating and analyzing the results. One of these reasons was to explore the abilities of the Fuzzy AHP and Ideal Point approaches in addressing the uncertainties associated with describing land properties in the process of land suitability evaluation.

The comparison between the results from these three models showed very interesting findings. It illustrated that there are big and obvious differences between Boolean results and fuzzy approaches results. The differences between fuzzy approaches and Boolean results were expected, because the Boolean approach is a limiting factor approach, while the Fuzzy AHP and Ideal Point approaches are continuous classification approaches. The differences in the results between Boolean and fuzzy approaches are mainly due to the fact that the Boolean approach does not have the ability to take into consideration the effect of properties which happen to have values near to class boundaries, while this is the advantage of using fuzzy approaches in the process of land suitability evaluation.

Land suitability maps derived from using fuzzy approaches show the interaction between fuzzy membership functions values and their weighting for the selected land properties, while with Boolean land suitability maps it is possible to show the suitability class for one factor, because it is a limiting factor approach.

The Boolean approach shows that the study area has only four suitability classes: highly suitable, moderately suitable, marginally suitable and currently not suitable, while the Fuzzy AHP and Ideal Point methods result in a wide range of suitability classes in the study area and are therefore more realistic, because so many elements in nature are not so clearly defined.

The comparison shows that land suitability maps derived from using the Fuzzy AHP approach are more similar to those derived from using the Ideal Point approach and the explanation of this similarity is that fuzzy weighted maps produced using the Fuzzy AHP methodology were the inputs for the Ideal Point approach.

The similarity between land suitability maps produced by using Fuzzy AHP and Ideal Point approaches was found only in some locations. For example, locations which were mapped at between 0.40 and 0.50 for barley using Fuzzy AHP were mapped at between 0.30 and 0.40 for barley using the Ideal Point approach. The differences between the results from using the Fuzzy AHP and Ideal Point approaches are mainly due to the fact that deriving the overall suitability or the JMFs by using the Ideal Point approach takes the maximum and the minimum values of the fuzzy weighted maps into account and ignores others; this means that the suitability classification derived from the use of the Ideal Point approach has some bias towards the positive and negative ideal points or the maximum and minimum values. The land suitability model using Fuzzy AHP does not apply this function.

The comparison between Boolean and fuzzy approaches has shown that each suitability class as determined by Boolean methods (highly suitable, moderately suitable, marginally suitable and currently not suitable) was associated with low and high joint membership functions values (JMFs). This means that the Fuzzy AHP and Ideal Point approaches are both attempting to extend the concept of continuous variation of land properties from the geographic space to the attribute space.

9.7 Discussion of the Map Agreement Results

The determination of the overall agreement for land suitability evaluation maps was one of the most essential stages in this research. The results derived from using the Composite operator to calculate the agreement between the maps indicated that there is always less overall agreement between Boolean maps and fuzzy maps (Fuzzy AHP and Ideal Point maps) for the three selected crops, while the overall agreement between the Fuzzy AHP and Ideal Point maps is always high.

The high overall agreement among the Fuzzy AHP and Ideal Point maps means that there was good correspondence between the pixels in land suitability classes for the crops, while the low overall agreement between Boolean and fuzzy maps (Fuzzy AHP and Ideal Point) means that there was less correspondence between the pixels in land suitability classes for the crops. The main reason for obtaining less agreement between Boolean and fuzzy maps was that land suitability maps under the use of the Boolean approach were based on hard classification while land suitability maps under the use of the fuzzy approaches were based on using soft classification.

It is evident from the results (8.31, 8.32 and 8.33) that the overall agreement between the maps was increased when the resolution scale was increased and this may be because, as Pontius and Cheuk (2006) state, ‘the composite operator examines the agreement within the boundaries of a pixel, so when the boundaries become larger, the potential for the agreement also becomes larger’. The results of deriving the overall agreement between the maps in this study could in fact be wrong and for that reason field trial plots will be needed to evaluate and validate the results.

CHAPTER 10

RESEARCH CONCLUSIONS AND RECOMMENDATIONS

10.1 Conclusion

This research has contributed to the development of a land suitability evaluation model for cash crops for the study area selected. The model of land evaluation in this study was appropriate for applications in which the main interest is in subtle differences in land properties. The approach developed in this research is helpful as it provides the GMPR project with information which can be beneficially employed in land use planning, particularly in the north-west of Jeffara Plain in Libya.

In this research, three land suitability models for the selected crops under irrigation conditions have been established: Boolean, Fuzzy AHP and Ideal Point methods. Applying Boolean mapping to the model of land suitability requires a degree of accuracy and detail in the information which is very difficult if not impossible to find in the real world. The application of the Fuzzy AHP and Ideal Point procedures to the model of land evaluation can deal with insufficient information and also can cope describe the uncertainty.

For land evaluation in the study area, the Fuzzy AHP and Ideal Point approaches produce important information for identifying major restrictions on crop production and strategies for overcoming them. The Fuzzy AHP and Ideal Point approaches can indicate land continuity in different land classes, and this is one of their advantages. Another advantage is that they allow nature to be inherently imprecise.

The Fuzzy AHP and Ideal Point approaches both gave good results, because they have succeeded in addressing the uncertainties associated with describing the boundaries and land criteria found by using Boolean mapping in the study area. Both of these methods have the ability to take into consideration the effect of properties which happen to have values close to category boundaries.

This researcher believes that the Fuzzy AHP approach gives considerably better results than the Ideal Point approach because the Ideal Point approach has some bias toward positive and negative ideal values.

In this study, local experts have contributed to the development of the land suitability evaluation model for the study area selected. All three land suitability evaluation models require the determination of land characteristics affecting agricultural growth and production. The Fuzzy AHP and Ideal Point approaches also require the selection of models for standardizing the raw data and weights that are not pre-established, and require expertise in the determination of the weights for each selected land characteristic.

In the Boolean approach, the suitability classes and the decisions about land characteristics also need the opinions of local experts. With a method such as Boolean to determine the land suitability, the ways to determine suitability classes can be straightforward or not straightforward; this means that weights derived through the pairwise comparison analysis can be used by means of the weighted overlay technique to produce the overall land suitability maps.

The general conclusions are listed in terms of the set of research questions posed in Chapter 1:

Research Question 1: Which land evaluation methods are suitable for generating land suitability mapping sensitive to Libyan environmental conditions?

As stated in Chapter 5, the application of the Boolean method to the model of land evaluation has been criticized by many authors, because, with the Boolean technique, boundaries between the classes are clearly defined, which does not always reflect the reality, because many elements in nature are not so obviously defined. In land evaluation using the Boolean method, a single low parameter is enough to decrease the suitability of land from a highly suitable class to a less suitable class. Furthermore, parameters in land evaluation using the Boolean method may have the same weights, and this will make the classification quite strict. This problem has been resolved in this research by taking the weights derived through the pairwise comparison into consideration to produce the overall land suitability maps for each crop, while another problem associated with Boolean mapping has been resolved in this research by using the Fuzzy AHP and Ideal Point methods. The results of the Ideal Point approach are satisfactory, but the problem with this approach is it has some bias toward negative and positive ideal point values, and therefore this research believes that the use the Fuzzy AHP approach to land evaluation is more suitable in the study area.

Research Question 2: Which evaluation criteria should be taken into account in designing a land suitability model for agricultural crops under irrigation conditions in the study area?

In Chapter 7, different land characteristics affecting the suitability of land for barley, wheat and maize in the study area have been identified and obtained from the GMPR project, discussion with the local experts and the literature review. This research takes fourteen land characteristics for defining the suitability of land for barley, wheat and maize production. Physical and chemical soil parameters include soil texture, available water holding capacity, stones at surface, rootable depth, infiltration rate, soil calcium carbonate, soil pH, soil organic matter, exchangeable sodium percentage, soil salinity, soil alkalinity and cation exchange capacity. Other parameters such as erosion hazard and percentage of slope are also considered as important parameters for the model of land evaluation in the study area.

Research Question 3: How can Fuzzy AHP and Ideal Point methods develop the process of land evaluation compared to the Boolean method?

From the results and discussions it is very clear that the Fuzzy AHP and Ideal Point methods of classifications are better than the Boolean method, because these models have resolved the uncertainties associated with describing the boundaries and the phenomenon. The selected fuzzy models employed in the Fuzzy AHP – asymmetrical left, asymmetrical right and symmetrical – help in class boundary definition and resolve the uncertainty problems derived from Boolean mapping. The application of the Fuzzy AHP and Ideal Point methods to the model of land evaluation has integrated local knowledge into the framework of decision making for land evaluation. In the Fuzzy AHP and Ideal Point methods, weights were produced through the pairwise comparison analysis according to their relative importance while taking the crop requirements for each crop under local conditions into consideration.

Research Question 4: How can local experts and land evaluators develop land suitability models in the study area?

Before this study, local experts in the study area were successful in defining land parameters affecting agricultural growth and production, but they failed to define the relative importance of factor A compared to factor B and to assign suitable weights to factors affecting agricultural production. In this research, local experts have contributed to the development of the land suitability models in the study area by weighting the selected land parameters through the pairwise comparison analysis and than using these weights to produce land suitability maps for the selected crops. The results obtained from using the pairwise comparison analysis were consistent and therefore the relative weights were suitable to be incorporated in land evaluation models. The accuracy of the results is mainly based on the weights obtained from the local experts for different land characteristics.

Research Question 5: Do the results obtained from Fuzzy AHP and Ideal Point methods correspond to the model outputs derived from the traditional land evaluation in the study area? Which results are more realistic?

From the comparison and evaluation it is clear that the Fuzzy AHP results correspond to the results derived from the Ideal Point approach, and both of these methods are less consistent with the results of Boolean mapping. The Composite operator with multiple-resolution analysis shows that less correspondence was obtained when comparisons were made between the Fuzzy AHP and Boolean results and between Ideal Point and Boolean results, whilst a good correspondence was found when the Fuzzy AHP and Ideal Point results were compared. According to the results, the Fuzzy AHP and Ideal Point methods present land suitability classes as continuous values, while the use of the Boolean method results in neat crisp sets, which are less realistic in nature. The use of the Fuzzy AHP and Ideal Point methods contain fewer errors compared with the Boolean approach. The use of continuous methods (i.e. Fuzzy AHP and Ideal Point) has resolved the disadvantages derived from applying Boolean mapping to the model of land evaluation in the study area.

10.2 Research recommendations and further applications

The most important development that has been made in this research is the introduction of local knowledge from different sources into the model of decision making for land evaluation applications. The Geographic Information System (GIS) and local knowledge have been combined in this study and this combination has led to the production of specific information for land evaluation for the study area selected.

This research is considered to be the first study incorporating local knowledge with Fuzzy AHP and Ideal Point methods in land evaluation studies in Libya, and this could play a vital role in the development of land evaluation models, land use planning and agricultural policy in Libya. It provides information and results relevant for decision making.

The results will assist the decision makers in Libya in selecting a suitable scenario for each land area, and will also provide the decision makers with more realistic information about the characteristics of different land areas and their behaviour under the selected crops. The implications of research findings are to select crop trial plots in the study area, and this will help the decision makers in Libya towards improving the management of the land and planning agricultural development.

The land evaluation methods which have been developed (i.e. Fuzzy AHP and Ideal Point methods) will contribute deeply to making the planning process more transparent and rational. The results show that the use of the land for the selected crops needs land management to be improved, and this is essential for planning future agricultural development in the study area.

For future evaluations of land suitability in the Jeffara Plain region of Libya, it is important for the Great Man-Made River project (GMPR) and the decision makers to take the following recommendations into consideration:

1. The model developed can be adapted for all parts of the Jeffara Plain region and the same methodology can be implemented for different agricultural crops.
2. Local knowledge is urgently needed in the model of decision-making used in the framework of land evaluation.
3. The Great Man-Made River project (GMPR) and Libyan decision makers should take the research findings into consideration for current and future land use planning.
4. There is a need to specify irrigation and management methods which planned to be used in the study area.
5. Particular attention should be given in the study area to the physical soil properties, to the quality and quantity of available water in relation to techniques of irrigation considered.
6. Trial plots should be established for the selected crops under irrigation conditions in the study area to validate the results.
7. There is a need to establish an economic database system. This database system will make land evaluation studies in Libya more effective and accurate.
8. Funding is needed for land evaluators and local expertise in Libya to develop land evaluation methods under local conditions.

References

Abdi1, E. B. Majnounian, A. Darvishsefat, Z. Mashayekhi1, J. Sessions (2009). 'A GIS-MCE based model for forest road planning'. *Journal of Forest Science*, 55, (4): 171–176.

Agricultural Research Center. (2000). *Agricultural Development Achievements Report* No.38. Tripoli: Ministry of Agriculture.

Alghraiani, A. (1996). *Satisfying future water demand of northern Libya*. Tripoli: Water Resources Development.

Baja, S., Chapman, D.M., and Dragovich, D. (2001). 'A Conceptual Model for defining and assessing land management units using a fuzzy modeling approach in GIS Environment'. *Environmental Management,* 29: 647–661.

Banai, R. (1993). 'Fuzziness in Geographical Information Systems: contributions from the Analytic Hierarchy Process'. *International Journal of Geographical Information Systems*, 7 (4): 315-329.

Bakker, M.M., Govers, G., and Rounsevell, M.D.A. (2004). 'The crop productivity erosion relationship: an analysis based on experimental work'. 57: 55-76.

Ben-Mahmoud, R. (1995). *Libyan Soils,* First Edition. Tripoli: National Scientific Research Organization.

Ben-Mahmoud, R., Mansur, S., and Al-Gomati, A. (2000). *Land degradation and desertification in Libya* Tripoli: Land Degradation and Desertification Research Unit, Libyan Center for Remote Sensing and Space Science.

Bibby, J.S., and Mackney, D. (1969). *Land Use Capability Classification*, Soil Survey Technical Monograph No.17.

Brady, N.C., and Weil, R.R. (1999) *The Nature and Properties of Soils*, 12th ed. Prentice Hall.

Brady, N.C. (1984). *The nature and properties of soils*. New York: Macmillan.

Boroushaki, S., and Malczewski, J. (2008). 'Implementing an extension of the analytical hierarchy process using ordered weighted averaging operators with fuzzy quantifiers in ArcGIS'. *Computers & Geosciences*, 34: 399–410.

Braimoh, K.A., Vlek, G., and Stein, A. (2004). 'Land Evaluation for Maize based on Fuzzy set and I interpolation'. *Environmental Management Journal*, 33: 226-238.

Burrough, P.A. (1986). *Principles of Geographical Information Systems for land resources assessment*. Oxford: Clarendon Press, p. 194.

Burrough, P.A. (1987). 'Mapping and mapping analysis: new tools for land evaluation'. *Soil Use Management*, 3: 20-25.

Burrough, P.A. (1989). 'Fuzzy mathematical methods for soil survey and land evaluation'. *Journal of Soil Science*, 40: 447-492.

Burrough, P.A., MacMillan, R.A., & Van Deursen, W. (1992). 'Fuzzy classification methods for determining land suitability from soil profile observations and topography'. *Journal of Soil Science*, 43: 193-210.

Carver, S. J. (1991). 'Integrating multi-criteria evaluation with geographical information systems'. *International Journal of Geographical Information Systems*, 5 (3): 321-339.

Ceballos-Silva, A., and Lopez-Blanco, J. (2003). 'Delineation of suitable areas for crops using a Multi Criteria Evaluation approach and land use/cover mapping: a case study in Central Mexico.' Agricultural Ecosystem and Environment, 77(2): 117-136.

Chang, L., and Burrough, P.A. (1987). 'Fuzzy reasoning: a new quantitative aid for land evaluation'. *Soil Survey. Land Evaluation*., 7: 69-80.

Chaddad, I., Feng, C.B., Al-Husni, M., and Jin Zhen, R. (2009). 'An application of land suitability evaluation for FTDP: a fuzzy MCDM approach'. *International Journal of Arab Culture, Management and Sustainable Development (IJACMSD)*, 1(2): 160-176.

Chakhar, S., and Mousseau, V. (2008). 'GIS-based Multicriteria spatial modeling generic framework'. *International Journal of Geographical Information Science*, (22): 1159–1196.

Chen, Y. J. Yu, Shahbaz, K., and Xevi, E. (2009). 'A GIS-Based Sensitivity Analysis of Multi-Criteria Weights'. *18th World IMACS / MODSIM Congress,* Cairns, Australia, 13-17 July 2009.

Chuong., H. V. (2008). 'Multicriteria Land Suitability Evaluation For Crops using GIS at community level in Central Vietnam, with case study in Thuy Bang-Thua Thien Hue province. *International Symposium on Geoinformatics for Spatial Infrastructure Development in Earth and Allied Sciences*.

Congalton, R. (1991). 'A Review of Assessing the Accuracy of Classifications of Remotely Sensed Data'. *Remote Sensing of Environment*, 37: 35-46.

Coulter, E.D., Sessions, J., and Michael, W.G. (2003). 'Scheduling Forest Road Maintenance Using the Analytic Hierarchy Process and Heuristics'. *Silva Fennica*, 40: 143–160.

Davidson, D.A. (1992). *The Evaluation of Land Resources*. London: Longman Group

Davidson, D. A., Theocharopoulos, S.P., and Bloksma, R.J. (1994). 'A land evaluation project in Greece using GIS and based on Boolean and fuzzy set methodologies'. *International Journal of Geographic Information Systems*, 8: 369–384.

Davidson, D.A. (2002). 'The assessment of land resources: Achievements and new challenges'. *Australian Geographic Studies*, 40: 109-128.

Deng, H. (1999). ‘Multicriteria analysis with fuzzy pairwise comparisons’. *International Journal of Approximate Reasoning* 21: 215-231.

De La Rosa, D., Moreno, J.A., and Garica, L.V. (1992). ‘Micro LEIS: A Microcomputer-Based Mediterranean Land Evaluation Information System’. *Soil Use and Management*, 6(1): 7-20.

Dent, D., and Young, A. (1981). *Soil Survey and Land Evaluation*. London: George Allen and Unwin.

Delgado, G V. Aranda, J. Calero, M. Sánchez-Marañón, J. M. Serrano, D. Sanchez, M. A. Vila., (2009). ‘Using fuzzy data mining to evaluate survey data from olive grove cultivation’**.** 65(1): 99-113.

Duc, T.T. (2006). ‘Using GIS and AHP Technique for Land Use Suitability Analysis’. *International Symposium on Geoinformatics for Spatial Infrastructure Development in Earth and Allied Sciences*.

Dumanski, J. (1994). *Proceedings of the International Workshop on Sustainable Land Management for the 21st Century* , Ottawa: Agricultural Institute of Canada.

Eastman, J. R., Kyem, P.A.K., Toledano, J., and Jin, W. (1993). *GIS and decision making*. Explorations in geographic information system technology, 4. Geneva: UNITAR.

Eastman, J.R. (2001). *Guide to GIS and Image processing*., Volume 2. IDRISI Release 2. Clark Labs.

Eastman, J.R. (2003). *IDRISI Kilimanjaro Tutorial*. Clark Labs.

Eastman, J.R. (2006). *IDRISI Andes Guide to GIS and Image processing*. Clark Labs.

Eldrandaly, K, Eldin, N., Sui, D., Shouman, M., and Nawara, G. (2005). 'Integrating GIS and MCDM Using COM Technology'. *The International Arab Journal of Information Technology*, 2(2).

Engelstad, O.P., Shrader, W.D., & Dumenill, L.C. (1961) 'The effect of surface soil thickness on corn yields: I. As determined by a series of experiments in farmer operated fields'. *Soil Science Society of America Journal*, 25: 494-497.

FAO. (1976). *A framework for land evaluation*. Rome: Food and Agricultural Organization of the United Nations.

FAO (1979) *Land Evaluation Criteria for Irrigation*. Rome: Food and Agriculture Organisation.

FAO (1983). *Guidelines: Land evaluation for irrigated agriculture*. Rome: Food and Agricultural Organization of the United Nations.

FAO (1985) .*Guidelines: Land evaluation for irrigated agriculture*. Rome: Food and Agricultural Organization of the United Nations.

FAO (2002). *Agricultural drainage water management in arid and semi-arid areas*. Rome: Food and Agriculture Organization of the United Nations.

FAO (2007). *Land evaluation: towards a revised framework*. Rome: Food and Agricultural Organization of the United Nations.

Florence (2000). Land resources and land evaluation of the central valley of Cochabamba (Bolivia).

Florence (2002). Land resources of the Oued Lebna catchment (Tunisia).

Florence (2002). Land evaluation in the Province of Ben Slimane (Morocco).

Fredrick, N.M., and Julie, V.B. (1997). 'Planning sustainable land management: finding a balance between user needs and possibilities'. *ITC Journal,* 3-4.

GMRP (1990). *Great Man-made River Project report*. Tripoli, Libya: The Great Man-Made River Authority.

GMRP (2008). *Great Man-made River Project report*. Tripoli, Libya: The Great Man-Made River Authority.

Hall, G. B., Wang, F., and Subaryono, J. (1992). 'Comparison of Boolean and fuzzy classification methods in land suitability analysis by using geographical information systems'. *Environment and Planning A,* 24: 497-516.

Hartati, S., and Sitanggang, I . (2010). 'A Fuzzy Based Decision Support System for evaluating land suitability and selecting crops'. *Journal of Computer Science,* 6(4): 417-424.

Heywood, I., Oliver, J., and Tomlinson, S. (1995). 'Building an exploratory multi-criteria modeling environment for spatial decision support', in P. Fisher, ed., *Innovations in GIS 2*. Bristol: Taylor & Francis, 127-136.

Hoobler, B.M., Vance, G.F., Hamerlinck, J.D., Munn, L.C., and Hayward, J.A. (2003). 'Applications of land evaluation and site assessment (LESA) and a geographic information system (GIS) in East Park County, Wyoming'. *Journal of Soil and Water Conservation*, 58: 105-112.

Hwang, C-L., and Yoon, K. (1981). *Multiple Attribute Decision Making: Methods and Applications*. Berlin: Springer-Verlag.

ILACO (1989). *Agricultural Compendium for Rural Development in The Tropics and Subtropics*, Second Edition. New York: Elsevier Science.

Jankowski, P., and Richard, L. (1994) 'Integration of GIS-based suitability analysis and multicriteria evaluation in a spatial decision support system for route selection'. *Environment and Planning B*, 21: 326–339.

Jankowski, P. (1995). 'Integrating geographical information systems and multiple criteria decision making methods'. *International Journal of Geographical Information Systems*, 9: 251–273.

Kanyand, C.W. (1988) .*Field application of the FAO guidelines for land evaluation for rainfed agriculture in comparison with the national guidelines: criticisms and proposal*, FAO World Soil Resources No.62.

Kalogirou, (2002). ‘Expert system and GIS: an application of land suitability evaluation’. *Computers, Environment and Urban Systems*, 26: 89-112.

Keshavarzi, A. (2010) ‘Land Suitability Evaluation using fuzzy continuous classification (A Case Study: Ziaran Region)’. *Modern Applied Science*, 4(7).

Klingebiel, A.A., and Montgomery, P.H. (1961). *Land-Capability Classification*. USDA-SCS Agricultural Handbook 210. Washington, D.C.: U.S. Government Printing Office.

Lai, S-K., and Hopkins, L.D. (1989). ‘The meanings of trade-offs in multiattribute evaluation methods: a comparison’. *Environment and Planning B*, 16: 155–170.

Land Capability Classification for Forestry (1967). The Canada Land Inventory Report No 4

Landon, (1984) *Booker Tropical Soil Manual*. New York: Booker Agriculture International.

Laurini, R., and Thompson, D. (1992). *Fundamentals of Spatial Information Systems*. The APIC series no.37. London: Academic Press.

Lodwick, W.A. (2007). Fuzzy Surfaces in GIS and Geographical Analysis: Theory, Analytical Methods, Algorithms and Applications.

Libyan Statistics Book. (2007). General Authority For Information and Yearly Bulletin.

MAFF (1988) *Agricultural land classification of England and Wales: Revised guidelines and grading the quality of agricultural land*. Ministry of Agriculture Fisheries and Food.

Malczewski, J. (1996). 'A GIS-based approach to multiple criteria group decision-making'. *Journal of Geographical Information Systems*, 10(8): 955-971.

Malczewski, J. (1999). *GIS and Multicriteria Decision Analysis.USA and Canada*. John Wiley & Sons.

Malczewski, J. (2004). *GIS-based land use suitability analysis: a critical overview*. Elsevier, 3-65.

Malczewski, J. (2006). Ordered weighted averaging with fuzzy quantifiers: GIS-based Multicriteria evaluation for land use suitability analysis.

Massam, B.H. (1988). 'Multi-criteria decision making techniques in planning'. *Program. Planning*, 30: 1–84.

Mayaki, W.C., Stone, L.R., and Teare, I.D. (1976) 'Irrigated and non-irrigated soybean, corn and grain sorghum root systems'. *Agronomy Journal*, 68: 532-53.

McHarg, I.L. (1969). *Design With Nature*. New York: Wiley.

McRae, S.G., and Burnham, C.P. (1981). *Land Evaluation*. Oxford: Clarendon Press.

McBratney, A.B., and Odeh, I.O.A. (1997). ‘Application of Fuzzy sets in soil science: Fuzzy logic, fuzzy measurements and fuzzy decisions’. *Geoderma,*.77: 85-113.

Mendoza, G.A., Macoun, P., Prabhu, R., Sukadri, D., Purnomo, H., and Hartanto, H. (1999). Guidelines for Applying Multi-Criteria Analysis to the Assessment of Criteria and Indicators.

Morgan, R.P.C. (1995) .*Soil erosion and conservation*, 2nd ed. London: Longman.

Moreno, J. (2007). ‘Applicability of knowledge-based and fuzzy theory-oriented approaches to land suitability for upland rice and rubber, as compared to the farmers’ perception. A case study of Lao PDR’, published Master’s thesis. Enschede, Netherlands: International Institute for Geo-Information Science and Earth Observation.

Nagowi, J., and Stocking, M. (1989). ‘Assessing land suitability and yield potential for coconuts in Tanzania’. *Applied Geography,* 9: 21-33.

Nisar Ahamed, T. R., Gopal Rao, K., and Murthy, J.S.R. (2000). ‘GIS-based fuzzy membership model for crop-land suitability analysis’. *Agricultural Systems,* 63 (2): 75-95.

Nwer, B., 2005. ‘The application of land evaluation technique in the north-east of Libya’, published PhD thesis, Cranfield University, Silsoe.

Orhan, D., llhami, B., and Mahmut, Y. (2003). 'Geographic Information System and Remote Sensing Based Land Evaluation of Beypazari Area Soils by ILSEN Model',27: 145-153.

Pereira, J.M.C., and Duckstein, L. (1993). 'A multiple criteria decision making approach to GIS-based land suitability evaluation'. *International. Journal . Geographic. Information. System*., 7 (5): 407–424.

Fisher, P.F., and Wood, J. (1998). 'What is a Mountain? or The Englishman who went up a Boolean geographical concept but realised it was Fuzzy'. *Geography*, 83(3): 247-256.

Phua, M., and Minowa, M. (2005). 'A GIS-based multi-criteria decision making approach to forest conservation planning at a landscape scale: A case study in the Kinabalu area, Sabah, Malaysia'. *Journal of Landscape and Urban Planning*, 71: 207-222.

Pontius, R.G., Jr., & Cheuk, M.L. (2006). 'A generalized cross-tabulation matrix to compare soft-classified maps at multiple resolutions'. *International Journal of Geographical Information Science*, 20(1): 1−30.

Prakash, J. (2003). 'Land Suitability Evaluation for Agricultural crops: A fuzzy multicriteria decision making approach', Published Master's thesis. Enschede, Netherlands: International Institute for Geo-Information Science and Earth Observation.

Rossiter, D.G., & van Wambeke, A.R. (1989). *ALES version 2.2. Users Manual*. Ithaca, NY: Department of Agronomy, Cornell University.

Rossiter, D.G. (1990). ‘ALES: a framework for land evaluation using a microcomputer’. *Soil Use & Management*, 6: 7-20.

Saaty, T.L. (1977). ‘A scaling method for priorities in hierarchical structures’. *Journal of Mathematical Psychology*, 15: 234-281.

Saaty, T.L. (1980). *The Analytic Hierarchy Process*. New York: McGraw–Hill.

Saaty, T.L. (2008). ‘Decision making with the analytic hierarchy process’. *International. Journal. Services Sciences*, 1(1).

Selkhozpromexport (1980). *Soils study in the Western zone of the Socialist People’s Libyan Arab Jamahiriya*. Tripoli: Secretariat for Agricultural Reclamation and Land Development..

Sekitani, K., and Yamaki, N. (1999) ‘A logical interpretation for the eigenvalues method in AHP’. *Journal of the Operations Research Society of Japan*, 42: 219-232.

Siddiqui, M.Z., Everett, J.W., and Vieux, B.E. (1996). ‘Landfill siting using geographical information systems: a demonstration’. *Journal of Environmental Engineering*, 122 (6): 515–523.

Sicat, R.S., Carranza, E.J.M., & Nidumolu, U.B. (2005). ‘Fuzzy modeling of farmers' knowledge for land suitability classification’. *Agricultural Systems,* 83: 49-75.

Stewart, G.A. (1968). ‘Land Evaluation’, in G.A. Stewart, *Land Evaluation*. Melbourne: Macmillan (Australia).

Stoms, D.M., McDonald, J., and Davis, F.W. (2002). ‘Fuzzy Assessment of land suitability for scientific research reserves’. *Environmental Management*, 29: 545-558.

Sys, C., Van Ranst, E., Debaveye, J. & Beernaert, F. 1993. *Land evaluation, Part 3 : Crop requirements.* Agricultural Publications 7. General Administration for Development Cooperation, Brussels.

Tanji, K.K. (1996). *Agricultural Salinity Assessment and Management*. ASCE Manuals and Reports on Engineering no. 71, 113-161.

Tkach, R. J., and Simonovic, S.P. (1997). ‘A New Approach to Multi-criteria Decision Making in Water Resources’. *Journal of Geographic Information and Decision Analysis*, 1(1): 25-44.

Triantaphyllou, E., and Lin, C.-T. (1996). ‘Development and Evaluation of Five Fuzzy Multiattribute Decision-Making Methods’. *International Journal of Approximate Reasoning*, 14: 281-310.

USBR (1951). *Bureau of Reclamation Manual, vol V: Irrigated land use, part 2: Land classification*. Denver: Department of the Interior Bureau of Reclamation.

Van Ranst, E., Tang, H., Groenemans, S., and Sinthurahat, S. (1996). 'Application of fuzzy logic to land suitability for rubber production in peninsular Thailand'. *Geoderma*, 70: 1-19.

Vogel, R. (2008) 'A Software Framework for GIS-based multiple criteria evaluation of land suitability'. *11th AGILE International Conference on Geographic Information Science*, [date of conference], University of Girona, Spain, p.1.

Wang, F.-J., Hall, G.B., Subaryono, [initials] (1990). 'Fuzzy information representation and processing in conventional GIS software: database design and application'. . *International. Journal . Geographic. Information. System.*, 4: 261-283.

Wood, S.R., and Dent, F.J. (1983). *LECS. A Land evaluation computer system methodology*. Bogor: Ministry of Agriculture / PNUD/FAO.

Wu, F. (1998). 'SimLand: a prototype to simulate land conversion through the integrated GIS and CA with AHP-derived transition rules'. *International Journal of Geographical Information Science*, 12: 63–82.

Xiang, W.-N., Gross, M., Fabos, J. & MacDougall, E. B. (1992). 'A fuzzy-group multicriteria decision making model and its application to land-use planning'. *Environment and Planning, B: Planning and Design*, 19**:** 61-84.

Zadeh, L.A. (1965). 'Fuzzy sets'. *Information and Control*, 8: 338-353.

Zeleny, M. (1982). *Multiple Attribute Decision Making*. New York: McGraw Hill.

Zonn, S.N. (1974) Soil Formation and Subtropical and Tropical Soils, International Congress of Soil Scientists . Moscow.

Zhu, X., and Dale, A.P. (2001). 'Java AHP: a Web-based decision analysis tool for natural resource and environmental management'. *Environmental Modeling and Software*, 16: 251–262.

Ziadat, F.M. (2007). 'Land suitability classification using different sources of information: Soil maps and predicted soil attributes in Jordan'. *Geoderma*, 140: 73-80.

Appendix A

A 1: A Brief Description for the soils in the study area

1. Siallitic Cinnamon Typical Soils

The siallitic cinnamon typical soils are found in the Jeffara Plain of Libya. It lies on the volcanic plateau, flat, undulating, plains, dingle bottoms, on gentle slopes and flat watershed areas of the dingle-to-ridgy and hilly relief; the ground water being deeply bedded. The main parent materials of soils are alluvial, alluvial- proluvial, eluvial-deluvial and proluvial deposits, mainly of light texture. The siallitic cinnamon typical subtype is subdivided into three genera: carbonate, carbonate saline and leached. The soils of the carbonate genus contain carbonates throughout the profile and effervesce from the surface. The leached soils are characterized by the absence of carbonates in the hummus accumulative horizon. In the carbonate saline soils, readily soluble salts are visually indentified. The profile of the fully developed siallitic cinnamon typical soils cantinas the following horizons: A, B_1ca, B_2ca, B_3ca, BCca, Cca and R.

2. Reddish Brown Arid Differentiated Soils

The reddish brown arid differentiated soils covers many areas of Jeffara Plain of Libya. Depending upon the relief features and the parent material, the reddish brown arid differentiated soils differs from soil contours of varying size and shape. The soils occur in relativity low areas of the plateau plains, as well as on flat plateau-like watershed areas of tablelands. The reddish brown arid differentiated soils in Jeffara Plain lie on flat terrain. The parent material is composed of alluvial and alluvial-proluvial deposits represented, mainly, by sand and loamy sand, less frequently by light clay loam. The reddish brown arid differentiated soils is subdivided into Carbonate, carbonate saline and carbonate gypsic. Normally, the reddish brown arid differentiated soils have the following genetic structure of the profile: A_1 or A_P, B_1ca (occasionally B_1), B_2ca, B_3ca (or BCca), Cca, occasionally R or Crca (at depth of over 120 cm).

3. Reddish Brown Arid Differentiated Crust Soils

The soils of reddish brown arid differentiated crust are mainly spread on the littoral and residual plains. In the Jeffara Plain they are most common it its costal northern part, while in the residual plain in its slightly inclined piedmont. Typical microrelief forms of the described soils are relative depressions, hollow-like depressions of various size, lower parts of the gentle slops of the residual massifs, and also flattened and plateau- like watershed areas of the residual hills and residual massifs. They are more often confined to the lower parts of the gentle and less frequently slanting slopes of the ridges and hills. The reddish brown arid differentiated carbonate crust soils are only one soil genera was found in the study area, but the rest of Jeffara Plain has different soil genera. Depending on the depth of the crust horizon bedding, the vertical profile is differentiated into the following horizons: A_1, B_1ca, B_2ca, B_3ca, BCca, and CRca.

4. Reddish Brown Arid Slightly Differentiated Soils

The reddish brown arid slightly differentiated soils are mapped on the littoral plain and on the Jebel Nefusa plateau. They are developing within the dissected plains (those dingle-ridgy, low hilly, hilly) of the uplands and residual tracts located on the relativity depressed elements of the microrelief, such as wadi bottoms, dingles, kettle depression , lower parts of slopes. The parent materials, on which the reddish brown arid slightly differentiated soils develop, are represented by alluvial, alluvial-proluvial, occasionally proluvial-deluvial and eolian deposits. The reddish brown arid slightly differentiated soils is subdivided into carbonate, carbonate saline, and carbonate solonetzic saline and carbonate gypsic and leached. The reddish brown arid slightly differentiated soils most often divided into horizons A_1B_1ca,B_2ca, B_2ca, (sometimes B_3ca) BCca, Cca. The transition between the horizons is gradual, without pronounced boundaries.

5. Reddish Brown Arid Slightly Differentiated Crust

On the Jeffara Plain the reddish brown arid slightly differentiated crust soils are to be found most frequently in its northern part. In the southern part of the Jeffara Plain these soils are most common on the piedmont slightly inclined residual plain. The parent material is basically made up of alluvial, alluvial- proluvial and proluvial-deluvial deposits. The reddish brown arid slightly differentiated crust soils are younger than the differentiated crust soils. The A_1, B1ca, CRca or A, B_1ca, BCca, CRca horizons are typical of soils. The reddish brown arid slightly differentiated crust soils are subdivided into the following genera: carbonate, carbonate saline, carbonate gypsic and leached.

6. Reddish Brown Arid Non-Differentiated Soils

The reddish brown arid non-differentiated soils occur mostly on the littoral plain and rarely on the Jeffara Plain. They are most widespread in the costal and central parts of the littoral plains in the areas of continental sands and maritime sands concentration, the relief being represented by hillocky, ridgy and ridgy- vesicular eolian forms. The parent material are mostly eolian, alluvial and alluvial-proluvial sandy and loamy sandy deposits. The reddish brown arid non-differentiated soils have the following genera: carbonate and non-carbonate. The humus horizons are very vaguely pronounced. That is why the profile of the described soils is subdivided into layers but not into horizons.

7. Reddish Brown Arid Non-Differentiated Crust Soils

The reddish brown arid non-differentiated crust soils occupy a small area in Jeffara Plain. The soils in question are mapped on the littoral and the residual plains of the Jeffara lowland. They are confined to relatively negative elements of the microrelief, i.e. kettle and dingle depressions and lower parts of declivous slops of residual hills and outlier tracts. The eolian formations are underlain by limestone diluvium and eluvium. The reddish brown arid non-differentiated crust soils fall into the following genera: Carbonate and carbonate saline. The reddish brown arid non-differentiated crust soils are like non-differentiated soils is subdivided into layers.

8. Alluvial Slightly Differentiated

The alluvial slightly differentiated soils have limited occurrence on the territory of the Jeffara Plain. They are found within the piedmont tails of the residual plain along the valley of Wadi al Hira, Wadi al Majanin, Wadi Muwayt, Wadi al Hammamm, Wadi Bir al War, and Wadi al Waayrah. They develop on poorly sorted alluvial deposits, most often represented by sand, clay with interactions of gravel, pebble and boulders. These soils are subdivided into layers and each layer has different parent material; based upon the materials comes by the flood. The alluvial slightly differentiated carbonate soils is the only soil genera has identified in the study area.

9. Cinnamonic Lithosols

The Cinnamonic lithosols are mainly widespread in the south- western part of Jeffara Plain. The Cinnamonic lithosols develop under the conditions of the semiarid climate characterized by an average annual precipitation of 300- 400 mm and an average annual air temperature of 18-20°C. The parent materials of the Cinnamonic lithosols are represented by eluvial-deluvial and eluvial deposits of limestones and marls. The

Cinnamonic lithosols is divided into the genetic horizon A_1, BR, R or AR, R. The Cinnamonic lithosols fall into the following genera Carbonate and carbonate saline.

10. Reddish brown Lithosols

These soils mostly occur in the regions of Al Aziziyah, Sid as Sid, Zliten and Homs. The reddish brown lithosols develop under conditions of the semiarid climate with an average annual amount of precipitation from 200 to 400 mm and mean annual air temperature of 18-21°C. They occur on slopes and watershed surfaces of the hilly, hilly- ridgy and dingle-ridgy types of plains. The parent material is predominately represented by eluvial-deluvial and eluvial deposits of limestones. The most typical horizons are: A_1, AR, R or AR, R. The reddish brown lithosols fall into the following genera: carbonate and carbonate saline.

11. Non-Monolithic

This is specific soils are characteristic component of the soil mantel of the littoral and slightly undulating residual plains of the Western zone. In the Western zone they developed within the boundaries of the Jeffara Plain on sandy, loamy sandy and, less frequently, loamy products of reworking of Upper Cretaceous limestones and their alluvial- deluvial formations. The crust formations are of a polygenetic nature. The most typical horizons are: A_1, AR, CR OR A_1, AR, and CRsica. The non-monolithic crust fall into the following genera: carbonate, carbonate saline and carbonate gypsic.

A2: Notes from Meeting with Local Staff (2008/2009)

Different meeting were arranged with local staff. These meetings were held in Tripoli between 22th of December 2008 to 12th February, 2009. These meeting were with the following local experts in Libya:

- Dr Bashir Nwer (land evaluation and soil experts in the Faculty of Agriculture, Alfateh University; Tripoli, Libya).
- Professor Ezzeddin Rhoma (land evaluation and soil classification experts in the Faculty of Agriculture, Alfateh University; Tripoli, Libya).
- Professor Khaled Ben Mahmod (land evaluation and soil classification experts in the Faculty of Agriculture, Alfateh University; Tripoli, Libya).
- Khalil Suleiman (Soil physics scientist in the Faculty of Agriculture, Alfateh University Tripoli, Libya).

The aim of these meeting was to discus two main topics. The first topic was about the main land factors which obtained from the GMPR to design land suitability evaluation model for barley, wheat and maize in the study area. The second topic was to use the pairwise comparison analysis for each crop for criteria weighting. These topics are covered in section A2.1 and A2.2.

1. Land Factors

All the local staff confirmed that land characteristics (i.e. rootable depth, available water holding capacity, soil pH, organic matter, soil salinity, cation exchange capacity, sodium exchangeable percent, soil calcium carbonate, Stones at surface, soil drainage, infiltration rate, soil texture, slope and soil erosion) which obtained from the GMPR report (2008) are the most important factors that should be taken into consideration to design land suitability evaluation in the north- west region of Jeffara Plain of Libya.

2. Weighting Factors

As mentioned in research methodology, pairwise comparison (PCs) analysis was applied to derive the weights for the 14th land characteristics for barley, wheat and maize based on discussion with local staffs. Dr Bashir Newer, Professor Ezzeddin Rhoma, Khaled Ben Mahmod and Khalil Suleiman have used their knowledge to assign different weights to the selected land proprieties for each selected crop and therefore, different eigenvector values were derived. Examples of how the pairwise comparison matrix works to produce the weights for the selected crops is given in figure 2.1, 2.2 and 2.3.

Figure 2.1: Example of how the pairwise comparison matrix works to produce the weights for barley.

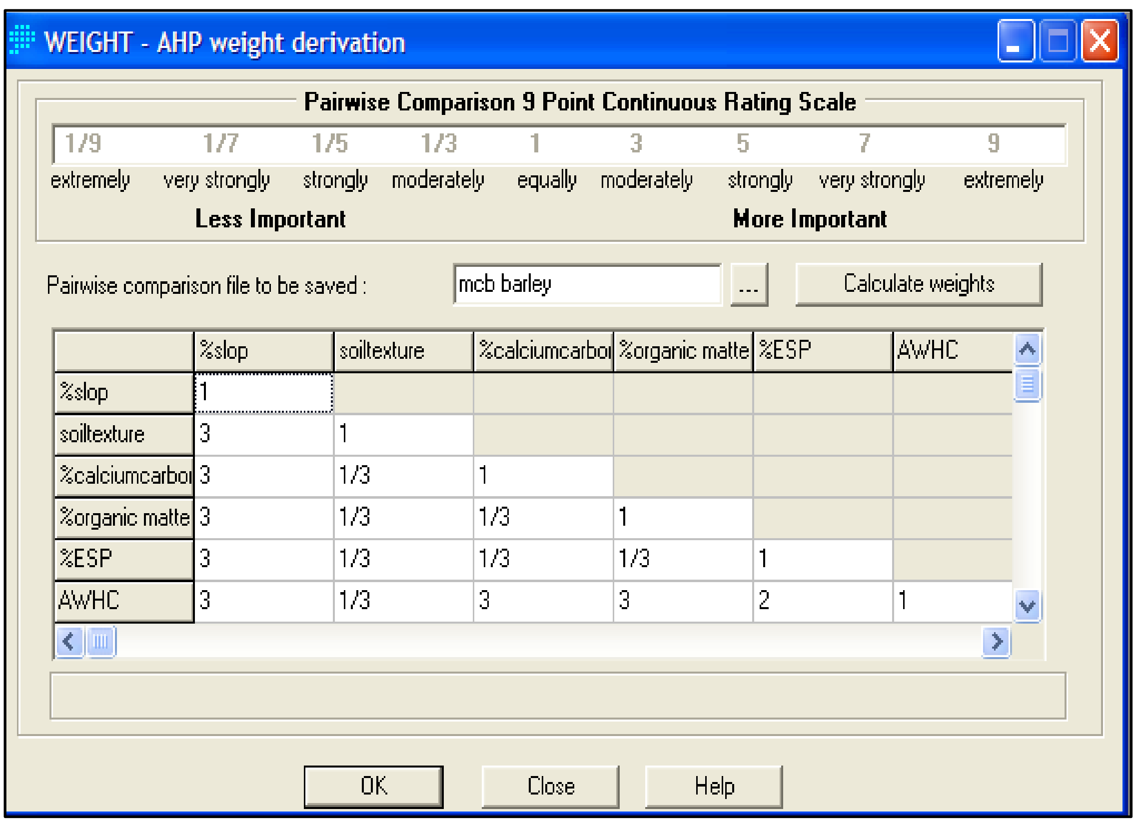


Figure 2.2: The eigenvector of weights for selected land characteristics for barley with unacceptable consistency ratio.

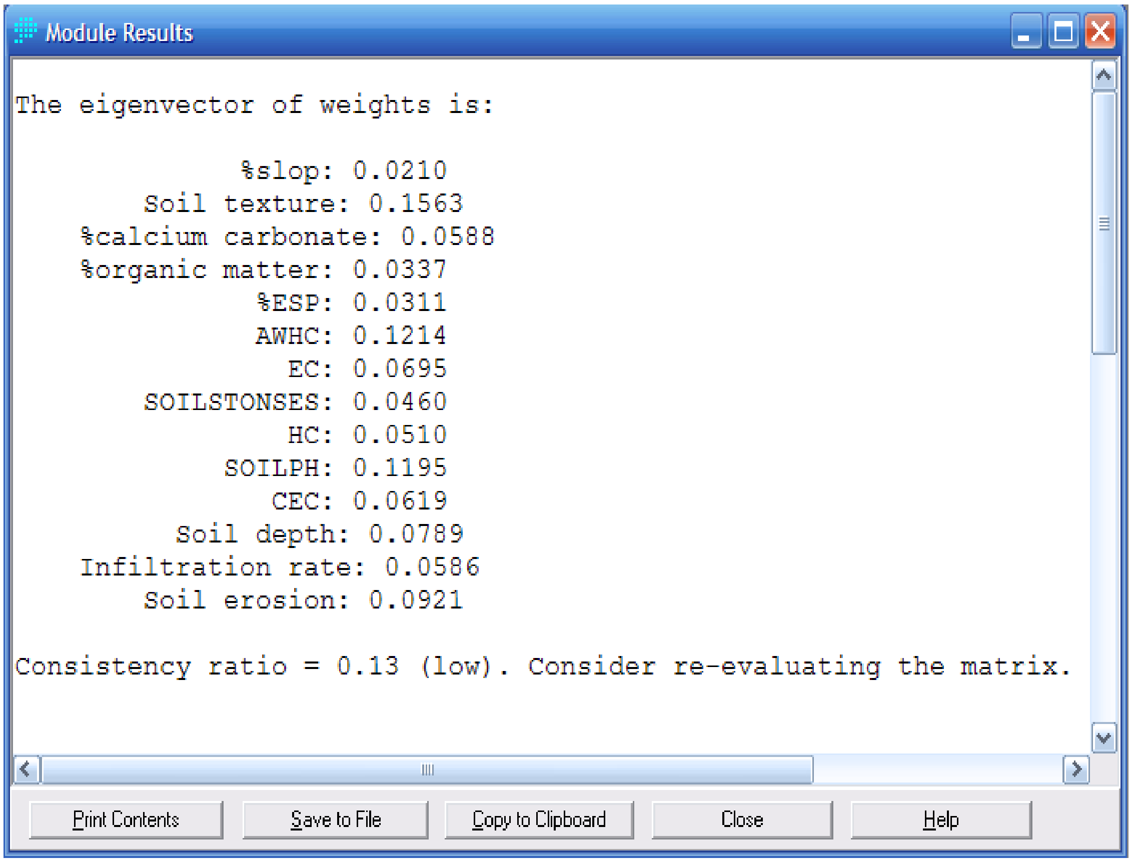
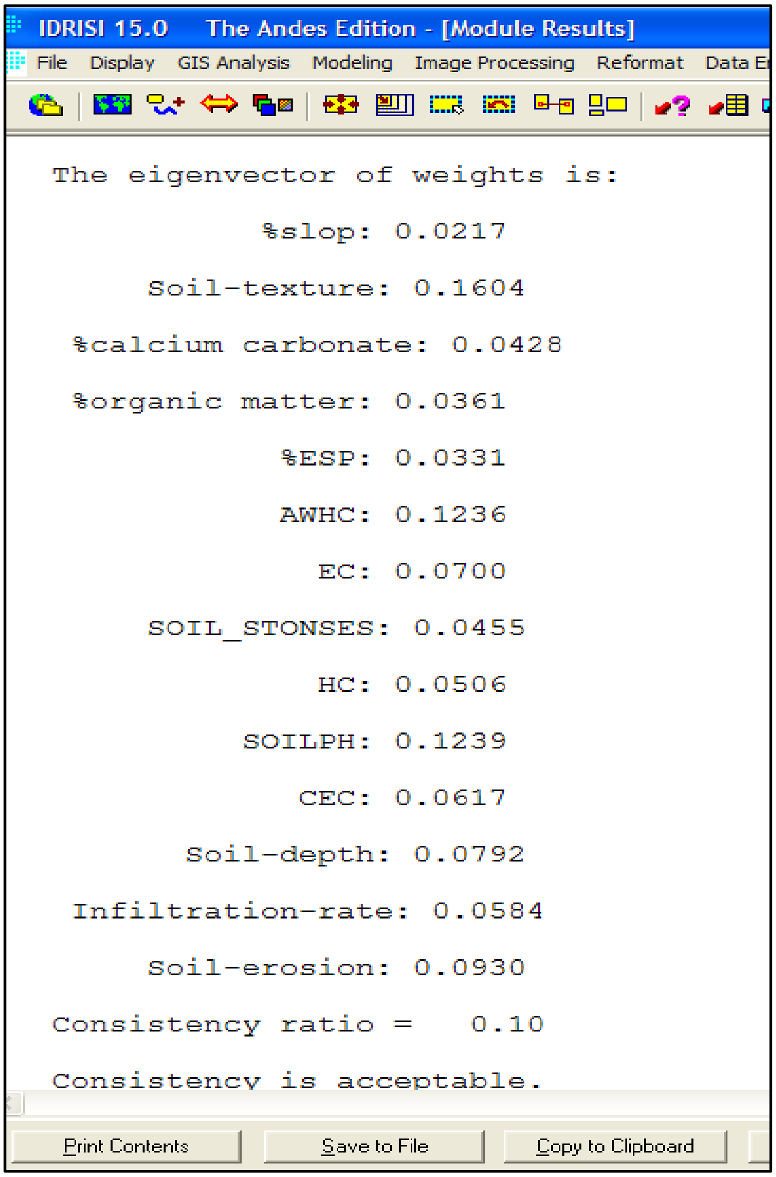


Figure 2.3: The eigenvector values for land characteristics for barley with acceptable consistency ratio.



Appendix B

Table B1: The cross-tabulation matrix based on using the Composite operator for the Fuzzy AHP and Ideal Point approaches for wheat.

Scale		1	2	3	Total	Overall agreement
1 x 1	1	0.1396	0.000	0.000	0.1396	0.9471
	2	0.000	0.7514	0.0515	0.8029	
	3	0.000	0.0014	0.0561	0.0575	
	Total	0.1396	0.7528	0.1076	1.000	
2 x 2		1	2	3	Total	Overall agreement
	1	0.1396	0.000	0.000	0.1396	0.9474
	2	0.000	0.7515	0.0514	0.8029	
	3	0.000	0.0012	0.0562	0.0575	
	Total	0.1396	0.7528	0.1076	1.000	
4 x 4		1	2	3	Total	Overall agreement
	1	0.1396	0.000	0.000	0.1396	0.9476
	2	0.000	0.7516	0.0513	0.8029	
	3	0.000	0.0011	0.0563	0.0575	
	Total	0.1396	0.7528	0.1076	1.000	
8 x 8		1	2	3	Total	Overall agreement
	1	0.1396	0.000	0.000	0.1396	0.9476
	2	0.000	0.7517	0.0513	0.8029	
	3	0.000	0.0011	0.0564	0.0575	
	Total	0.1396	0.7528	0.1076	1.000	
16 x 16		1	2	3	Total	Overall agreement
	1	0.1396	0.000	0.000	0.1396	0.9477
	2	0.000	0.7517	0.0512	0.8029	
	3	0.000	0.0011	0.0564	0.0575	
	Total	0.1396	0.7528	0.1076	1.000	

Table B1 continued

Scale		1	2	3	Total	Overall agreement
32 x 32	1	0.1396	0.000	0.000	0.1396	0.9492
	2	0.000	0.7524	0.0505	0.8029	
	3	0.000	0.0004	0.0571	0.0575	
	Total	0.1396	0.7528	0.1076	1.000	
64x 64		1	2	3	Total	Overall agreement
	1	0.1396	0.000	0.000	0.1396	0.9497
	2	0.000	0.7527	0.0502	0.8029	
	3	0.000	0.0001	0.0574	0.0575	
	Total	0.1396	0.7528	0.1076	1.000	
128 x 128		1	2	3	Total	Overall agreement
	1	0.1396	0.000	0.000	0.1396	0.9498
	2	0.000	0.7527	0.0502	0.8029	
	3	0.000	0.0001	0.0574	0.0575	
	Total	0.1396	0.7528	0.1076	1.000	
256 x 256		1	2	3	Total	Overall agreement
	1	0.1396	0.000	0.000	0.1396	
	2	0.000	0.7528	0.0501	0.8029	
	3	0.000	0.000	0.0575	0.0575	
	Total	0.1396	0.7528	0.1076	1.000	

Table B2: The cross-tabulation matrix based on using the Composite operator for the Fuzzy AHP and Ideal Point approaches for maize.

Scale		1	2	3	Total	Overall agreement
1 x 1	1	0.1396	0.000	0.000	0.1396	0.9805
	2	0.000	0.1042	0.0187	0.1229	
	3	0.000	0.0008	0.7367	0.7375	
	Total	0.1396	0.1051	0.7553	1.000	
2 x 2		1	2	3	Total	Overall agreement
	1	0.1396	0.000	0.000	0.1396	0.9805
	2	0.000	0.1042	0.0187	0.1229	
	3	0.000	0.0008	0.7367	0.7375	
	Total	0.1396	0.1051	0.7553	1.000	
4 x 4		1	2	3	Total	Overall agreement
	1	0.1396	0.000	0.000	0.1396	0.9805
	2	0.000	0.1042	0.0187	0.1229	
	3	0.000	0.0008	0.7367	0.7375	
	Total	0.1396	0.1051	0.7553	1.000	
8 x 8		1	2	3	Total	Overall agreement
	1	0.1396	0.000	0.000	0.1396	0.9806
	2	0.000	0.1043	0.0186	0.1229	
	3	0.000	0.0008	0.7367	0.7375	
	Total	0.1396	0.1051	0.7553	1.000	
16 x 16		1	2	3	Total	Overall agreement
	1	0.1396	0.000	0.000	0.1396	0.9809
	2	0.000	0.1045	0.0185	0.1229	
	3	0.000	0.0006	0.7369	0.7375	
	Total	0.1396	0.1051	0.7553	1.000	

Table B2 continued

Scale		1	2	3	Total	Overall agreement
32 x 32	1	0.1396	0.000	0.000	0.1396	0.9813
	2	0.000	0.1047	0.0183	0.1229	
	3	0.000	0.0004	0.7371	0.7375	
	Total	0.1396	0.1051	0.7553	1.000	
64x 64		1	2	3	Total	Overall agreement
	1	0.1396	0.000	0.000	0.1396	0.9821
	2	0.000	0.1051	0.0179	0.1229	
	3	0.000	0.000	0.7375	0.7375	
	Total	0.1396	0.1051	0.7553	1.000	
128 x 128		1	2	3	Total	Overall agreement
	1	0.1396	0.000	0.000	0.1396	0.9821
	2	0.000	0.1051	0.0179	0.1229	
	3	0.000	0.000	0.7375	0.7375	
	Total	0.1396	0.1051	0.7553	1.000	
256 x 256		1	2	3	Total	Overall agreement
	1	0.1396	0.000	0.000	0.1396	0.9821
	2	0.000	0.1051	0.0179	0.1229	
	3	0.000	0.000	0.7375	0.7375	
	Total	0.1396	0.1051	0.7553	1.000	

Table B3: The cross-tabulation matrix based on using the Composite operator for the Boolean and Fuzzy AHP for barley.

Scale		1	2	3	Total	Overall agreement
1 x 1	1	0.1396	0.0000	0.0000	0.1396	0.2690
	2	0.0000	0.0436	0.0000	0.0436	
	3	0.0000	0.2193	0.0858	0.3051	
	4	0.0000	0.3042	0.0271	0.3313	
	5	0.0000	0.0484	0.0414	0.0898	
	6	0.0000	0.0782	0.0125	0.0907	
	Total	0.1396	0.6936	0.1668	1.000	
2 x 2		1	2	3	Total	Overall agreement
	1	0.1396	0.0000	0.0000	0.1396	0.2749
	2	0.0000	0.0436	0.0000	0.0436	
	3	0.0000	0.2134	0.0918	0.3051	
	4	0.0000	0.3057	0.0255	0.3313	
	5	0.0000	0.0517	0.0381	0.0898	
	6	0.0000	0.0793	0.0114	0.0907	
	Total	0.1396	0.6936	0.1668	1.0000	
4 x 4		1	2	3	Total	Overall agreement
	1	0.1396	0.0000	0.0000	0.1396	0.2805
	2	0.0000	0.0436	0.0000	0.0436	
	3	0.0000	0.2078	0.0973	0.3051	
	4	0.0000	0.3073	0.0239	0.3313	
	5	0.0000	0.0545	0.0353	0.0898	
	6	0.0000	0.0805	0.0102	0.0907	
	Total	0.1396	0.6936	0.1668	1.0000	

Table B3 continued

Scale		1	2	3	Total	Overall agreement
8 x 8	1	0.1396	0.0000	0.0000	0.1396	0.2883
	2	0.0000	0.0436	0.0000	0.0436	
	3	0.0000	0.2000	0.1051	0.3051	
	4	0.0000	0.3098	0.0215	0.3313	
	5	0.0000	0.0584	0.0314	0.0898	
	6	0.0000	0.0819	0.0088	0.0907	
	Total	0.1396	0.6936	0.1668	1.0000	
16x 16		1	2	3	Total	Overall agreement
	1	0.1396	0.0000	0.0000	0.1396	0.2982
	2	0.0000	0.0436	0.0000	0.0436	
	3	0.0000	0.1901	0.1150	0.3051	
	4	0.0000	0.3150	0.0162	0.3313	
	5	0.0000	0.0620	0.0278	0.0898	
	6	0.0000	0.0830	0.0076	0.0907	
	Total	0.1396	0.6936	0.1668	1.0000	
32x 32		1	2	3	Total	Overall agreement
	1	0.1396	0.0000	0.0000	0.1396	0.3122
	2	0.0000	0.0436	0.0000	0.0436	
	3	0.0000	0.1761	0.1290	0.3051	
	4	0.0000	0.3208	0.0104	0.3313	
	5	0.0000	0.0671	0.0227	0.0898	
	6	0.0000	0.0860	0.0046	0.0907	
	Total	0.1396	0.6936	0.1668	1.0000	

Table B3 continued

Scale		1	2	3	Total	Overall agreement
64x 64	1	0.1396	0.0000	0.0000	0.1396	0.3339
	2	0.0000	0.0436	0.0000	0.0436	
	3	0.0000	0.1544	0.1507	0.3051	
	4	0.0000	0.3249	0.0064	0.3313	
	5	0.0000	0.0818	0.0080	0.0898	
	6	0.0000	0.0890	0.0017	0.0907	
	Total	0.1396	0.6936	0.1668	1.0000	
128x 128		1	2	3	Total	Overall agreement
	1	0.1396	0.0000	0.0000	0.1396	0.3482
	2	0.0000	0.0436	0.0000	0.0436	
	3	0.0000	0.1401	0.1650	0.3051	
	4	0.0000	0.3302	0.0010	0.3313	
	5	0.0000	0.0891	0.0007	0.0898	
	6	0.0000	0.0906	0.0000	0.0907	
	Total	0.1396	0.6936	0.1668	1.0000	
256x 256		1	2	3	Total	Overall agreement
	1	0.1396	0.0000	0.0000	0.1396	0.3499
	2	0.0000	0.0436	0.0000	0.0436	
	3	0.0000	0.1384	0.1668	0.3051	
	4	0.0000	0.3313	0.0000	0.3313	
	5	0.0000	0.0898	0.0000	0.0898	
	6	0.0000	0.0907	0.0000	0.0907	
	Total	0.1396	0.6936	0.1668	1.0000	

Table B4: The cross-tabulation matrix based on using the Composite operator for the Boolean and Fuzzy AHP for wheat.

Scale		1	2	3	Total	Overall agreement
1 x 1	1	0.1396	0.0000	0.0000	0.1396	0.2319
	2	0.0000	0.0436	0.0000	0.0436	
	3	0.0000	0.3605	0.0488	0.4092	
	4	0.0000	0.2442	0.0139	0.2581	
	5	0.0000	0.0137	0.0127	0.0264	
	6	0.0000	0.0908	0.0322	0.1231	
	Total	0.1396	0.7528	0.1076	1.0000	
2 x 2		1	2	3	Total	Overall agreement
	1	0.1396	0.0000	0.0000	0.1396	0.2370
	2	0.0000	0.0436	0.0000	0.0436	
	3	0.0000	0.3554	0.0538	0.4092	
	4	0.0000	0.2445	0.0136	0.2581	
	5	0.0000	0.0150	0.0115	0.0264	
	6	0.0000	0.0944	0.0287	0.1231	
	Total	0.1396	0.7528	0.1076	1.0000	
4 x 4		1	2	3	Total	Overall agreement
	1	0.1396	0.0000	0.0000	0.1396	0.2425
	2	0.0000	0.0436	0.0000	0.0436	
	3	0.0000	0.3499	0.0593	0.4092	
	4	0.0000	0.2452	0.0129	0.2581	
	5	0.0000	0.0165	0.0099	0.0264	
	6	0.0000	0.0976	0.0254	0.1231	
	Total	0.1396	0.7528	0.1076	1.0000	

Table B4 continued

Scale		1	2	3	Total	Overall agreement
8 x 8	1	0.1396	0.0000	0.0000	0.1396	0.2496
	2	0.0000	0.0436	0.0000	0.0436	
	3	0.0000	0.3428	0.0664	0.4092	
	4	0.0000	0.2466	0.0116	0.2581	
	5	0.0000	0.0182	0.0082	0.0264	
	6	0.0000	0.1016	0.0214	0.1231	
	Total	0.1396	0.7528	0.1076	1.0000	
16x 16		1	2	3	Total	Overall agreement
	1	0.1396	0.0000	0.0000	0.1396	0.1231
	2	0.0000	0.0436	0.0000	0.0436	
	3	0.0000	0.3328	0.0765	0.4092	
	4	0.0000	0.2492	0.0089	0.2581	
	5	0.0000	0.0196	0.0068	0.0264	
	6	0.0000	0.1077	0.0154	0.1231	
	Total	0.1396	0.1077	0.1076	1.0000	
32x 32		1	2	3	Total	Overall agreement
	1	0.1396	0.0000	0.0000	0.1396	0.2743
	2	0.0000	0.0436	0.0000	0.0436	
	3	0.0000	0.3181	0.0911	0.4092	
	4	0.0000	0.2509	0.0072	0.2581	
	5	0.0000	0.0222	0.0042	0.0264	
	6	0.0000	0.1180	0.0051	0.1231	
	Total	0.1396	0.7528	0.1076	1.0000	

Table B4 continued

Scale		1	2	3	Total	Overall agreement
64x 64	1	0.1396	0.0000	0.0000	0.1396	0.2905
	2	0.0000	0.0436	0.0000	0.0436	
	3	0.0000	0.3019	0.1074	0.4092	
	4	0.0000	0.2581	0.0001	0.2581	
	5	0.0000	0.0264	0.0000	0.0264	
	6	0.0000	0.1229	0.0001	0.1231	
	Total	0.1396	0.7528	0.1076	1.0000	
128x 128		1	2	3	Total	Overall agreement
	1	0.1396	0.0000	0.0000	0.1396	0.2908
	2	0.0000	0.0436	0.0000	0.0436	
	3	0.0000	0.3016	0.1076	0.4092	
	4	0.0000	0.2581	0.0000	0.2581	
	5	0.0000	0.0264	0.0000	0.0264	
	6	0.0000	0.1231	0.0000	0.1231	
	Total	0.1396	0.7528	0.1076	1.0000	
256x 256		1	2	3	Total	Overall agreement
	1	0.1396	0.0000	0.0000	0.1396	0.2908
	2	0.0000	0.0436	0.0000	0.0436	
	3	0.0000	0.3016	0.1076	0.4092	
	4	0.0000	0.2581	0.0000	0.2581	
	5	0.0000	0.0264	0.0000	0.0264	
	6	0.0000	0.1231	0.0000	0.1231	
	Total	0.1396	0.7528	0.1076	1.0000	

Table B5: The cross-tabulation matrix based on using the Composite operator for the Boolean and Fuzzy AHP for maize.

Scale		1	2	3	Total	Overall agreement
1 x 1	1	0.1396	0.0000	0.0000	0.1396	0.2319
	2	0.0000	0.0436	0.0000	0.0436	
	3	0.0000	0.3605	0.0488	0.4092	
	4	0.0000	0.2442	0.0139	0.2581	
	5	0.0000	0.0137	0.0127	0.0264	
	6	0.0000	0.0908	0.0322	0.1231	
	Total	0.1396	0.7528	0.1076	1.0000	
2 x 2		1	2	3	Total	Overall agreement
	1	0.1396	0.0000	0.0000	0.1396	0.2370
	2	0.0000	0.0436	0.0000	0.0436	
	3	0.0000	0.3554	0.0538	0.4092	
	4	0.0000	0.2445	0.0136	0.2581	
	5	0.0000	0.0150	0.0115	0.0264	
	6	0.0000	0.0944	0.0287	0.1231	
	Total	0.1396	0.7528	0.1076	1.0000	
4 x 4		1	2	3	Total	Overall agreement
	1	0.1396	0.0000	0.0000	0.1396	0.2425
	2	0.0000	0.0436	0.0000	0.0436	
	3	0.0000	0.3499	0.0593	0.4092	
	4	0.0000	0.2452	0.0129	0.2581	
	5	0.0000	0.0165	0.0099	0.0264	
	6	0.0000	0.0976	0.0254	0.1231	
	Total	0.1396	0.7528	0.1076	1.0000	

Table B5 continued

Scale		1	2	3	Total	Overall agreement
8 x 8	1	0.1396	0.0000	0.0000	0.1396	0.2496
	2	0.0000	0.0436	0.0000	0.0436	
	3	0.0000	0.3428	0.0664	0.4092	
	4	0.0000	0.2466	0.0116	0.2581	
	5	0.0000	0.0182	0.0082	0.0264	
	6	0.0000	0.1016	0.0214	0.1231	
	Total	0.1396	0.7528	0.1076	1.0000	
16x 16		1	2	3	Total	Overall agreement
	1	0.1396	0.0000	0.0000	0.1396	0.1231
	2	0.0000	0.0436	0.0000	0.0436	
	3	0.0000	0.3328	0.0765	0.4092	
	4	0.0000	0.2492	0.0089	0.2581	
	5	0.0000	0.0196	0.0068	0.0264	
	6	0.0000	0.1077	0.0154	0.1231	
	Total	0.1396	0.1077	0.1076	1.0000	
32x 32		1	2	3	Total	Overall agreement
	1	0.1396	0.0000	0.0000	0.1396	0.2743
	2	0.0000	0.0436	0.0000	0.0436	
	3	0.0000	0.3181	0.0911	0.4092	
	4	0.0000	0.2509	0.0072	0.2581	
	5	0.0000	0.0222	0.0042	0.0264	
	6	0.0000	0.1180	0.0051	0.1231	
	Total	0.1396	0.7528	0.1076	1.0000	

Table B5 continued

Scale		1	2	3	Total	Overall agreement
64x 64	1	0.1396	0.0000	0.0000	0.1396	0.2905
	2	0.0000	0.0436	0.0000	0.0436	
	3	0.0000	0.3019	0.1074	0.4092	
	4	0.0000	0.2581	0.0001	0.2581	
	5	0.0000	0.0264	0.0000	0.0264	
	6	0.0000	0.1229	0.0001	0.1231	
	Total	0.1396	0.7528	0.1076	1.0000	
128x 128		1	2	3	Total	Overall agreement
	1	0.1396	0.0000	0.0000	0.1396	0.2908
	2	0.0000	0.0436	0.0000	0.0436	
	3	0.0000	0.3016	0.1076	0.4092	
	4	0.0000	0.2581	0.0000	0.2581	
	5	0.0000	0.0264	0.0000	0.0264	
	6	0.0000	0.1231	0.0000	0.1231	
	Total	0.1396	0.7528	0.1076	1.0000	
256x 256		1	2	3	Total	Overall agreement
	1	0.1396	0.0000	0.0000	0.1396	0.2908
	2	0.0000	0.0436	0.0000	0.0436	
	3	0.0000	0.3016	0.1076	0.4092	
	4	0.0000	0.2581	0.0000	0.2581	
	5	0.0000	0.0264	0.0000	0.0264	
	6	0.0000	0.1231	0.0000	0.1231	
	Total	0.1396	0.7528	0.1076	1.0000	

Table B6: The cross-tabulation matrix based on using the Composite operator for the Boolean and Ideal Point for barley.

Scale		1	2	3	Total	Overall agreement
1 x 1	1	0.1396	0.0000	0.0000	0.1396	0.1938
	2	0.0000	0.0436	0.0000	0.0436	
	3	0.0000	0.2945	0.0106	0.3051	
	4	0.0000	0.3218	0.0095	0.3313	
	5	0.0000	0.0814	0.0084	0.0898	
	6	0.0000	0.0856	0.0050	0.0907	
	Total	0.1396	0.8269	0.0335	1.0000	
2 x 2		1	2	3	Total	Overall agreement
	1	0.1396	0.0000	0.0000	0.1396	0.1956
	2	0.0000	0.0436	0.0000	0.0436	
	3	0.0000	0.2927	0.0124	0.3051	
	4	0.0000	0.3229	0.0084	0.3313	
	5	0.0000	0.0814	0.0084	0.0898	
	6	0.0000	0.0863	0.0044	0.0907	
	Total	0.1396	0.8269	0.0335	1.0000	
4 x 4		1	2	3	Total	Overall agreement
	1	0.1396	0.0000	0.0000	0.1396	0.1974
	2	0.0000	0.0436	0.0000	0.0436	
	3	0.0000	0.2909	0.0142	0.3051	
	4	0.0000	0.3239	0.0074	0.3313	
	5	0.0000	0.0817	0.0081	0.0898	
	6	0.0000	0.0868	0.0038	0.0907	
	Total	0.1396	0.8269	0.0335	1.0000	

Table B6 continued

Scale		1	2	3	Total	Overall agreement
8 x 8	1	0.1396	0.0000	0.0000	0.1396	0.1996
	2	0.0000	0.0436	0.0165	0.0436	
	3	0.0000	0.2887	0.0064	0.3051	
	4	0.0000	0.3248	0.0077	0.3313	
	5	0.0000	0.0821	0.0030	0.0898	
	6	0.0000	0.0877	0.0335	0.0907	
	Total	0.1396	0.8269	0.0335	1.0000	
16x 16		1	2	3	Total	Overall agreement
	1	0.1396	0.0000	0.0000	0.1396	0.2034
	2	0.0000	0.0436	0.0000	0.0436	
	3	0.0000	0.2849	0.0203	0.3051	
	4	0.0000	0.3264	0.0048	0.3313	
	5	0.0000	0.0835	0.0063	0.0898	
	6	0.0000	0.0885	0.0021	0.0907	
	Total	0.1396	0.8269	0.0335	1.0000	
32x 32		1	2	3	Total	Overall agreement
	1	0.1396	0.0000	0.0000	0.1396	0.2088
	2	0.0000	0.0436	0.0000	0.0436	
	3	0.0000	0.2794	0.0257	0.3051	
	4	0.0000	0.3293	0.0020	0.3313	
	5	0.0000	0.0854	0.0044	0.0898	
	6	0.0000	0.0892	0.0015	0.0907	
	Total	0.1396	0.8269	0.0335	1.0000	

Table B6 continued

Scale		1	2	3	Total	Overall agreement
64x 64	1	0.1396	0.0000	0.0000	0.1396	0.2167
	2	0.0000	0.0436	0.0000	0.0436	
	3	0.0000	0.2716	0.0335	0.3051	
	4	0.0000	0.3313	0.0000	0.3313	
	5	0.0000	0.0898	0.0000	0.0898	
	6	0.0000	0.0907	0.0000	0.0907	
	Total	0.1396	0.8269	0.0335	1.0000	
128x 128		1	2	3	Total	Overall agreement
	1	0.1396	0.0000	0.0000	0.1396	0.2167
	2	0.0000	0.0436	0.0000	0.0436	
	3	0.0000	0.2716	0.0335	0.3051	
	4	0.0000	0.3313	0.0000	0.3313	
	5	0.0000	0.0898	0.0000	0.0898	
	6	0.0000	0.0907	0.0000	0.0907	
	Total	0.1396	0.8269	0.0335	1.0000	
256x 256		1	2	3	Total	Overall agreement
	1	0.1396	0.0000	0.0000	0.1396	0.2167
	2	0.0000	0.0436	0.0000	0.0436	
	3	0.0000	0.2716	0.0335	0.3051	
	4	0.0000	0.3313	0.0000	0.3313	
	5	0.0000	0.0898	0.0000	0.0898	
	6	0.0000	0.0907	0.0000	0.0907	
	Total	0.1396	0.8269	0.0335	1.0000	

Table B7: The cross-tabulation matrix based on using the Composite operator for the Boolean and Ideal Point for wheat.

Scale		1	2	3	Total	Overall agreement
1 x 1	1	0.1396	0.0000	0.0000	0.1396	0.2131
	2	0.0000	0.0436	0.0000	0.0436	
	3	0.0000	0.3792	0.0300	0.4092	
	4	0.0000	0.2530	0.0052	0.2581	
	5	0.0000	0.0144	0.0120	0.0264	
	6	0.0000	0.1127	0.0104	0.1231	
	Total	0.1396	0.8029	0.0575	1.0000	
2 x 2		1	2	3	Total	Overall agreement
	1	0.1396	0.0000	0.0000	0.1396	0.2150
	2	0.0000	0.0436	0.0000	0.0436	
	3	0.0000	0.3774	0.0318	0.4092	
	4	0.0000	0.2526	0.0055	0.2581	
	5	0.0000	0.0160	0.0104	0.0264	
	6	0.0000	0.1133	0.0097	0.1231	
	Total	0.1396	0.8029	0.0575	1.0000	
4 x 4		1	2	3	Total	Overall agreement
	1	0.1396	0.0000	0.0000	0.1396	0.2173
	2	0.0000	0.0436	0.0000	0.0436	
	3	0.0000	0.3751	0.0341	0.4092	
	4	0.0000	0.2522	0.0059	0.2581	
	5	0.0000	0.0179	0.0085	0.0264	
	6	0.0000	0.1142	0.0089	0.1231	
	Total	0.1396	0.8029	0.0575	1.0000	

Table B7 continued

Scale		1	2	3	Total	Overall agreement
8 x 8	1	0.1396	0.0000	0.0000	0.1396	0.2198
	2	0.0000	0.0436	0.0000	0.0436	
	3	0.0000	0.3726	0.0366	0.4092	
	4	0.0000	0.2519	0.0062	0.2581	
	5	0.0000	0.0198	0.0066	0.0264	
	6	0.0000	0.1151	0.0080	0.1231	
	Total	0.1396	0.8029	0.0575	1.0000	
16x 16		1	2	3	Total	Overall agreement
	1	0.1396	0.0000	0.0000	0.1396	0.2242
	2	0.0000	0.0436	0.0000	0.0436	
	3	0.0000	0.3682	0.0410	0.4092	
	4	0.0000	0.2526	0.0055	0.2581	
	5	0.0000	0.0222	0.0042	0.0264	
	6	0.0000	0.1164	0.0067	0.1231	
	Total	0.1396	0.8029	0.0575	1.0000	
32x 32		1	2	3	Total	Overall agreement
	1	0.1396	0.0000	0.0000	0.1396	0.2307
	2	0.0000	0.0436	0.0000	0.0436	
	3	0.0000	0.3617	0.0475	0.4092	
	4	0.0000	0.2530	0.0051	0.2581	
	5	0.0000	0.0244	0.0020	0.0264	
	6	0.0000	0.1202	0.0029	0.1231	
	Total	0.1396	0.8029	0.0575	1.0000	

Table B7 continued

Scale		1	2	3	Total	Overall agreement
64x 64	1	0.1396	0.0000	0.0000	0.1396	0.2406
	2	0.0000	0.0436	0.0000	0.0436	
	3	0.0000	0.3517	0.0575	0.4092	
	4	0.0000	0.2581	0.0000	0.2581	
	5	0.0000	0.0264	0.0000	0.0264	
	6	0.0000	0.1231	0.0000	0.1231	
	Total	0.1396	0.8029	0.0575	1.0000	
128x 128		1	2	3	Total	Overall agreement
	1	0.1396	0.0000	0.0000	0.1396	0.2406
	2	0.0000	0.0436	0.0000	0.0436	
	3	0.0000	0.3517	0.0575	0.4092	
	4	0.0000	0.2581	0.0000	0.2581	
	5	0.0000	0.0264	0.0000	0.0264	
	6	0.0000	0.1231	0.0000	0.1231	
	Total	0.1396	0.8029	0.0575	1.0000	
256x 256		1	2	3	Total	Overall agreement
	1	0.1396	0.0000	0.0000	0.1396	0.2406
	2	0.0000	0.0436	0.0000	0.0436	
	3	0.0000	0.3517	0.0575	0.4092	
	4	0.0000	0.2581	0.0000	0.2581	
	5	0.0000	0.0264	0.0000	0.0264	
	6	0.0000	0.1231	0.0000	0.1231	
	Total	0.1396	0.8029	0.0575	1.0000	

Table B8: The cross-tabulation matrix based on using the Composite operator for the Boolean and Ideal Point for maize.

Scale		1	2	3	Total	Overall agreement
1 x 1	1	0.1396	0.0000	0.0000	0.1396	0.2131
	2	0.0000	0.0436	0.0000	0.0436	
	3	0.0000	0.3792	0.0300	0.4092	
	4	0.0000	0.2530	0.0052	0.2581	
	5	0.0000	0.0144	0.0120	0.0264	
	6	0.0000	0.1127	0.0104	0.1231	
	Total	0.1396	0.8029	0.0575	1.0000	
2 x 2		1	2	3	Total	Overall agreement
	1	0.1396	0.0000	0.0000	0.1396	0.2150
	2	0.0000	0.0436	0.0000	0.0436	
	3	0.0000	0.3774	0.0318	0.4092	
	4	0.0000	0.2526	0.0055	0.2581	
	5	0.0000	0.0160	0.0104	0.0264	
	6	0.0000	0.1133	0.0097	0.1231	
	Total	0.1396	0.8029	0.0575	1.0000	
4 x 4		1	2	3	Total	Overall agreement
	1	0.1396	0.0000	0.0000	0.1396	0.2173
	2	0.0000	0.0436	0.0000	0.0436	
	3	0.0000	0.3751	0.0341	0.4092	
	4	0.0000	0.2522	0.0059	0.2581	
	5	0.0000	0.0179	0.0085	0.0264	
	6	0.0000	0.1142	0.0089	0.1231	
	Total	0.1396	0.8029	0.0575	1.0000	

Table B8 continued

Scale		1	2	3	Total	Overall agreement
8 x 8	1	0.1396	0.0000	0.0000	0.1396	0.2198
	2	0.0000	0.0436	0.0000	0.0436	
	3	0.0000	0.3726	0.0366	0.4092	
	4	0.0000	0.2519	0.0062	0.2581	
	5	0.0000	0.0198	0.0066	0.0264	
	6	0.0000	0.1151	0.0080	0.1231	
	Total	0.1396	0.8029	0.0575	1.0000	
16x 16		1	2	3	Total	Overall agreement
	1	0.1396	0.0000	0.0000	0.1396	0.2242
	2	0.0000	0.0436	0.0000	0.0436	
	3	0.0000	0.3682	0.0410	0.4092	
	4	0.0000	0.2526	0.0055	0.2581	
	5	0.0000	0.0222	0.0042	0.0264	
	6	0.0000	0.1164	0.0067	0.1231	
	Total	0.1396	0.8029	0.0575	1.0000	
32x 32		1	2	3	Total	Overall agreement
	1	0.1396	0.0000	0.0000	0.1396	0.2307
	2	0.0000	0.0436	0.0000	0.0436	
	3	0.0000	0.3617	0.0475	0.4092	
	4	0.0000	0.2530	0.0051	0.2581	
	5	0.0000	0.0244	0.0020	0.0264	
	6	0.0000	0.1202	0.0029	0.1231	
	Total	0.1396	0.8029	0.0575	1.0000	

Table B8 continued

Scale		1	2	3	Total	Overall agreement
64x 64	1	0.1396	0.0000	0.0000	0.1396	0.2406
	2	0.0000	0.0436	0.0000	0.0436	
	3	0.0000	0.3517	0.0575	0.4092	
	4	0.0000	0.2581	0.0000	0.2581	
	5	0.0000	0.0264	0.0000	0.0264	
	6	0.0000	0.1231	0.0000	0.1231	
	Total	0.1396	0.8029	0.0575	1.0000	
128x 128		1	2	3	Total	Overall agreement
	1	0.1396	0.0000	0.0000	0.1396	0.2406
	2	0.0000	0.0436	0.0000	0.0436	
	3	0.0000	0.3517	0.0575	0.4092	
	4	0.0000	0.2581	0.0000	0.2581	
	5	0.0000	0.0264	0.0000	0.0264	
	6	0.0000	0.1231	0.0000	0.1231	
	Total	0.1396	0.8029	0.0575	1.0000	
256x 256		1	2	3	Total	Overall agreement
	1	0.1396	0.0000	0.0000	0.1396	0.2406
	2	0.0000	0.0436	0.0000	0.0436	
	3	0.0000	0.3517	0.0575	0.4092	
	4	0.0000	0.2581	0.0000	0.2581	
	5	0.0000	0.0264	0.0000	0.0264	
	6	0.0000	0.1231	0.0000	0.1231	
	Total	0.1396	0.8029	0.0575	1.0000	