Fuzzy-GIS Development of Land Evaluation System for Agricultural Production in North West Libya

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ABSTRACT

The continuing deterioration of land and water resources occurring in several regions of the world is partly as a result of the mismatch between land suitability or capability and land use. Failure to achieve a perfect match between land capability and use can be particularly problematic for agricultural production because cultivating the wrong crops on wrong soils can only result in poor yields and its associated financial and other losses. There is therefore, a pressing need for effective land evaluation through better matching of land characteristics with land use to achieve optimal utilisation of available land resources for sustainable agricultural production. As far as agriculture is concerned such an exercise will result in defining which part of an area is suitable for particular crops, based on the available land resources and other production inputs, and which parts are better left for other uses. In this study, a land evaluation system for predicting the physical suitability of land for key crops, namely Wheat, Barley and Olive in the north west of Libya was developed based on matching land use requirement for these crops with the available land resources in the area. It involved a modelling strategy based on Boolean and Fuzzy logic sets, implemented within a Geographic Information System (GIS) environment. While the Boolean method assumes that the attributes of a given soil type are known with certainty and the boundaries between soil types are clearly defined, Fuzzy logic can be used to accommodate uncertainties in the available knowledge on these attributes through the use of membership functions. The GIS-based models developed comprise four layers; namely, soil, climate, slope and erosion hazard all of which have been shown directly influence land suitability for agricultural production. This resulted in the classification of the soil into 4 suitability classes, i.e. high suitability, moderate suitability, marginal suitability and not suitable. The results show that for Barley for example 52% of the soil in the north western Libya is highly suitable using Fuzzy approach while the corresponding figure for the Boolean is 62%. The two approaches were compared on cell by cell basis using map agreement. The comparison shows that there were reasonable agreements in evaluations by the two approaches for barley, wheat and olive of 51%, 46% and 56% respectively.

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INTRODUCTION

1.1 Problem background

To increase food production in line with growing population is the greatest challenge for the coming decades especially in countries with limited water and land resources. Libya is one of those countries, because the country suffers from limited renewable water resources due to low rainfall, high evaporation and excessive withdrawal of ground water. In addition, arable land is limited in Libya. According to a World Bank report, over 90% of the country is classified as agriculturally useless desert (World Bank, 2010). In fact, the cultivable area of the country is estimated at about 2.2 million hectares which is a mere 2% of the total land area. In addition, about 13.3million hectares are natural pastures (Aquastat, 2010). The increasing and competitive demand for land, both for agricultural production and other purposes, requires that decisions be made on the most beneficial use of the limited land resources.

The high average population growth rate in Libya of over 2.8% per annum and the limited area suitable for food production have both combined to significantly exacerbate this problem over time (Aquastat, 2010). As population and aspirations increase in Libya, so land has become an increasingly scarce resource (FAO, 1993). Moreover in many parts of Libya, rangelands are converted into rainfed agriculture. This is often the start point of degradation which has caused destruction of natural vegetation cover and leading to accelerated erosion problems (Ben-Mahmoud, Mansur, et al., 2003). Thus, the institutions concerned with cultivation must ensure that land is not degraded but that it is used according to its capacity to satisfy human needs for present and future generations. Therefore, arable land in the country needs to be evaluated for current and future agricultural uses in support of rational land-use planning, as well as appropriate and sustainable use of natural resources.

Food security is one of the most important issues of the agricultural policy in Libya (Azzabi, 2000). The country aims to meet through local production a substantial part of the main crops such as barley and wheat which are required as part of a balanced diet of most of the country's population. Hence the Great Manmade River project has been developed to transport about six million cubic meter of groundwater daily from the desert in the south of the country to the north coast where most of the population live. About eighty per cent of this water is being used for irrigating agricultural lands; production of cereal crops such as wheat and barley, is given the highest priority in the allocation of the irrigation water (GMRP., 2008).

The Jeffara plain in the northwest of Libya will receive about 950×10^3 m³ fresh water daily from the great man made river by 2014, all being abstracted from the stressed aquifer systems in the desert in the southwest of the country (GMRP, 2008). But since the Saharan and Sub-Saharan aquifers are non-renewable, or their rate of renewal is much less than the planned abstractions of these projects(Alghariani and GMMR., 2004), this is clearly unsustainable. Therefore, there is the pressing need to develop an optimal management of land and water resources in irrigated agriculture, so as to conserve the dwindling water resources by defining which part of a region is suitable for particular crops and by so doing improving the water productivity for such regions (GMRP., 2008). In this way, water productivity will be improved because the most suitable land will be chosen for each crop.

The continuing deterioration of land and water resources occurring in several regions of the world, especially in arid and semi-arid regions, is partly as a result of the mismatch between land suitability and land use. According to the *Food and Agriculture Organization of the United Nations* (FAO), there have been many reported cases of damage to natural resources and of unsuccessful land use enterprises due to failure in the selection of suitable land for specific use (FAO, 1979). Such problems can be prevented through effective land evaluation for agricultural production and better matching of land characteristics with land uses.

Decision-makers and planners require information in simplified form about the available natural resources to be easily interpreted for the purposes of land use planning. The absence of such information could be the reason for the absence of appropriate land use plans in some countries including Libya that lack the good governance of natural resources (FAO, 1993). Soil survey maps and reports along with data on other natural resources e.g. water exist in Libya; however, this information alone does not present direct guidance on land use planning (FAO, 1993), especially given the general scarcity of some of the resources such as water. Rather, what is required is land evaluation which will help decision-makers and planners to make the best utilization of these limited land and water resources, so that these resources are better committed to areas and activities that result in maximum productivity.

Land evaluation is the process of predicting the use potential of land on the basis of its attributes (Rossiter, 1996). Land evaluation is the first step in the preparation of comprehensive land use plan. It gives information that could be used as a starting point for making decisions in land use about the suitability of land for the present and potential uses, and by so doing contributes to the solution of land use constraints (Smit, Brklacich, et al., 1984). The suitability land map produced as a result of land evaluation will reduce the diversity and complexity of information that decision-makers have to deal, thus improving the efficiency of land use planning (FAO, 1993).

Land evaluation initially emerged from soil survey interpretations, but since the 1970s it has become more plant-specific. While soil classification was the output of land evaluation system before 1970s, presently soil is one of the main inputs in land evaluation studies along with other environmental factors. Land evaluation has been adapted and developed in many countries taking into the consideration crop-growth and production factors, including climatic, soil and management aspects. This has led to a diversity of approaches, ranging from straightforward soil survey interpretations to more sophisticated, multidisciplinary, integrated, regional studies, and to the application of simulation techniques (Verheye, 2003).

In the final analysis, however, the selected land evaluation approach should be based on the local conditions, especially the level of data available for the associated analysis. So the selection of an appropriate approach is an important step for the success of land use planning. This is because the selected approach has to optimize the use of the available land resources data and their ability to be adaptable to suit regional conditions to produce the best land suitability maps. The model should be developed in accordance with the priorities of the Libyan Government in developing a practical and applicable land evaluation system that can be used by the average computer user.

In this research, the FAO framework will be adapted and modified to overcome the limitation posed by the limited data availability in Libya. For example there is insufficient detailed data about socio-economic factors in the study area. Also there is no data for factors such as Radiation regime, air humidity as affecting growth conditions, condition for ripening. FAO (1983) suggested a list of twenty four land qualities that should be considered for land suitability assessment ranging from radiation regime to flood hazard to soil degradation hazard. Some of these land qualities are only applicable for certain crops. In addition, while some of these land qualities may be important in one environment they may not be important in other environments (Beek, 1978). Based on this consideration, only a subset comprising twelve of the total 24 land qualities were found to be important for each crop in the current study. The rationale governing the selection of these appropriate land qualities in the study area will be presented later in chapter 4. However, the ability to adapt such a proven FAO methodology to an area where its application would otherwise be impossible because of lack of data is a major outcome of this research.

Conventional methods of land evaluation are based on Boole's Two-valued logic that the boundaries of different land suitability classes are sharply defined. These methods have been criticized by many authors (Burrough, MacMillan et al. 1992; Baja, Chapman et al. 2002; Delgado, Aranda et al. 2009), because they do not take into account the continuous nature of soil and landscape variation, and

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uncertainties in measurement. As result, an area that just fails to match strictly defined requirements will be classified in the incorrect set of suitability. Fuzzy logic approach appears as an alternative to deal with these continuous or uncertain environments. While in Boolean logic a value is true or false, with fuzzy logic the value could be partially false or partially true which gives a more realistic representation. Thus, Fuzzy set models 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 (Sarmadian, Keshavarzi, et al., 2010).

While Boolean and Fuzzy can be distinguished as outlined above, both of them do have their relative merits and demerits. For example, where the needed information is unavailable, implemented the fuzzy approach especially in relation to developing the membership functions can become problematic. A possible way out of such difficulties will be to have an integrated system where both the fuzzy and Boolean approaches are combined. The case study in Libya because of the lack of data is such that for some of the land qualities, sufficient data needed to implement a fuzzy approach will be unavailable and for these, a straightforward Boolean method will be applied. For the parameters or land qualities that have the data, a fuzzy approach will be used.

Thus, another major aspect of the research is the combination of Fuzzy and Boolean approaches in land evaluation. Its successful development will serve other regions in land evaluation assessment when the available data are as limited as the current situation in Libya.

1.2   The Aim and Objectives

The aim of this research is to develop GIS-based Boolean and Fuzzy logic model for land evaluation system for predicting physical suitability of land for crop production in north-west of Libya.

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The research objectives are to:

- Review the literature on land evaluation methodologies and select/adapt a suitable methodology to suit the Libyan conditions.
- Evaluate the available information for the north-west of Libya including soil, crop and climate data and select data appropriate to the selected land suitability method.
- Develop land suitability assessment to determine which areas are suitable for barley, wheat and olive cultivation in the north-west of Libya.
- Provide a land suitability map that can be used/ interpreted by farmers, water resources and agriculture managers involved with policy formulations in Libya.
- Compare and assess the results obtained from Fuzzy logic approach with those from the Boolean approach and the integrated approach to check if there is any difference between them and which results seems to be more realistic.

1.3   Structure of the thesis

The thesis consists of eight chapters starting with the introduction that clarifies the problem background and provides a justification for the study.

Chapter 2 reviews existing land evaluation approaches and discusses the strengths and weaknesses of each approach. The appropriate land evaluation approach is selected taking into account the limitation of data availability and the suitability of the results for land use planning.

Chapter 3 presents the difference between Boolean and Fuzzy logic theory and their applications in land suitability analysis and land evaluation studies.

Chapter 4 introduces the research approach and outlines the various data and information that will be required for its implementation.

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Chapter 5 provides the description and background of the study area in terms of the climate and available water and land resources. The need to have a land evaluation system for prioritising the allocation of these limited resources is also highlighted.

Chapter 6 presents the development of the model using both the Boolean and Fuzzy logics in the study and explains in detail the data sets used.

Chapter 7 presents the results and discussion of the research. The land suitability model results are explained and the resulting maps from the Boolean and Fuzzy are compared.

Chapter 8 presents the conclusions of the study and explains its contribution on agriculture development in Libya. Also the chapter discusses the recommendations and future application in land suitability assessment.

Chapter 2

LAND EVALUATION TECHNIQUES

2.1 Introduction

The previous chapter has demonstrated the need for a land evaluation system in Libya that will help in enhance agricultural production where faced with limited water availability. The development of a land evaluation system requires of a lot of data and ideally for this to be feasible. However, this may not be the situation in Libya and so it is important that any method that will be used is such that a subset of the recommended array of data will be sufficient. Additionally, while it might be more helpful to base the evaluation on purely economic consideration because that is much more direct indication of farmers' income and hence, the benefit of adapting the system for their farming practices, the market for agricultural produce is not sufficiently developed in Libya to warrant such an economic approach. Additionally, the needed data to carry out such as economic evaluation are out routinely collected in Libya. As a result of the above limitations, the review carried out in this work will focus on physical (or qualitative) evaluation approach because the possibility of having the required data for their implementation is higher.

2.2 Land Evaluation Concepts and Definition

The FAO (1983) defined land evaluation as the process of assessment of land performance when used for specified purposes. In this way land evaluation can be useful for predicting the potential use of land based on its attributes (Rossiter, 1996). Land evaluation has developed from soil survey interpretation and land classification. Soil survey interpretations are predictions of performance, not recommendations for the use of soils (Beek, 1980). Agricultural land use requires not only that good soil, but also there are other factors limit the productivity of the land such as climate, erosion hazard and topography. Nowadays, these factors are included in the most of land evaluation systems.

 The basic feature of land evaluation is the comparison of the requirement of land use types with the characteristics of the available land resources, and involves the interpretation of surveys and studies of soils, vegetation, climate and landforms. Fundamental to the evaluation process therefore is the fact that different kinds of land uses have different requirements (Dent and Young, 1993). Land evaluation presents information and recommendations which can assist planners and decision makers to decide which crops to grow where, and the limitation of land use. Land evaluation is the selection of suitable land and suitable cropping. The main product of land evaluation investigation is a land classification that indicates the suitability of different types of land for specific land uses, mostly described on maps with accompanying reports (FAO, 1981).

According to FAO (1976), land evaluation should provide answers to such questions as:

- What other uses of land are physically possible and economically and socially relevant?
- What inputs are necessary to achieve a required level of production and minimize the adverse effects?
- What are the current land uses and what are the consequences if current management practices stay the same?

Land evaluation can be carried out either for the purpose of *land capability* or *land suitability* assessment. These may appear similar but they are different. Land capability describes the agricultural potential of land in a general way. During land evaluation for capability assessment, the soils are grouped on the basis of their capability to produce common cultivated crops and pasture plants without deteriorating over a long period (Boonme, 2005). In contrast, land suitability involves the assessment of the fitness of a given type of land for a defined use. In land suitability classification specific areas of land are grouped in terms of their suitability for defined uses, e.g. the cultivation of a specific crop (FAO, 1976).

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Land suitability evaluation is thus considered one of the most effective methods for proper agricultural land use planning which it comes to decisions on specific crops.

The term *land suitability* is more commonly used particularly in developing countries. This is because the evaluation is carried out to estimate the suitability of land for a specific use such as arable farming or irrigated agriculture which is more appropriate to give details of land conditions in the study area. For this reason, the term *land suitability* is used in this study to express the land evaluation.

Land evaluation is carried out to estimate the suitability of land for a specific use such as arable farming or irrigated agriculture. Land suitability is the fitness of a given type of land for a defined use. The land may be considered in it is present condition or after improvements. Generally, there are two kinds of land suitability assessment approaches. First, the qualitative approach is used to assess land suitability at a broad scale in which relative suitability is expressed in qualitative terms only, without precise calculation of costs and returns (Baja, Chapman, et al., 2002). Qualitative approach is based mainly on the physical productive potential of the land, with economics only present as a background. They are commonly employed in reconnaissance studies, aimed at a general appraisal of large areas. The results of qualitative classification are given in qualitative terms, such as highly suitable, moderately suitable, and not suitable. Second, the quantitative approach is using parametric techniques involving more detailed land attributes, which allows objective comparison between classes relating to different kinds of land use (FAO, 1981). Quantitative approach normally involves considerable use of economic criteria, e.g. costs and prices, applied both to inputs and production. Recently, most studies combined the qualitative and quantitative approaches in the process of land suitability assessment. One of the most recently models used the combination between qualitative and quantitative approaches in land evaluation is fuzzy model (SarmadianA, KeshavarziA, et al., 2010) .

Land evaluation can be conducted based on physical parameters (e.g. soil properties, vegetation, topography and climate) and can be followed by socio-economic conditions e.g. population density, transportation and market for the agricultural produce and were there or not farmers receive fair price for the produce (FAO, 1976). While physical parameters tend to remain stable, socio-economic are affected by social, economic and political performances and are thus very dynamic (Dent, Young, et al., 1981). Thus, physical land suitability evaluation is more reliable tool for land-use planning and development (Sys, 1985); (Van Ranst, Tang, et al., 1996), because it can provide stable and robust information on the constraints and opportunities for the use of the land and therefore can represent a better guide on optimal utilization of land resources (FAO, 1985). Recently, most of studies combined physical parameters affecting the yield agricultural crops and socio-economic factors in the process of land suitability assessment (Sarmadian, Keshavarzi, et al., 2010).

The selection of an appropriate land evaluation approach is an important step for the success of the whole process. This is because the selected approach has to optimise the use of the available data for land resources to produce the best land suitability maps taking in the consideration the ability to integrate these maps easily in further studies with further factors such as water availability or socio-economic factors, when the required data for these factors is available. The most important factor in selection one of these approaches is the availability of data and the possibility of collecting new data. When detailed data is not available, it is more realistic to use the qualitative approach for land evaluation (Ziadat, 2000).

2.3 Land Evaluation Approaches

The development and application of land evaluation system grew rapidly throughout the 1950s and 1960s as a result of which many land evaluation approaches have been established in different countries (Verheye, 2003). A general overview of the most widely applied land evaluation approaches are presented in the next sections.

2.4   USBR Land Classification for Irrigated Land Use

The U.S. Bureau of Reclamation designed this method to select suitable lands for irrigation (USBR, 1951). The main purpose of this method is to classify land according to its potential under irrigated agriculture. The system is based on an economic principle for distinguishing between different land classes. Land class is defined as a category of lands with similar physical and economic attributes that affect the suitability of land for irrigation. Physical attributes of the land such as soils, topography and drainage are functionally related to its economic value, which is measured by the payment capacity or the money remaining for the farmer after all costs are met (FAO, 1985).

The criterion for the designation of suitability classes is the payment capacity which is defined as the "residual available to defray the cost of water after all other costs have been met by the farm operator" (USBR, 1951). The higher this residual, the higher is the suitability class. The planner can then set a repayment threshold to determine which lands should be included in an irrigation project. Since irrigation water will be applied, this system effectively removes the limitation posed by climatic factors, especially water availability in determining the suitability of soil. With water non limiting, the crop yield from cultivating a given land is then more a function of the soil nutrient and other physical characteristics.

In this classification *arable* land is defined as "land which, in adequate-sized units and if properly provided with the essential improvements of levelling, drainage, irrigation facilities and the like, would have productive capacity, under sustained irrigation, sufficient to meet all production expenses, including irrigation operation and maintenance costs and produce reasonable return for the farm investment (FAO, 1985).

There are six suitability classes in this system. Classes 1, 2, and 3 have respectively the highest, moderate and lowest irrigation suitability and hence payment capacity. Class 4 is special use lands, which is suitable for some kinds of uses for example fruit, rice. Class 5 is temporary class reserved for non-arable

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lands due to some temporary problem such as excessive salinity, or these requiring further studies before they can be precisely allocated into one of the above 4 classes. Class 6 is considered unsuitable land under existing economic conditions for a project and will include lands with inadequate drainage or steep lands, as well as lands that could be developed but which would not meet repayment criteria (FAO, 1985).

The USBR system does not take into account the physical suitability of individual crops other than general conditions of soil for crop production. Furthermore, some factors that affect crop yield such as climate are assumed to be non-limiting (FAO, 1985).

2.5   Land Capability Classifications

Land Capability System was developed by the Soil Conservation Service of the United State Department of Agriculture (USDA., 1961). The main aim of the system is to classify land according to the limitations imposed by permanent properties of soil and other physical factors (Davidson, 1992). The most important factors used to interpret the capability of land in the system are the slope, soil texture, soil depth, permeability, water holding capacity and type of clay (Beek, 1978). There are eight classes denoted by Roman numerals, with limitations to use increasing and versatility of use decreasing from Class I to Class VIII (Table 2-1).

Table 2-1 *Increasing limitation to use and decreasing versatility of use (Lynn, 2009)*

LUC Class	Arable cropping suitability	Pastoral grazing suitability	Production forestry suitability	General suitability
I	High	High	High	Multiple use land
II				
III				
IV	Low			
V				Pastoral or forestry land
VI	Unsuitable			
VII		Low	Low	
VIII		Unsuitable	Unsuitable	Conservation land

Increasing limitations to use → *Decreasing versatility of use →*

The USDA method includes three levels in its capability classification structure: classes, subclasses and units. Soils are ranked into one of eight capability classes which indicate the degree of limitation with respect to land use (*Table 2-2*). The Land Use Capability (LUC) Classes (I, II, III) have respectively slight, moderate, high limitation that restrict their uses for crop production, whereas class IV requires very careful management and classes (V, VI, VII, VIII) have gradual limitations slight to high that make them unsuited to cultivation but could be used to pasture, range, wildlife.

Table 2-2: *Structure of land capability classification (Dent and Young, 1980)*

Capability classes	Capability subclasses	Capability unit
Arable I II III IV	 IIw, IIs, IIe, IIc IIIw, IIIs, IIIe, IIIc IVw, IV,s, IVe, IVc	IIe-1 IIe-2 IIe-3 Etc
Non-arable V VI VII VIII	N/A	N/A

- *N/P Not applicable*

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Land Use Capability (LUC) Subclasses describe the limitation risk caused by four kinds of management problems as follow:

1. Erodibility (e), where susceptibility to erosion is the dominant limitation.
2. Wetness and drainage (w), the dominant limitation is a high water table, slow internal drainage.
3. Soil (s), the dominant limitation is shallow soil depth, low soil water holding capacity, low fertility and salinity.
4. Climatic (c), the dominant limitation is uneven rainfall distribution, effect of wind in exposed areas and temperature (Grose, 1999).

Subclasses are not assigned to soils in capability class (I) because it considered ideal for crops. Also subclasses are not used in classes (V,VI,VII,VIII) because already are not suitable for crops as shown in (*Table 2-1*) (Lynn, 2009). In this classification the soils of different type could be grouped in the same capability class as they share the same degree of limitation (Davidson, 1992).

Land Use Capability (LUC) Unit group together areas where similar land inventories have been mapped, which require the same kind of management and conservation requirements. Land use capability units are identified by numbers at the end of LUC code. An example of the LUC nomenclature is (IIe1), where II is the LUC Class, (IIe) is the LUC subclass and (IIe1) is the LUC Unit (Lynn, 2009), The USDA methodology was originally used for the planning of individual farms and it was a response to the serious soil erosion problems which occurred in the U.S.A. at that time. The main aim of the classification was to reflect the risk of erosion and to indicate sustainable land uses (Davidson, 1992). The system is widely used around the world and it has been adapted in many countries such as the British Land Use Capability Classification, the Canadian Land Capability Scheme and the Dutch system, which is a clear indication of its value in helping land use planning and management. However, there are disadvantages of using this system. Firstly, there is no indication of the suitability of land for specific crops. Secondly, it is negative by emphasizing the limitations rather than the

positive potential of land and does not take into account possible soil improvements such as decrease soil salinity after installation of irrigation and drainage systems. Finally, because of the system does not take into account the difference in crop requirements between the crops the rank order of potential land uses may give the wrong impression, for instance, the lower classes could be acceptable and much valued for certain crops (McRae and Burnham, 1981) .

2.5.1   Parametric Land Evaluation System

The parametric method of land evaluation combines the different land characteristics (e.g. soil depth, soil salinity, soil reaction, etc) which are believed to influence land productivity using mathematical formula, to produce a productive rating for the land. Each land characteristic is given numeric value depending on its importance. These values are combined by adding or multiplying to get an overall rating of the land (Storie, 1978).

Storie (1978) developed Index Rating (SIR) in California, originally derived for land taxation as a main application. The SIR can be calculated as follows:

$$\text{SIR} = \text{A1} \times \text{A2} \times \text{A3} \times \ldots \ldots \text{An}/100^{n-1} \qquad\qquad (2.1)$$

where (A1, A2, A3 …An) are values of individual land characteristics on the scale from 0 (useless) to 100 (excellent land). Each factor is scored as a percentage then all factors are multiplied. The final index is expressed as a percentage. The rating of slope factor and overall topographic conditions as defined in the Storie index is shown in *Table 2-3* as example. The factor ratings provided by Storie can be taken as guides rather than as absolute values and, with these ratings changing as soil scientists gained experience with the index (De la Rosa and Van Diepen, 2002).

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Table 2-3 *The rating of slope factor in Storie index (Verheye, 2008)*

Slope situation	Slope %	Storie index for slope %
Nearly level	0-2	100
Gently undulating	2-3	95-100
Gently sloping	3-8	85-95
Undulating	3-8	85-95
Rolling	9-15	80-85
Hilly sloping	16-30	70-80
Steep	30-45	30-50
Very steep	45 and over	5-30

Parametric systems are simple and easy to apply. However, they do not take the land use requirement into account. Moreover, the reliability of the results is highly dependent on the characteristics used and of course their respective ratings. This arbitrariness in factor choice and their ratings is a major source of uncertainty when using parametric system (Ziadat, 2000). As the evaluator has to assign separate ratings to each one of several land characteristics or factors depending on its importance, and then take the product of all factor ratings as the final rating index by multiplying these factor ratings.

Ben-Mahmoud (1995) developed the parametric productivity index rating for Libyan soils by using eleven soil characteristics to determine the productivity rating:

Productivity Rating = (A×B×C×D×E×F×G×H×I×J×K)   (2.2)

Where A = texture of topsoil, B= soil compaction extent, C= soil depth, D= water table level, E=internal soil drainage, F= soil salinity, G = Exchangeable sodium percentage, H= soil reaction, I= calcium carbonate percentage ($CaCo_3$ %), J= soil erosion, K= soil slope. Each soil characteristic was given a different value between 0-1 depending on the effect of that factor on agricultural production according to previous studies and experience in Libya. The rating values for soil

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texture factor and the corresponding index values are shown in *Table 2-4* as example and the index values of the rest of soil characteristics are presented in appendix (C). The result is multiplied by 100 to produce suitability classes as a percentage. The productivity rating and suitability classes are shown in *Table 2-5*

Table 2-4*: The rating index of soil factor (Ben-Mahmoud, 1995)*

Soil texture	Gravel %	Rating index	
		Annual crops	Perennial crops
Clay, clay loam	<15	0.90	0.70
	15-50	0.80	0.65
	>50	0.70	0.55
Sandy clay	<15	0.85	0.90
	15-50	0.75	0.80
	>50	0.60	0.60
Sandy loam	<15	0.70	0.70
	15-50	0.55	0.60
	>50	0.45	0.35
Sand	<15	0.55	0.55
	15-50	0.45	0.45
	>50	0.25	0.25

Table 2-5: *Productivity rating and suitability classes (Ben Mahmod, 1995)*

Productivity rating %	Suitability class
0-20	Not suitable
20-30	Marginally suitable
30-60	Moderately suitable
60-80	Moderately Highly Suitable
80-100	Very High Suitable

This method was adapted from the (SIR), taking into account local environmental conditions to define soil properties to classify the soil suitability. The method is simple, although the subjectivity in the choice of the weights is a problem. Furthermore, like the SIR, the multiplicative form of the rating function ensures

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that the limiting physical characteristics, e.g. that with the least weighting has the most influence of the rating. For example, if one of the eleven physical factors is zero- weighted, then the overall productivity rating for the soil will be zero (unsuitable for cultivation) irrespective of the values or weights assumed by the other characteristics. This is a further limitation of the approach in that it forecloses possible management corrective intervention for the undesirable characteristics, e.g. high water table can be remedied by pumping that removes any water logging and enhances the suitability of the land. Finally, the results can be misleading because they do not account for other factors essential for successful agriculture production such as the temperature. For example orange trees will not grow in cold mountainous area even if the soil is suitable.

2.5.2 *Fertility Capability Soil Classification*

The *Fertility Capability Classification* (FCC) system is a technical soil classification system developed to evaluate soil properties affecting crop regarding to fertilization and to assist in making fertilizer recommendations. It was proposed by Buol et al., (1975) and modified by Sanchez et al., (1982). The FCC system classifies soils into groups according to their fertility constraints as determined by the chemical and physical properties such as organic matter, nutrient, pH, calcium carbonate and soil depth. The classes created with the FCC indicate the soil limitations related to fertility which can guide the user in the choice of practices e.g. type of fertilisers, soil tillage interventions etc to redress the problem (Sanchez, Palm, et al., 2003) .The FCC has been used and adapted in many countries such as United States (Naderman, Nelson, et al., 1986), Peru (Paredes, 1986) and South America (Cochrane, Sanchez, et al., 1983) and Cambodia (White, Oberthür, et al., 1997) . However, there is some weakness of using this system. Firstly, the FCC is confined only to fertility and other land problems such as slope, salinity and climate were omitted. Secondly, the system does not take into account the difference in the crop requirements and only give general fertility limitations, which is not enough to make specific fertility management recommendations for different crops (Rossiter, 1994).

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2.5.3   The FAO Framework for Land Evaluation

In 1976, the FAO provided a general framework for land suitability classification. The framework in itself, does not propose a specific method for doing this classification (Keshavarzi, Sarmadian, et al., 2010);   rather it is a set of methodological guidelines for the determination of land suitability. It was basically designed to address any kind of environment and at any scale, and to be utilized especially in regions with limited data (FAO, 1976).   The FAO framework has three different guidelines. These guidelines are: 1) land evaluation for rainfed agriculture (FAO, 1983), 2) land evaluation for irrigated agriculture (FAO, 1985), and 3) land evaluation for natural forests (FAO, 1984). These guidelines are designed to assess crop, management, environmental and conservation requirements. The guidelines for rainfed agriculture may be considered the norm for land evaluation. The main different between the guidelines for land evaluation for rainfed and the guidelines for irrigated agriculture is that the latter takes into the account quantity and quality of water resources and economic factors. Special features of guidelines for land evaluation for natural forests are therefore that the land-use types may be related to conservation rather than production, that the land use is commonly multiple uses (including wood production, conservation, recreation, grazing etc.). A checklist of land qualities for assessing land suitability that suggested from the guidelines for land evaluation for rainfed agriculture is presented in Chapter 4 (Table 4.1).In later years, the set of methods in land evaluation were emerged based on the FAO framework (FAO, 1985).

The   important definitions that are used in the framework (FAO, 1976) are presented in the glossary

The FAO framework describes a methodology for land suitability classification and the term *suitability* is used rather than *capability*. The FAO identified land suitability as "the fitness of a given tract of land for a defined use" (FAO, 1976). According to the FAO, the term "land suitability evaluation" could be interpreted as the process of assessment of land performance when the land is used for specified purposes.

The FAO (1976) presented basic principles in which the Framework is based on:

1. Land suitability is assessed and classified with respect to specified kinds of use.

2. A multidisciplinary approach is required (in practice, not just soil surveyors).

3. The suitability classes are defined in terms relevant to the physical, economic and social context of the area concerned.

4. Suitability refers to land use on a sustained basis (e.g., can't deplete the resource base, in practice this is rarely achievable, and this principle is being weakened).

5. Evaluation involves comparison of two or more alternative kinds of use.

The FAO assessed and classified land suitability with respect to particular uses since what is suitable for one kind of cultivation may not be suitable for another. The process of land suitability classification is assessment and grouping of specific areas of land in terms of their suitability for defined uses (FAO, 1976). For instance, an alluvial flood plain with impeded drainage might be highly suitable for rice cultivation but not suitable for many kinds of agriculture or for forestry (FAO, 1981). The concept of land suitability is only meaningful in terms of specific kinds of land use, each with their own requirements, e.g. for soil moisture, rooting depth etc. The qualities of each type of land, such as moisture availability or liability to flooding, are compared with the requirements of each use.

The framework classifies the suitability of land into four categories: land suitability orders, classes, subclasses and units. Suitability orders indicate whether land is assessed as suitable (S) or not (N) for the use under consideration. Classes indicate the degree of suitability (up to five), for example, highly suitable (S1), moderately suitable (S2), marginally suitable (S3), currently not suitable (N1) and permanently not suitable (N2). Subclasses indicate the kind of requirements or limitations and are presented by lower case letters, for example S2m for suitable land with specific limitations of moisture availability. There are no subclasses in

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Class S1. Land suitability units are subdivisions of subclasses for example, S2m-1, S2m-2, S3m-3...etc. see (*Table 2-6*). All the units within a subclass have the same degree of suitability at the class level and the similar kinds of requirements or limitations at the subclass level .The units differ from each other in their production characteristics or in minor aspects of their management (often definable as differences in detail of their limitations) (FAO, 1976). The number of subclasses and the limitations chosen to distinguish them will differ in classifications for different purposes (FAO, 1985).

From the above, it is not difficult to see that the FAO framework has taken some concepts from its two precursors: the USDA land capability classification (section 2.2.1) and the USBR system of land suitability for irrigation (section 2.2.2). For example, *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 (Dent, Young et al. 1981).

Table 2-6: *Structure of the suitability classification (FAO 1976)*

Order	Categories Class	Subclass	Unit
Suitable	S1 S2 S3	S2m S2e S2 me etc	S2m-1 S2e-2 etc.
Not Suitable	N1 N2	N1y N1z Etc.	

In light of the above, it is not difficult to see that to implement the framework will involve establishing the crop requirements of the different land uses, which are then evaluated against the actual land characteristics of each land mapping units to

see how well they provide optimum conditions. This comparison of land mapping unit with land requirements is called "matching". Matching represents the meeting of physical requirements of specific crops with the land conditions to give estimation of crop performance (FAO, 1976). In the framework crop yields were used to define crop requirements for each crop. There are two methods for applying yield data to evaluation: direct and indirect. The direct method is simply to plot crop yield data onto the map of land units. Those land units on which high yields are consistently obtained are classed as highly suitable, and so on. This method is achieved by the matching procedure (FAO, 1983). The indirect method is through deriving regression equations for relationships between crop yields (dependent variable) and land qualities. Its use needs a large amount of yield data from trial plots or farmer's fields. The resulting land suitability classes refer only to the crop components of land utilization types (FAO, 1983).

The results of land evaluation using this approach were validated by FAO using yield data drawn from many studies, and it was able to accurately predict yield in more than 80% of all crop suitability classes (Hennebert, Tessens, et al., 1996). However, many authors have also concluded that the use of this framework has proved to be beneficial even when the available data about yields are limited and detailed soil information is insufficient (Goldschmidt and Jones, 1988, Sys and Riquier, 1980).

The FAO framework for land evaluation has been widely applied and adapted in many developing countries, such as Zimbabwe, Jordan, Nigeria, Syria, north east of Libya and Bangladesh (FAO, 2007, Kanyand, 1988, Nwer, 2006, Ziadat, 2000). Nwer (2005) determined land suitability for barley, wheat, maize and sorghum using Boole's approach in north east Libya.

2.6 GIS Applications in Land Evaluation

GIS-based techniques for land use suitability analysis developed from the practise of manually overlaid maps which were developed in the USA in the last century. GIS capabilities for spatial analysis overcome the drawbacks of the paper map

overlay approach (Malczewski, 2004). However, GIS has now become a powerful tool for land use planning due to its ability to deal with different functions, which is very useful for land use planning. Of these functions, the most important are database management, cartographic analysis and modelling function. The ability to integrate data in GIS is one of the most important advantages of the system, involving collection of data from different sources, formats, and scales and making them compatible with each other (Flowerdew, 1991).

The main feature of integrated data management is the ability to present the information of different layers at the same time, which can help planners and decision makers by showing together distinct factors that affect land use (FAO, 1985). Moreover, GIS has the ability to integrate variety of geographic technologies such as Global Position System (GPS) and Remote Sensing.

Another important function of GIS is the cartographic analysis of different layers. When these layers are integrated in a GIS environment, overlay analysis enables the production of new layers of information. This facility can improve the accuracy and reduce the required time for these analyses, compared with traditional methods. An example for using this function is the overlay of different layers describing land characteristics to produce land suitability map for each land use type. In addition these land suitability maps can be overlaid with each other to produce a suitability map illustrating the best use of each area of land (Flowerdew, 1991).

The modelling function provided by GIS can benefit land evaluation by providing the ability to analyse and model data layers by automatic approach. Once a model has been built and validated, the repetition of the analysis, as assumptions and /or conditions change, is a quick and easy task. This function also provides an interface between GIS and other modelling software which can integrate non-spatial data. An example, suitability maps can be integrated with non-spatial data, such as socio-economic data to model the effect of these data on the land use. This

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function of GIS can save time and cost in the evaluation of land use options compared with conventional methods (Burrough, McDonnell, et al., 1998).

Currently GIS techniques have been used in many land suitability studies. For example, Mongkolsawat et al., (1997) revealed the land suitability classes for assessing suitable land for rice cultivation in the Northeast of Thailand using GIS. They used the process of land evaluation based on Guideline of land evaluation for rainfed agriculture (FAO, 1983). The characteristics believed to affect land quality were aggregated in five layers; water availability, nutrient availability, soil texture, salt hazard, and topography. These characteristics were collected from the existing information and satellite data. Analyses of rainfall data and irrigation requirement gave the water availability. Soil texture, nutrient availability and soil salinization were obtained from soil map. Topography factors were obtained from satellite imagery and topography maps. Each of the land qualities with their associated attribute data was digitally encoded in a GIS database to finally establish five thematic layers. Overlaying these layers gave the resultant suitability map (Mongkolsawat, Thirangoon, et al., 1997).

Messing et al. (2003) developed Land suitability classification in China based on the FAO Framework (1976). Fifteen Land characteristics were selected to classify Land qualities into six classes namely: available water, slope aspect, erosion hazard, soil workability, available nutrients and flooding hazard. Then GIS was used for the comparison between the current land use and the land suitability for agriculture. The result was four scenarios for planning suitable land use in the study area (Messing, Hoang , et al., 2003).

The integration of Multi-criteria decision making methods MCDM with GIS has considerably advanced the conventional map overlay approaches to the land-use suitability analysis (Malczewski, 1999)**.** GIS-based MCDM can be thought of as a process that combines and transforms geographical data (input) into a resultant decision (output). The MCDM procedures (or decision rules) define a relationship between the input maps and the output map. The procedures involve the

utilization of geographical data, the decision maker's preferences and the manipulation of the data and preferences according to specified decision rules. MCDM problems involve criteria of varying importance to decision makers and information about the relative importance of the criteria is required. This is usually obtained by assigning a weight to each criterion. The derivation of weights is a key point in defining the decision maker's preferences. A weight can be defined as a value assigned to an evaluation criterion indicative of its importance relative to other criteria under consideration. The larger the weight, the more important is the criterion in the overall utility (Drobne and Lisec, 2009, Malczewski, 1999).

There are four main kinds of techniques for the development of weights (Malczewski, 1999): 1) ranking methods, which are the simplest methods for assessing the importance of weights: every criterion under consideration is ranked in the order of the decision maker's preferences; 2) rating methods, which require the estimation of weights on the basis of predetermined scale; 3) pairwise comparison methods, which involve pairwise comparison to create a ratio matrix to deal with the relative importance of the two criteria involved in determining suitability for the stated objective; 4) trade-off analysis methods, which make use of direct trade-off assessments between pairs of alternatives (Drobne and Lisec 2009).

Van Huynh and Michael (2005) carried out a study whose aim was to determine the physical land suitability areas for grapefruit crop production in Vietnam and sustainable agriculture development of a representative village Thuy Bang, Hue, Vietnam. The methodology used for the physical land suitability analysis for "Thanh Tra" pomelo is a multi-criteria evaluation approach within GIS context, based on FAO land evaluation framework (1976, 1983), modified for Vietnamese conditions. The methodology consists in matching land qualities against crop requirements of "Thanh Tra" grapefruit. The important parameters were categorized into six maps namely; soil unit's map, slope map, texture map, soil effective depth map, organic material map, soil fertility map. Land Evaluation

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Units (LEUs) map and physical land suitability classification were obtained by overlapping the above mentioned maps within a GIS system. The study concluded that lack of irrigation, erratic rainfall and poor soil fertility are the most serious problems influencing yield and quality of "Thanh Tra" pomelo (Van Chuong and Boehme, 2005).

Elaleem (2010) carried out a study whose aim was to determine the physical land suitability areas for barley, wheat and maize crops in the north western region of Libya. The FAO framework for land evaluation with Fuzzy Analytical Hierarchy Process (AHP) and Ideal Point methods were employed to determine land suitability classes for the selected crops. Pairwise comparisons method was applied for determining the weights of criteria for land characteristics. The findings emphasized 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. The study applied manual Fuzzy logic method based on some membership functions developed by some researchers. However, the membership functions that have been successfully developed in a different environment may not be appropriate for other environment.

All of the above are examples of effort to automate the FAO land evaluation framework taking advantage of the pervasiveness of the computer and the veracity offered by GIS in the land mapping and manipulation of spatial data indeed, since the FAO land evaluation framework was published in 1976 and the emergence of GIS as an effective tool in land evaluation, a number of computer systems have been developed for land evaluation based on the framework.

2.7   Computerized Land Evaluation Methodologies

A number of automated land evaluation methods have been developed in the last 3 decades. Some of these methods used geographic information systems (GIS) technology, while others do not. In the next sections a brief description of computerized land evaluation methods will be presented.

2.7.1 *The Automated Land Evaluation System (ALES)*

The Automated Land Evaluation System (ALES) is a computer program developed by Rossiter (1989) to evaluate land suitability according to the FAO framework. ALES offer the integration of local knowledge, by allowing the user to insert their expertise in land evaluation, to evaluate the physical and economic suitability of land. ALES has no prescribed list of land use requirements by which land uses are evaluated, and has no fixed list of land characteristics from which land qualities are inferred. Instead, these lists are determined by the evaluator to suit local conditions and objectives. The model is built in the following manner. First, the evaluator builds a preliminary version of the model by: (1) selecting land utilization types; (2) expressing utilization types in terms of their most important land use requirements; (3) determining which land characteristics are available to form the basis of evaluation and (4) determining prices and interest rates that related to economic evaluation. The economic evaluation of land mapping unit for a land utilization type is determined from the predicted annual gross margin per unit area. Increasing limitations result in increased costs of production, decreased yields. Evaluator build decision trees to express inferences from land characteristics to land qualities, from land qualities to predicted yields, and from land qualities to overall physical suitability(Rossiter and Van Wambeke, 1997).

After building the preliminary model the evaluator uses the program to compute and display evaluation matrices, which show five kinds of ratings for each land utilization type, namely: physical suitability subclasses, economic suitability subclasses, predicted gross margin, expected yield and rating for single land qualities (Rossiter, 1990). ALES is not a GIS and does not itself display maps. It can, however, analyse geographic land characteristics if map units are appropriate defined, and it can directly reclassify IDRISI or Arc/Info maps with the same mapping unit legend as the ALES database.

2.7.2   The Land Evaluation Computer System LECS

The Land Evaluation Computer System LECS was one of the implementations of the FAO framework development by Wood and Dent (1983) and applied in Indonesia to select the physical and economic data for each land unit and to match them with crop requirements of each utilisation type. These data were analysed in two steps, firstly, the potential productivity of each land unit was evaluated then the computer runs a soil erosion model based on a Universal Soil Loss Equation (USLE) (Wood and Dent, 1983) , which estimates soil loss under each land use. Thus giving an indication of the level of conservation measures required. Secondly, it then assesses the potential productivity on an economic basis by predicting the effects of improved management. The conservation model selects options for conservation management and estimates the cost of each. The final output provides the recommendations of suitable crop for each land unit based on economic conditions.

2.7.3   The Intelligent System for Land Evaluation (ISLE)

The Intelligent System for Land Evaluation (ISLE) was also developed according to the FAO framework approach for land evaluation (Tsoumakas and Vlahavas, 2001). The input data of this system is digital soil map of a study area together with information about the associated land characteristics that the FAO framework method requests. The system displays this map and evaluates the land units selected by the user and finally visualises the results of the evaluation by map (Tsoumakas and Vlahavas, 2001).

2.7.4   Land Evaluation Intelligent GIS (LEIGIS)

Land Evaluation Intelligent Geographical Information System (LEIGIS) is a software designed in Greece (Kalogirou, 2002). The LEIGIS software aims to produce a physical evaluation of land capabilities and to use this to introduce an economic evaluation for different uses in agriculture production. For the physical evaluation, data for 17 land characteristics have been used to characterize land suitability for general cultivation into five suitability classes. Those characteristics

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form three main Factors that then are combined and then the total score is calculated. The detailed classes of suitability and scoring for land qualities for general cultivation are shown in (*Table 2-7*).

Table 2-7: *land characteristics and score assignment for each suitability class* (Kalogirou, 2002)

Land Characteristics	Class	S1	S2	S3	N1	N2
	Score	100-98	98-85	85-65	65-40	<40
Factor A Soil toxicities	% Organic matters	>1.5	1.5-1	1-0.6	<0.6	-
	% Base Saturation	>60	60-50	50-40	<40	-
	Cation Exchange Capacity (mq/100gm)	>18	18-12	12-6	<6	-
	% Carbonate ($CaCo_3$)	0.3-10	10-30	30-50	50-80	>80
	% Sulfates ($CaSo_4$)	0-2	2-4	4-10	10-15	>15
	Soil reaction (pH)	6-7.5	5.5-6 7.5-8.5	4.5-5.5 8.5-9	4-4.5 9-9.5	<4 >9.5
Rooting conditions	Soil depth	>90	90-60	60-40	40-20	<20
	% Fine Gravel Volume	0-15	15-40	40-75	>75	-
	% Coarse Gravel Volume	0-3	3-15	15-40	40-75	>75
	% stones volume	0-3	3	3-15	15-40	40-75
	% slope	0-3	3-12	12-18	18-36	>36
	Erosion hazard	E0	E1	E2	E3	E4
Factor B Excess of salt	Salinity EC (mmhos/cm)	0-4	4-8	8-10	10-14	>14
	% Sodicidy (ESP)	0-8	8-12	12-20	20-30	>30
Factor C	Water level (cm)	>120	60-120	40-60	20-40	<20
	Flood hazard	F0	F1	F2	F3	F4
	Drainage	A	B	C	D or E	F or G

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In this system, scores are assigned for each land characteristics depending on crop requirements. Then the total score is calculated used (Kalogirou, 2002):

Final Score = (Average score of Factor A) × (Average score of Factor B) × Average score of Factor C)/1000 (2.3)

The classes of land suitability and their corresponding final score and the expected performance for each score are shown in Table 2.8. The model has adapted the FAO classification system for crops (FAO, 1976, 1984, 1985), in which land suitability classes are classified into five classes (three suitable and two not suitable) for general cultivation, However, the equal interval classification (five intervals of 20% in the range 0–100) was not used in LEIGIS method. Instead, for the highly suitable class, the score interval 98–100 was adopted which makes this score almost impossible for any land (Kalogirou, 2002).

Table 2-8 : Expected land performance for each score

Class	Score	Expected performance: % of the perfect performance
Highly Suitable (S1)	98-100	>90
Moderately Suitable (S2)	85-98	60-90
Marginally Suitable (S3)	65-85	35-60
Currently not Suitable (N1)	40-65	<35
Permanently not Suitable (N2)	<40	-

For the economic evaluation, the expected yield is calculated based on the score of the land parcel for cultivation, and the corresponding maximum yield. Then the expected income for all possible types of cultivation is calculated and the cultivation that gives the highest expected income is selected (Kalogirou, 2002).

2.7.5   The Land Use Suitability Evaluation Tool (LUSET)

The Land Use Suitability Evaluation Tool (LUSET) was developed and applied in many Asian countries as part of Land Use Planning and Analysis System (LUPAS) (Kam, Yen, et al., 2000). The LUSET is a model used to assess land suitability for multiple crops and is also based on the FAO framework for land evaluation (FAO, 1976). LUSET works by matching the present land use or the intended use with the qualities of the land. The land qualities of each land were defined by a set of its properties such as (soil, climate, topography, water, etc). The Land Utilization Type (LUT) used as expression of the intended use of land for agriculture purpose (cropping system). For each cropping system there are specific requirements, which are necessary for successful cultivation e.g. (soil properties, climatic conditions, quality and availability of water).

LUSET has been applied in many countries using multiple linear programming for planning optimal land use for different purposes and for assessment land suitability for different crops. LUSET is programmed in Microsoft Excel and coded using visual basic to be user friendly. It comprises three components:

(i)   the main program contains the commands and calculations for matching crop requirements with land qualities;
(ii)   the crop requirement information file contains parameters of soil, terrain ,climate, etc., that influence crop growth; and
(iii)   the land quality information file contains detailed descriptions of the land and other (may also include socio -economic) characteristics for the study area of interest.

LUSET package includes three files: the main program LUSET.xls, the crop information file CropInfo.xls and the land quality information file LUAttribute.xls (*Yen.*, *Pheng.*, et al., 2006), (Slingerland, 2010).

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2.8   Discussion

The FAO framework for land evaluation has been successfully applied in various parts of the world for over 30 years and has become the main point of reference for land evaluation in many developing countries (H. George, 2010). There are several essential points that distinguish the FAO framework from previous land classification systems. Firstly, the FAO framework assesses land suitability for each particular use and then combines and compares the uses. Secondly, land is defined broadly not just by soil characteristics but takes into account many other factors such as climate, topography, erosion, water and socio-economic impacts. The framework recognises that land should be evaluated on the basis of physical consideration and could be followed by economic evaluation depending on the availability of economic data. Economic evaluation is used to predict the gross margin, based on predicted costs and returns, in units of currency per hectare/year. All this makes the FAO approach powerful and flexible methodology(Manna, Basile, et al., 2009, Rossiter, 1996).

The FAO framework for land evaluation has been selected to evaluate the land suitability in this study. The selection of the FAO approach in the study area was based on following points:

1. Land resources inventories are placed at the centre of the evaluation process in the FAO method. This is very important because it requires a comprehensive integration and compilation of different data in a natural resources database.

2. The FAO framework is based on process which involves matching the requirements of each land utilization kinds with the available land resources. This is important because the agricultural land in the study area is restricted; therefore this approach will achieve maximum benefit for the use of limited land productivity.

3. It enables the evaluator to choose either physical or economical evaluation. This is important because data may not be available to implement an economical evaluation, especially in developing countries where economic data are incomplete or lacking. The latter is certainly the case in Libya which is why the aim has been to focus on the physical evaluation.

The FAO framework for land evaluation is only a set of guidelines and evaluators have to select land characteristics and qualities which differ from one environment to another. Therefore, already developed computer systems used in different environments and different sets of data may not be used for other sets of data and conditions (FAO, 2007). The framework involves the construction of matching tables or the transfer functions and subsequent calculations of suitability. These processes are time-consuming and are liable to errors. Therefore, there are a great number of benefits to be gained in automating the FAO procedures (Davidson, 1992).

There is no doubt that computer systems and GIS allow land evaluation to be performed more efficiently; they limit the margin of human error, and save time and cost. However, most of automated land suitability methods require high level of information technology. Libya like many developing countries has low level of information technology access in agriculture sector. Moreover, the existing tools are not very user-friendly making it difficult for non-IT expert to make use of (Kalogirou, 2002). Therefore, there is a present need to develop a practical, automated land evaluation tool and easy to use in Libya that is consistent with the current conditions of the country. In this study, therefore the land suitability analysis approach that will be developed in this research has been designed to be applied through a spreadsheet model such that it can be utilized subsequently by those with simple GIS modeling capabilities.

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2.9 Summary

This chapter has outlined the most widely applied land evaluation methods, such as the USDA land capability classification, the United States Bureau of Reclamation (USBR) land classification for irrigated land suitability, parametric system, the fertility capability classification (FCC), and FAO framework in order to select or adapt an evaluation method for agricultural development in Libya. From the literature review it is also clear that the use of Geographic Information Systems (GIS) has become a powerful tool in land evaluation applications, due to its flexibility and accuracy in handing and displaying spatial data and information.

This study will develop a GIS-based Boolean and Fuzzy logic model for land evaluation system for predicting the physical suitability of land using the FAO framework. It will apply this to specific crops: wheat, barley and olive under Libyan conditions. Automatic fuzzy tool in MATLAB based on rules is applied for establishing membership functions for each land characteristics to overcome the drawbacks of manual Fuzzy method.   Economic evaluation will be excluded in this study due to the difficulty of providing reliable information about the economy, as well as the lack of price stability in the Libyan market.

Chapter 3

ESSENTIALS OF BOOLEAN AND FUZZY LOGIC SYSTEMS

3.1 Boolean Logic Theory

Boolean logic was developed by George Boole in the 1840s. It has been mostly used where on attribute can only be one of two distinct possibilities and the boundaries between these possibilities or classes are thus clearly defined. Boolean algebra is a mathematical system for the manipulation of variables that can have one of two values represented by:

- True or False
- Yes or No
- On or Off
- 1 or 0

Boolean logic has three basic operators: Intersection (the logical term AND), Union (the logical term OR) and Inverse (the logical term NOT). These Boolean operators use integers or terms such as (True and False) as input raster 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:

3.1.1 Boolean Intersection (AND)

If both values are true or nonzero values, the output is one. If one or both values are false or zero, the output is zero (*Figure 3-1*). In the other word the output will be one only if all inputs values are nonzero values such as (1,2,3,…..).

Input1 $\neq$ 0, Input2 $\neq$ 0, Output = 1

Input1 $\neq$ 0, Input2 = 0, Output = 0

Input1 = 0, Input2 $\neq$ 0, Output = 0

Input1 = 0, Input2 = 0, Output = 0

If either of the inputs is No data, the output is No data.
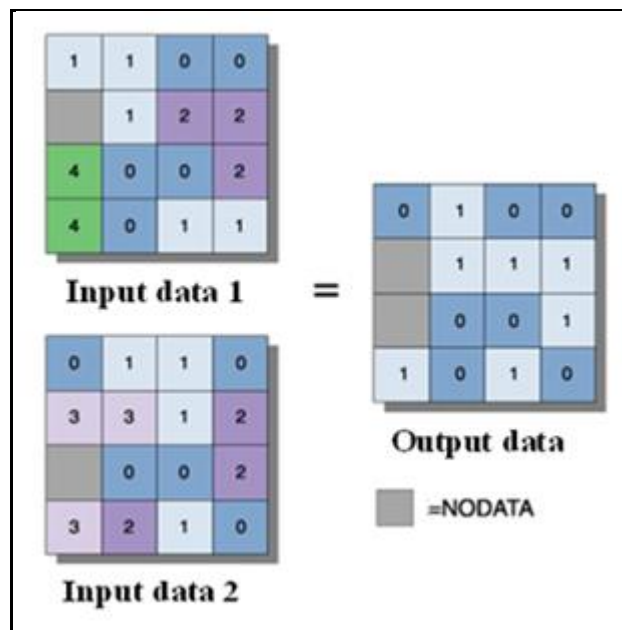
Figure 3-1: Boolean Intersections (AND)

3.1.2   Boolean union (OR)

If one or both values are true or nonzero values, the output is one. If both values are false or zero, the output is zero (*Figure 3-2*). In this case the output equal zero only if all values are false or zero, otherwise the output will be one.

Input1 $\neq$ 0, Input2 $\neq$ 0, Output   1
Input1 $\neq$ 0, Input2 = 0, Output   1
Input1 = 0, Input2 $\neq$ 0, Output   1
Input1 = 0, Input2 = 0, Output   0

If either of the inputs is No data, the output is No data.
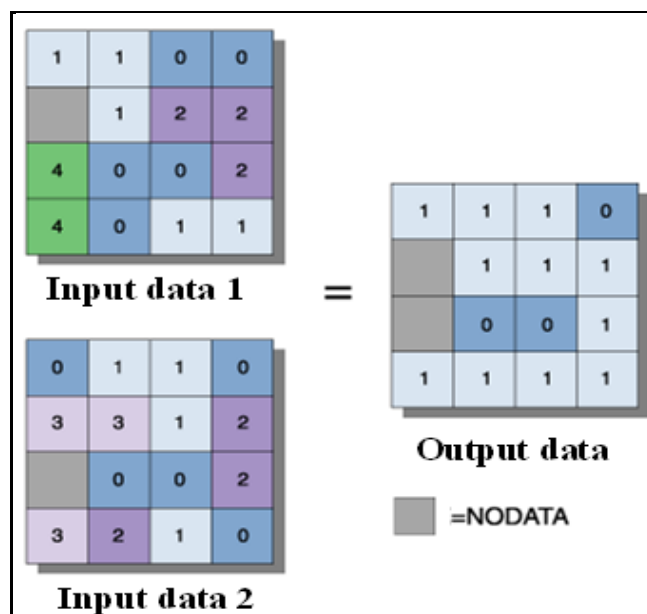
Figure 3-2: *Boolean union (Or)*

3.1.3   Boolean (NOT)

If the value is true or nonzero value, the output is zero. If the value is false or zero the output is one (*Figure 3-3*).

Input1 $\neq$ 0, Output = 0

Input1 = 0, Output =1

If the value is No data, the output value is No data.
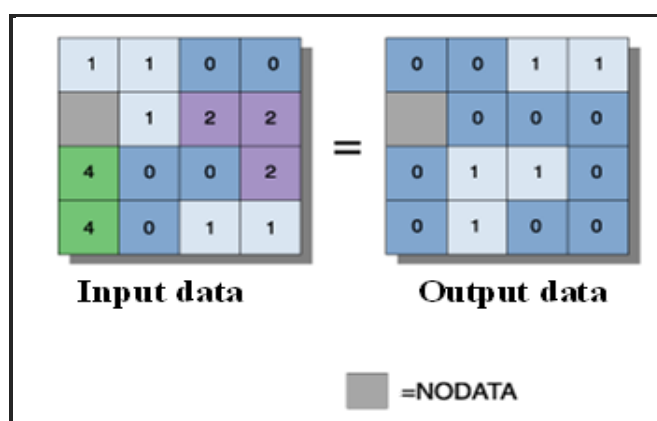
Figure 3-3: *Boolean Inverse (Not)*

3.2 Fuzzy Logic Theory

Fuzzy logic was originally proposed by Zadeh in 1965 to deal with uncertain and imprecise data. Fuzzy logic theory was presented as alternative approach to situations where zones of gradual transition are used to divide classes instead of the conventional crisp boundaries (Burrough, MacMillan, et al., 1992). The concept of fuzzy logic was defined by (Zadeh, 1965) as "a class of objects with continuum of grades of memberships"; the membership function values assigned to each object   are ranging between 0 and 1, the higher the grade of membership the closest class value to 1.

Basically, fuzzy logic is an extension of conventional Boolean logic that was introduced to handle the concept of partial truth between completely true and completely false (Ziadat, 2007). Thus fuzzy logic can be thought of as providing a means for representing uncertainties. Fuzzy logic models called fuzzy inference systems consist of a number of conditional linguistic *if-then* rules that depend on fuzzy set theory to model the uncertainty of natural language. This technique can be formulated mathematically and processed using computers (Rustum, 2009).

Land evaluation deals with many factors that are continuous in nature, like soil characteristics, and climatic parameters. The basic soil characteristics used for land evaluation to distinguish between the classes is mostly described using some vague linguistic terms such as "deep soil", "poorly drained", "fine texture", etc., (Burrough, 1989). Using Boole's logic it is impossible to model such vagueness. The use of fuzzy logic operations makes it possible to improve analysis and simplification of the soil characteristics in most precise representation of such vague information (McBratney et al 1997). Fuzzy logic has been applied to land evaluation in order to deal with such ambiguity and vagueness and to handle inexactness.

There are several essential points distinguishing the use of Fuzzy logic approach in various uses:

- Fuzzy logic is based on natural language built on the structures of qualitative description used in everyday language

- Fuzzy logic is flexible. With any given system, it is easy to use more functions without starting again from scratch. Since each stage of the system is processed individually.

- Fuzzy logic can model nonlinear functions of arbitrary complexity. Fuzzy logic can be created to match any set of input-output data.

- Fuzzy logic allows decision making with estimated values under incomplete or uncertain information.

- Fuzzy logic can be blended with conventional techniques. Fuzzy systems do not necessarily replace conventional approaches, rather in many cases fuzzy systems enhance them and simplify their implementation (Chennakesava, 2008).

3.2.1 Fuzzy Sets

Fuzzy logic starts with the concept of a fuzzy set. A *fuzzy set* characterizes classes without a crisp, clearly defined boundary in which the transition from one set to another is gradual rather than abrupt. It can contain elements with a partial degree of membership that rang in value between 0 and 1. In contrast to Boolean sets theory, the membership of sets is defined as 1 or 0. However, membership of a fuzzy sets are defined by the membership functions (MFs) in which represent a continuous increase from non-membership 0 to complete membership 1 (Zadeh, 2008).

Figure (3.4) presents a comparison of conventional Boolean sets and fuzzy sets. While with Boolean logic the boundary between sets is sharply defined (0 or 1), with fuzzy logic there is a transition zone where each set has membership grade less than 1.
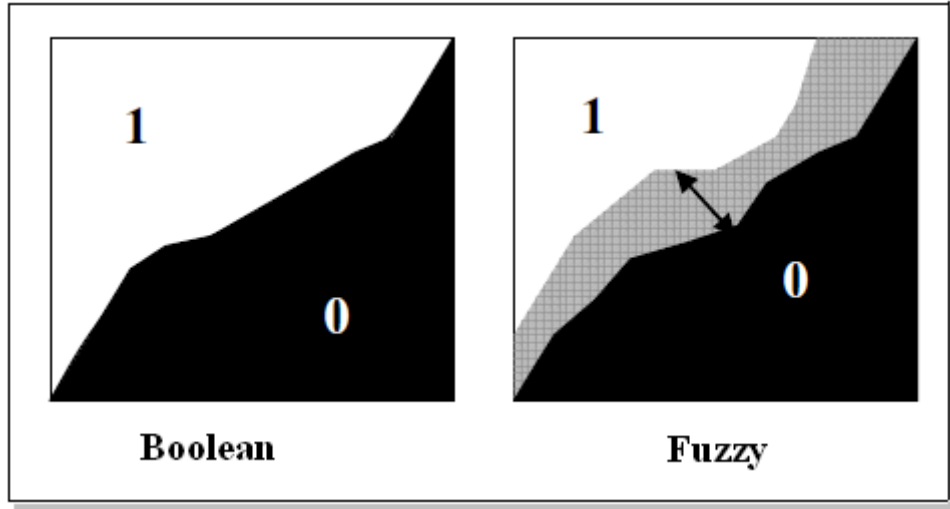
Figure 3-4*: Representation of Boolean and fuzzy sets* (*Moreno, 2007*)

To understand how a fuzzy set works it is useful to start with one of the most commonly used examples of a fuzzy set which is the set of tall people (Rustum, 2009). Mathematically, a classic set can be defined as:

$$X = \{(x_1, x_2, \ldots, x_n) : x_n \in X\} \tag{3.1}$$

where x_n refers to all the possible tall values (cm) of an adult person. A classical crisp set C_{tall} of X is defined as a function μ called characteristic function of C_{tall} as in Equation 3.2. For any element x of the universe X, the characteristic function μ is equal to 1 if x is an element of set X, and is equal to 0 if x is not an element of X.

$$\mu_{tall}(x) = \begin{cases} 1 & if \quad x \;\; is \;\; l\arg er \;\; than \;\; 180cm \\ 0 & otherwise \end{cases} \tag{3.2}$$

Just as tall, another two similar crisp sets $C_{average}$ and C_{short} can be defined as in Equations 3.3 and 3.4 respectively:

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$$\mu_{aver.}(x) = \begin{cases} 1 & \text{if} \quad x \quad \text{is} \quad \text{between} \quad 160cm \quad \text{and} \quad 180cm \\ 0 & \text{otherwise} \end{cases} \qquad (3.3)$$

$$\mu_{short}(x) = \begin{cases} 1 & \text{if} \quad x \quad \text{is} \quad \text{less} \quad \text{than} \quad 160cm \\ 0 & \text{otherwise} \end{cases} \qquad (3.4)$$

One problem arises in the definition of linguistic term "*tall*". For instance, the above description of crisp sets indicates that a person whose length is equal or greater than 180 cm is considered to be (tall *man*). However, a 179.99 cm-person is considered to be "*not tall*". In contrast to a crisp set above, a fuzzy set is a set without such sharp boundaries. The membership function of a fuzzy set is allowed to have values between 0 and 1, and it expresses the degree in which an element belongs to a given fuzzy set. This transition makes fuzzy sets more flexible and credible.

By using the same example as above, new fuzzy sets F_{tall}, $F_{average}$, and F_{Short} of X can be defined as in Equations 3.5, 3.6 and 3.7 respectively.

$$F_{tall} = \{(x, \mu F_{tall}(x)\}, x \in X \qquad (3.5)$$

$$F_{aver} = \{(x, \mu F_{aver}(x)\}, x \in X \qquad (3.6)$$

$$F_{short} = \{(x, \mu F_{short}(x)\}, x \in X \qquad (3.7)$$

where μF is the membership function (MF) that defines the grade of MF of x in F. The membership function $\mu F(x)$ takes values between and including 0 and 1 for all F, according to the degree of membership. The difference between fuzzy and crisp definition of tall can be better illustrated using Figure (3.5). For example, if a person is 170 cm tall then the membership degree for the fuzzy subset tall is

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about 0.6. At the same time, the membership degree for the fuzzy subset short equals to 0, and the membership degree for fuzzy subset average is equal to 1.
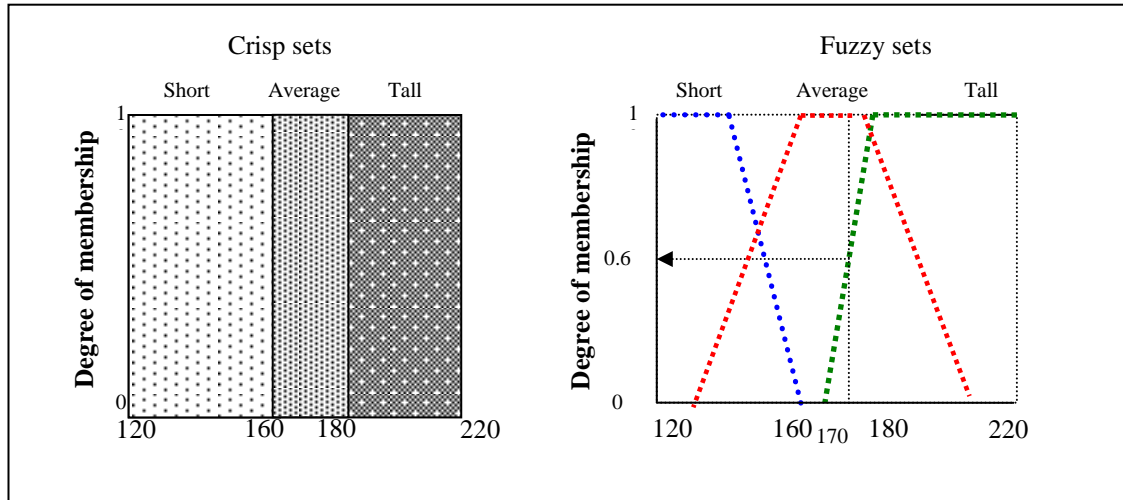
Figure 3-5*: Example of typical crisp sets (left) and typical fuzzy sets (right) characterising the human tall values (cm)*

(*Adapted* from Rustum, 2009)

The membership function can take any shape and can be symmetrical or asymmetrical. The most common membership functions are *triangular*, *trapezoidal* and *Gaussian* (MATLAB Fuzzy Logic Toolbox™ User's Guide, 2009). The simplest is the *triangular* membership function, and it has the function name *trimf*. The *triangular* curve is a function of three parameters expressed in a three points forming a triangle (*Figure 3-6*). The *trapezoidal* curve is a function of four parameters *trapmf*, and it has a flat top (*Figure 3-7*). These straight line membership functions have the advantage of simplicity.

The triangular curve is a function of a vector, x, and depends on three scalar parameters **a**, **b**, and **c**, as given by Equation 3.8.

$$f(x;a,b,c) = \begin{cases} 0, & x \leq a \\ \dfrac{x-a}{b-a}, & a \leq x \leq b \\ \dfrac{c-x}{c-b}, & b \leq x \leq c \\ 0, & c \leq x \end{cases}$$

(3.8)

Where the parameters a and c locate the "feet" of the triangle and the parameter b locates the peak (*Figure 3-7*).

$$trimf = f(x;3,6,8)$$
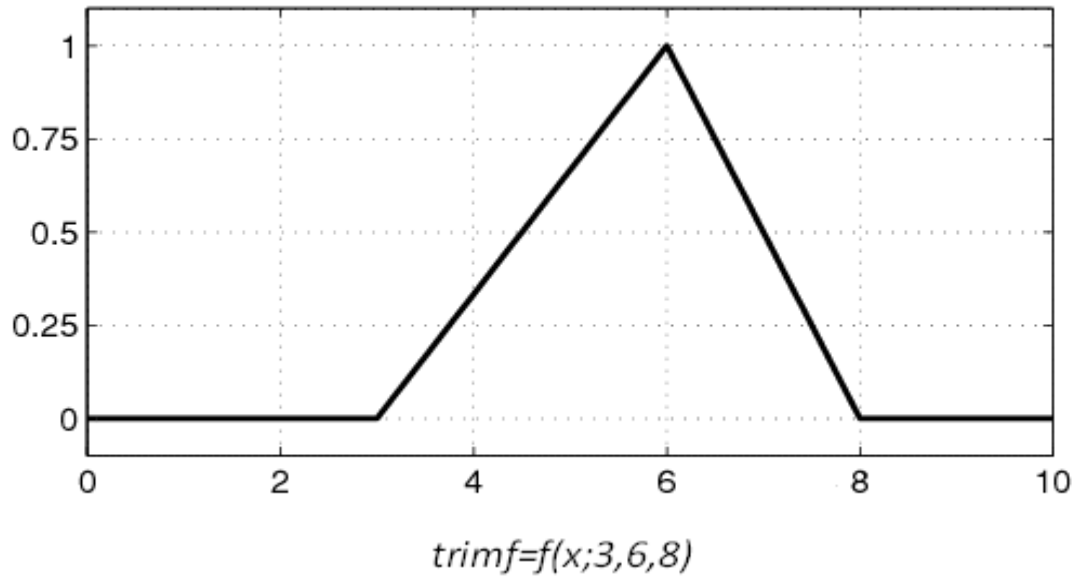
Figure 3-6: Triangular Membership Function (trimf)

The trapezoidal curve is a function of a vector, x, and depends on four scalar parameters a, b, c, and d, as given by Equation 3.9.

$$f(x;a,b,c,d) = \begin{cases} 0, & x \leq a \\ \dfrac{x-a}{b-a}, & a \leq x \leq b \\ 1, & b \leq x \leq c \\ \dfrac{d-x}{d-c}, & c \leq x \leq d \\ 0, & d \leq x \end{cases}$$

(3.9)

The parameters *a* and *d* locate the "feet" of the trapezoid and the parameters *b* and *c* locate the "shoulders."

$$trapmf=f(x;1,5,7,8)$$
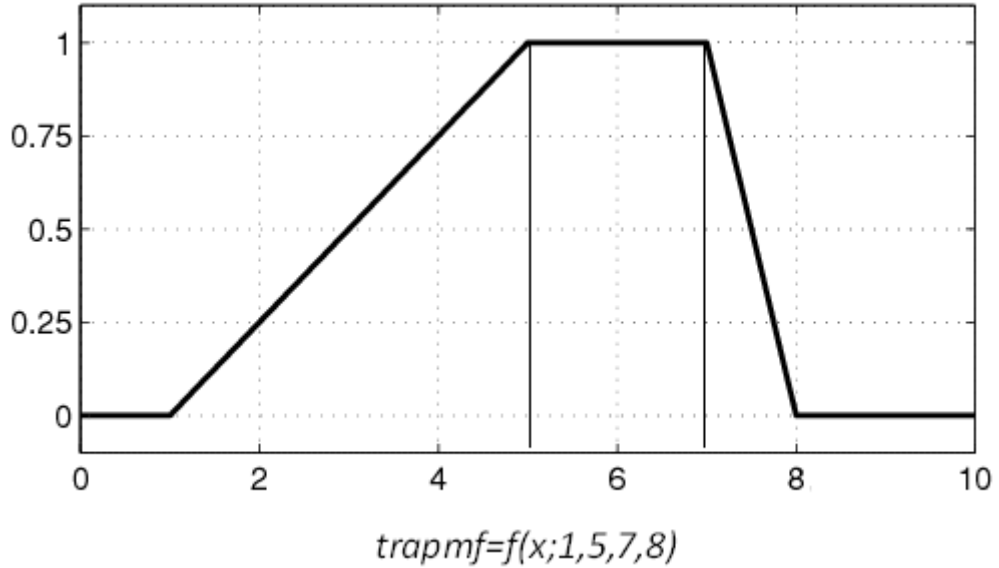
Figure 3-7: *Trapezoidal Membership Function (trapmf)*

The other common shapes of membership functions are *Gaussian* and *generalized bell*. The *Gaussian* distribution curve function is specified by two parameters, the mean (*c*) and the standard deviation (σ). The mean identifies the position of the center and the standard deviation determines the height and width of the bell. For example, a large standard deviation creates a bell that is short and wide while a small standard deviation creates a tall and narrow curve (*Figure 3-8*). The *Gaussian* distribution curve function has function name *gaussmf*.

The symmetric Gaussian function depends on two parameters σ and *c* as given by Equation 3.10.

$$f(x;\sigma,c) = e^{\frac{-(x-c)^2}{2\sigma^2}}$$

(3.10)

gaussmf=f(x,5,2)
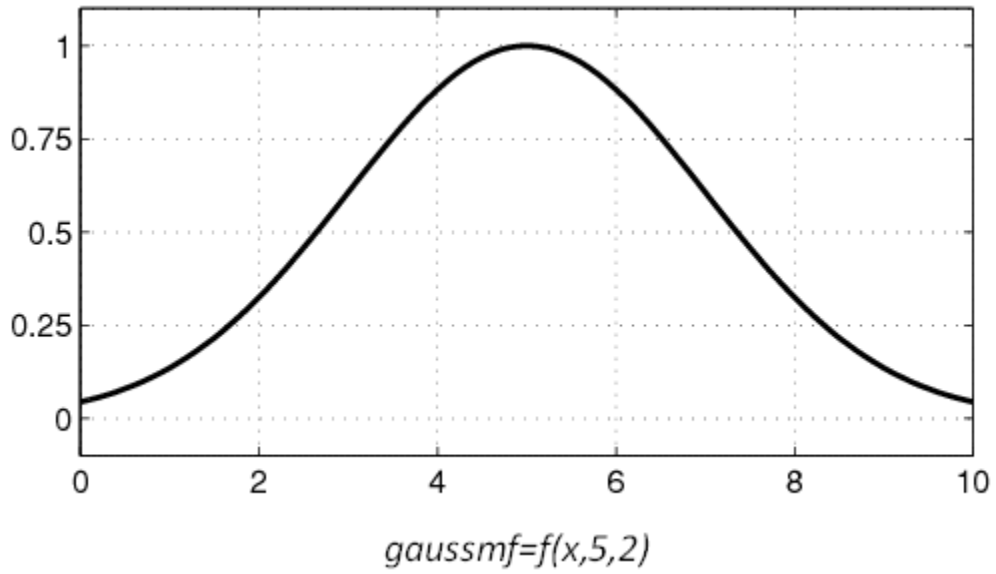
Figure 3-8: *Gaussian Membership Function (gaussmf)*

The *generalized bell* membership function is specified by three parameters and has the function name *gbellmf*. The bell membership function has one more parameter than the Gaussian membership function, Gaussian and bell membership functions are popular methods for specifying fuzzy sets. Both of these curves have the advantage of being smooth at all points (Fuzzy Logic Toolbox™ User's Guide, 2009).

The generalized bell function depends on three parameters *a*, *b*, and *c* as given by Equation 3.11.

$$f(x; a, b, c) = \frac{1}{1 + \left| \frac{x - c}{a} \right|^{2b}}$$

(3.11)

where the parameters *a* and *b* vary the width of the curve and the parameter *c* locates the center of the curve (*Figure 3-9*).

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The parameters *a*, *b*, and *c* give:

a = controls the width of the curve at f(x) = 0.5;

f(c-a) = f(c+a) = 0.5

b = controls the slope of the curve at x = c-a and x = c+a;

f'(c-a) = b/2a and f'(c+a) = -b/2a

c = the center of the curve

gbellmf=f(x;2,4,6)
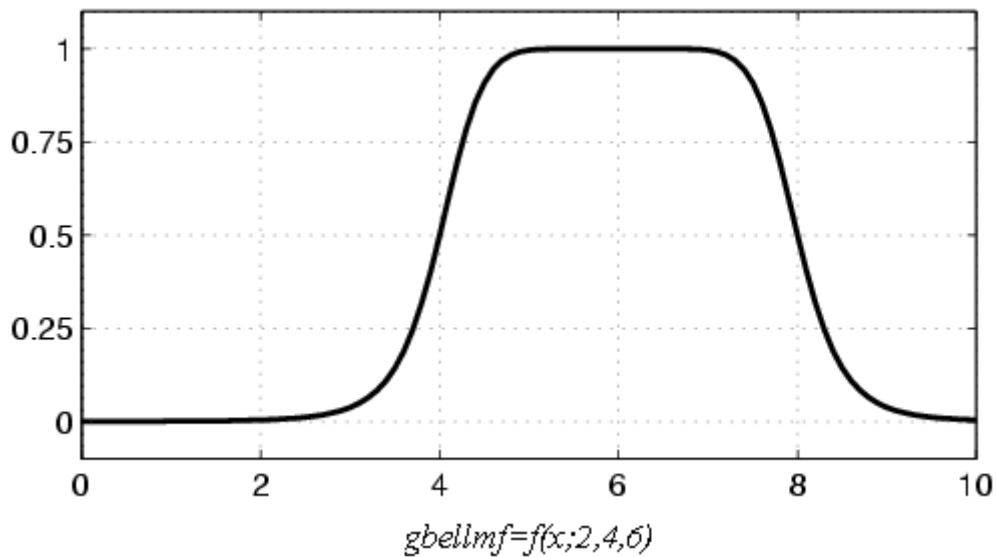
Figure 3-9: *Generalized bell member function*

The shape of the membership function to use in a given application is often determined by the number of threshold values which will form the boundaries of suitability classes for each parameter. For example, if the parameter has 3 critical values according to the threshold values for each suitability class such as (50 100 150), the triangular membership function can be the best to describe the situation. If the parameter has 4 critical values such as (50 100 120 200) the trapezoidal membership function can be the best to use.

3.2.2 Fuzzy Logic Process

Fuzzy logic system (FLS) is a rule based system in which the operation of a fuzzy logic model proceeds in three steps as shown in *Figure 3-10*. The first step is *fuzzfication* where measurements are converted into memberships in the fuzzy sets (converted from crisp number to a fuzzy value). The second step is the application of the linguistic model, usually in the form of *if-then* rules. Finally the resulting fuzzy output is converted back into crisp values through a *defuzzfication* process (Ross, 2004).
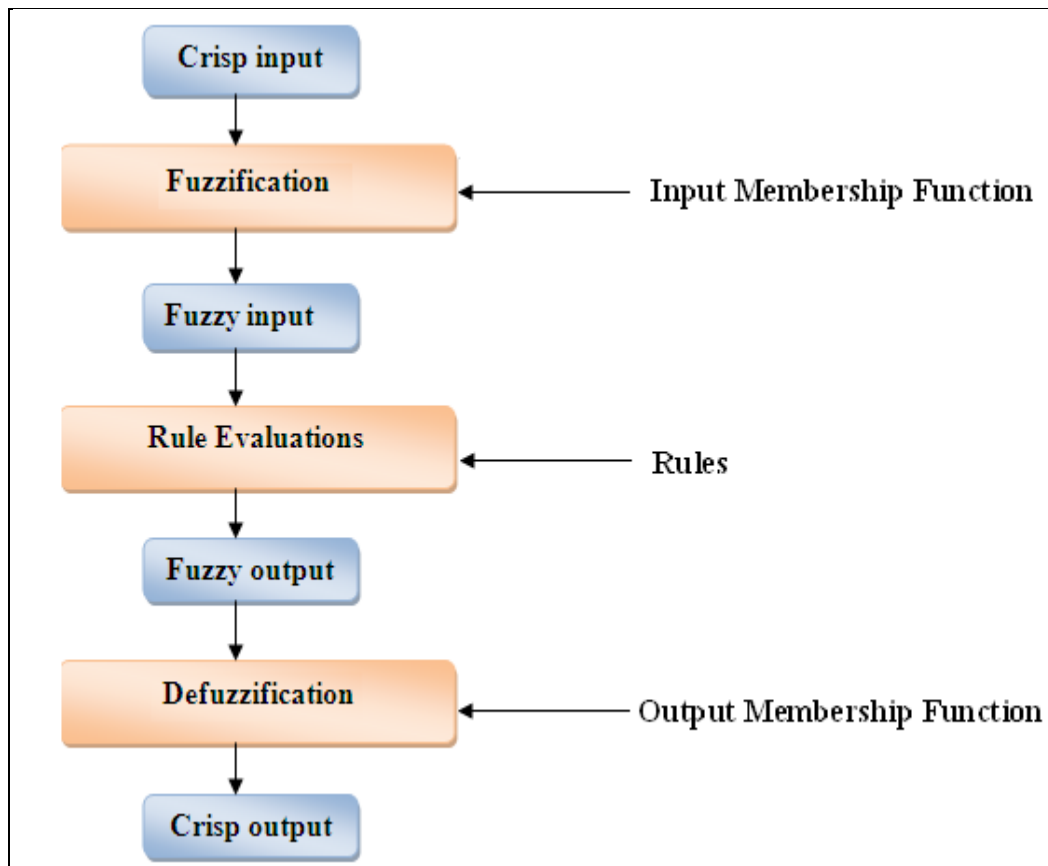
Figure 3-10: *The Process of Fuzzy Logic Model*

A brief explanation of the steps of fuzzy logic system in general is presented in the next subsections.

3.2.2.1   Fuzzification

In the fuzzification stage the membership degree of each input is determined. The input empirical values are processed in this stage and converted into linguistic variables (e.g. high, moderate and low) and the threshold values for the variables are determined. The proper membership functions are selected based on the specified threshold values for each variable or input. The outputs of this layer are fuzzy membership degree of the inputs given values between 0 and 1 for each of the linguistic variables (Joss, Hall, et al., 2008). As explained earlier, different membership functions can be used such as *triangular*, *trapezoidal* and *Gaussian*. The choice of the appropriate function depends on the number of critical values for each input and the influence of the function on the output. The accuracy of the model can be tested manually by changing the values of the parameters in rule viewer in the model. For example by increasing the value of soil salinity should be the degree of land suitability is decreasing.

3.2.2.2   Fuzzy Rules Inference

 The second step in the fuzzy logic modelling process is the definition of the rules. These rules represent the conclusion of integrating the linguistic variables to derive the required output. The rules can be designed to show the increasing importance of some of the attributes. These rules are based on conditional statements IF-part and a conclusion THEN-part. The IF- part may include more than one condition linked together by linguistic conjunction such as AND and OR (Bardossy, 1996, Reshmidevi, Eldho, et al., 2009). A fuzzy rule can have multiple antecedents, for example:

IF (traffic is light **AND** weather is good) **THEN** (travel time is short)

There are a number of factors that can influence the design and the implementation of fuzzy rules. These factors are the selection of input and output variables, the generation methods of fuzzy rules and the implementation method on fuzzy rules (Rustum, 2009):

i) *The selection of input variables*

The selection of input variables affects the number of rules and the performance of the FLS. The selection of these variables depends on experience on one hand and the relation between these inputs and the desired output on the other. The number of rules increases according to the increase in the number of input variables and the number of membership functions. The possible number of rules can be calculated using Equation 3.12 (Chopra, Mitra, et al., 2005). For example, in a two-inputs with 3 membership functions for each input, the possible rules are $3^2 = 9$, and if the number of inputs are increased, this number will quickly increase. To overcome this problem, the user may want to put constraints on the type of fuzzy model (e.g., number of membership functions and inputs) (Chopra, Mitra, et al., 2005) .

$$N = mf^x \qquad\qquad\qquad\qquad (3.12)$$

where, N is the number of rules, x is the number of inputs and mf is the number of membership functions.

ii) *Generation method of fuzzy rules*

There are two methods to derive fuzzy rules. The first method is to generate fuzzy rules based on prior experience. In this method, the expert put his experience as a linguistic relation between input and output variables of the FLS. The second method is based on the observed input-output data (MATLAB, 2009). For example, convert a training data to fuzzy rules.

iii) *Implementation method of fuzzy rules*

Fuzzy implication rule describes how several logic formulas involving linguistic variables are combined together. The combination can be achieved in many ways, all of which are derived from three fundamental operations, conjunction (AND), disjunction (OR), negation (NOT), (MATLAB, 2009).

3.2.2.3   Defuzzification

The defuzzication is the last step in the fuzzy logic modelling process, which is the process of converting the degrees of membership of output linguistic variables into numerical values. In the defuzzification the outputs of all the rules combined to produce a crisp output. In other words, the fuzzy output is converted back to crisp value (Rustum, 2009).

The Centroid defuzzification method is one of the most popular defuzzification methods, and was developed by Sugeno in (1985). The procedure (also called center of area, center of gravity) measures the centre of area under the curve. (MATLAB., 2009, Ross and Mexico, 2004, Sujit and Keith, 2004) using:

$$z = \frac{\int z_i \mu_{zi}(z_i)dz}{\int \mu_{zi}(z_i)dz} \tag{3.13}$$

Where z is the center of area (crisp output), μ_{zi} is the fuzzy membership value at z_i.

Figure (3-11) shows the procedure of defuzzification of the aggregate outputs of all of the rules using the center of area defuzzification method to produce a crisp output. The figure shows the flow proceeds up from the inputs in the lower left, then across each row, or rule, and then down the rule outputs to finish in the lower right. This compact flow shows everything at once, from linguistic variable fuzzification all the way through defuzzification of the aggregate output.
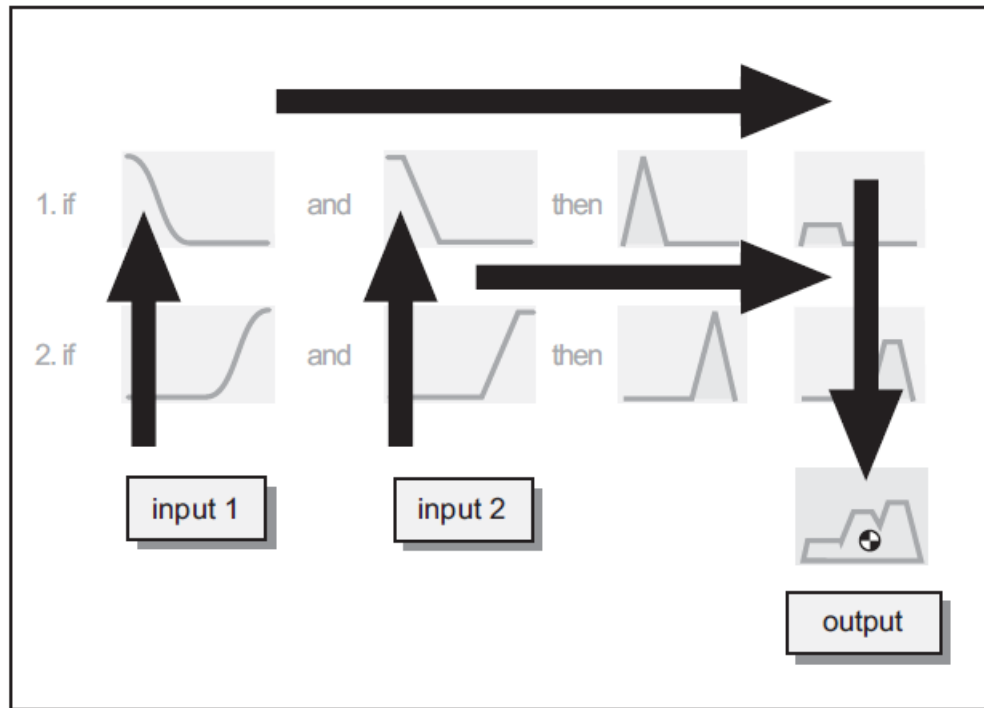
Figure 3-11: *The Process of Centroid Defuzzification Method*

*(**Adapted** from MATLAB Fuzzy Logic Toolbox™ User's Guide line, 2009)*

3.2.3   Types of Fuzzy Logic Systems

Depending on the structure of the *if-then* rules, two main types of fuzzy models can be distinguished: The Mamdani model (Mamdani and Assilian, 1975) and Takagi-Sugeno model (Takagi and Sugeno, 1985). The differences between these two types of fuzzy rules appear in the consequence part of the rule. For the Mamdani fuzzy model both antecedent and consequent are fuzzy propositions. While with the Takagi-Sugeno fuzzy model, the antecedent is a fuzzy proposition but the consequent is a crisp function usually expressed as an equation (Babuška, 1998).

3.2.3.1   *Mamdani fuzzy model*

Ebrahim Mamdani in (1975) built one of the first fuzzy systems to control a steam engine and boiler combination. And the model is considered the most commonly used method in FLS technique**.** The Mamdani model is a type of fuzzy relational model where each rule is represented by an *if-then* relationship. It is also called a

linguistic model because both the antecedent (if-part of the rule) and the consequent (then-Part rule) are fuzzy propositions expressed as linguistic terms like high, moderate, low. In this model, the relationships between parameters are represented by means of *if-then* rules (Babuška, 1998). The size, the shape, and the parameters of these fuzzy regions are decided by experience and the fuzzy rules are generated based on human expert. The output from a Mamdani model is a fuzzy membership function based on the rules created. The disadvantages of the Mamdani model are that the number of fuzzy rules increases dramatically as the number of input variable increase. In such a strategy, if we have no a priori knowledge about the system, the structure of the model becomes a difficult task and we have to select the structure by a trial and error process (Rustum, 2009). An example of Mamdani rule is presented in Equation 3.14.

If Input 1 = x and Input 2 = y, then Output is z $\qquad\qquad$ (3.14)

where x , y and z are linguistic terms (such as high, moderate, low, etc) represented by fuzzy sets. The linguistic fuzzy model is useful for representing qualitative knowledge, for example:

If temperature is high and relative humidity is low then evapotranspiration is high

3.2.3.2   *Takagi-Sugeno model*

The other kind of the FLS technique is Takagi-Sugeno model**.** In this model**,** the antecedent is defined in the same way as in the Mamdani model, while the consequent part is a function of the input variables. A typical rule in a Sugeno fuzzy model has the form:

If Input 1 = x and Input 2 = y, then Output is $z = ax + by + c$ $\qquad$ (3.15)

Where x and y are term values for input 1 and input 2, z is the crisp output of the rule expressed as an equation, *a, b, c* are constants,

3.3   Applications of Boolean approach in Land Evaluation

Boolean logic has been used in GIS to produce maps based on if particular mapping units meet the defined requirements for proposed land use or cropping. Many studies based on Boolean theory have been conducted in the past for land suitability evaluation in different parts of the world for example: (IAO., 2004) in Tunisia, (Hoobler, Vance, et al., 2003) in the USA, (Ziadat, 2000), in Jordan, (Aldabaa, Zhang, et al., 2010) in Egypt and (Shahbazi, Jafarzadeh, et al., 2009) in Iran. Aldabaa et al. (2010) stated that soil evaluation system for 12 different types of crops indicated that the soils in Wadi El-Rayan Depression in Egypt are not suitable for the selected crops due to one or more limiting factors. This means that if one factor was assigned as S2 or moderately suitable, the overall suitability will not be high suitable.

These studies concluded that the use of a Boolean approach is very simple to apply for land evaluation analysis and it is possible to manage and trace which parameters are affecting the suitability of land. On the other hand there are several problems associated with this approach. The methodology assumes the biophysical phenomena are crisply delineated in both attribute and geographic space resulting in homogenous polygons with single attribute values (Burrough, 1989). However, soil and vegetation characteristics naturally are changing transitionally. As a result, the boundaries between soil landscape units should be in transition zones rather than sharp boundaries (Joss, Hall, et al., 2008). Thus, application of Boolean mapping approach in the FAO framework for land suitability has been criticized by a number of authors e.g. (Baja, Chapman, et al., 2002, Burrough, 1989, Davidson, Theocharopoulos, et al., 1994, Delgado, Aranda, et al., 2009, Hall, Wang, et al., 1992, Keshavarzi, Sarmadian, et al., 2010, McBratney and Odeh, 1997) because the Boolean representations ignore the continuous nature of soil, landscape variation and uncertainties in measurement. Each of these aspects can result in areas being excluded from the set of suitable land because they fail to match strictly defined requirements, when in reality they may be quite suitable.

The main weakness for Boolean logic is that the membership function (MF) value is expressed only as true or false i.e. 1 or 0, while on the ground the boundary between sets is not as sharply defined (Burrough, MacMillan, et al., 1992). Boolean logic takes no account of partial membership of an object in a set (Banai, 1993). There is therefore considerable uncertainty associated with the above mentioned approach for land evaluation exists. Due to this shortcoming there has been a great interest in the use of fuzzy logic in land evaluation in recent years to deal with these imprecision and uncertainties. Fuzzy modelling and its application to land evaluation are discussed in the next section.

3.4   Applications of Fuzzy approach in Land Evaluation

Fuzzy logic approach has been proposed as a method for overcoming problems related to ambiguity in definition and other uncertainties. The use of fuzzy logic approach in land suitability evaluation allows imprecise representations of vague, incomplete and uncertain information. Fuzzy land evaluations define continuous suitability classes rather than "true" or "false" as in the Boolean model. Fuzzy logic methodologies have the potential to provide better land evaluations compared to Boolean approaches because they are able to accommodate attribute values and properties which are close to category boundaries (Elaalem, Comber, et al., 2011).

The use of fuzzy logic approach for the assessment of land suitability for agricultural crops was first introduced by Burrough (1989, who noted that the soil information being used as inputs to land suitability evaluations were mainly defined by imprecise terms such as 'moderate nutrient availability', 'poorly drained' and etc. These were used to determine a number of clearly defined boundaries between land suitability classes. Different fuzzy set models have been used to determine membership functions values (MFs). Applying fuzzy logic for values of soil characteristics will decrease the ambiguity in definition of boundaries between soil map units, because each value will meet its appropriate membership function.

Burrough (1989) presented two kinds 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 choice of symmetric or asymmetric model depend on the trend of performance of the respective land attribute in accommodating a favourable condition for a select land use type (Baja, Chapman, et al., 2002). Different equations have been presented to determine membership functions of symmetrical and asymmetrical models (e.g. Burrough, 1989; Davidson et al., 1994; McBratney and Odeh, 1997; Baja et al., 2001; Moreno, 2007). These membership functions and their equations are presented in the next subsections:

The symmetric model is used where the attribute of land has two critical points. As an example the optimum level of soil pH for growing crops is specified in the range between 6 and 8 which mean PH values less than 6 (lower crossover points *LCP*) or upper than 8 (upper crossover point *UCP*) are considered not suitable (*Figure 3-12*).
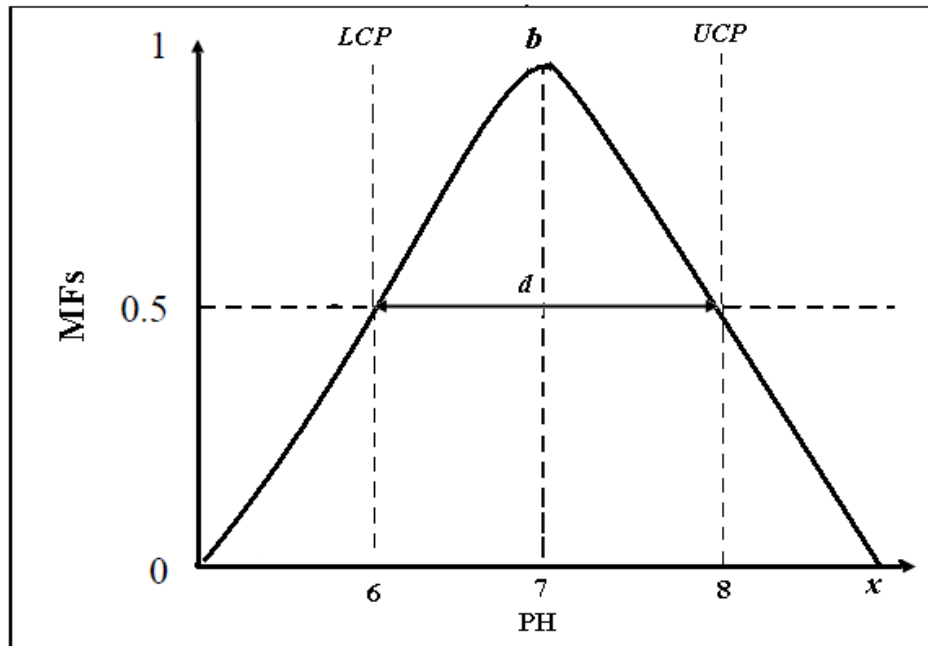
Figure 3-12: *Symmetric fuzzy model*

(*Adapted from Baja, et al*, 2001)

The membership function of symmetrical model can be calculated using Equation 3.16 (Burrough, 1989):

$$MF_x = \frac{1}{[1+\{(x-b)/d\}^2]} \tag{3.16}$$

Where MF_x is a membership function of land characteristic x, b defines the value of the characteristic x at the central concept or ideal point and d is the *width* of transition zone.

The asymmetric fuzzy set model has two kinds of functions (asymmetric left and asymmetric right model). The asymmetric model has been used where only the lower and upper boundaries of a category have practical importance. For example, land attribute such as soil depth takes an asymmetric left function. An optimum soil depth for barley crop was set at 80 cm or more (adapted from Sys, 1995), while, the *LCP* threshold value was specified at 50 cm or less (*Figure 3-13*).
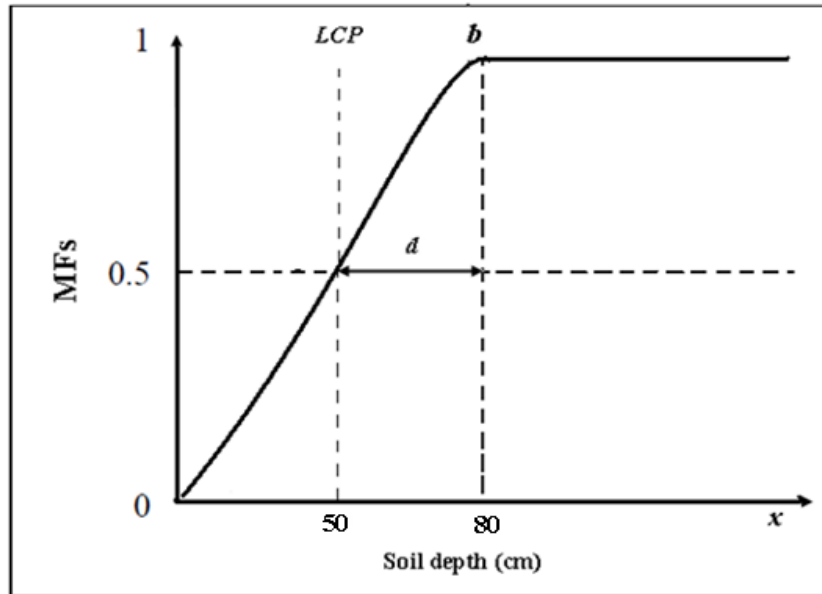
Figure 3-13: *Asymmetric left model*

(*Adapted from Baja, et al*, 2001)

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The asymmetrical left model can be calculated using Equation 3.17 (Burrough, 1989, Davidson, Theocharopoulos, et al., 1994):

$$MF_x = \frac{1}{1+\frac{1}{d^2}(x-b)^2} \qquad \begin{cases} 1 \ if \ x \ \geq b \\ 0 \ otherwise \end{cases} \qquad (3.17)$$

The asymmetric right function is the other kind of asymmetric model. An example, the salinity of soil takes asymmetric right function. An optimum salinity for barley is 8 ds/m or less, while the *UCP* threshold value is 13 ds/m (*Figure 3-14*). So it is not important to know how much the salinity levels are less than the optimum level, but it is necessary to know whether the value exceeds that level due to their impact on the degree of land suitability for agricultural use.
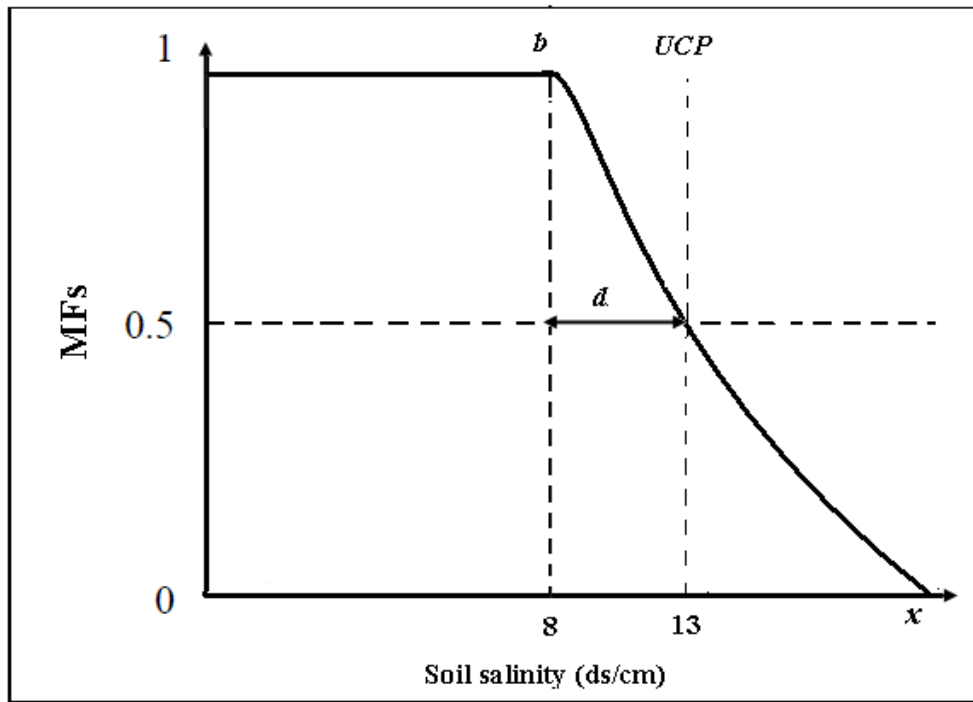
Figure 3-14 *Asymmetric right model*

(*Adapted from Baji, et al*, 2006)

The asymmetrical right model can be calculated using Equation 3.18 (Burrough, 1989, Davidson, Theocharopoulos, et al., 1994):

$$MF_x = \frac{1}{1+\frac{1}{d^2}(x+b)^2} \qquad \begin{cases} 1 \; if \; x = b \\ 0 \; otherwise \end{cases} \qquad (3.18)$$

Many studies have applied fuzzy logic modelling to assess agriculture land suitability. Change and Burrough (1987) employed fuzzy logic methodology to define the land suitability to grow Apple in the northeast of China. Burrough et al (1992) applied fuzzy logic modelling to determine land suitability for different agriculture uses. Burrough (1992) stated that fuzzy logic methodology was much more satisfactory in producing suitability classification than methods based on Boolean. (Van Ranst, Tang, et al., 1996) classified soil properties, climate and topography using fuzzy logic to determine the influence of land qualities on rubber production in Thailand. Braimoh et al (2004) applied fuzzy logic modelling to assess land suitability for growing maize in Ghana and demonstrated that a high correlation ($R^2 = 0.87$) exists between land suitability indices for growing maize and observed maize yield (Braimoh, Vlek, et al., 2004). Reshmidevi et al (2009) presented a GIS-integrated fuzzy rule-based inference system for land suitability evaluation based on soil properties and the availability of surface water for irrigation. A fuzzy rule-base is developed using the farmer's knowledge and local experts. Sarmadian et al., (2010) used fuzzy approach and Boolean approach in form of parametric method to determine the land suitability classes for irrigated wheat field in Takestan in Iran. The results indicate that the correlation coefficient between land suitability classes and observed yield were 0.91 and 0.85 for the fuzzy approach and parametric approach respectively. Similar results were obtained by Van Ranst et al. (1996) in Thailand, which found the correlation coefficient between land suitability assessment for rubber and observed yield were 0.89 for fuzzy method and 0.81 for Boolean method.

All these studies have demonstrated the superiority of the fuzzy approach over the Boolean logic in land evaluation. The studies have concluded that the main limitation in the application of Boolean logic to land evaluation is the assumption

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.

3.5   Summary

The main context of the chapter is an overview of the basics of Boolean and Fuzzy approaches and the integration of these approaches with GIS in land suitability evaluation. In addition, the advantages and disadvantages of employing Boolean and fuzzy approaches in land evaluation are discussed.

This research will address the possibilities of the Boolean and Fuzzy methods for addressing the uncertainties in the process of land suitability evaluation for a number of agricultural crops. The Fuzzy logic will be compared with Boolean logic in the north-western region of Libya as the case study for this research. The next chapter will present brief description of the study area, as well as land resources including: Soil resources, climate, water recourses and natural vegetation.

Chapter 4

RESEARCH APPROACH

4.1 Land Evaluation Approach

As mentioned in Chapter 2, the FAO framework for land evaluation is selected for evaluation land suitability in the study area. The rationale governing the selection of the FAO approach has been critically assessed in Chapter 2. The FAO framework is an approach for land suitability evaluation, which classifies land in terms of suitability ratings from highly suitable to not suitable. The assessment of land performance is based on its physical suitability for the proposed land utilisation types. This will provide estimates of the maximum available suitable area for each type. The approach involves the implementation and interpretation of basic surveys of soils, climate and terrain properties (Ziadat, Wadaey, et al., 2011).

The FAO framework for land evaluation is just a set of guidelines and they are not strict instruction manuals. However, evaluators have to select land characteristics and qualities, which fit their requirements, which are different from one environment to another. Therefore, computer systems used in different environments and different sets of data may not be used for other sets of data and conditions (FAO 2007). As a result, a number of computer systems have been used to develop land evaluation methods in several regions of the world e.g ALES, LECS, ISLE, LEIGIS and LUSET as reviewed earlier.

The basic requirements of applying the FAO framework are the selection and definition of land utilisation types for which the land is to be evaluated. The requirements of the land utilisation types are compared with the land resources. In this process, land resources are described as land qualities and land characteristics. In

the following sections, land utilisation types and land use requirements for the study area are identified.

4.2   Defining Land Utilisation Types (LUTs)

The land utilisation types (LUTs) are kind of land use described or defined in more detail according to a set of technical specifications in a given physical, economic and social setting. The selection of land utilisation types is one of the basic requirements of applying the FAO Framework for land evaluation (FAO, 1976, FAO, 1983).

There is no structured methodology to select LUTs for a certain area. (FAO, 1985) offered outline method can be used for description of most agricultural land utilisation types. The guidelines offered are the different factors that determine alternative land uses, namely: existing land use, the prevailing rainfall and other climate elements, soil characteristics, the wishes and preferences of farms and other social and economic conditions necessary for their success (Ziadat, 2000).

4.3   Selection of Land Utilisation Types (LUTs)

There are a number of constraints that should be taken into account regarding the use of land in the study area, when new land utilization types are proposed. The most important of these are: low rainfall, high rainfall variability, soil conditions and social and economic acceptability. The low rainfall within the study area restricts the productivity of crops under rainfed cultivation. Therefore, specific management practices have to be introduced to improve the productivity in the area and the management of water resources is one of the most important practices. Many technologies to improve water productivity and the management of scarce water resources can be implemented in the study area. Among these technologies are: (i) supplemental irrigation for optimizing use in rainfed, and (ii) water harvesting for improved farmer income in drier environment (Oweis and Hachum, 2006).

According to research results conducted in Libya from the International Center of Agricultural Research in the Dry Areas (ICARDA., 2009), the results showed substantial increases in crop yield in response to the application of relatively small

amounts of irrigation water. Several barley genotypes were irrigated at different levels to replenish 33, 66, and 100% of the soil moisture deficit in the crop root zone in an area under a Mediterranean climate with total rainfall of 186mm. The mean grain yield (in t/ha) for the barley genotypes was 0.26 t/ha (rain-fed), 1.89 t/ha (33% SI), 4.25 t/ha (66% SI), and 5.17 t/ha (100% SI) (ICARDA, 2009). This increase covers areas with low as well as high annual rainfall. This depends on meeting the crop water requirements in critical stages of growth.

Supplemental irrigation is an option with high potential for increasing water productivity in rainfed areas. Scarce water, now used for full irrigation, could be reallocated to supplement dry farming for improved water productivity. However, to maximize the benefits of supplemental irrigation other inputs and cultural practices must also be optimized such as suitable crop varieties, sowing dates, soil fertility management, weed control, pests and diseases control. Water harvesting project in Libya is a research project undertaken by the Agricultural Research Center in Libya (ARC) in cooperation with ICARDA. The main objective of the project is improved agricultural and rainwater productivity in the costal zones of Libya through integrating appropriate water harvesting techniques in the agricultural system (ICARDA., 2009). (Oweis and Hachum, 2006) state that water harvesting can significantly increase rainwater productivity in the drier marginal environments.

Wheat and barley are the most important cereal crops grown in Libya .Wheat is grown both under rainfed and irrigated conditions, while barley is largely grown under rainfed conditions. Despite efforts to increase cereal production in the country, local production does not meet consumption needs (see Table 5-4). Wheat is mostly imported, while barley is largely produced locally (ICARDA., 2009). Three land uilisation types were selected in the study area to accommodate three main crops, barley, wheat and olive under supplementary irrigation.

In the FAO framework the requirement of each land utilization type should be matched with the available land resources. In this matching process, land resources

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are described as land qualities. The reliability of land suitability evaluation is controlled by choosing the most limiting land characteristics and their ratings for the proposed land utilization types (LUTs) (Ziadat, Wadaey, et al., 2011).

4.4   Defining Land Characteristics (LC) and Land Qualities (LQ)

Land characteristics as mentioned in chapter 2 are attributes of land which can be measured or estimated in routine survey or by natural resource inventory and include soil depth, slope, soil salinity, soil reaction, soil texture, organic matter, etc. Land characteristics are generally used to describe land mapping units and give the direct meaning of land property. Land qualities are the result of interaction between a set of land characteristics which have a direct influence on land capability for specific use (FAO, 1976). Land qualities are derived from land characteristics. For example of land qualities is ʿ *nutrient retention'* which is an indication to soil fertility (influenced by organic matter O.M and cation exchange capacity CEC). The soils with high value of CEC and high percentage of organic matter, the higher fertility. They can be difficult to use land characteristics directly in land evaluation due to interactions between them and the fact that their numbers will be often large. Therefore land qualities are preferred to use in evaluation (Ziadat, 2000).

4.5   Selection of Land Characteristics (LC) and Land Qualities (LQ)

FAO, 1983 suggested a list of land qualities which should be considered for land suitability assessment (*Table 4-1*). Some of these land qualities are only applicable for certain crops or certain areas. In addition, some of these land qualities which are important in one environment may not be important in other environments (Beek, 1978). The selection of land qualities for land suitability classification is based on agronomic experience at research stations and existing farms in the study area. FAO, (1983) suggested that the selection of land qualities should be based on three criteria: i) the effect of these land qualities on the use of the land;ii) the availability of the critical values such as might adversely or favourably affect that crop or use occur in the study area; iii) the relative ease of collecting information about these land qualities. Based on these considerations, twelve land qualities and fourteen land

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characteristics were determined to be matched with the requirements of the land utilization type for each crop in the current study (*Table 4-2*). Brief description of these land qualities are presented in the next section.

Table 4-1: *List of land qualities for assessing land suitability (FAO, 1983)*

Land Qualities
1- Radiation Regime
2- Temperature Regime
3- Moisture Availability
4- Oxygen Conditions (soil drainage)
5- Nutrient Retention
6- Nutrient Availability
7- Rooting Conditions
8- Germination Conditions
9- Air Humidity as Affecting Growth Conditions
10- Condition for Ripening
11- Climate Hazards (frost, storm)
12- Excess of Salts (salinity, sodicity)
13- Soil Toxicities (calcium carbonate, gypsum)
14- Flood Hazard
15- Pests and Diseases
16- Soil Workability
17- Potential for Mechanization
18- Condition for Land Preparation or Clearance
19- Condition for Storage and Processing
20- Condition Affecting Timing of Production
21- Access Within the Production Unit
22- Size of Potential Management Units
23- Erosion Hazard
24- Soil Degradation Hazard

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Table 4-2: *The selected land qualities and characteristics for the study area*

Group	Land Qualities	Land Characteristics	Unit
Soil	Rooting Conditions	Rootable Depth	*mm*
	Texture	Soil Texture	Class
	Nutrient Availability	Soil Reaction	PH
	Nutrient Retention	Soil Organic Matter	%
		Cation Exchange Capacity	*Meq/100g*
	Excess of Salts	Soil Salinity	*dS/cm*
		Soil Alkalinity	%
	Soil Toxicities	Calcium Carbonate in Root Zone	%
	Conditions for Germinations	Gravel and Stones at surface	%
	Infiltration	Infiltration Rate	$mm\,hr^{-1}$
	Moisture Availability	Available Water Holding Capacity	*mm*
Climate	Length of Growing Period	Evapotranspiration	*mm/month*
		Rainfall	mm/month
Erosion	Erosion Hazard	Soil Erosion model (USLE)	$t\,ha^{-1}tyr^{-}$
Topography	Potential for Mechanization	Slope Steepness	%

4.5.1   Rooting conditions

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 available water holding capacity (Mayaki, Stone, et al., 1976). Plants need a satisfactory rooting condition in order to extract moisture and nutrients from the soil. (Stewart and Nielsen, 1990) stated that there is a significant decline in production of most crops when the soil depth is less than 30 cm. (GMRP., 2002) found the similar results from the experiments conducted in Tarhunah project in the

northwest of Libya in the experimental farm. The findings of the study confirmed that crops grown at a soil depth of less than 30 cm gave the lowest yield, while the production noticeably increased in soils with depths of more than 50 cm.

4.5.2   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, infiltration rate and soil fertility (Brady and Weil, 1999). Soil textures are classified according to soil particle size range (sand, silt, and clay) present in a soil. Classifications are typically named according to the prevailing type of particles size or a combination of the most abundant particles sizes, e.g. "sandy clay" or "silty clay." A fourth term, loam is used to describe a roughly equal content of sand, silt, and clay. Twelve major soil texture classifications are defined by the USDA. Soil textural triangle is often used to determine soil textural class from the percentages of sand, silt, and clay in the soil (*Figure 4-1*). Recently, there are many softwares developed based on soil texture triangle theory such as *Texture AutoLookup* (TAL, 2009). The program is an Excel add-in that works within a spreadsheet to determine the soil texture classes based on 4 soil classification schemes:

1. USDA (U.S. Dept. of Agric.)
2. UK (England and Wales)
3. Canadian
4. International
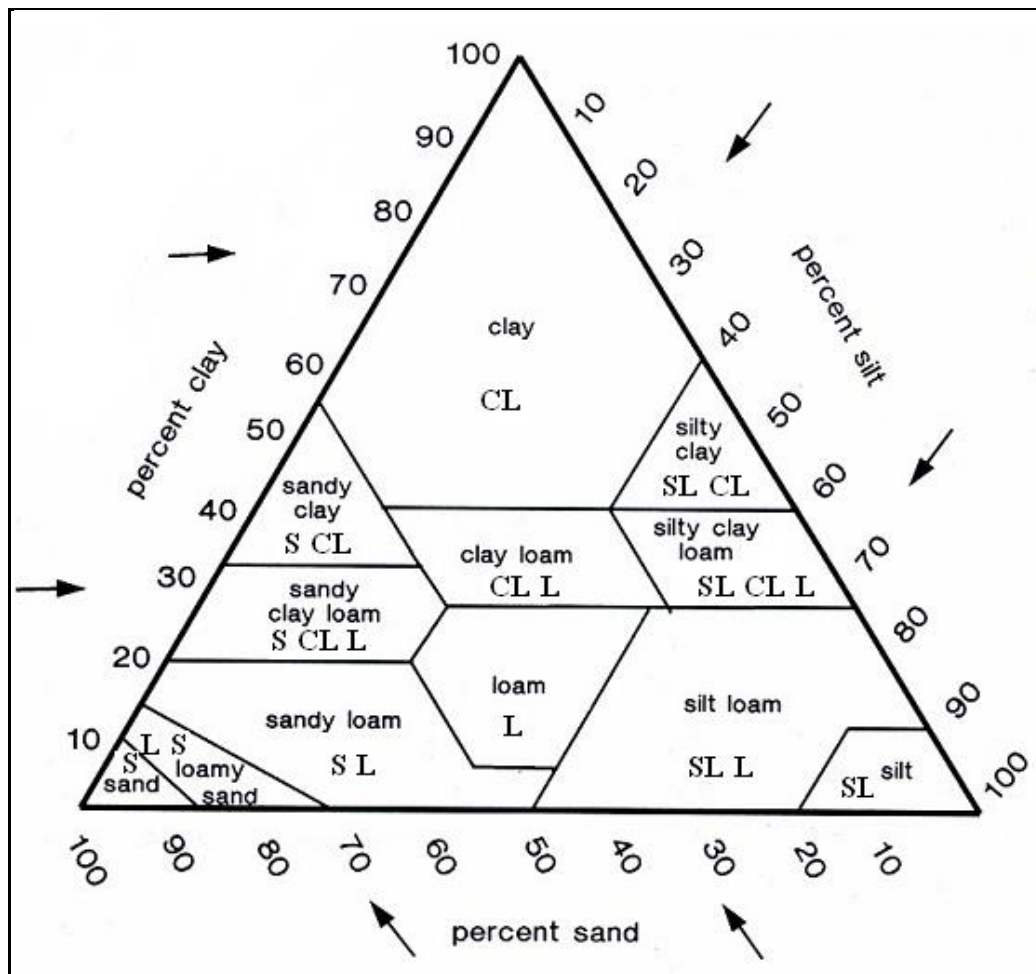
Figure 4-1: *Soil textural triangle*

Source :(USDA, 1961)

4.5.3 Available water holding capacity (AWHC)

AWHC is considered an important soil criterion in land suitability classification and planning for irrigation. AWHC gives an indication of the ability of the soil to provide moisture over a non-irrigated drought period. This capacity is influenced by soil texture and soil organic matter. Sand has low AWHC, while silt, clay and soils rich in organic matter have high values. Available water-holding capacity is defined as the amount of water retained between field capacity and the permanent wilting point (ILACO., 1989, Landon, 1984). (Calvino, Andrade, et al., 2003) stated that there is a

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strong correlation between yield and available water during the period bracketing flowering in cereal crops. Selkhozpromexport (1980) stated that AWHC values of more than 150 mm were considered the upper threshold value and AWHC values less than 75 mm the lower limit.

4.5.4   Nutrient availability (Soil reaction)

Nutrient availability can be assessed by measure soil reaction (Soil pH). Soil reaction is a very important parameter in land suitability classification. 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, 2004). The majority of plants prefer to grow in pH between 5 and 7.5, whereas soil pH below 5 adversely affects roots and their ability to absorb nutrients (Orzolek, 1991). If the pH is higher than 8.5 the soils are considered to be alkaline soils. This causes some essential nutrients such as magnesium (Mg) and calcium (Ca) to be unavailable. In addition, there is possible boron toxicity (ILACO., 1989)**.**

4.5.5   Nutrient retention

4.5.5.1   Soil organic matter

 This is a very important soil parameter and is considered the main source for nutrients in soil. Organic matter has both a direct and indirect effect on the availability of nutrients for plant growth. In addition to serving as a main source of nitrogen, phosphorus and sulphur, organic matter influences the supply of nutrients from other sources (for example, organic matter is required as an energy source for nitrogen-fixing bacteria).Soil organic matte increases the ability of the soil to resist erosion. It enables the soil to hold more water, and helps to maintain the aggregates of soils. Increasing organic matter in soils will increase the amount of water for plant

growth (Brady and Weil, 1999). In general, the soil in the study area is considered poor in its content of organic matter with maximum content 1.2%. This is due to low rainfall, high temperature and poor vegetation in the study area.

4.5.5.2   *Cation exchange capacity (CEC)*

The cation exchange capacity (CEC) is defined as the degree to which a soil can adsorb and exchange cations. CEC is used as indicator of soil fertility. Soils with a high value of CEC are considered fertile, and soils with a low value of CEC are considered infertile (Landon, 1984). CEC is highly dependent on soil texture and organic matter content. In general the more clay and organic matter in the soil, the higher the CEC. Clay content is important because these small particles have a high ration of surface area to volume (FAO, 1976). (Yahia, 1982) stated that soil with a CEC less than 4 milliequivalent per 100 gram soil (meq/ 100g) is unsuitable for irrigated agriculture and the CEC values of > 16 meq/ 100g soil can be considered as highly suitable for irrigated field crops.

4.5.6   *Excess of salts*
4.5.6.1   *Soil salinity*

Saline soils are those soils which have an electric conductivity (EC) of more than 2 DeciSiemens per meter (ds/m); 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, 1990). Salinity affects plants through inhibiting the absorption of water by osmosis. In addition, salinity can affect plant growth by increasing the concentration of certain ions that have a toxic effect on plant metabolism (FAO, 1995). This is because some are better able to make the needed osmotic adjustments to enable them to extract more water from saline soil (FAO, 1985).

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4.5.6.2   *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). ESP is the amount of adsorbed sodium on the soil exchange complex expressed as a percent of the cation exchange capacity in mill equivalents per 100 g of soil as following:

$$ESP = \frac{\text{Exchangeabl Sodium (meq/100g soil)}}{\text{CEC}} \times 100 \qquad\qquad (4.1)$$

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 more than %15. This limit has been markedly found to be useful because many soils show sharp physical property deterioration around and above this value (Ben-Mahmoud, 1995).

Alkalinity can be adversely affected plants into two main ways. First, excess sodium levels in soil have toxic effect on plant growth. Second, excess sodium present in soil can cause dispersal of soil particles. Soil dispersal causes loss of soil structure and surface crusting. Surface crusting leads to reduced hydraulic conductivity, reduced water infiltration, and increased water runoff. These conditions can make seedling establishment very difficult, if not impossible (Tanji, 1990)**.**

4.5.7   *Soil toxicities (Calcium carbonate)*

Calcium carbonate ($CaCO_3$) in the soil profile affects soil structure and interferes with infiltration and the evapotranspiration process. It influences both the soil moisture regime and availability of nutrients (FAO, 2002). Selkhozpromexport

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(1980) stated that soil of calcium carbonate more than 40 % limited the yield to 15-20 % in Libyan conditions.

4.5.8 Condition for germination

Surface stoniness can hinder cultivation and harvesting as well as seed germination and establishment. Also Increasing stones on the soil surface may limit the use of mechanization. The publications from Agricultural research center in Libya indicated that the stones and gravel on the surface should be less than 3 % for irrigated cereal crops. In addition, when the stones and gravel exceed 20 % the land becomes unsuitable for irrigation (ARC., 2000).

4.5.9 Infiltration

Infiltration rate refers to the entry of water into soils. Infiltration rate is affected by many physical soil characteristics such as soil texture, structure and moisture content. Infiltration rate is an important parameter in defining the irrigation method in a soil. Landon (1984) reported that appropriate infiltration rates for surface irrigation systems range from 7 to 35 *mm/hr* .when infiltration rates are higher than 35 *mm/hr* , the soil is considered unsuitable for surface irrigation and sprinkler irrigation method becomes preferable. Diamond and FAO (1985) stated that an infiltration rate as low as 3 *mm/hr* is considered low, while a rate above 12 *mm/hr* is relatively high

4.5.10 Erosion hazard

Soil erosion leads to a reduction in soil quality and productivity and hence crop yield. Soil erosion degrades the soil fertility and also leads to a loss of vegetation cover (Bakker, Govers, et al., 2004). The FAO (1976, 1983) lists erosion hazard as one of the important factors that reflect land productivity and should be included in land evaluation. The main objective of erosion hazard assessment is to identify those areas

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where the maximum sustained productivity is threatened by extreme soil loss (Morgan, 2005).

In this study the universal soil loss equation (USLE) was applied to assess the potential soil loss rate (*tonne/ha/year)*. The USLE is an empirical model originally developed in the USA and it is widely known erosion model (Van der Knijff, Jones, et al., 1999).

4.5.11 Topography (Slope)

Slope is considering an important factor in land suitability classification. It influences the irrigation system, irrigation efficiency, soil drainage, soil erosion, labour requirements and mechanization use (FAO, 1979). Field slope and its uniformity are two of the most important topographical factors. Surface irrigation method requires uniform grades less than 5%. When, some of sprinkler systems can be used to some extent on steeper slopes up to 20% such as overhead irrigation system. However, serious erosion risk could be started at slope 10 – 12% (FAO, 1989).

4.5.12 Climate

Temperature and rainfall are the two main climatic factors that can affect land suitability in the study area. The average mean temperature for 12 climatic stations in the study area over the growing period from October to May varies between 14C° to 17.7 C°. This range is within the optimal temperature for the selected crops; consequently, temperature is not considered a limiting factor in the area. On the other hand the rainfall is limiting and will effectively determine the Length of Growing Period (LGP) without irrigation. The term LGP refers to the period of the year in which agricultural production is possible from the viewpoint of moisture availability and absence of temperature limitations. A detailed explanation of this term is presented in Chapter six.

4.6   Crop Requirements

For each land utilisation type it is very important to generate the best conditions for its cultivation which ranged between optimal conditions and the conditions that are unsatisfactory (FAO, 1976; 1983).

The term *'requirement'* is commonly used when describing the specific land conditions required for the suitable cultivation of some crops. For example, requirements include: water, nutrient and climate conditions for certain crops. These land requirements are the most basic aspects of the land utilisation type for the purpose of land evaluation (McRae and Burnham, 1981). The availability of information about these land requirements is a critical aspect of land evaluation, especially in developing countries. This is because often there are difficulties in obtaining this information, and may be incomplete or unspecific. Advanced information on the relevant land utilisation types and their land requirements will increase the effectiveness and reduce the cost of the field surveys and the studies on which land evaluation is based (Dent, Young, et al., 1981).

 McRae, (1981) stated that there is no easy solution to the problem of collecting land use requirements data. Therefore, the evaluator has to collect local and regional experiences and compare them in order to evolve knowledge and worldwide experience in this field to identify the best prediction of the land use requirements.

It is not common to find handbooks on the cultivation of crops giving the perfect local land conditions. Such knowledge must be gathered from a literature review of optimal crop requirements and used to build the land use requirements. This information and knowledge may then be used to generate the critical limits of land characteristics and qualities. These critical limits are matched with data from study area (land mapping units) to find the land suitability. The next sections explain the requirements of the selected crops based on the literature and local experience where it is available.

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4.6.1 Barley

Barley is the fourth most important cereal crop in the world, after wheat, maize and rice (Langridge and Barr, 2003). In European Union barley is the second after wheat (Taner, Muzaffer, et al., 2004). Barley plays a major role in Libya's agricultural sector. It is considered as a principal food grain in the daily life of the Libyan people. In North Africa, barley is often grown in marginal agricultural areas. Barley is grown in Libya on the coastal strip and its adjacent highlands along the coast where there is enough rainfall to meet the water requirements. Barley needs at least 220 mm of well distributed rainfall, although the crop is relatively drought tolerant (Czembor, et al, 2002). While wheat is the preferred food grain, barley is more adaptable in marginal climate and soils, so it is a popular choice for the Libyan farmer located in the drier hinterland. Fall planting typically begins in October, after the first fall rains arrive, and can last into December. Harvest begins in April and May. The length of total growing period of barley in the study area thus ranges between (150-180) days (Czembor and Czembor, 2002).

Soils best suited to barley are sandy loam texture with good internal drainage. The optimal soil depth is more than 0.9 m. The crop is resistant to salinity, as a yield decline is only about 10% when the salinity in the soil profile reaches up to 12 deciSiemens per metre (dS/m) expressed as electrical conductivity of the saturation extract (CEe) (Sys, Van, et al., 1993). The optimum soil reaction (pH) for growing barley ranges between 6.2 and 8. Hot dry winds after heading decrease the grain yield (Sys, Van, et al., 1993). In this study crop requirements were defined by the combination between the results of some local studies (Yahia, 1982; Ben Mahmood, 1995; Nwer, 2006) with other international reports about studies conducted in similar environment conditions *(Sys, et al, 1993, FAO, 1983).* Summary of the land requirements for barley is shown in *Table 4-3*.

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Table 4-3: Land suitability rating for Land characteristics for barley

Land characteristics	Highly Suitable S1	Moderately suitable S2	Marginally Suitable S3	Not Suitable N
Rootable Depth (cm)	>100	>100-70	>70-30	<30
Soil Texture (classes)	SL, SL CL L, CL,	S CL, S CL L	L S, S L	S
Available Water-holding Capacity (mm)	>150	>110-150	>75-110	<75
Soil Salinity (EC) ds/m	0-8	>8-10	>10-13	>13
Soil Alkalinity (ESP) (%)	0-15	>15-25	>25-45	>45
Soil Reaction (PH)	6.2-8	>6.2-5.3	>5.3-5	<5
Cation Exchange Capacity (CEC)me/100 g soil	>16	<16-8	<8-5	<5
Organic Matter (%)	>1.5	<1.5-1	<1-0.4	<0.4
CaCo3 in root Zones) %)	0-15	>15-20	>20-30	>30
Infiltration rate (mm h^{-1})	>12	<12-8	<8-6	<6
Gravel and stones at surfaces (%)	<3	>3-10	>10-20	>20
Soil Erosion (ton^{-1} ha^{-1} yr^{-1})	0-2	2-5	5-7	>7
Slope Steepness (%)	0-2	>2-4	>4-8	>8
Length of Growing Period (month)	4-6	<4-3	<3-2	<2

Adapted from (Sys, et al, 1993, FAO, 1983)

4.6.2   Wheat

Wheat is one of the most important cereal crops in the world. The origin of wheat is found in Mediterranean countries and today the major producing countries are U.S.A, China, India, France and Turkey (ILACO, 1989). Wheat needs at least 240 mm of well-distributed rainfall (ILACO, 1989). In Libya, wheat is grown in the coastal strip and its adjacent highlands along the coast where the rainfall rates meet the water requirements. The total growing period of wheat is between (150-210) days, depending on variety, temperature and day length.

Soils best suited to wheat are sandy loam to clay loam texture with good internal drainage. The optimal soil depth is more than 0.9 m. The crop is fairly resistant to salinity, as an EC of 7 dS/m results in a yield reduction of about only 10 %. The optimum soil pH ranges between 6.2 and 8. High air humidity combined with high temperature causes wheat rust disease. Strong wind may flatten the crop and make harvesting difficult (Sys, Van, et al., 1993). The main requirements for wheat are summarized in *Table 4-4*.

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Table 4-4: *Land suitability rating for Land characteristics for wheat*

Land characteristics	Highly Suitable S1	Moderately suitable S2	Marginally Suitable S3	Not Suitable N
Rootable Depth (cm)	>120	>80-120	>50-80	<50
Soil Texture (classes)	SL, SL CL L, CL, L,	S CL, S CL L	LS, SL	S
Available Water-holding Capacity (mm	>175	>100-150	>75-100	<75
Soil Salinity (EC) ds/m	0-6	>6-7.4	>7.4-9.5	>9.5
Soil Alkalinity (ESP) (%)	0-15	>15-25	>25-35	>35
Soil Reaction (PH)	6.5 -8	>5.5-6.5	>5-5.5	<5
Cation Exchange Capacity (CEC) meq/100 g soil	>24	<16-24	<12-16	<12
Organic Matter (%)	>1.5	<1.5-1	<0.5-1	<0.5
CaCo3 in root Zones) %)	>15	>15-20	>20-30	>60
Infiltration rate (mm h-^{1})	>12	>8-12	<8-6	<6
Gravel and stones at surfaces (%)	<3	>3-9	>9-15	>15
Soil Erosion (ton-^{1} ha-^{1} yr-^{1})	0-2	2-5	5-7	>7
Slope Steepness (%)	0-2	>2-4	>4-8	>8
Length of Growing Period (LGP)	4-6	<4-3	<3-2	<2

Adapted from *(Sys, et al, 1993, FAO, 1983)*

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4.6.3   Olive

Olive is an important perennial crop in many agricultural regions of the Mediterranean countries, as it is the most important olive growing region (Fayed, 2010)**.** Olive harvesting in Libya takes place in the autumn and winter, usually from September to February. Green olives are collected from the end of September to about the middle of November. Black olives are picked from the middle of November to February.

Olive trees show a marked preference for calcareous soils, loamy, deep, and well drained. The temperature range for the growth of olive trees is between 0 and 38°C. However, the growth is optimal at temperature between 15 and 22°C. Olive trees need a dormancy period of 2 months with an average temperature of less than 10°C; otherwise flowering will be poor or will not happen at all. During that time temperature as low as (-8°C) can be tolerated but it is best not to plant in regions where the temperature regularly fails below (-4°C). Olive is fairly sensitive to salinity, as a yield decline of about 25% when the salinity in the soil profile is 5.5dS/cm. The optimum soil pH ranges between 6.2 and 8 (Sys, *et al*, 1993). Summary of the land requirements for olive is shown in (*Table 4-5*).

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Table 4-5: *Land suitability rating for Land characteristics for olive*

Land characteristics	Highly Suitable S1	Moderately suitable S2	Marginally Suitable S3	Not Suitable N
Rootable Depth (cm)	>120	>100-120	>80-100	<80
Soil Texture (classes)	SL, SL CL L,	S CL,	LS, SL	S
Available Water-holding Capacity (mm)	>150	>110-150	>75-110	<75
Soil Salinity (EC) ds/m	0-8	>8-15	>15-20	>20
Soil Alkalinity (ESP) (%)	0-20	>20-30	>30-45	>45
Soil Reaction (PH)	6.2-8	>6.2-5.3	>5.3-5	<5
Cation Exchange Capacity (CEC) meq/100 g soil	>16	<16-8	<8-5	<5
Organic Matter (%)	>1.5	<1.5-0.8	<0.8-0.4	<0.4
CaCo3 in root Zones (%)	10-25	>25-50	>50-60	>60
Infiltration rate (mm h^{-1})	>12	<12-8	<8-6	<6
Gravel and stones at surfaces (%)	<15	>15-40	>40-70	>70
Soil Erosion ton^{-1} ha^{-1} yr^{-1}	0-2	2-5	5-7	>7
Slope Steepness (%)	0-2	>2-4	>4-8	>8
Length of Growing Period (month)	4-6	<4-3	<3-2	<2

Adapted from *(Sys, et al, 1993, FAO, 1983)*

4.7   Data Collection

For the purpose of land suitability determination for agricultural, the main required data are soils, climate and crops information. The data used in this research were collected from different sources during a visit to Libya. These data are available as reports, maps, tables and digitized information. The most important data for this research are soil maps and the soil properties for each type of soil.

4.7.1   Soil information in the Study Area

The soil studies in the north west of Libya were conducted by Selkhozpromexport (1980). A detailed report was published (Selkhozpromexport, 1980; Ben-Mahmoud, 1995). The studies included: field survey, laboratory investigations and office studies resulting in soil maps for Jeffara plain at a scale 1:50,000. The soil survey was carried out using aerial photographs to plot roads and other reference points necessary for field soil mapping. The soil survey included 26667 soil profiles at a rate of one control profile per 60 ha and 2667 representative profiles at a rate of one representative profile per 600 ha. Samples taken from the representative and control profiles were analysed for soil texture, electric conductivity, $CoCa_3$ and pH while in the representative profiles the following tests were conducted: soil texture, mineralogical composition analysis of the clay, total chemical composition (Si O_2, AlO_2, Fe_2O_3, CaO, MgO, MnO, SO_3, Na_2O), organic matter, total nitrogen, total phosphorus, total potassium, exchange capacity and exchangeable cations, Ca and Mg of carbonates, SO_4 of gypsum and trace elements (B, Cu, Zn, Co, Mo, Fe, Mn) (Selkhozpromexport., 1980).

Soil was classified using the taxonomy of the Russian pedology. The classification system distinguishes the soil in several orders: class, subclass, type, subtype and soil genus. The definitions of these orders are presented in (*Table 4-6*).

The classification was based on soil properties and diagnosis was observed in the field or implied from observation or based on laboratory measurements. Six soil

types, eleven soil subtypes and forty-nine soil genera have been recognized in the study area as shown in *Table 4-7* and *Figure 4-2*, further descriptions of the soils in the area of study are given in Appendix A1.

Table 4-6: *Soil terminology used in the Russian Taxonomy*
(Selkhozpromexport, 1980)

Order	Description
Class	Soils of a 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 material (weathering crusts).
Subclass	Soils 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	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.
Sub-type	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.

Table 4-7: Soils in the study area using Russian soil classification (Selkhozpromexport, 1980)

Soil type	Soil Subtype	Soil Code
Siallitic cinnamon	Siallitic cinnamon typical soils	CSt
Reddish brown arid	Reddish Brown arid differentiated soils	FBd
	Reddish Brown Arid Slightly Differentiated Soils	FBsd
	Reddish Brown Arid Slightly Differentiated Crust	FBsdcr
	Reddish Brown Arid Non-Differentiated Soils	FBnd
	Reddish Brown Arid Non-Differentiated Crust Soils	FBndcr
Alluvial	Alluvial Slightly Differentiated Soils	Asd
Lithosols	Cinnamonic Lithosols	Lcs
	Reddish Brown Lithosols	Lfb
Crusts	Non-monolithic soils	CRnm
Solonachaks	Hydromorphic Solonachaks Soils	Sh
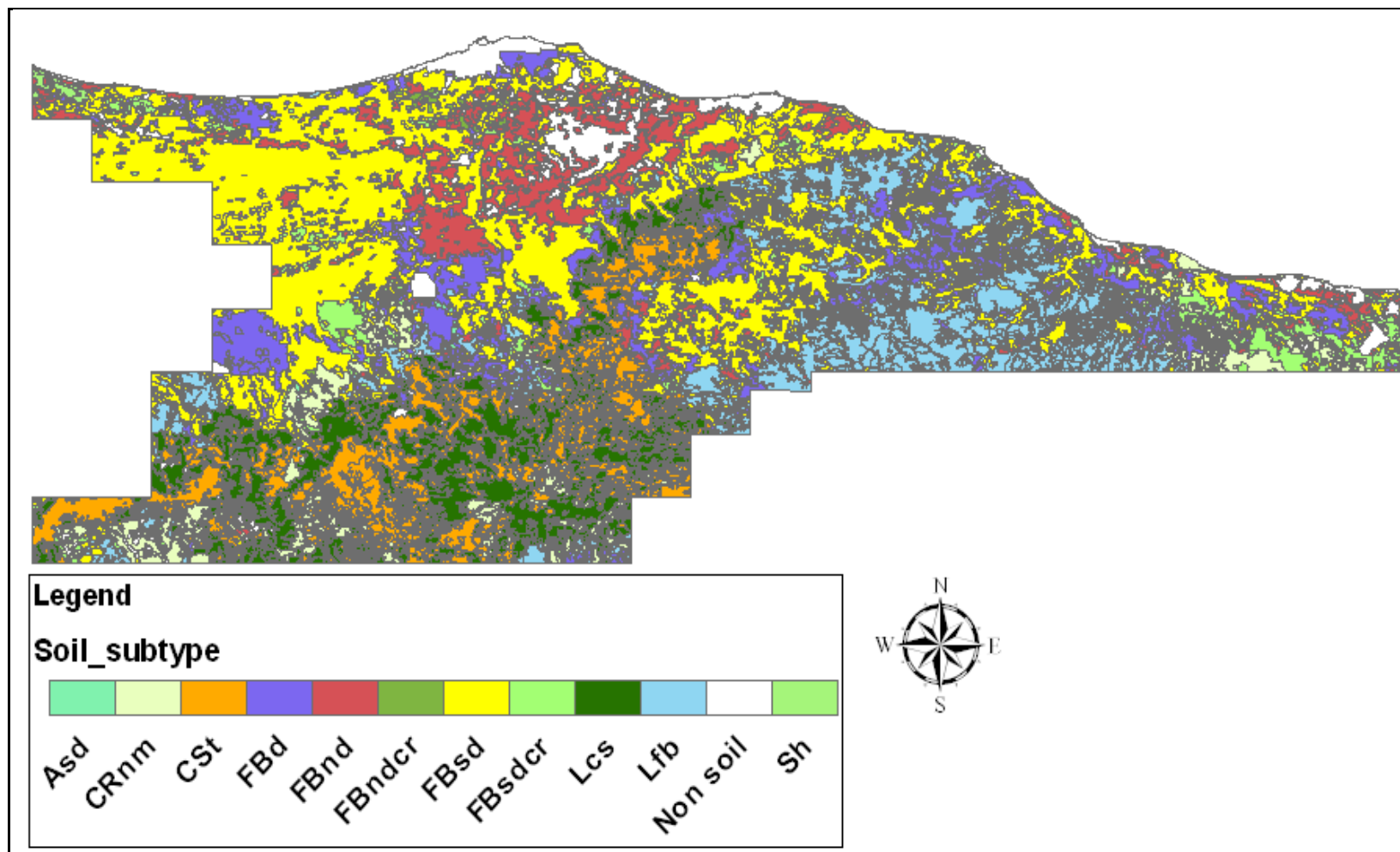
Figure 4-2: *Soil map at soil subtype level for the study area*

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4.7.1.1   Soil Characteristics

The physical and chemical soil characteristics which are available in the study area are: topsoil texture, soil depth, stones on the surface, available water holding capacity soil salinity and soil alkalinity, percentage of calcium carbonate in the soil (%CaCO3) , soil reaction (pH), organic matter, cation exchange capacity and infiltration rate. All of the above parameters directly or indirectly can affect the production of crops, and therefore physical suitability of a soil for crop production. Some indicators of soil characteristics can be extracted from the reports of soil studies in the study area published by (Ben-Mahmoud, 1995, Selkhozpromexport., 1980). There are only five kinds of soil texture found in the study area namely: sand, loam, loamy sand, sandy loam and sandy clay loam. The soil depth in study area ranges from very shallow depth of 18 cm to greater than 300 cm Cation exchange capacity for the soils in the study area is considered fairly low ranging between (2-14) meq/100g soil. The soils of the study area are low in organic matter, with most of soils having less than 1 % organic matter. The carbonate content of the soils in study area generally is high: the lowest value was found in Reddish brown arid non-differentiated soils (FBnd), which had less than 1 %. The highest carbonate content value was found in non-monolithic siallitic carbonat crust soils, which had more than 50%. The full physical and chemical soil properties data are given in Appendix A2.

4.7.1.2   Data Merge and Mapping

The soil map of the study area was provided by Selkhozpromexport (1980). The soil map for Jeffara plain is stored in a digital shapefile format, with the soil genera name as identifier for each polygon. There are 49 such polygons covering the study area .The table for the soil characteristics were derived from the original report associated with the study and these were transferred into excel spreadsheet . The tables of soil attributes in Excel format were linked to the shapefile to be available for GIS applications.

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4.7.2 Climatic Information in the Study Area

Climate is by nature a rather complex subject, because of the manifold earth atmosphere interaction which considerably varies over space and time and finally creates a specific type of climate at a particular location (El-Tantawi, 2005). The study area lies between the coastal strip in the north and Jebal Nefusa in the south. The climate data for 12 stations covering most of the study area were collected from Libyan National Meteorological Centre (LNMC). The data include: temperature, precipitation, wind speed, sunshine hours and relatively humidity are presented in (Appendix A3). The mean annual temperature and the minimum and maximum seasonal temperature are summarized in *Table 4-8*.

Table 4-8: The annual and seasonal temprature in the study area

	Mean minimum temperature				Mean maximum temperature				Mean temperature
Station	Autumn	winter	spring	summer	Autumn	winter	spring	summer	Annual
Tripoli	16.2	7.3	12.3	11.9	28.6	18.6	25.8	35.0	20.5
Alhadbah	16.8	8.0	12.3	12.4	28.7	18.7	25.0	34.1	20.4
Alkomes	17.4	9.1	13.1	13.2	28.0	18.7	23.0	29.7	20.0
Yefren	16.5	7.3	12.9	12.2	24.8	13.3	22.3	32.9	18.9
Sorman	17.0	8.5	13.2	12.9	27.6	18.5	24.0	31.4	20.1
Zawia	17.1	7.6	12.6	12.4	29.2	18.9	25.2	33.5	20.6
Alzahra	16.3	7.5	12.2	12.0	29.3	19.1	26.6	35.8	20.9
Zwara	17.1	7.6	12.6	12.4	29.2	18.9	25.2	33.5	20.6
Esbaae	18.4	9.2	13.6	13.7	26.8	18.1	21.9	29.5	20.0
Grian	14.2	5.9	11.0	10.4	24.1	13.5	21.9	32.4	17.8
Rojban	13.2	3.9	10.0	9.0	25.7	14.3	23.3	33.6	17.8
Misurata	19.0	10.3	14.3	14.5	27.7	18.5	22.9	30.7	20.7

Data source: Libyan National Meteorological Centre (LNMC)

4.7.2.1 Climate Characteristics

The mean monthly temperature in the study area ranges between 7.9 °C as lowest in January and February and the highest mean temperature is 26 °C recorded in July and August. The study area receives on average 270 mm of precipitation annually. The rainfall falls mainly in winter.

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Figure 4-3 shows the range distribution of rainfall in the north west of Libya. The wind speeds ranging from 3.5 knots in Zawia and Azahra where there is a density of forest trees to 11 knots in open area such as Zwara. The sunshine hours are almost similar in the study area. The lowest sunshine is 6 hours occurred in January and increasing gradualy to reach the maximum 12 hours in July. The obove climate paremetres are used to estimate evapotransperation using Penman Monthiet method.
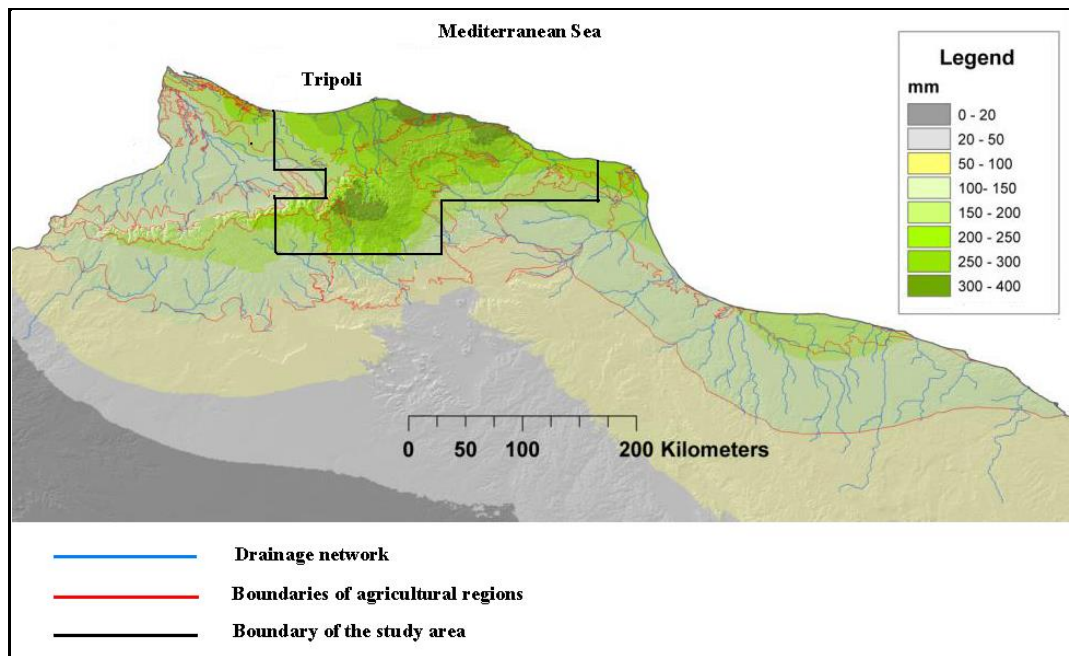
Figure 4-3*: Mean annual precipitations in the Northwest of Libya*

Source: *(ICARDA and ARC-Libya, 2009)*

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4.8   Summary

In this chapter, the basic requirements of applying the land suitability framework for each of the selected crops are reviewed. Land qualities, characteristics and their threshold values were determined based on the literature review and local experience.

The land qualities and characteristics which are available in the study area are: temperature, rainfall, topsoil texture, soil depth, stones on the surface, available water holding capacity, soil salinity, soil alkalinity, percentage of calcium carbonate in the soil (%CaCO^3) , soil reaction (pH), organic matter, cation exchange capacity (CEC) and infiltration rate.   The land characteristics are different from region to other depending on the parent material and environment conditions in the area which reflect the processes of weathering and soil formation. Also the crop requirements are vary from crop to another since land what is suitable for one kind of cultivation may not be suitable for another.

The most important climate elements for cultivation are temperature and rainfall. The study concluded that there is an upward trend in the minimum temperature and downward trend in maximum temperature during the period (19451–2007). The results also indicated that there is a drop in rainfall volumes and irregular distribution over the season in the area. Climate change could affect agriculture in several ways such as the availability of water in rainfed agriculture areas land, degradation risks and soil erosion.

In the next chapter, the description and background of the study area is presented to identify land use requirement and land characteristics of the Libyan case.

Chapter 5

DESCRIPTION OF THE STUDY AREA

5.1   Brief description of Libya

Libya is located in the north of Africa between 20° and 33° latitude North and between 10° and 25° longitude East. It is bordered in the north by the Mediterranean Sea with a coastline of about 2000 km, in the east by Egypt and Sudan, in the south by Chad and Niger, and in the west by Algeria and Tunisia (*Figure 5-1*). The total area of Libya is about 1,759,540 million km². Only 4 per cent of the country is considered arable land, while the rest of the area are rocky and desert land. Arable land in general means a land that can be used for growing crops. In addition, there is a shortage of land receiving sufficient rainfall for agriculture. The highest rainfall occurs in two places: the Jabal al Akhdar region around Benghazi city in the north east of the country, and Jifara Plain around Tripoli in the North West (*Figure 5-1*). These two areas are the only regions where the average annual rainfall exceeds the minimum (250-300 mm) considered necessary to sustain rainfed agriculture (Ben_Mahmood, 2001)(*see Figure 5-2*). Rainfall occurs during the winter months but great variability is observed from place to place and from year to year (Pallas, 1980). The distribution of mean annual precipitation in Libya is shown in (*Figure 5-2*).

As a result of the low rainfall, the essentially nonrenewable groundwater resources have been used in the development of agriculture in Libya. The expanding economy and growing population in Libya is creating an increasing demand on groundwater resources. This has caused serious declines in water levels and quality, especially along the Mediterranean coast where most of the domestic, industrial and agricultural activities are concentrated, making the coastal groundwater resources almost unusable because of their high salinity (Alfarrah, Martens, et al., 2011).

Higgins and Kassam (1981) state that the ability of land for crop production is limited in Libya, due to extreme climatic condition (high temperature and low

rainfall) and poor soils in terms of nutrients (Higgins and Kassam, 1981). Most of the soils in Libya are either less developed, classified as Aridisols & Entisols according to USA Soil Taxonomy or undeveloped (parent material such as sand dunes) (Sherif, 2004.). Therefore, there is a pressing need for effective land evaluation to achieve optimal utilisation of available land resources for sustainable agriculture production.
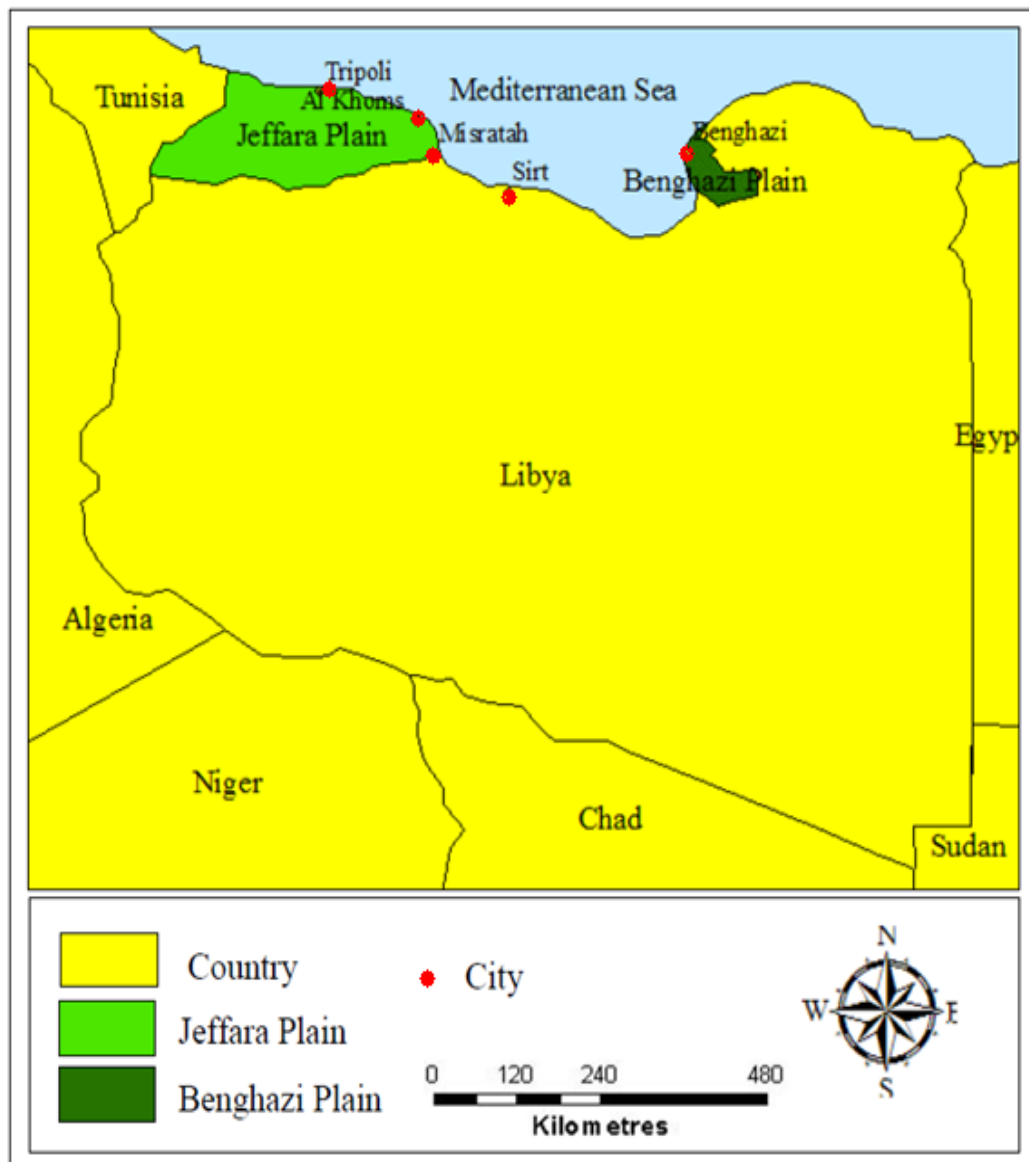
Figure 5-1: *Map of Libya*

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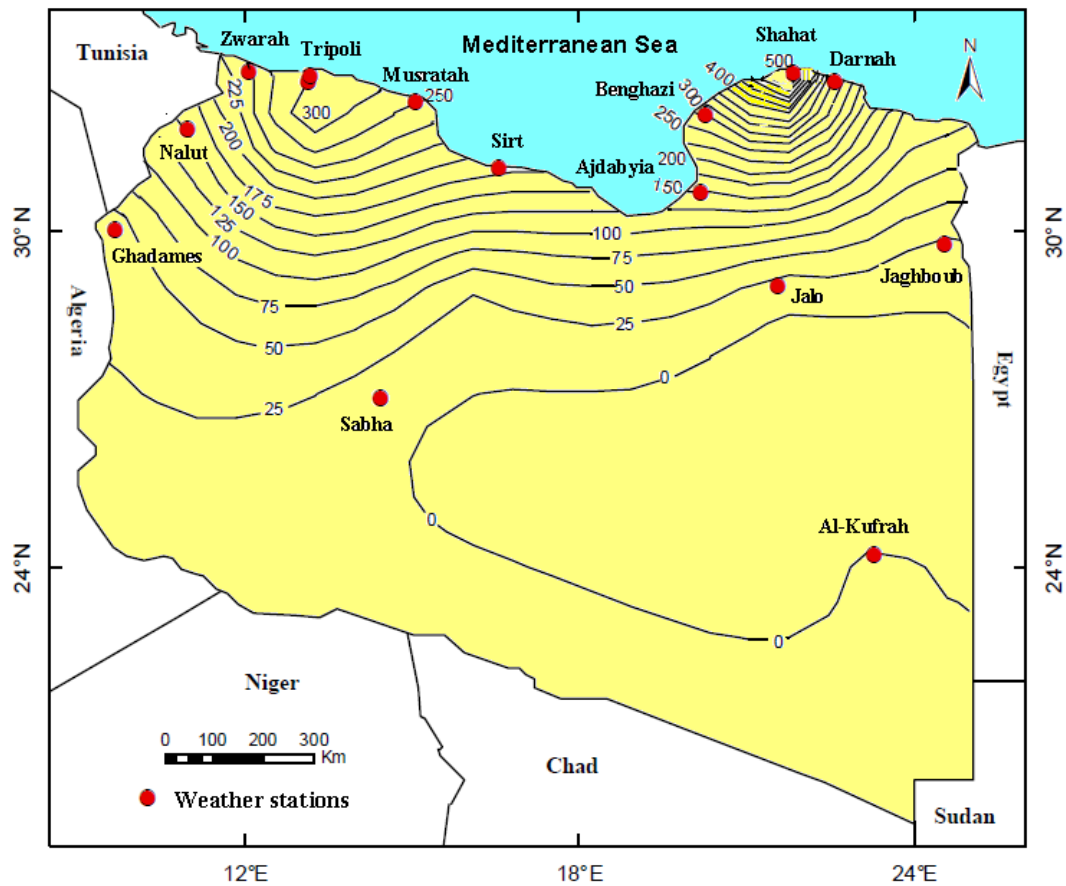
Figure 5-2: *Distribution of mean annual precipitation (mm) in Libya, 1946-2009*

Source: *Libyan National Meteorological Centre (LNMC)*

5.2   The Location of Study Area

The study area is called Jeffara plain. It is located in the northwest of Libya (*Figure 5-3*). The study area is a flat area of triangle shape, its width (distance from the sea) varies between 8 and 115 km. The total area is about 17,000 km²; it is bordered by the Mediterranean Sea in the north, the Tunisian border in the west and Jabil (mountain) Naffusah in the south. The study area lies between 12° 00´ - 15° 00´ E longitude and 31° 52´ - 32° 54´ N latitude. The plain lies in the agriculturally productive region of north Libya, where more than 50% of the country's population is concentrated (ALfarrah, *et al*, 2011). The main reasons for this concentration are the availability of fertile soils and seasonable, moderate climatic conditions compared with other places in the country.

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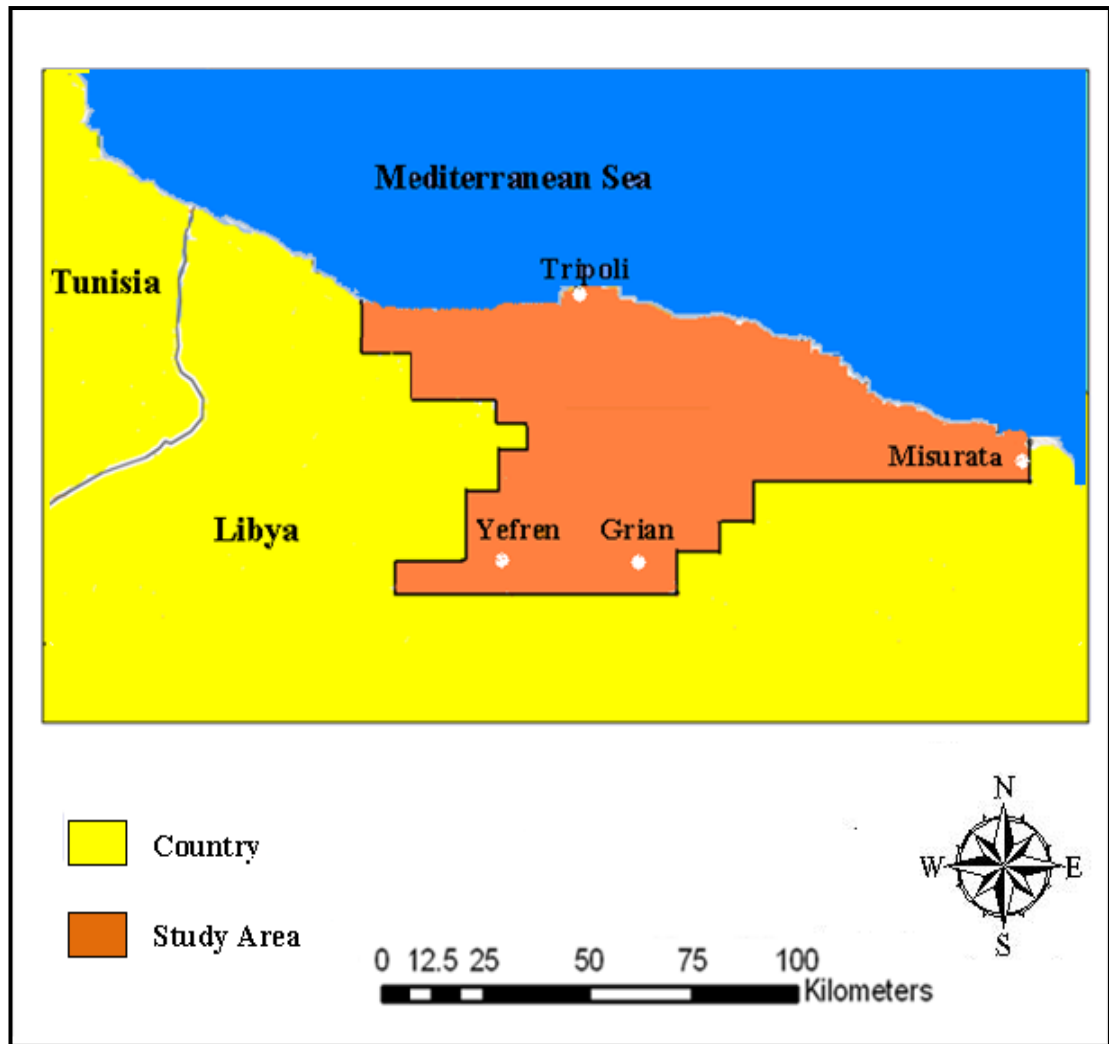
Figure 5-3: *The study area location*

In the next subsections a brief description of natural resources (soil, water, climate and vegetation) in Libya are presented.

5.3 Climate

The main characteristics of the climate in Libya are the aridity and variability. The climate in Libya is influenced by two main climatic systems; the Mediterranean Sea in the north and the Sahara desert in the south, resulting in an abrupt transition from one kind of climate system to another. The climate in Libya is distinguished into three main climate systems:

(i)   The Mediterranean coastal belt, with dry summers and relatively wet winters.

(ii)   Mountainous area, Jabal Nafusah in the North West and Jabal Akhdar highlands in the north east of the country, experience a plateau climate with higher rainfall and low winter temperatures including snow on the hills.

(iii) Desert area in the south of the country, with pre-desert and desert climatic conditions prevail, with hot temperatures and large daily thermal amplitudes. Rain is rare and irregular and diminishes progressively towards zero in the south (Ben-Mahmoud, 2001).

5.3.1 Rainfall

The average annual rainfall varies from region to another according to the geographic position and the topography (*Table 5-1*). The highest average rainfall is about 560 mm/year in the Jabal Akhdar in the northeastern part of the country, whereas the lowest average rainfall is in the southern regions (see also *Figure 5-2*). The rainfall in Jeffara plain varies between an average of approximately 300 mm/year in Tripoli and an average of 150 mm in the plain north of Nalut (Pallas, Dams, et al., 1980, Salem, 1992) the rainy season starts usually in autumn to winter and end in spring, but great variability is observed over space and time (year to year). For example, the total rainfall at Tripoli in 1990 was 124 mm, whereas in 1993 it was 468 mm as reported by Libyan Meteorological Department (LMD, 2009). Increasing variability and uncertainty of precipitation over Libya causes critical moisture stress on crops production and reduce yields especially given the large proportion of water lost through evaporation without any benefit to agriculture because of the high temperature, while only a small percentage of rainfall infiltrates to groundwater. The monthly rainfall in Libya for the period (1945-2009) is shown in *Table 5-1*.

***Table 5-1**: Monthly rainfall (mm) in Libya for the period (1945-2009)*

Region	Station	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Total
North west	Zwarah	36.4	22.1	17.3	12.3	5.6	1.0	0.0	0.7	13.5	35.0	38.1	46.3	228.3
	Tripoli	75.5	35.1	21.6	10.9	5.8	0.3	0.4	0.5	7.7	23.6	62.4	63.5	307.5
	Nalut	16.1	19.2	26.0	16.5	10.7	2.4	0.0	0.2	5.3	18.6	14.0	18.5	147.6
	Yefren	51.4	37.5	39.6	14.4	10.6	2.1	0.4	3.2	4.1	26.8	26.8	51.4	268.3
	Khomus	62.7	48	31.8	12.3	3.9	0.4	0.1	0.2	10.1	23.1	44.3	56.7	293.6
	Musratah	56.5	29.0	21.8	9.8	4.5	1.1	0.0	0.5	11.3	37.9	45.9	58.4	276.6
North central	Sirt	38.8	23.2	15.2	4.5	3.0	0.8	0.0	0.0	10.0	23.3	24.5	43.4	186.8
North east	Ajdabyia	39.1	20.4	11.1	3.4	2.5	0.1	0.0	0.0	1.5	9.1	18.9	44.7	150.6
	Benghazi	66.0	40.9	25.9	6.3	4.4	0.3	0.0	0.2	3.2	19.4	34.5	66.3	267.6
	Shahat	123.8	87.5	66.9	22.7	8.9	1.4	0.9	1.7	9.2	52.2	68.5	116.3	560.1
	Darnah	60.1	39.6	23.6	8.3	5.7	2.4	0.0	0.4	5.6	34.7	28.7	56.8	265.8
South	Ghadames	5.3	5.5	5.7	2.9	1.8	0.5	0.0	0.3	1.1	3.4	1.7	5.3	33.6
	Al-Garyat	8.7	4.3	7.9	3.5	4.6	1.4	0.3	0.2	4.1	8.8	6.6	5.7	56.2
	Jalo	1.5	1.8	1.3	0.8	0.6	0.0	0.0	0.0	0.1	1.1	0.8	1.4	9.5
	Jaghbob	3.6	2.6	2.7	0.8	0.6	0.1	0.0	0.0	0.4	0.5	0.6	3.1	14.8
	Sabha	1.8	0.9	1.0	0.7	0.6	0.3	0.0	0.1	0.2	1.2	1.5	0.8	9.2
	Al-Kufrah	0.4	0.3	0.2	0.2	0.4	0.0	0.0	0.2	0.1	0.1	0.0	0.1	2.0

***Source**: Libyan National Meteorological Centre (LNMC)*

5.3.2 Temperature

The temperature is lowest in January and starts to increase gradually from February until July and August when the highest temperatures are reached. The temperature also varies from region to region depend on latitude and elevation (*Table 5-2*). In the coastal region, the mean monthly temperature is between $23°C$ and $25°C$. In the semi-desert regions the mean monthly temperature is between $25°C$ and $28°C$, whereas, the maximum temperature in the desert regions may exceed 30 $°C$. However, temperatures are normally pleasantly cool at night in the Sahara desert. In some parts of Libya temperatures drop to freezing in winter, for example, in January 1962 temperature recorded (-6 $°C$) east of Ghadames in west south of Libya (El-Tantawi, 2005). The locations of climate stations are shown in Figure 5-2.

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Table 5-2: *The annual, winter and summer temperatures for the period (1945-2009) in Libya*

Location	Station	Latitude N	Elevation (m)	Annual (°C)	Winter (Dec.-Feb.)	Summer (Jun.-Aug.)
North west	Zwarah	32.53	3	19.8	13.3	25.8
	Tripoli	32.54	25	20.2	14	26.4
	Nalut	31.52	621	19.1	10.5	27.2
	Musratah	32.19	32	20.4	14.1	26.2
North central	Sirt	31.12	13	20.5	13.4	25.5
North east	Ajdabyia	30.43	7	20.5	13.5	26.5
	Benghazi	32.05	129	20.1	13.4	26.1
	Shahat	32.49	621	16.5	10.1	22.8
	Darnah	32.47	26	20	14.8	25.1
South	Ghadames	30.48	357	21.9	11.8	31.4
	Jalo	29.02	60	22.4	14.1	29.8
	Jaghbob	29.5	-1	21.3	12.9	28.8
	Sabha	27.01	432	23.4	12.8	30.6
	Al-Kufrah	24.13	436	23.3	14.2	30.8

Source: Libyan National Meteorological Centre (LNMC)

5.3.3 Relative humidity

Relative humidity varies between winter and summer. On the coastal strip, summer values are at most stations higher than winter values, while in the desert, winter values are mostly higher. The annual relative humidity at the coast is between 60-80%, while in the desert between 25-55% (El-Tantawi, 2005), favourable huge evaporation loss by mass transfer.

5.3.4 Winds

Libya is affected by atmospheric depressions during the winter time and northeastern trade winds in the summer. Libya is also exposed to strong southerly winds known locally as (Ghibli), a dry and hot wind that blows from the desert several times a year most notably from late spring throughout summer season (Abohedma and Alshebani, 2010). Typically, this type of hot winds is laden with

dust and sand. This raises temperatures dramatically to approximately 50 C°. These strong dry winds are a major erosion factor in the desert, transporting sand from one place to another (Ben-Mahmoud, Mansur, et al., 2003).

5.4 Soil Resources

One of the major constraints to agriculture in Libya is the scarcity of arable land; sandy soils are prevalent in most of the country and are subject to limited natural fertility (Ramali, , et al., 2012). Many soil studies have been conducted in Libya in the last 40 years. Most of these studies focused mainly on the northern part of the country and on small scattered areas in the southern desert. Different classification systems were used in these studies according to the company executing the study. The major soil classification systems used in these studies are the Russian soil classification, the USA Soil Taxonomy, the French soil classification, and the FAO/UNESCO system.

The main soil orders in Libya are Entisols, Aridisols, Mollisols, Alfisols, Vertisols, and Inceptisols (Ben-Mahmoud, 1995, Selkhozpromexport., 1980). Three of these soil orders, Entisols , Aridisols and Inceptisols are more dominant in the country. However, the other soil orders exist only in some parts of the Jabal Akhdar and Jabil Nafusah where the highest rates of rainfall.

Entisols are soils that show little or no evidence of pedogenic horizon development. They occur in areas of recently deposited parent materials or in areas where erosion or deposition rates are faster than the rate of soil development; such as dunes, steep slopes and flood plains. Aridisols are common in deserts or arid environments, the lack of moisture greatly restricts the intensity of weathering processes and limits most soil development processes to the upper part of the soil (USDA, 2013). Both of them show less soil development as evidenced by the absence of soil horizons found within the soil profile. Inceptisols are soils that exhibit minimal horizon development. The differences between horizons are just beginning to appear .They has more profile development than Entisols, but they have no accumulation of clays, Fe, Al or organic matter (Kettler, Zanner, et al., 2009). In general, both of these kinds of soils need some

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treatments to be able for agricultural production, such as agricultural fertilizers, while the other kinds of soils consider more suitable for agricultural use. The main orders of Libyan soils are shown in *Table 5-3*. The main soil orders in the study area are shown in *Figure 5-4*, where Null means settlements in the study area.

Table 5-3: The main soil orders in Libya soil orders

(American classification)	Russian Classification	FAO & UNESCO Classification
Entisols	Reddish Brown Arid	Regosols
Aridisols	Serozems, Desert Soils	Luvisols
Alfisols	Red Ferrisiallitic Typical	Chromic Luvisoils Calcic Chromic Luvisols
Mollisols (Rendolls)	Rendzinas Dark Red Rendzinas	Rendzins Leptosols
Vertisols	Dark Compact Typical soil	Pellic Vertisols
Inceptisols	Siallitic Cinnamonic	Cambisols

Source: (Selkhozpromexport, 1980; Ben-Mahmoud, 1995)
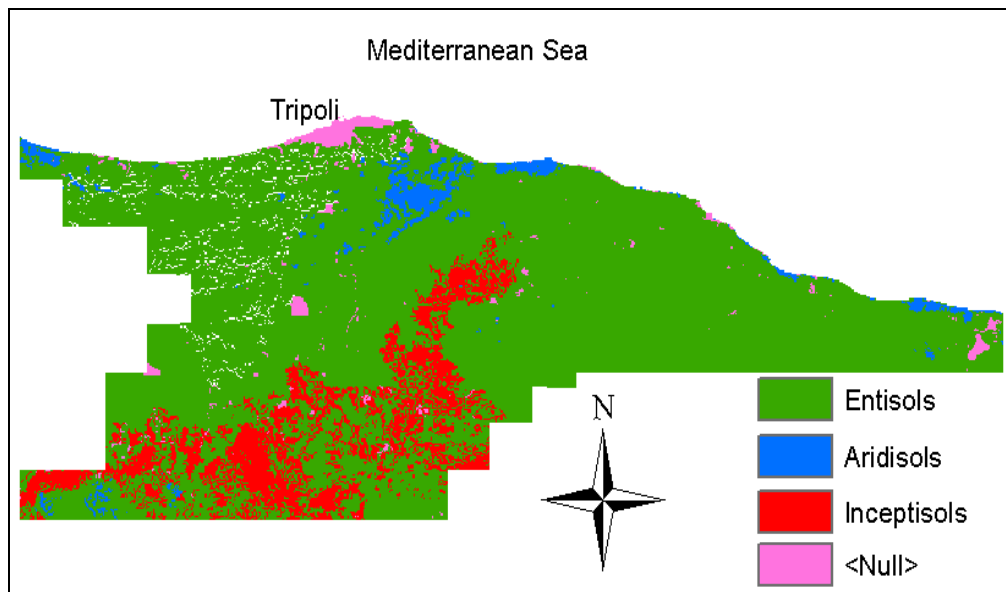
Figure 5-4: Soil orders in the study area

*Source: (**El-Takhtiet, 1978**)*

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5.5   Water Resources

Libya is mostly arid and semiarid with water resources that are not only limited but also poorly distributed both in time and location(Almiludi, 2001). Water resources of Libya could be classified into three categories: ground water, surface water and non-conventional water resources. Ground water represents the main source of water supply in Libya, meeting about 88% of the total water use for the different activities especially in irrigated agriculture. Agriculture had the highest consumption quantity about (85%) but the domestic and industrial sector withdrawals only (11.5%) and 3.5% respectively. Surface water is controlled by rainfall reflecting its shortage in an absence of permanent streams. It supplies about 3 % of the total water consumption (Wheida and Verhoeven, 2007). The different water sources in Libya are shown in *Figure 5-5.*
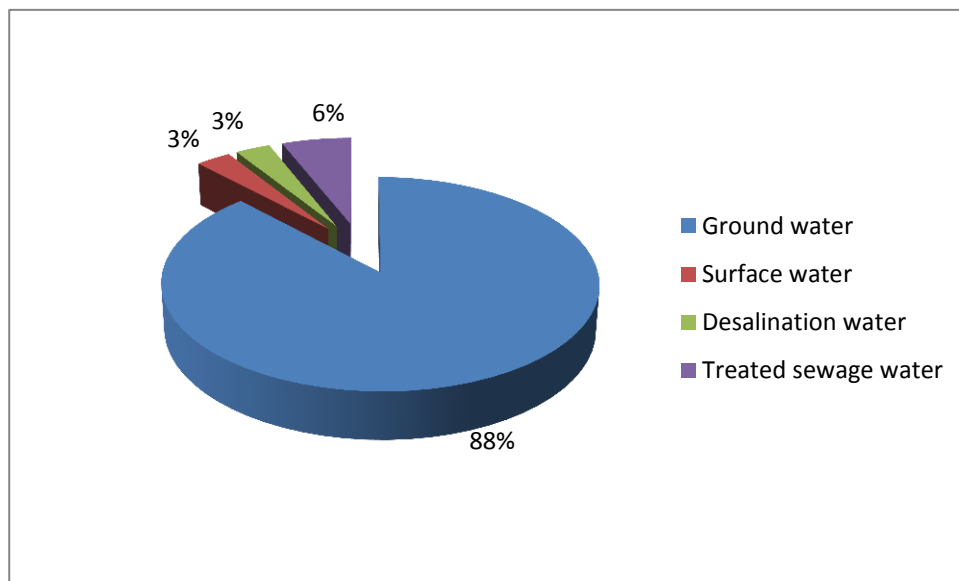
Figure 5-5: *water resources in Libya*

Source :(Salem, 2007)

Non-conventional water resources include desalination and treated sewage. Desalination water covers only a small portion about 3% of the domestic and industrial water demand. Water production from treated sewage is still very limited and contributes about 6% of total water used mainly in irrigation purposes (Salem 2007b).

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5.5.1 Surface water

The surface water resources in Libya are limited and contribute only a small quantity to the total water consumption. The total average annual runoff of surface water in the northeast and northwest of the country is roughly estimated at 200 million m³ per year. However, about 50% of the runoff water is either evaporated or infiltrated for recharging the aquifers. Currently there are 16 dams and several reservoirs were established to collect yearly about 60 million m³ in the north of Libya, where the average of rainfall above 200 mm. The total storage capacity of these dams is about 385 million m³. In addition, these dams serve both as water reservoirs and to protect cities from flooding and erosion control (Salem 2007a).

5.5.2 Desalination

Desalination of seawater can be considered as one of the most promising water supply techniques in many coastal countries that have limited conventional water resources. Libya, such as many other countries in the arid region, turned to desalination as a supplemental water resource since 1964. Both thermal and membrane desalination technologies have been used to provide water for domestic and industrial purposes (Wheida a and Verhoeven, 2007). A number of desalination plants with different sizes ranging from less than 100 m³/d to 40,000 m³/d have been constructed near to large municipal centers and industrial complexes. Applications included both brackish and seawater desalination with a total cumulative installed capacity exceeding 60 Million m³/y. However, the overall water produced is only between 20 and 30 million m³ per year due to most of the desalination plants are not in good operating condition as a result of poor management and lack of spare parts and local skills for repair (ALghariani, 2002). The cost of desalinated seawater has witnessed a significant drop during the last two decades due to dramatic revolution in desalination industry. The average price of desalinated sea water has dropped from $5.5/ m³ in 1979 to less than $0.55/ m³ in 1999 including interest, capital recovery and operation and management as a result; the desalination has become a rival source of water (Owens and Brunsdal, 2000).

5.5.3   Wastewater recycling

Recycling domestic wastewater has been used in Libya since 1963, with some problems associated with operation and maintenance (Wheida and Verhoeven, 2005). In the last three decades, the country has witnessed a rapid increase in population associated with relatively dense urbanization in some cities especially those in coastal areas. This development led to establishing the necessary infrastructure such as wastewater treatment plants to achieve two main goals firstly, to protect the environment by limiting the amount of polluted water and its negative impact on public health and secondly, to cover a part of the agricultural water requirement by reusing the effluent. Two kinds of wastewater treatment technique were used in Libya: Trickling filters (TF) and Activated sludge (AS). The Trickling filters (TF) technique was used in Libya by the first generation of treatment plants in the sixties. However, most of this type of treatment plants is currently out of order. The Activated sludge (AS) technique is used for treating wastewater since 1972 and became the most common technique used in the country. Twenty-five such treatment plants were built during the period of (1963–1995). Three out of the 25 work with a good efficiency; two with medium efficiency and the rest either work inefficiently or are out of order (Wheida and Verhoeven, 2007). The design capacities vary from 150m³/day to larger ones of 110000m³/day. Most of these treatment plants were designed to produce treated water suiting agriculture purposes. The present produce of wastewater treatment is estimated approximately 40 million m³ per year. However, this amount is much smaller than the designed capacity (Wheida and Verhoeven, 2007). The treated wastewater is used for agriculture utilization only in the major cities Tripoli and Benghazi.

5.5.4   Ground water

Groundwater is the main source for freshwater in Libya. It supplies about 88 % of the total water consumption for different activities; domestic, industry and agriculture. Ground water in the country has been divided into five water zones representing the major ground water basins, three of them in northern Libya: Jeffara Plain, Jebal Akhdar, Hamada Hamra, two in southern Libya: Murzuq and

Kufra-Serir (*Figure 5-6*). The aquifers in the northern region could be recharged if sufficient rainfall is available, while those belonging to the great sedimentary basins in the central and southern parts are considered not renewable. However, the great part of ground water is located at the southern Libya in the desert regions such as Murzuq, Tazrboo, Kufra-Serir basins (Pallas, Dams, et al., 1980, Shaki, 2002).
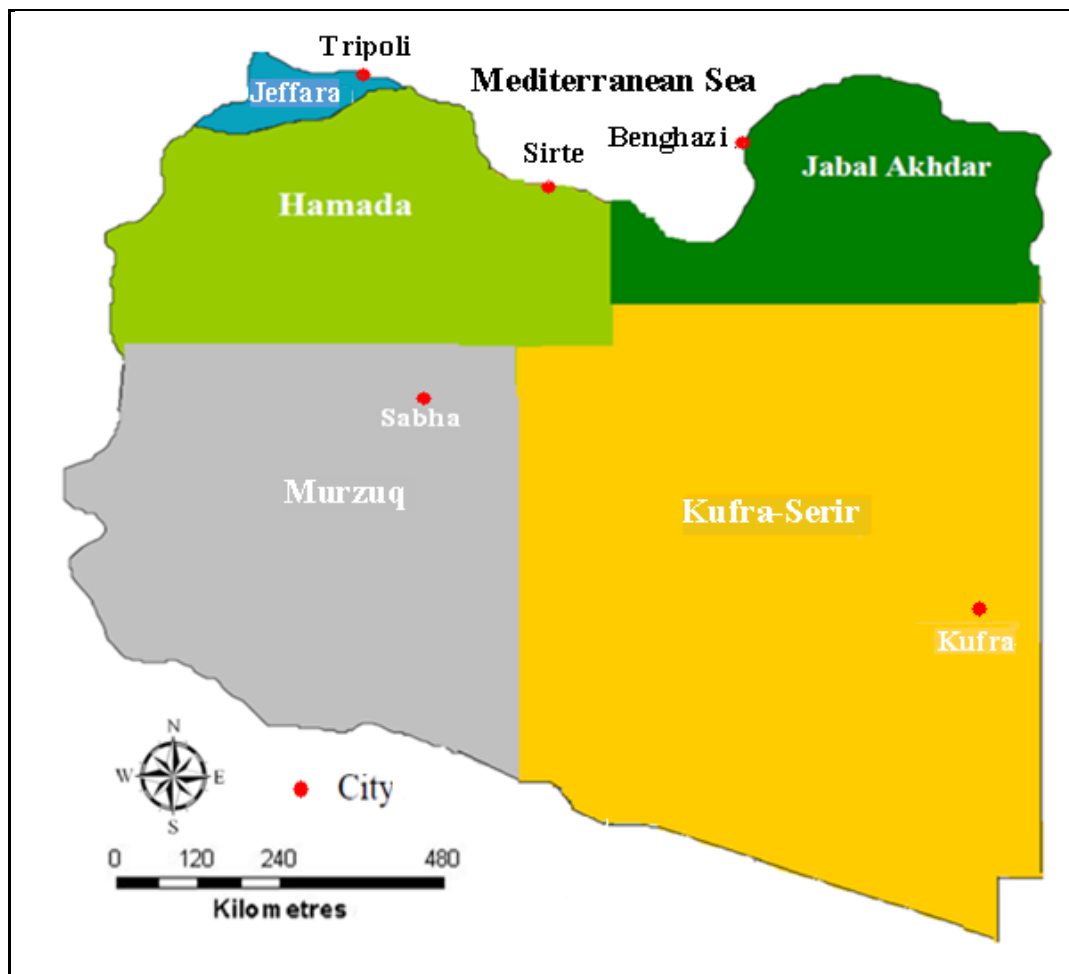
Figure 5-6: *Groundwater basins in Libya*

According to water balance of the groundwater basins in Libya, a severe deficit in water supply exists in the Jeffara Plain basin and moderate deficit in Jebal Akhdar basin due to the high density of population in these regions. While there is no

deficit water in the southern basins (Kufra-Serir and Murzuq), this water is not renewable. *Figure 5-7* shows the overall water balance per basin for the year 1995. It is clear that the gap between the supply and demand is extremely high in northern basins (Jeffara plain and Jebal Akhdar) which is about 77% and 52% respectively (Ben-Mahmoud, Mansur, et al., 2003).
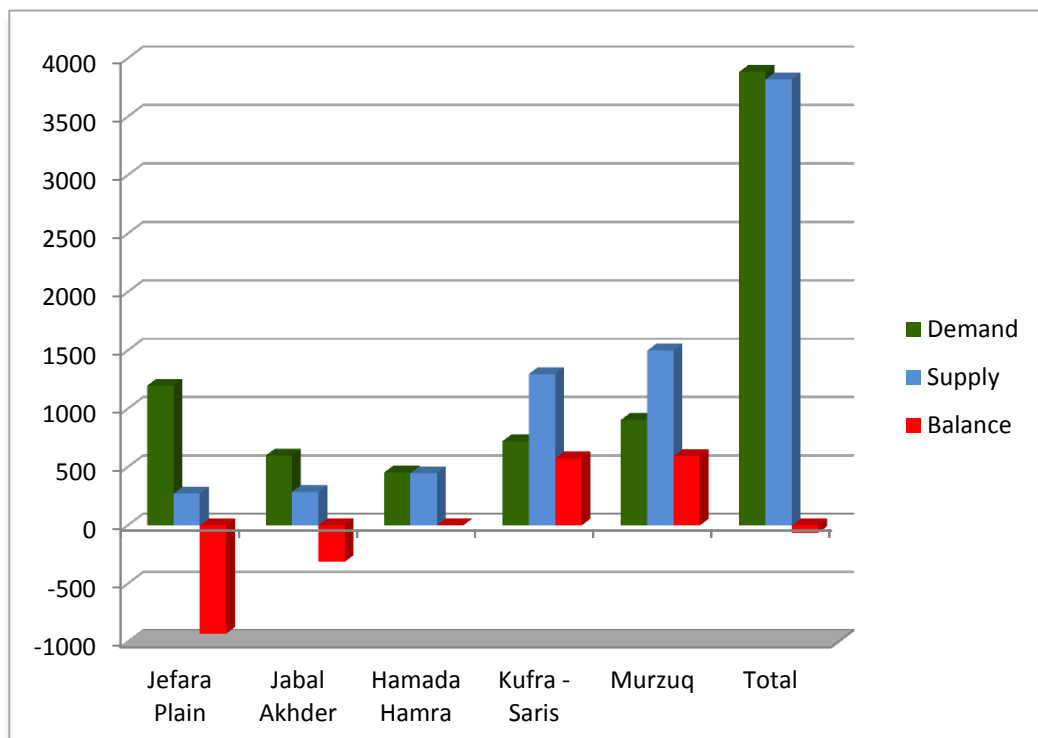
Figure 5-7: *Water balance in the ground water basins in Libya*

Source: *(Ben-Mahmood et al, 2000)*

The water supply in the study area is controlled by Jeffara plain basin located in the northwest part of Libya, which represents more than 80 per cent of the irrigated area in the country. On the other hand there is no regulation of the water extraction and still the sprinkler system is the most common irrigation system use in Libya. The current groundwater production in this region is about 1750 million cubic meters per year. The annual recharge rate is estimated to be around 300 million cubic meters per year. Therefore, this aquifer is greatly over exploited and

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the biggest negative water balances occurs in this region (El Fleet and Baird, 2001).

Over-extraction of groundwater in the coastal belt (particularly in Tripoli region) is leading to a continuing drawdown in the groundwater level, resulting in seawater intrusion. *Figure 5-8* shows the evolution of seawater intrusion during the period from 1957 to 1995, the significant intrusion seawater into coastal aquifers was noted in Gargaresh and Ain Zara for 12 km south the Mediterranean Sea. Groundwater level declines of over 1 meter per year and salinity exceeding 9000 ppm during the last four decades have been observed. The impacts of water salinization have been reported in many of these areas resulting in socio-economic and environmental impacts. These impacts, along with recurrent droughts and uneven population distribution, have led the decision makers to think about transferring of fresh ground water from the south where huge quantities of groundwater are available to the north where it is urgently needed through the implementation of the Great Man Made River (GMMR) (Abufayed and El-Ghuel, 2001).
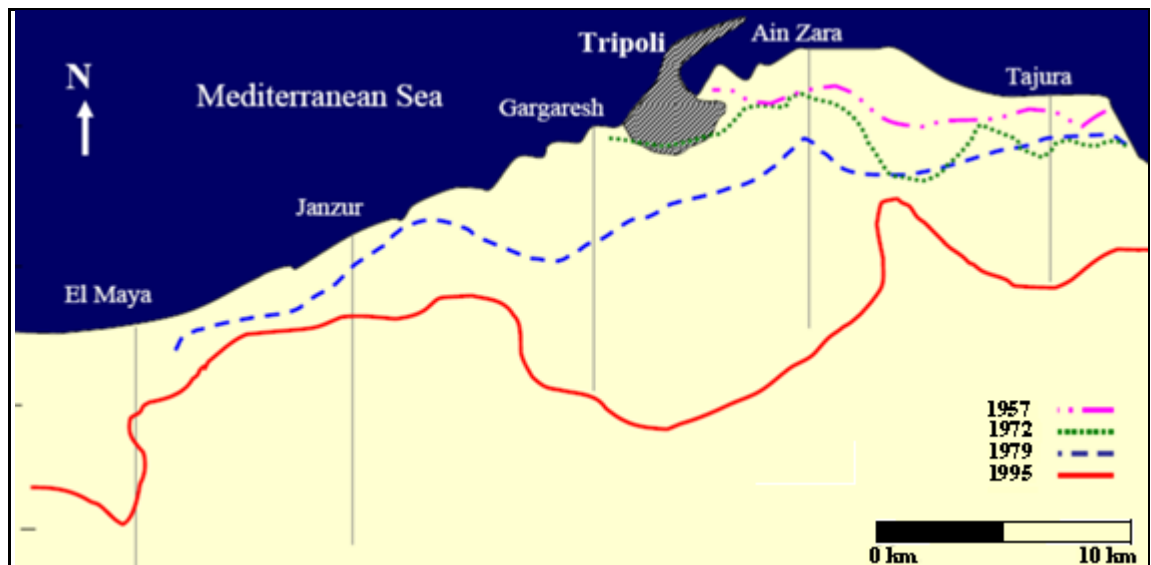
Figure 5-8: Evolution of seawater intrusion in Tripoli region (Salem, 2007)

5.5.5 Water Transfers

To minimize the water deficit in the northern areas of Libya, the country has embarked on one of the world's largest and most expensive groundwater pumping and conveyance project. It is called the *Great Manmade River Project* (GMRP). Construction on this project started in 1984 and the last stage is still under construction. Geological surveys and studies during explorations for oil in southern Libya during the 1960s led to the discovery of large quantities of fresh groundwater in the southern aquifers in the desert (GMRP., 2008). The project aims to use 4m diameter pipes over a length of about 4000 km to transfer 5.68 million *m³/day* from the southern basins to the densely populated areas in the north: 3.68 million *m³/day* to the eastern conveyance system and 2 million *m³/day* to the western system, with 80% of its water being used for irrigation (GMRP., 1990).

The GMRP consists of five stages (*Figure 5-9*). The first and the largest stage is already constructed. It aims to transfer 2 million *m³/day* of water to the east coastal regions extending from Benghazi city to the city of Sirt 500 km west Benghazi. The water is transferred through two pipelines discharge a combined constant flow of 700 million *m³* annually in a huge balancing circular reservoir of 4 million *m³* capacity. The water is carried to Sirt and Benghazi from well fields at Sarir and Tazirbu. The reservoir is located near the city of Ajdabiya on the Mediterranean coast and divided into other two branches. The first branch transfers the ground water eastward toward the city of Benghazi and its surrounding plains. The 2nd branch transfers water westward along the coast toward the city of Sirt. The water flows from the two well fields toward the end of the routes by gravity. In addition, the project is designed to be expanded to carry 3.68 million *m³/day* of water from well fields in Kufrah (GMRP., 1990). The first stage was formally inaugurated in August 1991.

The second stage aims to transfer one million *m³* of water daily from well fields in Murzuq Basin to the western coastal regions and in particular to Jeffara Plain. It is designed to accommodate a further one million m³ a day in the future (GMRP.,

1990). This stage was completed in September 1996 and started supplying Libya's capital, Tripoli with drinking water.

The third stage is an expansion of the first stage (*Figure 5-9*). It designed to increase water flow by 1.68 million *m³* daily. The additional water will be obtained from Kufrah Basin via 700 km of new pipeline and new pumping stations to produce a final total capacity to be 3.68 million *m³/day*. It is also designed to connect the first stage with the second stage to overcome the need of water in the western part of the country (Jeffara plain) (GMRP., 1990). The fourth stage aims to delivers fresh ground water through a pipeline from the Gadammes region to the northern cities as Zawara and Zauia, whereas the 5th stage is to develop a pipeline from the Jaghboub oasis to the city of Tobruk in the eastern part of the country. All stages will be completed in 2015 (El-Tantawi, 2005).

According to GMRP (1990) water transfer is the cheapest option at that time to meet water requirement of the country. In particular, transfer of water is cheaper than water desalinisation. (El_Asswad, 1995) stated that the estimated cost per *m³* is about $ 0.20 and states that the cost is very small compared to other sources such as coastal desalinisation where the cost is approximately $ 3.75 per *m³*. However, (Alghariani and GMMR., 2004) stated the cost of ground water extracted from GMRP was competitive with desalination alternative at the beginning of GMRP, when the desalination still expensive and he said the situation shifted in favour of sea water desalination. The average price of desalinated sea water is dropped from 5.5 US Dollars per cubic meter in 1979 to less than 0.55 $ in 1999 (Owens and Brunsdal, 2000) , according to these figures the water transfer projects as GMRP seems to have to lost their economic benefits over the rapidly development and expanding desalination technology. Since that the major efforts of the local Authority was focused on the GMRP, that the non-conventional sources of water such as desalination plants and wastewater treatment were unconcerned. In order several factors, including poor management and lack of spare parts and local skills for repair, have contributed to the low operating capacities of these units compare with their full operation. These factors

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indicate that desalination has not been taken seriously in the past. In addition wastewater has the potential to play an important role to meet the increasing water demand in the country particularly in the agriculture and industrial sectors since it is one of the renewable resources of water.
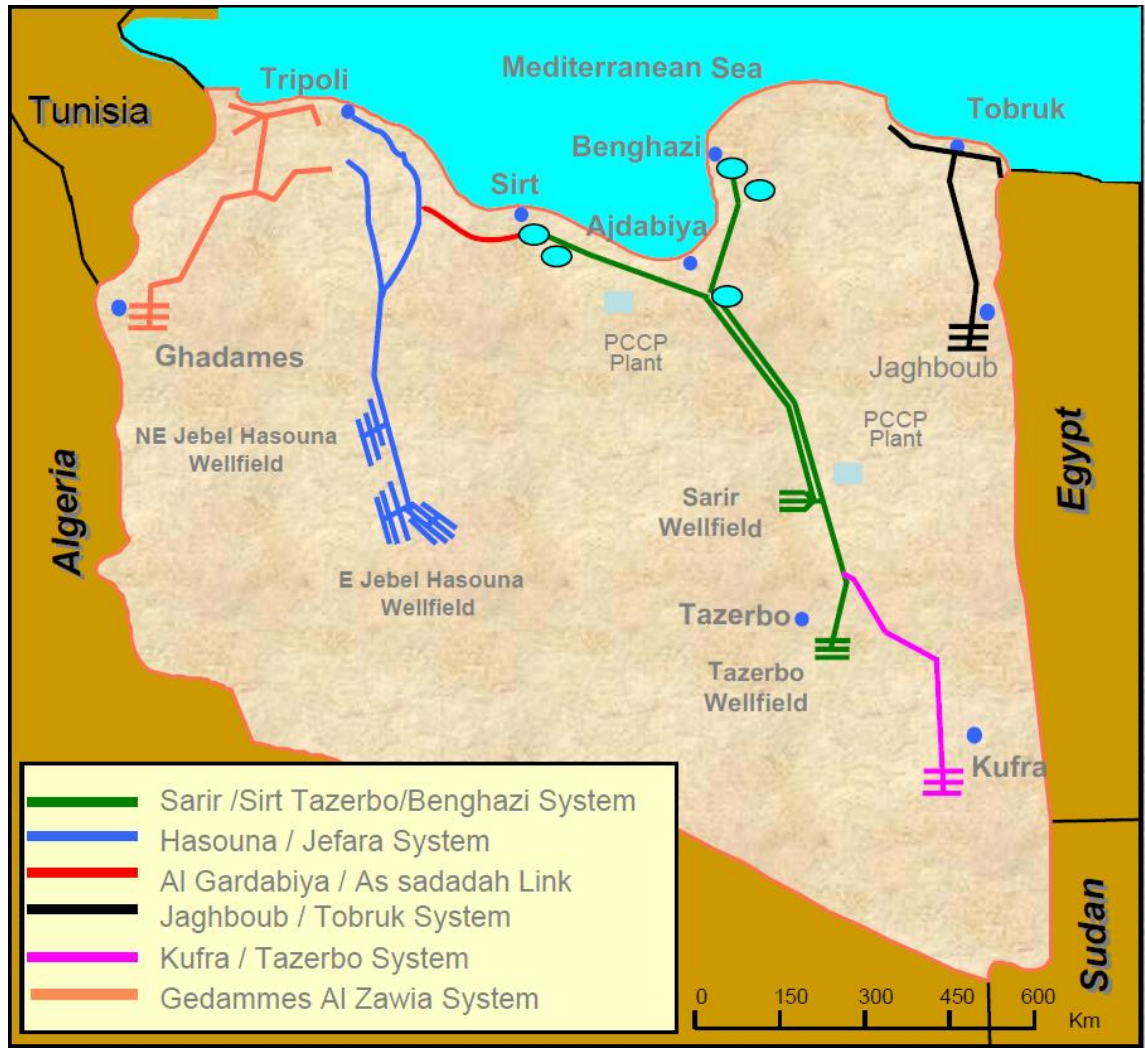
Figure 5-9: *The stages of the Great Man-made River Project*

Source: *(GMRP, 1990)*

5.6   Natural Vegetation

Vegetation in Libya like the arid lands in northern Africa is characterized by scatter distribution and usually referred to as steppes. In years of good rainfall the coastal plains are covered by annual grasses and other herbaceous vegetation (El-Tantawi, 2005). The flora of Libya is not rich in the number of species. However, the landscape of Jabal al-Akhdar comprises the richest vegetation and the highest number of species known in Libya (Hegazy, Boulos, et al., 2011).

In Jeffara Plain, the steppe in the northern and eastern parts seems as spots and in the western part is negligible**.** Deforestation and over-grazing process in Jeffara plain affect both soil and vegetation, by the loss of the organic matter in the soil profile. In the last 30 years, a large area of vegetation was cleared in Jeffara Plain for increasing cereal crops cultivation. Most of the land cover in Jeffara plain is rangeland which represents 67.9% of the total area, while irrigated land and rainfed land represent 2.5 and 8.2 respectively (*Figure 5-10*).

In pastoral rangelands, there is an initial deterioration in the composition of pastures is observed. This is because of excessive grazing in dry periods. Jifara Plain has been significantly degraded in quantity and quality of vegetation. Vegetation destruction takes place by overgrazing and over cultivation. For example growing wheat and barley in marginal lands, climatically unsuitable or without adequate water resources, both activities being driven by the needs of rapidly growing population (El-Tantawi, 2005).

Degradation of the natural vegetation, already in a precarious balance with the low and variable precipitation in the country, is caused by heavy overgrazing and expressed by a loss of cover and palatable species. The comparison of remote sensing imagery between 1986 and 1996 in a pilot area in the rangelands of the north-western Jeffara Plain indicated a 52% reduction in vegetation cover, accompanied by a 227% increase in sand dune formation, as a result of both overgrazing and fuel wood extraction (Ben-Mahmoud, Mansur, et al., 2003).
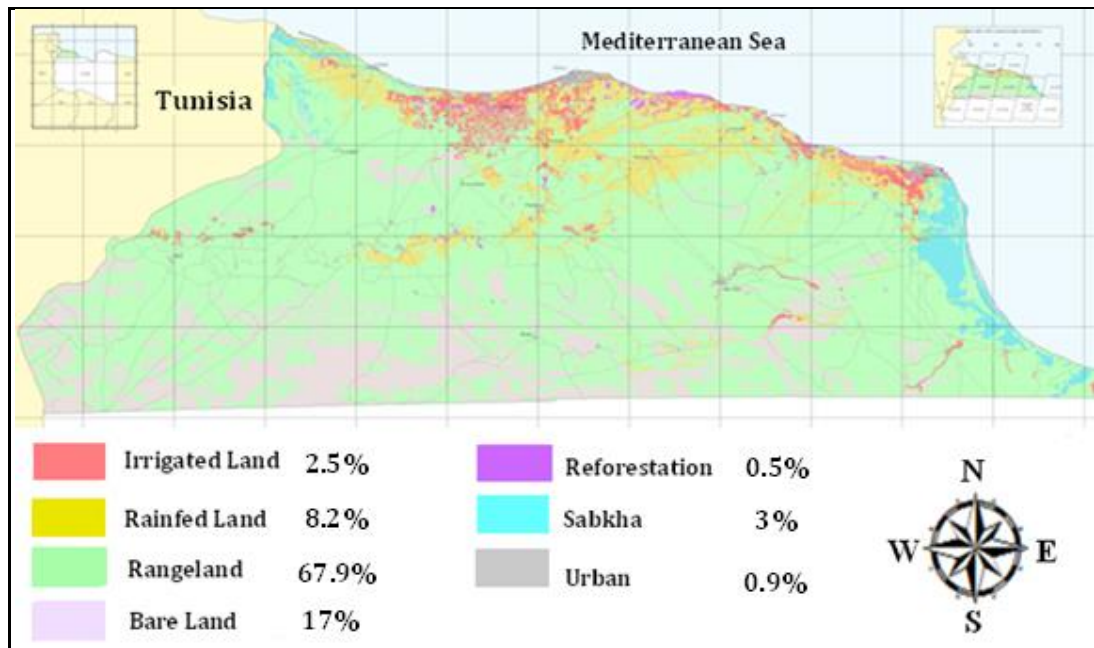
Figure 5-10: *Land cover in the north west of Libya (ARC, 2004)*

5.7 Agriculture in Libya

The arable areas in Libya are estimated at about 2.28 million ha (1.25% of the country's total area), with 1.93 million ha for annual crops such as (barley, wheat, oats and alfalfa), and 0.35 million ha for permanent crops such as olive, palm, almonds, apples, figs and citrus. In addition there are 13.3 million ha of permanent pastures. There are recent agricultural development projects in the southern desert that are also being cropped (about 35000 hectares). The agricultural areas can be divided into four physiographic regions: The coastal plains that stretch along the Libyan coast; the northern mountains that located close to coastal plains and include the Jabal Nafusa in the west and the Jabal Al-Akhdar in the east, the internal depressions that cover the center of Libya and include several oases; and the southern mountains and sand dunes (Ben-Mahmoud, 2001).

In recent years food security has taken centre stage in the country's policy. The aim is to achieve self-sufficiency for some agricultural products that contribute largely to the diet of most Libyans, thus decreasing the requirements for food

imports (GMRP., 1990). The major agricultural products in Libya are: cereals, legumes, vegetables, fruits, meat, and dairy products. *Table 5-4* shows the production/supply situations for the main agricultural production during the late of nineties, from which it is clear that self-sufficiency for fruit and oil crops are almost achieved, but not for the rest of products (Wheida b and Verhoeven, 2007).

Table 5-4: *Food supply in Libya (Wheida, et al, 2007)*

Crop	Production (1000 tons)	Supply (1000 tons)	Self-sufficiency rate (%)
Wheat	142	1360	10
Barley	165	0	100
Legumes	18	25	42
Fruit	366	388	95
Vegetables	864	1340	64
Olive	202	233	87

The recent development in agriculture is directed towards increasing the total production of cereals in order to reduce the gap between the production and supply. The implementation of the irrigation projects (GMRP) will contribute to total production and, therefore, decrease the deficiency in these products. According to agricultural census conducted by General Information Authority (GIA) in 2007, wheat production in 2007 achieved an increase in production by 41.9% compared with the year 2001(GIA., 2007)**.**

The increase in the agriculture production has been due to an increase in the extent of irrigated areas. However, this increase in production can be associated

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with a number of predominant soil-related issues, particularly in some parts of the north west of Libya. One of the most important issues is the increased soil salinity. Selkhozpromexport (1980) stated that about 12% of the land in the north west are affected by salinity. This may have resulted from irrigation with saline water or over-irrigation causes capillary movements of hidden salts from lower layers in this soil (Fernández, 2009). In many areas, rising water tables have led subsequently to water logging and associated salinity problems. This has happened where drainage development has not kept pace with irrigation development, or where maintenance of drainage facilities has largely been neglected. Therefore, it is a vital that these soil related issues to be considered in the design of future irrigation schemes and their subsequent operation.

5.8 Summary

In this chapter, a brief description of Libya was introduced .The main context of the chapter is an overview of natural resources (soil, water, climate and vegetation) in Libya. It is clear that the country suffers from the limitation in fertile soils and water supplies as well, due to low rainfall and high temperature. The expanding economy and growing population in Libya are creating increasing pressures on groundwater resources in the coastal area where about 70% of population are concentrated. To minimize the water deficit in the northern areas of Libya, the country decided to transfer fresh ground water from the desert aquifers to the coastal area and water desalination is considered as a future alternative. It is planned to utilise about 80% of the transferred water to produce the most important crops for Libyan diet such as barley and wheat. In order to achieve the best use of the transferred water, there is a need to develop land evaluation methodology for Libya.

In the next chapter, the methodology and the needed data for assessing land suitability in the study area are discussed.

Chapter 6

THE LAND SUITABILITY MODEL IN THE STUDY AREA

6.1 Land Suitability Assessment in the Study Area

As noted earlier, the assessment of land suitability for crop production usually uses either quantitative or qualitative approach. Quantitative evaluation is particularly important for economic surveys and depends on detailed information regarding the present agricultural and other rural economy statistics such as estimates of crop yields, an inventory of the technical and institutional infrastructure, available information on population and its present and probable future rates of change, labour potential, educational levels, etc (FAO, 1976). Qualitative classification describes relative suitability in qualitative terms only, without reference to economic conditions such as the costs and return of investment (Rossiter and Van Wambeke, 1997). Qualitative procedures give suitability expressions, such as highly suitable, moderately suitable, marginally suitable and not suitable for each land use. A physical suitability evaluation indicates the degree of suitability for a land use, without reference to economic conditions.

As mentioned earlier in Chapter 2, the evaluation in this research is limited to qualitative land evaluation based on physical conditions. Currently there is no plan to conduct any economic evaluation in the study area. The main reasons for the difficulty of conducting an economic evaluation in the study area are:

1. There are rapid changes in the market in Libya. Therefore any economic evaluation in Libya may become outdated rapidly;
2. Economic evaluation requires the availability of relevant data. There is no reliable economic database in Libya and usually the available information is incomplete.

6.2 Database for Land Suitability Assessment in the Study Area

Land suitability assessment for crop production involves the interpretation of data relating to soils, climate and topography into a suitable format to allow land suitability analysis to take place. Land qualities and their associated land characteristics were presented in Chapter Four and are arranged in four categories. The process of assessment the land suitability is based on matching land characteristics with crop requirements to produce thematic map layers for each category as outlined in *Figure 6-1*.
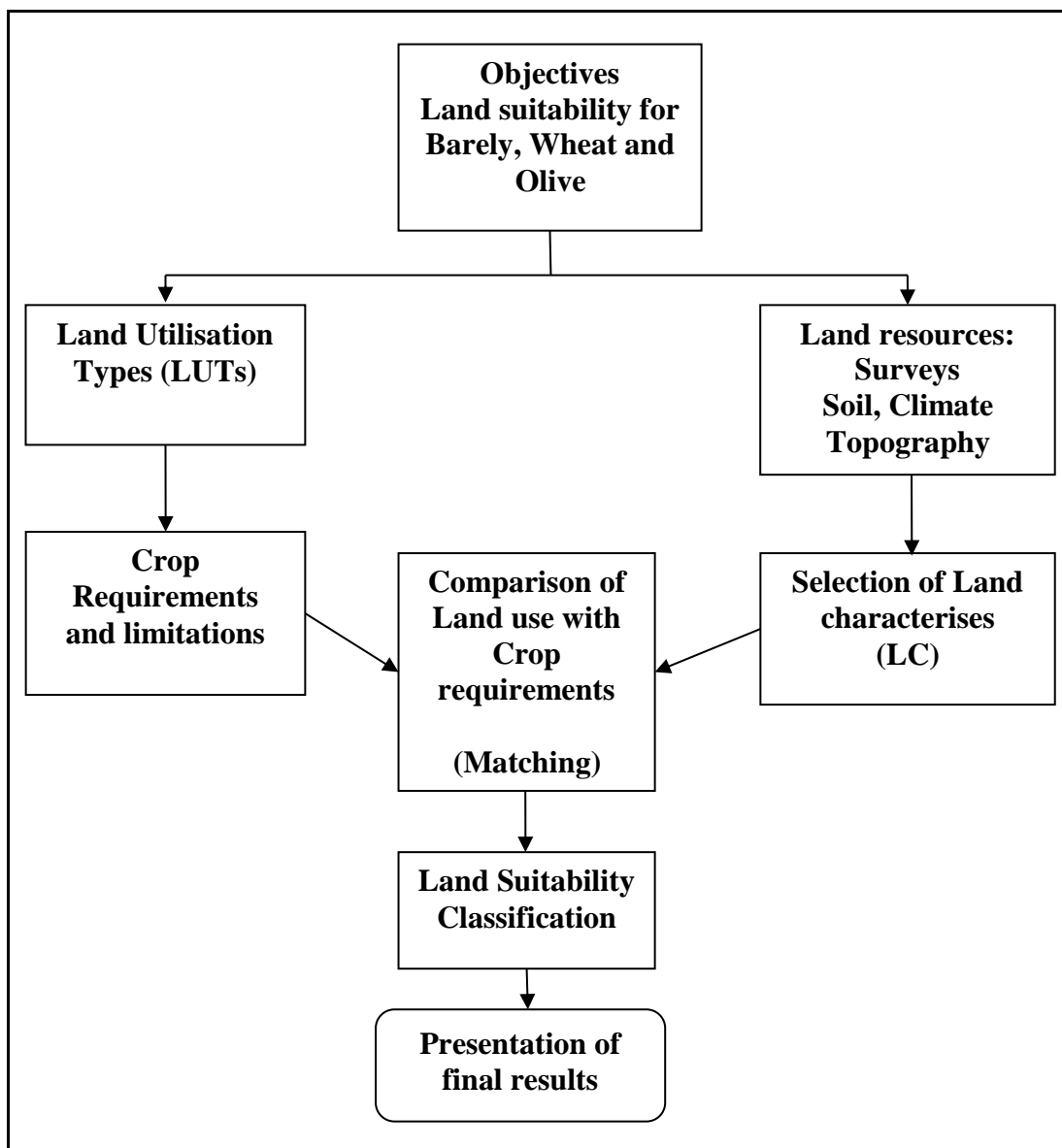
Figure 6-1: *Outline of the land suitability evaluation process*
Source: (FAO 1976)

The physical and chemical soil characteristics for each of the soil subtypes were joined with soil classification map (scale 1:50 000) and prepared for use in GIS as data layer. Moreover, contour map for the study area is available at a scale of 1:50 000. The contour map was applied in GIS to produce slope map. The details for producing each layer are presented later in section (6.5).

6.3   Land Evaluation Modelling

Boolean logic as mentioned in Chapter 3 has only two possible suitability classes only true or false in the classification system. A class in Boolean approach is expressed only as being full or none, or 1 or 0. The conventional concept of modeling has been used a Boolean approach to produce land suitability map for specific land use. The deficiencies of conventional Boolean logic for designing land suitability evaluation have been discussed by many authors such as (Burrough, MacMillan, et al., 1992, Keshavarzi, Sarmadian, et al., 2010) and are documented in chapter 3. Therefore, Fuzzy modelling appears as an alternative approach to situations where zones of gradual transition are used to divide classes instead of the conventional crisp boundaries. While in Boolean logic a value is true or false, with fuzzy logic the value could be partially false or partially true which allows for a representation that is more according to the reality (Burrough, MacMillan, et al., 1992).

6.4   Fuzzy Modelling for Land Suitability

Fuzzy logic application in land evaluation studies has seen resurgence since then 1987 (Sicat, Carranza, et al., 2005). As mentioned in Chapter 3, the Fuzzy logic is an extension to classic Boolean logic to present the concept of partial truth between completely true and completely false (Zadeh, 2008). Through the use of fuzzy logic approach the strict Boolean logic of suitability as determined by suitable or non-suitable land qualities is replaced by fuzzy membership functions. Land qualities that exactly match the strictly defined suitable situation are assigned a membership value of 1. Land qualities which do not match the defined class will get membership values between 0 and 1 corresponding to their

closeness to defined class, the closer membership values to 1 the higher land suitability (Joss, Hall, et al., 2008). The membership function of a fuzzy logic illustrates how the grade of membership of a land quality in the different land units is determined. The membership function values assigned to each object range between 0 and 1, the higher grade of membership the closest class value to 1. *Figure 6-2* shows the difference in land suitability between Boolean and fuzzy sets according to soil depth as example.
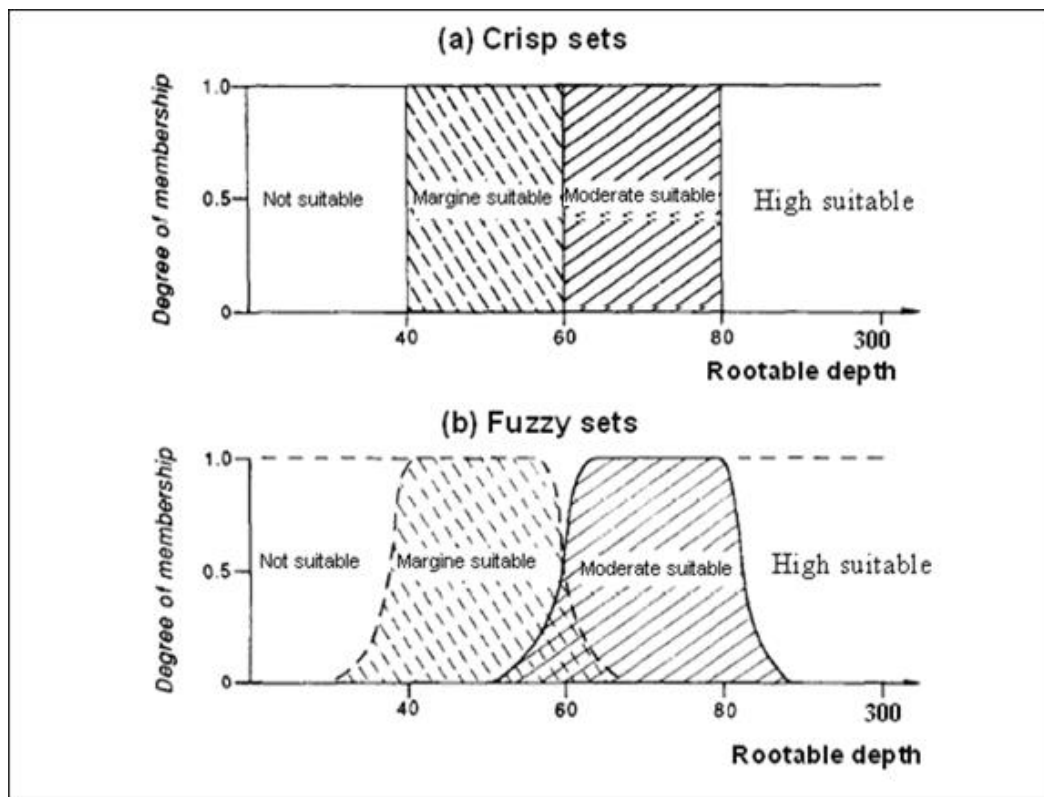
Figure 6-2: Typical presentation of crisp sets and fuzzy sets

The selection of membership functions is a critical issue in the use of fuzzy logic methodology since the degree of land suitability will be defined according to the membership value. The rationale governing the selection of the type of membership function has been presented in chapter 3. In the present study, different kind of membership functions were used depending on the threshold

values of land characteristics and the way in which these factors affect land suitability Other critical issues are the definition of weights, which represent the degree of importance of each land quality regarding to crop yield or land suitability, and the combination of all land qualities to produce final overall land suitability (Groenemans, Van Ranst, et al., 1997). However, often the selection of these weights is subjective; consequently to avoid the uncertainty from such subjectivity no weighting of the soil characteristics has been carried out in the study.

6.5   Methodology

The methodology is based on matching land characteristics with crop requirements (FAO Framework, 1976) to produce four layers namely: Soil, climate, erosion hazard and slope, which are important for land suitability for the selected crops in the study area. These layers were integrated into the GIS environment as information layers and then the overall land suitability map for the selected crops was produced using raster overlay as shown in Figure 6-3.

The methodology of study consisted of three steps:

1. Soil layer was created by matching soil characteristics with crop requirements based on the theory of fuzzy logic. Also Boole's logic is used to compare the results obtained from using fuzzy.

2. Climate, slope and erosion layers were created using conventional Boolean approach due to the difficulty of applying fuzzy logic from the available data and also because most of the study area are considered either highly suitable or moderately suitable class regarding these factors. For soil layer each polygon in the area represents a kind of soil and has specific properties (soil characteristics) which can be applied in Fuzzy logic. However, with other layers there are no individual properties for each polygon, because the map is in raster format, based on contour map e.g. the slope layer or based on the location of climate stations in the case

of climate layer. The Kriging tool in GIS was used for interpolation to cover whole of the study area. The pixel size for each cell was 200×200 meter.

3. The four layers: soil, climate, erosion hazard and slope were overlaid to produce the overall land suitability for each kind of the crops.
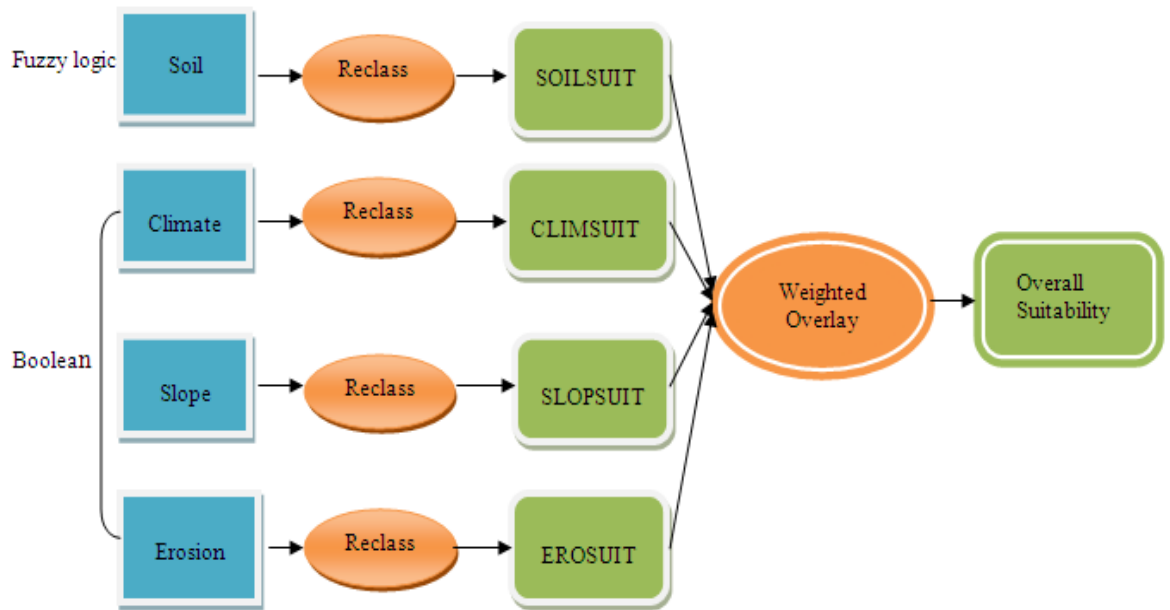
Figure 6-3: Overlay of layers to produce land suitability map

6.5.1   Soil layer

The available spatial information to this study is limited to 1:50,000 soil maps and soil survey. In this study both Boolean and fuzzy approach were used. Firstly conventional Boolean was used to produce soil layer by using a spreadsheet to match soil characteristics with crop requirements (Figures 6-4, 6-5 and 6-6). The thresholds values for crop requirements are deduced from some experiments and studies in Agriculture Resource Centre (ARC) in Tripoli and other sources, e.g. (FAO, 1983 and Sys, 1993). The details of requirements for each crop were obtained from literature and data provided by the Agriculture Research Centre in Libya. These details have been presented in Chapter 4. Secondly, Fuzzy logic

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approach was used to avoid the sharp definition of the boundaries between land suitability classes or land characteristics.

6.5.1.1 *Boolean based soil layer*

Physical and chemical soil characteristics were stored in spreadsheet model in excel (*Figure 6-4)*. The Boolean "if" function was used to set the suitability class, each type of soil takes a degree of suitability class for each soil characteristics by matching soil characteristics with crop requirements for each crop (*Figure 6-5*). For example, soil salinity for soil class name *Siallitic cinnamon typical carbonate soils* (CS_t_ca) is 9.6 ds/m (Selkhozpromexport, 1980), by applying this value in the model we got moderately suitable (2) for barley and not suitable (4) for wheat because soil salinity of more than 9.6 ds/m is considered not suitable for wheat while, values between 8 and 10 ds/m is moderately suitable for barley.

The overall soil suitability classes for each crop was determined using Mode function in excel (*Figure 6-6*) and exported from the spreadsheet model to the soil classification map in GIS and then the soil layer was created for each crop.
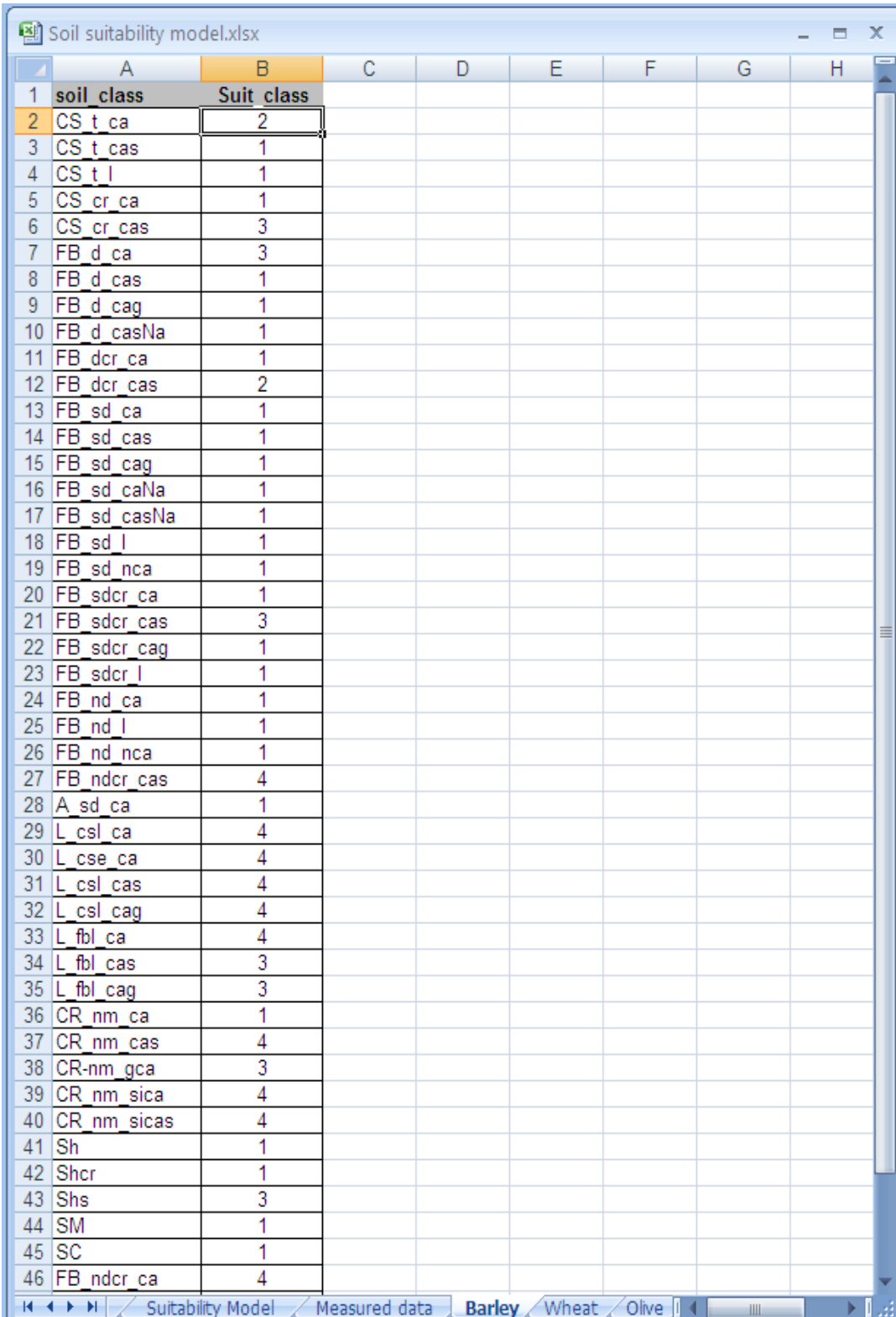
	B	C	D	E	F	G	H	I	J	K	L
	B1	▾	f_x	Soil_Depth (cm)							
1	Soil Depth (cm)	AWHC (mm)	pH	EC(ds/m)	ESP (%)	CaCo$_3$ (%)	stoness (%)	Infi_rate(mm/hr)	CEC (meq/100g)	OM (%)	Soil Texture
2	300	97.2	8.3	9.6	0.03	15.0	0.0	6.6	9.6	0.35	sandy clay loam
3	300	133.2	8.3	7.3	0.09	37.4	2.2	6.6	7.26	0.43	sandy loam
4	300	97.8	8.1	3.6	0.04	1.0	0.0	6.6	3.59	0.17	sand
5	120	170.4	8.9	7.5	0.09	14.3	4.0	7.8	7.45	0.29	sandy loam
6	50	187.2	8.4	7.7	0.1	12.9	23.1	7.8	7.68	0.5	loamy sand
7	300	136.9	8.7	10.9	0.02	13.7	3.3	6	10.88	0.25	sandy loam
8	150	143.8	9.0	6.6	0.02	16.1	0.0	6	6.64	0.26	sandy loam
9	180	176.7	7.9	4.6	0.07	32.9	0.0	6	4.58	1.21	sandy clay loam
10	230	114	8.0	6.4	0.22	31.8	2.8	6	6.41	0.31	sandy loam
11	120	99.4	8.0	5.9	0.03	12.4	0.6	15	5.93	0.26	sandy loam
12	72	133.4	8.7	4.6	0.21	17.1	3.7	15	4.55	0.33	sandy clay loam
13	215	79.7	8.6	4.6	0.02	28.6	0.0	10.2	4.63	0.2	sand
14	300	94.5	8.6	7.5	0.04	10.7	0.0	10.2	7.53	0.21	sandy loam
15	203	36	8.2	7.8	0.05	19.7	0.0	10.2	7.81	0.33	sandy clay loam
16	195	98.3	8.7	6.0	0.32	12.3	0.0	10.2	6.01	0.3	sandy loam
17	300	94.7	8.3	8.9	0.84	9.8	0.0	10.2	8.94	0.24	sandy loam
18	300	101.9	8.2	5.1	0.02	0.8	0.0	10.2	5.1	0.09	sand
19	300	313.2	7.7	3.5	0.02	0.0	0.0	10.2	3.51	0.17	sand
20	120	79	8.3	5.8	0.02	12.3	0.0	10.8	5.8	0.25	loamy sand
21	50	92.4	8.2	5.4	0.17	15.3	4.5	10.8	5.4	0.41	sandy loam
22	102	133	8.6	5.3	0.07	12.6	0.0	10.8	5.28	0.12	sandy loam
23	77	71.5	8.0	5.4	0.02	0.2	0.0	10.8	5.41	0.13	sand
24	300	58	6.6	5.4	0.01	1.9	0.0	13.2	5.43	0.05	sandy clay loam
25	120	77.4	7.6	5.4	0.02	0.1	0.0	13.2	5.38	0.01	loamy sand
26	300	57.8	8.2	4.5	0.01	0.0	0.0	13.2	4.52	0.02	sand
27	75	110.2	8.3	4.8	0.03	11.5	1.5	6	4.83	0.1	sand
28	300	85	8.1	9.6	0.01	8.1	0.0	5.4	9.58	0.28	sandy loam
29	28	109.2	8.5	8.8	0.44	17.9	36.7	3	8.8	0.94	sandy loam
30	21	125	8.5	8.9	0.12	29.9	21.7	3	8.92	0.93	loam
31	28	155.4	8.0	8.0	0.12	21.8	37.3	3	7.97	0.63	loam
32	13	103	7.7	6.6	0.12	10.2	28.8	3	6.62	0.65	loam
33	18	81	9.0	9.2	0.26	15.5	25.0	6	9.2	0.82	sandy clay loam
34	18	134	8.1	12.3	0.22	13.3	51.4	6	12.26	1	sandy loam
35	18	90	7.5	6.6	0.1	7.2	11.8	6	6.6	0.61	sandy loam
36	38	165	8.0	5.0	0.27	21.4	4.3	2.4	5.04	0.09	sand
37	40	126.6	8.4	8.7	0.2	33.6	22.9	2.4	8.71	0.8	loam
38	55	76	8.2	8.3	0.11	6.3	0.0	2.4	8.34	0.25	sandy loam
39	38	78.7	8.5	4.9	0.16	51.0	10.2	2.4	4.88	0.11	sand
40	18	80.2	8.5	4.4	0.24	42.7	13.5	2.4	4.4	0.12	loam
41	80	269.7	8.6	4.7	0.19	26.6	1.0	1.8	4.67	0.31	sandy loam
42	90	270.7	8.9	9.1	0.12	8.9	1.7	1.2	9.07	0.65	sandy loam

Figure 6-4: *Database for soil characteristics*

Soil suitability model.xlsx

Crops			Barley				Wheat			
Land Use Requirements	Unit	**Suitability Classes**					**Suitability Classes**			
Land Characteristics (LC)		S1	S2	S3	N1		S1	S2	S3	N1
Rootable depth	cm	100	100	70	30		120	80	50	50
			70	30				100	80	
AWHC	mm	150	110	75	75		150	150	100	80
Soil reaction	pH	6.2	5.3	5	5		6.5	5.5	5	5
		8	6.2	5.3			8	6.5	5.5	
Organic Matter %	O.M	1.5	1	0.4	0.4		1.5	1	0.5	0.5
Soil Salinity	EC	0	8	10	13		0	6.0	7.4	9.5
		8	10	13	24		6	7.4	9.5	13
Cation Exchange Capacity	CEC	16	8	5	5		24	16	12	12
Soil alkalinity	ESP	0	15	25	50		0	15	25	35
Calcium Carbonate	CaCo3%	0	15	20	30		0	15	20	30
CaCo3		15	20	30			15	20	30	
Stones	%	0	3	9	15		0	3	9	15
		3	9	15	40		3	9	15	40
Inflirtration rate	mm/hr	12	8	6	6		12	8	6	6
Soil Texture										

BARLEY

Land Characteristics		Unit	CS_t_ca	CS_t_cas	CS_t_l	CS_cr_ca	CS_cr_cas	FB_d_ca	FB_d_cas	FB_d_cag	FB_d_casNa
LC1	Rootable depth	cm	1	1	1	1	3	1	1	1	1
LC2	AWHC	mm	3	2	3	1	1	2	2	1	2
LC3	Soil reaction	pH	4	4	4	4	4	4	4	1	1
LC4	Organic matter	O.M %	4	3	4	4	3	4	4	2	4
LC5	Cation Exchange Capacity	CEC	2	3	4	3	3	2	3	4	3
LC6	Soil salinity	EC	2	1	1	1	1	3	1	1	1
LC7	Soil alkalinity	ESP	1	1	1	1	1	1	1	1	1
LC8	Carbonate	%	2	4	1	1	1	1	2	4	4
LC9	Stones	%	1	1	1	2	4	2	1	1	1
LC11	Infiltration rate	mm/hr	3	3	3	3	3	3	3	3	3
LC12	Soil Texture	Class	2	4							

Land Qualities		CS t Ca	CS t Cas	CS t l	CS cr ca	CS cr cas	FB d ca	FB d cas	FB d cag	FB d casNa
LQ1	Rooting Conditions	1	1	1	1	3	1	1	1	1
LQ2	Moisture Availability	3	2	3	1	1	2	2	1	2
LQ3	Nutrient Availability	4	4	4	4	4	4	4	1	1
LQ4	Nutrient Retention	4	3	4	4	3	4	4	4	4
LQ5	Excess of Salts	2	1	1	1	1	3	1	1	1
LQ6	Soil Toxicities	2	4	1	1	1	1	2	4	4
LQ7	Conditions for germinations	1	1	1	2	4	2	1	1	1
LQ8	Infiltration	3	3	3	3	3	3	3	3	3
LQ9	Texture	2	3	4	3	3	3	3	2	3
Overall Suitabilty rating	LUT1	2	1	1	1	3	3	1	1	1

Figure 6-5: *Suitability Model for the study area*

1 is high suitability (S1), 2 is moderate suitability (S2), 3 is margin suitability and 4 means not suitable (N)

	A	B	C	D	E	F	G	H
1	soil_class	Suit_class						
2	CS_t_ca	2						
3	CS_t_cas	1						
4	CS_t_l	1						
5	CS_cr_ca	1						
6	CS_cr_cas	3						
7	FB_d_ca	3						
8	FB_d_cas	1						
9	FB_d_cag	1						
10	FB_d_casNa	1						
11	FB_dcr_ca	1						
12	FB_dcr_cas	2						
13	FB_sd_ca	1						
14	FB_sd_cas	1						
15	FB_sd_cag	1						
16	FB_sd_caNa	1						
17	FB_sd_casNa	1						
18	FB_sd_l	1						
19	FB_sd_nca	1						
20	FB_sdcr_ca	1						
21	FB_sdcr_cas	3						
22	FB_sdcr_cag	1						
23	FB_sdcr_l	1						
24	FB_nd_ca	1						
25	FB_nd_l	1						
26	FB_nd_nca	1						
27	FB_ndcr_cas	4						
28	A_sd_ca	1						
29	L_csl_ca	4						
30	L_cse_ca	4						
31	L_csl_cas	4						
32	L_csl_cag	4						
33	L_fbl_ca	4						
34	L_fbl_cas	3						
35	L_fbl_cag	3						
36	CR_nm_ca	1						
37	CR_nm_cas	4						
38	CR-nm_gca	3						
39	CR_nm_sica	4						
40	CR_nm_sicas	4						
41	Sh	1						
42	Shcr	1						
43	Shs	3						
44	SM	1						
45	SC	1						
46	FB_ndcr_ca	4						

Figure 6-6: Land suitability for barley

6.5.1.2   *Fuzzy based soil layer*

With using the fuzzy approach, six of the soil properties were selected to produce the soil layer. The properties are namely: Available water holding capacity; Soil depth; Infiltration rate; Soil texture; Soil salinity; Soil reaction. The selection of these characteristics is based on the recommendation from local experts and literature review. The aforementioned characteristics are the most influential on land productivity in Libyan conditions (Ben-Mahmoud, 1995). The other 5 soil characteristics that featured in the Boole's analysis, i.e.(stones, calcium carbonate, organic matter, cation exchange capacity and soil alkalinity) do not show significant spatial variability in the area. This is why they have not been included in the fuzzy analysis because including them would have increased the number of rules enormously without providing any significant effect on the outcome of the fuzzy analysis.

Fuzzy logic method presented in (Section 3.5) was used to generate continuous values of soil suitability based on matching soil characteristics with crop requirements. The model consisted of 3 sub models, each with 2 parameters that are closely related i.e.: i) soil depth and available water holding capacity, ii) infiltration rate and soil texture and iii) soil salinity and soil reaction). The outputs of these models were used as inputs to a fourth sub model to arrive at the overall soil suitability (*Table 6-1*).

***Table 6-1:** The inputs and output of Fuzzy logic models*

Model	Inputs	Output
Model (1)	1. Available water holding capacity (AWHC) 2. Soil depth (RD).	The suitability degree of AWHC and RD
Model (2)	1. Infiltration rate. 2. Soil texture.	The suitability degree of infiltration rate and soil texture.
Model (3)	1. Soil salinity (EC). 2. Soil reaction (pH).	The suitability degree of EC and pH.
Model (4)	1. The output of model 1. 2. The output of model 2. 3. The output of model 3.	Overall soil suitability.

The model was divided into 3 sub models, so as to minimise the number of rules which grows exponentially with the number of input variables. This increases the incidence of error in the results because of overlapping between the rules. (Kaehler, 1998) stated that Fuzzy logic can process any reasonable number of inputs but system complexity increases rapidly with more inputs and outputs. He concluded that distributed processors would be easier to implement.

AS mentioned in Chapter 3 the membership function can take any shape and can be symmetrical or asymmetrical. In this study *triangular* and *trapezoidal* membership functions were used because these functions gave the best representation of the model by observing the change in the output values by changing the input values manually. *Triangular* function (trimf) was used to describe marginal suitability class (MS) because it has tree distinct points, while *trapezoidal* function (trapmf) was used to describe functions that have four distinct points such as high suitability class (HS) and not suitable class (NS). For example, membership function of not suitable class for soil depth for barley Trapmf (NS) has 4 distinct points (0, 0, 30, 50) (*Table 6-2*). The values which are

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less than 30 cm is considered completely not suitable and take membership function 1 for not suitable, the values between 30 and 50 cm take membership function partially marginally suitable and partially not suitable. For example, the membership functions for 35 cm soil depth are 0.30 marginally suitable and 0.7 not suitable (*Figure 6-8*). The value 0 is repeated to indicate that all values which are less than 30 cm take a straight line and that means these values are completely not suitable and take membership function 1for not suitable function (N).

Table 6-2 presents the inputs for each sub model and the shape of membership functions associated with threshold values for the variables of each sub model according the land suitability rating for land characteristics for the selected crops as mentioned earlier in Chapter 4. The rationale governing the selection of the type of membership function and whether the model is symmetrical or asymmetrical has been explained in Chapter 3. Both symmetrical and asymmetrical models were used in this study. The membership functions for each model are tested by observing in rule viewer the changes in the output to see if such changes are consistent with the changes in the input values one would expect that. For example, if the value of soil salinity increases the soil suitability should decrease and so a membership function that does not provide this consistent outcome will be rejected as an unsuitable function. The way the rule viewer tool is used for this purpose is illustrated later in *Figure 6.11*.

Table 6-2: *The kind of membership functions and threshold values for each input*
for Barley

Model	Inputs	Membership Functions	Threshold values	Fuzzy set models
1	Soil depth (RD)	Trapmf (HS)	50, 80, 200, 200	Asymmetrical left
		Trimf (MS)	30, 50, 80	
		Trapmf (NS)	0, 0, 30, 50	
	Available water holding capacity (AWHC)	Trapmf (HS)	110, 150, 200, 200	Asymmetrical left
		Trimf (MS)	75, 110, 150	
		Trapmf (NS)	50, 50, 75, 110	
2	Infiltration rate (IR)	Trapmf (HS)	9, 12, 20,20	Asymmetrical left
		Trimf (MS)	6, 9, 12	
		Trapmf (NS)	0, 0, 6, 9	
	Soil texture	Trapmf (HS)	0, 0, 1, 3	Asymmetrical right
		Trimf (MS)	2, 3, 4	
		Trapmf (NS)	3, 4, 5, 5	
3	Soil salinity (EC)	Trapmf (HS)	0, 0, 4, 10	Asymmetrical right
		Trimf (MS)	7, 10, 13	
		Trapmf (NS)	10, 13, 15, 15	
	Soil reaction (pH).	Trimf (HS)	5, 7, 9	Symmetrical
		Trimf (MS)	4, 5, 7	
		Trapmf (NS)	8, 10, 12, 12	
4	Outputs for sub models (1, 2, 3)	Trimf (HS)	6, 9, 12	Asymmetrical left
		Trimf (MS)	3, 6, 9	
		Trimf (NS)	0, 3, 6	

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Figure 6-7 shows the process of producing the soil layer. Soil suitability results for each crop were joined with the soil classification map then soil layer is produced.
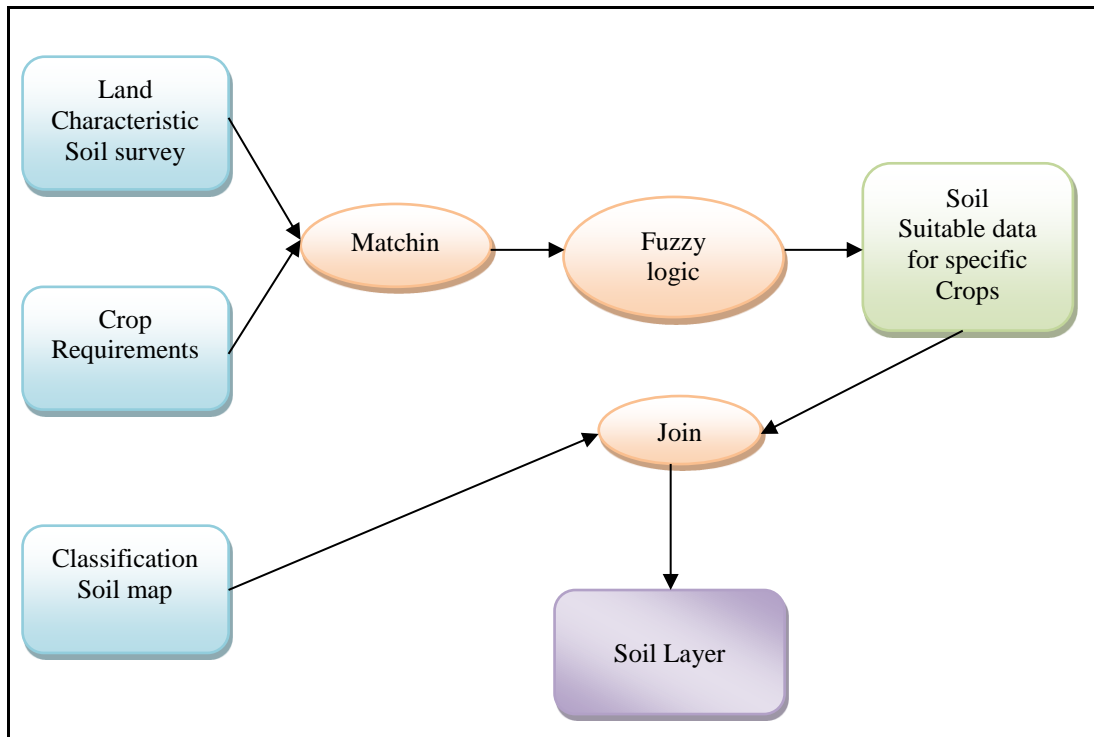
Figure 6-7: *The process of produce soil layer*

The process of fuzzy logic model as mentioned earlier in Chapter 3 consists of three main steps: *fuzzyfication*, *fuzzy rule inference*, and *defuzzification*. Fuzzy logic modelling was performed using software fuzzy logic Toolbox- MATLAB (2009) and the model results were spatialized and mapped using a GIS environment.

6.5.1.3 Fuzzification

 In this step the quantitative values for each soil characteristics were converted into linguistic terms. The *fuzzification* includes three steps (Joss, Hall, et al., 2008).

(a) Translating the empirical values into linguistic variables.

(b) Defining membership functions to represent the linguistic variables.

(c) Applying membership function to each input empirical value to determine degree of class membership (i.e., from 0 to 1) for each of the linguistic variables.

The values of each soil characteristics were converted into three linguistic variables according to suitability rating for soil characteristics for each crop that were: highly suitable (HS), marginally suitable (MS) and not suitable (NS). The number of membership functions was limited to three to keep the number of rules needed for fuzzy inference low to avoid the error that may occur when the number of rules is high. The output values of the model are soil suitability expressed as a percentage ranging between 0 and 100. These values can be divided on 4 classes to match the 4 classes of the rest of layers.

Thus three membership functions were defined for each soil characteristics as input environmental variable, one for each linguistic variable. A membership function translates the fuzzy subset (A) to a membership value between and including 0 and 1, where $\mu A(x) = 0$ means that x does not belong to subset A, $\mu A(x) = 1$ indicates that x fully belongs, and $0 < \mu A(x), < 1$ means that x belongs to some degree to subset A (Burrough et al. 1992). For instance, the values of soil depth for barley were translated into the linguistic variables: values above 80 cm were considered high suitability; values ranging between 30cm to 80 cm rated marginal suitability and those less than 30 cm were considered not suitable. The membership functions for soil depth are shown in (*Figure* 6-8).
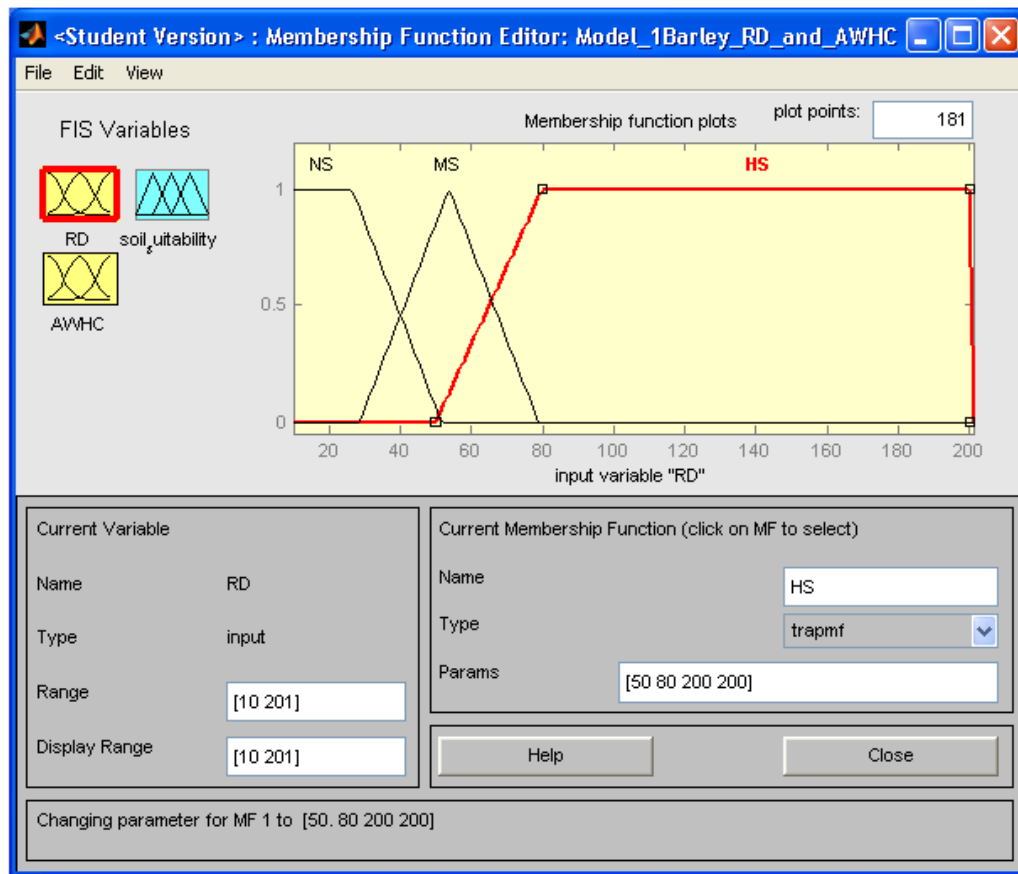
Figure 6-8: *Membership function for soil depth*

6.5.1.4   *Fuzzy rule inference*

The second step in the fuzzy logic modelling process was the definition of the rules to model the output into one of three suitability classes as mentioned before. These rules translate the linguistic variables into numerical output. These rules are based on conditional statements *IF*-part and a conclusion *THEN*-part. The *IF*- part may include more than one condition linked together by linguistic conjunction such as *AND* and *OR* (Bardossy, 1996).

As noted previously, the possible number of rules can be calculated using *Equation 3.12*. The number of rules is dependent on the number of inputs and the number of membership functions. In this study, 9 rules are created to define the conditions in models 1, 2 and 3, while 27 rules were created for model 4 because there are 3 inputs and 3 membership functions for each input in this model.

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Table 6-3 presents the fuzzy rules generated for sub models (1, 2 and 3) with 9 rules for each sub model. *Table 6-4* presents the fuzzy rules generated for overall soil suitability model 4 which consists 27 rules describing the relationship between the input variables and the output variable. Each rule listed in the table consists of an IF and THEN part. The IF part specifies a set of conditions and the THEN part specifies the conclusion; For example, rule 2 in (*Table 6-3)* and rule 3 in (*Table 6-4)* can be read as:

IF soil depth is highly suitable *AND* available water holding capacity is moderately suitable *THEN* soil is high suitability.

IF the output of model 1 is highly suitable *AND* the output of model 2 is highly suitable *AND* the output of model 3 is non-suitable *THEN* the soil is moderate suitability.

Table 6-3: *The fuzzy rules generated for sub model 1*

Rule No	Rule Antecedent (IF)			THEN	Consequent Parameters
	Soil depth RD	AND	AWHC		
1	High		High		High suitability
2	High		Moderate		High suitability
3	High		Not suitable		Moderate suitability
4	Moderate		High		High suitability
5	Moderate		Moderate		Moderate suitability
6	Moderate		Not suitable		Not suitable
7	Not suitable		High		Moderate suitable
8	Not suitable		Moderate		Not suitable
9	Not suitable		Not suitable		Not suitable

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Table 6-4: *The fuzzy rules generated for overall soil suitability model 4*

Rule Number	Rule Antecedent (IF)			THEN	Consequent Parameters
	Output 1	Output 2	Output 3		
1	High	High	High		High suitability
2	High	High	Moderate		High suitability
3	High	High	Not suitable		Moderate suitable
4	High	Moderate	High		High suitability
5	High	Moderate	Moderate		Moderate suitability
6	High	Moderate	Not suitable		Moderate suitability
7	High	Not suitable	High		Moderate suitable
8	High	Not suitable	Moderate		Moderate suitable
9	High	Not suitable	Not suitable		Not suitable
10	Moderate	High	High		High suitable
11	Moderate	High	Moderate		Moderate suitable
12	Moderate	High	Not suitable		Moderate suitable
13	Moderate	Moderate	High		Moderate suitable
14	Moderate	Moderate	Moderate		Moderate suitable
15	Moderate	Moderate	Not suitable		Moderate suitable
16	Moderate	Not suitable	High		Moderate suitable
17	Moderate	Not suitable	Moderate		Moderate suitable
18	Moderate	Not suitable	Not suitable		Not suitable
19	Not suitable	High	High		Moderate suitable
20	Not suitable	High	Moderate		Moderate suitable
21	Not suitable	High	Not suitable		Not suitable
22	Not suitable	Moderate	High		Moderate suitable
23	Not suitable	Moderate	Moderate		Moderate suitable
24	Not suitable	Moderate	Not suitable		Not suitable
25	Not suitable	Not suitable	High		Not suitable
26	Not suitable	Not suitable	Moderate		Not suitable
27	Not suitable	Not suitable	Not suitable		Not suitable

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6.5.1.3 *Defuzzification*

The *defuzzication* is the last step in the fuzzy logic modelling process. In the *defuzzification* the outputs of all the rules are combined to produce a crisp output. In other words, the fuzzy output is converted back to crisp value (Rustum, 2009). The centroid calculation method is the most commonly used methods of *defuzzification* because it provides an accurate result based on the values of the output membership functions. The method measures the centre of area under the curve in the intersection of the horizontal axis and the centroid(Fuzzy Logic Toolbox™ User's Guide line, 2009, Bai,20006, Nazz, 2011).. The only disadvantage of this method is that it is computationally difficult for complex membership functions (Nazza, 2011).

As mentioned earlier in (*Table 6-1*) the model consists of 3 sub models, each with 2 parameters that have an impact on each other. For example, in sub model 1 soil depth affects available water holding capacity. The output values of sub models 1, 2 and 3 are aggregated and used as inputs in model 4 (overall soil suitability). The process of aggregation output values for barley as example is shown in Figures (6.9 – 6.12)**.**

Figure 6.9 shows the process of aggregation output values for sub model (1). The sub model consists of the combination of two land characteristics soil depth and available water holding capacity. The sub model includes 9 rules describing the suitability of these two land characteristics for cultivation at different values for these two factors. For example, looking at row 1 (rule1) which is available in table (6.3) if soil depth (RD) is high and available water holding capacity is high then soil suitability is high suitability. The user just needs to put the input values to get the output value as seen from *Figure 6.9*. For example if soil depth is 106 cm and the available water holding capacity is 125 mm then the degree of soil suitability regarding to these two factors is 10/12 which equals 0.83 (*Figure 6.9*).
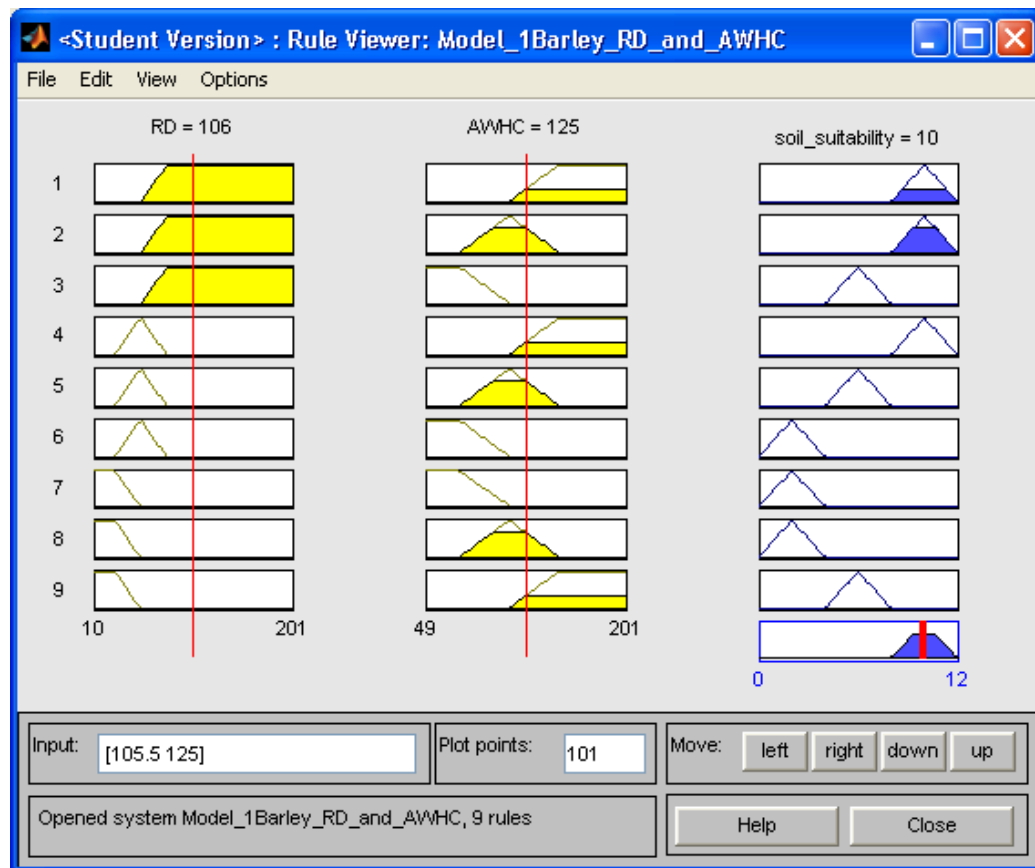
Figure 6-9*: The process of aggregation output values for sub model (1)*

Figure 6.10 shows the process of aggregation output values for sub model (2). The sub model consists of the combination of two land characteristics infiltration rate and soil texture. An example of this sub model if infiltration rate is 10 mm/hr and soil texture class is 2.5 then the degree of soil suitability regarding to these two factors is 7.7/12 which equals 0.64 see (*Figure 6.10*).
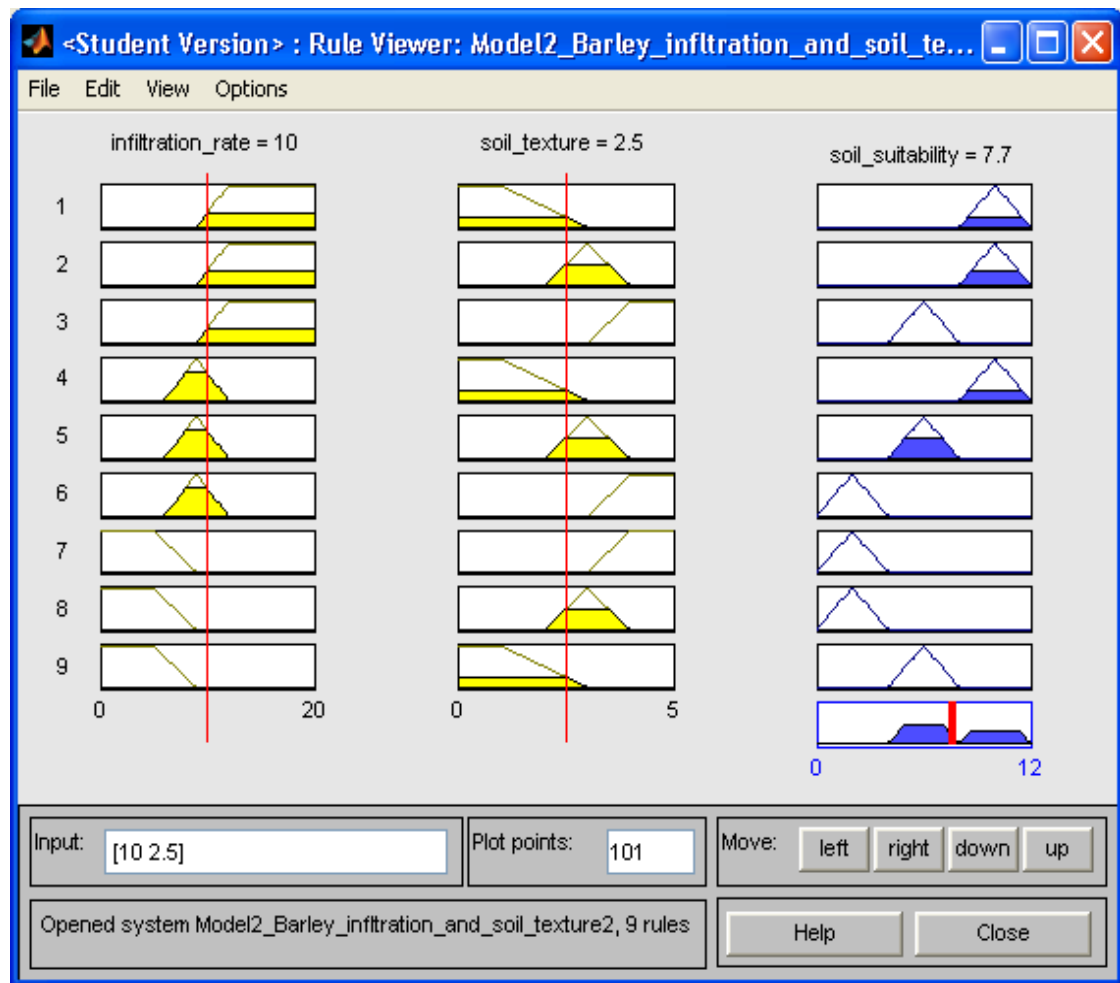
Figure 6-10: *The process of aggregation output values for sub model (2)*

Figure 6.11 shows the process of aggregation output values for sub model (3). The sub model consists of the combination of two land characteristics: soil salinity (EC) and soil reaction (pH). An example of this sub model if soil salinity is 7.5 ds/m and soil reaction (pH) is 7.5 then the degree of soil suitability regarding to these two factors is 10/12 which equals 0.84 (*Figure 6.11*).

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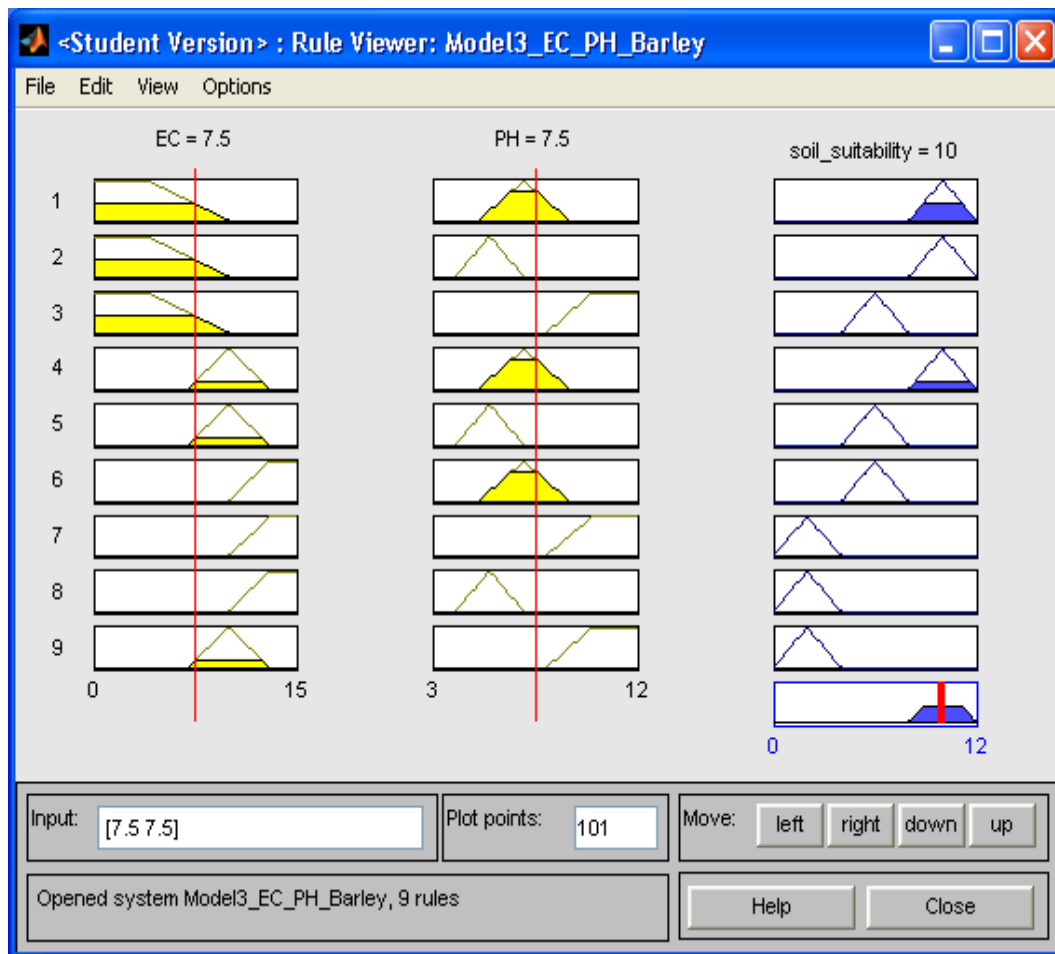
Figure 6-11: The process of aggregation output values for sub model (3)

The process of aggregation output values for model (4) which presents the overall soil suitability is illustrated in *Figure 6-12*. As mentioned previously the model consists of 27 rules because there are 3 inputs and 3 membership functions. An example of this model, if the output of sub model 1 is 4, the output of sub model 2 is 3 and the output of sub model 3 is 3 then the output of the model is 0.167 which means that this soil is not suitable. There are four defined classes were created to correspond to the four suitability classes S1 from (60-84%), S2 (40-60%), S3 (25-40%) and N less than 25%.

The output values of model 4 (overall soil suitability) are aggregated and joined with the soil classification map of the study area to produce soil layer for each crop.
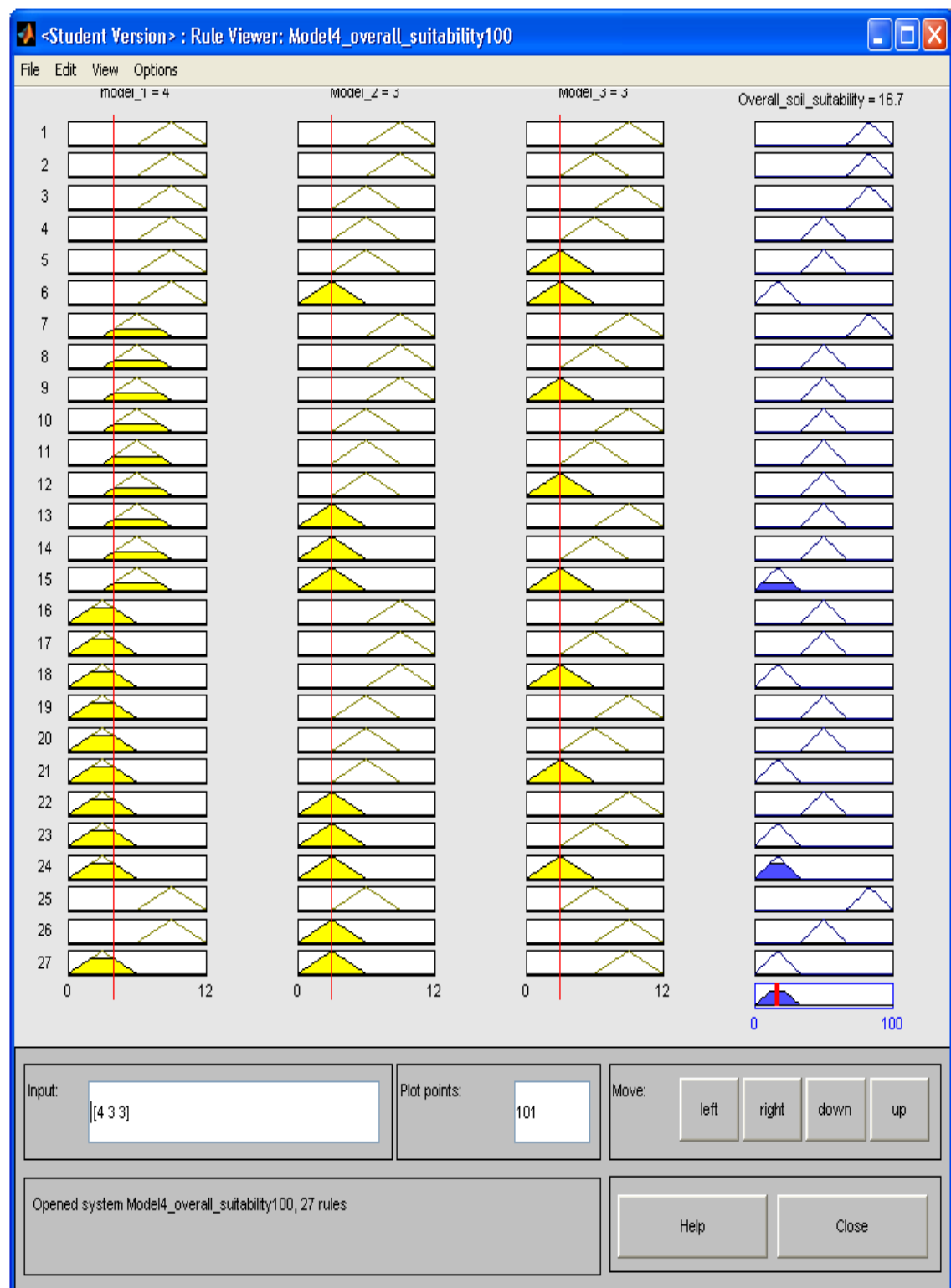
Figure 6-12: *The process of aggregation output values for model (4)*

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6.5.2   Slope Layer

The slope layer was produced from the contour map of study area. The map is available from (Development of a Data Integration and Analysis Tool for Environment and Natural Resources Assessment) in Libya. Surface function of ArcGIS was applied to convert contour map to slope grid map. The classes of Slope layer was produced according to slope suitability categories mentioned in Chapter 4. Slope layer for the study area is shown in *Figure 6-13*. It is clear that the slope in most of the study area is considered in the suitable range.
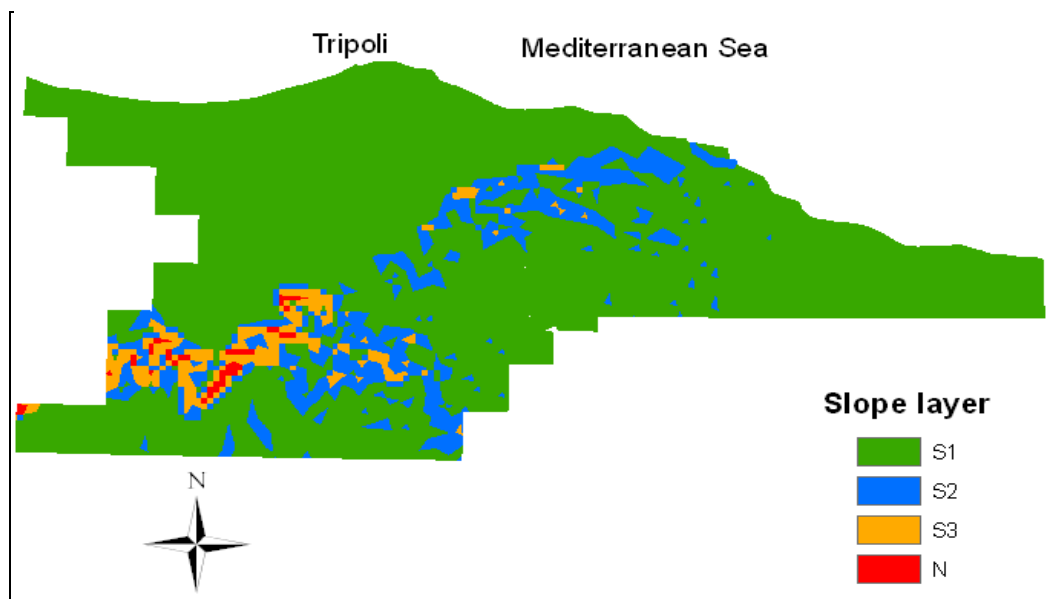
Figure 6-13: *Slope layer for the study area*

6.5.3   Climate Layer

As noted earlier, temperature and rainfall are the two main climatic factors that can affect land suitability in the study area. The average mean temperature for 12 climatic stations in the study area over the growing period from October to May varies between 14C° to 17.7 C°. This range is within the optimal temperature for the selected crops. The rainfall in this study is used to determine the Length of Growing Period (LGP). This term refers to the period of the year in which agricultural production is possible from the viewpoint of moisture availability and absence of temperature limitations. In addition, the amount of soil moisture stored in the soil profile can be taken into account to define the (LGP). FAO

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(1978) recommended a general figure of 100 mm storage water based on the knowledge that annual crops can utilize stored soil moisture in the range of 75-125 mm. The average available water holding capacity for the soils in the study area is 117mm. Therefore, in this study a value of 100 mm was used to estimate the contribution of soil moisture in the LGP.

The number of days in which the soil can retain moisture after rainfall can be estimated by dividing the 100 mm by the value of potential evapotransperation (ETP). For example, if the rate of ETP is 3mm/day in March then the number of days that moisture can be kept stored in the soil profile is 33 days, and available to a crop which means if there was sufficient rainfall in February we can add March into LGP (months) even there was no rainfall in March.

FAO (1978) stated that for rainfed crops, $0.4 - 0.5$ times the level of potential evapotranpiration (ETP) is considered sufficient to meet water requirements of dryland crops. Based on (FAO, 1978) recommendation the (LGP) can be estimated as follows:

$$x_m = P_m - \frac{ETP_m}{2} \tag{6.1}$$

Where:

m = months (1, 2,………,12)

$x_m x_m x_m =$ net rainfall in month m (mm)= net rainfall in month m *(mm)*

P_m = mean precipitation in month m (mm).

ETP_m = mean potential evapotranspiration in month m (mm).

Then determine LGP (months) as:

$$LGP = \sum_{m=1}^{12} n_m \tag{6.2}$$

Where

$$n_m = \begin{cases} 1; & if\, x_m > 0 \\ 0; & otherwise \end{cases}$$

6.5.3.1 Potential Evapotranspiration (ETP)

Potential Evapotranspiration (ETP) was assessed using Penman Montheith method (1991). The FAO was recommended this method as a standard method for estimating evapotranspiration (Allen, Pereira, et al., 1998). The method takes into account most of the factors that affect evapotranspiration such as temperature, wind speed, relative humidity and solar radiation. The climate data for 12 stations covering most of the study area were collected from Libyan National Meteorological Centre (LNMC). The data include: temperature, precipitation, wind speed, sunshine hours and relatively humidity are presented in (Appendix A3). These climatic elements as well as latitude and longitude were applied in (CROPWAT 8) to estimate ETP for each station based on Penman Montheith method. CROPWAT is a computer program for the calculation of crop water requirements and irrigation requirements developed by the Land and Water Development Division of FAO (FAO, 2008). The monthly values of ETP for 12 stations in the study area for the period (1994-2008) are shown in (*Table 6-5*).

Table 6-5*: The mean ETP values (mm/day) for the period (1994-2008)*

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Longitude	Latitude
Tripoli	2.2	2.9	4.0	5.5	7.2	8.3	8.2	7.7	6.3	4.5	2.9	2.2	13.09	32.42
Alhadbah	1.8	2.3	3.1	4.3	5.3	6.2	6.3	5.9	4.7	3.3	2.2	1.7	13.1	32.48
Alkomes	2.1	2.7	3.2	4.2	5.1	5.8	6.2	5.4	5.2	4.1	3.0	2.3	14.17	32.37
Yefren	2.1	2.9	3.9	5.7	7.2	8.3	8.6	7.9	6.3	4.6	3.2	2.2	12.31	32.04
Sorman	2.1	2.8	3.5	4.6	5.5	6.0	6.4	6.2	5.1	3.8	2.6	2.1	12.35	32.46
Zawia	1.9	2.5	3.2	5.0	6.0	6.7	6.7	6.5	5.3	3.9	2.6	2.1	12.45	32.45
Alzahra	1.9	2.5	3.4	5.0	6.1	6.8	7.0	6.6	5.2	3.1	2.5	1.9	12.53	32.4
Zwara	2.6	3.2	3.9	5.1	5.8	6.4	6.6	6.7	5.8	4.7	3.4	2.7	12.05	32.56
Esbaae	2.2	2.9	4.0	5.5	7.2	8.3	8.2	7.7	6.3	4.5	2.9	2.2	13.1	32.32
Grian	2.1	2.7	3.6	5.2	6.8	8.1	8.0	7.4	6.1	4.1	3.0	2.3	13	32.1
Rojban	2.2	3.0	4.1	6.0	7.6	8.8	8.9	8.1	6.7	4.9	3.3	2.4	12.07	31.59
Misurata	2.7	3.3	3.8	4.9	5.6	6.3	6.3	6.2	5.7	4.6	3.6	3.0	14.59	32.22

Rainfall and potential evapotranspiration are the two factors which are essential for estimating the LGP values. Using *Equation 6.1* we can obtain a single value of the mean LGP for each station in the study area these are shown in *(Table 6-6)*. In general as seen in table 6.8, the LGP is highly variable in Libya, varies from the minimum of 2.50 months at Rojban in the south western to 4.90 months at Alzahra in the wetter north western part of the country. Since the evapotranspiration values at the stations are broadly similar as shown in 6.7, the large variation in the LGP values presented in *Table 6.8* could be attributed to the large spatial variation in the rainfall and the dominant influence of the rainfall on the LGP as expected.

However, this value does not give any information about the uncertainty associated with the prediction of the LGP. In reality, since both the rainfall and evaporation (especially rainfall) exhibit within-month (temporal) variability. In the next sub section confidence interval estimation was presented to determine the uncertainty associated with the estimate of the LGP.

6.5.3.2   *Confidence Interval Estimation*

For each station, the LGP formula was applied *(Equation 6.1)* to each of the 12 months for 15 years and hence the estimation of the LGP for each year was obtained.

By Assuming that the LGPs values are normally distributed, then the 95% confidence interval for the LGP value can be calculated using *Equation 6.3*. The 95% confidence interval for the LGP values is shown in *Table 6-6*.

$$95\% \ CONF \ (LGP) = \mu \pm 1.96 \ \sigma \qquad\qquad (6.3)$$

Where

(Mean) $\mu = \dfrac{1}{N} \sum\limits_{i=1}^{N} (LGP_i)$ $\qquad\qquad$ (6.4)

N is the number of years

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$$\text{(Standard deviation)} \quad \sigma = \sqrt{\frac{1}{N-1} \sum_{i=1}^{N} (LGP_i - \mu)^2} \tag{6.5}$$

Table 6-6: *The 95% confidence interval for the LGP values*

Station	LGP_mean (month)	LGP_lower (month)	LGP_ upper (month)
Tripoli	2.70	0.03	5.30
Alhadbah	4.20	2.07	6.30
Alkomes	4.00	2.15	5.80
Yefren	3.50	1.09	5.90
Sorman	3.30	0.54	6.00
Zawia	3.10	0.18	6.08
Alzahra	4.90	0.27	9.44
Zwara	2.90	0.31	5.54
Esbaae	2.70	0.00	5.40
Grian	4.10	1.80	6.40
Rojban	2.50	0.09	4.97
Misurata	2.70	0.24	5.08

Similarly, the 95% confidence limits for the mean LGP can be calculated using *Equation 6.6*. The 95% confidence limits for the mean LGP is shown in *Table 6-7*

$$95\% \; CONF \; (\mu) = \mu \pm 1.96 \frac{\sigma}{\sqrt{N}} \tag{6.6}$$

Table 6-7: *The 95% confidence limits for the mean LGP*

Station	LGP_mean (month)	LGP_min (month)	LGP_max (month)
Tripoli	2.70	1.98	3.34
Alhadbah	4.20	3.60	4.70
Alkomes	4.00	3.40	4.60
Yefren	3.50	2.90	4.16
Sorman	3.30	2.56	3.96
Zawia	3.10	2.37	3.89
Alzahra	4.90	3.10	6.59
Zwara	2.90	2.25	3.60
Esbaae	2.70	2.00	3.40
Grian	4.10	3.50	4.70
Rojban	2.50	1.9	3.2
Misurata	2.70	2.04	3.29

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In this study, the LGP mean values were used to give a suitable grade for each station regarding the contribution of LGP in crop growing. Numerical numbers were given for each suitability class to be applied in geographic information system (GIS). *Table 6-8* presents the suitability class for LGP values and their corresponding numbers.

Table 6-8: *The suitability class for LGP values*

LGP_mean (month)	Suitability class
0-2	Not suitable (4)
2-3	Marginally suitable (3)
3-4	Moderate suitable (2)
4-6	Highly suitable (1)

6.5.3.3   *Producing Climate map*

To produce climate map, the suitability classes for the LGPs mean were exported to GIS and joined with stations location map of the study area. Climate layer was created using Kriging tool in ArcGIS. The climate layer for the study area is shown in *Figure 6-14*. The climate layer shows that most of study area is moderately suitable which is to be expected since the area receives a reasonable amount of rainfall for rainfed agriculture (see Chapter 5). For irrigated agriculture the most influential climate factor will be temperature.
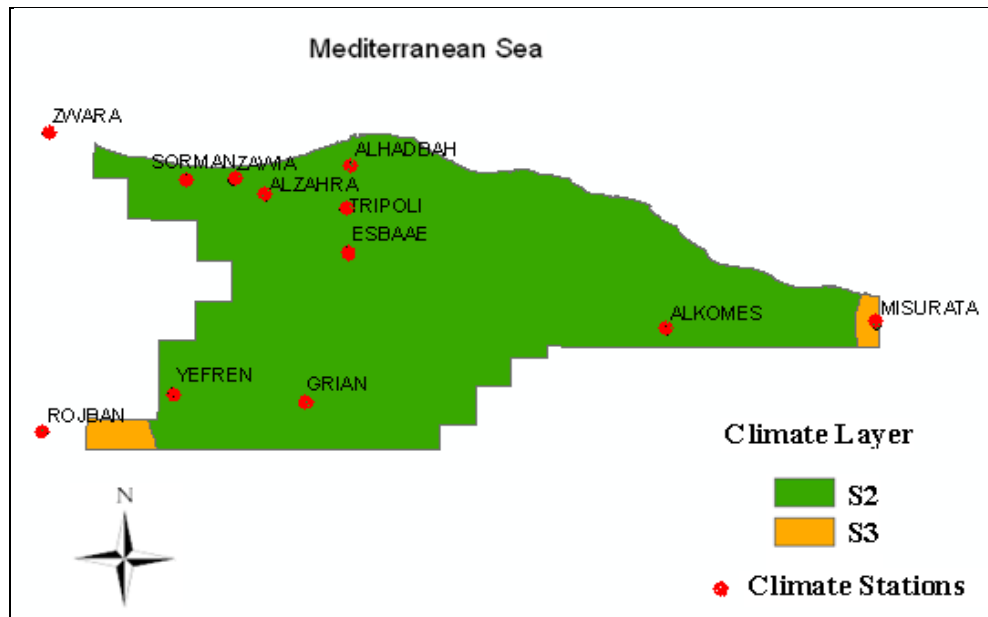
Figure 6-14: *Climate Layer for the study area*

6.5.4   Erosion Layer

Erosion layer gives information or indicators about predicted hazard erosion that could be occur in the area. Field measurement of soil erosion is expensive, time-consuming and always problematic due to the variation rates of soil erosion cross the landscape and even within the small areas. Therefore, the most of erosion hazard assessment methods are based on predicting soil loss by modelling the parameters of climate, soil erodibility, slope and vegetation (FAO, 1983). The Universal Soil Loss Equation (USLE) is the most widely accepted model of estimating soil loss. The model originally developed in the USA to predict average annual soil loss for a long term under different types of crop management system. The USLE is an empirical model developed by analysing more than 10,000 plot-years of runoff and soil loss data from small plots distributed across the USA, which gives a good representation of different environmental conditions (Wischmeier and Smith, 1978).

Selkhozpromexport (1980) in their study in Libya stated that water erosion is common in the north western zone where the area receiving more than 200 mm of rainfall per year. The study indicated that 70% of north western zone and 88% of north eastern zone are subject to water erosion. Ben-Mahmood (2001) stated that

wind erosion is prevalent in arid climate area where there is the absence of adequate vegetation cover and the soil is light texture.

6.5.4.1 *Determining Soil Erosion*

The USLE model is a relatively simple erosion model and easy to apply and thus requires less data. Integrating the model with GIS environment facilitates data manipulation, data input and output display. The major advantage of using GIS in the USLE model is GIS spatial display and analysis facility allow the USLE model to be applied for individual raster cells. Another advantage of GIS USLE approach is its ability to predict the annual soil loss for a large area due to the interpolation capabilities of GIS (Lufafa, Tenywa, et al., 2003).

The USLE equation (Wischmeier and Smith, 1978) was applied in a GIS environment to estimate the annual average soil loss in the study area. The factors that control the soil erosion namely: climate, soil, vegetation, topography and management are combined in the empirical USLE model (*Equation 6.7*) to predict soil loss for a given site, each values at a particular location can be expressed numerically (Wischmeier and Smith, 1978). The USLE soil erosion is calculated as follows:

$$A = R \times K \times L \times S \times C \times P \qquad\qquad (6.7)$$

Where:

A = Annual soil loss in $(t. ha^{-1}. yr^{-1})$

R = Rainfall erosivity factor $(MJ. mm. ha^{-1}. yr^{-1})$

K = Soil erodibility K- factor $(t. MJ^{-1}. mm^{-1})$

L = Slope length factor

S = Slope steepness factor

C = Crop and management factor

P = Conservation-supporting practices factor

The data for the model were collected for 12 climate stations in the study area and soil survey data and topographic maps. Individual GIS files were built for each

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factor of the USLE and combined by using raster calculator in ArcGIS to predict soil loss in the spatial domain then erosion layer is produced.

(a) Determining rainfall factor (R)

Rainfall erosivity is considered the most important factor in soil erosion. Soil erosion by running water occurs where the intensity and duration of rainstorms exceeds the capacity of the soil to infiltrate the rain. The R factor of USLE (Wischmeier and Smith, 1978), for any given period is determined by summing the kinetic energy of the rainstorms maximum 30-minutes intensity. However, these figures are rarely available at standard meteorological stations. Therefore, some other equations have been proposed such as that by Fournier (1960):

$$F = \frac{(p_m)^2}{p_a} \tag{6.8}$$

Where

F is Fournier index;

p_m is the maximum monthly rainfall depth (mm)

Pa is the annual rainfall depth (mm)

Arnoldus (1980) revealed that Fournier index gave poorly correlated ($r^2 = 0.55$) with R_factor values at 178 climate stations (164 stations in the USA and 14 stations in West Africa). In order to avoid this drawback, Arnoldus (1980) proposed the following modified Fournier index, also named the FAO index because FAO used it to establish erosion risk areas in North Africa and the Middle East (FAO, 1979):

$$MFI = \frac{\sum\limits_{i=1}^{N}\left(p^2{}_i\right)}{pa} \tag{6.9}$$

Where:

MFI is modified Fournier index

pi is the rainfall depth in month *i* (mm)

Pa is the annual rainfall depth (mm)

N is number of months

Arnoldus (1980) stated that using the same data set but with the modified Fournier index as the independent variable obtained a much improved correlation with R_factor (r²= 0.83) (Arnoldus, 1980). In order to estimate the most appropriate *R-Factor* using the calculated *MFI*, an equation relating the R-factor to the *MFI* was developed in Morocco as (Arnoldus, 1980):

$$R_{factor} = 0.264 MFI^{1.50} \tag{6.10}$$

Where *R_factor* is rainfall erosivity ($MJ.mm.ha^{-1}.yr^{-1}$)

In this study, *Equation 6.10* developed in Morocco was applied to estimate rainfall factor (R). The equation was selected due to the similarity of climatic conditions between Morocco and Libya. The rainfall data collected from 12 weather stations represent the study area and the resulting values are shown in *Table 6-9*. This equation was selected due to the similarity of climatic conditions between Morocco and Libya. The table shows the values of *Modified Fournier index (MFI)*, annual rainfall values (P) and rainfall factor (R). The highest R-values were recorded in Alhadbah, Grian and Alzahra with 101.3, 100.8 and 99.6 ($MJ.mm.ha^{-1}.yr^{-1}$) respectively while the lowest value was recorded in Esbaae with 44.0. For the purpose of understanding the relationship between *Modified Fournier index (MFI)*, annual rainfall values (P) and rainfall factor (R), regression analysis was conducted between these factors. The results indicate that there is a high correlation coefficient (r²= 0.99) between the annual rainfall values (P) and rainfall or erosivity factor (R). Also the correlation coefficient between the *Modified Fournier index (MFI)* and rainfall factor (R) is high (r²=0.94). From this linear strong positive relationship, it is clear that the trend of rainfall erosivity (R) strongly depends on annual rainfall and *MFI*. The higher annual rainfall and *MFI*, the higher rainfall erosivity.

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Table 6-9: R_factor values for the study area

Climate station	*MFI*	Annual rainfall (mm)	R= $0.264 MFI^{1.50}$
Tripoli	40.6	262.2	68.3
Alhadbah	52.8	307.9	101.3
Alkomes	48.8	286.7	90.0
Yefern	39.6	249.6	65.7
Sorman	41.6	251.7	70.8
Zawia	39.7	243.8	65.9
Alzahra	52.2	305.0	99.6
Zwara	40.6	236.8	68.2
Esbaae	30.3	196.5	44.0
Grian	52.6	351.1	100.8
Rojban	33.1	208.6	50.3
Misurata	46.6	262.0	84.0

(b) Determining Soil Erodibility (K)

The K_factor accounts for the influence of soil properties on soil erosion. Wischmeier and Smith (1978) stated that the most important soil properties affecting K values are soil texture, organic matter and permeability. The classification soil map and the survey data for the study area provided by Selkhozpromexport (1980) were used to estimate the erodibility K_factor using the USLE erodibility nomograph (*Figure 6-15*). The K_factor was determined for each soil class. *Figure 6-16* shows the classification map of K values and its distribution in the study area. The results show that values of erodibility K factor are ranging from moderate 0.40 to high $1 (t.MJ^{-1}.mm^{-1})$. This due to the fact that most of the soils in the study area are poor in organic matter, also the percentage of sand is considered high.
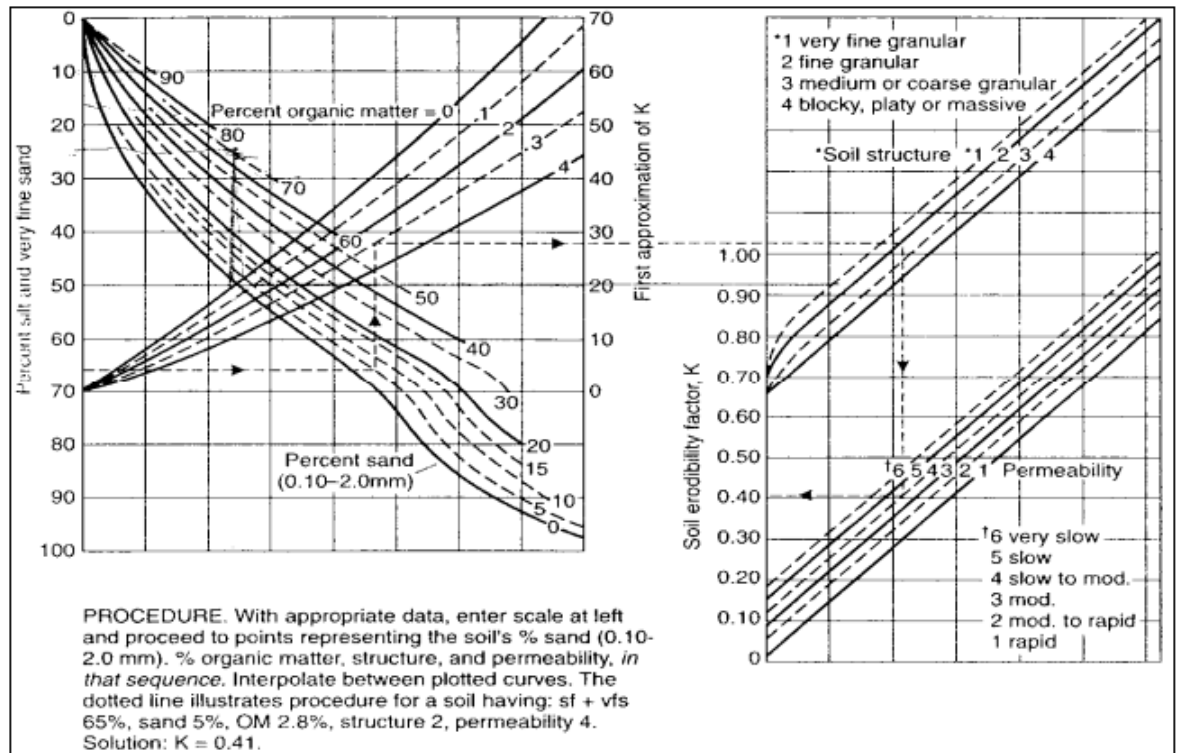
Figure 6-15: *Nomograph for estimateing the K value of soil erodibility*

(Source: Wischmeier and Smith, 1978)
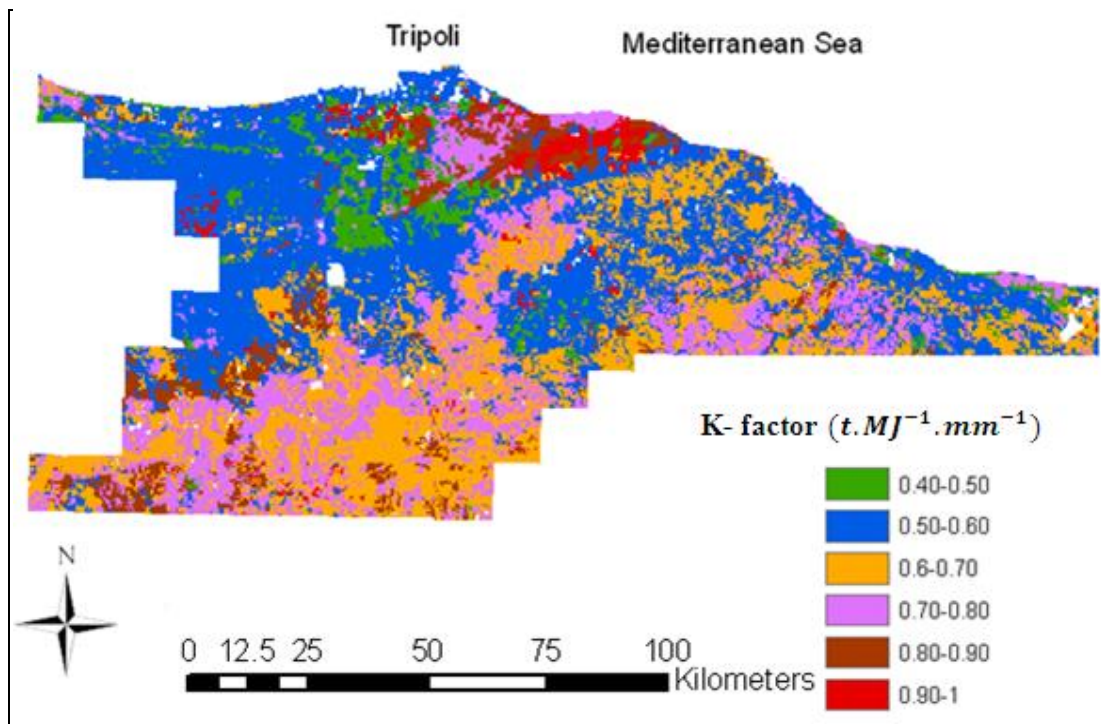
Figure 6-16: *Soil erodibility (K) in the study area*

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(c) Crop and management factor (C)

The crop and management factor (C) reflects the vegetation condition in the ground cover. Its value depends on vegetation cover and management practices. Factor (C) represents the effect of cropping and management practise in agricultural management, and the effect of ground, tree and vegetation covers on reducing soil loss. As the vegetation cover increases, the soil loss decreases. The land cover map of the study area produced by the FAO and UNDP (2004) was used to estimate the (C) factor using guide tables developed by (Stone and Hilborn, 2000). An example, if the field was plowed in the spring and fruit trees was planted. The C factor is obtained from the crop type factor *(Table 6-10)* and the tillage method factor *(Table 6-11)*.

Crop type factor for fruit trees = 0.10

Tillage method factor for spring plow = 0.90

Then C factor = 0.1× 0.90= 0.09

Table 6-10*: Crop type factor*

Crop type	Factor
Grain Corn	0.40
Silage Corn, Beans	0.50
Cereals (spring& Winter)	0.35
Seasonal Horticultural Crops	0.50
Fruit trees	0.10
Hay and Pasture	0.02

(Source: Stone et al, 2000)

Table 6-11: Tillage method factor

Tillage method	Factor
Fall Plow	0.1
Spring Plow	0.90
Mulch Tillage	0.60
Ridge Tillage	0.35
Zone Tillage	0.25
No-Till	0.25

(Source: Stone et al, 2000)

(d) Conservation-supporting practices factor (P)

The P_factor represent the effect of conversation practices used in the landscape to mitigate erosion such as contouring, terracing and sub-surface drainage. The P _factor was predicted using guide table developed by (Stone and Hilborn, 2000). The corresponding values of factor P to the conservation-supporting practices are shown in (*Table 6-12*). The P values range from about 0.25 for strip cropping contour to 1 where there are no erosion control practices.

Table 6-12: P Factor

Support practice	P Factor
Up & down slope	1
Cross slope	0.75
Contour farming	0.50
Strip cropping, cross slope	0.37
Strip cropping, contour	0.25

(Source: Stone et al, 2000)

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(e) Determining to the topographic factor LS

The LS factor represents the influence of slope length (L) and Slope percent (S) on soil loss. The steeper and longer the slope, the higher is the risk for erosion. The LS factor can be obtained from the equation developed by Stone *et al* (2000) as follows:

$$LS = [0.065 + 0.0456(slope)^2] \times \left[\frac{slope\ length}{const}\right]^m \qquad (6.11)$$

Where:

Slope is slope steepness (%)

Slope length is length of slope (m)

(*m*) is an exponent that depends on slope steepness such that *m* is 0.5 for slope steepness exceeding 5 percent slopes, 0.4 for 4 per cent slopes and 0.3 for slopes less than 3 percent.

Constant= 22.1 for metric unit or 72.5 for feet unit

In this study the slope map for the study area was used with *Equation 6.11* to determine the values of LS factor.

An excel spreadsheet was used to calculate the multiplication of the variables: rainfall factor R, Crop and management factor (C) and Conservation-supporting practices factor (P) for each climate station. Then the result was exported to ArcGIS to produce RPC Layer using Kriging tool in ArcGIS. To produce soil erosion layer, the raster calculator ability in GIS was applied to compute the multiplication of each of the RPC layer, Soil erodibility (K) layer and topographic factor LS layer. The map of soil losses in the study area is shown in *Figure 6-17*.
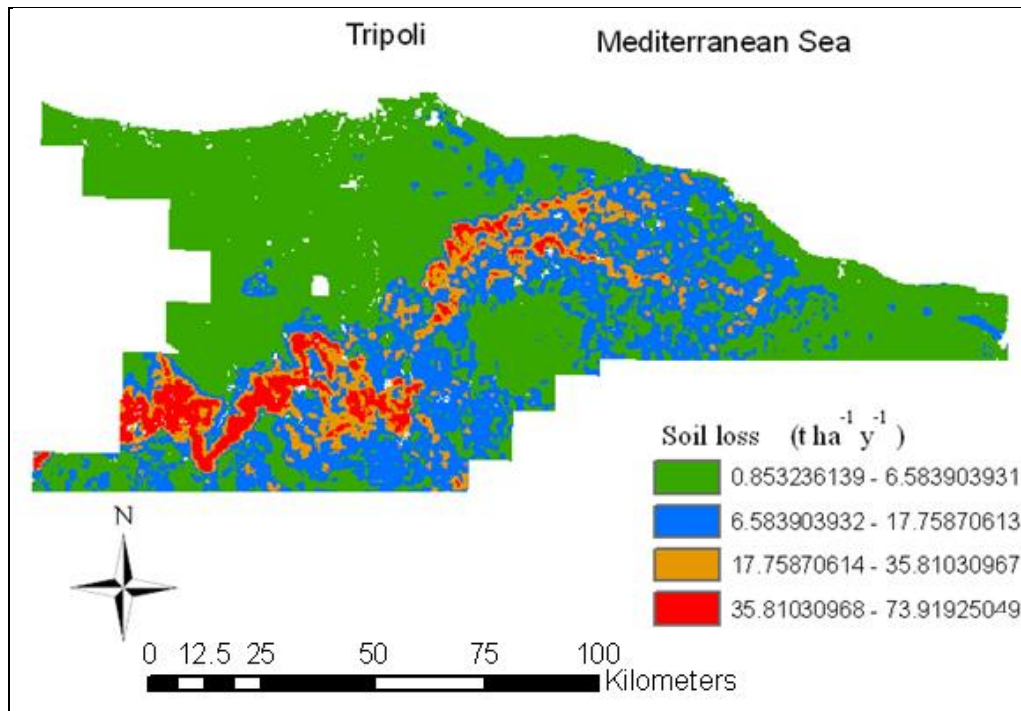
Figure 6-17: Soil losses in the north west of Libya

As shown in *Figure 6.17*, the soil losses are ranging from 0.85 to 73.9 ($t.ha^{-1}.yr^{-1}$). The lowest values of soil loss were recorded in the coastal area where the ground is plain and the vegetation is fairly good. In the other hand, the highest soil loss values were in the southern region of the study area where there are some hills and highlands; also most of the area is rangeland or fallow land.

6.5.4.2   *Soil loss tolerance*

Soil loss tolerance (or T_value) is defined as "the maximum rate of soil erosion that Permits an optimum level of crop productivity to be sustained economically and indefinitely" (ISSS, 1995), which is related to the average annual soil loss.

Soil depth is the critical soil property for degradation caused by surface erosion (FAO 1983). Surface rain erosion may cause soil depth to become a limitation to use, a land characteristic which adversely affects the potential of land for a specified use (FAO 1983). Wischmeier and Smith (1978) considered that the

overall accepted rate of soil loss or (T_value) in the USA is limited to 11.2 t/ha/y, while Morgan (1988) supposes a T_value of 20 t/ha/y in Spain.

Estimation of T-values in this study was based on the recommendation of many studies such as (DLWC., 2000, Singh and Phadke, 2006, USDA., 1973). The suitability rating for soil loss is shown in (*Table 6-13*).

Table 6-13: Suitability classes for soil loss

Suitability Classes	Tolerable Soil Loss (ton h^{-1} yr^{-1})
S1	<5
S2	>5-10
S3	>10-25
NS	> 25

The erosion hazard layer was produced by reclassify the soil loss map into 4 classes namely: high suitability (S1), moderate suitability (S2), margin suitability (S3) and non-suitable (N) as shown in *Figure 6-18.*
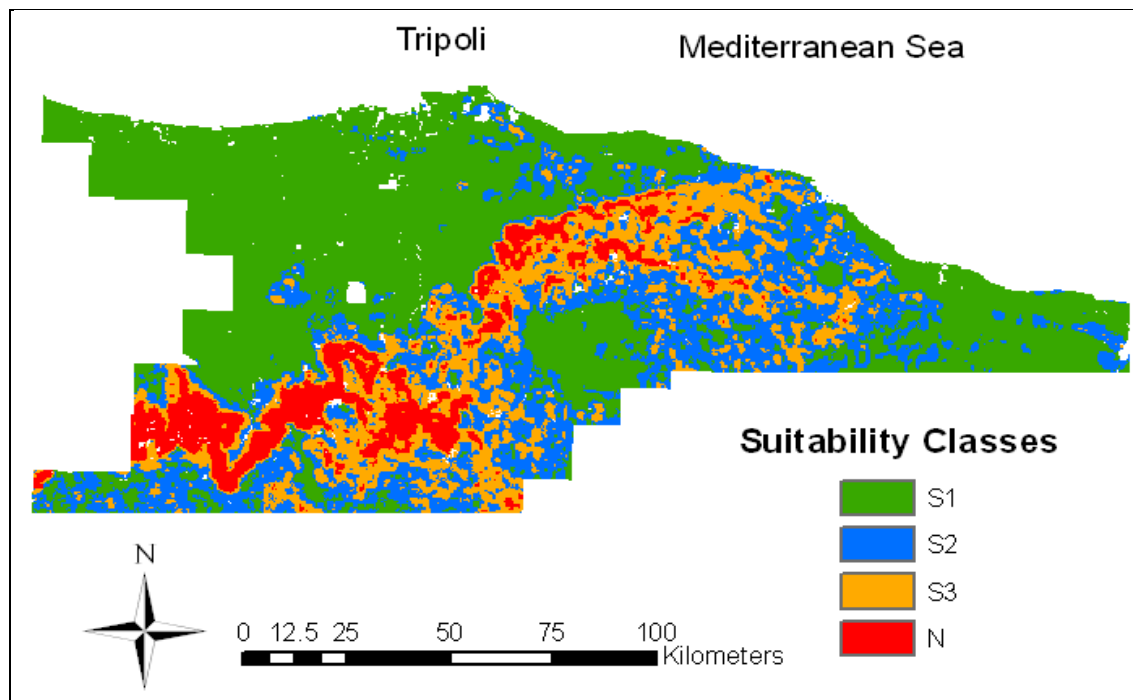
Figure 6-18: Soil Erosion layer

6.6   Summary

In This chapter, land suitability model based on FAO framework was established using GIS functions. The model consists of four layers: soil, climate, slope and erosion hazard which have been shown to be the most important indicators of land suitability. A number of land characteristics were selected and were matched with crop requirements for the selected crops (Barley, wheat and Olive) to produce these layers.

The process of producing the four layers was explained in detail. Soil layer was created by matching soil characteristics with crop requirements based on the theory of fuzzy logic. Also Boolean logic is used to compare the results obtained from using fuzzy and Boolean. Climate, slope and erosion layers were created using conventional Boolean approach due to the difficulty of applying fuzzy logic from the available data and also because most of the study area are considered moderately suitable class regarding these factors. Climate layer was created by computing the Length of Growing Period (LGP) for 12 meteorological stations covering the study area. Slope layer was created from the contour map of study area. The Universal Soil Loss Equation (USLE) was used to create soil erosion layer.

In the next chapter the four layers were overlaid in GIS to produce the overall land suitability map. Also map agreement was created to compare the overall agreement and disagreement between Boolean and fuzzy logic results.

Chapter 7

RESULTS AND DISCUSSION

7.1 Results

The overall land suitability maps were produced from the spatial overlay of four layers namely; Soil, climate, slope and erosion layer. The model outputs of land suitability using Boolean and fuzzy logic are presented in the next sections.

The overall suitability maps for barley, wheat and olive were produced by using the weighted overlay technique. The weighted overlay technique allows different weights to be applied for different thematic map layers. The weighting values of each layer are given depending on the importance of each layer. In this study the weighted values were 40% for soil, and 20% for the climate, slope and erosion layers. These values were supported by the discussion with local experts in Agriculture research center in Tripoli. Variations to these will be tested in a sensitivity study. The output data is a raster (grid) file containing the suitability classes. Each cell in a grid stores a number which indicates the suitability class for that cell.

7.2 Land Suitability Based on Boolean Theory

7.2.1 Barley suitability results

Figure 7-1 shows the results of land suitability map for barley derived by the Boole's method. The figure presents a summary of the different land suitability classes in the study area. The map shows that about 58 % of the total study area is highly suitable (S1) for barley; 21 % of the total study area is moderately suitable (S2); 20 % of the total study area is marginally suitable (S3); only 1 % of the total area is not suitable (N) for barley production. It is clear from (*Figure 7-1)* that the north western part of the study area has high potential to produce barley since

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most of this area is considered either highly suitable or moderately suitable. This is not surprise since the area has one of the best soils in the region and its rainfall is usually much higher than in other parts of the country.
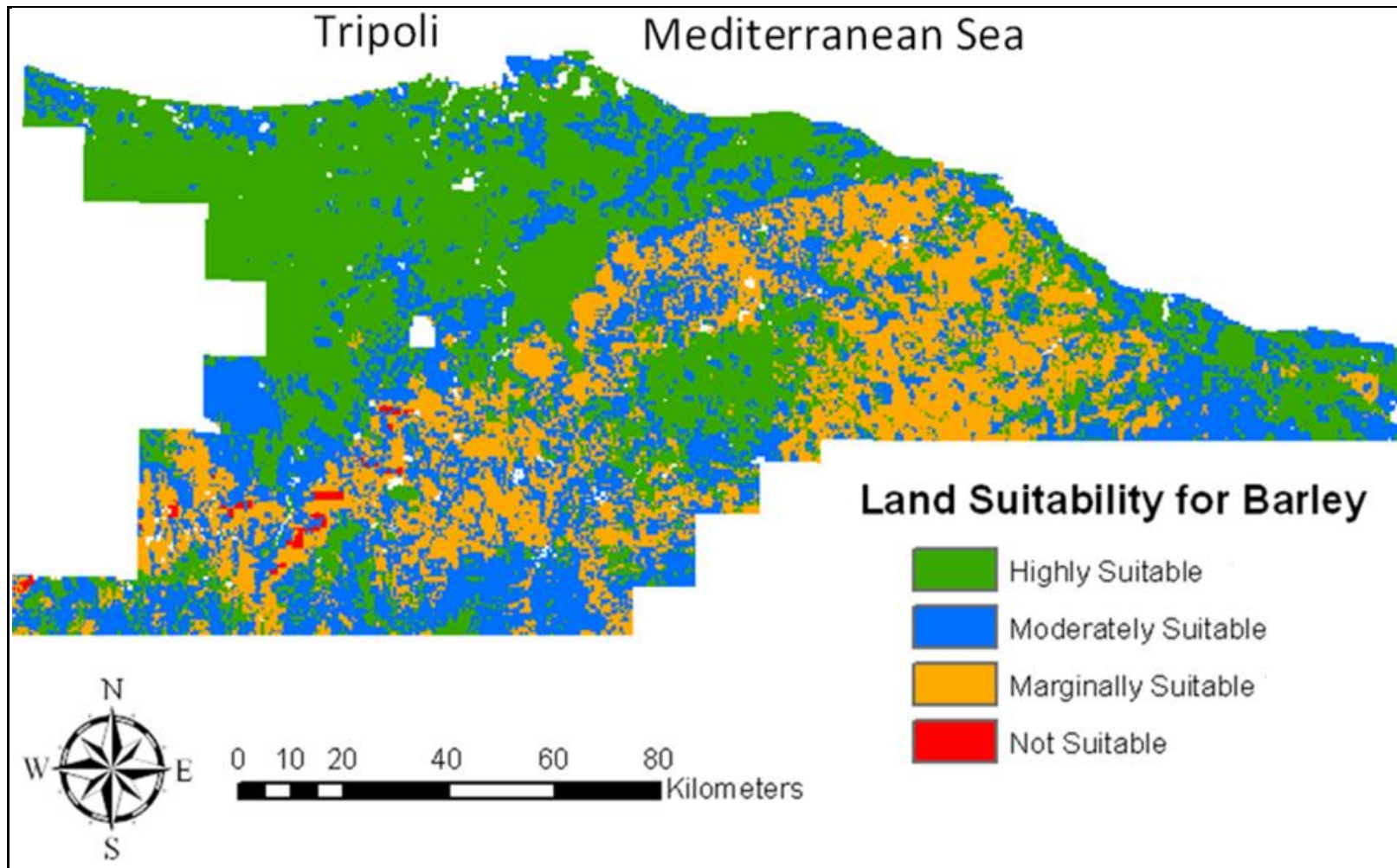
Figure 7-1*: Land suitability map for barley using Boolean theory*

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7.2.2   Wheat Suitability Results

Figure 7-2 shows the results of land suitability for wheat derived by the Boolean method. The results show that about 51 % of the total study area is highly suitable (S1) for wheat production; 27 % of the total study area is moderately suitable (S2); 21 % of the total study area is marginally suitable (S3); only 1 % of the total area is considered not suitable (N) for wheat.
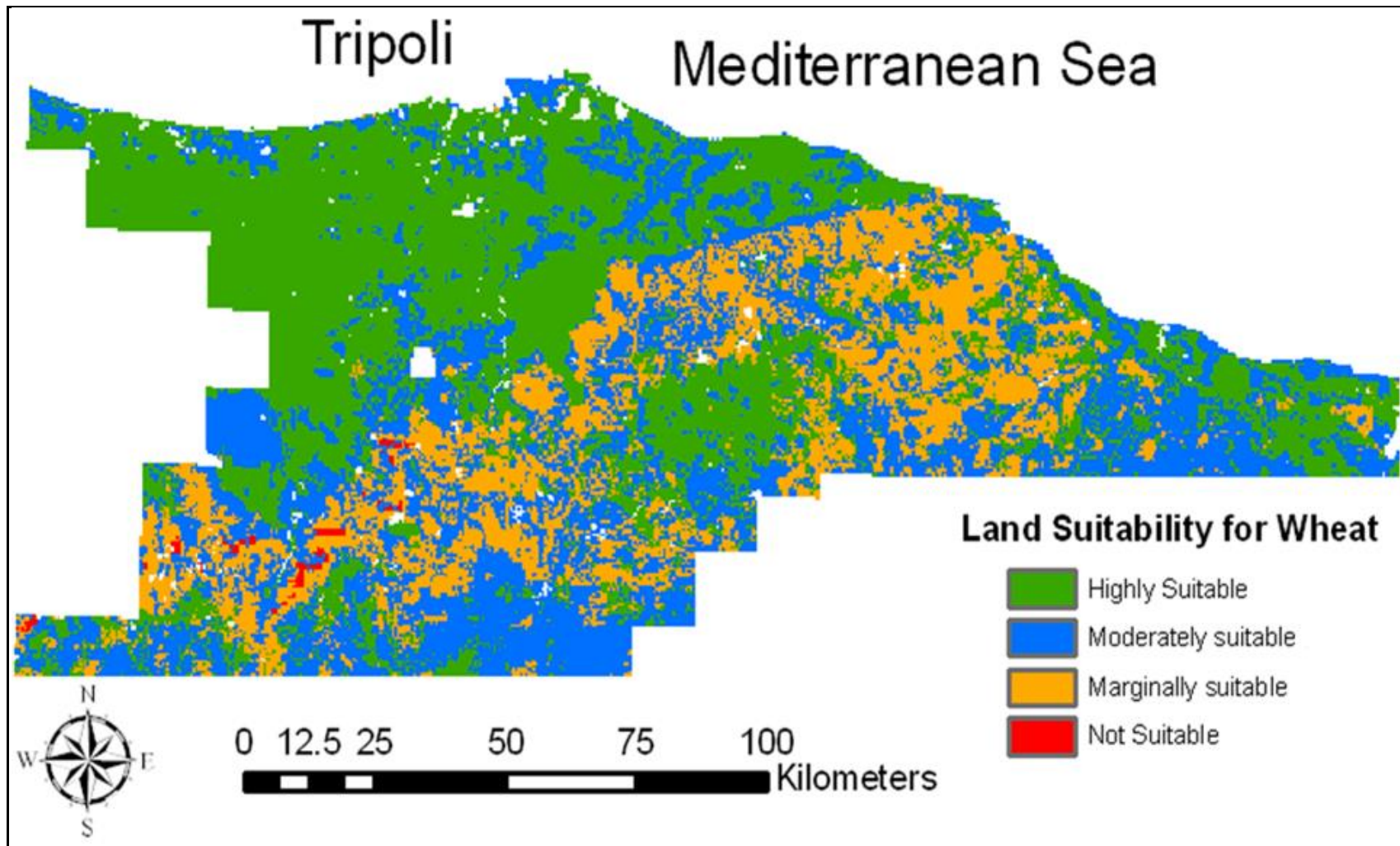
Figure 7-2: *Land suitability map for wheat using Boolean*

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7.2.3 Olive Suitability Results

Figure 7-3 shows the results of land suitability for olive based on Boolean approach. The results show that about 55% of the total study area is highly suitable (S1) for olive production; 40 % of the total study area is moderately suitable (S2); 4 % of the total study area is marginally suitable (S3); 1 % of the total area is not suitable (N) for olive.
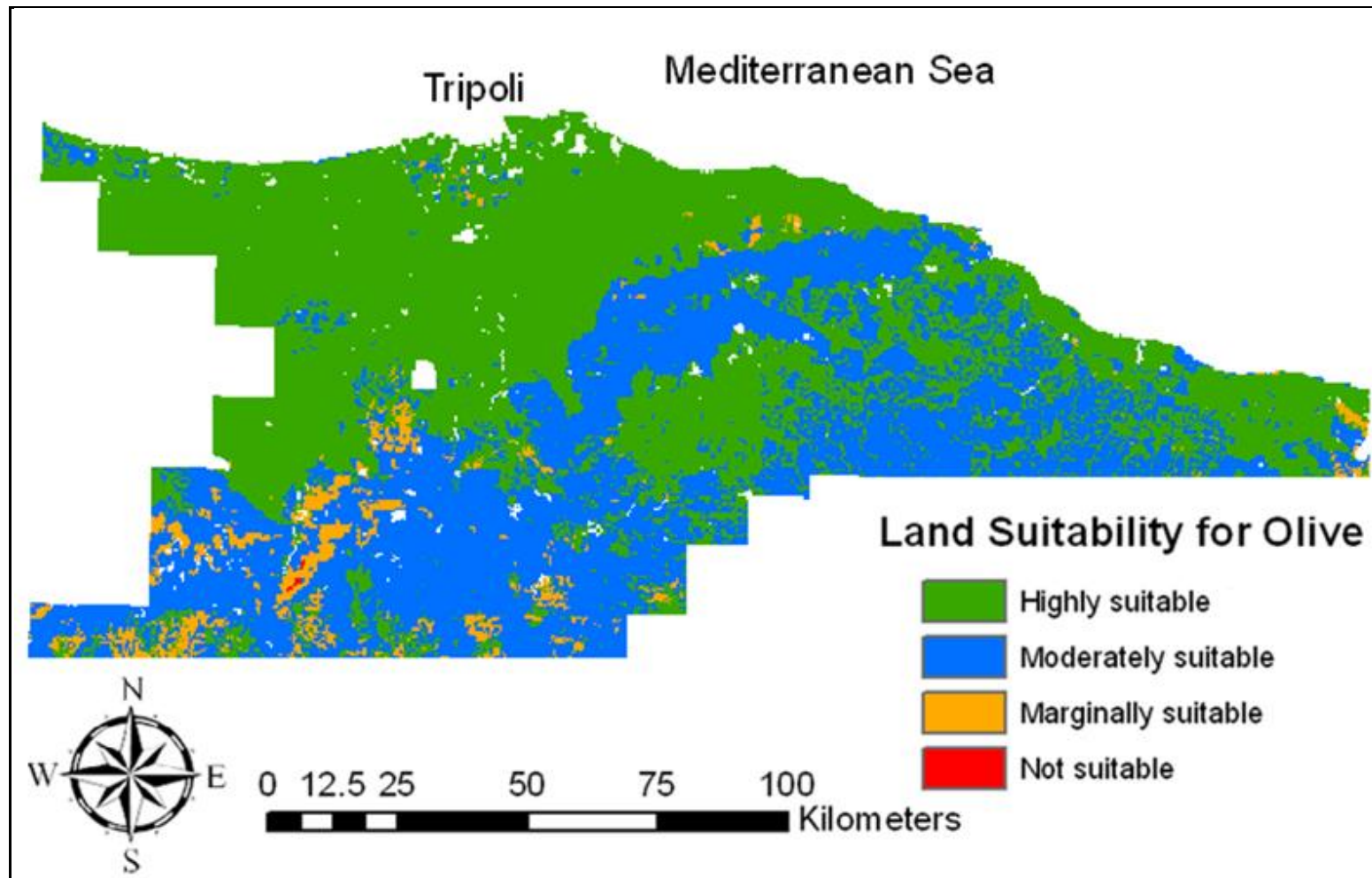
Figure 7-3: *Land suitability map for olive using Boolean theory*

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7.2.4   Summary of Boolean results

The percentage area of land suitability for the selected crops is summarized (*Table 7-1*). The results indicate that the study area has good potential to produce barley, wheat and olive. More than 50% of the study area is considered highly suitable for the selected crops. From (*Table 7-1*) the results indicate that about 21% and 27% of the study area are moderately suitable for barley and wheat respectively while the corresponding value for olive is a bit higher at 40%. Marginal suitable land of study area represents 20% and 21% for barley and wheat respectively, and only 4% for olive. Only 1% of study area is not suitable for the selected crops. In the next section, land suitability based on Fuzzy logic is presented.

Table 7-1: Overall land suitability using Boolean approach

Crop	High suitability (S1)		Moderate suitability (S2)		Margin suitability (S3)		Not suitable (N)	
	Area (%)	Area (ha)	Area (%)	Area (ha)	Area (%)	Area (ha)	Area (%)	Area (ha)
Barley	58	965468	21	349566	20	332920	1	16646
Wheat	51	848946	27	449442	21	349566	1	16646
Olive	55	915530	40	665840	4	665840	1	16646

7.3   Land Suitability Based on Fuzzy Theory

As explained in (Chapter 6) the Fuzzy logic model was designed to produce the soil suitability map. In the Fuzzy model the suitability is given membership between 0 and 1 where 0 is not suitable area and 1 is highly suitable area. *Figure 7-4* and *Figure 7-5* show the reclassified values of the suitability soil for barley and olive; the result

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of wheat is similar to barley and so has not been presented here separately (*See Table 7-2*).

After reclassifying the suitability values based on natural breaks of the raster histogram using classify tool in ArcGIS, four defined classes were obtained, judged to correspond to the four suitability classes S1, S2, S3 and N. In the fuzzy model the suitability has been distinguished based on the histogram breaks of the cell groups, in this way it was possible to define highly suitable areas even if the maximum value was 0.84 instead of 1. Based on natural breaks of the raster histogram, four defined classes were created to correspond to the four suitability classes S1 from (60-84%), S2 (40-60%), S3 (25-40%) and N less than 25%.
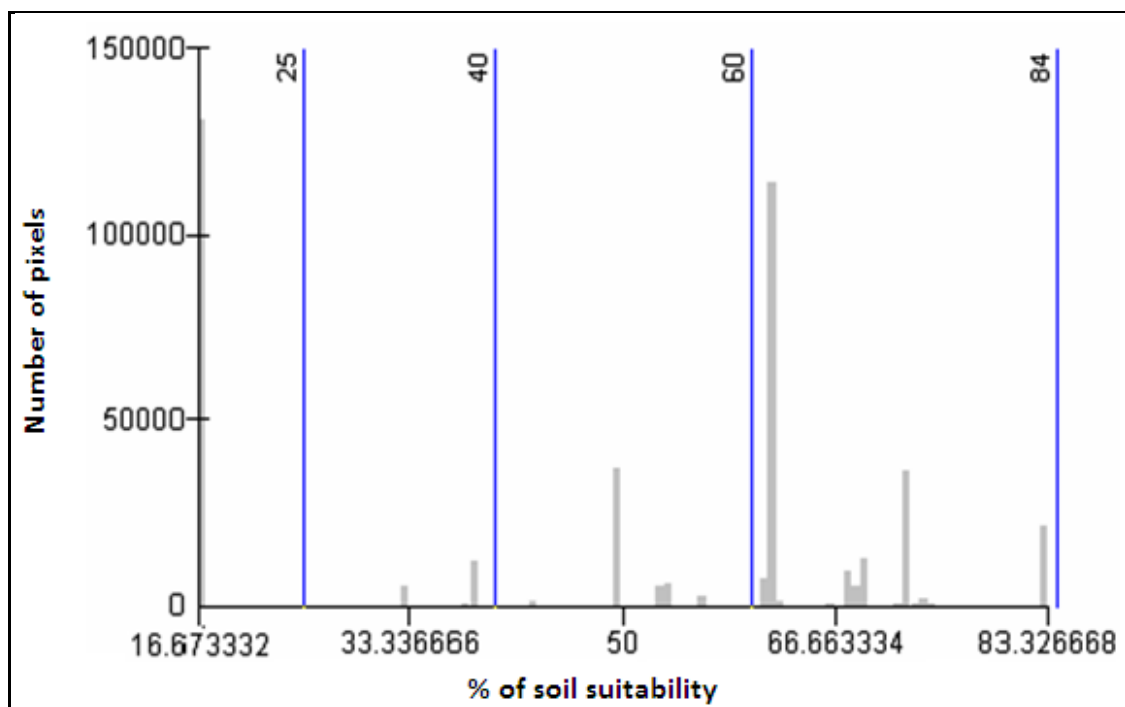
Figure 7-4: *Reclassification histogram of soil suitability based on Fuzzy logic for Barley*
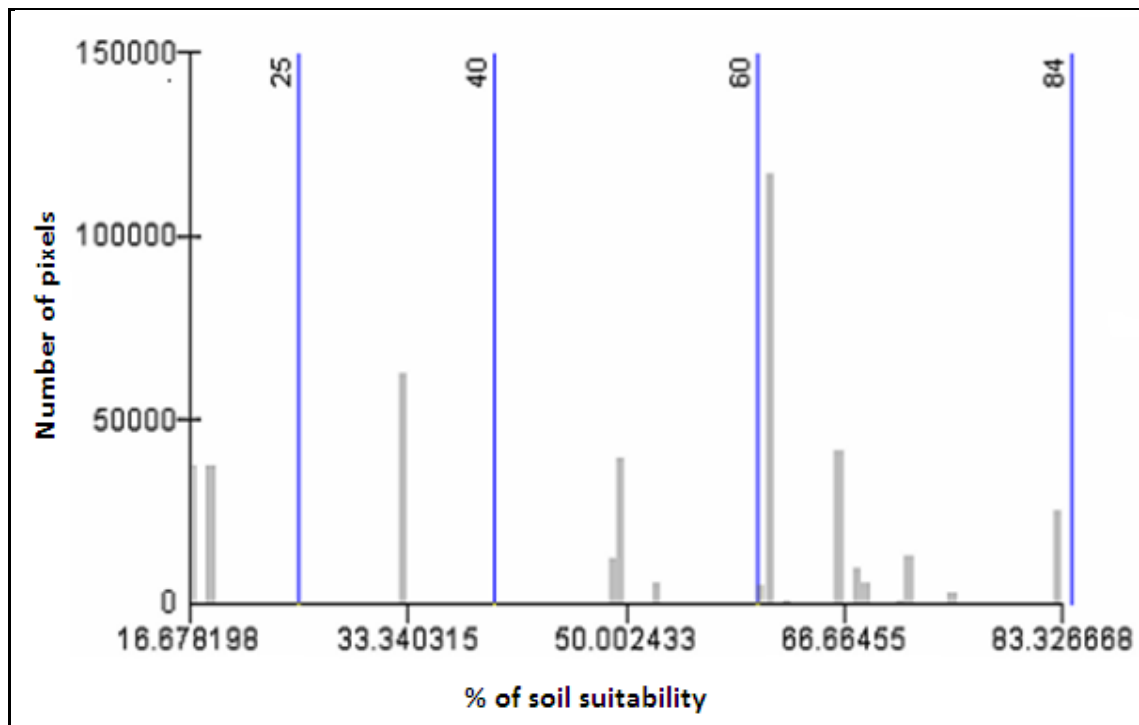
Figure 7-5: *Reclassification histogram of soil suitability based on Fuzzy logic for Olive*

7.3.1 Soil suitability results

 The percentage area of soil suitability is summarized in *Table 7.2*. The soil suitability maps for barley, wheat and olive are shown in *Figure 7-6, Figure 7-7 and Figure 7-8*. The results revealed that about 52% of the study area is highly suitable (S1) to produce the selected crops, which is quite different from the conventional Boolean logic approach that resulted in about 57% of the study area is being highly suitable soil for wheat, 60% and 62% of study area is highly suitable soil for olive and barley respectively (*Table 7-2*). The percentage area that is considered moderately suitable soil (S2) is significantly different as shown in *Table 7-2* between the two models. While the fuzzy logic approach resulted in almost same figure of 14% of study area is moderately suitable soil to produce barley and wheat respectively while the Boolean approach resulted in mere 1%. In the case of olive, 14% of study area is moderately

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suitable soil based on fuzzy method while, with Boolean the percentage area was 34%.

***Table 7-2:** Soil suitability using fuzzy and Boolean logic*

Crop	Barley		Wheat		Olive	
Suitability	% Area Fuzzy	% Area Boolean	% Area Fuzzy	% Area Boolean	% Area Fuzzy	% Area Boolean
High	52	62	52	57	53	60
Moderate	13	1	14	1	14	34
Margin	4	13	5	12	15	1
Non	31	24	29	30	18	5

The Fuzzy and the Boolean classifications are obviously different due to the suitability reclassification of the fuzzy maps. For example, soil suitability under fuzzy approach for the selected crops has a maximum membership value with 83.3%. So the highly suitable areas have this value as a maximum limit. In other words, in fuzzy an area could be classified as S1 with a membership value not so close to 1, whereas Boolean approach it is required that most of parameters for that soil unit have a value 1 when using mode as statistical choice.
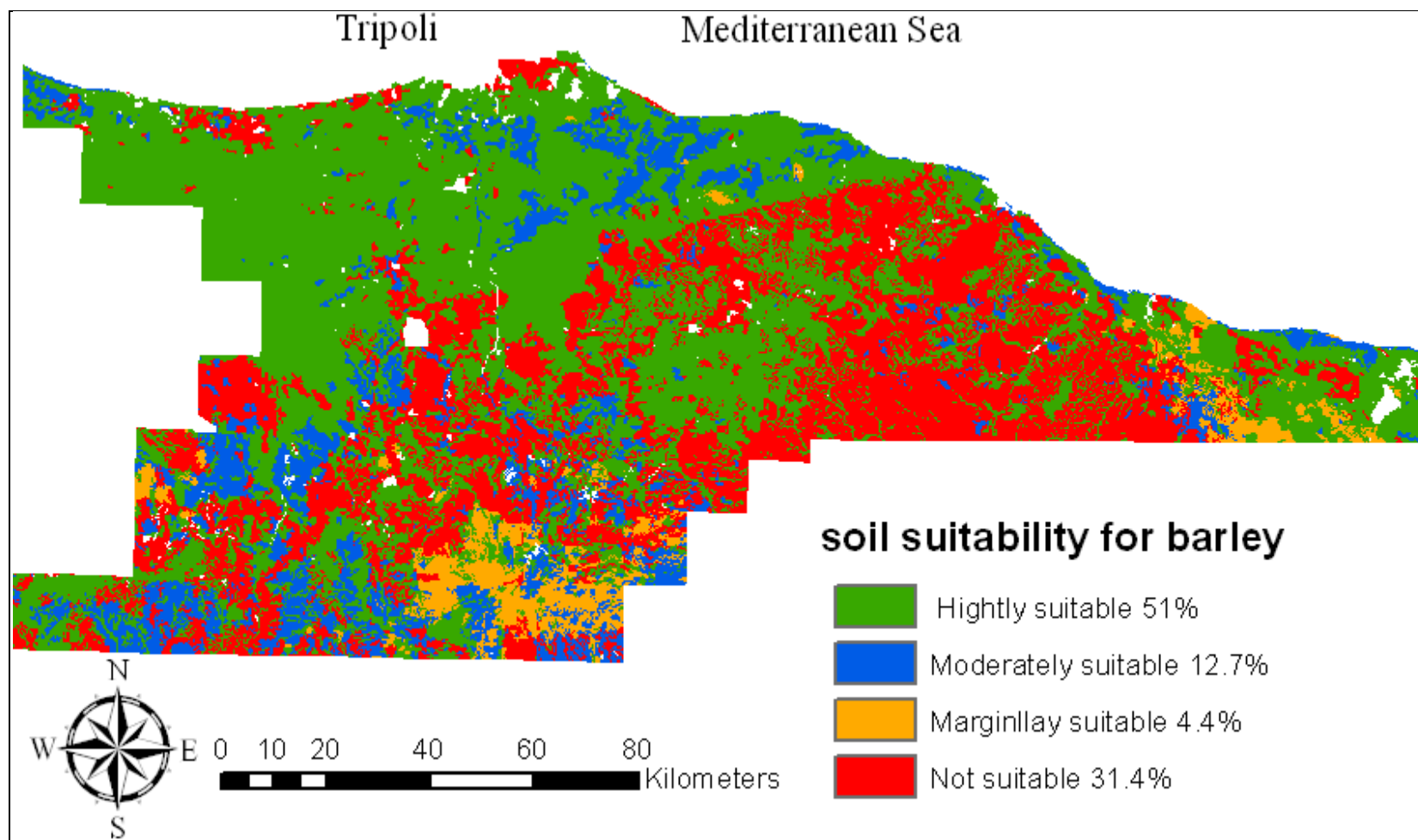
Figure 7-6: *Soil suitability map for barley using fuzzy logic*
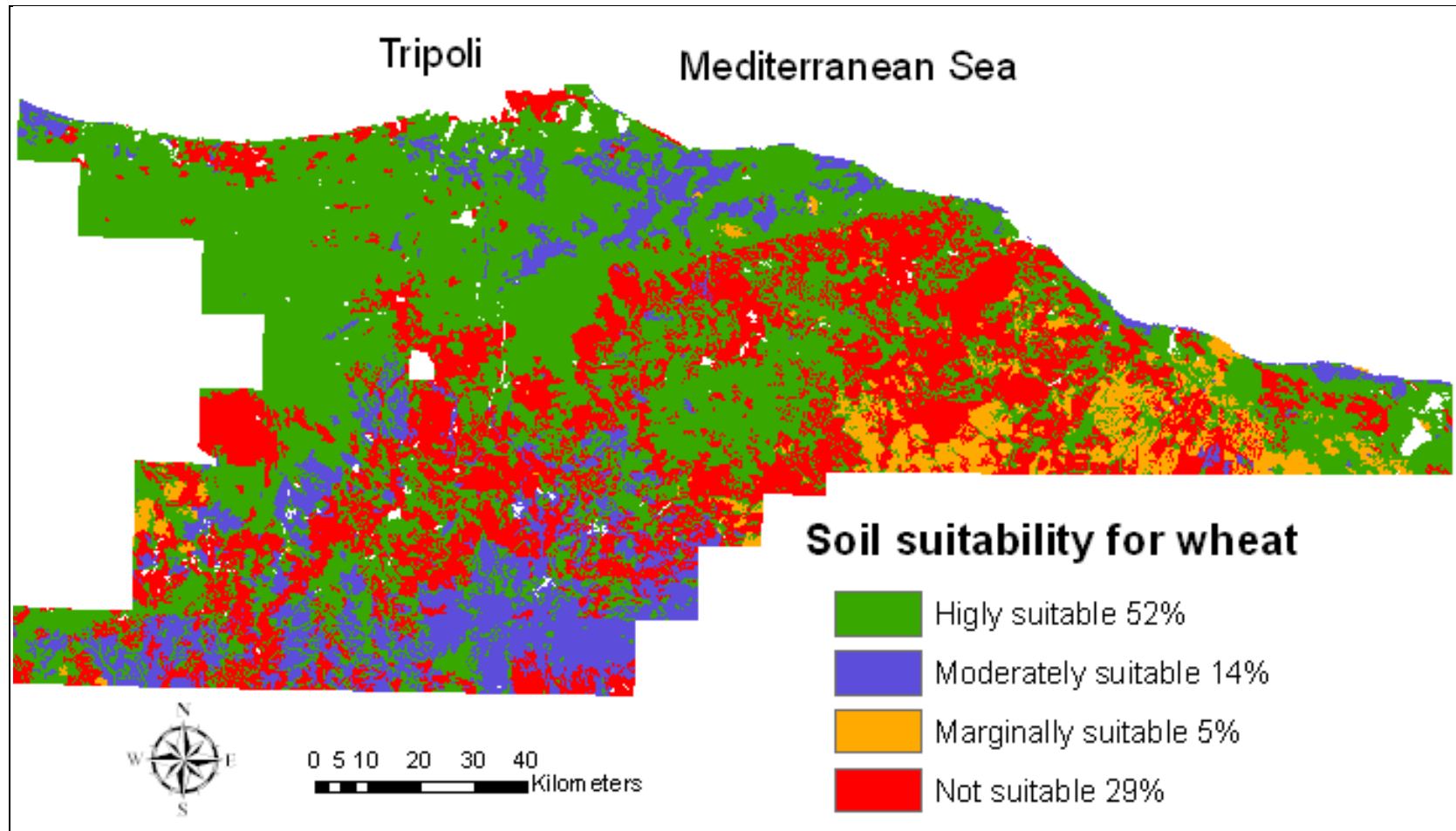
Figure 7-7: *Soil suitability map for wheat using Fuzzy logic*
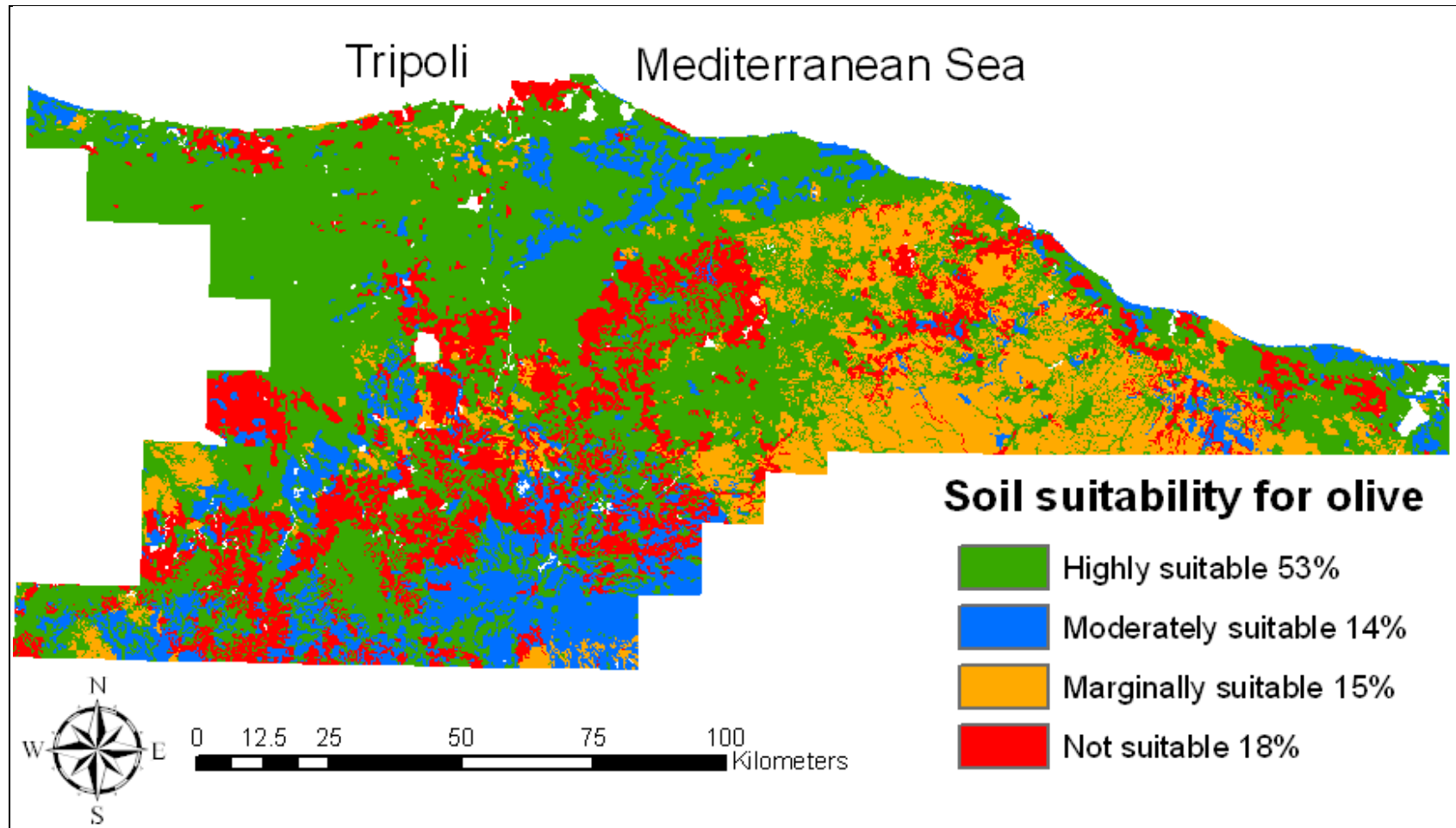
Figure 7-8: *Soil suitability map for olive using Fuzzy logic*

7.3.2 Barley suitability results using fuzzy theory

The fuzzy based classification shows that most of the study area falls within different suitability classes while 1% of the total area is not suitable. 42% of the study area is considered high suitability, 34% is moderate suitability and 24% is margin suitable for barley production. A land suitability map for barley using fuzzy logic is presented in *Figure 7-9*.
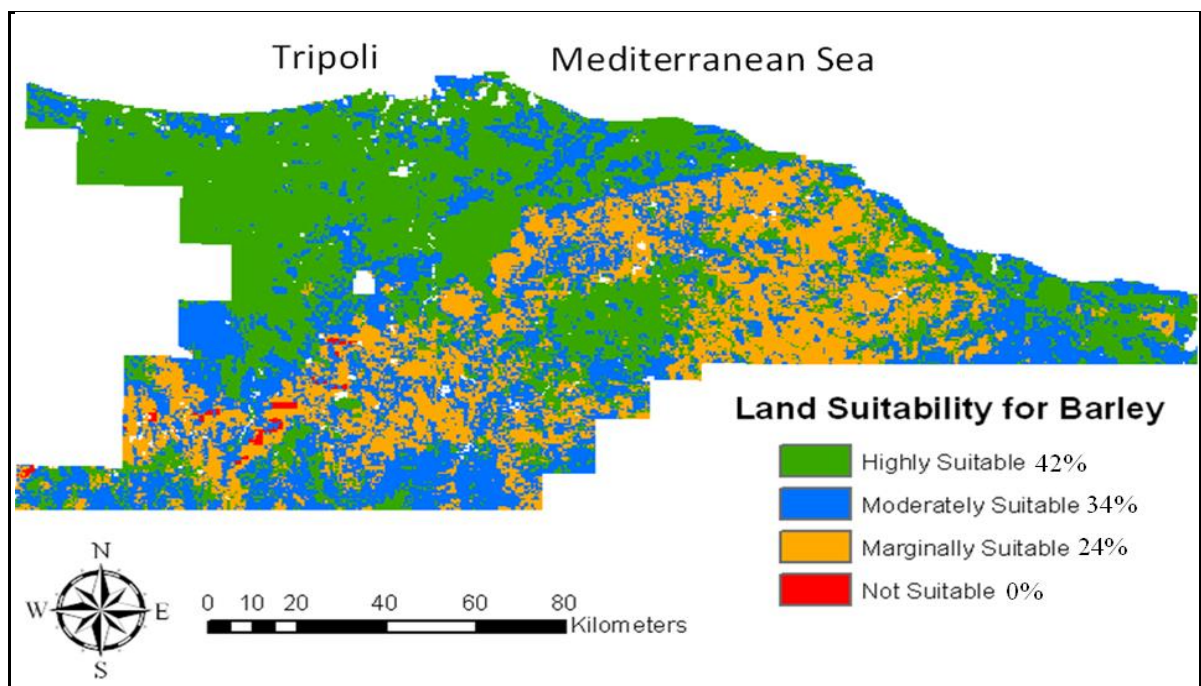
Figure 7-9: *Overall land suitability map for barley using fuzzy logic*

7.3.3 Wheat suitability results using fuzzy theory

Figure 7-10 shows land suitability map for wheat obtained by using fuzzy theory. The results reveal that 42 % of the total study area is highly suitable for wheat; 36 % is moderately suitable; 21 % of the study area is marginally suitable; less than 1% of the total study area is considered not suitable for wheat production.
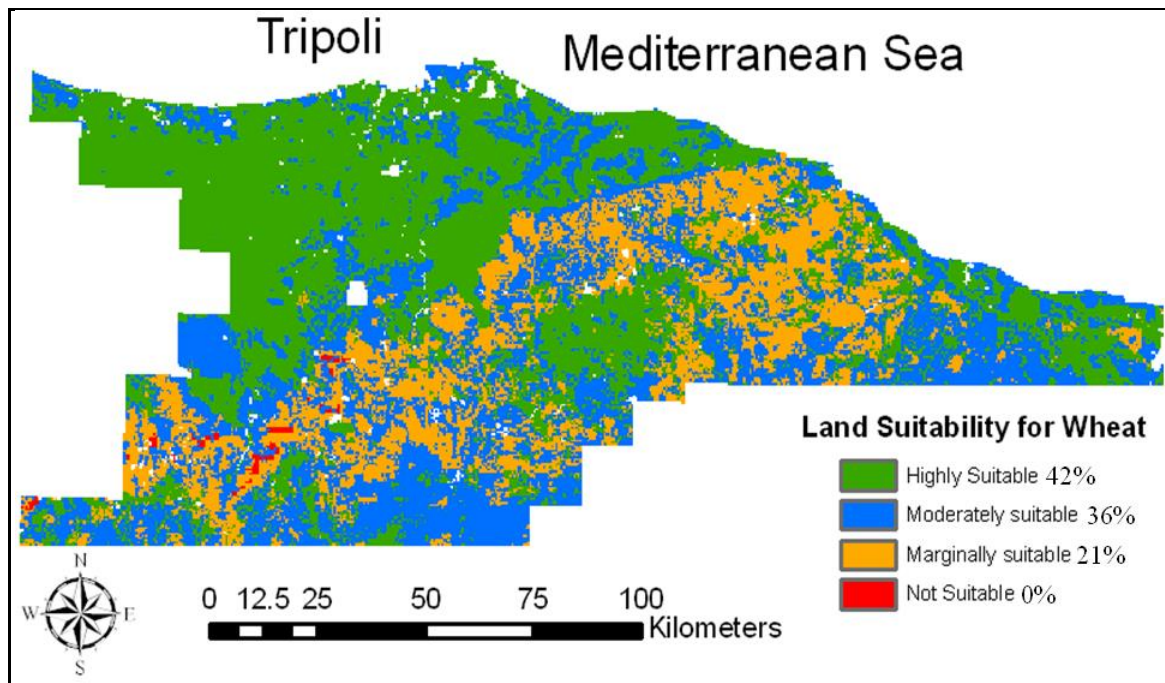
Figure 7-10: *Overall land suitability map for wheat using fuzzy logic*

7.3.4 Olive suitability results using fuzzy theory

The results obtained from the overall land suitability map for olive based on fuzzy theory are presented in *Figure 7-11*. The results indicate that about 47% of the total study area is highly suitable for olive; 40% of the study area is moderately suitable; 13% of the study area is marginally suitable while only 4% of the study area is not suitable.

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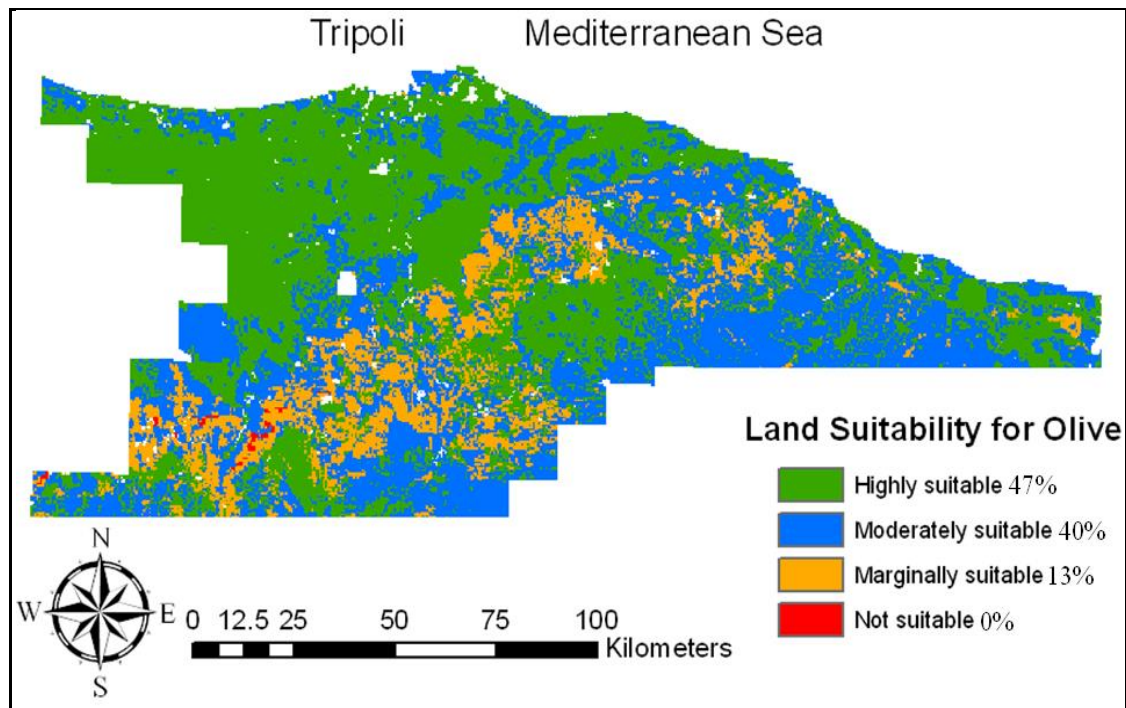
Figure 7-11: *Overall land suitability map for olive using fuzzy logic*

7.3.5   *Summary of Fuzzy Results*

The overall land suitability map was produced from the spatial overlay of four layers namely; Soil, climate, slope and erosion layer. The final results are summarised in *Table 7-3*.

The results indicate that about 42% of study area is highly suitable (S1) for both barley and wheat while the corresponding value for olive is a bit higher at 47%. For moderate suitability (S2) barley and wheat are 34% and 36% respectively and 40% for olive, Marginal suitable land (S3) of study area represent 24% and 21% for barley and wheat respectively, and 13% for olive.

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Table 7-3: Overall land suitability using fuzzy and Boolean logic

Crop	Barley		Wheat		Olive	
Suitability	% Area Fuzzy	% Area Boolean	% Area Fuzzy	% Area Boolean	% Area Fuzzy	% Area Boolean
High (1)	42	58	42	51	47	55
Moderate (2)	34	22	36	27	40	40
Margin (3)	24	20	21	21	13	4
Non (4)	0	0	0	1	0	1

7.4 Model Evaluation

The capability of GIS to perform an integrated analysis of spatial and attribute data has been used in this study to conduct a suitability analysis, and to produce maps from multi-source datasets (climate, soil, topography). Data input used in implementation of any model is usually subject to various sources of uncertainty (measurement errors in data acquisition, format conversions, lack of information, etc.) that could have considerable influence on the output (Servigne, Lesage, et al., 2010). Therefore, it is important to conduct a certain amount of testing to gain confidence in any model, as well as demonstrate that the model is a reliable representation of a real system. In addition, field trial plots will be needed to evaluate and validate the results. In this study, maps comparison and sensitivity analysis were conducted.

7.4.1 Maps Comparison

Maps comparison is considered one of the most important stages that can be employed to check the validation and understanding of the results. The results maps from Boolean soil suitability were rasterized and compared on a cell by cell basis with the fuzzy soil suitability maps results. Disaggregated comparisons were made

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for only soil suitability maps because of the fuzzy logic were applied only for soil layer as explained in Chapter 6. To perform the comparisons, the fuzzy soil suitability maps were reclassified into 4 classes (corresponding to the four suitability classes, 1 is highly suitable, 2 is moderately suitable, 3 is marginally suitable and 4 is not suitable). To determine the comparison results between fuzzy and Boolean maps raster calculator function in ArcGIS were used to multiply one raster by 10, so the four classes of this map become 10, 20, 30 and 40 instead of 1, 2, 3 and 4. Then the classes from the second raster map are added to the first raster map. Values such as 11, 22, 33 and 44 represent correspondence between cell values from both maps. The number of appearances is used to create agreement maps for each crop.

7.4.1.1   Agreement Maps

The grade of agreement between soil suitability classifications has been mapped using colours: green corresponds to agreement between the areas classified in both maps, blue represents a level of disagreement (i.e. S1 classified as S2 in one map, or S2 classified as S3); and red denotes areas completely misclassified in which represents two levels or more of disagreement (i.e. S1 classified as S3, or S2 classified as Not suitable). The agreement maps of soil suitability for each crop are shown in *Figures 7-12, 7-13 and 7-14*. The results of the overall agreements and disagreements between the maps for the crops are summarized below:

(a) Map Agreement for Barley

*Figure 7-12*shows the comparison map between the Boolean soil suitability map and the fuzzy soil suitability map for barley. The results indicate that the overall agreement between soil suitability maps for barley was moderate agreement with 51% of the area being in complete agreement, while 32% of the area was in disagreement and 17% is misclassified only in one class.

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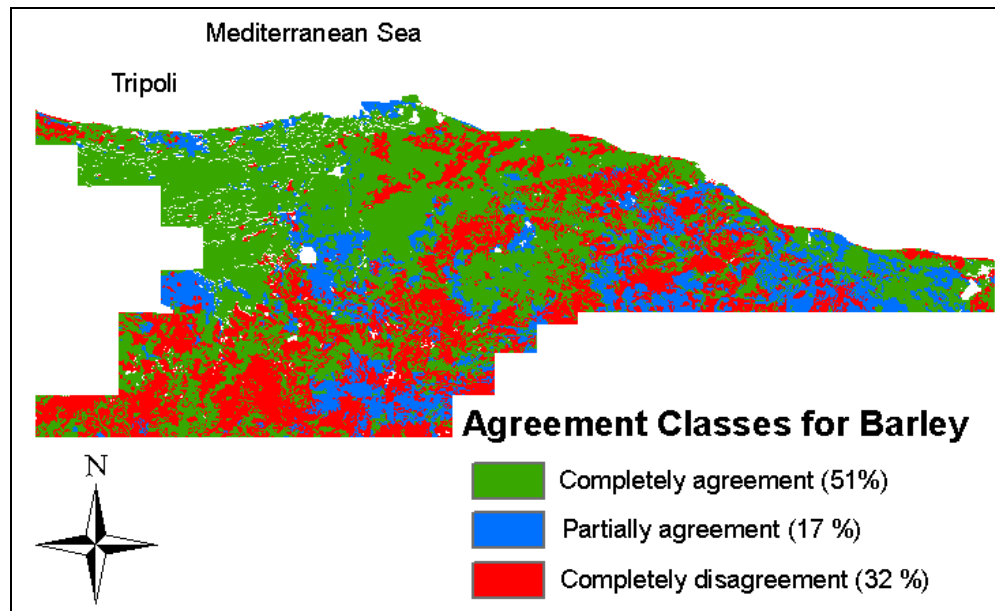
Figure 7-12: Agreement Map of soil suitability for Barley

(b) Map Agreement for Wheat

The overall agreements for the fuzzy soil suitability map for wheat compared to the Boolean map was fairly low with 46% completely agreeing. The percentage of area that partially agreeing was 41% which is the higher compared with barley and olive while, only 13% of the area was in disagreement (*Figure 7-13*).

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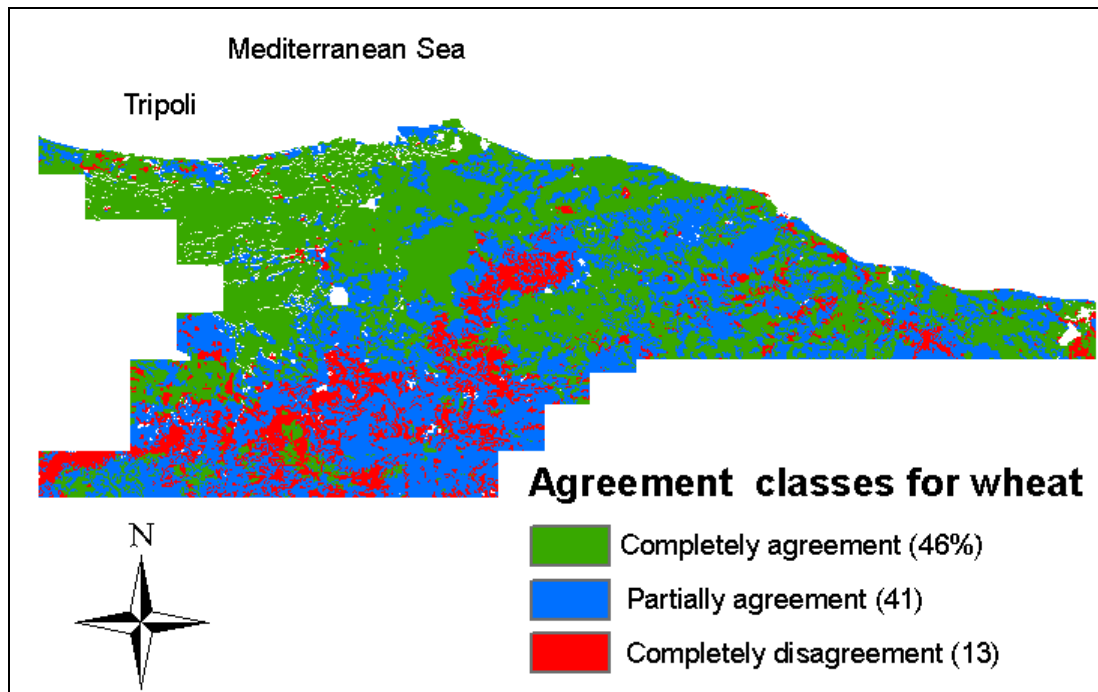
Figure 7-13: Agreement Map of soil suitability for Wheat

(c) Map Agreement for Olive

 In the case of olive, the overall agreement obtained from the comparison between the fuzzy map and Boolean map was 56% of the area being in complete agreement. The percentage of the area that partially agreeing and completely disagreeing was almost similar being 17% and 27% respectively (*Figure 7-14*).

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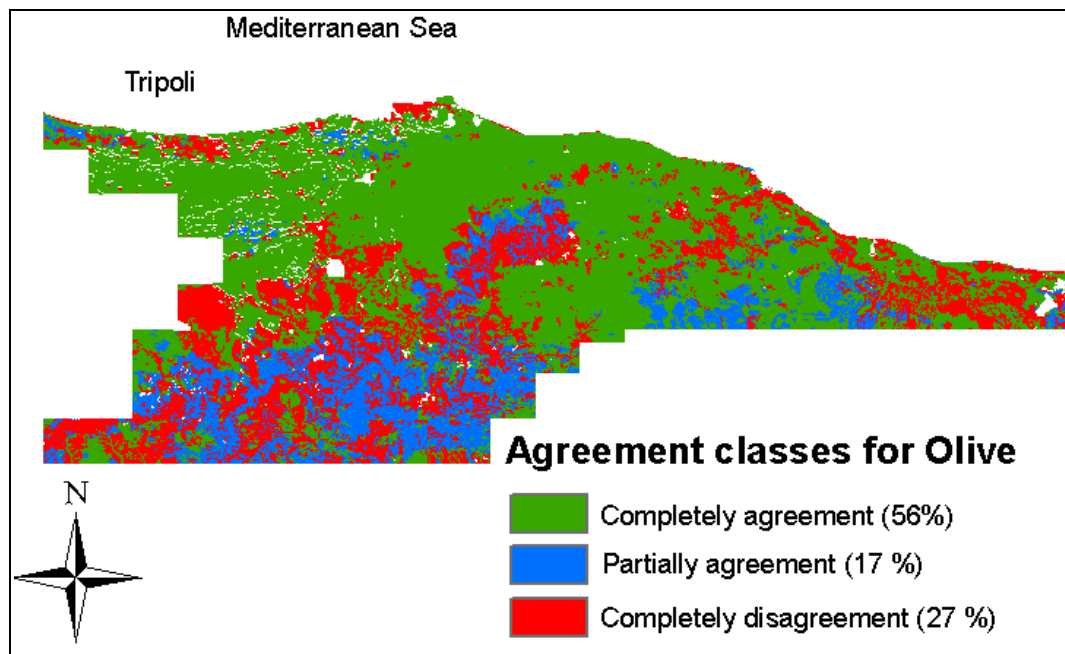
Figure 7-14: Agreement Map of soil suitability for Olive

7.4.1.2   *Discussion of Map Agreement Results*

The results show that the overall agreement obtained from comparing the Fuzzy map and Boolean map for olive is higher than the overall agreement obtained from the comparison of the Fuzzy maps and Boolean maps for barley and wheat, while, the higher disagreement percentage was mapped for barley and olive with 32% and 27% respectively. It is clear from the agreement maps that most of the areas considered complete agreement are located at the north west part of the study area.

The main reason for obtaining low agreement between Boolean and fuzzy maps was that soil suitability maps using the Boolean approach were based on hard classification of soil characteristics, while the fuzzy approach is based on using soft classification. An example, with Boolean approach only one low factor is sufficient to decrease the suitability of lands from highly suitable classes to not suitable classes (N). While, with fuzzy logic there is a transition zone where each factor has a grade less than

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optimum. Also in fuzzy there is an interaction between the factors that will reduce the impact of one factor on the overall results.

The differences between fuzzy approaches and Boolean results were expected, because the Boolean approach is a strict approach, while the Fuzzy 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*.*

7.4.2 Sensitivity Analysis

Sensitivity analysis aims to determine how each model input factor affects the model output. Sensitivity analysis indicates which input parameters may be critical to the stability of the model, and which input parameters are less important. Sensitivity analysis gives further confidence in the model and indicates the priority area for developing further versions of the model (Qureshi, Harrison, et al., 1999).

In this study, the sensitivity analysis was conducted on the four factors involved in the model namely: soil, climate, slope and erosion to find out the influence of different criteria weights on the behavior of the model's results to see how the outputs will change if the weights are changed. This can be useful to define which factors are more important in suitability classification and should be given greater effect in its determination. Sensitivity analysis was used by applying different weighting plans for the four factors (soil, climate, slope and erosion), twenty four weighting plans were established and run using Arc GIS. The weighting plans were applied for all the crops (barley, wheat and olive) are shown in *Table 7-4*. The baseline situation, as a reminder, was 40, 20, 20, and 20 see number 3 in *Table 7.4*. As shown in table 7.4, all the weights add % to 100 % for each sensitivity scenario.

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Table 7-4: *The weighting plans for the suitability factors*

Model run	Soil%	Climate%	Slope%	Erosion%
1	10	30	30	30
2	25	25	25	25
3	40	20	20	20
4	55	15	15	15
5	70	10	10	10
6	85	5	5	5
7	30	10	30	30
8	25	25	25	25
9	20	40	20	20
10	15	55	15	15
11	10	70	10	10
12	5	85	5	5
13	30	30	10	30
14	25	25	25	25
15	20	20	40	20
16	15	15	55	15
17	10	10	70	10
18	5	5	85	5
19	30	30	30	10
20	25	25	25	25
21	20	20	20	40
22	15	15	15	55
23	10	10	10	70
24	5	5	5	85

For the purpose of sensitivity analysis, suitability maps for every weighting plan were produced. The outputs (suitability maps) were compared to find out the impact of each factor on the overall suitability for each crop. The suitability classes and the percentage area calculation of suitability classes were computed to interpret the output of the sensitivity analysis. The sensitivity analysis for the three crops is presented in the next sections.

7.4.2.1   Sensitivity analysis for Barley

The sensitivity analysis indicated that the soil is a highly sensitive factor in the suitability classification for barley. *Figure 7-15*shows the land suitability classes for different weighting plans. As can be seen, the output of land suitability classes is changed by increasing the influence of the soil criteria. For example, when the soil weighting were 10% and 25%, the moderate suitability class (S2) was about 50%. However, when the soil weighting was increased to 85%, S2 decreased to 12% and a significant percent of the study area were classified as not suitable (N) (31%). There were no (N) classes when the soil weightings are 10%, 25% and 40%. The high suitability class (S1) increased from 32% to 52% when the soil weighting was increased from 25% to 85%.
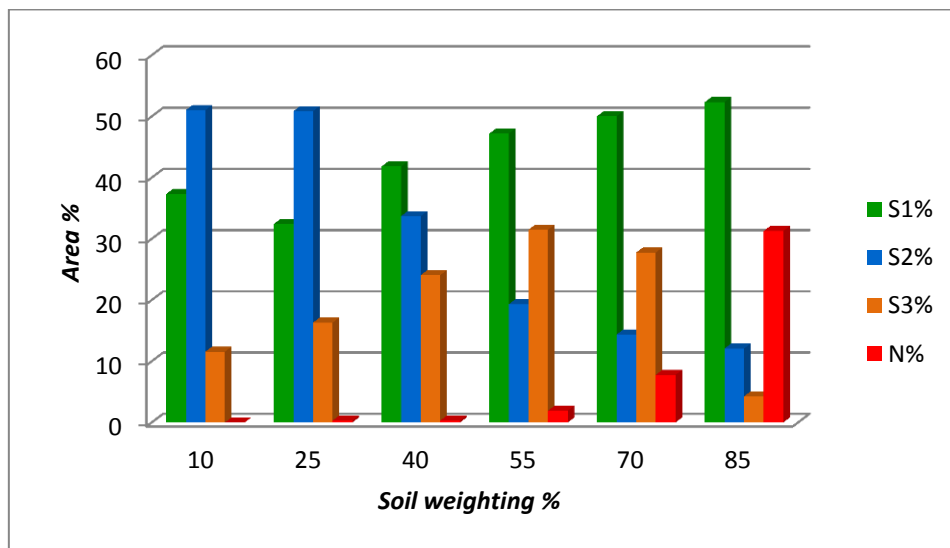
Figure 7-15: *Sensitivity analysis for Soil factor for (Barley)*

Figure 7-16 shows the overall land suitability maps. As can be seen in the figure the land suitability classification was changed by assuming different soil weightings. From these findings it is clear that the soil factor has important influence on the overall of land suitability and should be given suitable weighting reflecting its importance for assessment of the overall land suitability for barley in the study area. These finding are supported by Elaalem, (2010) in his study about the application of land evaluation techniques in Jeffara plain in Libya. The study indicated that the soil factor is the most important factor in land suitability assessment.

For the climate factor, the sensitivity analysis indicated that climate is less sensitive compared to the soil factor. *Figure 7-16* shows that when the climate weighting is 25% and 40% there is no significant difference in the overall suitability classification. Also by increasing the importance of climate to 55% or more most of the study area about 95% is classified as moderately suitable class S2. This result is expected because the climate is considered moderately suitable in most of the study area.
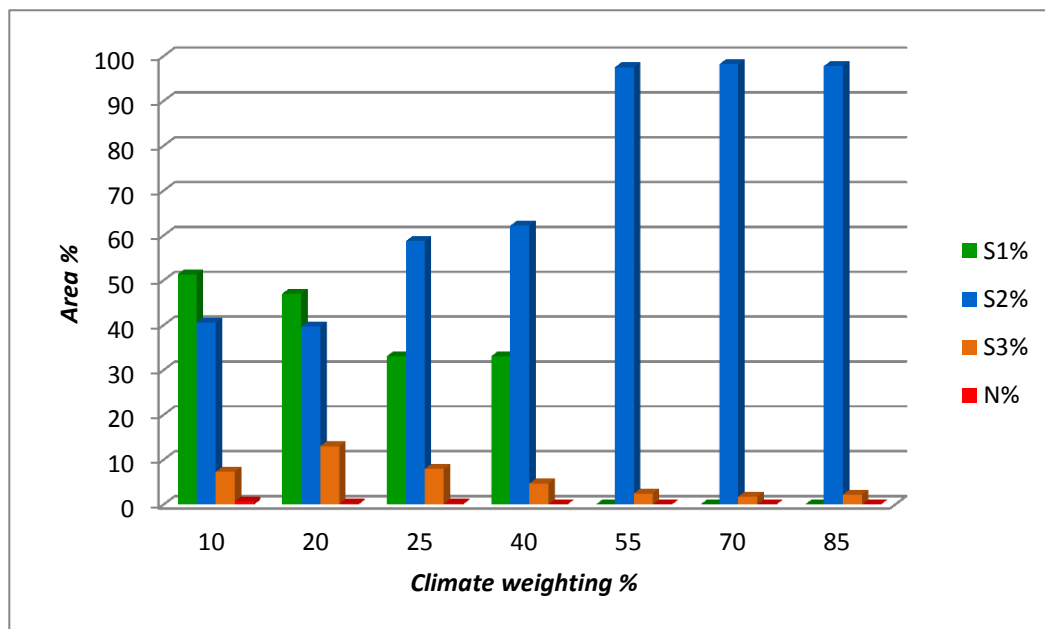
Figure 7-16:*Sensitivity analysis for Climate factor for (Barley)*
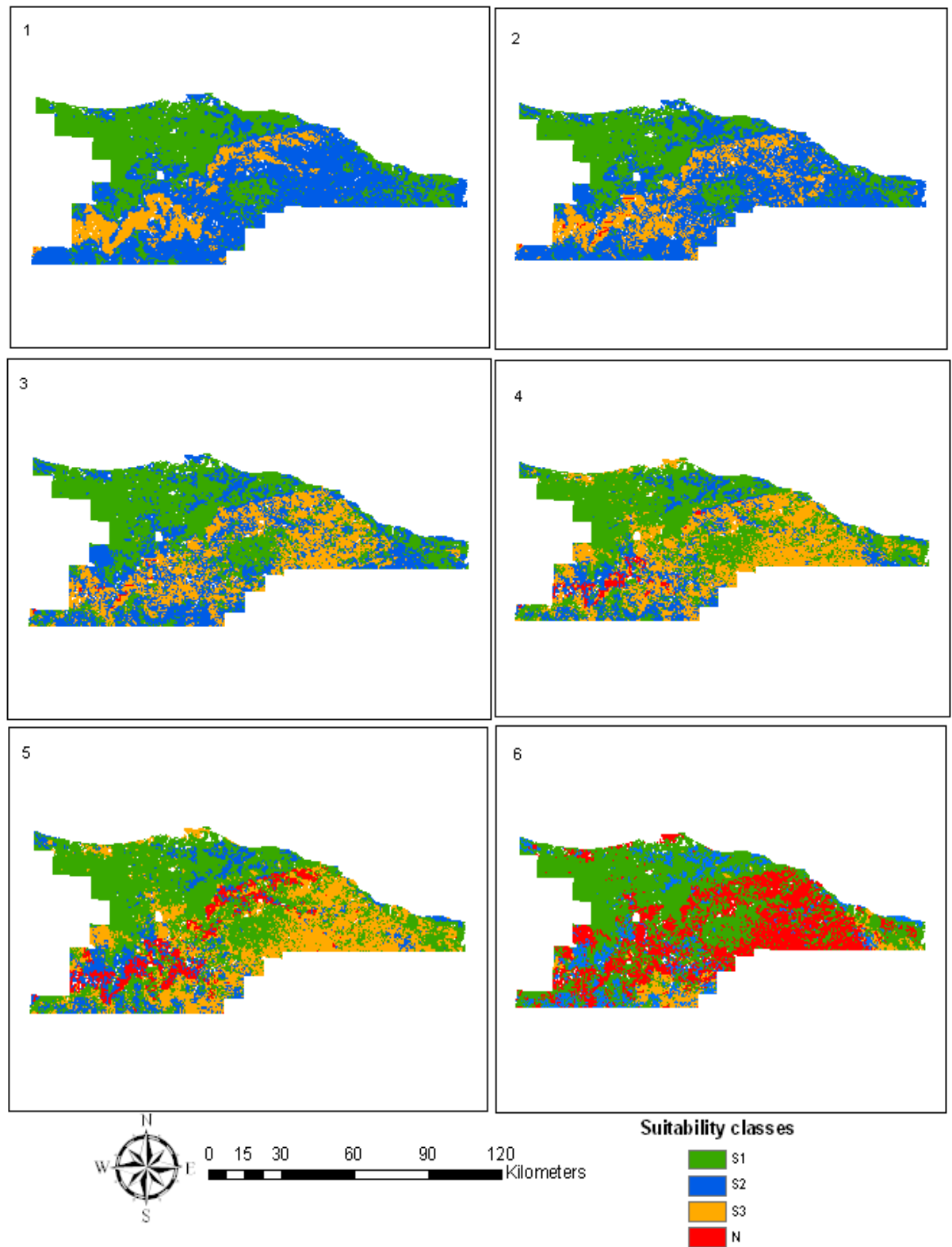
Figure 7-17: *Land suitability mapse in different weighting plans for (Barley)*

(Soil weighting plans, 1= 10%, 2= 25%, 3=40%, 4=55%, 5= 70%, 6= 85%)

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The sensitivity analysis indicated that by increasing the slope weighting, the proportion of high suitability classes increases (*Figure 7-18*). The increase was due to the fact that most of the study area is plain so the slope is highly suitable in the study area. *Figure 7-18* shows the prevailing increase is occurred in the high suitability class when the slope weighting is 10% the high suitability class S1 is 32%, whereas by increasing the importance of slope factor to 85% the high suitability class changed to 83%. Moreover, the moderate suitability class S2 is decreased from 50% to 12.2% when the importance of slope changes from 25% to 85%. The marginally suitable class also decreased from 16% to 4%. This implies that slope factor has to be given a suitable weight reflect its importance.
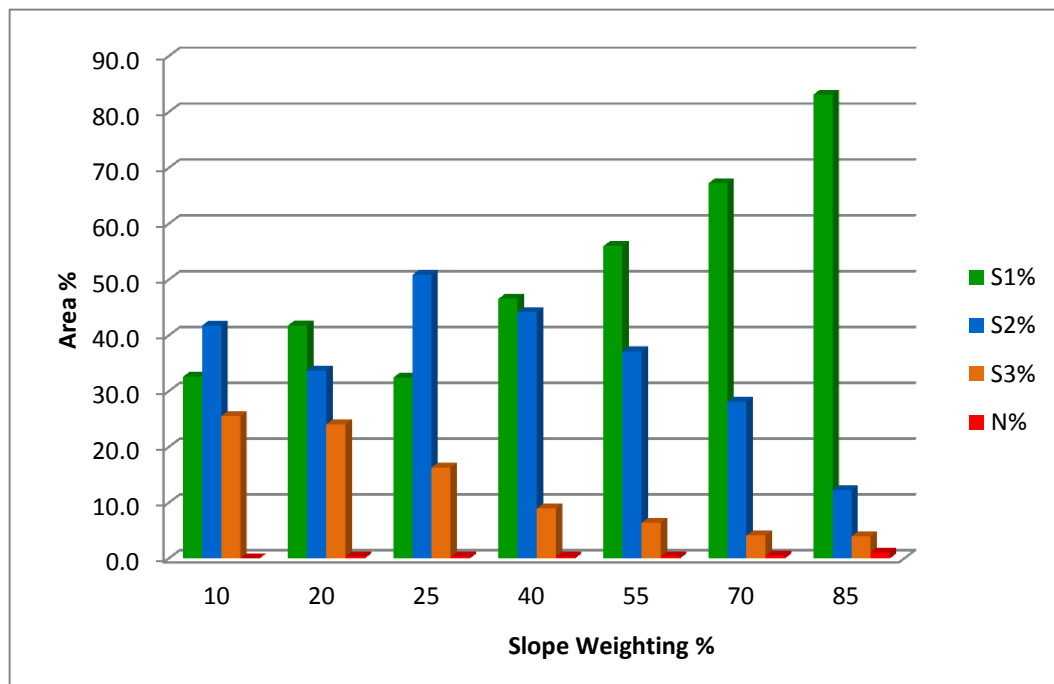
Figure 7-18: *Sensitivity analysis for Slope factor for (Barley)*

For the erosion factor the sensitivity analysis revealed that by the change of the erosion weighting the suitability pattern has changed slightly (*Figure 7-19*). The proportion of high suitability class is increased from 41% to only 48% by changing the erosion weighting from 10% to 85% whilst the moderate suitability class decreased dramatically from 51% to 25% when the erosion weighting is

changed from 25% to 85%. In addition, the margin suitability class has not changed by increasing the erosion weighting from 25% to 85%.
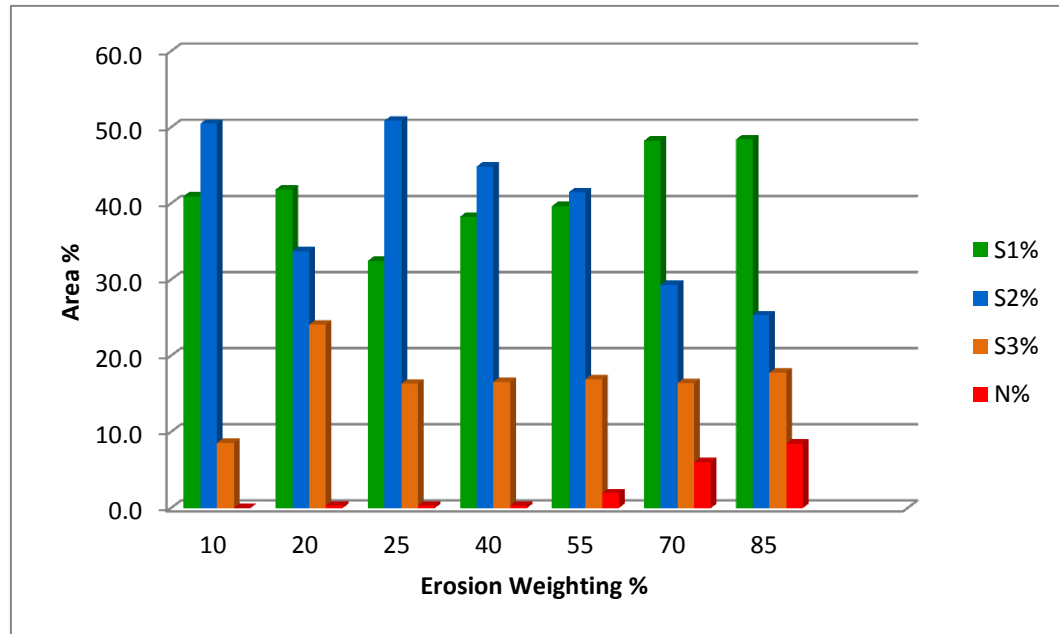
Figure 7-19: *Sensitivity analysis for Erosion factor for (Barley)*

The sensitivity analysis revealed that soil is the most sensitive factor in the suitability classification for barley. Slope and erosion are the second sensitive factors in the suitability classification. In accordance with these findings a weight of 40% was given for soil factor whereas a weight of 20% was given for the other factors (climate, slope and erosion).

7.4.2.2   *Sensitivity analysis for Wheat*

The sensitivity analysis indicated that the soil is a highly sensitive factor in the suitability classification for wheat. As shown in *Figure 7-20* output of land suitability classes are changed by increasing the influence of the soil criteria. The percentage of moderately suitable class (S2) was 50% when the soil weighting was 10% and 25%. However, this figure decreased to 12% when the soil weighting increased to 85%. Also a significant percent of the study area classified

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as not suitable (N) (31%) with 85% soil weighting. Up to 40% soil weighting no (N) classes was mapped. The high suitability class (S1) was increased gradually from 32% to 52% when the soil weighting was increased from 25% to 85%.
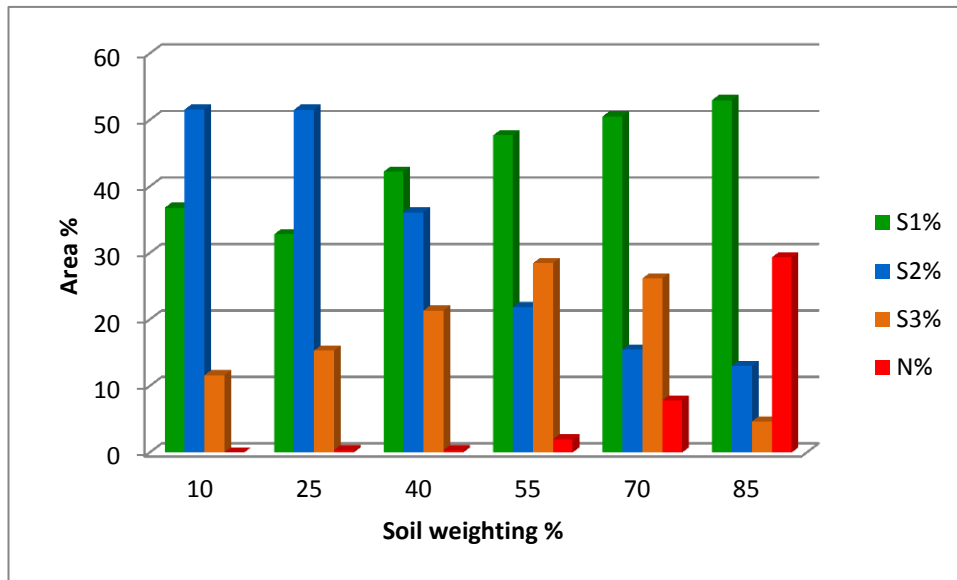
Figure 7-20*: Sensitivity analysis for Soil factor for (Wheat)*

As can be seen in *Figure 7-20* the land suitability classification was changed by assuming different soil weightings. From these findings it is clear that the soil factor has important influence on the overall of land suitability and should be given suitable weighting reflecting its importance for assessment of the overall land suitability for wheat in the study area**.**

For climate, the analysis indicated that the moderately suitable class (S2) is increased dramatically from 53% to 92% with the increase in the weighting of climate more than 40% (*Figure 7-21*). In addition, the disappearance of the rest of suitability classes can be observed when the weightings of climate were more than 40%.   This because of the climate layer in the most of study area is classified as moderately suitable.

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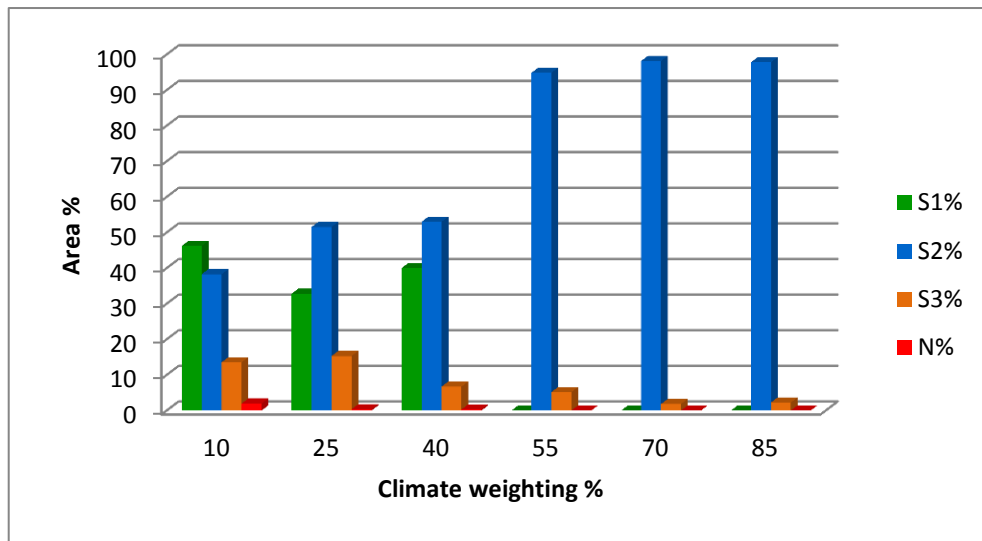
Figure 7-21: *Sensitivity analysis for Climate factor for (Wheat)*

The sensitivity analysis for slope revealed that by changing the weighting schemes, the suitability pattern changes *(Figure 7-22).* The highly suitability class (S1) increases in line with the increase of slope weighting. When the slope weighting is 10 % the proportion of highly suitable class was 30% and with the slope weighting is 85% the highly suitable class increased to 82%. In addition, the moderately suitable class decreases from 50 % to 12 % when the weighting of slope changes from 25 % to 85 %. The marginally suitable class also decreases from 14% to 3 %.
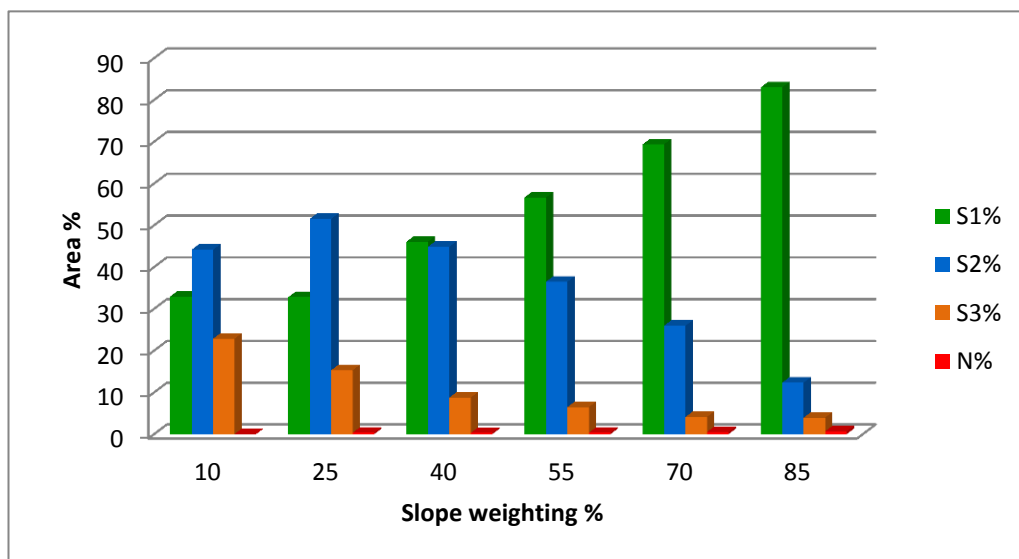
Figure 7-22: *Sensitivity analysis for Slope factor for (Wheat)*

The variation of erosion weighting produced two different suitability patterns. The first pattern was dominated by the moderately suitable class. The second suitability pattern was dominated by the highly suitable class (*Figure 7-23*). When erosion weighting was set at 10 %, the resulting moderately suitable class was 49 %, while when erosion weighting was 85 %, the highly suitable class was 48 %. From *Figure 7-23* it is clear that the marginally suitable class was almost steady at 17%, whereas not suitable class does emerge only when erosion weighting is 55% or more. The results proved that the erosion is moderately sensitive. However, the change is not found to be as dramatic as it is found to be in the soil.
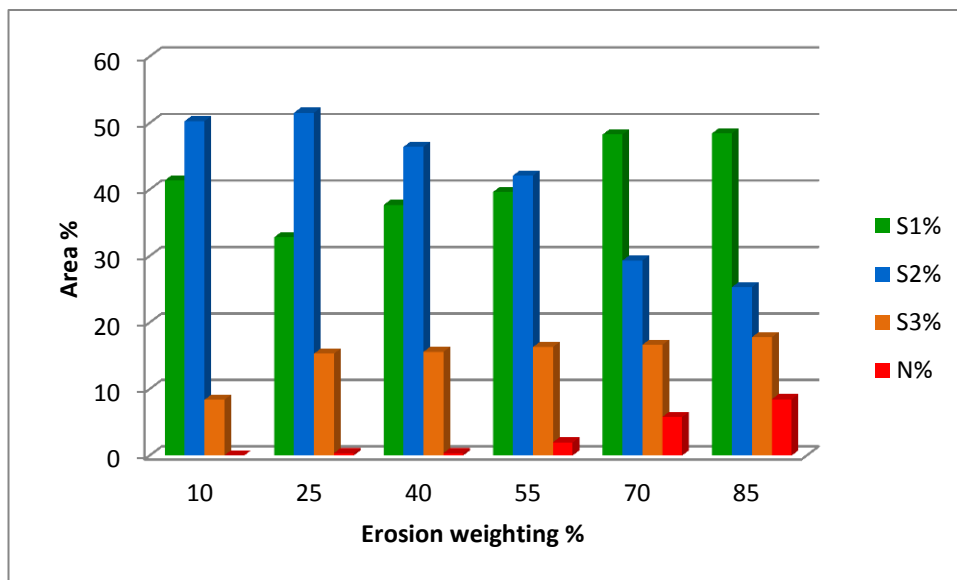
Figure 7-23: Sensitivity analysis for Erosion factor for (Wheat)

7.4.2.3   Sensitivity analysis for olive

The sensitivity analysis indicated that the soil is a highly sensitive factor in the suitability classification for olive. *Figure 7-24* shows the sensitivity analysis of the soil based on the numerous weighting values. As can be noted, when the soil weighting was increased from 25% to 70%, the high and the marginally suitability classes were increased gradually while the moderate suitability class decrease dramatically. Moreover, not suitability class appears only when soil weighting was 55% or upper. The results show that the increase in the soil weighting has a

dramatic effect on the suitability pattern in the study area. Therefore, the soil factor has important influence on the overall of land suitability and should be given suitable weighting reflecting its importance for assessment of the overall land suitability for olive in the study area.
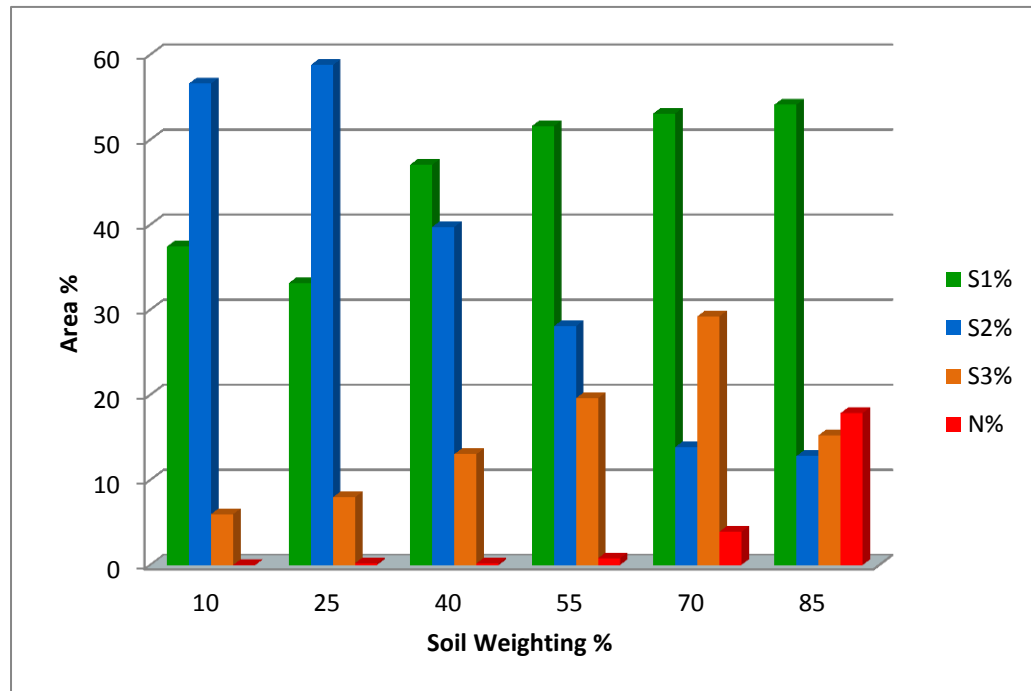
Figure 7-24: Sensitivity analysis for Soil factor for (Olive)

The sensitivity analysis for the climate factor is conducted in the present study as shown in *Figure 7-25*. The results proved that the climate is moderately sensitive. However, the change is not found to be as dramatic as it is found to be in the soil case. When the weighting of climate is represented by 10%, the highly suitable class is seen as 50%, whereas as the weighting of climate increases up to 40%, the highly suitable class (S1) decreases to 32%. The moderately suitable class (S2) is increased dramatically from 53% to 92% with the increase in the weighting of climate more than 40%. In addition, the disappearance of the rest of suitability classes can be observed when the weightings of climate were more than 40%. This because of the climate layer in the most of study area is classified as moderately suitable.

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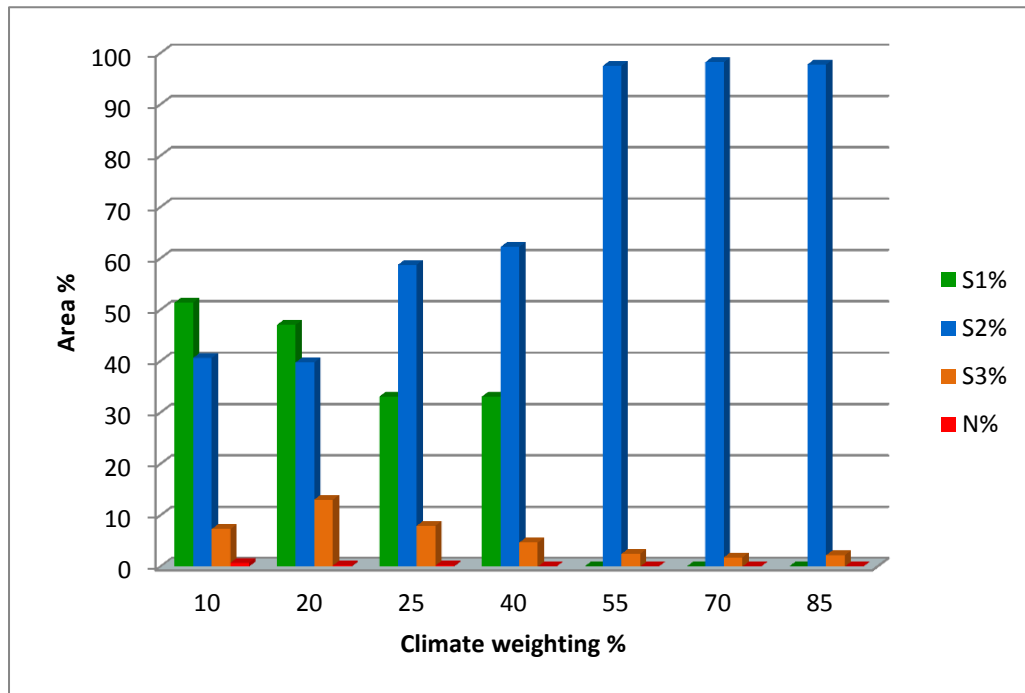
Figure 7-25: *Sensitivity analysis for climate factor for (Olive)*

The sensitivity analysis revealed that the slope is a moderately sensitive in the suitability classification for olive. *Figure 7-26* shows the land suitability classes for different weighting schemes. As it is noted from increasing the influence of the slope factor from 25% to 85%, the highly suitable class (S1) was increased, whereas the moderately suitable class (S2) was decreased. This is expected because of slope layer in the most of study area is classified as highly suitable.

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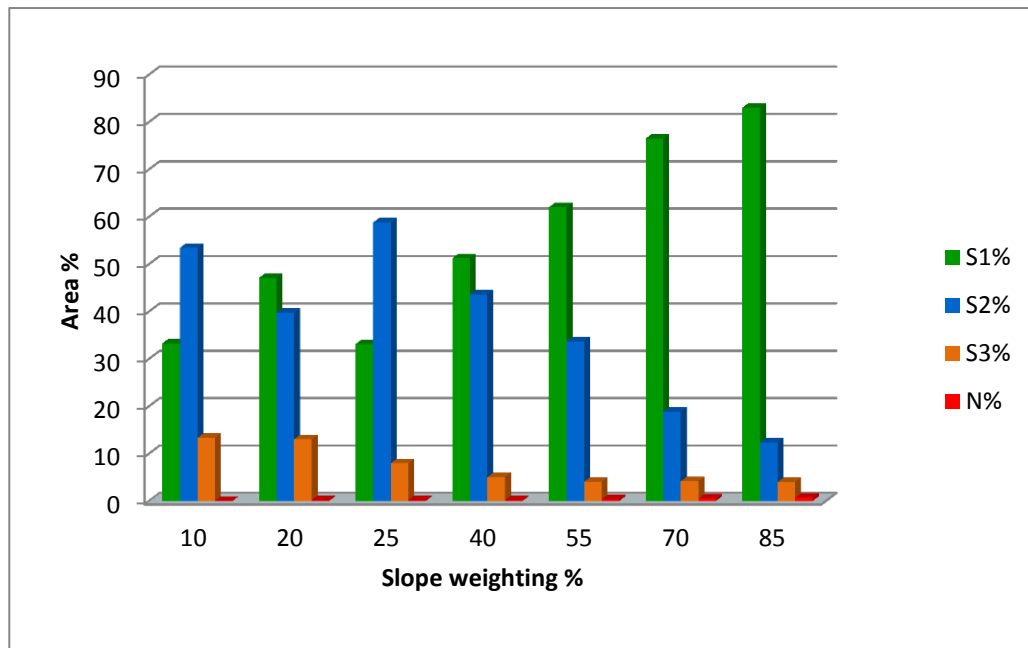
Figure 7-26: *Sensitivity analysis for slope factor for (Olive)*

For the erosion factor the sensitivity analysis revealed that by the change of the erosion weighting the suitability pattern has changed slightly (*Figure 7-19*). The proportion of high suitability class is increased from 32% to 48% by changing the erosion weighting from 25% to 85%, whereas the moderate suitability class decreased from 58% to 42%. In addition, the suitability classes were not changed by increasing the erosion weighting from 70% to 85%. The results proved that the erosion is moderately sensitive for olive.
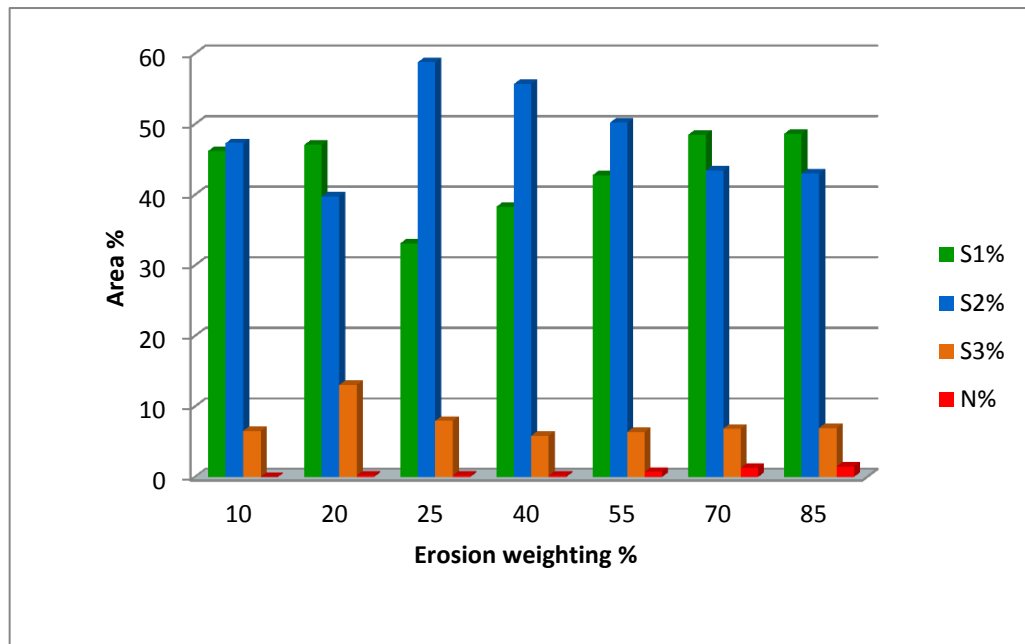
Figure 7-27: *Sensitivity analysis for erosion factor for (Olive)*

In conclusion, it is evident that the soil is a highly sensitive in the study area. Therefore, it should be given suitable weighting reflecting its importance. The results suggest that the climate, slope and erosion are not as sensitive as the soil and therefore, the criterion weighting for each factor should be different when the suitability model is used.

7.5   Summary

In this chapter, land suitability classification maps for the selected crops in the study area were produced from the spatial overlay of four layers (Soil, climate, slope and erosion). Two models Boolean and Fuzzy logic have been established for the selected crops. The Boolean model for land evaluation has been developed by chosen the most influential characteristics on land suitability, and their threshold values in line with the environmental conditions in Libya. This was implemented from a discussion with local experts by in-depth knowledge about agricultural practices in Libya and literature review. The Fuzzy model has been used to explore and address the uncertainty associated with the conventional Boolean method. Both of Boolean and Fuzzy models were compared using map

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agreement. The overall agreement and disagreement between the maps has been computed. In addition, sensitivity analysis was conducted in order to gain confidence in the suitability model developed in this research.

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

Chapter 8

CONCLUSION AND RECOMMENDATIONS

8.1 Conclusion

This research has developed a land suitability model for the northwest of Libya, which can be used in other arid and semi-arid areas. The research involved a modelling strategy based on Boolean and Fuzzy logic sets, implemented within a Geographic Information System (GIS). The land suitability maps for the selected crops wheat, barley and olive were produced.

The generated land suitability map can be further used for the developing priority-based supplementary irrigation plans. For example, using the findings of land suitability map in case of water scarcity, water supply can be prioritised by giving least priority to the less suitable areas. In addition, crops to be cultivated can be identified according to their importance in economic terms taking into account the water consumption of these crops. For example, if the available water for supplementary irrigation is limited in the area, it is better to choose barley crop instead of wheat which needs more water comparing with barley.

The following conclusions can be drawn from the present study listed according to the specific objectives of this study:

Objective 1

Review the literature on land evaluation methodologies and select/adapt a suitable methodology to suit the Libyan conditions. The most common methodologies used in land evaluation were discussed in Chapter 2 considering advantages and disadvantages of each method, resulted in the selection and development a powerful framework, suited to Libyan agricultural policy requirements. The methodology based on process which involves matching the requirements of each land utilisation type with crop requirements. This approach achieves the optimum utilization of agricultural land and water resources which

are already limited in Libya. This will help decision makers and planners to achieve maximum benefit for the use of limited land productivity. In this research the combination of Boolean and Fuzzy approaches was used for addressing the uncertainties in the process of land suitability evaluation for the selected crops.

Objective 2

Evaluate the available information for the north-west of Libya including soil, crop and climate data and select data appropriate to the selected land suitability method. The data available to this research were reviewed in order to select the land characteristics which are important in assessment of land suitability classification for barley, wheat and olive in the study area. The rationale for the selection of these characteristics was based on agronomic experience at research stations and existing farms in the study area. The important consideration in this selection was the effect of these land characteristics on the use of the land and the availability of the critical values in the study area. Based on these considerations fourteen land characteristics were determined to be matched with the requirements of the land utilization type for each crop in the current study. The selected land characteristics which are available in the study area are: topsoil texture, soil depth, stones on the surface, available water holding capacity, soil salinity, soil alkalinity, percentage of calcium carbonate in the soil ($\%CaCO^3$) , soil reaction (pH), organic matter, cation exchange capacity and infiltration rate, length of growing period, slope steepness and erosion hazard.

Objective 3

Develop land suitability assessment to determine which areas are suitable for barley, wheat and olive cultivation in the north-west of Libya. This objective was fulfilled; the assessment of land suitability for the selected crops was conducted using both crisp and fuzzy logic based on the requirement for each crop. The model involves the interpretation of data relating to soils, climate and topography into a suitable format, allowing land suitability analysis to take place. The combination of these data together with the specific model framework, being capable of producing thematic interpretations maps for each crop. One of the most

important developments made in the study is the integration of different GIS functions and local knowledge within the process of land evaluation techniques in GIS environment for the study area.

Objective 4

Provide a land suitability map that can be used/ interpreted by farmers, water resources and agriculture managers involved with policy formulations in Libya. The methodology of producing land suitability maps was based on matching land characteristics with crop requirements to produce four layers namely: Soil, climate, erosion hazard and slope, which are important for land suitability for the selected crops in the study area. These layers were integrated into the GIS environment as information layers and then the overall land suitability map for the selected crops were produced. The process of producing the four layers was explained in Chapter 6.

The results showed that the study area has a good potential to produce the selected crops. The results obtained from the use of Boolean approach are about 58% of the study area is highly suitable for barley, 51% is highly suitable for wheat cultivation and 55% is highly suitable for olive. In addition, the proportion of highly suitable land using Fuzzy approach was 42% for both barley and wheat and 47% for olive.

The suitability land maps produced as a result of land evaluation will benefit the farmers and stakeholders and decision makers to deal with and improved the efficiency of land use by chosen which part of region is better to cultivate by specific crop. This will lead to improved crop yields and optimal utilisation of available water resources. This in turn can reduce the overall cost of agricultural production.

Objective 5

Compare and assess the results obtained from Fuzzy logic approach with those from the Boolean approach to check if there is any different between them and

which results seems to be more realistic. The overall land suitability results for the selected crops are almost similar; the main difference is in the suitability classes. In the Fuzzy classification 42% of the study area was found highly suitable for both barley and wheat and 55% for olive, while with the Boolean classification about 58% of the total study area was highly suitable for barley, 51% for wheat and 55% for olive (Table 7.3). While the Boolean classification gave values higher than Fuzzy classification regarding to high suitability class, the Boolean classification gave values less than fuzzy classification regarding the moderate suitability. This is because with Boolean the class boundaries of the criteria values are sharply defined. For example, high suitability class of soil depth for barley is the soils with depth greater than100 cm that means if the soil depth is 101 cm then this soil is considered high suitability regarding the soil depth. However, with fuzzy logic this value does not consider completely high suitability but in the other hand it takes partial membership that ranging in value between 0 and 1. As a result, the soils that classified as high suitability class with Boolean logic might be classified as moderate suitability class with fuzzy logic.

The results maps from Boolean soil suitability were compared with the fuzzy soil suitability maps using raster calculator function in ArcGIS. The results show that the overall agreement obtained from comparing the Fuzzy maps and Boolean maps was moderate. The percentage area that considered completely agreement was ranging from 46% to 56%. The main reason for miss agreement classes between Boolean and fuzzy was the lack of moderate and margin suitability classes in Boolean model and the difference in suitability areas location.

Which results seems to be more realistic? It is difficult to determine which results are closer to the real situation. However, as known fuzzy approach presents soil suitability classes without a crisp, clearly defined boundary in which the transition from one class to another is gradual rather than abrupt, while with Boolean logic the boundary between classes is sharply defined which are less realistic in nature. The transition between boundary classes in fuzzy logic makes fuzzy approach more flexible and credible. In addition, field trial is needed to validate these

models and identify which approach is more realistic on the ground. It has been the plan to carry out such a ground truthing activity but this was thwarted by the Arab spring revolution and ensuing chaos, which prevented me from making a trip to Libya.

8.2   Recommendations and further research

The most important development that has been made in this research is the combination of conventional Boolean approach with fuzzy logic approach in GIS. The fuzzy logic theory was used for creation soil suitability map while the Boolean theory was used for creation the rest of maps (climate, slope and erosion). The use of local knowledge in the data set of the study area and its application in GIS has enabled the production of specific information for land evaluation for the study area.

This research is considered to be the first study using fuzzy rule-based systems for linguistic modelling in Libya. This involves adjusting the membership functions according to the threshold values of each factor in line with agricultural condition in Libya. In which used automated fuzzy tool in MATLAB based on rules instead of the manual method used by (Elaalem, 2010) which applied some membership functions developed by some researchers. The membership functions that have been successfully developed in a different environment may not be appropriate for other environment. The conventional Boolean method has also been used in this study to benefit from the advantages of this method and compared their results with the results obtained from fuzzy method. The main advantage of the Boolean model is the possibility of controlling and tracing which factors are affecting the suitability of a plot, while with the fuzzy model it is necessary to review the interaction between membership functions, which is not a straightforward process. Fuzzy theory allows intermediate possibilities of suitability beyond the conventional classes given by the Boolean methods, but on the other hand it can overestimate the potential of a land as a moderate and margin suitability classes. On contrary, the Boolean theory can underestimate the real potential of a plot. In

this sense, maybe the land evaluator has to try with both theories and check with information on the field which one agrees better with the reality.

The model developed in the study area will assist the planners and decision makers in Libya in the selection of appropriate scenario for each land in the study area and that could play an essential role in agriculture production in the country. The research findings and procedures can be beneficially applied to land use planning in other regions with similar conditions.

The findings of this study have a number of important implications for future practice concerning land evaluation and agricultural development in Libya. In the light of this research, it is recommended:

1. There is a need for specific field tests to validate the model results by comparing the results of the model with what already exists on the ground. This would increase the confidence in the model and detects any weakness can be happen in the model.

2. Soil survey data, especially those factors that directly affect the soil fertility such as soil pH, salinity, and organic matter content in the soil are not very accurate. These factors can be changed after each crop season depending on land use management in the area. A future challenge will be to improve the efficiency of the maintenance and updating of the land use data sets, that can be done by inventories and monitoring of the soil regularly. Such an exercise is certainly beyond the scope of this research but should be the responsibility of specialized soil science institutions in the country.

3. Social and economic factors may play a significant role in the distribution of crops in the area that unexplained by environmental conditions alone. As noted earlier, the lack of reliable socio-economic data was why a truly quantitative land assessment approach was not attempted in the study. So

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it is important to create social-economic database system. This information will make land evaluation studies in Libya more effective and accurate.

4. To take full advantage of the available arable land in the study area, there is a need for improving the yields by using modern cultivation techniques such as use of biotechnology in the development of resistant crops to salinity and drought, and using supplementary irrigation to cope with irregular rainfall. The current study has shown that the soil is the most important and so while supplemental irrigation could improve the crop production potential, such is unlikely to change the situation in areas where the soil quality is poor or marginal.

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Glossary

- **Land characteristics** are attributes of land that can be measured or estimated such as slope, soil texture, soil depth, available water holding capacity, etc.

- **Land qualities (LQ)** are the result of interaction between a set of land characteristics which have a direct effect on land capability for a specific use. Land qualities are thus derived from land characteristics. An example of land qualities is ' availability of nutrients' which is influenced by two land characteristics organic matter O.M and cation exchange capacity CEC.

- **Land mapping unit** is a mapped area of land with specified characteristics. Land mapping units are defined and mapped by natural resources surveys, e.g. soil surveys, forest inventory.

- **Land Utilisation Types (LUTs)** The land utilisation types (LUTs) represent land uses in more detail than general land use categories according to physical, economic and social conditions.

- **Land use requirements** are expressed mainly as crop requirements which refer to the set of land characteristics that determine the production and management conditions of a kind of land use.

Appendix A

A brief description for the subtype soils in the study area

1. Siallitic Cinnamon Typical Soils

The siallitic cinnamon typical soils are found in the Jifara Plain of Libya. It lies on the volcanic plateau, flat, undulating, plains. The main parent materials of soils are alluvial, alluvial- proluvial, eluvial-deluvial. 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. The profile of the fully developed siallitic cinnamon typical soils continas the following horizons: A, B1ca, B2ca, B3ca, BCca, Cca and R.

2. Reddish Brown Arid Differentiated Soils

The reddish brown arid differentiated soils covers many areas of Jifara 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: A1 or AP, B1ca, (occasionally B1), B2ca, B3ca (or BCca), Cca, occasionally R.

3. Reddish Brown Arid Slightly Differentiated Soils

The reddish brown arid slightly differentiated soils are spread on the littoral plain and on the Jebel Nefusa plateau. The parent material is composed of 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 A1B1ca,B2ca, B2ca, (sometimes B3ca) BCca, Cca. The transition between the horizons is gradual, without pronounced boundaries.

4. 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 A1, B1ca, CRca or A, B1ca, 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.

5. 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. 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.

6. Reddish Brown Arid Non-Differentiated Crust Soils

The reddish brown arid non-differentiated crust soils occupy a small area in Jeffara Plain. The soils are most common on the littoral and the residual plains of the Jeffara lowland. The parent materials are represented by proluvial- deluvial and eolian deposits. 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.

7. Alluvial Slightly Differentiated

The alluvial slightly differentiated soils are found within the piedmont tails of the residual plain along the valleys. 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.

8. Cinnamonic Lithosols

The Cinnamonic lithosols soils are mainly widespread in the south- western part of Jifara Plain. They are found on the Jabil Nefusa upland. 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 A1, BR, R or AR, R. The Cinnamonic lithosols fall into the following genera Carbonate and carbonate saline.

9. Reddish brown Lithosols

These soils mostly occur in the regions of Al Aziziyah, , Zliten and Homs. 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: A1,

AR, R or AR, R. The reddish brown lithosols fall into the following genera: carbonate and carbonate saline.

10. 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 Jifara 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: A1, AR, CR OR A1, AR, and CRsica. The non-monolithic crust fall into the following genera: carbonate, carbonate saline and carbonate gypsic.

11. Hydromorphic solonachaks

The hydromorphic solonachaks are developed in the coastal area around the sebkha solonchaks. The soil-forming rocks include marine lagoon sediments, eluvial-devial and deluvial deposits of a different granulometric composition. These soils are spread mainly on the coastal regions such as Zawia, Homs and Sebratah.

Appendix B

Table (B1) the chemical and physical characteristics for soil sub-types in the

Study area

Soil-class	Root_Depth cm	AWHC mm	pH	EC dc/cm	ESP (%)	$CaCo_3$ (%)	Infi_rate mm hr^{-1}	CEC Meq/100g	O.M (%)
CS_t_Ca	300	97	8.3	9.6	0.3	15	6.6	9.6	0.4
CS_t_Cas	300	133	8.3	7.3	0.9	37	6.6	7.3	0.4
CS_t_l	300	98	8.1	3.6	0.4	1	6.6	3.6	0.2
CS_cr_ca	120	170	8.9	7.5	0.9	14	7.8	7.5	0.3
CS_cr_cas	50	187	8.4	7.7	1	13	7.8	7.7	0.5
FB_d_ca	300	137	8.7	10.9	0.2	14	6	10.9	0.3
FB_d_cas	150	144	9.0	6.6	0.2	16	6	6.6	0.3
FB_d_cag	180	177	7.9	4.6	0.7	33	6	4.6	1.2
FB_d_casNa	230	114	8.0	6.4	2.2	32	6	6.4	0.3
FB_dcr_cas	120	99	8.0	5.9	0.3	12	15	5.9	0.3
FB_dcr_cas	72	133	8.7	4.6	2.1	17	15	4.6	0.3
FB_sd_ca	215	80	8.6	4.6	0.2	29	10.2	4.6	0.2
FB_sd_cas	300	95	8.6	7.5	0.4	11	10.2	7.5	0.2
FB_sd_cag	203	36	8.2	7.8	0.5	20	10.2	7.8	0.3
FB_sd_caNa	195	98	8.7	6.0	3.2	12	10.2	6.0	0.3
FB_sd_casNa	300	95	8.3	8.9	8.4	10	10.2	8.9	0.2
FB_sd_l	300	102	8.2	5.1	0.2	1	10.2	5.1	0.1
FB_sd_nca	300	313	7.7	3.5	0.2	0	10.2	3.5	0.2
FB_sdcr_ca	120	79	8.3	5.8	0.2	12	10.8	5.8	0.3
FB_sdcr_cas	50	92	8.2	5.4	1.7	15	10.8	5.4	0.4
FB_sdcr_cag	102	133	8.6	5.3	0.7	13	10.8	5.3	0.1
FB_sdcr_l	77	72	8.0	5.4	0.2	0	10.8	5.4	0.1

Soil-class	Root_Depth cm	AWHC mm	pH	EC dc/cm	ESP (%)	$CaCo_3$ (%)	Infi_rate mm hr^{-1}	CEC Meq/100g	O.M (%)
FB_nd_ca	300	58	6.6	5.4	0.1	2	13.2	5.4	0.1
FB_nd_l	120	77	7.6	5.4	0.2	0	13.2	5.4	0.0
FB_nd_nca	300	58	8.2	4.5	0.1	0	13.2	4.5	0.0
FB_ndcr_cas	75	110	8.3	4.8	0.3	11	6	4.8	0.1
A_sd_ca	300	85	8.1	9.6	0.1	8	5.4	9.6	0.3
L_csl_ca	28	109	8.5	8.8	4.4	18	3	8.8	0.9
L_cse_cas	21	125	8.5	8.9	1.2	30	3	8.9	0.9
L_csl_cas	28	155	8.0	8.0	1.2	22	3	8.0	0.6
L_csl_cag	13	103	7.7	6.6	1.2	10	3	6.6	0.7
L_rbl_ca	18	81	9.0	9.2	2.6	15	6	9.2	0.8
L_rbl_cas	18	134	8.1	12.3	2.2	13	6	12.3	1.0
L_rbl_cag	18	90	7.5	6.6	1	7	6	6.6	0.6
CR_nm_ca	38	165	8.0	5.0	2.7	21	2.4	5.0	0.1
CR_nm_cas	40	127	8.4	8.7	2	34	2.4	8.7	0.8
CR-nm_gca	55	76	8.2	8.3	1.1	6	2.4	8.3	0.3
CR_nm_sica	38	79	8.5	4.9	1.6	51	2.4	4.9	0.1
CR_nm_sicas	18	80	8.5	4.4	2.4	43	2.4	4.4	0.1
Sh	80	270	8.6	4.7	1.9	27	1.8	4.7	0.3
Shcr	90	271	8.9	9.1	1.2	9	1.2	9.1	0.7
Shs	40	146	8.0	3.2	2.3	20	6	3.2	0.5
SM	300	120	8.8	2.2	0.1	14	6	2.2	0.1
SC	300	89	7.1	2.9	0	71	6	2.9	0.1

Table (B2) soil texture for the soil sub-types in the study area

Soil_class	Stones%	Sand %	Clay %	Silt %	Soil texture
CS_t_Ca	0	59	21	20	sandy_clay_loam
CS_t_Cas	2	74	13	13	sandy_loam
CS_t_l	0	96	1	3	sand
CS_cr_ca	4	72	13	15	sandy loam
CS_cr_cas	23	85	4	12	loamy sand
FB_d_ca	3	74	13	13	sandy loam
FB_d_cas	0	75	15	10	sandy loam
FB_d_cag	0	62	33	6	sandy_clay_loam
FB_d_casNa	3	76	11	13	sandy loam
FB_dcr_ca	1	76	15	9	sandy loam
FB_dcr_cas	4	68	21	11	sandy_clay_loam
FB_sd_ca	0	90	7	3	sand
FB_sd_cas	0	59	16	25	sandy loam
FB_sd_cag	0	59	20	21	sandy clay loam
FB_sd_caNa	0	67	14	19	sandy loam
FB_sd_casNa	0	56	15	29	sandy loam
FB_sd_l	0	95	3	2	sand
FB_sd_nca	0	92	3	4	sand
FB_sdcr_ca	0	85	8	7	loamy sand
FB_sdcr_cas	5	74	13	12	sandy loam
FB_sdcr_cag	0	79	14	7	sandy loam
FB_sdcr_l	0	94	2	4	sand
FB_nd_ca	0	68	27	5	sandy_clay_loam
FB_nd_l	0	86	14	1	loamy sand

Soil_class	Stones%	Sand %	Clay %	Silt %	Soil texture
FB_nd_nca	0	94	1	4	sand
FB_ndcr_cas	1	92	4	4	sand
A_sd_ca	0	63	15	23	sandy loam
L_csl_ca	37	62	13	25	sandy loam
L_cse_ca	22	51	21	28	loam
L_csl_cas	37	51	21	28	loam
L_csl_cag	29	53	9	38	loam
L_rbl_ca	25	52	22	26	sandy_clay_loam
L_rbl_cas	51	69	10	21	sandy loam
L_rbl_cag	12	73	8	19	sandy loam
CR_nm_ca	4	90	4	5	sand
CR_nm_cas	23	49	14	37	loam
CR-nm_gca	0	67	7	26	sandy loam
CR_nm_sica	10	88	5	6	sand
CR_nm_sicas	14	76	11	13	loam
Sh	1	71	18	11	sandy loam
Shcr	2	71	12	17	sandy loam
Shs	0	40	27	34	loam
SM	0	99	1	0	sand
SC	0	79	20	1	sandy_clay_loam

Table (B3) Maximum monthly temperature of 12 stations for the period

(1985-2009)

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Tripoli	17.6	19.1	21.7	25.7	30.1	34.1	35.1	35.8	33.5	29.1	23.2	19.0
Alhadbah	17.6	19.2	21.2	25.1	28.6	33.3	34.0	34.9	33.1	29.5	23.6	19.2
Alkomes	17.8	18.4	20.2	22.9	25.9	29.4	30.9	28.9	31.1	28.8	24.1	20.0
Yefren	12.1	14.3	17.0	22.4	27.4	32.0	33.2	33.4	30.4	25.0	18.9	13.6
Sorman	17.5	19.2	20.7	24.0	27.2	29.2	31.8	33.1	31.7	28.4	22.6	18.8
Zawia	17.9	19.0	21.5	25.1	29.0	32.4	33.2	34.8	33.4	29.9	24.3	19.8
Alzahra	18.3	19.2	22.0	26.2	31.7	34.6	35.6	37.2	34.6	29.2	24.1	19.9
Zwara	17.9	19.0	21.5	25.1	29.0	32.4	33.2	34.8	33.4	29.9	24.3	19.8
Esbaae	17.4	17.8	19.1	21.8	24.7	27.8	29.5	31.1	30.3	27.2	23.0	19.0
Grian	12.4	14.2	17.1	21.8	26.8	31.7	32.7	32.9	29.9	24.2	18.3	14.0
Rojban	13.1	15.2	18.0	23.5	28.5	32.8	33.9	34.2	31.3	26.0	19.9	14.7
Misurata	17.7	18.4	19.4	23.0	26.2	29.7	30.6	31.8	31.3	28.4	23.5	19.4

Table (B4) Minimum monthly temperature of 12 stations for the period

(1985-2009)

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Tripoli	6.8	7.0	9.1	12.0	15.9	19.6	20.4	21.4	20.3	16.8	11.5	8.1
Alhadbah	7.4	7.9	9.4	12.0	15.5	19.1	20.3	20.4	20.1	17.9	12.5	8.7
Alkomes	8.9	8.6	10.3	12.6	16.3	20.0	21.5	20.1	19.6	18.8	13.9	9.9
Yefren	6.5	7.4	9.2	12.6	16.9	20.4	21.8	22.5	20.5	16.9	12.1	7.9
Sorman	7.9	8.4	10.2	13.1	16.4	18.8	20.8	21.8	21.0	17.7	12.4	9.1
Zawia	7.2	7.2	9.3	12.3	16.3	19.6	20.5	21.6	21.2	17.4	12.6	8.5
Alzahra	7.0	6.9	9.0	11.9	15.7	19.4	19.8	21.0	20.6	16.7	11.6	8.6
Zwara	7.2	7.2	9.3	12.3	16.3	19.6	20.5	21.6	21.2	17.4	12.6	8.5
Esbaae	8.6	8.9	10.7	13.2	17.0	20.4	22.6	23.6	22.4	19.0	13.8	10.1
Grian	5.3	6.1	7.7	10.7	14.5	18.6	19.7	20.4	18.2	15.0	9.5	6.2
Rojban	3.3	4.0	6.3	9.8	14.0	17.6	18.3	19.1	17.6	13.7	8.2	4.3
Misurata	9.7	10.1	12.2	13.9	16.8	20.3	22.1	23.3	22.7	19.6	14.8	11.0

Table (B5) Rainfall (mm/month) of 12 stations for the period (1985-2009)

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Tripoli	50.9	29.4	21.9	13.5	4.7	0.5	0.2	0.2	8.5	23.6	38.6	43.1
Alhadbah	75.7	35.1	21.6	10.9	5.8	0.3	0.4	0.5	7.7	23.6	62.4	63.5
Alkomes	62.7	48	31.8	12.3	3.9	0.4	0.1	0.2	10.1	23.1	44.3	56.7
Yefren	51.4	37.5	39.6	14.4	10.6	2.1	0.4	3.2	4.1	26.8	26.8	51.4
Sorman	44.4	27.2	22.5	11.3	4.7	0.8	0.2	0.1	7.8	26.6	43.9	13.1
Zawia	54.3	31.5	25.2	8.9	4.4	1	0.2	0	10.1	28.3	63.9	57.4
Alzahra	72.7	57.9	47.5	9.5	3.2	1.5	0.0	0.2	24.9	25.7	39.7	52.9
Zwara	41.8	24.7	15.6	8.5	3.7	0.7	0	1.6	12.4	21.4	43.2	47.9
Esbaae	36.9	29.9	23.0	12.6	2.3	0.1	0.0	0.0	6.5	31.3	26.3	36.5
Grian	66.2	54.7	60.3	30.5	13.2	3.1	0.0	0.5	10.6	44.2	42.3	52.9
Rojban	34.0	31.9	46.3	15.2	9.1	3.7	0.1	2.0	9.3	25.3	19.1	36.9
Misurata	56.4	29.3	25.5	9.6	3.8	1.6	0	0.8	12.1	26.9	53.6	58.3

Table (B6) Wind speed (knots) of 12 stations for the period (1985-2009)

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Tripoli	6.1	6.4	7.1	8.4	9	8.7	7.6	7	7.3	6.4	6.1	6.3
Alhadbah	4.4	4.2	4.6	4.7	4.8	4.1	3.6	3.4	3.7	3.6	3.9	4.2
Alkomes	6.7	7.2	7.7	7.4	7.3	6.9	6.9	6.5	7.1	6.1	6.3	6.6
Yefren	8.3	8.5	8.5	9	8.7	8.2	7.6	7.1	7.5	7.7	7.7	7.7
Sorman	5.4	5.4	5.8	5.7	6.3	5.8	5.2	5.0	5.1	5.0	4.9	5.5
Zawia	4.2	4.6	5.4	6.1	6.0	5.8	5.0	4.7	4.8	4.4	4.0	4.6
Alzahra	3.7	4.0	4.2	5.3	4.5	4.6	4.2	3.8	3.9	3.7	3.5	3.9
Zwara	8.1	8.4	9.3	9.7	9.7	9.3	8.7	8.6	9.2	8.1	7.9	7.9
Esbaae	9.1	9.1	9.2	10.0	9.0	8.0	9.0	7.5	9.5	8.7	8.4	8.8
Grian	8.9	8.6	8.7	8.9	8.5	7.8	6.9	6.3	7.4	7.4	8.3	9.2
Rojban	7.2	8.2	8.7	9.3	9.6	9.2	8.3	7.3	7.7	8.1	7.8	7.7
Misurata	10	10.4	10.9	10.9	10.3	9.1	8.3	7.9	8.9	8.6	9.3	9.8

Table (B7) Relative humidity (%) of 12 stations for the period (1985-2009)

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Tripoli	74	71	69	63	58	58	59	61	63	65	69	72
Alhadbah	71.7	71.6	70.4	62.4	58.7	58.6	58.0	57.7	64.7	67.0	67.0	71.4
Alkomes	75	74	76	73	73	73	74	75	73	71	70	72
Yefren	66	60	56	49	44	42	42	45	52	54	59	65
Sorman	71.0	68.3	69.1	66.1	65.3	66.5	68.2	69.2	69.2	69.8	70.0	70.2
Zawia	75.5	72.7	70.2	63.3	60.9	62.0	65.0	65.4	66.5	67.1	69.0	69.8
Alzahra	71.7	71.6	70.4	62.4	58.7	58.6	58.0	57.7	64.7	67.0	67.0	71.4
Zwara	73	72	74	74	76	78	78	76	75	73	70	73
Esbaae	70.0	71.1	73.8	71.9	75.3	77.4	76.3	75.5	73.2	70.4	67.9	67.9
Grian	68.5	64.4	61.6	54.2	48.0	42.6	44.6	45.5	53.0	60.7	63.1	67.6
Rojban	66.4	59.9	55.3	46.8	41.6	39.4	40.6	41.2	48.7	55.7	59.8	63.6
Misurata	69	68	69	68	70	72	74	73	71	69	67	67

Table (B8) Sunshine duration (h) of 12 stations for the period (1985-2009)

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Tripoli	5.6	6.8	8.1	9.0	9.9	11.2	12.0	11.4	9.2	7.6	6.2	5.2
Alhadbah	6.1	6.7	7.6	8.7	9.4	10.5	12.0	11.3	9.2	7.4	6.3	6.3
Alkomes	6.4	7.2	7.8	8.3	9.8	10.7	11.8	10.9	9.0	7.7	6.6	5.6
Yefren	9.1	7.2	7.9	8.8	9.5	10.6	11.9	11.1	9.0	8.1	6.8	5.4
Sorman	6.4	7.5	8.1	8.9	9.3	10.5	11.9	11.4	9.3	7.8	7.1	6.3
Zawia	6.2	8.0	8.2	9.4	9.9	10.7	12.0	11.5	9.0	7.9	6.9	6.2
Alzahra	6.4	7.5	8.4	9.2	9.8	10.7	11.7	11.0	8.8	7.8	6.9	6.4
Zwara	6.5	7.6	7.7	8.4	8.9	9.7	11.0	10.8	8.7	7.7	6.8	5.8
Esbaae	5.6	6.8	8.3	9.2	10.0	11.0	12.0	11.5	9.3	7.5	6.4	5.5
Grian	6.0	7.0	7.6	8.8	9.7	10.7	12.0	11.4	9.0	7.5	6.8	6.4
Rojban	6.4	7.4	7.7	8.7	8.6	9.7	11.6	11.1	9.4	8.1	6.6	5.6
Misurata	6.5	7.4	7.7	8.9	9.5	10.7	11.9	11.4	9.3	8.2	7.0	6.2

Appendix C

Table (C1) *The rating index of the impact soil compaction extent on crop production (Ben-Mahmoud, 1995)*

Soil cohesion	Rating index	
	Annual crops	Perennial crops
Cohesion less soil	1	1
Cohesive soil	1	1
Very Cohesive soil	0.85	0.90

Table (C2) *The rating index of the impact of Soil depth on crop production (Ben-Mahmoud, 1995)*

Soil depth (cm)	Rating index	
	Annual crops	Perennial crops
> 150	1	1
100-150	1	0.9
30-50	0.8	0.5
< 30	0.5	0.1

Table (C3) *The rating index of the impact water table on crop production (Ben-Mahmoud, 1995)*

Water table level (cm)	Rating index	
	Annual crops	Perennial crops
Water table does not exist	1	1
Deeper than 300 cm	1	1
200-300	1	0.95
150-200	1	0.90
50-100	0.80	0.40
< 50	0.60	0.20

Table (C4) The rating index of the impact of internal soil drainage on crop production (Ben-Mahmoud, 1995)

Hydraulic conductivity (cm/day)	Rating index	
	Annual crops	Perennial crops
>300	0.5	0.6
100-300	1	1
10-40	0.75	0.6
1-10	0.6	0.3
<1	0.4	0.2

Table (C5) The rating index of the impact of soil salinity on crop production (Ben-Mahmoud, 1995)

Soil electrical conductivity (ds/m)	Rating index	
	Annual crops	Perennial crops
< 1	1	1
1-3	0.9	0.85
3-6	0.8	0.7
6-9	0.6	0.5
9-12	0.4	0.3
12-15	0.3	0.2
>15	0	0

Table (C6)The rating index of the impact of exchangeable sodium percentage on crop production (Ben-Mahmoud, 1995)

Ecchangeable sodium percentage (%)	Rating index	
	Annual crops	Perennial crops
0-2	1	1
2-10	1	0.9
10-20	0.95	0.8
20-40	0.8	0.6
40-60	0.6	0.3
> 60	0.3	0.1

Table (C7)The rating index of the impact of soil reaction (pH) on crop production (Ben-Mahmoud, 1995)

Soil reaction(pH)	Rating index
< 8.5	1
8.5-9	0.9
> 9	0.8

Table (C8)The rating index of the impact of calcium carbonate percentage on crop production (Ben-Mahmoud, 1995)

Calcium carbonate percentage ($CaCo_3$ %)	Rating index	
	Annual crops	Perennial crops
< 0.3%	1	0.95
0.3- 10	0.95	0.9
10-25	0.9	0.8
25-50	0.85	0.75
> 50	0.75	0.70

Table (C9) *The rating index of the impact of soil erosion on crop production (Ben-Mahmoud, 1995)*

Soil erosion	Rating index	
	Annual crops	Perennial crops
None erosion	1	1
Low	0.95	1
Moderate	0.80	0.95
Strong	0.65	0.80

Table (C10) *The rating index of the impact of soil slope on crop production (Ben-Mahmoud, 1995)*

Slope %	Rating index	
	With terraces	Without terraces
0-3	1	1
3-8	1	0.95
8-16	0.95	0.90
16-30	0.85	0.75