EVALUATING AGRICULTURAL POTENTIAL OF A CAPE METROPOLITAN CATCHMENT: A FUZZY LOGIC APPROACH

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AUTHOR’S DECLARATION

I, the undersigned, hereby declare that the work contained in this thesis is my own original work and that I have not previously in its entirety or in part submitted it at any university for a degree.

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ABSTRACT

Sustainable use of the earth's resources is seen by many authorities as critical to ensure the planet's survival. In this regard agriculture is seen as a major role player and fundamental link in the chain of sustainability. South Africa, a country with relatively little favourable agricultural land, should therefore preserve high potential areas for agricultural purposes. The Western Cape, with 75% of all medium-potential arable land in South Africa, is a valuable asset. One region targeted for development and where uncertainty prevails regarding its agricultural potential, is the G21B catchment in the Atlantis Growth Corridor (AGC). The AGC is envisaged as long-term growth axis for the Cape Metropole, but conflicting opinions exist on its agricultural possibilities and suitability to absorb urban growth.

Consequently, the aim of this project was to evaluate the suitability of this catchment for a number of agricultural landuses. Fuzzy logic, a modification of the land evaluation approach originally developed by the Food and Agricultural Organization of the United Nations (FAO), was used to address this problem. Input data consisted of a soil map and digital elevation model (DEM) of the area. Parameters identified from these sources and applicable to the study were soil texture of the first, second and third horizons, as well as coarse fragments in the top soil, wetness, weathered rock, average pH, effective root depth, and slope. These parameters were compared to the requirements of six landuses, i.e. wheat, wine grapes, potatoes, tomatoes, onions, and citrus, and a fuzzy representation for every landuse was constructed. Expert opinion aided in a weighting process whereby the relative weights of parameters were computed and incorporated into the evaluation.

Results showed extensive areas with a relatively high agricultural potential for potatoes and wine grapes. In addition, areas with potential were also identified for wheat, citrus, and tomatoes, albeit on more limited scale. Large areas, however, were deemed unsuitable for the aforementioned agricultural crops and would therefore be suitable to absorb metropolitan growth or to be maintained as conservation areas.

The fuzzy logic approach provided insightful results. Problematic parameters were easily identified and no information was lost in the evaluation process. It also allowed for an objective quantitative comparison between crops. This provided freedom in deciding which landuse should be practiced, especially if the focus is on a sustainable rather than the most productive crop.

KEYWORDS: sustainable, agriculture, land evaluation, fuzzy logic

OPSOMMING

Volhoubare gebruik van die aarde se hulpbronne word deur baie owerhede gesien as krities ten einde die planeet se voortbestaan te verseker. In hierdie verband word landbou beskou as ’n belangrike rolspeler en fundamentele skakel in die volhoubaarheidsketting. Suid-Afrika, ’n land met relatief min gunstige landbougrond, moet derhalwe areas met hoë potensiaal bewaar vir landboukundige gebruik. Die Wes-Kaap, wat oor 75% van alle medium-potensiaal bewerkbare grond in Suid-Afrika beskik, is dus ’n waardevolle bate in hierdie verband. Een streek wat vir ontwikkeling geteiken word en waar daar onsekerheid heers aangaande die landboupotensiaal, is die G21B opvangsgebied in die Atlantis Ontwikkelings Korridor (AOK). Die AOK word beskou as langtermyn groei-as vir die Kaapse Metropool, maar teenstrydige opinies heers oor die gebied se landbou moontlikhede en geskiktheid om stedelike groei te absorbeer.

Gevolglik was die doel van hierdie projek om die geskiktheid van die opvangsgebied te evalueer vir ’n aantal landboukundige gebruike. Vae logika, ’n modifikasie van die grond evaluasie benadering wat oorspronklik deur die Voedsel en Landbou-organisasie van die Verenigde Nasies (VLO) ontwikkel is, is ingespan om hierdie probleem aan te spreek. Toevoer data het bestaan uit ’n grondkaart en digitale elevasie model (DEM) van die area. Parameters verkry vanuit die grondkaart was grondtekstuur van die eerste, tweede en derde horisonte, sowel as growwe fragmente in die bogrond, natheid, verwerende rots, gemiddelde pH, en effektiewe worteldiepte. Die helling-parameter is verkry vanuit die DEM. Hierdie parameters is met die vereistes van ses grondgebruike, nl. koring, wyndruiwe, aartappels, tamaties, uie en sitrus vergelyk, en ’n vae logika uitbeelding vir elke grondgebruik is saamgestel. Deskundiges is genader om bystand te verleen in ’n gewigstoekenningsproses waarby die relatiewe gewigte van parameters bereken en in die evaluasie geïnkorporeer is.

Die resultate het uitgebreide areas met ’n relatiewe hoë potensiaal vir aartappels en wyndruiwe uitgewys. Daarbenewens is areas met potensiaal ook vir koring, sitrus, en tamaties geïdentifiseer, hoewel op ’n meer beperkte skaal. Groot areas is egter as ongeskik gereken vir bogenoemde landboukundige gewasse en sal dus geskik wees om stedelike groei te absorbeer of as bewaringsareas instand te hou.

Vae logika het insiggewende resultate gelewer. Problematiese parameters is maklik geïdentifiseer en geen informasie het verlore gegaan tydens die proses nie. Dit het ook ’n objektiewe kwantitatiewe vergelyking tussen gewasse toegelaat. Hierdie aspek het vryheid verleen aangaande

’n keuse van watter grondgebruik toegepas kan word, veral wanneer die fokus op ’n volhoubare eerder as die mees produktiewe gewas val.

KERN BEGRIPPE: volhoubaarheid, landbou, grond evaluasie, vae logika

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CHAPTER 1: INTRODUCTION

Sustainable development is on the agendas of governments worldwide. Development is shifting from a pure expansion viewpoint to a more holistic approach whereby the natural resources and available land are used in a more sustainable and optimal way, ensuring their longevity. This mentality is highlighted in the *White Paper on Environmental Management Policy for South Africa* where emphasis is on moving from a previous situation of unrestrained and environmentally insensitive development to sustainable development (DEAT 1998). Additionally, this attitude is also emphasized in the *White Paper on Agriculture* (DoA 1995:13), whereby Government will "encourage integrated land-use planning….to ensure optimum management and utilization of the natural resources". The agricultural sector is frequently mentioned in the above sources as a major role player in sustainable development. As sustainability also includes the growth of the economic sector, agriculture's role is seen as "crucial" in the "economic growth of less developed countries" (DoA 1996:vi).

Furthermore, South Africa is poorly endowed with high quality agricultural land and it should therefore be protected for agricultural purposes (DoA 1995). Nearly 75% of South Africa's available medium-potential arable land occurs in the Western Cape (DoA 1996). Farming therefore plays an important role in this province's economy and valuable agricultural land should not be used for urban development.

The agricultural potential of the Western Cape's undeveloped land should be assessed before a decision is made about how it should be used. These choices are often complex in nature and necessitate the use of appropriate tools or guidelines to direct decision-making. One such tool proposed by the Food and Agricultural Organization of the United Nations (FAO), and applied in various formats today, is land evaluation. The concept of land evaluation is fundamental in "land-use planning" and in line with the current sustainable development paradigm (DoA 1995:13).

1.1 DIFFERENT PERSPECTIVES ON DEVELOPMENT

The Atlantis Growth Corridor (AGC) is envisaged as a long term urban growth axis for the Cape Metropolitan Region in the Western Cape. The area is fairly undeveloped and different parties have different visions for the expansion of the region. Conflicting opinions exist on the land's farming possibilities, with one report underlining the agricultural potential (CMC 1997) while another believes that the area is suitable for metropolitan growth due to the limited potential of the soils

(CMC 1998). No consensus exists about the types of agriculture that could be practiced in the area either. Ellis & Schloms (1999) believe some areas are suitable for high quality viticulture while Louw (pers comm. 2004) disagrees due to the shallow topsoil layer, insufficient water in the subsoil, and the occurrence of strong south-easterly winds. In addition, environmental organizations, such as the Western Cape Nature Conservation Board (WCNCB), are also concerned about the impact of development, as much of the area is classified as ecologically sensitive with regard to the fynbos species.

It is evident that the AGC is under scrutiny by several involved parties. Much interest is focused on the future use of the area, albeit agricultural, conservation, recreational or urban. Contradictory statements and conflicting interests should therefore be reconciled in an encompassing study whereby multiple factors are considered.

Land evaluation, as set out by the FAO (1976), was developed with this type of scenario in mind. Consequently, these guidelines should be followed in order to reach a workable solution. Yet, there are limited applications of these guidelines in a South African context, even though it frequently features in the literature (Prinsloo 1996; Theocharopoulos *et al.* 1995; Yizengaw & Verheye 1995; McRae & Burnham 1981; Beek 1978).

Many land evaluation exercises follow a Boolean approach whereby the area is rated as either suitable or unsuitable for a particular use. Areas should therefore be developed into the landuse which would best match its characteristics. However, determining the potential of an area is not always straightforward.

Malczweski (2002) demonstrates this problem and argues that the screening methods involved in determining cut-off points are often not clean-cut and natural. This could be demonstrated by using an example whereby a potential building site is required to be within 5 km from a river. As 5 km is the cut-off point, sites that fall within this radius will be classified as suitable or a Boolean ‘True’, and those outside as unsuitable or a Boolean ‘False’. However, why should a site 4.99 km from a river be deemed as suitable, but a site 5.01 km as unsuitable, as no natural cut-off point exists?

This rigid approach causes conflict and opinions should be relaxed to be more accommodating of other landuses for such areas (Burrough 1989). An objective assessment of the different scenarios is needed whereby the landuses can be compared to each other based on a set of common criteria. Triantafilis, Ward & McBratney (2001) also state that different factors that determine landuse should be assessed in concert, rather than individually by separate rules. One method of doing so is the application of fuzzy theory in land evaluation. In fuzzy theory, a membership function is used to determine the degree of membership of a specific landuse for a specific area. This typically results in a membership score ranging between 0 and 1, where 1 is an indication of full membership and 0 indicates no membership. Values between 0 and 1 indicate to what degree there is a match between the land qualities, i.e. what the land can offer, and the land requirements, or in other words what the specific landuse requires to be successful (Triantafilis, Ward & McBratney 2001; Burrough 1989).

1.2 AIM AND OBJECTIVES

This study aims to apply land evaluation principles on a catchment in the Atlantis Growth Corridor. The approach taken will focus on a number of possible landuses for the area. As fuzzy theory is one of the methods which expands on the original land evaluation principles, it will be applied here to award a suitability rating for each landuse, similar to Burrough (1989), Kollias & Kalivas (1998), Malczewski (2002), and Triantafilis, Ward & McBratney (2001).

Specific objectives in attaining this aim would be to:

1. assess the land’s characteristics and parameter identification;
2. identify landuses or land utilization types (LUTs) and their requirements;
3. choose the appropriate membership functions and the application of fuzzy logic;
4. verify input data through expert opinion; and
5. evaluate overall land suitability for the area.

1.3 FOCUS OF STUDY: THE G21B CATCHMENT

A quaternary catchment (G21B), which falls within the Berg/Bot/Potberg river catchment on the West Coast of South Africa, was chosen as study area. It is located between 18° 21’ 36’’ and 18° 34’ 12’’ east and, -33° 30’ 36’’ and -33° 49’ 12’’ south, and approximately 20 km north of Cape Town (see Figure 1.1).

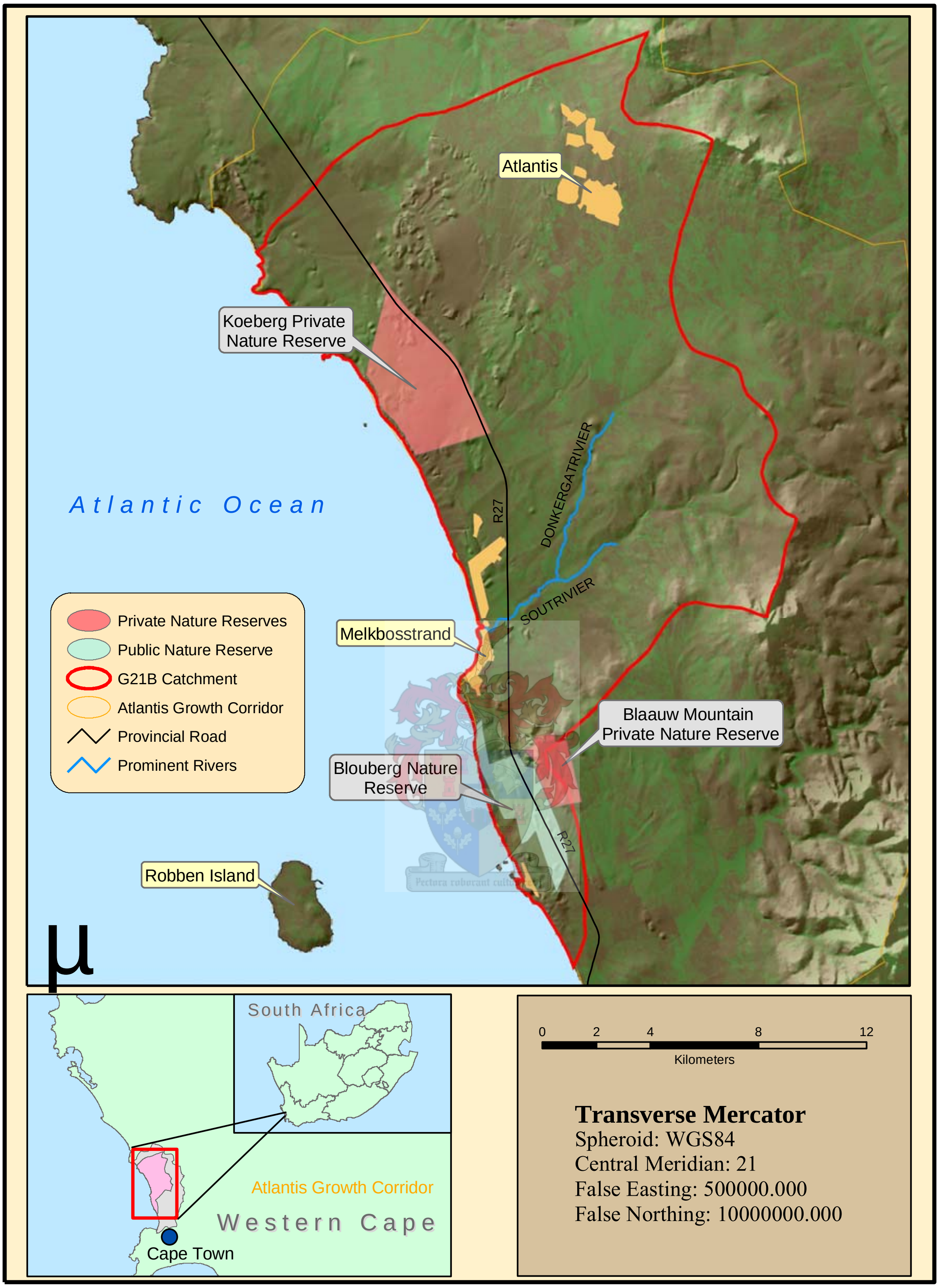

Figure 1.1 The G21B catchment in relation to the Western Cape and South Africa

The area generally consists of a coastal plain, formed by erosion of the slates, phylllites, quartzites, and siltstones of the Malmesbury Series. The result is a surface of mostly moderate slopes and level areas (Talbot 1947). Isolated hills interrupt the landscape further inland and can be attributed to granitic masses (see Figure 1.2).

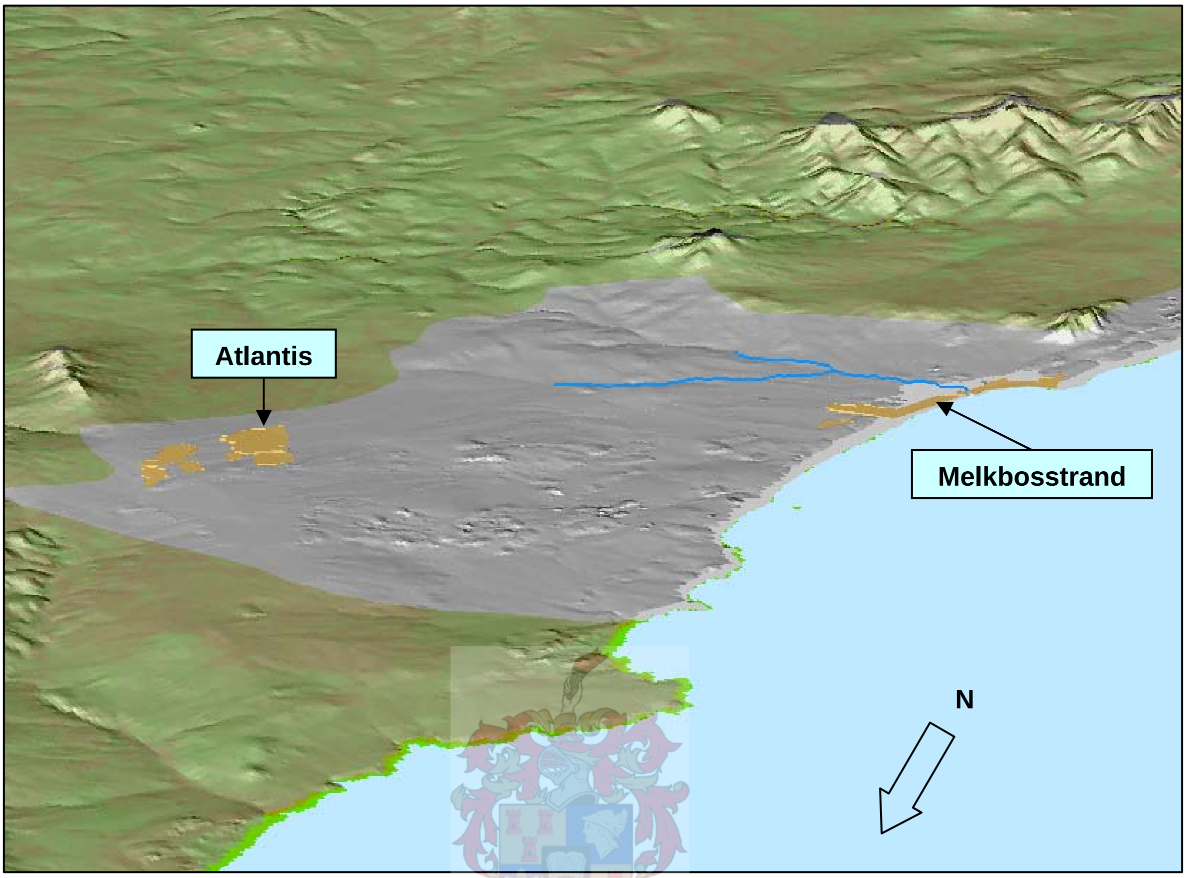

Figure 1.2 North western perspective of the study area, indicating the landscape

These parent materials gave rise to predominantly regic sands, which originate from the weathered shale. Non-red B horizons are also prevalent in the area, as well as predominantly deep Lamotte form soils (see Figure 1.3). The granitic hills are drained by a number of small rivers, including the Modder, Sout, and Diep Rivers.

Apart from these small rivers, there is a lack of continuous well-defined water sources in the area. From a climatic perspective, direct rainfall contributes little to the available water, with a Mean Annual Precipitation (MAP) of 400mm (Ellis & Schloms 1999). Most of this rain occurs during the colder (16.6°C on average) winter months (June to August), due to unstable north-westerly prefrontal winds (Tyson 1969). Furthermore, according to Schulze (1997), this rain occurs with a natural year-to-year variability of between 30-35% in the region, indicating a somewhat irregular rainfall pattern.

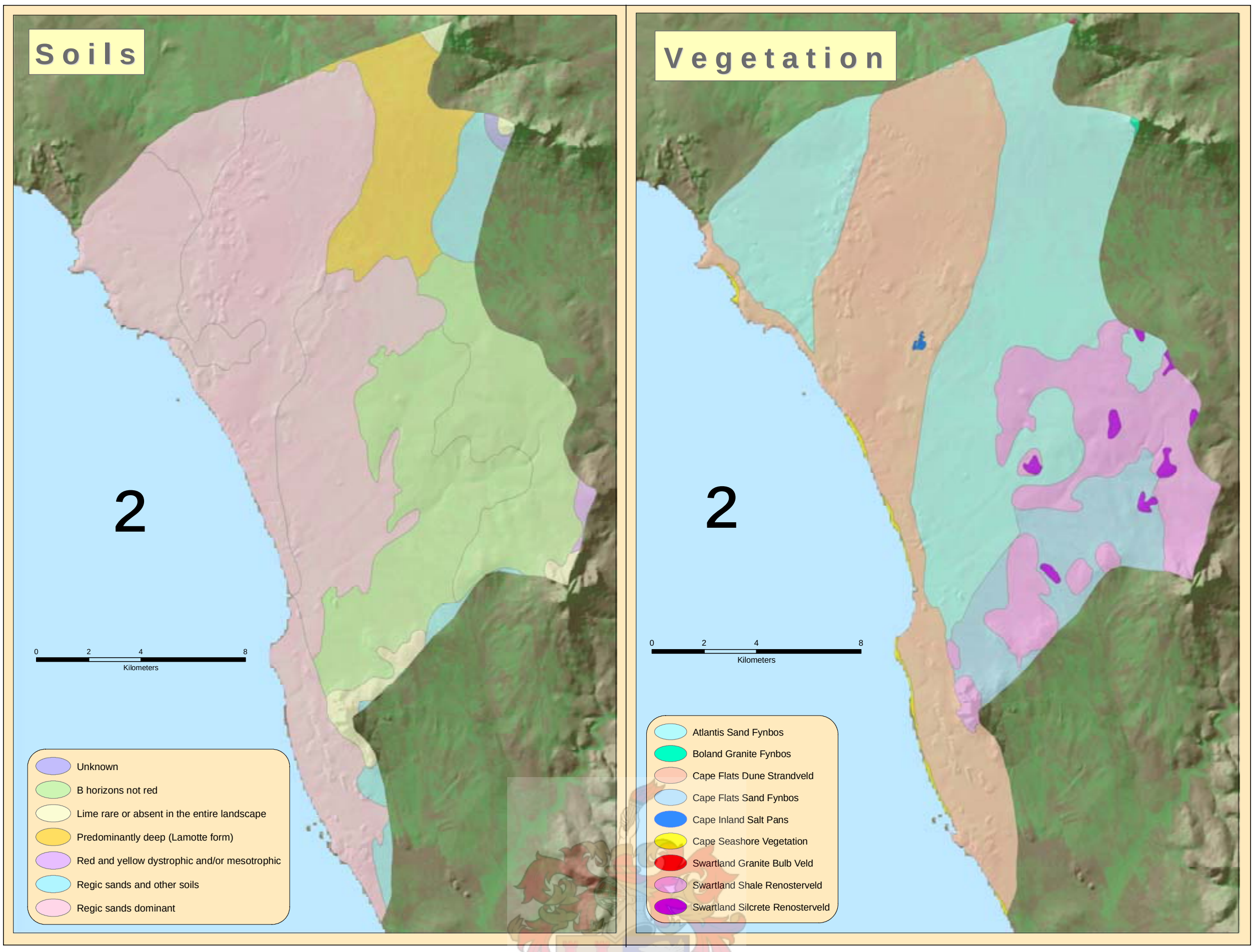

Figure 1.3 Predominant soil and vegetation types in the area

The main reason for the limited rainfall can be attributed to subtropical high pressure cells which inhibit rainfall generation because of predominantly subsiding air (Schulze 1997). This coincide with a temperature rise during the warm summer months (December to February), with an average maximum temperature of 25.5°C. Circulation around the South Atlantic high-pressure system creates the Benguela-Upwelling zone and, when warm moist air moves across the current, fog occurs (South African Weather Bureau 1996). The elevated hills in the area have a slightly cooler climate in the hot, dry summer months due to light breezes from the sea, especially in the afternoons (Ellis & Schloms 1999).

This combination of soils and climate gave rise to a number of well adapted indigenous botanical species, in particular the well-known Fynbos. These species are of considerable importance, since they form part of the Cape Floral Kingdom, one of the most diverse floral kingdoms in the world. Three types of Fynbos are predominant in the area: renosterveld, sand plain Fynbos, and Strandveld (see Figure 1.3). Vegetation on some hill slopes is generally in a good condition and worth conserving. However, according to the Cape Metropolitan Council (CMC 1998), the lower lying areas suffer from especially Port Jackson and Black Wattle infestations.

The G21B catchment is part of the Atlantis Growth Corridor (AGC), and seen as a possible long-term growth axis towards the north for the Cape Metropolitan region (CMC 1997). This means that the area is becoming increasingly important as industrial corridor and for possible urban expansion. Already important human influences can be observed in the area, including agricultural practices and urban settlements (see Figure 1.4). Farms in the area are large due to the low and declining productivity of the soils (CMC 1998). Even though the Atlantis aquifer is present, groundwater abstracted at the two well fields, Silwerstroom and Witzand, are mainly for domestic use (CMC 1998).

Crops produced include wheat, triticale, oats, clover, lupine, canola and vegetables (Louw 2004 pers comm.). According to the 1:50 000 toposheet of Melkbosstrand obtained from the Chief Directorate: Surveys and Mapping (South Africa 2000), orchards and vineyards are also present on a limited scale. Urban areas are present throughout the region, including the towns of Atlantis, Melkbosstrand and Bloubergstrand. Apart from agricultural and residential occupation, the study area is also home to a number of features with historic value, including the Battle of Blouberg site, Pella (origin of the wool industry in South Africa) and Mamre, known for its significant West Coast cottage architecture.

A major restriction for development in the catchment is the location of Koeberg Nuclear Power Station (KNPS). Population restrictions are imposed by KNPS, which will constrain possible urban development along the immediately adjacent west coast. Furthermore, a number of private and public nature reserves are also restricting development in some of the western and southern parts of the study area.

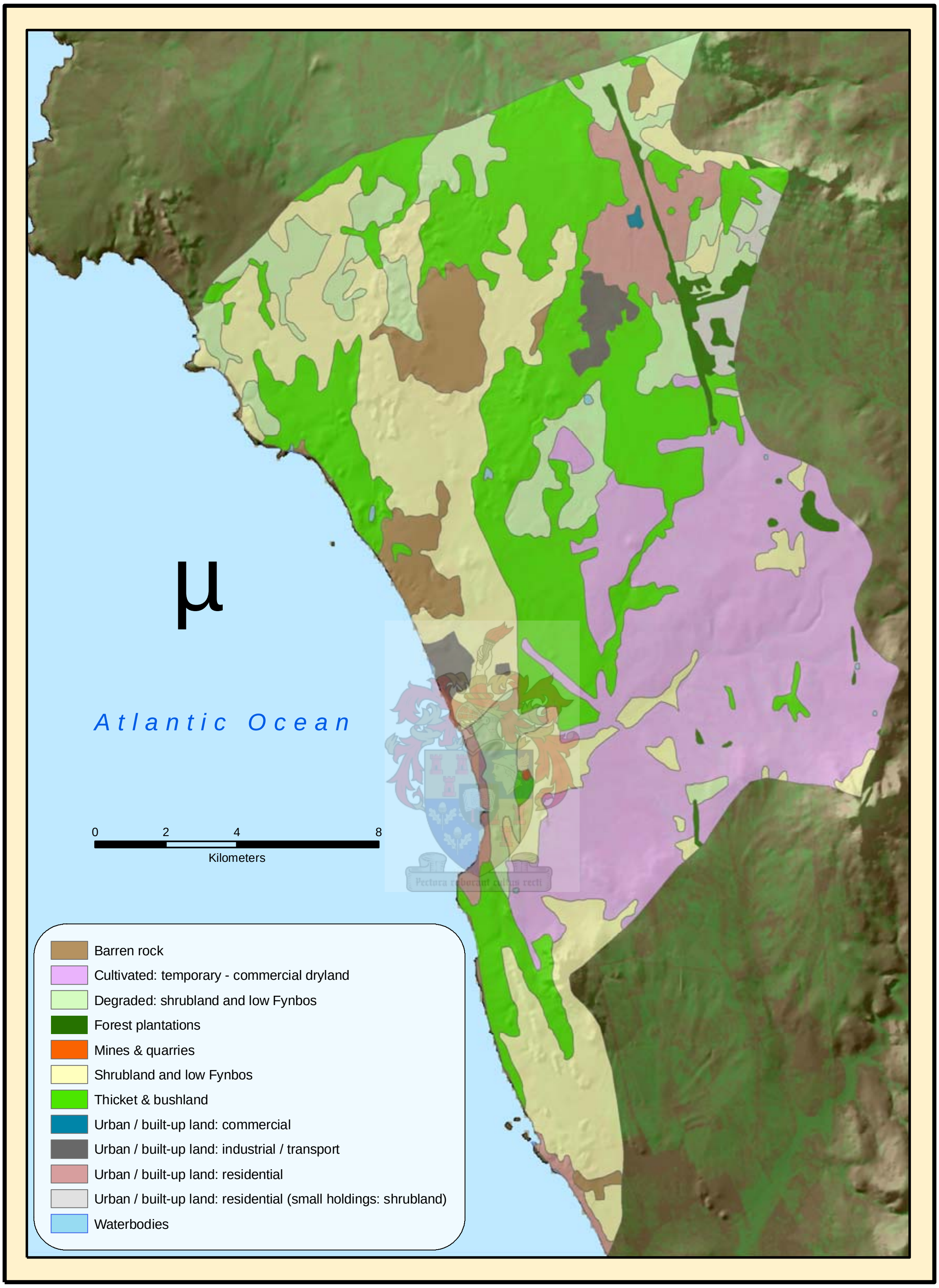

Figure 1.4 Landuses in the study area

1.4 THE RESEARCH APPROACH

According to Mouton (2001) the methodology used in research depends on the type of questions that is asked (empirical vs. non-empirical), the type (primary, secondary or a combination of both) and nature (numerical vs. textual) of the data that is used, and the degree of control (high, medium or low) of the research. This study is empirical in nature as questions of physical objects or a real-life problem are being asked. A medium degree of control is possible as the data used is secondary in nature and could not be improved upon. As a result, some of the soil map parameters could not be included due to a lack of data in the primary source. Both primary (Digital Elevation Model) and secondary data (existing soil map) was used.

This study combines evaluation research as well as computer simulation studies, since a desired scenario is modelled and then compared to the current real-life setting in the area. Qualitative terms were incorporated into the framework of quantitative research by awarding scores to them. Sampling was not deemed necessary as a significant percentage of the data used was obtained from field reports by experts in the field of soil science. The validity of the final result was verified by consulting expert opinion and comparing it to the current situation.

To realize the aim and objectives of this study, this research combined of methods gleaned from the literature. For a more comprehensive description of the different techniques, the reader is referred to Chapter 2. According to Mouton (2001:163), there are no specific meta-theoretical paradigms associated with this design type, but all forms of modelling are “consistent with a realist theory of the world.”

1.5 REPORT STRUCTURE

In order to clarify how land evaluation for this area was accomplished, this thesis is divided into five chapters. In the second chapter, an overview of the literature is given to establish the different approaches to land evaluation, as well as explaining the approach taken in this study. Chapter 3 discusses the materials/data used, where it was obtained and data preparation. In addition, the methods implemented in this land evaluation exercise are addressed, specifically fuzzy logic theory and the weighting process. In Chapter 4, the results of the study are presented and verified by comparing it to current agricultural activities. The areas most suitable for the different landuses are highlighted and arguments provided. Chapter 5 concludes the study by providing an overview of the principles applied in this thesis. It explains why fuzzy logic theory is more appropriate to use than Boolean logic. Further recommendations for research are also given.

CHAPTER 2: THE ESTABLISHMENT AND DEVELOPMENT OF LAND EVALUATION

Land evaluation covers a wide spectrum of fields and should therefore be thoroughly explained in terms of definitions and the application thereof. This chapter commences with definitions and explanations regarding land evaluation, as well as different approaches to the process. The section following focuses on specific instances of land evaluation and how it is applied in practice. The chapter concludes with a description of the role of land information systems in land evaluation and how these systems can contribute to the exercise.

2.1 DEFINITION AND EXPLANATION

Dent & Young (1981) define land evaluation as the process of estimating the potential of land for alternative kinds of use and reason that its fundamental purpose is to predict the consequences of change. A comparison is made between the land requirements (LRs) and the resources offered by the land, otherwise known as land qualities (LQs). Given that different kinds of landuses have different requirements, a match between the LRs and the LQs is the essence of land evaluation. A typical LQ that would be of interest to land evaluation would be moisture availability to plants. However, moisture availability is determined by different land characteristics such as amount of rainfall, its seasonal distribution and variability, potential evapotranspiration, and available moisture capacity of the soil. Hence, it is often necessary to determine a LQ using characteristics which are easier and simpler to measure.

Davidson (1986) distinguishes between a number of forces behind land evaluation emerging as a distinct subject. Firstly, there is an increasing availability of soil, geology and climate maps, and a need to present this information in a more comprehended form. Secondly, the adoption of land planning policies in most countries indicates the commitment of countries towards this challenge. In South Africa, for instance, there is an intertwining relationship between sustainable development and landuse planning (DEAT 1998; DoA 1995). In addition, there is an ever-increasing concern about human population growth and global land resource availability. Davidson (1986) also reasons that rapid technological advancements in computing permit much easier handling and processing of vast quantities of data.

Land evaluation combines knowledge from several disciplines, including environmental, agricultural and biological sciences, to the principles of economics and sociology. Thus, it is evident that the evaluation process can become quite intricate and even overwhelming at stages. However, a number of different approaches have been developed to confront the complexity of land evaluation. The latter includes qualitative, quantitative, and economic evaluations (Dent & Young 1981; FAO 1976), as well as the fuzzy logic approach (Malczewski 2002; Triantafilis, Ward & McBratney 2001; Kollias & Kalivas 1998; Burrough 1989). These approaches, as well as other relevant literature will be reviewed in the following pages, giving the reader an in-depth look at the process and instances of land evaluation. Furthermore, the role of expert systems and Geographic Information Systems (GIS), and how it fits into the evaluation framework, will also be discussed.

Given that the focus, scale and extent of a land evaluation study must be determined beforehand, it is necessary to further examine the difference between general purpose and specific purpose studies, as well as direct vs. indirect methods of land evaluation. These methods largely determine the approach taken and the requirements of each. Explanation of these principles are often omitted in the literature, except in sources which concentrate solely on the process of land evaluation, such as the FAO (1976), Beek (1978), Dent & Young (1981) and McRae & Burnham (1981), and not the outcome of a land evaluation.

2.1.1 General purpose and specific purpose studies

According to Beek (1978), the distinction between general and specific purpose land evaluation is probably the most fundamental subdivision as far as the role of the land utilization type (LUT)[1] in land evaluation is concerned.

In general purpose land evaluation, the LUT is a standardized, broadly defined unit and not the subject of study during land evaluation (Beek 1978). Dent & Young (1981) defined this broad unit as one of the few major subdivisions of rural landuse. They adopted the term *major kind of landuse*, and give examples (Table 2.1).

A good example of a general purpose study is the United States Department of Agriculture (USDA) Land Capability Classification (LCC), where the capability of the physical environment to support a certain type of landuse, is expressed in terms of the limitations or hazards of that environment. The focus is more on the physical environment (e.g. a soil map) than on the landuse.

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[1] A land utilization type is defined as a specific way of using the land, actual or alternative, described in terms of produce, labour, capital, management, technology and scale of operations (Beek 1978).

Table 2.1: Major kinds of landuse

rain fed arable farming (annual crops)
tree and shrub crops (perennial crops)
intensive, specialized agriculture
swamp rice cultivation
grazing of natural pastures (ranching)
grazing of improved pastures
production from natural forests (logging)
forest plantations
recreation and tourism
wildlife conservation
water catchments
engineering works
military use

(Dent & Young 1981)

Specific purpose land evaluations, on the other hand, pursue a more realistic approach, where not only the land itself is studied, but emphasis is also put on the landuse possibilities. For instance, many soil suitability classifications for specific crops fall in this category. In specific purpose studies, the LUT is not standardized, but has to be selected. Thus, a LUT can be defined as wheat growing for a specific area, considering the physical environment, as well as the requirements of the LUT. The *Framework for Land Evaluation* (FAO 1976) mainly follows this approach. There is a clear distinction between a major kind of landuse and a LUT, since the major kind of landuse is standardized, but the LUT is selected for each unique situation. Specific purpose studies are complex and require the services of a range of different disciplines (Beek 1978).

2.1.2 Direct vs. Indirect methods

In McRae & Burnham (1981), distinction is made between direct and indirect land evaluation approaches. In direct land evaluation, land is evaluated directly by means of field trials, resulting in data only applicable for that particular use. They argue that direct land evaluation is of limited use unless the evaluator has the resources to collect a large amount of data.

In indirect land evaluation, the assumption is made that certain soil and site properties, i.e. soils, climate, topography, composite environmental and socio-economic variables, influence the success of a particular landuse in a reasonably predictable manner. After these properties are identified, a system is constructed so that the values of these properties can either define categories (Categoric systems) or may be combined in a mathematical equation to give an index on a sliding scale (Parametric systems). Most land evaluation systems follow the indirect route.

2.2 INSTANCES AND APPLICATIONS OF LAND EVALUATION

Both Dent & Young (1981) and the Food and Agricultural Organization (FAO 1976) distinguish between the qualitative or reconnaissance study, the quantitative study, and the economic evaluation. Therefore, the mentioned methods will be explained in greater detail, as these authoritative sources place great emphasis on the three types of land evaluation. In addition to this, modified applications of the basic FAO principles, such as fuzzy theory, as well as other alternative ways of land evaluation, will also be reviewed.

2.2.1 Qualitative/Reconnaissance studies

The FAO (1976) stipulates that reconnaissance surveys deal with a broad spectrum of resources, typically on a regional or national scale, and where economic analysis includes a rough estimate between profit and loss. Results would identify areas of priority for conservation or areas suitable for development. These approaches are mainly based on expert judgement and, using qualitative procedures, the suitability is ranked in discrete classes, i.e. highly suitable, moderately suitable, or not suitable.

Since two of the methods mentioned, the USDA Land Capability Classification and the FAO’s Land Suitability Evaluation, are featured frequently in the literature, the difference between the two will be explained. The value properties and how it could be accommodated will also be discussed.

2.2.1.1 Land Capability Classification (LCC)

The capability of land can be defined as the potential of land for use in specified ways or specified management practices. It is based on the concepts of capability and limitations. Limitations can be seen as a land characteristic which has an adverse effect on the capability (Dent & Young 1981), and can be divided into permanent and temporary limitations. The land capability classification (LCC), as defined by Klingebiel & Montgomery (1961), is grouped into three categories: capability unit, capability subclass and capability class.

Land units' capability classes can range from I to VIII. The risks for certain landuses increase progressively from class I to VIII. Classes I to IV have the potential to produce common cultivated field crops. In classes V – VIII, the soils are suited to the use of adapted plants and are generally not suited for cultivation, unless major earthmoving or other costly reclamation methods are applied.

Dent & Young (1981) identified a number of shortcomings in the LCC-system:

1) LCC attempts to provide a single-scale grading of land from 'best' to 'worst';
2) it assumes arable use to be the most desirable;
3) it is strongly biased towards considerations of soil conservation;
4) it is based on negative land features, namely the limitations;
5) economics are only included as background information; and
6) LCC cannot distinguish between 'elite' soils and 'unique' soils.

Its main disadvantage is the system's failure to classify land adequately for uses other than arable. However, the LCC-system has stood the test of time and has met the needs of the users well. It should be noted that the system was designed for farm planning and that is also the context in which it should be used. It is considered a general purpose study as opposed to the specific purpose of the FAO's land suitability evaluation.

The application of the LCC-system has been practiced extensively despite its shortcomings. Hoobler *et al.* (2003) combined Land Evaluation and Site Assessment (LESA) and a Geographic Information System (GIS) to do landuse planning, including land capability classification as one of the factors determining land evaluation scores. The LESA development plan has also been applied in DeKalb County, Illinois, USA (Unknown 2000). A modified version of LESA, called FLESA (Forest Land Evaluation and Site Assessment), was used by Millette, Sullivan & Henderson (1997) for evaluating forestland uses. Both LESA and FLESA follow a quantitative approach, ranking both the physical characteristics of the land and the aesthetic, cultural, and economic values of local residents. Andriesse & Scholten (1983) also enhanced the qualitative LCC with more quantitative methods. They used it to determine viable landuses and related farm sizes for the development plan of a smallholder settlement.

2.2.1.2 Land Suitability Evaluation

This is the process whereby the suitability of land for specified kinds of use is assessed (Dent & Young 1981). The results of this suitability evaluation are three-fold:

1) Description of land utilization types (LUTs).
2) Suitability maps: each land mapping unit's suitability for each defined kind of landuse is described through a graphic representation.
3) Statements of the consequences, favourable and unfavourable, of applying each kind of landuse to each area of land.

There are four categories/levels of classification: land suitability orders, classes, subclasses, and units. In suitability orders, land is classified as either 'suitable' (S) or 'not suitable' (N). The latter classification is mainly based on the fact that it is technically impracticable, environmentally undesirable or economically unprofitable to develop that land. Suitability classes indicate degrees of suitability. Within the order 'suitable', there are 3 classes: 'highly' (S1), 'moderately' (S2), and 'marginally' (S3). Within the order 'not suitable', there are two classes: 'currently not suitable' (N1) and 'permanently not suitable' (N2).

The boundaries between these classes are not always fixed. Between S3 and N1, the boundary is defined in economic terms. For example, a rise in the market value of a certain crop could upgrade land classed as N1 to S3. However, there is a relatively permanent physical boundary between N1 and N2. Suitability subclasses indicate the limitations of land.

Suitability units are divisions of the subclasses and differ from each other in detailed aspects. Land in a specific unit has similar productive potential and requires similar management practices. The definition of a suitability unit is similar to that of the capability unit in the LCC. Figure 2.1 provides a hypothetical example of the type of maps that could be expected from a land suitability evaluation and similar examples are demonstrated by Prinsloo (1996) and Theocharopoulos *et al*. (1995).

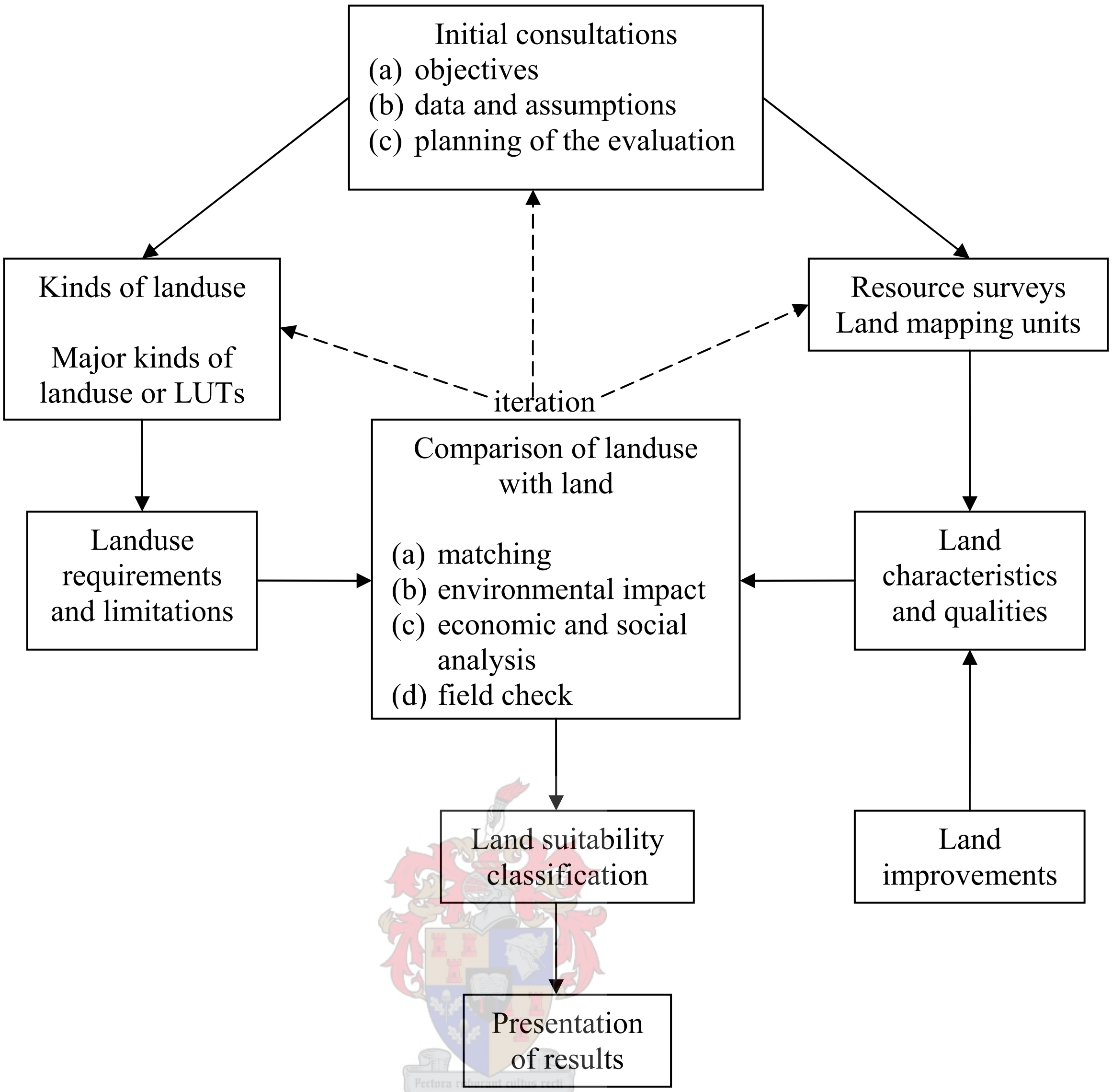
In Figure 2.1, for example, the centre section of map (a) indicates a suitability rating of S2 for the cultivation of wine grapes. This means that the area is moderately suitable for wine grapes. The same area is evaluated for perennial crops (b) which scored a S3, forestry (c) which scored N1, and tourism & conservation in (d) where the area was deemed permanently not suitable for this landuse.

Figure 2.1 Hypothetical example of qualitative suitability classes (according to the FAO Framework) for major kinds of landuses. (a) arable farming: wine grapes; (b) arable farming: perennial crops; (c) forestry: plantations; (d) tourism and conservation;

The sequence of activities that are followed during a land suitability evaluation is shown in Figure 2.2. A typical land evaluation starts with objectives, an investigation into available data, and planning of the exercise. Characteristics regarding the land and landuse requirements that were obtained are compared and from there a land suitability classification is compiled.

Dent & Young (1981) provide a list of possible data sets necessary for land evaluation studies:

1) land systems survey (qualitative);
2) landform survey;
3) engineering geology;
4) climatic studies;
5) hydrological studies;
6) soil survey (soil moisture properties are often of particular importance);
7) vegetation surveys; and
8) surveys of fauna and disease.



Source: Dent & Young 1981

Figure 2.2 Schematic representation of activities in land evaluation

The *Framework for Land Evaluation* (FAO 1976) is based on the land suitability approach. Since it is considered fundamental literature in the land evaluation discipline, many workers have applied it in their surveys.

The FAO approach is most commonly applied, and can be complemented and enhanced by more quantitative methods (Yizengaw & Verheye 1995). The FAO approach is also flexible enough to incorporate process modelling (Van Lanen in Triantafilis, Ward & McBratney 2001). Applications of this process modelling, with the FAO's principles as basis, were demonstrated by Burrough (1989), Kollias & Kalivas (1998), Malczewski (2002), and Triantafilis, Ward & McBratney (2001). In their study, Messing *et al.* (2003) concentrated on land qualities and land characteristics.

Several ‘expert systems’ are also based on the FAO’s principles, e.g. the ALES (Automated Land Evaluation System) computer software package (Wandahwa & Van Ranst 1996; Yizengaw & Verheye 1995) and a microcomputer-based Mediterranean land evaluation information system developed by De la Rosa *et al.* (1992). Bouma *et al.* (1993) tested land evaluation at farm level using the FAO framework and a computer simulation model.

Although the FAO’s guidelines were primarily developed for use in the agricultural sector, Dumanski, Marshall & Huffman (1979) derived an urban ‘suitability’ map and compared it to the regional development plan for the area. A number of maps with basic land factor limitations were used and each map was evaluated for biological and non-biological uses. The South African Development Countries (SADC 1994) also recommended the FAO guidelines for land evaluation in different countries.

2.2.1.3 Accommodation of the value properties

In both the USDA’s LCC and the FAO’s Land Evaluation the values of these properties can either define categories (categoric systems) or may be combined in a mathematical equation (parametric systems), as mentioned before. In the parametric method the suitability of land is assessed on a continuous scale, rather than using the discrete classes of the land capability classification. These methods are expressed in mathematical terms which could be multiplicative (i.e. $P = A \times B \times C$) or additive (i.e. $P = A + B + C$), where P is the parametric score, and A, B and C are the ratings of the land qualities. The best land receives the maximum score, while lower scores are assigned to less suitable land (Triantafilis, Ward & McBratney 2001). The best example of the use of a parametric system is the Storie Index Rating (SIR). Singer (1978) compared the USDA Land Capability Classification (categoric system) with the SIR (parametric system), and found that the two systems gave similar results, but that they could not be used interchangeably.

Qualitative surveys act usually as preliminaries to more detailed investigations. For this reason, Dent & Young (1981) argue that qualitative studies are of little value in developed countries, but useful in developing countries. However, from the above mentioned literature it is evident that even these largely qualitative approaches can be improved by incorporating more quantitative methods.

2.2.2 Quantitative studies

Quantitative studies are more concerned with specific aims, such as feasibility studies of development projects. This provides information on project selection, or whether a particular development or other change should continue (FAO 1976). In quantitative surveys, production potential or other benefits are expressed in quantitative terms, example crop yields, beef/wool production, etc. It is therefore necessary to specify inputs in a quantitative manner, example tonnes of fertiliser, man-days of labour, etc. Economic analysis is present as background information, but does include some approximate calculation of costs and prices, in order to decide on appropriate levels of inputs on which to base the estimates. Dent & Young (1981) agree with the concept of quantitative surveys as a form of feasibility study, and see it as the precursor for economic evaluation.

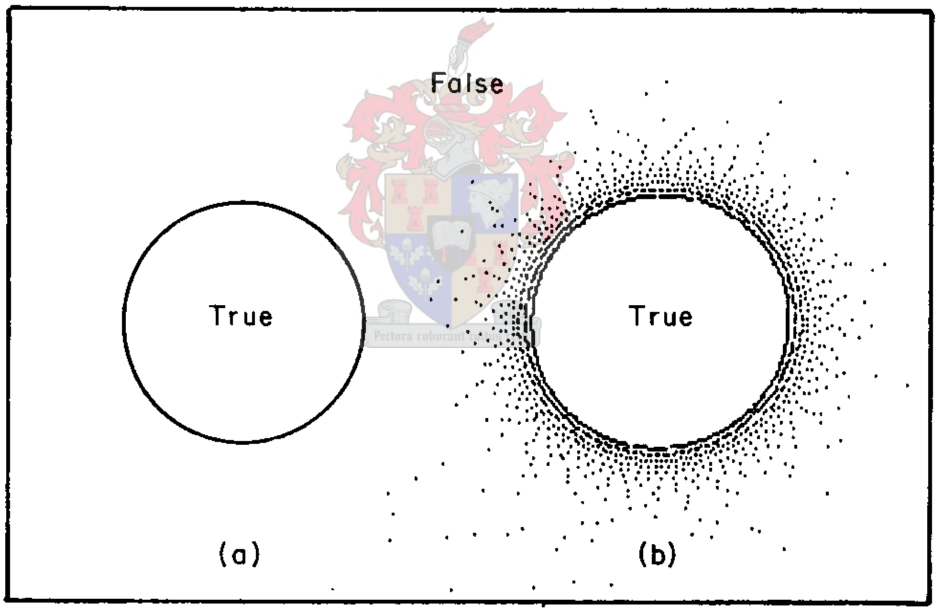
As mentioned elsewhere, the FAO's approach is flexible enough to be complemented and enhanced by more quantitative methods (Yizengaw & Verheye 1995). One such example is the study done by Andriesse & Scholten (1983), whereby land capability assessment was based on the principle of LUTs as subjects for classification. Inputs and outputs were quantified in economic terms (dollars/ha) for each LUT.

2.2.3 Economic evaluation

Land by itself rarely possesses productive potential; some input is usually needed in the form of fertilizer, seed, labour, etc. (Dent & Young 1981). The question of profit and loss is, in this regard, of particular importance. An economic evaluation includes a detailed description of the estimated profit and loss for each specified enterprise on each kind of land (Dent & Young 1981). This type of evaluation is always required for project appraisal and most planning decisions for private investment. Economic evaluation should always distinguish between current land suitability and potential land suitability, i.e. a future value of the land based on some kind of major land improvement, e.g. planning that precedes an irrigation scheme. The FAO (1976) considers economic implications of a proposed landuse as one of the basic principles of land evaluation (FAO 1976). Rossiter (1995) also strongly supports economic land evaluation and is of the opinion that it should become the rule, rather than the exception.

2.2.4 Fuzzy sets

Fuzziness is a concept whereby the Boolean approach where areas with a strict value designation, and the sharply defined boundaries associated with it, is generalized. Some data sets cannot be described with sharply defined boundaries, or do not have such boundaries (Burrough 1989). Consequently, fuzzy sets were developed to accommodate the uncertain nature of these data values and to more accurately portray spatial reality. In Boolean logic, a value is only allowed a binary membership, whereas fuzzy sets allow partial membership to a class (Kollias & Kallivas 1998). Using a Boolean approach, considerable information loss can occur, because the factors involved are evaluated on an individual level. It is therefore necessary to assess the different factors in concert to achieve a more correct analysis of the area being evaluated. Fuzzy set theory offers a useful alternative where entities are modelled with zones of gradual transition, rather than sharp boundaries as illustrated in Figure 2.3.



Source: Burrough 1989

Figure 2.3 Visualizations of (a) Boolean or crisp set, (b) fuzzy set, using a modification of Venn diagrams

In the next section a theoretical overview of fuzzy theory is provided, followed by a description of membership functions.

2.2.4.1 Definition and theory

Mathematically, a fuzzy set can be defined through the following equation: if X is a set of objects, i.e. $X = \{x\}$, then fuzzy set A in X is the set of ordered pairs

$$A = \{x, \mu_A(x)\} \qquad x \,\varepsilon\, X \qquad [2.1]$$

where $\mu_A(x)$ is the grade of membership of x in A and $x \,\varepsilon\, X$ means that x is contained in X (Burrough 1989). The value of $\mu_A(x)$ can range from 0 to 1, where 1 indicates full membership to the set and 0 represents non-membership. A value in-between 0 and 1 give the degree of membership to the set.

2.2.4.2 Membership functions

Membership functions determine how $\mu_A(x)$ is calculated. Various membership functions suitable for soil and landscape data can be used. Equation 2.2 is one such a function that is frequently featured in the literature:

$$\mu_A(x) = \frac{1}{\{1 + a(x-c)^2\}} \text{ for } 0 \le x \le P \qquad [2.2]$$

where a is a parameter governing the shape of the function and c defines the central value of x in the set. P refers to any other value that x might adopt in the given set. A graphical representation of the above equation is shown in Figure 2.4. Burrough (1989) also distinguishes between symmetric and asymmetric functions. Figure 2.4 is a symmetric function where both the upper and lower values of x are of importance, e.g. soil pH, where the optimum pH for a given crop would be 5.0 - 6.5. In this case, 5.0 would be the lower and 6.5 would be the upper boundary. Thus a symmetric function is used to calculate the membership scores.

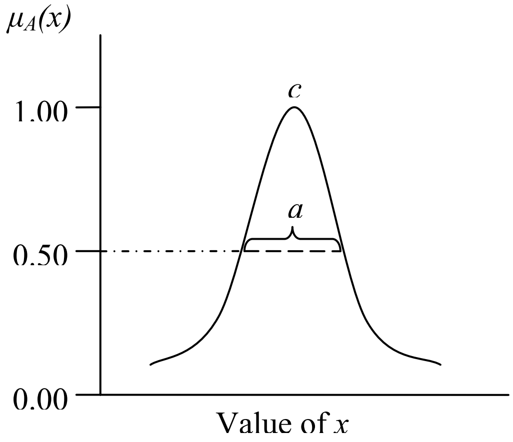


Figure 2.4 Graphical representation of Equation 2.2 – symmetric function.

Situations arise where only the lower or upper boundary of a set is of importance, for example effective root depth. If a crop requires a root depth of 100cm, a deeper soil will automatically meet this criterion; therefore, the definition of an upper boundary is unnecessary. In this situation, the membership function can be truncated on the lower or upper side to produce an asymmetric function. Figure 2.5 illustrates the asymmetric function with *a* governing the gradient of the function and *c* as the required soil depth, or the lower boundary of the function.

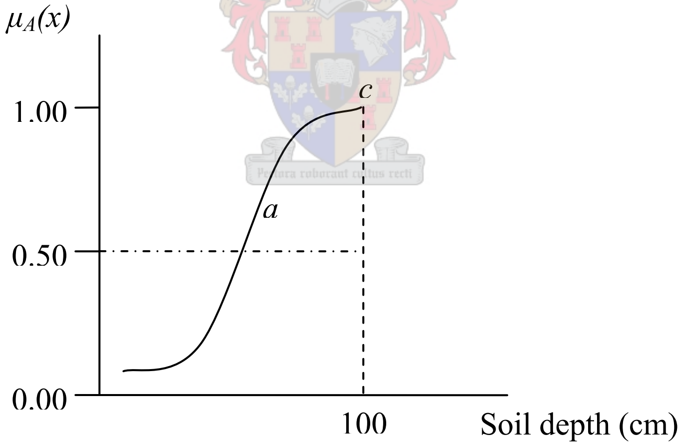


Figure 2.5 Graphical representation of an asymmetric function.

Support for the use of fuzzy theory has grown, notably in the last decade. Many workers have used fuzzy theory in their land evaluation studies and achieved good results. Triantafilis, Ward & McBratney (2001) and Ahamed, Rao & Murthy (2000) used the FAO approach, together with fuzzy theory to obtain suitability ratings for certain crops, for their respective study areas. Burrough (1989) and Malczewski (2002) demonstrated the effectiveness of fuzzy theory and its superiority to conventional Boolean approaches. Their case studies obtained more meaningful results than the Boolean method. Kollias & Kalivas (1998) customized a commercial GIS software package to incorporate fuzzy theory, thereby revealing the ease of use of the customized system and its effectiveness to handle land evaluation problems.

2.2.5 Alternative approaches

Sondheim & Klinka (1983) followed an ecological approach whereby they used a phytosociologically based, ecological classification system to explain the variability of soil and physiographic properties tested. The underlying assumption was that this soil-plant relationship could be a good predictor of specific soil properties. Louw (1995) developed a classification system based on site associations, which is climatically suitable for *Pinus patula* and *P. elliottii*. An ecological approach, whereby landscape ecological principles and land evaluation were integrated, was also followed by Bo-Jie & Li-ding (1999). Bastian (2000) was of the opinion that environmental goals are essential for a genuine holistic approach.

In another approach, some workers have opted for an evaluation of the physical landscape, its characteristics and patterns that are recognizable in the landscape. Land includes a variety of factors, contributing to the ‘land’ definition, such as vegetation, climate, soil and relief. ‘Terrain’, however, is much narrower and was traditionally used in military studies. Terrain analysis follows an engineering or geotechnical focus.

Two approaches using terrain evaluation are worth mentioning. The first is the PUCE (Pattern-Unit-Component-Evaluation) system, developed by Grant (1975). The system defines any area of land in terms of its topography, underlying lithologic and structural (tectonic) characteristics, as well as soil and vegetation features. The PUCE system is applied in an engineering environment.

The second approach was the development of a technique by Wermund *et al.* (1974) for rapid reconnaissance mapping of environmental geologic units. The motivation for this study was to provide planners with more knowledge about the underlying aquifer in order to protect the water source. Topographic maps and aerial photographs, together with limited field data, were used.

2.3 LAND INFORMATION SYSTEMS

The nature of land evaluation and the processes involved are concerned with the spatial distribution of land properties. Results are mostly presented in either tabular or map format, making graphic representation a powerful and important component/tool of land evaluation. These results must be meaningfully conveyed by the land evaluator to the planners, decision-makers or other parties involved in the evaluation survey.

More importantly, some of the central processes involved in land evaluation are time consuming and can be particularly complex. Consequently, the ideal way of dealing with these processes is through the use of Geographic Information Systems (GIS). GIS have taken land evaluation to a new level with speedy processing and advanced graphic display capabilities. As Davidson (1986) argues, the advent of technologically advanced computer systems is one of the reasons for the emergence of land evaluation as a distinct discipline, since these systems can handle and process vast quantities of data.

Ren (1997) developed a GIS training package specifically designed for land evaluators, planners and decision-makers. The study also discussed the importance of weighting of the relevant factors, such as slope, elevation, soil types, existing landuse, infrastructure, and social services. Kuiper (1999) supported and applied weighting in his landuse planning study.

Bryan (2003) opted for a fully automated approach and assembled a multivariate spatial database of biologically significant physical environmental parameters. He incorporated a spatial decision support tool, *SimilarAreas*, which use data sources, such as a Digital Elevation Model (DEM), to calculate primary and compound attributes. This system was then linked to a GIS.

As opposed to the other approaches using expert knowledge or other parameters, Leitao's (*s.d.*) landscape evaluation model, developed in a GIS, focused purely on the visual aspect of landscape planning.

Apart from using GIS to implement process modelling like fuzzy theory and ordinary Boolean approaches, another branch of computer-related land evaluation techniques, namely that of 'expert systems', is frequently featured in the literature. 'Expert systems' refers to the capturing of expert knowledge on a subject, in an information system. These systems adhere to rules and facts specifically stipulated by the expert knowledge.

Both De la Rosa *et al.* (1992)'s MicroLEIS and the Automated Land Evaluation System (ALES) are expert systems based on the FAO's principles. De la Rosa *et al.* (1992) developed an expert system for the optimal use of agricultural and forestry land systems under Mediterranean conditions. Machin & Navas (1995) combined MicroLEIS with the IDRISI GIS for the conservation of semiarid agrosystems. ALES was also applied in several studies done by Wandahwa & Van Ranst (1996) and Yizengaw & Verheye (1995).

Kalogirou (2002) developed an expert system known as LEIGIS (Land Evaluation using Intelligent Geographic Information Systems). It consists of two parts: a physical evaluation and economic evaluation. Chuenpichai, Chuenpichai & Somrang, on the other hand, integrated the ArcView GIS with an expert system, known as Knowledge Pro. A connection between the GIS and Knowledge Pro was established through the Dynamic Data Exchange (DDE) functionality.

There are more aspects concerning land evaluation that deserve closer scrutiny, e.g. whether a participatory approach (as done by Bacic, Rossiter & Bregt 2003; Messing *et al.* 2003; Bojórquez, Diaz-Mondragón & Ezcurra 2001; Xiang 2001; Hill & Nel 2000) need to be followed in order to successfully evaluate the land. Biermann (1997) identified suitable land for low income residential development, opting for a Multicriteria Evaluation participatory approach, combined with GIS. There is also the relatively unexplored genre of whether to include year to year weather variability as done by Hudson & Bernie (2000). In the context of global warming, climatic variability over years can become decisive in land evaluation studies. Also noteworthy is the theoretical framework for land evaluation, as set out by Rossiter (1996), wherein a number of analytical land evaluation models are discussed.

2.4 CONCLUDING REMARKS

Land evaluation can be approached from a number of different perspectives. One aspect mentioned throughout the literature is the definition of clear objectives. After the project's aims have been formulated, an approach can be decided upon, paving the way for a determination of land requirements and land qualities. In this study, a combination of methods was used to apply land evaluation principles. This project can be seen as a specific purpose study, as the LUTs were not standardized, but uniquely selected for the region. Furthermore, it called upon the expertise of a number of fields in order to successfully address the problem. This exercise was qualitative in nature, but enhanced with quantitative methods. An indirect approach was followed as assumptions on the site's properties and how it influenced the different landuses, were made. The value properties were expressed in a parametric scoring system. Qualitative terms were converted to quantitative values and also included in this scoring system. A previous section has already explained that fuzzy theory, as an instance of land evaluation, was used in this exercise.

The next chapter will give a detailed description on the data and methods used to conduct this study, including parameter definition for the land and LUTs, as well as fuzzy theory and calculation of the membership functions used. In addition, pair-wise comparison weighting to determine the relative importance of each parameter, and research design will also be addressed.

CHAPTER 3: MATERIALS AND METHODS USED TO CONDUCT A FUZZY LAND EVALUATION

The original concept of land evaluation was developed by the FAO (1976). In this approach, a tract of land is divided into classes of suitability for all landuses, as shown in Table 3.1. Herewith, every zone of the land is awarded a suitability rating for every landuse included in the evaluation. The final output is a suitability map, reflecting which zones are most suitable for which landuse. Additionally, this outcome can be further refined by completing an economic evaluation, indicating the financial viability of the respective landuses.

Table 3.1 Suitability classes from the FAO's land evaluation approach

Suitability rating	**Interpretation**
S1	Highly suitable
S2	Moderately suitable
S3	Marginally suitable
N1	Temporarily not suitable
N2	Permanently not suitable

The original land evaluation approach was enhanced by applying fuzzy logic, whilst the principles remained the same. The crops' requirements for the S1-class were used as input parameters for the membership functions. Therefore, the fuzzy scores obtained demonstrate to what degree the land is a member of the S1-class. A high fuzzy score means that the land is suitable for the landuse and vice versa. Some authors (Ahamed, Rao & Murthy 2000; Burrough 1989) have normalized the fuzzy scores back to the qualitative categorical system, shown in Table 3.1. However, Triantafilis, Ward & McBratney (2001) employed the original scores directly.

The following section is an explanation of the procedure followed in this thesis and is based on the activities as illustrated by Dent & Young (1981). The reader is referred to Figure 2.2 (Chapter 2) for a diagrammatic example of a land evaluation exercise.

3.1 STEPWISE EXPOSITION OF THE G21B CATCHMENT LAND EVALUATION EXERCISE

The need for land evaluation should first be assessed through the identification of a spatial problem, where after the objectives are clearly defined, as this would influence the approach taken (Beek

1978; FAO 1976). The next step is to identify data with the relevant scale and accuracy needed for the evaluation. Figure 3.1 gives a schematic explanation of the steps followed in this exercise.

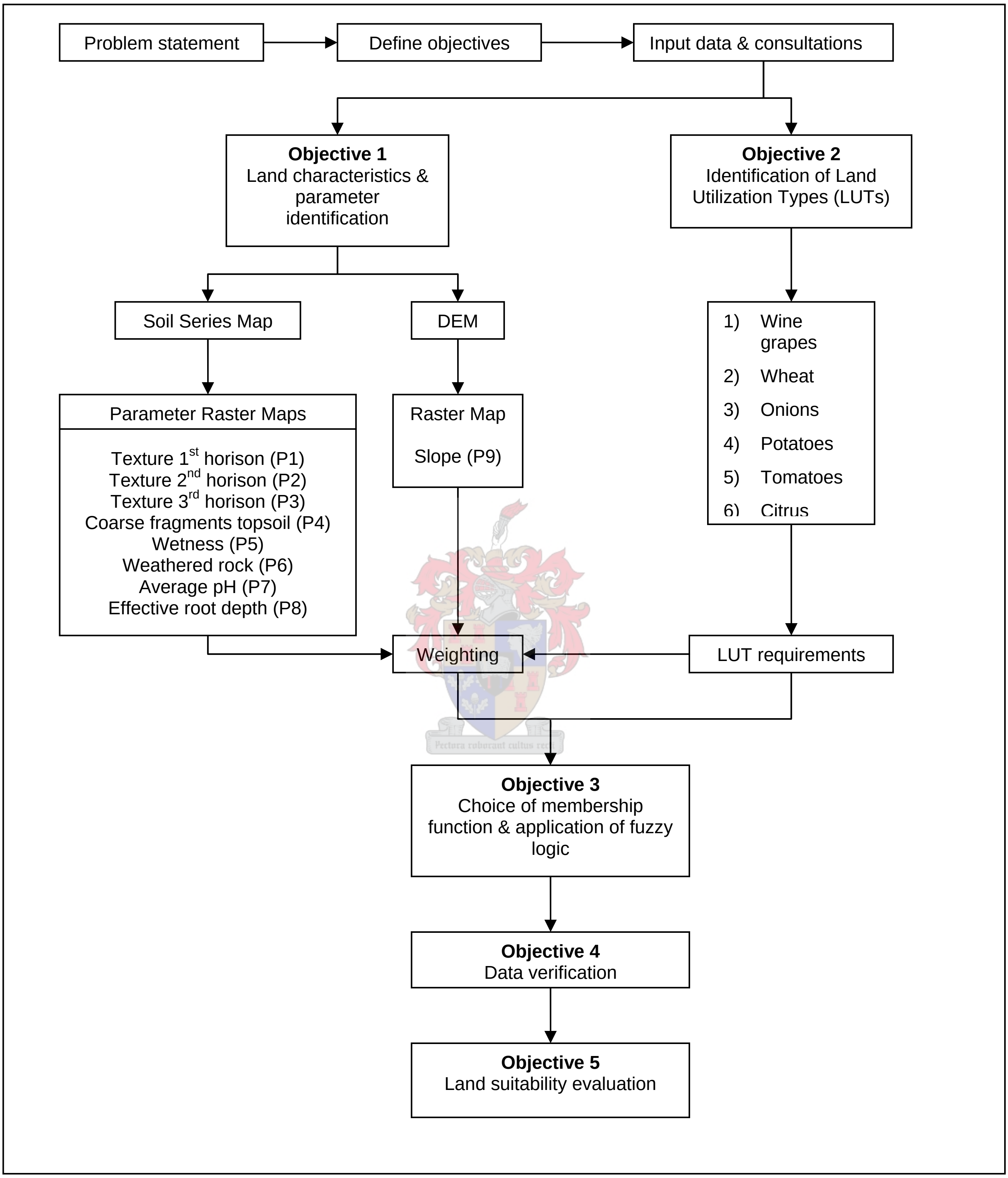


Figure 3.1 Stepwise exposition of the land evaluation exercise followed in this study.

In the first objective, the land characteristics of the area and parameters applicable to the study were identified. Eight of these parameters were derived from a soil map, and included soil texture of the first, second and third horizons, as well as coarse fragments in the top soil, wetness, weathered rock, average pH, and effective root depth. Additionally, a digital elevation model (DEM) was used to compute slope (%), the ninth parameter.

Concomitantly to the aforementioned step, land utilization types (LUTs) were identified in the second objective. These were wine grapes, wheat, onions, potatoes, tomatoes and citrus. Only these six LUTs were included in order to finish the research in the desired timeframe. Their requirements were established by consulting the literature and interviewing experts. These landuses occurred in the study area and were therefore already adapted to the environment. After completion of the first two objectives, weights were assigned to the parameters. In objective three, the membership functions were determined and fuzzy logic was applied to the data sets. The results were verified in the fourth objective and modifications to the process followed where deemed necessary. The final step was to compile a land suitability map, highlighting objective five and also concluding the land evaluation exercise.

Throughout the study, expert knowledge was used and applied. In particular, a soil scientist (Ellis 2004 pers comm.), a local agricultural expert (Louw 2004 pers comm.), viticulturist (Saayman 2005 pers comm.), two agronomists (Agenbag 2005 pers comm.; Langenhoven 2005 pers comm.), and citrus specialist (Barry 2005 pers comm.) were consulted.

3.2 LAND CHARACTERISTICS AND LANDUSE REQUIREMENTS

In line with the first objective, the parameters needed for the evaluation of the catchment were derived from the existing data sources, i.e. the soil map and DEM. These parameters are described below and followed by an account of the LUTs identified in the area.

3.2.1 Parameters

Although a multitude of parameters would be necessary to complete a thorough land evaluation, limited data availability imposed constraints on the number of parameters that could be used. However, these parameters provided a reasonable overview of the area’s characteristics and were deemed invaluable in the exercise.

3.2.1.1 Climatic parameters

Climate is considered to be the most important parameter in land evaluation and all other parameters are subject to that (Agenbag 2005 pers comm.; Barry 2005 pers comm.; Bland 1971; Langenhoven 2005 pers comm.; Saayman 2005 pers comm.; Acquaah 1999). Although climatic parameters like annual rainfall, average temperatures, and frost were not directly incorporated in the study, the researcher did evaluate whether the LUTs would acclimatize to the area. Climatic parameters were not directly included due to the assumption that little variation occurred throughout the relatively small study area. In addition, the available climatic data were too coarse to significantly improve the final result.

Climate is one of the main reasons why citrus, potatoes, tomatoes, onions, wheat, and wine grapes were selected as LUTs (Louw 2004 pers comm.; CMC 1997). Temperatures in the area will not limit the cultivation of the selected crops. However, apart from the wine grapes, the 400mm annual rainfall will not be sufficient and irrigation is therefore a necessity. Climatic requirements for the individual crops will be discussed later in this chapter.

Detailed information regarding wind was omitted from the study due to a lack of data. However, according to Agenbag (2005 pers comm.) and Saayman (2005 pers comm.) frequent south-easterly winds in the summer could pose a significant problem due to the sandy nature of the soils. Not only would the wind be an important erosion factor, but it could potentially jeopardize the growth of crops in the vicinity due to high speed.

3.2.1.2 Soil parameters

Soil parameters used in this study included the texture of the first three horizons, average soil pH, effective root depth, coarse fragments in the topsoil, wetness, and weathered rock. Of these, only texture of the first three horizons, effective root depth and soil pH could be estimated with reasonable certainty. Texture was quantified in terms of percentage clay, sand, and silt. Clay percentage is important as it determines the water holding capacity of the soils in this relatively dry area (Ellis 2004 pers comm.; Saayman 2005 pers comm.). If a soil type was found to consist of only two horizons, the assumption was made that the second or B-horizon would be prevalent further down in the soil.

Qualitative terms for coarse fragments in the topsoil, wetness, and weathered rock, were gained from Ellis & Schloms (1999). The terms, in Table 3.2, describe each soil unit's degree of limitation in the above-mentioned parameters:

Table 3.2 Qualitative limitation descriptions and corresponding symbols

LIMITATION CLASS	**TERM**
No limitation	(no term)
Low limitation	Low
Moderate limitation	Moderate
Severe limitation	Severe

(Ellis & Schloms 1999)

These qualitative parameters were quantified (see Section 3.4.1.3) in order to compare it to the quantitative requirements of the different landuses.

3.2.1.3 Slope

Slope percentage was calculated from a DEM. The slope restrictions for the different soil types were obtained from the Conservation of Agricultural Resources Act (DoA 1984) and were classified into having no, low, slight, moderate, or severe restrictions for agricultural purposes. Accompanying these qualitative terms, were also a set of quantitative guidelines obtained from the Conservation of Agricultural Resources Act, provided in the 'Slope restriction' column in Table 3.3. From these guidelines it is evident that some soil types are more susceptible to erosion than others, hence explaining the differences regarding the slope restriction.

Concurrently with the assessment of the land characteristics and parameter identification, objective two was executed, whereby landuses and their requirements had to be determined. This process is described in the next section.

Table 3.3 Characteristics of the individual soil units

	Texture[*]			Slope restriction (%)				Avg pH	Root depth (cm)	Coarse frgmts[**]	Wetness	Weathered rock
	Hor 1	Hor 2	Hor 3	Low	Slight	Moderate	Severe					
Dr	S	LS	CL	<10	10-12	12	>12	4.6	73	Low	Moderate	Low
Gs	LS	CL	n.a.	<10	10-12	12	>12	5	65	Moderate	Low	Moderate
Hu	LS	SCL	CL	<15	15-20	20	>20	4.5	95	Low		Low
Ks 1	S	S	LS	<10	10-12	12	>12	6.5	104			
Ks 2	S	S	SCL	<10	10-12	12	>12	6.4	93			
Ks 3	S	S	LS	<10	10-12	12	>12	6.7	77			
Po	PS	PS	LS	<10	10-12	12	>12	5	45		Low	
Rc	Mostly rock, with little sand, clay, and silt			<10	10-12	12	>12	5	29	Severe		Severe
Sa	Saline river course			n.a.				n.a.	n.a.	n.a.	n.a.	n.a.
Si	S	SL	CL	<10	10-12	12	>12	4.6	54	Severe	Moderate	Moderate
dHu	LS	SCL	CL	<15	15-20	20	>20	4.5	95	Low		Low
mDr	S	LS	CL	<10	10-12	12	>12	4.6	45	Low	Moderate	Low
mGs	LS	CL	n.a.	<10	10-12	12	>12	5	45	Moderate	Low	Moderate
mKm	S	SCL	CL	<10	10-12	12	>12	4.5	68	Low	Moderate	Low
mTu	LS	SCL	CL	<15	15-20	20	>20	4.6	45	Low	Low	Low
mdHu	LS	SCL	CL	<15	15-20	20	>20	4.5	65	Low		Low

[*]	Sand (%)	Clay (%)	Silt (%)
Sandy loam (SL)	50-70	15-20	0-50
Sandy clay loam (SCL)	45-79	20-40	0-28
Clay loam (CL)	20-45	28-40	15-52
Loamy sand (LS)	70-80	10-15	0-30
Pure sand (PS)	95-100	0-5	0-5
Sand (S)	85-95	5-10	0-15
Silt clay loam (SiCL)	0-20	28-40	60-72

(Department of Agricultural Development 1991)

[**] An open space indicates that the restriction is not present in that unit.

3.2.2 Landuses and their requirements

Landuses, or land utilization types (LUTs), were identified from the literature (Ellis & Schloms 1999; CMC 1997) and from Louw (2004 pers comm.). This includes wheat and vegetables (potatoes, tomatoes, onions). Although wine grapes are present on limited scale (CMC 1997), Ellis & Schloms (1999) is of the opinion that the area has the potential to sustain more extensive wine grape activity. Orchards are also present on very limited scale (South Africa 2000; CMC 1997). Citrus, as the most important subtropical crop and fourth largest export product in the South African economy was therefore included in the study (DoA 2003; DoA 1996:xi).

3.2.2.1 Wheat

Wheat is the dominant agricultural crop in the study area. Cultivated throughout the winter months and harvested at the beginning of spring (Agenbag 2005 pers comm.), the 400mm annual rainfall of the region is sufficient to meet this crop's moisture needs of 300 - 900mm per annum (Hartmann, Flocker & Kofranek 1981). Wheat do well in well-drained silt, silty clay loams, sandy clay loams, and sandy loams with a pH ranging from 5.5 - 6.5 (Hartmann, Flocker & Kofranek 1981; Bland 1971; Bland 1994; Delorit & Ahlgren 1967) while sandy soils are less suitable, due to the low water holding and cation exchange capacity.

3.2.2.2 Citrus

Although winters should be cold enough for fruit to set, citrus require a frost free environment where temperatures seldom drop below 3°C. Moisture is a limiting factor in citrus production and frequent irrigation in smaller volumes, rather than larger volumes less frequently, is almost without exception necessary. In terms of soil, weathered rock in the subsoil will be limiting if it causes excessive wetness or prevents growth. Well-aerated, well-drained, fertile soils, with a clay content of 10 - 40% and an effective root depth of at least 60cm is preferable. The ideal pH would be in the range of 6.0 - 6.5, but more acidic soils can be tolerated (DoA 2000; Gilbert & Hadfield 1987).

3.2.2.3 Vegetables

Vegetables evaluated in this study are potatoes, tomatoes, and onions. According to Hadfield (1985), vegetables acquire most of their nutrition in the upper 150 - 300mm of the soil. Therefore, the first horizon will play a significant role in determining the success of the crop, depending on the depth of this horizon.

The onion plant is a cool season crop, especially during the development stage. The optimum temperature ranges from 16 - 20°C and the issue of irrigation is frequently touched upon (Nonnecke 1989; Fordham & Biggs 1985; Hartmann, Flocker & Kofranek 1981). Fertile soils with a sandy loam, loamy or peat texture are best for the cultivation of onions (Brewster 1994; Hadfield 1985; Hartmann, Flocker & Kofranek 1981). Fordham & Biggs (1985) also stress the superiority of coarse-textured, large-particle sandy soils over clays and soils with small-sized particles. However, sandy soils will be suitable if there is enough organic material and sufficient soil moisture. Onions require a soil pH of 6.0 - 7.5, as they are very sensitive to acidic conditions and do not do well on soils with a pH of less than 6 (Nonnecke 1989; Fordham & Biggs 1985; Hartmann, Flocker & Kofranek 1981). Onions are not tolerant to anaerobic conditions (Fordham & Biggs 1985; Hadfield 1985), and coarse fragments in the topsoil can make mechanical harvesting difficult (Brewster 1994).

Tomatoes are a summer crop and are tolerant of temperatures of up to 30°C. They require sand with much the same texture as for onions and would also not do well in waterlogged conditions (Gilbert & Hadfield 1987; Atherton & Rudich 1986), but can be produced in slightly more acidic soil conditions (5.5 - 7.0 pH). Both Atherton & Rudich (1986) and Nonnecke (1989) emphasize the importance of sufficient moisture levels, mainly supplied by irrigation, for the plant to survive.

Potatoes, like onions, are suited for cooler weather especially during the development stage. Optimum temperature ranges from 16 - 20°C and soil conditions similar to that of onions and tomatoes are necessary for potato cultivation. Potatoes are heavy users of mineral nutrients and therefore require a good amount of organic material in the soil, while the optimum pH ranges from 5.0 - 6.5 (Nonnecke 1989; Gilbert & Hadfield 1987; Hartmann, Flocker & Kofranek 1981). As with the previous two vegetable crops, potatoes cannot tolerate anaerobic conditions (Dean 1994).

3.2.2.4 Wine grapes

Climate is the most important factor that influences the quality of wines and wine grapes do best in a Mediterranean climate with cold, wet winters and warm, dry summers. The moisture-holding capacity of soils is also important with specific emphasis placed on the clay content. Saayman (1981) is of the opinion that heavy textured soils in South Africa may give good results under dry land conditions. However, well-drained light- to medium textured soils are preferred for quality cultivation. Sandy loams, loamy and sand clay loams are therefore ideal. Wine grapes prefer a pH of 5.0 - 7.0 and a soil depth of at least 100cm. The deeper the soil and effective root depth, the more the vineyard plant will be able withstand adverse climatic conditions (Saayman 2005 pers comm.; Saayman 1981).

Wine grapes are fairly resistant to wetness if it occurs in the plant’s resting period (i.e winter in the Western Cape). Coarse fragments are not seen as an important constraint, but the two restrictions that will have the most profound effect on vineyard cultivation are wetness and low pH (Saayman 2005 pers comm.).

After the parameters for the evaluation were identified and the landuse requirements were determined, fuzzy logic could be applied to the data sets. The following section describes the data sources used in this fuzzy land evaluation, as well as calculation of the membership scores. Further, an overview of the weighting process involved is given.

3.3 DATA COLLECTION AND PREPARATION

The data used in this study consisted primarily of a 1:20 000 soil map (see Figure 3.2) and a digital elevation model (DEM) of the study area. The soil map was obtained from Ellis (2004 pers comm.) who was also one of the compilers. The soil map was compiled using a technique whereby landforms, which were associated with certain soils, were identified and used as surrogates to identify the underlying soils. Due to the large extent of the area, limited soil samples were taken. Consequently, identification of the specific properties of the soils relied heavily upon the soil surveyor's interpretation (Ellis 2004 pers comm.). Additional information on the general properties of soils in South Africa was obtained from the Department of Agricultural Development (Soil Classification Working Group 1991). From Figure 3.2 it can be seen that the Dr, Ks1, Ks2, Ks3 and Po soil forms cover the majority of the area, with other minor soil forms also of considerable importance.

The DEM was acquired from the Centre for Geographical Analysis (CGA), associated with the Department of Geography and Environmental Studies, University of Stellenbosch. The DEM was projected to Transverse Mercator, with WGS_1984 as ellipsoid and a central meridian of 21. This projection was used throughout the exercise. The original DEM had a resolution of 20m, but was resampled to 125m to match the cell size of the soil map, and to ensure that the two data sets would align properly. Misalignment between the data sets will lead to inaccurate and meaningless results.

Determination of the analysis cell size to be used in the study was based on a method developed by Forbes, Rossiter & Van Wambeke (1987). This involves the definition of the *minimum legible area* (MLA), the smallest land area that can be legibly represented on the map at a given scale. It may be calculated from the map scale by Equation 3.1 (Forbes, Rossiter & Van Wambeke 1987):

$$\frac{\left(\frac{1}{RF}\right)^{2}}{2.5\times10^{8}} = \text{minimum legible area, ha} \qquad [3.1]$$

where RF is the representative fraction, indicating the scale of the map. The scale of one of the primary data sources, the soil map, is 1:20 000, thereby indicating that a MLA of 1.6 ha would be sufficient for the analysis.

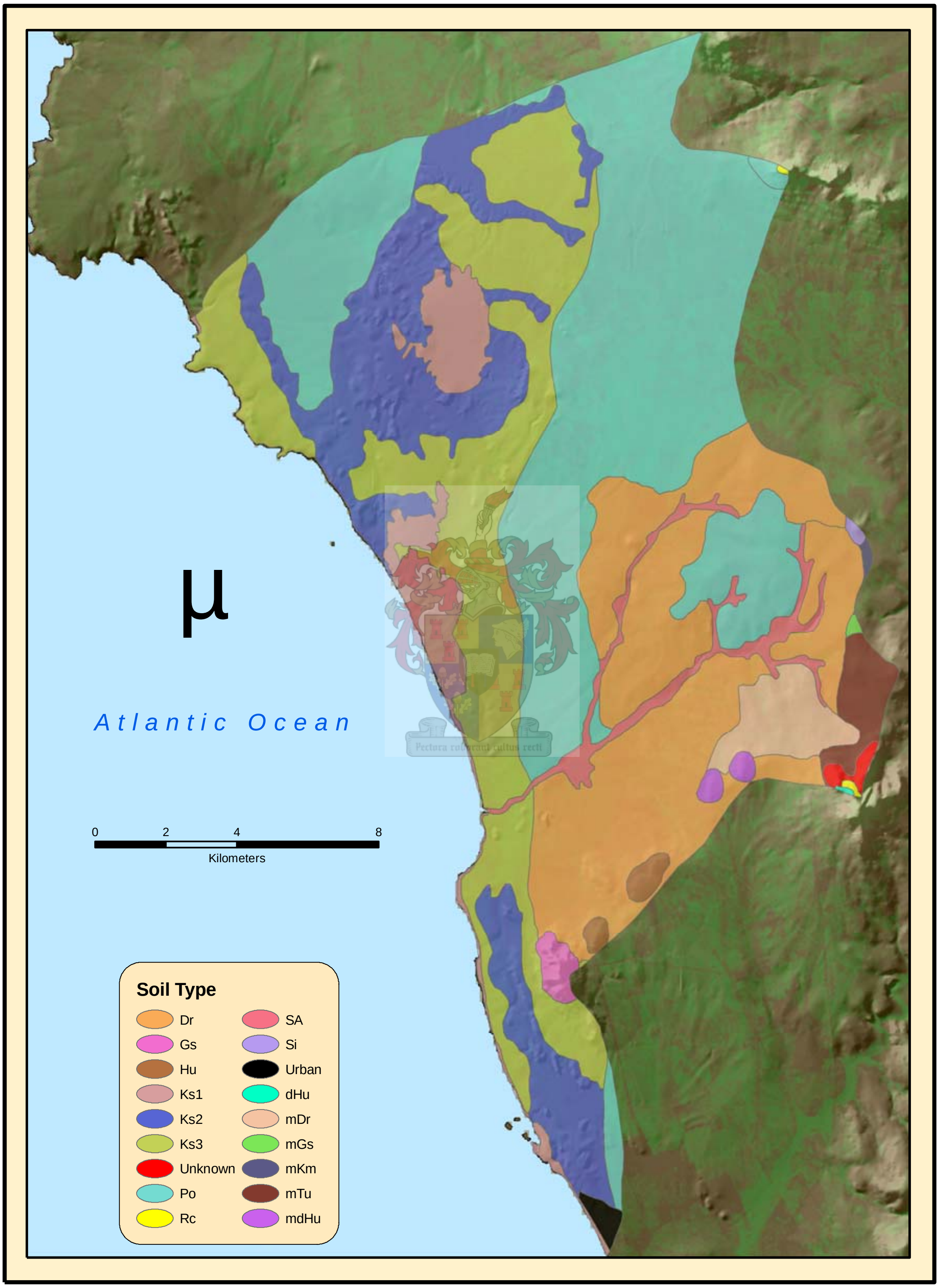


Figure 3.2 Soils found in study area

Consequently, cells with a 125m resolution were used and each cell portrays an area of 1.5625 ha. Original cell sizes of both the soil map and the DEM were resampled to 125m resolution. Due to the nominal nature of the soil data, the nearest neighbour technique was used for resampling of the soil map, whilst bilinear interpolation was used for the DEM due to its continuous character.

The subsequent section describes how the membership scores were calculated, and the weighting process that assigned different weights to the respective parameters.

3.4 FUZZY THEORY AND PAIRWISE COMPARISON WEIGHTING

Objective three of the research was concerned with a decision regarding the choice of membership function for each parameter, as well as the application of fuzzy theory to the data sets. In this section the choice of membership function, calculation of membership scores and weighting process are discussed.

3.4.1. Calculation of membership scores

As previously mentioned, the ideal values of the parameters for each crop were gathered from the literature and expert knowledge. A symmetric function was used for texture of the first three horizons, and pH. Lower, upper and central values were defined for every parameter. With effective root depth, only a lower critical boundary had to be defined, and an asymmetric function was used to calculate the membership scores. Slope, on the other hand, had an upper critical boundary as it could not exceed specified limits for different soil types. Soils with different slope restrictions had different values for *c*. An example of the parameters used can be found in Table 3.4, and were determined for all the crops. Parameters for all the crops can be found in Appendix A and the equation used in this exercise was:

$$\mu_A(x) = \frac{1}{\left\{1 + a(x-c)^2\right\}} \text{ for } 0 \le x \le P$$

To determine the value of *a*, a membership score of 0.5 was awarded to $\mu_A(x)$, *x* received the lower cross-over value, and *c* is the central value for symmetric functions. With effective root depth, $\mu_A(x)$ received a 0.5 score, *x* received the minimum soil depth required for the crop to survive, and *c* received an ideal depth (deeper than the minimum depth). Soils where $x \ge c$, received a membership score of 1. Slope was reclassed into having no, low, slight, moderate or severe restrictions, and the value of $\mu_A(x)$ remained 0.5. In addition, the value of the slight restriction was used for x, and c was taken as ‘0’, since a flat tract of land in this area would be ideal for cultivation. Through this calculation, a value for a could be determined.

Table 3.4 Summary of a number of parameters used for wheat

Soil property	**Type of function**	**Lower cross-over value**	**Central value**	**Upper cross-over value**	**Value of *a***
Horizon 1: sand %	S	50	60	70	0.01
Horizon 1: clay %	S	15	17.5	20	0.16
Horizon 1: silt %	S	0	25	50	0.002
Horizon 2: sand %	S	0	39.5	79	0.00064
Horizon 2: clay %	S	20	30	40	0.01
Horizon 2: silt %	S	0	36	72	0.00077
Horizon 3: sand %	S	0	39.5	79	0.00064
Horizon 3: clay %	S	20	30	40	0.01
Horizon 3: silt %	S	0	36	72	0.00077
pH	S	5.0	6.0	7.0	1
Rootdepth	A	30	50	50	0.0025

In the remainder of the parameters, i.e. wetness, coarse fragments in the topsoil, and weathered rock, the qualitative terms, as used by Ellis & Schloms (1999), were converted to quantitative scores. The method developed by Zhang (1989) and adopted by Triantafilis, Ward & McBratney (2001), was used, whereby each restriction term had a parametric score assigned to it. Table 3.5 presents the restriction terms as used by Ellis & Schloms (1999) and the corresponding quantitative scores awarded to them.

Table 3.5 Qualitative restriction terms and the corresponding quantitative scores

Qualitative term	**Quantitative score**
no limitation	0
low limitation	1
moderate limitation	3
severe limitation	9

To determine the value of a, the low-limitation score, i.e. ‘1’, was used for the value of x. As no limitation in the soils is the ideal situation, c was awarded a ‘0’, with $\mu_A(x)$ again at 0.5. This ensured that only soils with no or a low limitation received a membership score of 0.5 or higher. After the parameters were fuzzified, the weighting process occurred to award a relative weight to each parameter.

3.4.2 Pair-wise comparison weighting

It is inevitable that some parameters will have a more profound influence than others. Therefore, to assign equal weights to the parameters would not produce a realistic account of the different soil types' potential. For example, soil pH will have a more important influence on the success of wine grapes, than do coarse fragments in the topsoil. Hence, different weights were assigned to the individual parameters to determine their relative importance.

One system used regularly in the literature is Saaty's (1980) analytical hierarchy procedure as described in Ahamed, Rao & Murthy (2000). An importance scale is used for the pair-wise comparison of parameters. After the parameters have been pair-wise compared to each other, the eigenvector is calculated and the weights of the parameters are estimated. Thus, different weights are assigned to the input membership scores, $\mu_A(x)$, of the different parameters. The overall membership score of the pixel for the landuse can then be determined as:

$$\mu_A(x)_{overall} = w1.\mu_A(x)_{pH} + w2.\mu_A(x)_{rootdepth} + w3.\mu_A(x)_{wetness} + \ldots \qquad [3.1]$$

where $\mu_A(x)_{overall}$ represent the final membership score for the crop and the elements at the right-hand side of the equation are the individual membership scores summing to unity. Table 3.6 shows an example of the pair-wise comparison matrix as implemented in the IDRISI GIS software package.

Expert opinion was of significant importance in the determination of the weights. Therefore experts were interviewed for wine grapes (Saayman 2005 pers comm.), wheat and potatoes (Agenbag 2005 pers comm.), onions and tomatoes (Langenhoven 2005 pers comm.), and citrus (Barry 2005 pers comm.). These experts also assisted in verifying that correct values for the parameters were used.

Consider row 2, where the relative importance of the second horizon is compared to the relative importance of the first horizon. The score of '1/3' indicates that, compared to the column variable (horizon 1), the row variable (horizon 2) is slightly less important. This can be attributed to the fact that the potato plant will acquire most of its nutrients from the first horizon and less nutrients from the second horizon. The first horizon plays a more significant role in the survival of the plant because, in the study area, the top horizon is on average 300mm thick. The matrix is reciprocal and also mathematically consistent (Ahamed, Rao & Murthy 2000). In IDRISI, the consistency ratio is calculated and relayed to the user, and a ratio ≤ 0.9 is considered adequate. The comparison matrices for the different crops can be found in Appendix B.

Table 3.6 Pair-wise comparison matrix for the parameter values of potatoes

Potatoes									
	hor1	hor2	hor3	pH	rootdepth	weathered rock	wetness	coarse fragments	slope
hor1	1								
hor2	1/3	1							
hor3	1/5	1/3	1						
pH	1/5	1/5	1/3	1					
rootdepth	1/7	1/7	1/5	1/5	1				
weathered rock	1/5	1/5	1	1/3	3	1			
wetness	1	1	5	5	7	7	1		
coarse fragments	1/5	1/5	1/3	1/3	5	3	1/5	1	
slope	1/3	1/3	1	1	5	3	1/3	3	1

In this example, parameter values of the landuse ‘potatoes’ are compared to each other, and the weights can be explained as follow:

1 = Both parameters are equally important
3 = In comparison with the column variable, the row variable is slightly more important
5 = In comparison with the column variable, the row variable is moderately more important
7 = In comparison with the column variable, the row variable is significantly more important
9 = In comparison with the column variable, the row variable is overwhelmingly more important
1/3 = In comparison with the column variable, the row variable is slightly less important
1/5 = In comparison with the column variable, the row variable is moderately less important
1/7 = In comparison with the column variable, the row variable is significantly less important
1/9 = In comparison with the column variable, the row variable is overwhelmingly less important

The next chapter discusses the results of the fuzzy land evaluation for each landuse, as well as the compilation of a suitability map. Results are also verified by comparing it to current agricultural landuses in the area where a concurrence between the two data sets would indicate the correct application of fuzzy theory.

CHAPTER 4: FUZZY LAND EVALUATION RESULTS AND DISCUSSION

This study aimed to evaluate the suitability of a catchment in the Atlantis Growth Corridor (AGC) for six agricultural crops: wine grapes, wheat, onions, potatoes, tomatoes, and citrus. Fuzzy reasoning was implemented in a Geographic Information System (GIS) and graphical representations for each crop were constructed. The reader is referred to Section 3.2.2 where the requirements of each crop are examined, and to Section 3.4.2 discussing the pair-wise comparison weighting process.

In the next section, the catchment's fuzzy scores for each crop is shown and interpreted. This is followed by Section 4.2 where all the crops were combined into an overall suitability map for the area. This suitability map indicates optimal crops for the region. The chapter concludes with the validation of the fuzzy results by comparing it to current crop location in the area.

4.1 INDIVIDUAL LANDUSE FUZZY SCORES

The catchment was evaluated for each crop, producing six individual suitability maps and accompanying graphs. These maps are interpreted and explained at the hand of the parameters.

4.1.1 Wine grapes

Important parameters in the suitability analysis of wine grapes were average pH, wetness, texture of the second horizon, and root depth. The weights awarded in Table 4.1 are the product of the pair-wise comparison matrix (see Table 3.6). These parameters carried the most weight for wine grapes. Parameters were pair-wise compared, the eigenvectors calculated, and a consistency ratio of 0.02 was achieved, indicating consistent comparison weighting.

Table 4.1 Weights assigned to the parameters for wine grapes

Horizon 1	0.0270
Horizon 2	**0.1303**
Horizon 3	0.0603
pH	**0.2689**
Rootdepth	**0.1303**
Weathered rock	0.0270
Wetness	**0.2689**
Coarse fragments	0.0603
Slope	0.0270
Total	**1.0000**

Different opinions exist regarding the catchment's potential for viticulture. Ellis & Schloms (1999) believe some regions in the catchment are suitable for high quality wine grapes, while Louw (pers comm. 2004) disagrees due to the shallow topsoil layer, insufficient water in the subsoil, and the occurrence of strong south-easterly winds. Figure 4.1 shows the distribution of fuzzy scores for wine grapes and supports Ellis & Schloms' (1999) findings, indicating the same areas as high potential areas for wine grape production.

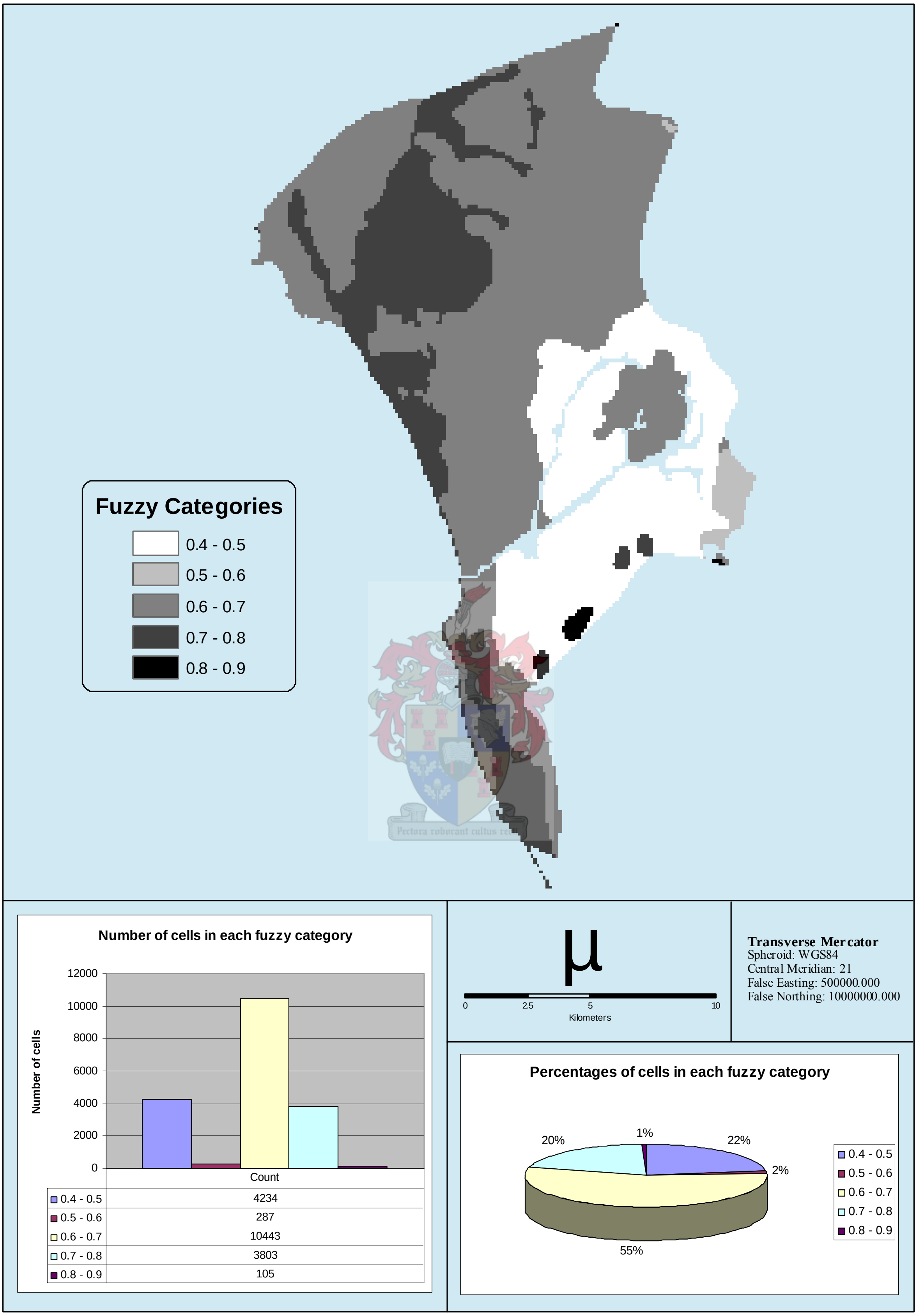
A large part (55%) of the study area obtained scores between 0.6 - 0.7. Limiting factors were texture of all three horizons (if present), wetness and effective root depth. Both Burrough (1989) and Triantafilis, Ward & McBratney (2001) consider a fuzzy score as low as 0.6 to have potential, therefore these areas are candidates for further evaluation. However, the added costs involved to improve the limiting factors, together with the possibility of gaining only a marginal return, might deter investors. The wetness and effective root depth limitations can still be resolved to some degree, but the textures of the horizons are more permanent in nature.

Almost 6000ha (20%), mostly throughout the southern and north-western parts of the study area, obtained scores between 0.7 - 0.8. These areas are suitable for wine grapes, but the sandy topsoil, relatively unfavourable texture of the subsequent horizons, and the considerably acidic nature of the soils are limiting factors. Improvements to the pH would up the scores and could very well place these regions in another category altogether. However, more detailed assessments are necessary before a final decision can be made.

Two isolated areas, totalling 164ha (1%) in the southern part of the study area, scored between 0.8 - 0.9, indicating that they are highly suitable for viticulture. This corroborates the findings of Ellis & Schloms (1999) that these areas have potential for high quality wine grape production.

4.1.2 Wheat

Wheat is the most abundant agricultural crop being cultivated in the study area (Agenbag pers comm. 2005; Louw pers comm. 2005) and acclimatizes well to its conditions. Important parameters influencing wheat include texture of the first and second horizon, pH, wetness, and coarse fragments. The textural parameters are the biggest limitation; while wetness, pH, and coarse fragments improved the scores (see Table 4.2). A consistency ratio of 0.02 was achieved.



	Count
0.4 - 0.5	4234
0.5 - 0.6	287
0.6 - 0.7	10443
0.7 - 0.8	3803
0.8 - 0.9	105

Figure 4.1 Fuzzy scores for wine grapes

Table 4.2 Weights assigned to the parameters for wheat

Horizon 1	**0.2560**
Horizon 2	**0.1135**
Horizon 3	0.0241
pH	**0.2560**
Root depth	0.0497
Weathered rock	0.0241
Wetness	**0.1135**
Coarse fragments	**0.1135**
Slope	0.0497
Total	**1.000**

Large areas of the catchment have a low suitability for wheat (see Figure 4.2): one section (≈11 800ha or 40%) along the coast and stretching inland scored 0.5 - 0.6, while another section (≈10 800ha or 37%) mainly on the eastern side scored 0.6 - 0.7.

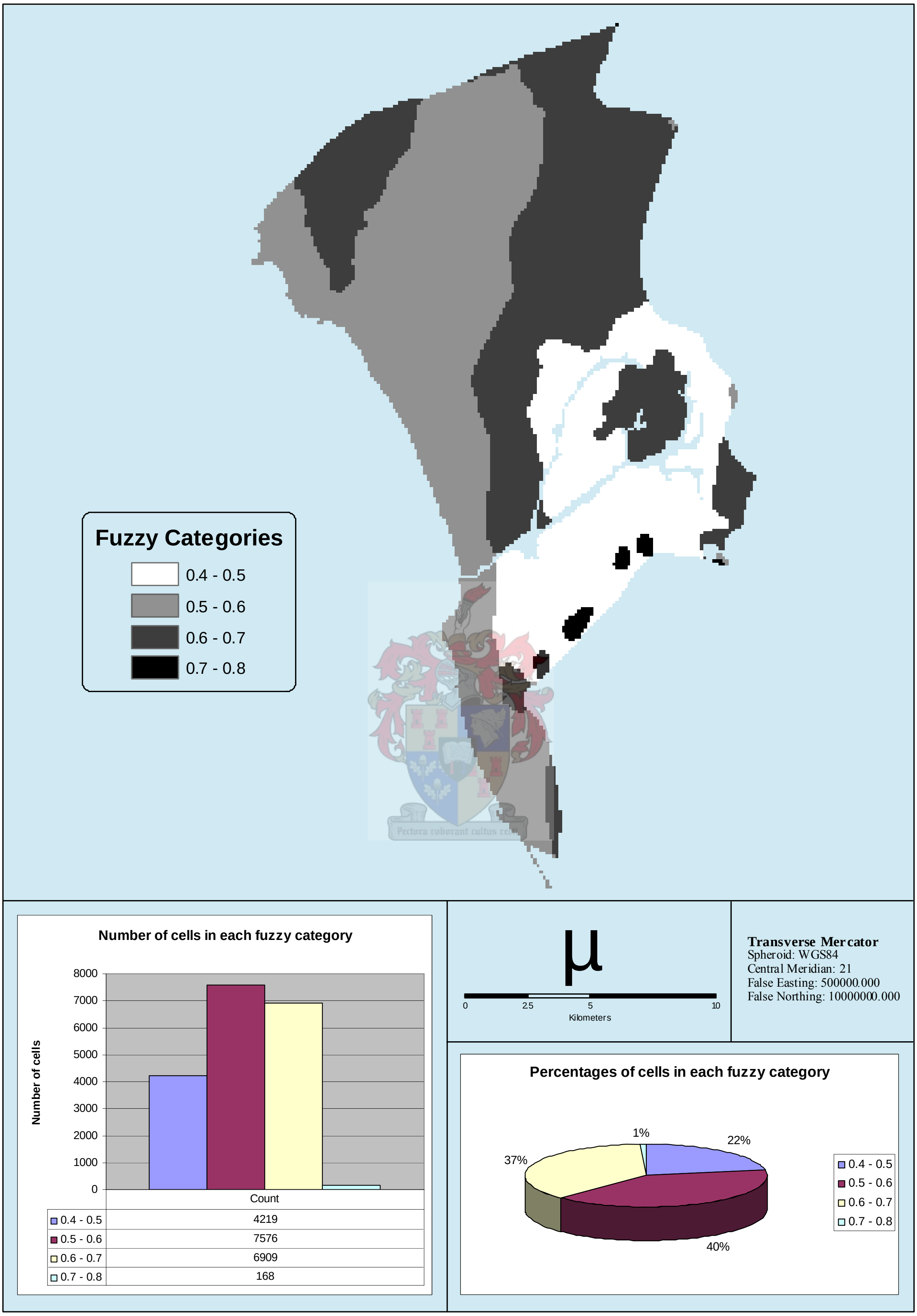
Areas corresponding to the same locations as wine grapes scored between 0.7 - 0.8 (263ha), the highest score for wheat. It is noteworthy that the catchment achieved lower scores for wheat than for wine grapes, even though wheat is the current dominant crop.

4.1.3 Citrus

Texture of the first horizon carried the heaviest weight in the fuzzy evaluation for citrus (see Table 4.3). With the citrus tree preferring a less sandy soil and a gradual transition into a more clayey sub-horizon, the sandy nature of the topsoil attributes greatly to the lower score. Other important parameters are the second horizon’s texture and pH, and the consistency ratio was 0.3.

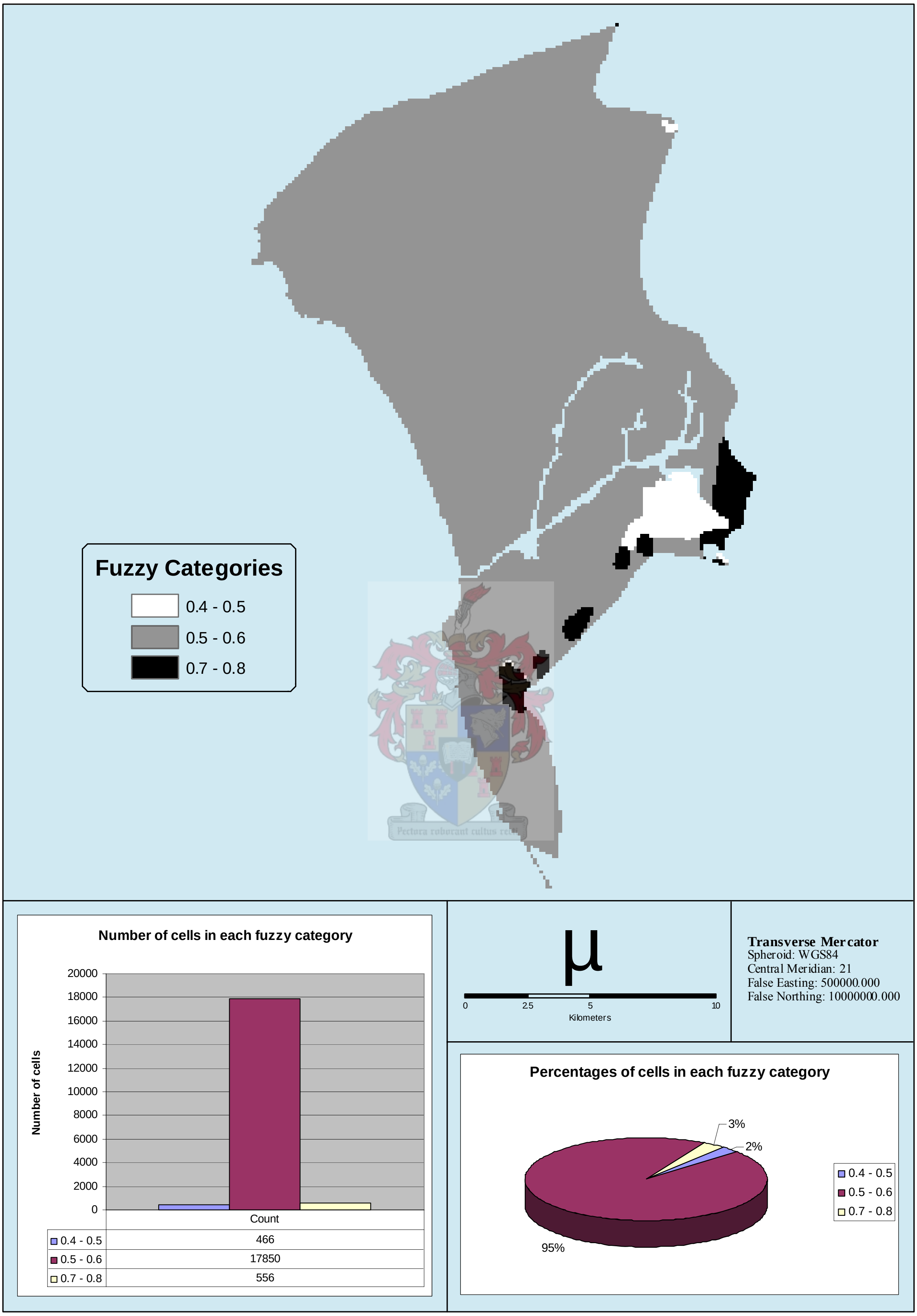
Table 4.3 Weights assigned to the parameters for citrus

Horizon 1	**0.3417**
Horizon 2	**0.1761**
Horizon 3	0.0805
pH	**0.1761**
Root depth	0.0805
Weathered rock	0.0216
Wetness	0.0805
Coarse fragments	0.0216
Slope	0.0216
Total	**1.000**



	Count
0.4 - 0.5	4219
0.5 - 0.6	7576
0.6 - 0.7	6909
0.7 - 0.8	168

Figure 4.2 Fuzzy scores for wheat



	Count
0.4 - 0.5	466
0.5 - 0.6	17850
0.7 - 0.8	556

Figure 4.3 Fuzzy scores for citrus

Figure 4.3 shows that 97% of the study area is not suitable for citrus cultivation, and scored below 0.6. Some isolated areas (869ha) in the south scored relatively high with 0.7 - 0.8, indicating potential. The higher score in these regions can mainly be elucidated by a favourable texture of the first and second horizons, while a poor pH lowered the score.

4.1.4 Vegetables

Commercial vegetable production is present in the area (Louw 2004 pers comm.; CMC 1997). Onions, tomatoes, and potatoes were selected for evaluation (refer to Section 3.2.2.3). Most significant parameters are the texture of the first horizon, wetness, and texture of the second horizon.

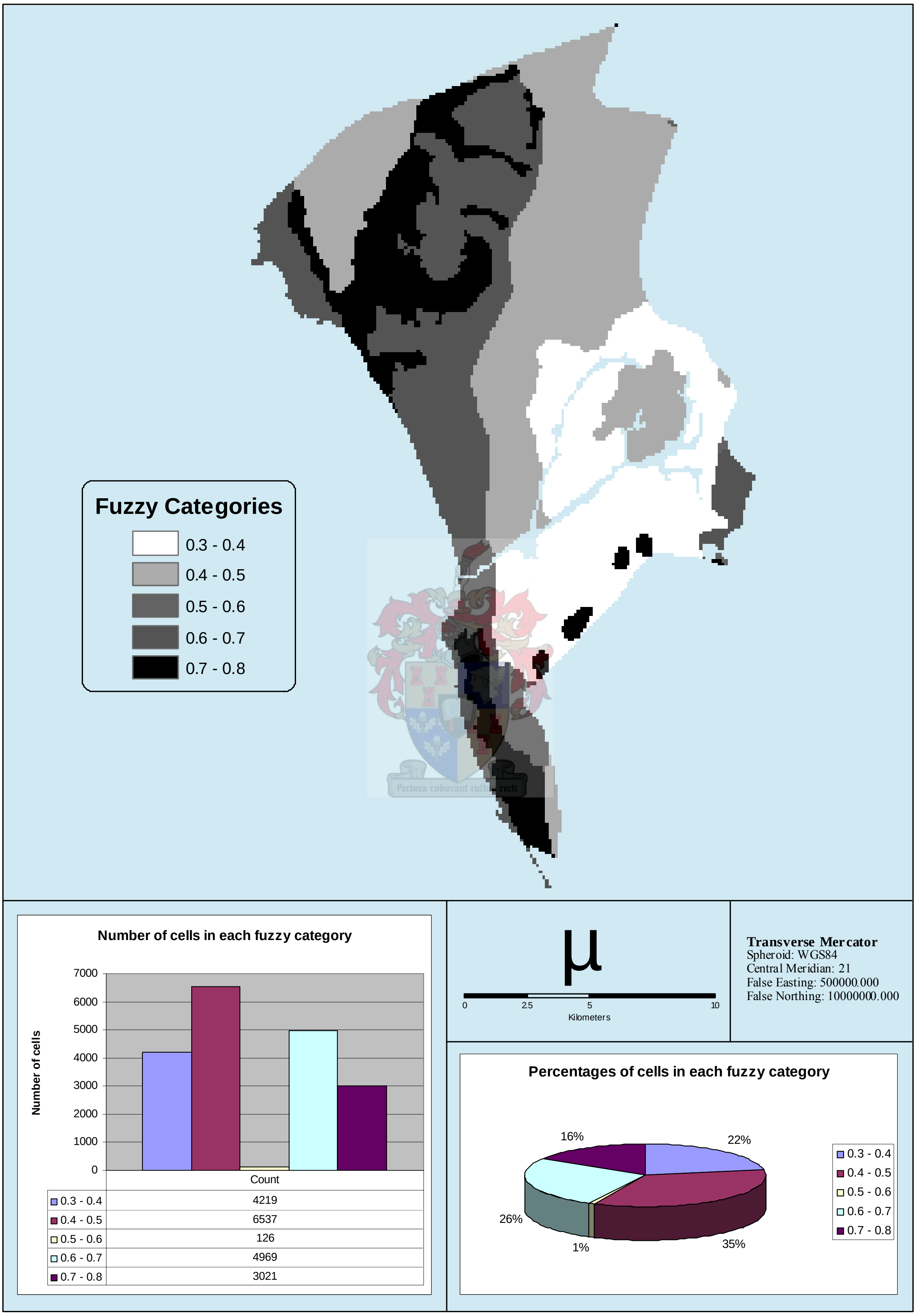
4.1.4.1 Onions

Texture of the first and second horizon, as well as wetness, carried the heaviest weights (see Table 4.4), with a consistency ratio of 0.06 achieved.

The sandy nature of the topsoil and presence of wetness make 58% (17 000ha) of the catchment unsuitable for onion cultivation. A further 7800ha (26%), mostly along the coast, scored between 0.6 - 0.7, indicating a relatively low potential compared to the other classes. However, the relatively favourable texture and absence of wetness contributed to 4700ha (16%) scoring 0.7 – 0.8, as shown in Figure 4.4. These areas are located in the northern and southern parts of the catchment.

Table 4.4 Weights assigned to the parameters for onions

Horizon 1	**0.2872**
Horizon 2	**0.1602**
Horizon 3	0.0462
pH	0.0936
Root depth	0.0166
Weathered rock	0.0462
Wetness	**0.2872**
Coarse fragments	0.0462
Slope	0.0166
Total	**1.000**



	Count
0.3 - 0.4	4219
0.4 - 0.5	6537
0.5 - 0.6	126
0.6 - 0.7	4969
0.7 - 0.8	3021

Transverse Mercator
Spheroid: WGS84
Central Meridian: 21
False Easting: 500000.000
False Northing: 10000000.000

Figure 4.4 Fuzzy scores for onions

4.1.4.2 Tomatoes

The relative weights of the parameters differed slightly from that of onions, yet texture and wetness still played a significant role (see Table 4.5). The differences in weights only influenced the combined suitability, and a consistency ratio of 0.04 ensured that the weights had been assigned correctly.

Table 4.5 Weights assigned to the parameters for tomatoes

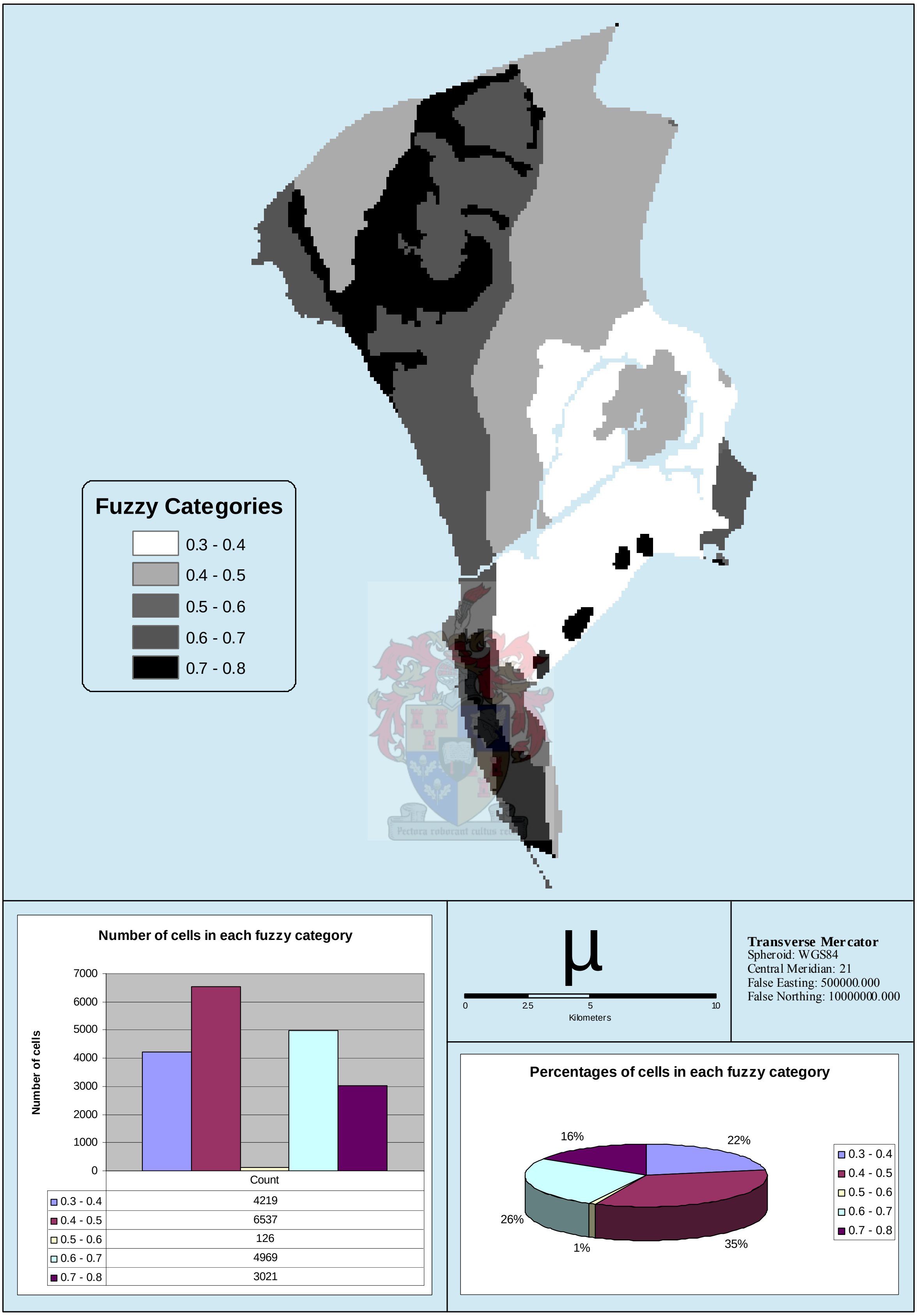
Horizon 1	**0.2937**
Horizon 2	**0.1644**
Horizon 3	0.0460
pH	0.0917
Root depth	0.0215
Weathered rock	0.0460
Wetness	**0.2937**
Coarse fragments	0.0215
Slope	0.0215
Total	**1.000**

Since tomatoes' requirements largely coincide with that of onions, the spatial patterns show a great deal of similarity. Of the catchment, 58% (17 000ha) is unsuitable for tomatoes, while 26% (7800ha) have a relatively low potential compared to other classes, scoring between 0.6 - 0.7. The remaining 16% (4700ha) shows a high potential for tomato cultivation with a score of 0.7 - 0.8. The areas for the two crops correspond well and the scores for tomatoes are shown in Figure 4.5. As with onions, texture of the first and second horizon, and wetness, largely determined the scores.

4.1.4.3 Potatoes

Most influential parameters for potatoes were the texture of the first horizon, wetness, pH, and coarse fragments in the topsoil, with texture and wetness carrying the heaviest weights (see Table 4.6). The consistency ratio was 0.05.

The catchment received significantly different scores for potatoes when compared to onions and tomatoes (see Figure 4.6). The majority of the catchment (≈22000ha or 75%) scored 0.6 - 0.7 and shows possibilities for potato cultivation. Most important limitations in these soils are the sandier nature of the first horizon and occasional wetness.



	Count
0.3 - 0.4	4219
0.4 - 0.5	6537
0.5 - 0.6	126
0.6 - 0.7	4969
0.7 - 0.8	3021

Figure 4.5 Fuzzy scores for tomatoes

Table 4.6 Weights assigned to the parameters for potatoes

Horizon 1	**0.2699**
Horizon 2	0.0391
Horizon 3	0.0164
pH	**0.1355**
Root depth	0.0322
Weathered rock	0.0322
Wetness	**0.2699**
Coarse fragments	**0.1355**
Slope	0.0693
Total	**1.000**

A further 430ha, located in the southeast of the catchment, scored 0.7 - 0.8. Although these soils are favourable for potatoes, they were penalized due to a slight wetness restriction. Isolated areas of 260ha in the southern parts of the catchment scored between 0.8 - 0.9. These higher scores can be ascribed to higher clay content, yet not high enough to cause wetness in the sub-horizons. Also, potatoes are more tolerant to acidic conditions than the other two vegetable crops.

4.2 COMBINED LANDUSE FUZZY SCORES

The aim of this research was to identify areas within the study area with a high production potential for the evaluated crops. After the fuzzy evaluation for each crop was completed, the scores were combined into an overall suitability map. Crops with the highest fuzzy score for each area were considered as first choice for cultivation in that area, resulting in the landuse pattern shown in Figure 4.7 (a). Large areas achieved the highest score for wheat, thus making it the first choice in those areas. Similarly, areas where the other landuses scored the highest, are shown in Figure 4.7 (a). Crops acquiring the highest scores were citrus, potatoes, tomatoes, wine grapes, and wheat. These scores ranged from 0.5 - 0.6 for citrus up to 0.8 – 0.9 for potatoes. Although the catchment could also have achieved high scores for other landuses, only the highest scores are depicted in Figure 4.7 (a). In terms of the parameters used, onions were the weakest competitor in all the areas evaluated and was therefore excluded from the overall suitability map. There are, however, areas suitable for onion production, and the reader is referred to Figure 4.4 for further information.

Furthermore, when a threshold of 0.6 is used as cut-off value, as done by Burrough (1989) and Triantafilis, Ward & McBratney (2001), land suitability is illustrated by Figure 4.7 (b). Cells with a score below 0.6 were excluded from the suitability map, resulting in a significantly changed proposed landuse. When investigating the fuzzy scores of the individual crops, a number of observations were made.

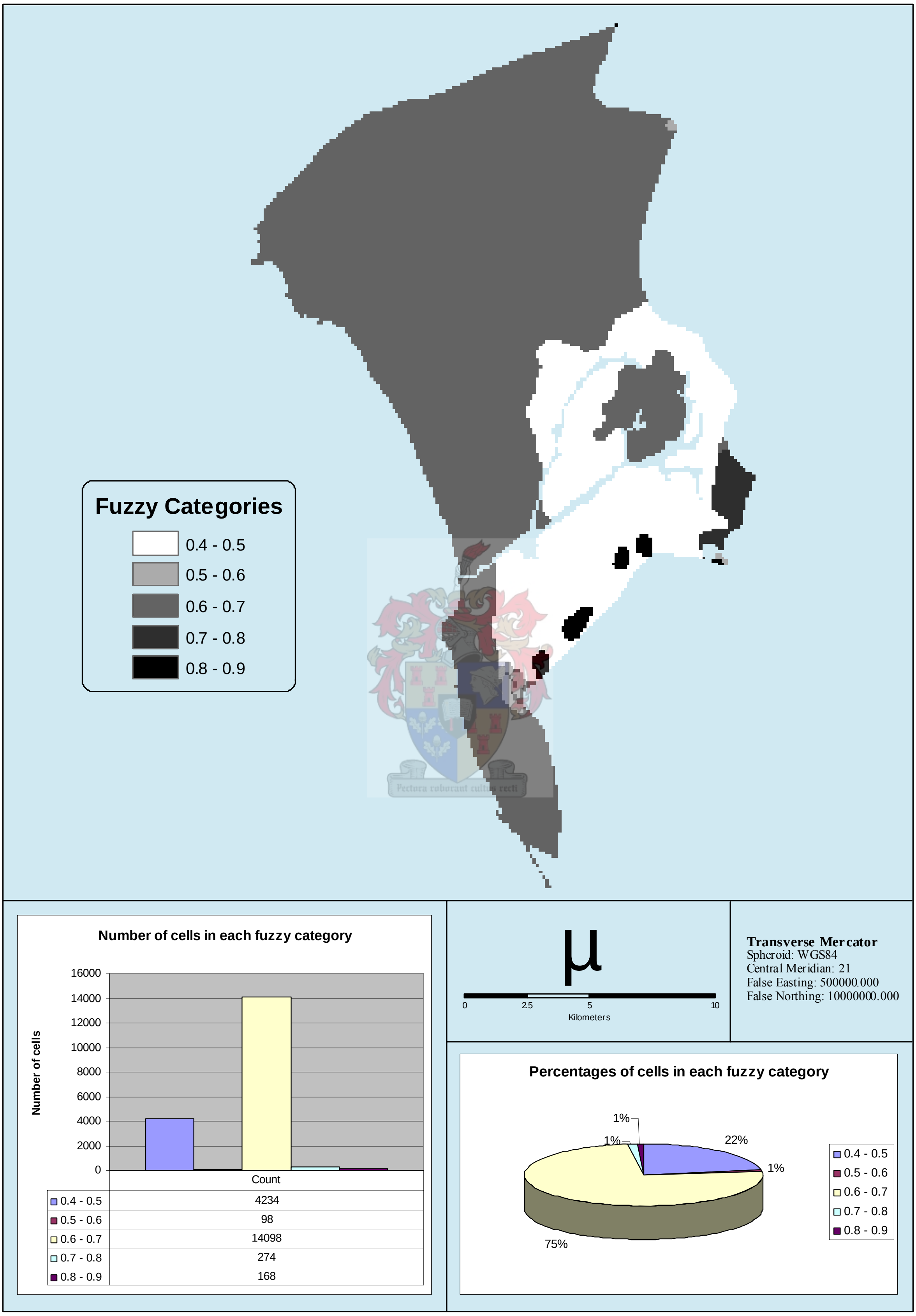


Figure 4.6 Fuzzy scores for potatoes

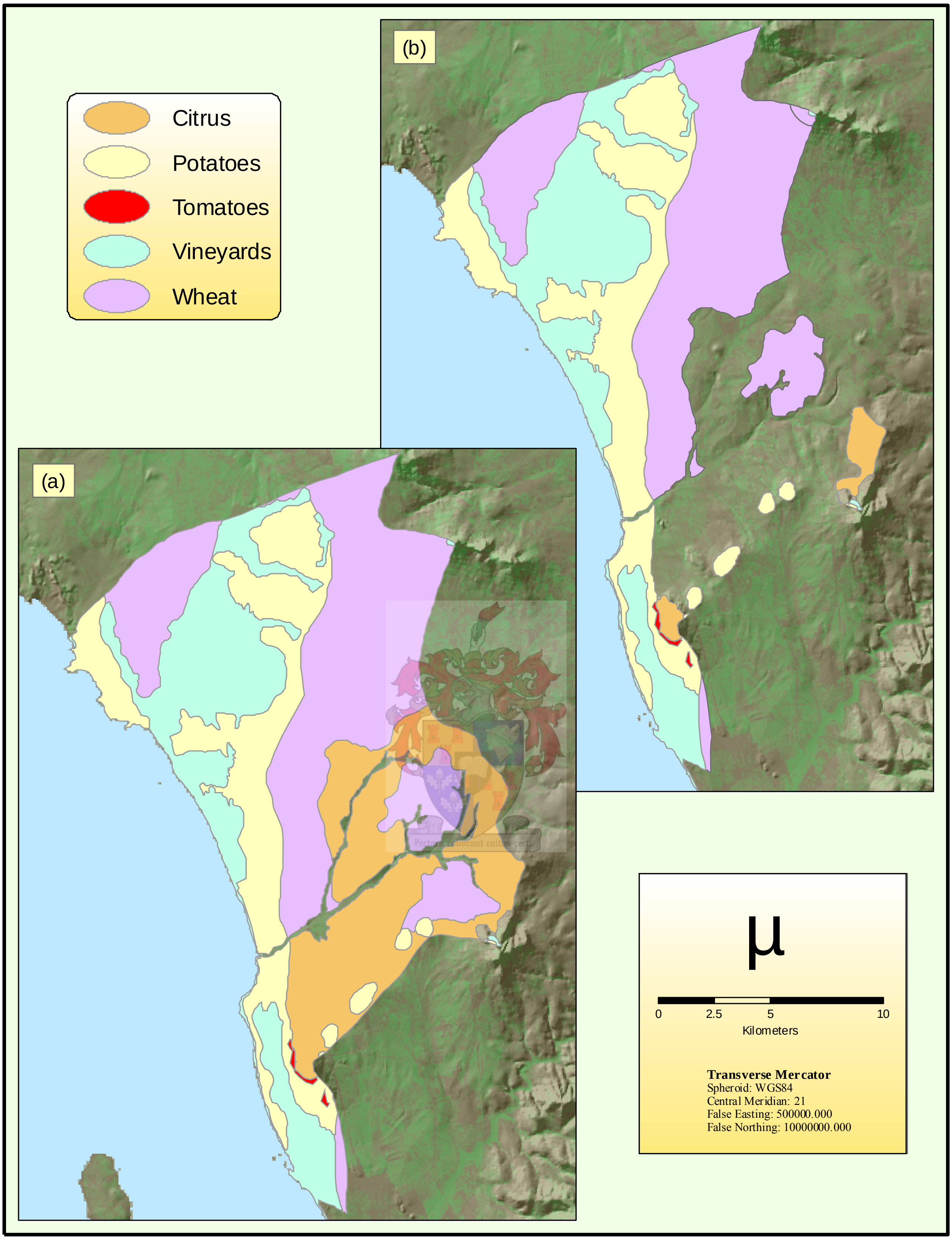


Figure 4.7 (a) Overall land suitability ignoring threshold fuzzy scores and (b) overall land suitability incorporating threshold fuzzy values

Firstly, areas with the potential for citrus were considerably smaller than illustrated in Figure 4.7 (a). Figure 4.7 (b) shows the areas where citrus fuzzy scores met the threshold with a score of 0.7 -

0.8. The higher scores indicate a potential for citrus growing and deserves closer scrutiny. In contrast to the relatively small areas for citrus growing, there are large areas throughout the catchment with a high potential for potato cultivation, and obtained a score of 0.6 or higher for potatoes.

There is also widespread potential for viticulture, with most areas scoring between 0.7 - 0.8. The areas suitable for wine grapes are more extensive than originally predicted by Ellis & Schloms (1999), yet further investigation on a larger scale should take place. There are also extensive regions suitable for wheat, albeit not as favourable as that for wine grapes. Also, the areas with a potential for wheat farming scored between 0.6 - 0.7, necessitating further inspection.

When investigating areas suitable for tomatoes, only a few cells at the base of some prominent hills were identified. These areas scored between 0.6 - 0.7, indicating possibilities for the cultivation of tomatoes. Together with the limited area available for tomato cultivation, it might not be financially viable to plant this crop. Although onions competed well against tomatoes, slight differences in the weights of the parameters favoured tomatoes.

Considering the above discussion, Figure 4.7 (b) gives a more accurate depiction of the catchment's potential for the cultivation of the aforementioned crops. However, no economic evaluation has been undertaken in this study, thereby necessitating further analysis of suitable areas before landuse planning can occur. As mentioned earlier, both the FAO (1976) and Rossiter (1995) support the concept of economic evaluation strongly. For example, although some areas obtained the highest fuzzy score for potatoes, wine grapes competed well in these areas with fuzzy scores of between 0.7 - 0.9. Given that wine grapes is a high-income crop when compared to potatoes, it would probably be more appropriate to opt for the former, rather than the latter.

Holistically seen, the study area's biggest limitation for all the landuses investigated would be the unfavourable texture of the first two soil horizons, where large areas were deemed unsuitable. These textural limitations will influence the soils' water holding capacity, nutrients available to the plant, and ability to support the plant amidst strong winds.

Due to data restrictions, only nine parameters were included. This limitation should be considered when interpreting results. A fuzzy score surpassing 0.6 indicates that, as far as the nine parameters are concerned, the area is suitable for cultivation of that crop. Still, areas with high potential should be further investigated, as parameters such as organic material, soil structure and cation exchange capacity (CEC) were not included. Potential influences of wind and the generality of the soil map should also be investigated, and additional soil samples in the high potential areas will provide considerable insight into those areas' characteristics.

4.3 RESULTS VALIDATION THROUGH COMPARISON

The results of the fuzzy land evaluation were verified by comparing it to current landuses in the area. These activities were obtained from a 1:50 000 map of the area (South Africa 2000) and expert knowledge (Louw 2004 pers comm.). According to Louw (pers comm. 2004), large areas towards the south of the study area are under wheat cultivation. He provided names for these farms, and their spatial extents were then digitized from the 1:50 000 map. The spatial occurrence of vegetables was done in a similar manner. The assumption is that, if a crop is cultivated in the area, it is probably financially viable to invest in that practice, and should therefore have obtained a fuzzy score of 0.6 or higher. Hence, a concurrence between the current and proposed landuse would indicate correct application of fuzzy land evaluation to the region. Figure 4.8 shows the location of some of the current farming activities in the area, overlain on the suitability map (Louw pers comm. 2004).

When comparing the current vegetable farming activities with the suitability map, the results indicate that the area would be more suitable for wheat than for vegetables. Of the three vegetable crops considered, the area achieved the highest score for potatoes with 0.6 - 0.7, suggesting that the region is fairly suitable for the cultivation of this crop (see Figure 4.6). Although both wheat and potatoes obtained a score of 0.6 - 0.7, wheat had a slight advantage (0.63 versus the 0.62 of potatoes). Therefore, the fuzzy prediction that the area is fairly suitable for vegetables, are supported by current practices.

On the other hand, significant differences were prevalent when comparing the current wheat growing areas to the suitability map. Some areas correspond well to the current practices, while other areas, suitable for wheat cultivation, are not yet utilized. However, apart from current agricultural practices, the types of landuse in these areas had not been identified in this study. Therefore, there is a possibility that it could not be available for agricultural purposes.

Figure 4.8 Current farming activities in the catchment overlain on the suitability map

In addition, wheat cultivation currently occurs in areas not deemed suitable for this crop. These areas achieved a fuzzy score of 0.4 - 0.5 (see Figure 4.2). One possible explanation could be that the fuzzy implementation was overly conservative with regards to the input parameters, and that these areas could easily obtain a higher score with more relaxed constraints. It should also be noted that the parameter cut-off values were chosen so as to represent the area's membership to the S1-class (FAO 1976). Consequently, a lower value in the S1-class would inevitably be a higher value in the S2-class, its follow-up. Another reason for the mismatch could be that, although the area did not perform well with regards to the nine parameters evaluated, additional parameters such as organic material or cation exchange capacity (CEC) could be more favourable, thereby shifting the area into a higher category. Additionally, a lack of accurate large-scale data could have had an influence on the fuzzy process, thus influencing the outcome of the operation.

Further investigation of the current wheat farming activities reveal that parts of them are situated on soil units deemed more appropriate for the cultivation of potatoes. These units obtained a fuzzy score of 0.7 - 0.8 for wheat, but 0.8 - 0.9 for potatoes. Evidently, these areas are also suitable for wheat cultivation, albeit not as well as for potatoes. There is thus a good correspondence between the current situation and the suitability map.

In conclusion it is noticeable that, even though limited validating data were available, fuzzy results obtained reflected the current agricultural practices well. Some areas with higher fuzzy scores are currently under cultivation, although these areas appear to be more suitable for alternative crops. However, as mentioned before, this assessment gives no indication of any economic implications. It could very well be that the current landuse is financially more viable than the proposed landuse. An assessment of the consumer demand also needs to be incorporated before a final development decision can be made.

CHAPTER 5: CONCLUSION OF THE FUZZY LAND EVALUATION AND RECOMMENDATIONS

Sustainable development is a paradigm shift from a pure expansion viewpoint, with little or no planning on the use of natural resources, to a more holistic approach whereby preservation of the natural resources for future generations are acknowledged. South Africa has committed itself to this notion, giving rise to a more complex planning environment. Future planning should now consider more aspects surrounding the optimal and sustainable use of natural resources than was practiced in the past.

One aspect of this environment that deserves special attention is the “crucial” role of agriculture in sustainable development, as mentioned by the Department of Agriculture (1996:vi). Moreover, as South Africa is poorly endowed with high quality agricultural land, added efforts should be made to protect this land for agricultural purposes (DoA 1995:13). With the Western Cape being home to nearly 75% of South Africa’s medium-potential arable land, this province is an integral part of the country’s economy. Therefore, decisions regarding development in the province should be taken only after thorough studies and careful consideration.

These studies, however, can become quite complex and intricate, necessitating the use of appropriate tools or guidelines. One such tool developed by the Food and Agricultural Organisation of the United Nations (FAO 1976), is land evaluation, and it is fundamental in land-use planning. In land evaluation, a tract of land or region is evaluated for a number of landuses, resulting in separate smaller units, each with a qualitative term awarded to it. This term reflects the unit’s suitability to accommodate that landuse, and the unit is evaluated for all the landuses.

One such case where complex decisions are involved, and where land evaluation proved invaluable, is the G21B catchment on the West Coast of South Africa. The catchment forms part of the Atlantis Growth Corridor (AGC), an area approximately 20km north of Cape Town and that is seen as a long-term growth axis for the Cape Metropolitan Region. Conflicting opinions exist regarding the area’s agricultural potential and how it should be developed. Some believe that there is significant agricultural potential (CMC 1997), while others disagree and are of the opinion that the area is suitable to absorb metropolitan growth (CMC 1998). There are also different opinions regarding the type of agriculture that should be practiced and where it should be located. Therefore, land evaluation was appropriate to use as it was developed with this type of scenario in mind.

A special case of land evaluation, namely the fuzzy approach, was applied in this study. In this approach, the conventional rigid boundaries of the original land evaluation that divides the land into discrete classes, was replaced by a membership score ranging from 0 to 1. The value of '0' indicates that the area is totally unsuitable for the landuse, and the value of '1' specifies that the landuse can be fully accommodated in the area. Thus, each cell in the catchment received a fuzzy score for each landuse, indicating the degree of membership of each landuse.

5.1 REVISITING THE AIM AND OBJECTIVES

The aim of this thesis was to apply the land evaluation principles within a fuzzy framework to the catchment, and to compile a final suitability map regarding development potential in the area. Specific objectives were followed to attain this goal.

Objective one saw the identification of nine parameters to portray the area's characteristics, specifically texture of the first three soil horizons (if present), coarse fragments in the top soil, wetness, weathered rock, average pH, effective root depth and slope. These parameters were obtained from an existing soil map and DEM of the area. In the second objective, some agricultural landuses for the area were identified as being wine grapes, wheat, onions, potatoes, tomatoes and citrus. The requirements of these landuses were obtained from the literature and expert opinion. These requirements were subsequently used to determine the cut-off values for the membership functions, which were decided upon and applied in the third objective. The area was evaluated for each crop and awarded a fuzzy score. In objective four, the results were validated by comparing it to current landuses in the area, where after the final agricultural suitability map could be composed in the last objective.

5.2 CONCLUSION AND RECOMMENDATIONS

In evaluating the G21B catchment, the results have shown that some areas exist with fairly high agricultural potential. The area shows some promising potential for agricultural activities that correspond to the findings of the CMC (1997), but there are also areas with little to no agricultural potential that would be suitable to absorb metropolitan growth, as suggested by the CMC (1998). With regards to the type of agriculture that can be practiced, the results verified that there are indeed areas suitable for the cultivation of wine grapes, as suggested by Ellis & Schloms (1999), but that these areas are more extensive than originally predicted. Additionally, there are also extensive areas suitable for the cultivation of wheat and potatoes. Furthermore, limited areas suitable for citrus development should also further be explored. Most of the soils with agricultural potential are still under shrub land, fynbos, bush land, and thicket, with a number of areas not available for agriculture due to urbanization (see Figure 5.1).

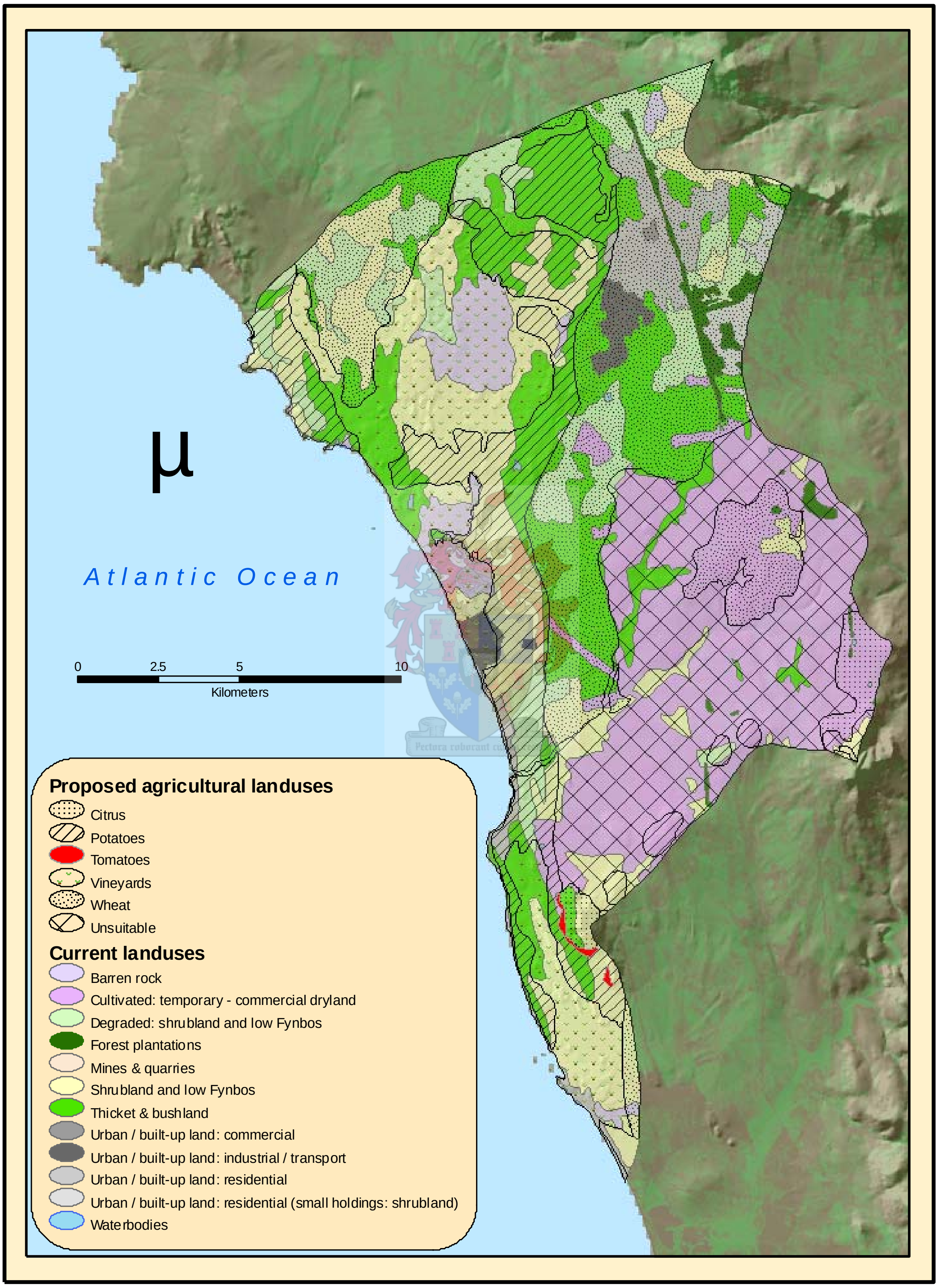


Figure 5.1 Proposed agricultural landuses overlain on current landuses

As mentioned elsewhere, the area's suitability was determined at the hand of nine parameters, and more detailed studies are necessary in order to refine the areas with true potential. This would include a more detailed soil sampling technique within the high potential areas, as well as the inclusion of additional parameters to give a more comprehensive description of the soils' character. Average wind speed within seasons should also be included in this study. This could be included in the fuzzy land evaluation as one of the parameters and would contribute to the accuracy thereof.

Burrough (1989) and Malczweski (2002) found that the fuzzy approach to land evaluation provided more insightful results than would the Boolean approach. Landuses can be better compared in a quantitative manner, and reasons for different scores can be identified more clearly, thereby indicating which problematic attributes could be resolved more easily than others. In this fuzzy land evaluation, the different parameters were assessed in concert as suggested by Triantafilis, Ward & McBratney (2001), rather than individually by separate rules. A further refinement to the evaluation could be the inclusion of economic parameters or an economic evaluation as follow-up. By performing an economic evaluation, a better picture for possible development can be obtained, and better financial decisions can be made. From a sustainable development point of view, a number of suitable crops can be included and the most sustainable crop, yet still financially viable, could be decided upon.

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APPENDICES

A. Parameters for all six crops

B. Pair-wise comparison matrix for the parameter values of all six crops

APPENDIX A: Parameters for all six crops

Wine grapes

Soil property	**Type of function**	**Lower cross-over value**	**Central value**	**Upper cross-over value**	**Value of *a***
Horizon 1: sand %	S	50	65	80	0.0044
Horizon 1: clay %	S	10	15	20	0.04
Horizon 1: silt %	S	0	25	50	0.0016
Horizon 2: sand %	S	20	49.5	79	0.0011
Horizon 2: clay %	S	15	22.5	30	0.0178
Horizon 2: silt %	S	0	26	52	0.0015
Horizon 3: sand %	S	20	49.5	79	0.0011
Horizon 3: clay %	S	15	22.5	30	0.0178
Horizon 3: silt %	S	0	26	52	0.0015
pH	S	80	100	120	0.0025
Rootdepth	A	5.0	6.0	7	1.00

Wheat

Soil property	**Type of function**	**Lower cross-over value**	**Central value**	**Upper cross-over value**	**Value of *a***
Horizon 1: sand %	S	50	60	70	0.01
Horizon 1: clay %	S	15	17.5	20	0.16
Horizon 1: silt %	S	0	25	50	0.002
Horizon 2: sand %	S	0	39.5	79	0.00064
Horizon 2: clay %	S	20	30	40	0.01
Horizon 2: silt %	S	0	36	72	0.00077
Horizon 3: sand %	S	0	39.5	79	0.00064
Horizon 3: clay %	S	20	30	40	0.01
Horizon 3: silt %	S	0	36	72	0.00077
pH	S	5.0	6.0	7.0	1
Rootdepth	A	30	50	50	0.0025

Citrus

Soil property	Type of function	Lower cross-over value	Central value	Upper cross-over value	Value of *a*
Horizon 1: sand %	S	50	65	80	0.0044
Horizon 1: clay %	S	10	15	20	0.0400
Horizon 1: silt %	S	0	25	50	0.0016
Horizon 2: sand %	S	45	62.5	80	0.0033
Horizon 2: clay %	S	10	25	40	0.0044
Horizon 2: silt %	S	0	25	50	0.0016
Horizon 3: sand %	S	45	62.5	80	0.0033
Horizon 3: clay %	S	10	25	40	0.0044
Horizon 3: silt %	S	0	25	50	0.0016
pH	S	5.25	6.25	7.25	1.0000
Rootdepth	A	50	80	80	0.0011

Onions

Soil property	Type of function	Lower cross-over value	Central value	Upper cross-over value	Value of *a*
Horizon 1: sand %	S	50	65	80	0.0044
Horizon 1: clay %	S	10	15	20	0.04
Horizon 1: silt %	S	0	25	50	0.0016
Horizon 2: sand %	S	50	65	80	0.0044
Horizon 2: clay %	S	10	15	20	0.04
Horizon 2: silt %	S	0	25	50	0.0016
Horizon 3: sand %	S	50	65	80	0.0044
Horizon 3: clay %	S	10	15	20	0.04
Horizon 3: silt %	S	0	25	50	0.0016
pH	S	5.8	6.8	7.8	1.00
Rootdepth	A	25	30	35	0.04

Tomtatoes

Soil property	Type of function	Lower cross-over value	Central value	Upper cross-over value	Value of *a*
Horizon 1: sand %	S	50	65	80	0.0044
Horizon 1: clay %	S	10	15	20	0.04
Horizon 1: silt %	S	0	25	50	0.0016
Horizon 2: sand %	S	50	65	80	0.0044
Horizon 2: clay %	S	10	15	20	0.04
Horizon 2: silt %	S	0	25	50	0.0016
Horizon 3: sand %	S	50	65	80	0.0044
Horizon 3: clay %	S	10	15	20	0.04
Horizon 3: silt %	S	0	25	50	0.0016
pH	S	6.0	7.0	8.0	1.00
Rootdepth	A	30	50	50	0.0025

Potatoes

Soil property	**Type of function**	**Lower cross-over value**	**Central value**	**Upper cross-over value**	**Value of *a***
Horizon 1: sand %	S	50	65	80	0.0044
Horizon 1: clay %	S	10	15	20	0.04
Horizon 1: silt %	S	0	25	50	0.0016
Horizon 2: sand %	S	50	65	80	0.0044
Horizon 2: clay %	S	10	15	20	0.04
Horizon 2: silt %	S	0	25	50	0.0016
Horizon 3: sand %	S	50	65	80	0.0044
Horizon 3: clay %	S	10	15	20	0.04
Horizon 3: silt %	S	0	25	50	0.0016
pH	S	4.5	5.5	6.5	1.00
Rootdepth	A	30	50	50	0.0025

APPENDIX B: Pair-wise comparison matrix for the parameter values of all six crops, including consistency ratios

Wine grapes									
	hor1	hor2	hor3	pH	root depth	weathered rock	wetness	coarse fragments	slope
hor1	1								
hor2	5	1							
hor3	3	1/3	1						
pH	7	3	5	1					
rootdepth	5	1	3	1/3	1				
weathered rock	1	1/5	1/3	1/7	1/5	1			
wetness	7	3	5	1	3	7	1		
coarse fragments	3	1/3	1	1/5	1/3	3	1/5	1	
slope	1	1/5	1/3	1/7	1/5	1	1/7	1/3	1

Consistency ratio: 0.02

Wheat									
	hor1	hor2	hor3	pH	root depth	weathered rock	wetness	coarse fragments	slope
hor1	1								
hor2	1/3	1							
hor3	1/7	1/5	1						
pH	1	3	7	1					
rootdepth	1/5	1/3	3	1/5	1				
weathered rock	1/7	1/5	1	1/7	1/3	1			
wetness	1/3	1	5	1/3	3	5	1		
coarse fragments	1/3	1	5	1/3	3	5	1	1	
slope	1/5	1/3	3	1/5	1	3	1/3	1/3	1

Consistency ratio: 0.02

Citrus

	hor1	hor2	hor3	pH	root depth	weathered rock	wetness	coarse fragments	slope
hor1	1								
hor2	1/3	1							
hor3	1/5	1/3	1						
pH	1/3	1	3	1					
rootdepth	1/5	1/3	1	1/3	1				
weathered rock	1/9	1/7	1/5	1/7	1/5	1			
wetness	1/5	1/3	1	1/3	1	5	1		
coarse fragments	1/9	1/7	1/5	1/7	1/5	1	1/5	1	
slope	1/9	1/7	1/5	1/7	1/5	1	1/5	1	1

Consistency ratio: 0.03

Onions

	pH	coarse fragments	root depth	slope	hor1	hor2	hor3	weathered rock	wetness
pH	1								
coarse fragments	1/3	1							
rootdepth	1/7	1/5	1						
slope	1/7	1/5	1	1					
hor1	5	7	9	9	1				
hor2	3	5	7	7	1/3	1			
hor3	1/3	1	5	5	1/7	1/5	1		
weathered rock	1/3	1	5	5	1/7	1/5	1	1	
wetness	5	5	7	3	1	1	5	7	1

Consistency ratio: 0.06

Tomatoes

	hor1	hor2	hor3	pH	root depth	weathered rock	wetness	coarse fragments	slope
hor1	1								
hor2	1/3	1							
hor3	1/7	1/5	1						
pH	1/5	1/3	3	1					
rootdepth	1/9	1/7	1/3	1/5	1				
weathered rock	1/7	1/5	1	1/3	3	1			
wetness	1	3	7	5	9	7	1		
coarse fragments	1/9	1/7	1/3	1/5	1	1/3	1/9	1	
slope	1/9	1/7	1/3	1/5	1	1/3	1/9	1	1

Consistency ratio: 0.04

Potatoes									
	hor1	hor2	hor3	pH	root depth	weathered rock	wetness	coarse fragments	slope
hor1	1								
hor2	1/7	1							
hor3	1/9	1/7	1						
pH	1/3	5	7	1					
rootdepth	1/7	1	3	1/5	1				
weathered rock	1/7	1	3	1/5	1	1			
wetness	1	7	9	3	7	7	1		
coarse fragments	1/3	5	7	1	5	5	1/3	1	
slope	1/5	3	5	1/3	3	3	1/5	1/3	1

Consistency ratio: 0.05