AGROCLIMATIC RESPONSE MAPPING FOR SUGARCANE PRODUCTION IN SOUTHERN AFRICA

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Submitted in partial fulfilment of the requirements for the degree of
MSc in Hydrology

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March 2008

ABSTRACT

As is the case in many other regions in the world, sugarcane production in southern Africa is affected by a wide range of climatic conditions, which can vary considerably from location to location and from year to year. As a result, the season length and growth cycles of sugarcane in southern Africa differ greatly. Such conditions include the hot and dry regions of northern KwaZulu-Natal, Swaziland and Mpumalanga, where sugarcane is mostly irrigated, to the humid sub-tropical coastal belt extending from the far north coast of KwaZulu-Natal to areas in the Eastern Cape, as well as the cool frost prone midlands regions of KwaZulu-Natal. Owing to the wide range of climatic conditions in which sugarcane is grown in southern Africa, there are many different external factors that affect sugarcane production, including a range of pests and diseases, frost occurrences and variations in soil water. The objective of this research was to (1) identify a number of important variables that affect cane production in southern Africa, (2) employ suitable models to reflect these variables, and (3) simulate and map the extent and severity of these variables at a high spatial resolution over southern Africa. Such variables include the *Eldana saccharina* and *Chilo sacchariphagus* stalk borers, sugarcane rust fungus, heat units with selected base temperatures, frost, soil water content, soil compaction, irrigation water demand, conducive and non-conducive growing conditions, flowering proficiencies for sugarcane, sugarcane yields and yield increments per unit of irrigation.

The distribution patterns of the above-mentioned variables relied greatly upon the various models employed to represent them, as well as the accuracy of the temperature and rainfall databases to which the various models were applied. Although not definitive, the models used to reflect the variables which had been identified were considered to be generally satisfactory. The resolution at which the variables which had been identified in this study were mapped, was also found to be adequate.

PREFACE

The work described in this dissertation was carried out in the School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu-Natal, Pietermaritzburg, from January 2005 to December 2007, under the supervision of Professor R.E. Schulze.

These studies represent original work by the author and have not otherwise been submitted in any form for any degree or diploma to any university. Where use has been made of the work of others it is duly acknowledged in the text.

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ACKNOWLEDGEMENTS

The author wishes to express his sincere appreciation and gratitude to the following people and institutions for the assistance rendered during this study:

Professor R.E. Schulze, School of Bioresources Engineering and Environmental Hydrology, for supervising this project and providing invaluable assistance throughout the duration of this study,

Dr C.N Bezuidenhout, School of Bioresources Engineering and Environmental Hydrology, for his co-supervision and vast knowledge in the field of sugarcane, which aided considerably in carrying out this study,

Mrs M. Maharaj, Mr. T, G. Lumsden and Mr. S.L.C Thornton-Dibb, School of Bioresources Engineering and Environmental Hydrology, for all their assistance in programming, modelling and mapping,

Professor P.W.L. Lyne and the staff at the South African Sugarcane Research Institute, for all their support and advice throughout this study,

The School of Bioresources Engineering and Environmental Hydrology, for providing the working environment and resources making this study possible, as well as the South African Sugarcane Research Institute, for funding and supporting this project,

To my friends, for all the encouragement and good times I have had during my days at University,

To Dad, Mom and family, Gregory, Andrew and Jilly, for all the support, encouragement, prayer and sacrifices made throughout my time at University-words cannot express my gratitude to you,

To my Lord and Saviour, thank you for providing me with the opportunity and giving me the ability to study, as without you none of what I have accomplished would have been possible.

Do not be anxious about anything, but in everything, by prayer and petition, with thanksgiving, present your requests to God. And the peace of God, which transcends all understanding, will guard your hearts and your minds in Christ Jesus.

Philippians 4 vs 6&7

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1. INTRODUCTION

The South African sugar industry is one of the most cost competitive producers of high quality sugarcane in the world (SASJ, 2007). The industry produces an average of around 2.5 million tons of sugar per season, of which approximately 50% is exported to markets in Africa, the Middle East, North America and Asia, generating an annual average direct income of approximately R6 billion (SASJ, 2007). In addition to this the sugar industry creates about 77 000 direct jobs, with a further 350 000 jobs being created indirectly. Approximately one million people depend on the sugar industry for a living (SASJ, 2007). The sugarcane growing sector is comprised of approximately 45 300 registered growers who farm predominantly in KwaZulu-Natal and Mpumalanga and, to a lesser extent, in the Eastern Cape (Anon, 2007).

As is the case in many other regions in the world, sugarcane production in southern Africa is affected by a wide range of climatic conditions, which can vary considerably from location to location and from year to year. As a result, the season lengths and growth cycles of sugarcane in southern Africa vary greatly. The climatic conditions include the hot and dry regions of northern KwaZulu-Natal, Swaziland and Mpumalanga, where sugarcane is largely irrigated (Statistics SA, 2002), the humid sub-tropical coastal belt extending from the far north coast of KwaZulu-Natal to areas in the Eastern Cape, as well as the cooler frost prone midlands regions of KwaZulu-Natal. With this wide range of climatic conditions under which sugarcane is grown in South Africa, many different external factors affect sugarcane production, including a range of pests and diseases, frost occurrences and various conditions of soil water.

In order to aid in assessing the effects of the different climatological variables on various agricultural and hydrological processes, Schulze (1997) published the "South African Atlas of Agrohydrology and -Climatology." This publication has been widely used in the agricultural sector (e.g. Bezuidenhout and Gers, 2002; Walker and Schulze, 2006). Since its publication, databases of rainfall and temperature have been expanded (Lynch, 2004; Schulze and Maharaj, 2004) and an updated and extended atlas has been produced (Schulze, 2007a), *viz*. the "South African Atlas of Climatology and Agrohydrology", published in 1997. Many relationships between climate and sugarcane production, as well as sugarcane specific pests and diseases, were not included in either of the two Atlases. Therefore, the South African Sugarcane Research Institute (SASRI) decided to fund a research project with the aim of producing an agrohydrological atlas in which factors affecting the growth and production of sugarcane in southern Africa were the main focus. The southern African region, in the context of this study, comprises of South Africa, Swaziland and Lesotho. The research conducted in this dissertation is contributing to this SASRI project. The main objectives of this dissertation are to:

- identify a number of important variables that affect sugarcane production in South Africa,
- employ suitable models to represent these variables, and
- simulate and map the extent and severity of these variables at a high spatial resolution over southern Africa.

The variables selected include:

- heat units,
- frost,
- *the Eldana saccharina* stalk borer,
- *the Chilo sacchariphagus* stalk borer,
- rust fungus,
- soil water content,
- soil compaction,
- irrigation water demand,
- conducive and non-conducive growing conditions,
- flowering proficiencies of sugarcane, and
- sugarcane yields.

A general introduction and background to a number of the variables considered in this dissertation is provided in Chapter 2 by way of a description of the agronomy, crop protection and harvesting of sugarcane in southern Africa. In Chapter 3 a review of the development of the temperature and rainfall databases (Lynch, 2004; Schulze and Maharaj, 2004) is given, followed by a description of the development of the spatio-temporal database used, *viz*. the southern African Quaternary Catchments Database (Hallowes *et al*., 2004; Schulze *et al*., 2007a), and the *ACRU* agrohydrological model (Schulze, 1995). Second order derivatives of temperature, including heat units and severe cold conditions are described and mapped in Chapter 4, followed by Chapter 5 in which climate based constraints in regard to pests and diseases are described and distributions mapped. Mapping soil water related constraints and potentials to sugarcane production in southern Africa are addressed in Chapter 6, while in Chapter 7 the mapping of cane yield estimates is undertaken. Chapter 8 contains a discussion of results, conclusions are drawn and finally recommendations for future research are made.

2. A DESCRIPTION OF SUGARCANE AGRONOMY, CROP PROTECTION AND HARVESTING

2.1 Introduction

Successful sugarcane farming in southern Africa depends upon correct agronomic practices as well as efficient harvesting and crop protection strategies. Identifying factors that promote and/or limit sugarcane production may potentially improve the management of the system and could significantly increase production rates.

As a result of the wide range of climatic variability experienced in southern Africa, the conditions under which sugarcane is grown varies greatly. Variables that affect the growth and production of sugarcane in southern Africa, including the influences of temperature and rainfall on both sugarcane plant growth and on pests and diseases affecting plant growth have, for the purposes of this dissertation, been broken up into a four categories, *viz*.

- second order derivatives of temperature,
- climate based constraints to sugarcane growth with regard to pests and diseases,
- soil water related constraints and potentials affecting sugarcane plant growth, and
- yield estimates.

A literature review relating to a number of pests and diseases, as well as to soil water related constraints and potentials affecting sugarcane plant growth, are addressed in this chapter. Each of the issues introduced in this chapter will be considered in greater detail in subsequent chapters.

2.2 Climate Based Constraints to Sugarcane Growth with Regard to Pests and Diseases

Correct control of pests and diseases in the southern African sugarcane industry is essential for successful crop production. Within the industry there are a number of pests and diseases that have the potential to cause significant yield losses. These include the *Eldana saccharina* stalk borer, the *Chilo sacchariphagus* stalk borer and the rust fungus.

2.2.1 The *Eldana saccharina* Stalk Borer

The stalk borer *Eldana saccharina* Walker, hereafter referred to as eldana, has been classed as one of the most serious sugarcane pests in southern Africa, causing substantial losses in sugarcane yield (Carnegie *et al*., 1976). Eldana is indigenous to southern Africa and can be found in a range of weeds and grasses (Carnegie and Smaill, 1980). It has, however, been found that the insect targets older or more mature and stressed plants. It is for this reason that eldana, although being a major problem in sugarcane, is not as big a problem in seed crops such as maize, where losses relative to those in sugarcane are small as a result of their comparatively short growing season (Cochereau, 1982).

2.2.1.1 History of eldana outbreaks in South Africa

The first documented outbreak of eldana in South Africa occurred in 1939 in parts of northern KwaZulu-Natal (Atkinson *et al*., 1981). This outbreak lasted approximately 10 to 13 years. Then between 1953 and 1969 no serious infestations of the pest were recorded. However, in the 1970s a second outbreak of eldana was recorded, once again in northern KwaZulu-Natal. This outbreak was more permanent, resulting in the pest spreading to other coastal regions. Numbers were, however, limited in the cooler, higher altitude areas (Atkinson *et al*., 1981).

Outbreaks of eldana in Swaziland were first recorded in the early 1970s, and eldana has since become a dominant pest in that countrys' sugar industry (Carnegie *et al*., 1976). It was not until the 1990s that eldana was recorded in Zimbabwe. In March 1999 a severe outbreak occurred in the Lowveld regions of Zimbabwe (Mazodze *et al*., 1999), which suggests that the pest is spreading.

2.2.1.2 The eldana life cycle

Eldana starts its life cycle as eggs, which are laid on the underside of plant leaves where they are fairly well protected. Once the eggs have hatched the larvae scavenge for approximately two weeks, after which they bore into the stalk of a mature sugarcane plant, normally at the leaf primodia and new buds. The rest of the larval stage is spent in the stalk, during which time they feed on the softer plant tissue. It is during this stage that the majority of damage to the crop is done. The next life stage is known as the pupae stage. The larvae exit the stalk and pupate by spinning a tough silken cocoon in the area under the leaf sheath. This stage is followed by the moth stage. Adult moths emerge from the cocoons and immediately begin mating on the night of their emergence. For three nights after emergence, moths actively lay their eggs. During the day the moths go into hiding in the dead sugarcane trash beneath the cane canopy (Atkinson, 1981; Hearne *et al*., 1994).

2.2.1.3 Quantifying eldana activity

In order to assess the amount of damage caused by the eldana stalk borer, it is important to quantify and understand factors affecting eldana activity. Way (1994) confirmed that temperature was one of the main drivers of eldana activity, affecting mating success, adult female longevity, oviposition and egg development. It was found that with an increase in temperature, there was a general increase in the activity levels of eldana. This increase in activity, however, peaked at a certain threshold temperature, beyond which a reduction in insect activity was observed. The effects of temperature on eldana may be seen in Table 2.1, where the number of eggs laid, as well as the number of eggs that hatched, were recorded for four different temperatures. From the table it may be seen that at certain temperatures the number of eggs laid and hatched increased. By identifying the temperatures when eldana reproduction is increased, it is possible to predict, according to temperature thresholds (given in Section 5.2.1), where eldana outbreaks are most likely to occur.

The length of time (*i.e.* physiological time) for eldana to complete a particular life stage is governed by temperature, and can be measured in heat units i.e. degree days (Horton *et al.,* 2001). Values for the different threshold temperatures and accumulated heat units (in degree days, ºC.d) for each of the eldana life stages are given in Table 2.2. Below these threshold temperatures, eldana goes into a state of dormancy.

Table 2.1 Eldana egg hatching rates at different temperatures (Way, 1994)

Temperature (ºC)	Number of Females	Eggs per Female	Number of Eggs Hatched	% of Eggs Hatched
15	45	9 260	0	0.0
20	38	15 847	8 715	54.9
25	104	45 015	22 178	49.3
35	89	16 304	0	0.0

Table 2.2 Stage specific threshold temperatures required for eldana development (Horton *et al*., 2001)

Life stage	Threshold temperature (ºC)	Approximate duration (ºC.d)
Eggs	5.3	102 - 136
Small larvae	10.2	185 - 253
Large larvae	11.7	371 - 439
Pupae	10.7	120 - 200

Meyer and Wood (2001) found that the probability of eldana outbreaks is increased with application of nitrate (N) fertilizers. The level of fertilizer application is, therefore, an important factor to consider when assessing eldana activity. The effect of N application on eldana populations may be seen in Figure 2.1 (Meyer and Wood, 2001). From this illustration it becomes evident that by increasing the N application up to 160 kg N/ha, eldana counts increased substantially; however, beyond this application amount the number of eldana counts decrease.

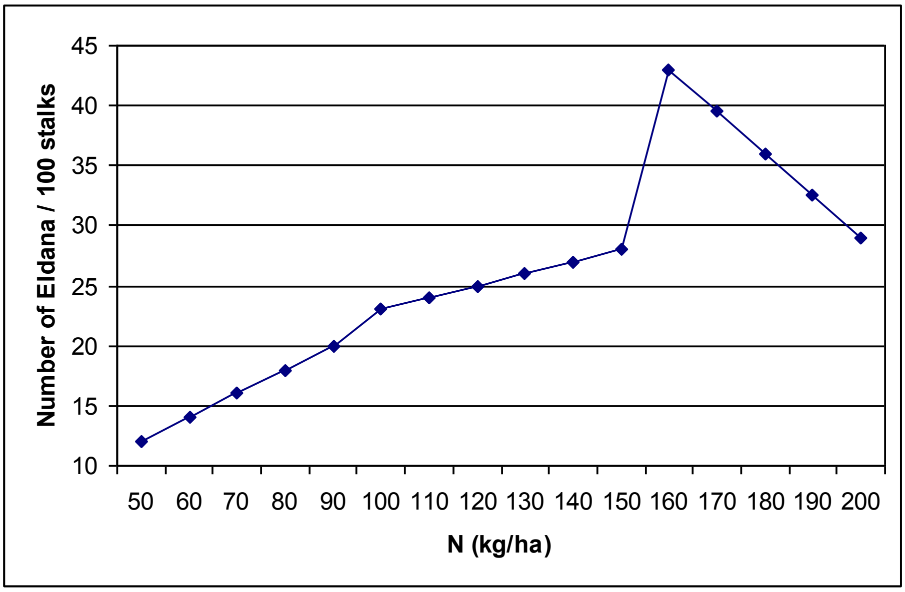

Figure 2.1 Relationship between the number of eldana larvae per 100 stalks and the level of nitrogen application (after Meyer and Wood, 2001)

2.2.1.4 Control methods for eldana

In order to effectively control eldana, an Integrated Pest Management Strategy (IPMS) is needed (Webster *et al.*, 2005). The suggested IPMS combines biological control, host plant resistance and appropriate farm management practices. An appropriate IPMS would include (Webster *et al.*, 2005):

- Cutting the sugarcane at an early age (12 months),
- Applying reduced nitrogen levels,
- Practising good field hygiene by removing host plant materials,
- Pre-trashing, i.e. removing trash from the sugarcane stalk between the months of August and October,
- Planting low risk sugarcane varieties, and
- Controlled pesticide applications.

Webster *et al.* (2005) state that the adoption of the above-mentioned IPMS has been problematic, due mainly to a lack in information, training and legislation governing IPMS in southern Africa. Likely distribution patterns of eldana are mapped and discussed in Section 5.2.

2.2.2 The Chilo *sacchariphagus* Stalk Borer

The sugarcane borer *Chilo sacchariphagus*, hereafter referred to as chilo, has the potential to cause substantial yield losses on the north coast of South Africa and in Mozambique (Way and Turner, 1999). The threat of this pest to the sugar industry makes it an important pest to consider.

2.2.2.1 History of chilo

Chilo has been recorded in Indonesia, Singapore, Malaysia, Philippines, India, Taiwan, China, Madagascar, Mauritius and Reunion, and more recently in Mozambique (Way and Turner, 1999). In August 1998, larvae of the chilo pest were collected and identified in sugarcane fields at Mafambisse estate in Mozambique. However, unpublished reports of the pest indicate that chilo had been present in Mozambique for at least eight years prior to the 1998 identification.

2.2.2.2 Biology of chilo

Chilo adults mate at dusk on the night that they emerge. The moths then lay their eggs on the sugarcane leaves at night, with between 300 and 850 eggs being laid per moth. Plant damage initially occurs on the leaf midrib or on the leaf blade, caused by emerging larvae. The larvae damage show characteristic ‘windows’ on the host leaves where leaf material has been eaten away. After a period of time, older larvae bore into the side of shoots of younger plants, resulting in damage to the growth tip of the sugarcane which, in some cases, will lead to the eventual death of the growing plant. Damage in the older cane occurs to the tissue below the growing point. This may result in side shooting or stalk destruction if extensive tunnelling occurs (Way and Turner, 1999).

Similar to eldana, temperature is one of the main drivers of chilo activity, affecting mating success, pest longevity, oviposition and egg development. Goebel (2006) found that chilo eggs would only hatch if the temperature was above 13 °C, pupa would only develop at temperatures above 12.7 °C and that mating would only occur when night temperatures were above 15 °C. Distribution patterns of chilo, according to a number of the specific temperature requirements of the pest, are mapped and discussed in Section 5.3.

2.2.3 The Rust Fungus

Rust, caused by *Puccinia melanocephela,* was first recorded in the South African sugar industry in 1941 (Ryan and Egan, 1989). The origin of the rust fungus in South Africa is not known. However, it is postulated that common rust originates from India. As a result of the above-mentioned outbreak, which extended into the 1950s, it is estimated that enough wind-borne rust spores were produced to infect the whole of southern Africa. Since this outbreak, rust has been found in Mozambique, Zimbabwe, Zambia, Malawi, Tanzania, Kenya and Uganda. Common rust is likely to be present in virtually all sugarcane growing countries in the future (Ryan and Egan, 1989).

2.2.3.1 Symptoms of rust

Early symptoms of rust occur upon the leaves of the infected plant, where small, elongated yellowish spots are visible on the top and underside of the leaf blade. With time these spots increase in size along the length of the leaf, and thereafter turn a red-brown to brown colour. A narrow, pale-green boundary then develops around the infected areas. In cases where a severe rust infestation occurs, affected crops take on a distinctive rusty to brown colour, which can be confidently identified from a distance (Purdy *et al.*, 1983). An example of different degrees of rust infection is shown in Figure 2.2, with more highly infected leaves on the left.

As a result of rust infections, the ability with which the plant is able to photosynthesise and, therefore, grow is limited. In the long term this will affect the potential yield of a crop. These effects are as a consequence of wilting of leaves, death of leaf tips and accelerated death of leaves in general (Ryan and Egan, 1989). Generally, rust is most severe in younger sugarcane, specifically from planting to 6 months (Comstock and Ferreira, 1986). It is also noted by Ryan and Egan (1989) that the susceptibility of sugarcane to the infection of rust decreases with sugarcane age.

Figure 2.2 Rust infected sugarcane leaves (Anon, 2005)

2.2.3.2 Transmission of rust

Rust pathogens are primarily transmitted by wind and water-splash, with wind being the more dominant means of spread. It is hypothesised that the spread of rust internationally is a result of wind currents carrying urediniospores. Wind is also the primary means in which rust is spread on a smaller scale, from field to field (Raid and Comstock, 1991).

The rate at which rust is able to spread is largely dependent on climatic conditions of the area in which the dispersal is occurring. Studies have shown that the rate at which rust is able to spread depends largely upon temperature and humidity (Ryan and Egan, 1989).

2.2.3.3 Control

There are a number of methods suggested to control rust. These include planting rust resistant varieties of sugarcane, the use of selected fungicides, applying irrigation and the careful selection of planting and ratooning dates (Raid and Comstock, 1991).

Fungicides are effective in the control of rust. However, research has shown, through a cost benefit analyses, that in many cases the use of fungicides is not economically viable (Ryan and Egan, 1989). They are therefore not used extensively as a means of rust control. The effects of rust on infected plants are amplified when the plant is stressed. It is for this reason that irrigation has been identified as a means of control. By irrigating a crop, the likelihood of stress is reduced and, therefore, the plants susceptibility to rust infection is also reduced. Careful selection of planting dates is another means by which rust infections can be reduced, such as planting during times that are not conducive to rust infection, reduces the chances of infection (Ryan and Egan, 1989).

Owing to the ways in which rust is able to spread and develop, the above-mentioned means of controlling rust are generally limited. The most effective means of control is to plant rust resistant sugarcane varieties (Ryan and Egan, 1989). A number of factors affecting the distribution of rust are mapped and discussed in Section 5.4.

2.3 Soil Water Related Constraints and Potentials Affecting Sugarcane Plant Growth

Successful sugarcane farming in South Africa is limited largely by climatological conditions which affect crop growth through limits in temperature parameters and rainfall. Climate is crucial in determining the suitability of a particular region for sugarcane production. Smith (1998) states that conditions conducive for sugarcane growth include mean daily temperatures of between 22 °C and 32 °C, and a mean annual precipitation (MAP) between 850 mm (minimum) and 1300 mm (optimum). Sufficient soil water content is essential for efficient sugarcane growth (Smith, 1998). Soil water directly and indirectly affects many sugarcane related issues (Slabbers, 1980; Donaldson and Singels, 2004; Keeping and Rutherford, 2004; Bezuidenhout *et al*., 2006). The estimation of soil water is, therefore, an essential component of this study.

2.3.1 Soil Water

Soils, and in particular soil water, play an important role in cane production. The direct effect of a soil water deficit on a plant includes a dehydrated protoplasm which results in a reduction in the plant's photosynthetic capacity. The indirect effects of a soil water deficiency include a loss of leaf turgidity, causing the stomatal guard cells to close, thus preventing the intake of CO_2 which is needed for photosynthesis (Chang, 1968). As a result of soil water deficiencies, yield is significantly reduced. Smith (1998) shows the extent of yield reductions due to soil water stress for the various growth stages of the sugarcane plant (Table 2.3).

Plant water is essential for the transportation of various sugars, salts and other solutes from the roots to the leaves, and *vice versa*. The transportation of these solutes is vital for plant growth and maintenance (Woodward, 1986). Plant water is also essential for cooling through the process of transpiration (Kramer, 1963).

Table 2.3 Reductions in sugarcane yields with soil water shortages (Smith, 1998)

Soil Water Shortage (%)	Percent Yield Reduction at		
	Establishment/ Vegetative	Yield Formation	Ripening
10	8	5	2
20	15	10	3
30	22	15	5
40	30	20	6
50	40	25	8

In addition to the direct effects of soil water on the growth of sugarcane, it also has many indirect effects on sugarcane related issues. Such issues include soil compaction, irrigation water demand, conducive and non-conducive growing conditions, flowering and maturing (sucrose accumulation).

2.3.1.1 Soil compaction

The use of machinery within sugarcane fields is necessary during land preparation, planting and especially during harvesting, when large masses of material are transported from a field. Regardless of how necessary it is to use machinery in a field, field traffic can cause considerable damage to the soil by altering its properties (Raper *et al*., 1999).

Soil compaction may be defined as a change in the volume of a given mass of soil as a result of a load, or pressure, exerted on the soil mass (McKibben, 1971). When soil compaction occurs the pore spaces containing air and water are compressed and filled by other soil particles. In the long-term this may result in a reduction in yield (Smith, 1999). The reduction in yield is caused by:

- the inability of the plant to take up nutrients and water from the soil (Williams *et al*., 2004),
- the rooting capability of the plant being reduced, this being caused by increased soil strength and a reduction of pore spaces (Smith, 1999), and
- the reduction of the infiltration rate of water, as well as the total water holding capacity of the soil (Smith, 1999).

The above imply that the amount of water available for plant uptake will be decreased, thereby increasing the possibility of the plant becoming water stressed.

There are a number of factors that affect the compaction of a soil, the main of which are soil water content (Bezuidenhout *et al*., 2006) and soil texture (Mitchell and Berry, 2001). Certain soil textures are more prone to compaction. For example, it has been found that loams are more compactable than clays and sands (Mitchell and Berry, 2001). It has also been found that, with an increase in the soil’s water content, the likelihood of compaction is increased (Mitchell and Berry, 2001). To avoid unnecessary compaction of soil, it is crucial for farmers to know soil texture classes in a field, as well as avoiding infield travelling during times when the soil water content is high. Mapping annual time periods when the risk of soil compaction is reduced, is undertaken in Section 6.3.

2.3.1.2 Irrigation water demand

During the colder winter months one of the main factors limiting sugarcane growth is temperature. However, during the summer months when higher temperatures are more conducive to higher evaporation and hence growth rates, the lack of soil water is often a limiting factor (Anon, 1977). It is, therefore, necessary to ensure sufficient soil water content during the summer months, in order to enable the sugarcane plant to transpire, and thus grow at its potential. In areas where rainfall often does not meet the transpiration demands of the sugarcane plant, supplementary irrigation becomes necessary (Anon, 2006). Supplementary irrigation requires a high degree of management in order to be efficient from a water supply perspective. In South Africa, generally, there is a shortage of water, and it is therefore necessary that correct application methods and application rates be used to maximise water use efficiency (Schulze, 2007b).

There are two main ways by which water can be lost through over-irrigation, namely by surface runoff and deep percolation (Schulze, 2007c). Surface runoff is particularly detrimental in that valuable topsoil may be lost from the irrigated land through erosion and, with that wash-off, attached phosphates are also lost. Deep percolation can be equally detrimental in that by flushing large amounts of water through the soil, plant nutrients (particularly nitrates) are lost through leaching (Schulze, 2007c). The result of this is inhibited plant growth and reduced yields. It is, therefore, important to ensure that the correct amount of water be applied to the field. This may be done through various methods of irrigation scheduling techniques and application rates.

There are a number of different modes of irrigation scheduling that may be used, depending on the management strategy implemented. One is demand irrigation. Within demand irrigation there are two modes of application, the first being irrigating until the soil profile's drained upper limit (DUL; i.e. field capacity) is reached and the second being deficit irrigation (Ritchie, 1972). Drained upper limit is reached when water has been allowed to percolate naturally from the soil until drainage ceases and the water remaining is held by capillary forces that are great enough to resist gravity (Schulze, 1995). Deficit irrigation is different in that the soil is not filled to its DUL. Rather, a portion of the potential soil water holding capacity is left free of water, *inter alia* to exploit possible forecasted rainfall events (Schulze, 2007b). In demand irrigation, water is usually applied once the soil dries to 50 % of the Plant

Available Water (PAW). Plant available water may be described as the portion of soil water that the plant is able to extract (Kramer, 1963).

A second method of scheduling is applying a predetermined, fixed amount of water at fixed intervals. This method of irrigation is frequently associated with centre pivot type irrigation. The disadvantage of this scheduling method is that it does not always take into account inter-cycle rainfall events, unless the rainfall event exceeds a threshold amount, in which case the cycle is skipped (Schulze, 2007b). This method of scheduling is often used because it is relatively easy to manage. Similar to the above-mentioned method of irrigation, scheduling irrigation with a fixed cycle, but with varying amounts of water application, is also common. This method is more efficient than the fixed cycle, fixed amount method. The reason for this is that it can take into account the actual crop water demand as well as rainfall distribution patterns. Consequently, only the water that is needed is applied, making this form of irrigation more efficient than the fixed cycle, fixed amount method (Schulze, 2007b).

In South Africa there are a wide variety of irrigation systems available. These can be divided into three main categories *viz*, overhead, drip and flood irrigation systems. Overhead irrigation systems comprise of, *inter alia*, centre pivots and dragline irrigation systems (Anon, 2006). A centre pivot is a self propelled system whereby a pipeline is pivoted around a central point in a field upon a series of towers. Sprinklers on top of, or hanging below, the pipeline emit water uniformly over the circular field. This system is usually very expensive to implement. However, once implemented, management demands are relatively small (Anon, 2006). Dragline systems involve a number of light-weight removable sprinkler sets that are moved manually within the field during irrigation. This type of irrigation system is relatively inexpensive. It is, however, labour intensive and less suitable to irrigating fully grown sugarcane owing to the difficulty in moving the sprinkler sets (Anon, 2006).

Drip irrigation, on the other hand, is a highly efficient method of irrigation, due mainly to the fact that emitters are placed just above or below the soil surface, i.e. close to the plant root zone. The system discharges water slowly and directly onto, or into, the soil (Anon, 2006). This reduces the amount of irrigated water lost to evaporation and interception. The slow rate of emission also minimises the amount of water lost to surface runoff or deep percolation. Drip irrigation systems are, however, expensive to implement. They also need a source of very clean water to avoid blocked emitters (Anon, 2006).

Flood/furrow irrigation is a system of irrigation whereby, through gravity and a series of canals, water is transported to the desired field. The water is then pumped or syphoned into the field where it flows in a sheet or in furrows from one end of the field to the other. The main benefit of this system is the low energy requirement needed for transporting the water to the field. This system is, however, relatively inefficient and is also labour intensive. The viability of the system depends largely on the extent of earthworks required for bed preparation, which is extremely important for application uniformity (Anon, 2006). A number of the above-mentioned irrigation modes are used in the estimation of irrigation water demands for South Africa, seen in Section 6.4.

2.3.1.3 Conducive and non-conducive growing units

Non-conducive plant growth may be defined as the period when a plant is not growing, or transpiring to its full potential owing to soil water stress. Plant soil water stress commences when Plant Available Water (PAW) drops below a threshold value which depends on the soil texture, the crop and on atmospheric demand (Slabbers, 1980). For sugarcane this threshold is frequently at 0.5 PAW (Schulze *et al*., 2007b). Identifying locations where a plant is more likely to become stressed, as well as identifying specific months in which plant stress is likely to occur, is valuable for planning. Additionally, Keeping and Rutherford (2004) state that sugarcane plants become more susceptible to certain pests during times when the plant is stressed.

There are three hypotheses that attempt to explain why sugarcane becomes more susceptible to pest and disease attacks when stressed (Keeping and Rutherford, 2004). These are:

- first, during times when the plant is stressed, the nutrient concentrations in the plant increase, and this results in an increase in potential growth and reproduction rates of the insect,
- secondly, the plant's ability to withstand insect predation is lowered when under soil water stress, thus making it more vulnerable to insect infestation, and
- thirdly, the warm and dry conditions promoting plant stress and increased plant temperatures are often naturally favourable for the prevalence of insects.

By identifying areas as well as time periods where and when plant stress is likely to occur, it is possible to predict future movements and possible present threats of pest invasions. The mapping of both conducive and non-conducive growth units are given in Section 6.5.

2.3.2 Flowering of Sugarcane

Flowering of sugarcane in South Africa has, in the past, caused significant losses in yield. When flowering occurs, vegetative growth of the sugarcane plant is terminated, as a result of the development of flower primordium (Donaldson and Singels, 2004). Once vegetative growth has been terminated, the stalks of the plant deteriorate because the plant does not replace dead or damaged leaves. The degree of loss of sugarcane yield is determined by the amount of growth that would have taken place between the time when vegetative growth was terminated, and the amount of growth that would have occurred had flowering not been initiated (Donaldson and Singels, 2004).

The flowering of sugarcane is triggered by a number of environmental and physiological conditions. If these specific environmental and physiological conditions are not met, flower initiation is inhibited, or its prevalence is significantly reduced. In order for flowering to occur, specific day lengths, temperatures and water requirements need to be met (Nayamuth *et al*., 2003). Donaldson and Singels (2004) note that sugarcane flowering is initiated when day length shortens to less than 12.5 hours. The optimum temperatures required for flowering to occur are a maximum temperature of 28 °C and a minimum temperature of 23 °C (Nayamuth *et al*., 2003). If, however, the temperature drops to below 18 °C or rises above 31 °C on a given day, flowering is reduced and / or its emergence is delayed. Critical soil water contents are also required for flowering to initiate. If the soil water content falls below 50 % of PAW, the sugarcane plant becomes stressed, which results in flowering being inhibited. In the time period in which all the above-mentioned criteria are met, flowering is induced. This time period coincides with 22 days from the time when day length shortens to below 12.5 hours (Donaldson and Singels, 2004), i.e. approximately the first three weeks in March for South Africa. The mapping of areas in which sugarcane flowering is likely, according to the above-mentioned requirements, and for how many days per year, is presented in Section 6.6.

2.3.3 Severe Cold Conditions

Another important factor limiting sugarcane production in South Africa is frost and severe cold conditions. Smith (1998) delineates the sugarcane growing areas in KwaZulu-Natal as those where the mean of July daily minimum temperatures exceed 5°C. When determining which areas are suitable for growth and production of sugarcane it is, furthermore, important to assess whether or not, during the colder winter months, temperatures decline below 0°C and frost forms. Additionally, the frequency of frost events is important (Schulze, 2007d), as the higher the number of frost incidents per annum, the less suitable the region is for sugarcane farming.

Schulze (1997) identified a number of factors that affect the prevalence of frost. These include altitude, latitude, distance from the ocean and topography. Frost occurs when the air temperature reaches, or drops below, 0°C and dew point temperature is near to, or below, 0°C. Once these criteria are met sublimation occurs, i.e. water vapour is converted directly into the solid ice state without first turning into liquid. The result of this is the formation of a layer of frost upon the plants' leaves, causing significant damage through intercellular freezing, leading to plant cell death or malfunction (Ventskevitch, 1961).

* * * * * * *

In this chapter a number of the factors affecting the growth and production of sugarcane in South Africa have been addressed. These factors were soil water content, soil compaction, irrigation water demand, conducive and non-conducive growing conditions, flowering and severe cold conditions. A number of the more serious pests and diseases affecting the South African sugar industry were also discussed. These were *Eldana saccharina*, *Chilo sacchariphagus* and the rust fungus. These factors are all climate dependent. In the following chapter, therefore, reviews are given of the climatic databases, models and simulation tools used in the course of this study.

3. CLIMATE DATABASES, MODELS AND SIMULATION TOOLS

3.1 Introduction

The accuracy with which agricultural and hydrological activities can be modelled depends largely upon the accuracy of the climatic databases, and on the process representations as well as the spatial and temporal resolutions of the simulation models used. Temperature and rainfall data are vital inputs in agrohydrological modelling. Tarimo and Takamura (1998) state that temperature is one of the most important ecological indicators for the efficient growth and production of sugarcane. Another such important ecological indicator for plant, and more specifically sugarcane growth, is that of rainfall (Smith, 1998). It is for this reason that a review of the development of the temperature and rainfall databases used in this study is included in this chapter.

Modelling of factors related to sugarcane production include soil water content, irrigation water demand, soil compaction and crop yields. For modelling purposes in southern Africa the *ACRU* agrohydrological modelling system (Schulze, 1995 and updates) is used extensively; therefore it will also be reviewed in this chapter, with particular reference to the simulation involving sugarcane.

3.2 Importance, Objectives and Development of the Southern African Temperature Database

Because of the relative abundance of temperature data, researchers have successfully used it as an input variable in many climatological, agricultural and hydrological applications (Schulze and Maharaj, 2007a). Temperature is used in the estimation of solar radiation, relative humidity, potential evaporation, and in the calculations of heat and chill units (Schulze and Maharaj, 2004). Furthermore, temperature affects the incidence and distribution of many pests and diseases (Atkinson, 1981; Leslie, 2006; Goebel, 2006). Pests and diseases that affect sugarcane growth and production have specific temperature thresholds, above and below which the pest or disease is not able to propagate. By understanding these thresholds, and applying them in conjunction with a temperature database, it is possible to map areas in which a particular pest or disease may occur.

Schulze and Maharaj (2004) identified two main objectives when compiling the daily temperature database for southern Africa. The first was to develop procedures to fill in missing daily maximum and minimum temperature values in order to extend the temperature database to a common 50-year base period spanning the years 1950 to 1999. The second objective was to generate daily maximum and minimum temperatures for the above-mentioned time period at a one arc minute resolution, i.e. on a grid of ~ 1.7 x 1.7 km covering South Africa, Lesotho and Swaziland (Schulze and Maharaj, 2004).

3.3 Development of the Southern African Temperature Database

In order to derive the southern African temperature database, numerous of steps were taken by Schulze and Maharaj (2004). These steps will be explained and summarised in this chapter. They include:

- first, the collation and quality control of temperature records from all the qualifying temperature stations in southern Africa up to the year 1999;
- secondly, the establishment of temperature lapse rates for each month of the year, for both maximum and minimum temperatures, for different lapse rate regions and sub-zones within southern Africa;
- thirdly, the extension and patching of temperature records at qualifying stations, termed “control” stations, to a common base period of 50 years; and
- fourthly, the development of techniques to estimate daily maximum and minimum temperatures for the entire base period at any location for the whole of the southern African region, as defined above, at a spatial resolution of 1 arc minute, i.e. on a 1' x 1' latitude x longitude grid.

3.3.1 Collation and Quality Control of Temperature Records

The raw data used by Schulze and Maharaj (2004) in the development of the daily temperature database were obtained from:

- the South African Weather Service (SAWS),
- the Institute for Soil, Climate and Water (ISCW), which is an institute of the Agricultural Research Council; and
- the South African Sugarcane Research Institute (SASRI).

The spatial distribution of the temperature stations from which data were used, and their associated record length, are shown in Figure 3.1.

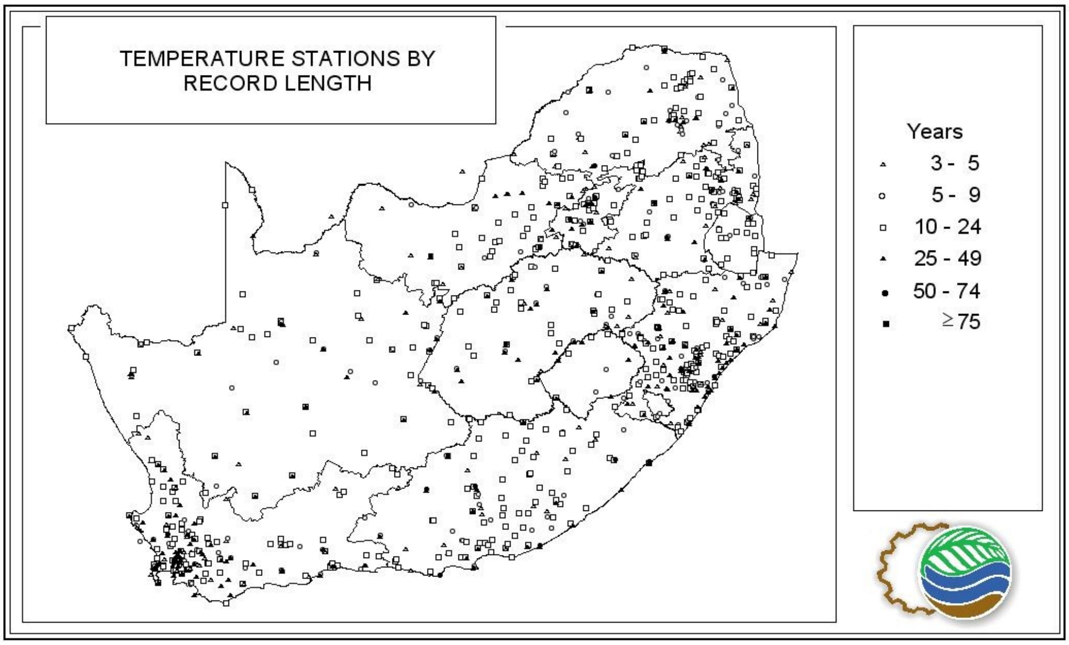

Figure 3.1 Distribution and record length of temperature stations in southern Africa from which data were used by Schulze and Maharaj (2004)

Of all the stations depicted in Figure 3.1 it was found that 23 had daily temperature records in excess of 50 years, and of those 4 had record lengths of more than 75 years. In order for a temperature station's record to be used, its data had to go through a stringent quality control process whereby any missing or doubtful values where flagged for later infilling or correction

(Schulze and Maharaj, 2004). Listed below are a number of the errors encountered while developing the database (Schulze and Maharaj, 2004):

- Some stations were found to have temperature data still in degree Fahrenheit. These records were identified by logical checks and then converted to degree Celsius.
- Temperature records where maximum temperatures were lower than the minimum temperatures for the same day were identified as errors and were infilled synthetically, as described later in this section.
- Temperatures exceeding 45°C were flagged and checked against the temperatures of surrounding stations for the same day. If found to be anomalous, these records were later corrected.
- Temperature records were flagged if the temperature range between maximum and minimum temperatures was less than 1°C on a given day. If both the maximum and minimum temperatures of these flagged records were above 20°C, these values were counted as errors and later infilled synthetically. If maximum and minimum temperatures of the flagged records were below 20°C, the values were checked against those from surrounding stations before either being flagged as errors or accepted.
- Temperatures that were identical (i.e. to the nearest 0.1°C) for more than 3 consecutive days were flagged as errors and later infilled synthetically from surrounding station values.
- It was found that many of the station locations (i.e. latitude, longitude and altitude) of the temperature stations were incorrect. These were corrected from 1: 50 000 topographical maps.

3.3.2 Delineation of Lapse Rates

Lapse rate region delineation is of vital importance in the estimation of temperature values at unmeasured locations. Temperature values are adjusted either up or down from those at a "control" stations to unmeasured locations by region, season and temperature parameter specific lapse rates. Lapse rates may be defined as the rate of change of temperature with an increase in altitude (Schulze and Maharaj, 2004). An internationally accepted standard lapse rate is -6.5 °C per 1 000 m altitude rise (South African Weather Bureau, 1965). However, it was found that lapse rates varied with location, season, maximum vs. minimum temperature, prevailing topography and the degree of cloudiness (South African Weather Bureau 1965; Torrance, 1973; Parry *et al*., 1988; Lennon and Turner, 1995; Schulze and Maharaj, 2004). Based on research undertaken by Clemence (1986), and the above mentioned factors, Schulze (1997) divided southern Africa into 12 lapse rate regions. Each of the defined regions was assigned specific monthly lapse rates for both maximum and minimum temperatures. The lapse rate regions, as defined by Schulze (1997), are shown in Figure 3.2.

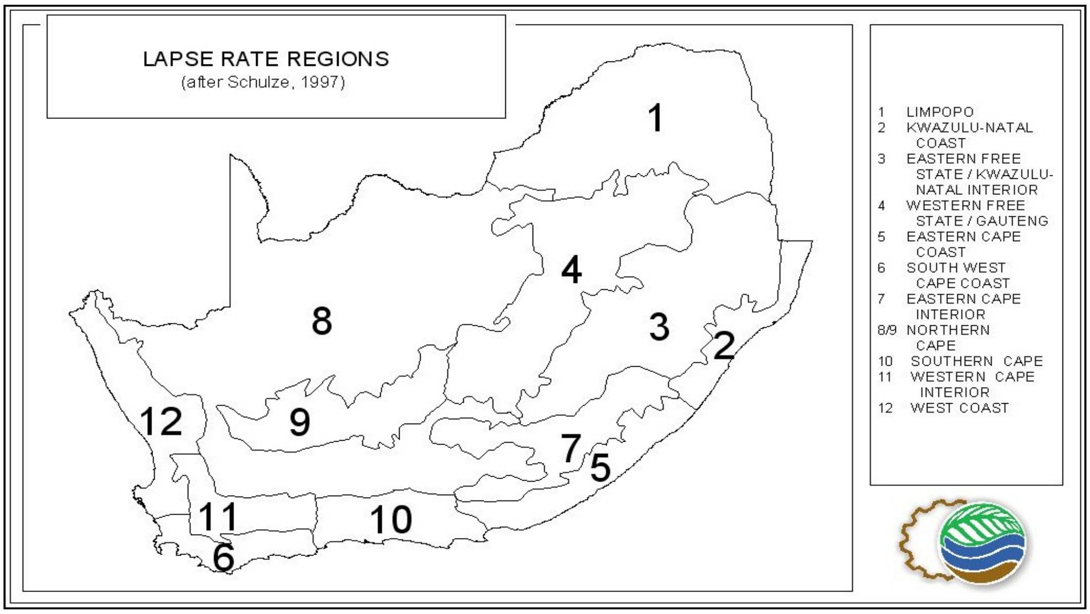

Figure 3.2 Temperature lapse rate regions derived for southern Africa (after Schulze, 1997)

3.3.3 Estimation of Daily Temperatures at Unmeasured Locations

Estimation of daily temperature values at unmeasured locations was undertaken by adjusting temperatures from control stations by specific monthly and regional lapse rates, to the unmeasured location (Schulze and Maharaj, 2004). Control stations were selected by the length and quality of the observed temperature records. A station's record length needed to be in excess of 1 500 days (i.e. ~ 50 months or 4 years) in order to be considered as a control station. From the available temperature database 973 stations qualified as potential "control" stations. Once control stations had been selected, their record lengths were extended to a common 50 year record length, spanning 1950-1999, so that they could later be used for temperature estimation.

"Target" stations were used to extend and patch, or infill, daily temperature values at control stations. For each of the control stations, up to nine target stations were selected according to their distance from the control station and the altitude difference between the control and target stations. Schulze and Maharaj (2004) then developed a method known as the Difference in Standard Deviation Method (DSDM) to infill and extend missing values. The DSDM first ranks each of the qualifying nine target stations according to the differences of the 12 months' standard deviation of daily temperature, with that of the control station. Thereafter, the data from the station with the lowest difference in a given month was first targeted whenever the control station's missing data were infilled or extended.

Once the 973 control stations' daily temperatures had been infilled and extended to the selected 50 year period, extending from 1950 to 1999 (as this time period coincides with the time period when the temperature station network was at its densest), these values were then used to estimate daily temperatures at unmeasured locations. The procedures used for temperature estimation at unmeasured locations included (Schulze and Maharaj, 2004):

- selection of the two most appropriate control stations for that location, according to specific criteria;
- application of the regional and monthly lapse rates to account for differences in temperature between the two control stations and the unmeasured location which result from differences in altitude; and
- computation and checking of estimated temperature values for the unmeasured locations, according to criteria specified in Schulze and Maharaj (2004).

3.3.4 Determination of Hourly Values of Temperature

Hourly temperatures, which are required in certain sugarcane pest algorithms, were determined by Schulze and Maharaj (2007b) from the 50 year daily temperature database described above and generated at a one arc minute resolution (i.e. ~ 1.7 x 1.7 km) for the area covering South Africa, Swaziland and Lesotho. Daily temperatures were disaggregated into hourly temperatures (Schulze and Maharaj, 2007b) through the sine-log equations (Equations 3.1 and 3.2) derived for South Africa by Linsley-Noakes *et al*. (1995). These equations are based on the premise that the day-time solar cycle follows a sine curve from sunrise to sunset, and night-time cooling follows a logarithmic equation. The day-time and night-time temperature equations for disaggregating daily to hourly temperatures are as follows:

- the day-time solar equation is expressed as

$$T_t = \left(T_{mxd} - T_{mnd}\right) \times \sin\left(\frac{\pi}{D_l + 4}\right) + T_{mnd} \quad \text{...........(3.1)}$$

- while the night-time equation, used when cooling takes place, is given by

$$T_t = T_{ss} - \frac{T_{ss} - T_{mnd}}{\ln\left(24 - D_l\right)} \times \ln\left(t\right) \quad \text{...........(3.2)}$$

where

T_t	=	hourly temperature (ºC) at time *t* after sunrise, or at time *t* > 1 hour after sunset, respectively,
T_{mxd}	=	daily maximum temperature (ºC),
T_{mnd}	=	daily minimum temperature (ºC),
D_l	=	daylength (hours), and
T_{ss}	=	temperature (ºC) at sunset, as obtained from the daytime solar cycle equation above.

3.4 Development of the Southern African Rainfall Database

Schulze (2007e) states that among the various individual climatic parameters affecting crop growth in southern Africa, water (which is limited) is considered the most vital since this region is not constrained by a lack of solar radiation. The quantification of available water, through the estimation of rainfall, for various activities relating to agriculture is, therefore, essential.

The measurement of rainfall is undertaken by measuring the amount of rain that has fallen at a point (raingauge) over a specific time period. The spatial and temporal distributions, as well as the frequency, duration and intensity of rainfall that has fallen in a particular region over a specific time period are important for agricultural analysis. Schulze (2007e) suggests that in addition to the above-mentioned types of analyses of rainfall, the variability of rainfall from year to year, and the likelihood and severity of drought are also important rainfall related indicators for farmers.

In this section some errors relating to the measurement of rainfall are discussed. In addition to this, methods used in the development of the most recent comprehensive southern African daily rainfall database are reviewed.

3.4.1 Errors Associated with Rainfall Measurement

In theory, the measurement of rainfall is a simple procedure, provided absolute accuracy is not essential. However, accurate measurement of rainfall is a near impossible procedure owing to the random and systematic errors which occur during measurement (Schultz, 1985). Schulze (2007e) states that it is not possible to measure "true rainfall amounts", but that it is nevertheless very important to improve methods used in the measuring of rainfall by reducing the known systematic errors that are associated with particular types of raingauges.

A factor contributing to the difficulty of measuring rainfall is the spatial variability with which it falls, and the comparatively small area over which measurement is undertaken. The standard South African raingauge, for example, with its 127 mm orifice diameter, samples only 1.267 x 10^{-8} % of a 1 km^2 area (Schulze, 2007e). It is very seldom that raingauges are found at a density of one gauge per km^2. Owing to the limited sample area over which rainfall is measured, the likelihood of spatial error is therefore very high, ranging from between 10% and 20%, which may increase to 60% in mountainous regions (Schulze, 1995).

Schulze (2007e) points out that the commonly used standard raingauge generally contains inaccuracies in measuring point rainfall. The factors that contribute to this inaccuracy are depicted in Figure 3.3. The most significant of these factors is that of wind. Larson and Peck (1974) found that wind accounts for a gauge catch deficiency of approximately 15%. Eddies that form around the orifice of the raingauge, owing to the shape of the gauge being an obstruction to wind flow, cause rain droplets to be deflected from the gauge orifice, resulting in an under-estimation in the amount of rainfall that has actually fallen at that location.

In addition to errors in rainfall records caused by wind, errors are also inherent during data capture through so-called date phasing and human error. In South Africa the standard time for recording daily rainfall is 08:00 and, if done correctly, that rainfall should be recorded against the previous day's date (Schulze, 2007e). However, it was found that in many cases the rainfall was recorded against the day on which the recording took place, resulting in the records being out of phase by one day. This is known as date phasing. In terms of monthly or annual statistics this error has a negligible impact. However, when simulating streamflow from multiple subcatchments at a daily time step, for example, major errors can occur if some subcatchments contain rainfall data that is out of phase by a day, because the accumulated hydrograph will be incorrect. Human error further accounts for inaccuracies in rainfall databases. Human error occurs during the data capturing process and through the incorrect reading and recording of rainfall events. It was noted by Schulze (1979) in studies on rainfall in the Drakensberg area of KwaZulu-Natal, that records were frequently incomplete during times when the operators recording the rainfall records took their annual leave. Incorrect capturing of rainfall amounts was also found to be a problem. By missing a decimal while keying in data, for example, 158 mm could be registered instead of 15.8 mm.

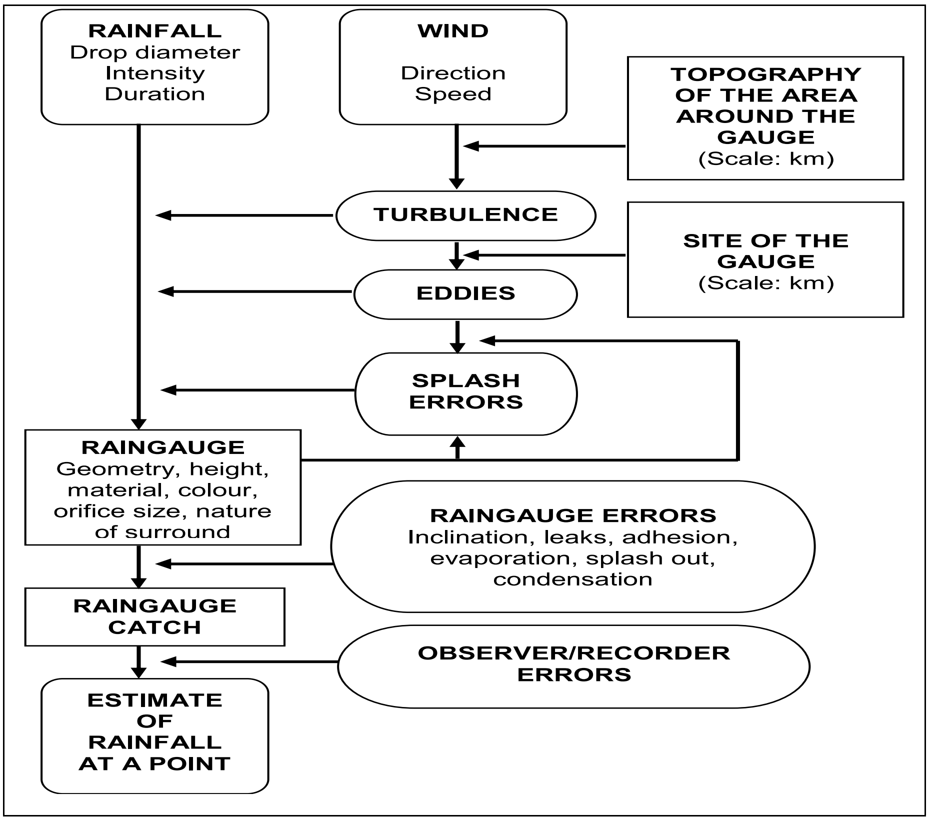

Figure 3.3 Factors affecting rainfall measurement accuracy (after Rodda, 1967; Schulze, 2007e)

Furthermore, what seems to be insignificant in error generation in the short term may become significant in the long term. For example, surface adhesion of water droplets to the funnel above the raingauge can account for a loss of up to 4% of annual rainfall. These errors result from between 0.2 and 0.4 mm per rainfall event being lost by adhesion, which can then accumulate over a year to a significant loss (Schulze, 2007e).

3.4.2 Development of the Daily Rainfall Database for Southern Africa

Correct rainfall records are essential for hydrological design, water resources planning and in crop modelling. The earliest general form of rainfall information for southern Africa was that of Mean Annual Precipitation (MAP) which was compiled in the mid 1960s by the erstwhile Hydrological Research Division of the Department of Water Affairs in the form of a series of 1:250 000 maps (Lynch, 2004). Since that time, rainfall records have been lengthened by over 40 years and advances in computer technology have significantly improved the capturing, synthesis and display of rainfall data.

Lynch (2004) identified two main steps in the formulation of the southern African rainfall database. The first was to synthesise (combine) all current and relevant daily rainfall datasets in southern Africa, and ensure that all datasets used where as error free as possible. The second step was to then infill missing rainfall values.

3.4.2.1 Synthesis of rainfall data

There were four main sources of daily rainfall records that were used in the development of the database, *viz*:

- the South African Weather Service (SAWS),
- the Agricultural Research Council (ARC),
- the South African Sugarcane Research Institute (SASRI), and
- a large number of municipalities, private companies and individuals (PVT).

The total number of stations with rainfall records that were contributed by the various sources and smaller companies are given in Table 3.1.

Once all the rainfall records had been combined into a single database it consisted of in excess of 100 million observed values. Owing to the sheer size of the database it was very likely that errors still existed (Lynch, 2004). Two main types of errors were identified, *viz.* date phasing and extreme daily rainfall events. In order to identify and correct for date phasing a computer based checking/correction program was developed and applied (Lynch, 2004). Although not as common as date phasing, extreme rainfall event errors were also found to be a problem. Extreme event errors occurred as a result of incorrect keying in of data. These errors were remedied by identifying the most extreme rainfall event in southern African observational history, and then flagging any values above this value. The most extreme verified daily rainfall amount was 597 mm that fell at St Lucia Lake on 31 January 1984. Therefore, any values exceeding 597 mm were flagged as suspect values and were then checked against values from adjacent raingauges and corrected (Lynch, 2004).

Table 3.1 Contributors of rainfall records (Lynch, 2004)

Organisation	No. of stations
SAWS	8 281
ARC	2 661
SASRI	161
PVT	1 050
Total	12 153

3.4.2.2 Patching missing data

Schulze (2007e) states that missing rainfall records can severely limit the use of rainfall data, especially in simulation modelling. Modelling cannot be undertaken without a continuous dataset. Lynch (2004) used four different patching, i.e. infilling, algorithms to develop a continuous dataset of daily rainfall values, *viz.*

- Inverse Distance Weighting (Meier, 1997), the

- Expectation Maximisation Algorithm (Dempster *et al.,* 1977 ; Makhuvah *et al*., 1997a; 1997b), the
- Median Ratio Method (Smithers, 2002), and a
- Monthly Infilling Technique (Dent *et al.*, 1989).

Inverse Distance Weighting (IDW) is a method that gives more weight to rainfall station values that are closer to the location where infilling is needed (Johnston *et al.,* 2001). It assumes that rainfall stations that are closer are more likely to have records similar to those that would have been recorded. Owing to the spatial variability of rainfall in southern Africa, Meier (1997) developed a method whereby rainfall stations were selected in the four quadrants surrounding the station the data of which needing patching. This was to eliminate bias that may have occurred had all the closest target stations been in one direction from the control station.

The Expectation Maximisation Algorithm (EMA), formalised by Dempster *et al.* (1977), was previously used by Makhuvha *et al*. (1997a; 1997b) to infill missing monthly rainfall records in South Africa. The EMA method is a complex method that interrogates stations' data being used for infilling, ensuring that daily in-filled values are as accurate as possible (Smithers and Schulze, 2000). The EMA recursively substitutes missing data and then re-estimates the multiple linear regression relationship between the control station and the target stations being used for infilling.

For the median ratio method, the ratio of median monthly values between the control station and the target control station were calculated. This ratio was then used to adjust daily values taken from the target station, either up or down so that infilled values were as accurate as possible (Lynch, 2004).

A monthly infilling technique for missing rainfall values was used by Dent *et al.* (1989). In this technique missing monthly totals are filled in by means of regression equations between target and control stations. One basic assumption of this technique is that if the monthly value for a particular station is zero, then all daily values for that month are zero. Similarly, if the monthly total for a particular station is ≤ 2mm, then that value is given to that station on the first day of the month and the remainder of the days of the month is given values of zero (Lynch, 2004).

Of the four techniques identified by for infilling, the EMA technique and the ratio approach were found to be the premier techniques (Lynch, 2004). However, where these two methods were not able to infill missing values, the IDW and monthly infilling techniques were used. As a result of infilling the total number of rainfall stations in South Africa, Lesotho and Swaziland each containing more than 15 years of data was increased from 5 118 to 9 641 stations (Lynch, 2004).

3.5 The *ACRU* Agrohydrological Model within the Context of the Southern African Quaternary Catchments Database

3.5.1 Introduction

The *ACRU* model had its origins in studies on evapotranspiration in the Drakensberg of KwaZulu-Natal (Schulze, 1975). It has since been developed into a daily time step multi-purpose, multi-level, physical-conceptual model (Schulze, 1995). The following review of the *ACRU* model comprises mainly of those sections relating to the processes which are of particular relevance to modelling soil water and sugarcane yield. The development of the southern African Quaternary Catchments Database (QCDB) is included in the section which then follows, as all the modelling performed by *ACRU* was done within the framework of the QCDB.

3.5.2 Process Representations in the *ACRU* Model which are Relevant to this Study

The *ACRU* model comprises of a two-layer (top- and subsoil) soil water budgeting system that simulates processes at a daily time step. The model is able to represent a number of hydrological, agricultural and climatological processes, which are shown schematically in Figure 3.4. Rainfall and/or irrigation that is not intercepted by vegetation, either runs off the soil surface as stormflow or infiltrates into the soil, in which case it is first stored in the soil's topsoil horizon. Soil water is stored in the topsoil until that horizon's drained upper limit (DUL) is reached, after which any excess water percolates down into the subsoil horizon. The rate of percolation is dependent on the soil's textural characteristics and other drainage related properties. Once DUL in the subsoil horizon is reached, excess water then drains into the intermediate and ultimately groundwater store, from which baseflow is generated. Distribution of water up and down the various soil horizons also occurs under unsaturated conditions, although at much slower rates. Evaporation occurs from both intercepted water and from the various soil horizons. Evaporation from within the soil horizons is from plant transpiration (both horizons) and soil water evaporation (topsoil horizon only). Evaporation is computed through a combination of atmospheric demand, water use characteristics of the crop and water availability in the soil (Schulze 1995).

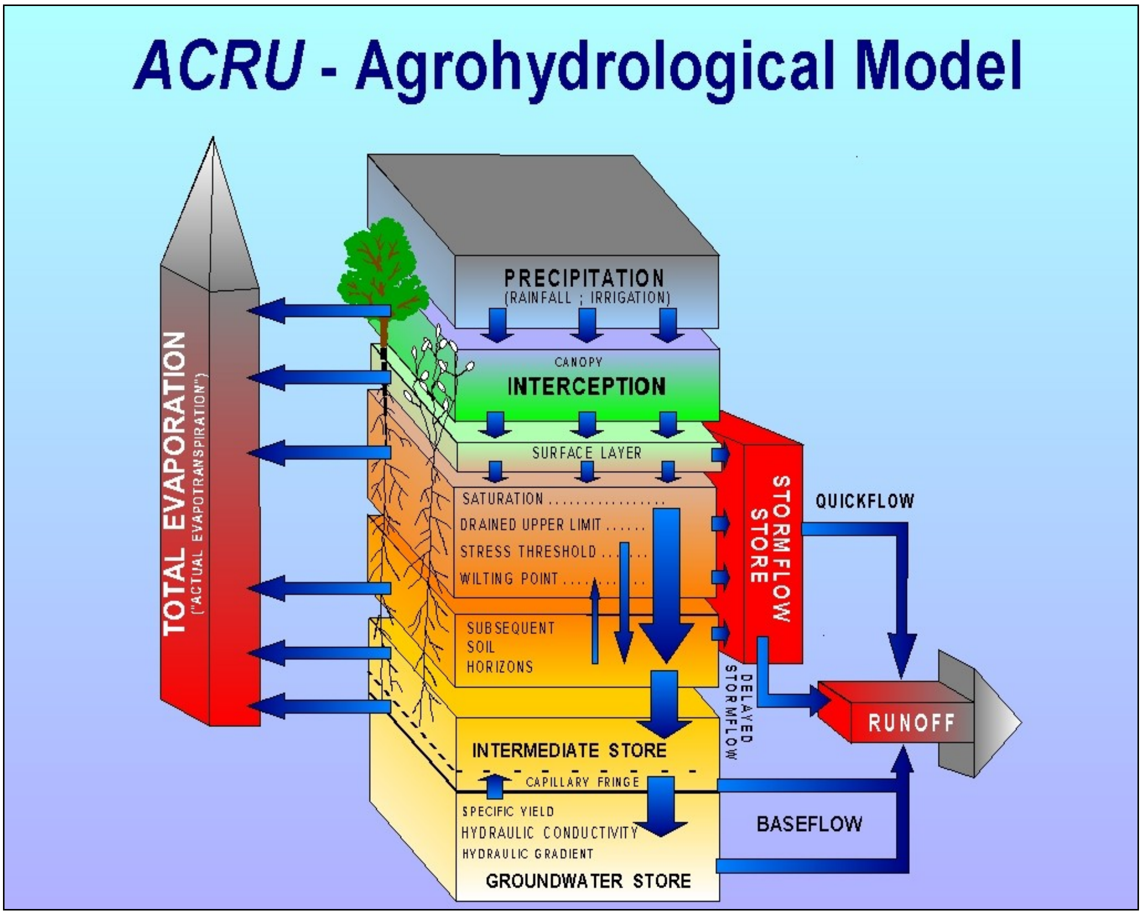

Figure 3.4 Schematic depiction of the general structure of the *ACRU* agrohydrological modelling system (Schulze, 1995)

3.5.2.1 More on the estimation of evaporation in the *ACRU* model

Daily atmospheric demand is calculated from a reference potential evaporation, usually taken to be either a daily A-pan equivalent potential evaporation or daily crop evapotranspiration calculated with the Penman-Monteith equation. The water use characteristics of the plant are represented by a crop coefficient. The crop coefficient is the ratio between the reference potential evaporation and maximum evaporation from the plant, and is dependent on climate and the crop's stage of growth. Maximum evaporation is determined by multiplying the specific crop coefficient by the reference evaporation. Transpiration is assumed to occur at a maximum rate until the soil water in the root zone decreases to a certain threshold, beyond which transpiration is reduced and plant stress sets in (Schulze, 1995). This threshold is vital in crop yield modelling, since plant stress also implies a reduction in yield (Lumsden, 2000).

3.5.2.2 Estimation of sugarcane yield using the *ACRU* model

Sugarcane yield was originally estimated in *ACRU* through a linear relationship, developed by Thompson (1976), between yield and evapotranspiration. The Thompson equation used in the *ACRU* model is given in Equation 3.3.

$$Y_{sc} = 9.53(\Sigma E)/100 - 2.36 \quad (3.3)$$

where

Y_{sc} = sugarcane yield in tons per hectare ($t.ha^{-1}$), and

ΣE = accumulated actual evapotranspiration (mm).

The *ACRU*-Thompson model originally estimated sugarcane yield on an annualised basis, from July 1 to June 30 the following year. This procedure was, however, refined and improved upon by Lumsden *et al.* (1998) and Lumsden (2000) to facilitate simulation of different growth cycle lengths and multi-harvesting dates using dynamic degree-day driven biomass equations developed by Hughes (1992).

The equations for these refinements are as follows:

$$K_c = 0.297 + (1.32 \times 10^{6} \times GD_a^{2}) - (6.83 \times 10^{-10} \times GD_a^{3}) - K_{red} \quad (3.4)$$

$$K_{red} = 0.05 + (1.32 \times 10^{-6} \times GD_r^{2}) - (6.83 \times 10^{-10} \times GD_r^{3}) \quad (3.5)$$

where

K_c	=	sugarcane crop coefficient, i.e. water use, coefficient,
GD_a	=	accumulated degree days (base 12°C) since planting and up to initiation of ripening at 1300 °C day (°C.day),
GD_r	=	accumulated degree days after initiation of ripening (°C.day),
K_{red}	=	reduction in crop coefficient after ripening,
Degree day	=	$((T_{max} + T_{min}) / 2) - 12$ (°C.day),
T_{max}	=	daily maximum temperature (°C), and
T_{min}	=	daily minimum temperature (°C).

Limits to K_c, taken from Hughes (1992), were:

K_c	≤	1 for plant crop,
	≤	0.96 for first ratoon crop,
	≤	0.92 for second and subsequent ratoons, and
	≤	0.5 after initiation of ripening.

The representation of different harvest dates depends upon daily observed maximum and minimum temperatures, which are input into the above equations to calculate crop coefficients, which are used to reflect the climate regime experienced by the crop during its growth cycle (Lumsden, 2000), which can be user specified. These crop coefficients are then used in the estimation of actual evapotranspiration, which is accumulated over the user specified growth cycle. The accumulated actual evapotranspiration is then used in the Thompson (1976) cane yield equation (Equation 3.3).

All simulations undertaken with the *ACRU* model were at the Quaternary Catchment scale. Each Quaternary Catchment contains specific climatic and agrohydrological information relating to the characteristics of that catchment, and required by the *ACRU* model in simulations.

3.6 Development of the Southern African Quaternary Catchments Database

Underpinning many of the analyses undertaken in this study is the southern African Quaternary Catchments Database (QCDB). A first version of a southern African spatio-temporal database originated in the late 1980s (Dent *et al*., 1989), and it has since been revised and improved upon in a number of iterations (e.g. Schulze and Lynch, 1992; Schulze *et al*., 1993; Meier, 1997; Perks *et al*., 2000; Hallowes *et al*., 2004).

The South African Department of Water Affairs and Forestry (DWAF) delineated South Africa, Swaziland and Lesotho in to a hierarchical system of catchments, from Primary Catchments (shown in Figure 3.5 by the different colours) which in turn are disaggregated into Secondary, then Tertiary and, at the fourth level, into 1 946 Quaternary Catchments (Midgley *et al*., 1994). Quaternary Catchments can be described as the most detailed level of catchment disaggregation used until recently (2007) for planning and modelling purposes.

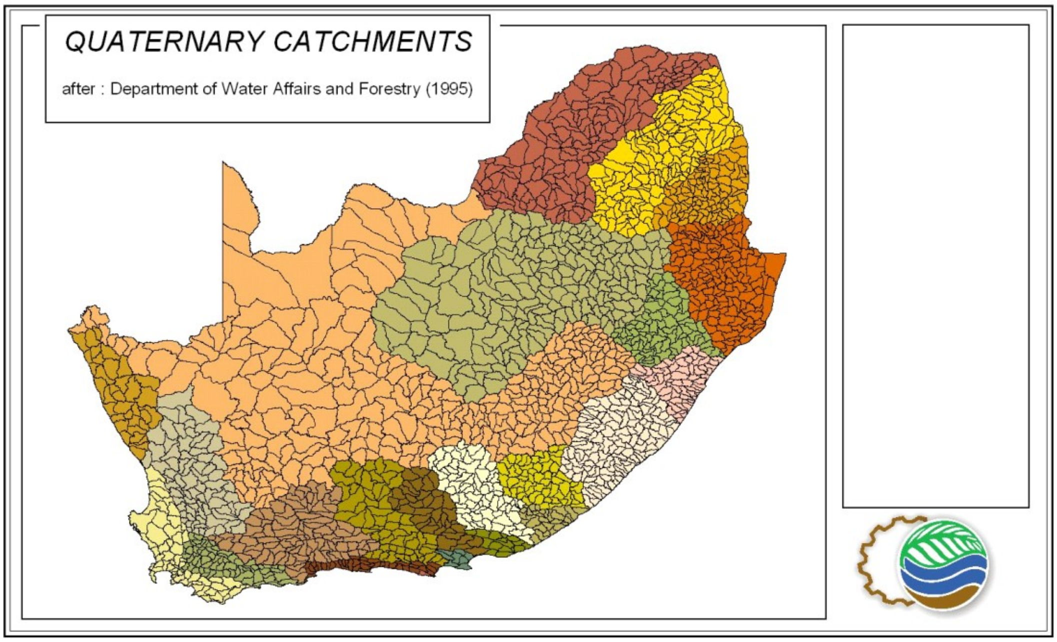

Figure 3.5 Southern African Quaternary Catchment delineation (Source: DWAF, 1994)

3.6.1 Populating the Quaternary Catchments Database

Information required by the *ACRU* model for agrohydrological simulations, such as temperature, daily rainfall, soils and land cover were input at a Quaternary Catchment (QC) scale. Each QC within the southern African study region was given an identification number (1 - 1 946).

3.6.2 Daily rainfall input per Quaternary Catchment

From the daily rainfall database developed by Lynch (2004), and described in Section 3.4, a rainfall station had to be selected for each QC. It was assumed that the daily rainfall data from the station selected was representative of the entire QC. The method used to select a suitable rainfall station for each QC included, first finding the centroid of each catchment and then identifying the closest 10 rainfall stations to that centroid point. These stations were then ranked and selected according to the following criteria (Kunz, 2004; Schulze *et al.,* 2005; Warburton and Schulze, 2005):

- distance from the rainfall station to the point of interest,
- length of rainfall data record,
- time period during which the rainfall was recorded,
- similarity between the proposed station values and the values obtained by the study done by Lynch (2004) of the 1' x 1' grid value of mean annual precipitation,
- proportion of observed to infilled rainfall values,
- topography of the catchment, i.e. the altitude of the rainfall station compared to the average altitude for the catchment, and
- prevailing direction of weather systems.

The average reliability of the rainfall station records, defined as the percentage of days in a required data period (in this case 1950 – 1999) for which there is a reliable observed rainfall record (Warburton and Schulze, 2005), was 79.2%. The majority of rainfall stations used (58.2%) displayed a reliability in excess of 90%. In total 1 248 rainfall stations were used to represent the 1 946 QCs, this implying that the records of 486 stations represented more than one QC. Warburton and Schulze (2005) state that the rainfall stations selected for each QC generally have data of high quality, with adequate reliability and record length.

3.6.3 Daily temperature input per Quaternary Catchment

Daily temperature values are used in the *ACRU* model to estimate, *inter alia*, potential evaporation, soil water content and irrigation demand. For purposes of running the *ACRU* model, a single set of 50 years of daily temperature values was required for each QC. In order to obtain representative temperature values, a grid point with a representative altitude close to the centroid point for each QC was first determined and, thereafter, 50 years of daily temperature values were generated at that point from the temperature database developed by Schulze and Maharaj (2004).

3.6.4 Baseline land cover per Quaternary Catchment

For each QC in southern Africa, a baseline land cover was selected from to the most dominant Veld Type according to Acocks' (1988) classification, in that particular catchment. Baseline land cover is required in agrohydrological studies, especially when comparing various land uses and their effect on hydrological responses (Schulze *et al.,* 2007a). A total of 70 Acocks' Veld Types were used to identify the different baseline land cover conditions in southern Africa. For each land cover type, specific hydrological attributes, i.e. month-by-month values of the water use coefficient, leaf area index (where available), interception per rainday, root distribution, a coefficient of infiltrability and soil loss factor related to vegetal cover, were assigned (Schulze, 2007a).

3.7 Map of Provinces, Countries and Sugarcane Growing Areas in South Africa

In order to round off this chapter on climate databases, models and simulation tools, Figure 3.6 depicts the areas in which sugarcane is currently grown in South Africa. These areas, as well as the provinces and countries shown in this map, are referred to in subsequent chapters when discussing the distribution patterns of variables affecting sugarcane production in southern Africa.

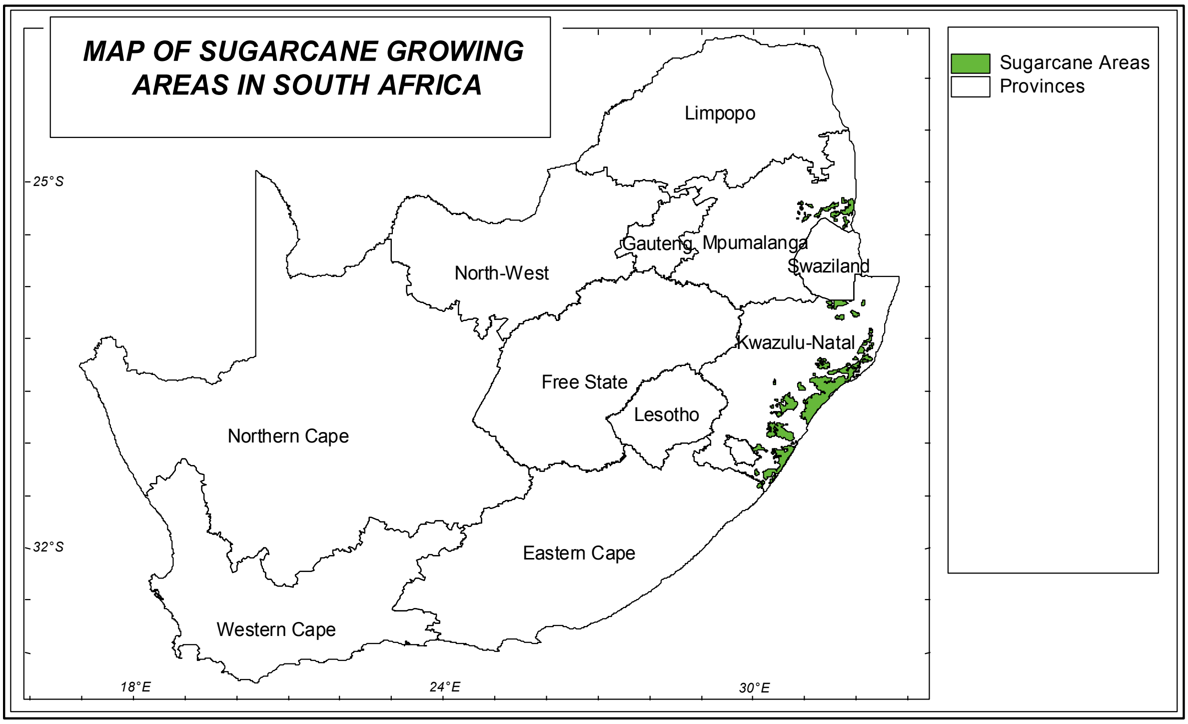

Figure 3.6 Map of sugarcane growing areas in South Africa

* * * * * * *

Mapping agroclimatic response surfaces for sugarcane in southern Africa requires a large deal of modelling. Accurate temperature and rainfall databases are essential in agroclimatic modelling. In this chapter the derivations of the southern African temperature and rainfall databases were described. All simulations completed in this project were done at a Quaternary Catchment scale, using the *ACRU* agrohydrological model. As a result, the development of the Quaternary Catchments database was reviewed, as was the *ACRU* model.

In regard to the latter, the specific sugarcane related equations were focused upon. Sugarcane plant growth relies largely upon conducive climatic conditions. In the following chapter, mapping second order derivatives of temperature which affect sugarcane plant growth will be addressed.

4. MAPPING SECOND ORDER DERIVATIVES OF TEMPERATURE

4.1 Introduction

Temperature is a basic climatological parameter often used as an index of the energy status of the environment (Schulze, 1997). Mapping derivatives of temperature may potentially include a large number of variables; however, in this chapter, only the concept and mapping of heat units as well as the mapping of frost parameters will be covered.

4.2 Heat Units

The concept of heat units revolves around the dependency of plants and organisms upon accumulated heat for development (Hughes, 1992; McMaster, 1997; Horton *et al.,* 2001). This may be divided into specific life stages or an entire life span (Horton *et al.,* 2001). The measure of accumulated heat is known as physiological time. Physiological time is estimated and expressed as so-called heat units in degree days (°C.d). Heat units are an accumulation, over a specified period of time, of mean daily temperatures above a certain lower threshold value below which active growth is assumed to be inhibited (Hughes, 1992; Horton *et al.,* 2001).

4.2.1 Limitations of the Heat Unit Concept

Chang (1968) points out that the heat unit concept is not without limitations, and these include that:

- a relationship is assumed to exist between growth and temperature,
- threshold temperatures may vary during the life cycle of the crop or pest,
- temperatures exceeding the upper threshold may have a detrimental effect on plant or pest development,

- in terms of biological processes, diurnal temperatures may be more significant than daily means, which are used in heat unit calculations, and that
- the heat unit concept does not distinguish between (say) a cool early summer/hot late summer vs. a hot early/cool late summer combination.

The heat unit concept nevertheless remains a simple empirical concept that may be applied to a number of agricultural operations (Schulze and Maharaj, 2007c).

4.2.2 Calculation of Heat Units

The estimation of Heat Units (HUs) over southern Africa was undertaken with the 50 year time series of daily maximum and minimum temperatures developed by Schulze and Maharaj (2004) and described in Section 3.3. Heat units that may be related to various processes affecting sugarcane growth were computed for base temperatures of 10°C, 12°C, 16°C and 18°C. The method used for computing HUs, accumulated over a period of time, is given as:

$$\sum HUs = \sum \left(\frac{T_{max} + T_{min}}{2} - T_{base}\right) \text{ for } HUs \geq 0 \qquad (4.1)$$

where

$\sum HUs$ = daily heat units (°C.d), accumulated over a period of time,

T_{max} = daily maximum temperature (°C) for a given day,

T_{min} = daily minimum temperature (°C) for a given day, and

T_{base} = base temperature (°C).

Each of the HU maps is significant to the sugarcane industry as the different threshold temperatures relate to various temperature related requirements of not only sugarcane growth, but also of temperature requirements of a variety of pests and diseases affecting the sugarcane growth. For example, Bezuidenhout (2000) found for sugarcane that prior to the emergence of canopy the base temperature required for HUs was 10°C. After canopy emergence, Singels and Donaldson (2000) found that a base temperature of 16°C was required for canopy development. The threshold temperature required for the development of the small and large larvae of the eldana pest (cf. Section 5.2) is approximately 10°C and 12°C, respectively (Horton *et al.,* 2001). These are a few examples of sugarcane related temperature requirements. The importance of HU maps for a range of base temperatures can therefore be seen to be applicable to a wide range of issues affecting the growth and production of sugarcane.

4.2.3 Distribution Patterns of Heat Units over Southern Africa

For the sake of completeness, seasonal distributions of heat units with various base temperatures were mapped for the entire study region of southern Africa, and not only for the sugarcane growing areas. In addition to this, tables of the mean numbers of heat units and their associated coefficients of variation were developed for all nine provinces of South Africa as well as for Lesotho and Swaziland.

The distribution patterns of heat units with a base temperature of 10°C show important differences between summer (Figure 4.1) and winter seasons (Figure 4.2). Table 4.1 indicates that in the summer season the majority of southern Africa experiences heat units in excess of 1200 °C.d, while in winter the opposite is true, with most of southern Africa accumulating fewer than 1200 °C.d. This is significant in that the development of many pests and diseases is severely limited in the winter season. For example, the development of eldana larvae is limited in winter for most of southern Africa; however in summer the conditions are far more favourable for their growth and development, as may be seen in Figures 5.5 and 5.6 in the following chapter. The seasonal range of HUs with a base of 10°C for the summer season from October to March is from an average of 2 474 °C.d in the Limpopo province to 1 086 °C.d in the higher altitude Lesotho region. Values of the coefficient of variation (CV) of gridded values per province/country associated with these distributions are generally low, with the highest value being 40% in Lesotho. The higher values of HUs during the winter season from April to September are generally limited to the northern and eastern parts of southern Africa, including the Northern Cape, North West province, Swaziland and the coastal and northern parts of KwaZulu-Natal. The CV values given are, however, higher than those for the summer months, with the highest value being 70% in Lesotho. These results suggest a higher spatial variability in temperatures during the winter months, compared to those in the summer. This is probably as a result of the temperature thresholds not being reached for some areas during the winter period.

Similar to Figures 4.1 and 4.2, the differences in the number of degree days with a base temperature of 12°C, shown in Figure 4.3 for summer and Figure 4.4 for winter, are considerable. Table 4.2 confirms this, as in winter the average accumulated HUs are generally less than half of those accumulated over the summer period. From Table 4.2, the CV values given for the winter period are generally double those for the summer period, again confirming the higher spatial variability of temperature thresholds being reached in winter. The general distribution of heat units is similar to that displayed in Figures 4.1 and 4.2, with the central parts of southern Africa experiencing low values of accumulated heat units, with higher values found in the north and northeastern parts of southern Africa.

Similar distribution patterns are shown in Figures 4.5, 4.6, 4.7 and 4.8 for summer and winter periods with base temperatures of 16°C and 18°C, respectively. The number of accumulated heat units does, however, decrease with an increase in base temperature, with the highest values for the summer periods being 1 383 °C.d and 1 028 °C.d for base temperatures of 16°C and 18°C respectively, in Limpopo. The lowest heat unit values are again in the Lesotho highlands region where, during the winter periods (Table 4.3 and 4.4) the values are less than 15 heat units for both base temperatures (Table 4.3 and 4.4). The significance of the lower values of heat units is that temperature dependent factors affecting the sugarcane industry, relating to minimum threshold temperatures of 16°C and 18°C, would be very limiting to growth and development, especially in the winter months. From Tables 4.3 and 4.4, the coefficient of variation increases with an increase in base temperature from 16°C to 18°C. An increase in the CV is also noted between the summer and winter periods.

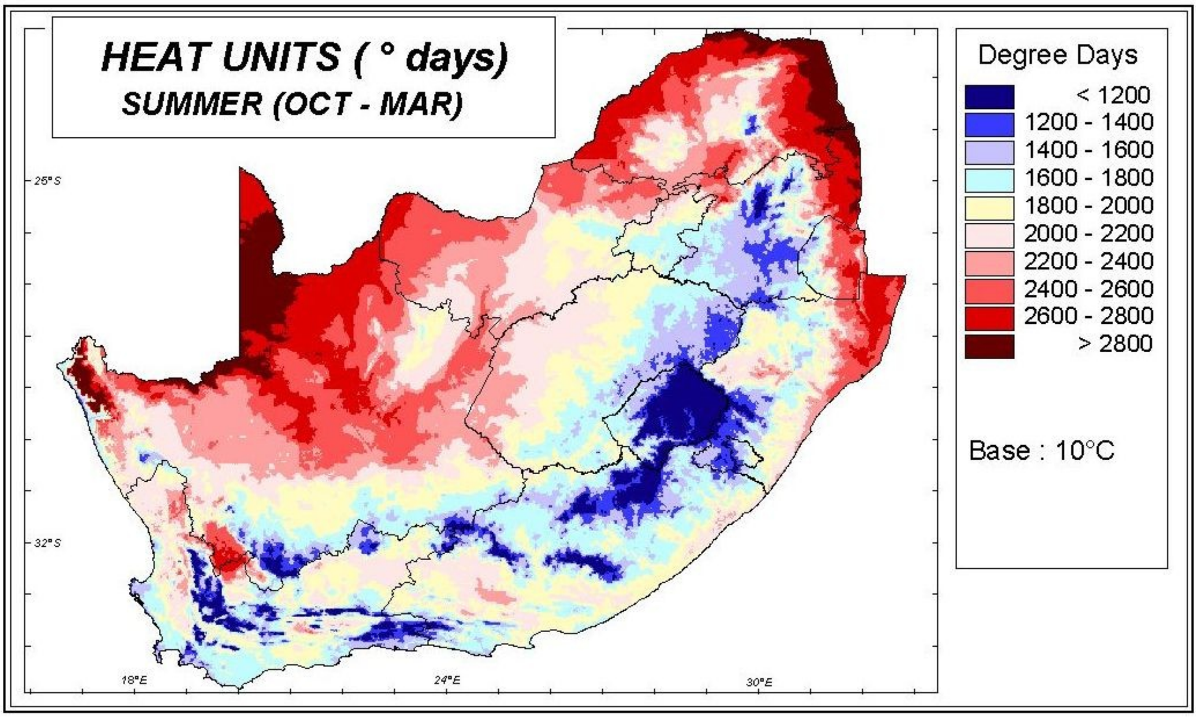

Figure 4.1 Heat units, base 10˚C, over southern Africa for the summer period from October to March

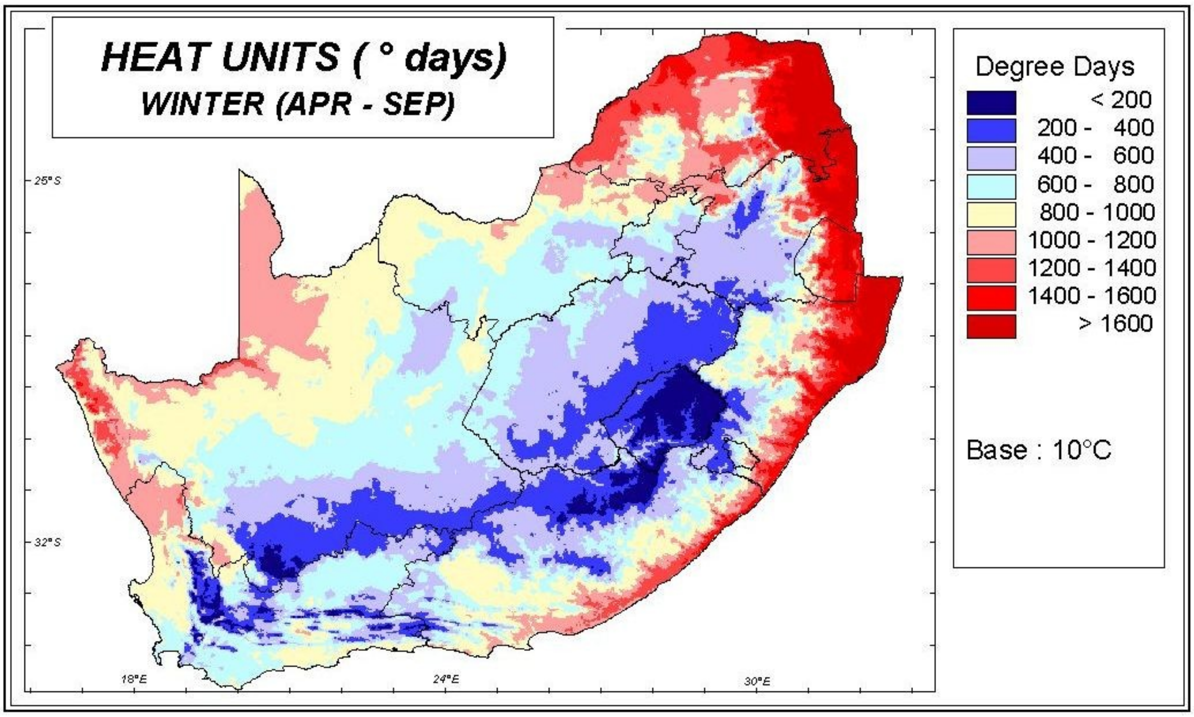

Figure 4.2 Heat units, base 10˚C, over southern Africa for the winter season from April to September

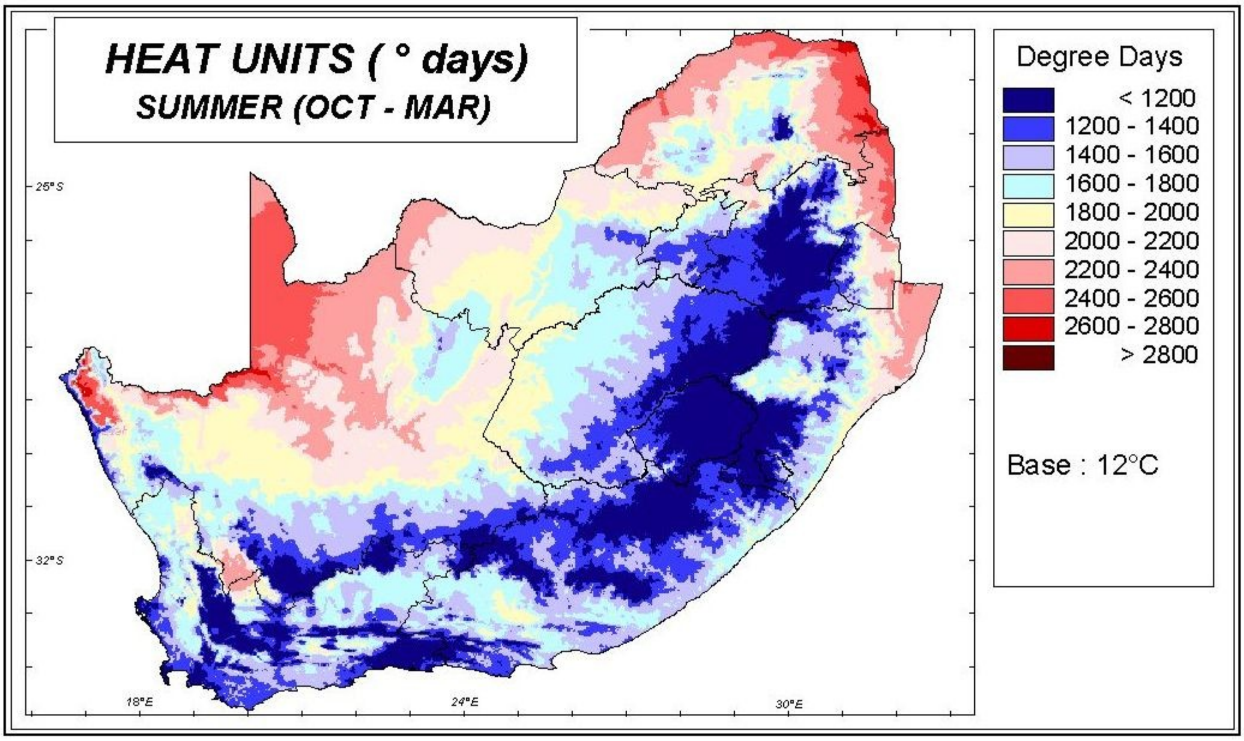

Figure 4.3 Heat units, base 12˚C, over southern Africa for the summer season from October to March

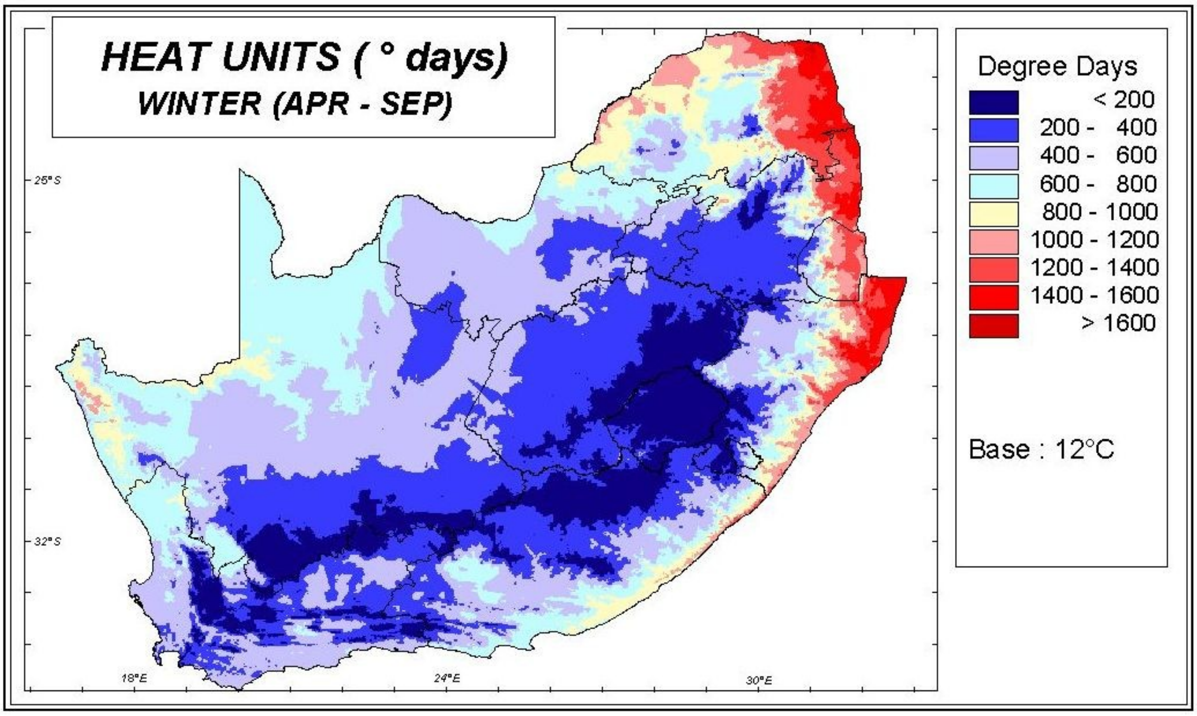

Figure 4.4 Heat units, base 12˚C, over southern Africa for the winter season from April to September

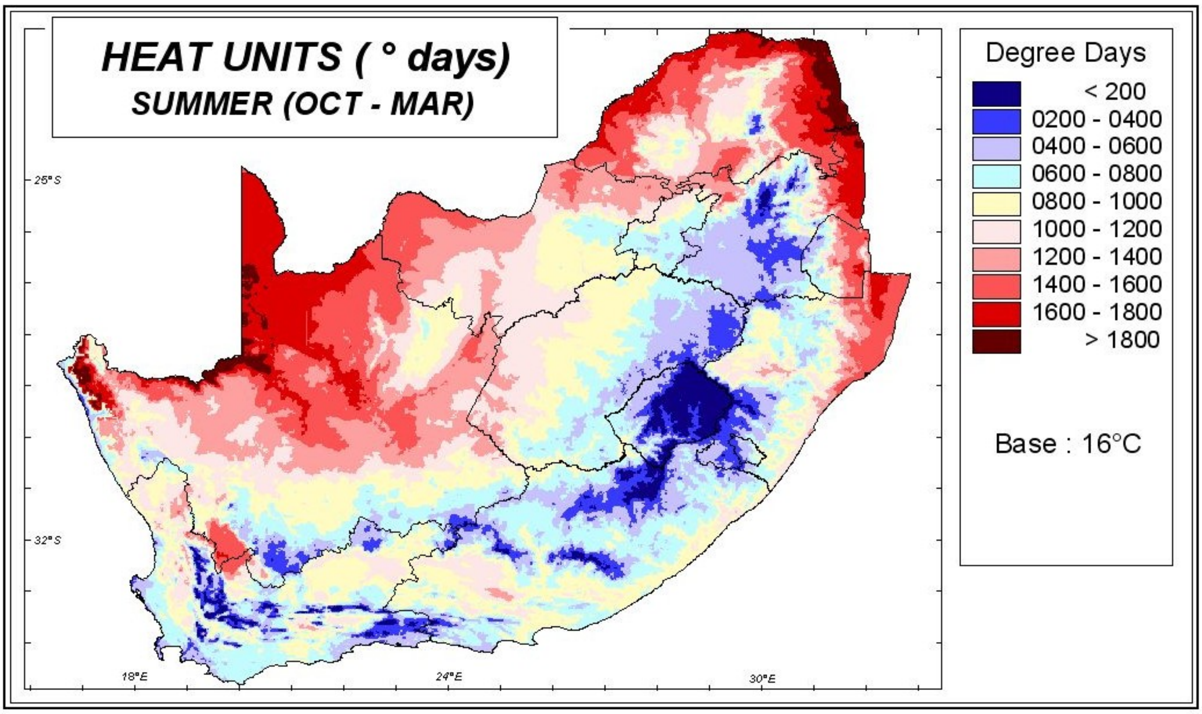

Figure 4.5 Heat units, base 16˚C, over southern Africa for the summer season from October to March

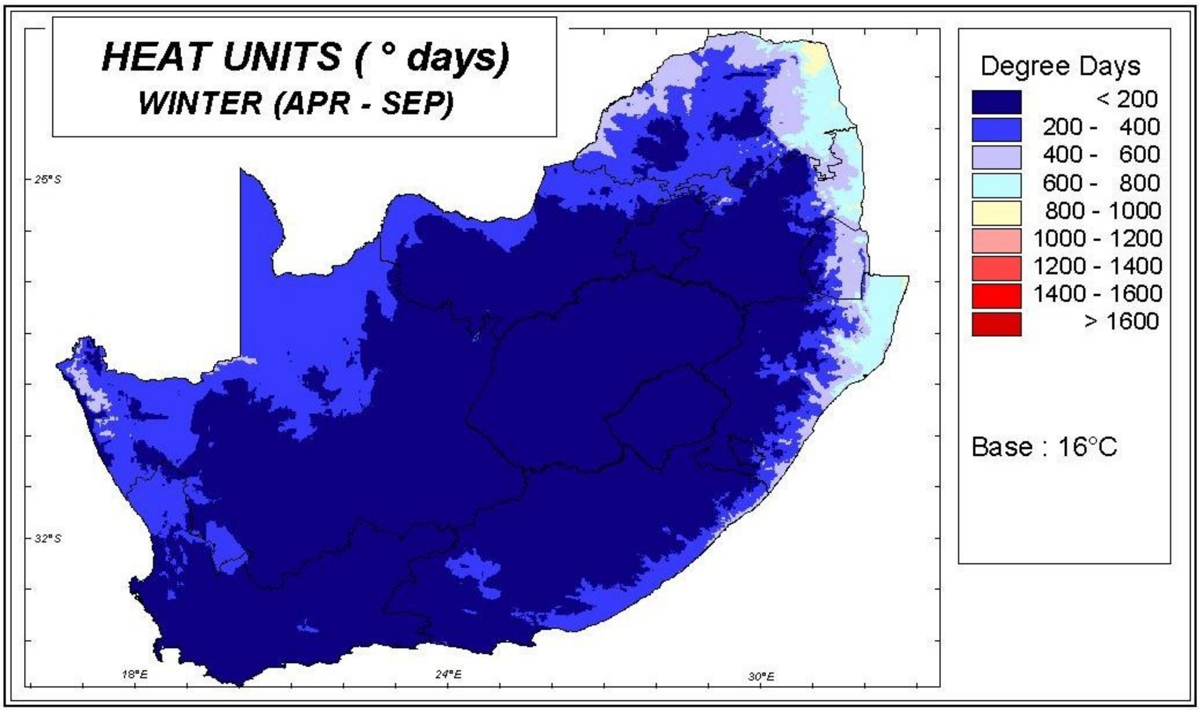

Figure 4.6 Heat units, base 16˚C, over southern Africa for the winter season from April to September

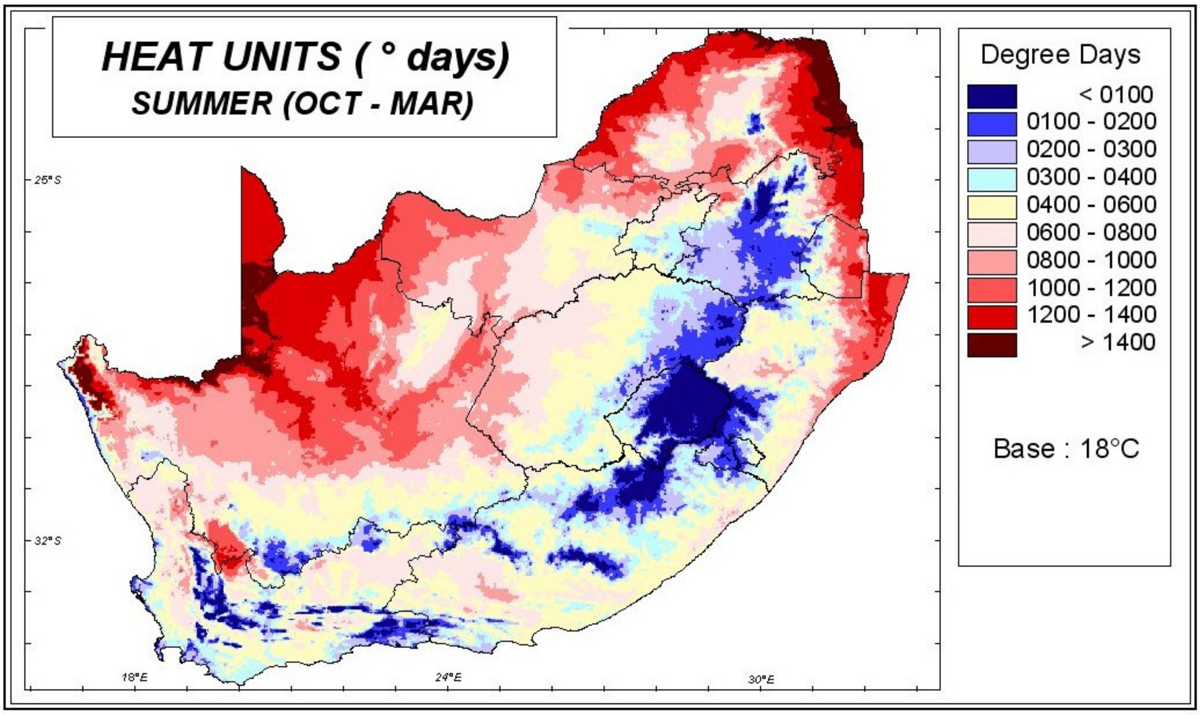

Figure 4.7 Heat units, base 18˚C, over southern Africa for the summer season from October to March

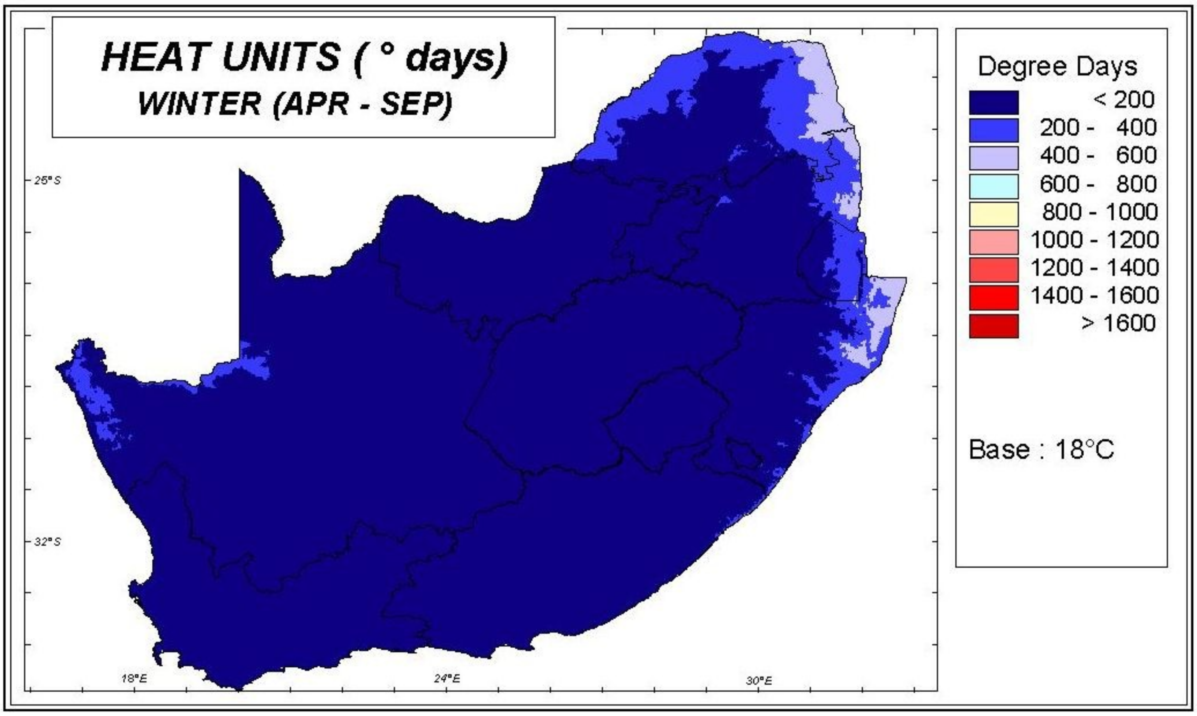

Figure 4.8 Heat units, base 18˚C, over southern Africa for the winter season from April to September

Table 4.1 Mean heat units (base 10˚C) and the CVs, for both the summer and winter periods for the different provinces and countries making up the study area

Heat Units (Base 10˚C) October - March			**Heat Units (Base 10˚C) April - September**		
Province	**Mean**	**CV (%)**	**Province**	**Mean**	**CV (%)**
Limpopo	2473.9	12	Limpopo	1296.4	25
Mpumalanga	1866.9	27	Mpumalanga	839.5	57
North West	2260.5	10	North West	796.9	18
Northern Cape	2291.3	17	Northern Cape	762.5	33
Gauteng	1877.1	10	Gauteng	661.8	25
Free State	1849.8	14	Free State	473.3	26
KwaZulu-Natal	1976.4	22	KwaZulu-Natal	1073.5	44
Eastern Cape	1708.7	17	Eastern Cape	677.8	46
Western Cape	1771.7	20	Western Cape	651.7	38
Swaziland	2206.1	17	Swaziland	1295.0	25
Lesotho	1086.3	40	Lesotho	193.4	70

Table 4.2 Mean heat units (base 12˚C) and the CVs, for both the summer and winter periods for the different provinces and countries making up the study area

Heat Units (Base 12˚C) October - March			**Heat Units (Base 12˚C) April - September**		
Province	**Mean**	**CV(%)**	**Province**	**Mean**	**CV(%)**
Limpopo	2109.5	15	Limpopo	951.7	32
Mpumalanga	1505.8	33	Mpumalanga	567.7	73
North West	1896.4	11	North West	521.1	22
Northern Cape	1929.7	20	Northern Cape	505.1	39
Gauteng	1513.6	13	Gauteng	405.6	32
Free State	1488.6	18	Free State	277.4	34
KwaZulu-Natal	1615.9	26	KwaZulu-Natal	763.3	54
Eastern Cape	1351.5	21	Eastern Cape	425.9	55
Western Cape	1414.6	24	Western Cape	395.0	46
Swaziland	1842.5	21	Swaziland	946.4	32
Lesotho	760.6	52	Lesotho	94.1	85

Table 4.3 Mean heat units (base 16˚C) and the CVs, for both the summer and winter periods for the different provinces and countries making up the study area

Heat Units (Base 16˚C) October - March			**Heat Units (Base 16˚C) April - September**		
Province	**Mean**	**CV (%)**	**Province**	**Mean**	**CV (%)**
Limpopo	1383.8	22	Limpopo	394.4	48
Mpumalanga	812.3	57	Mpumalanga	196.0	115
North West	1174.8	18	North West	165.4	33
Northern Cape	1227.6	29	Northern Cape	174.2	54
Gauteng	800.7	23	Gauteng	103.0	53
Free State	795.8	31	Free State	63.8	58
KwaZulu-Natal	923.8	41	KwaZulu-Natal	287.3	80
Eastern Cape	688.8	34	Eastern Cape	116.3	77
Western Cape	750.5	37	Western Cape	105.8	65
Swaziland	1127.0	32	Swaziland	362.0	48
Lesotho	261.1	90	Lesotho	13.4	125

Table 4.4 Mean heat units (base 18˚C) and the CVs, for both the summer and winter periods for the different provinces and countries making up the study area

Heat Units (Base 18˚C) October - March			**Heat Units (Base 18˚C) April - September**		
Province	**Mean**	**CV (%)**	**Province**	**Mean**	**CV (%)**
Limpopo	1028.7	28	Limpopo	213.6	58
Mpumalanga	512.8	82	Mpumalanga	96.1	140
North-West	826.9	25	North-West	73.4	44
Northern Cape	901.4	36	Northern Cape	87.0	66
Gauteng	474.8	35	Gauteng	37.2	75
Free State	492.5	43	Free State	22.5	76
Kwazulu-Natal	615.5	54	Kwazulu-Natal	141.1	96
Eastern Cape	417.4	44	Eastern Cape	48.3	88
Western Cape	474.0	48	Western Cape	46.3	81
Swaziland	789.9	42	Swaziland	179.9	59
Lesotho	118.1	117	Lesotho	3.7	153

4.3 Frost in Sugarcane

In the KwaZulu-Natal midlands sugarcane is grown at altitudes of between 750 and 1 100 m, and owing to the relatively high altitudes, minimum temperatures often drop below 0 °C during the winter months. Mann (1991) states that severely cold winters may cause significant crop losses in sugarcane. Valleys often act as cold air pockets, resulting in varying distributions and intensities of frost for the same night (Mann, 1991). It is, therefore, very difficult to predict or map frost accurately.

Sugarcane is most prone to frost damage while still young, prior to full canopy development (Mann, 1991). Much of the damage caused by frost results in either a stunting of the growth of the sugarcane plant, or a reduction in its photosynthetic ability. Wilson (1960) disaggregated four different severities of frost damage to sugarcane, *viz*:

- fully developed or exposed parts of sugarcane plants leaves are killed, but the more protected inner parts of the spindle leaves are unaffected and can remain green,
- the inner, more protected leaves of the spindle are killed, but the apical growing point and basal parts of other leaves in the spindle are unaffected,
- the apical growing point is killed in addition to the first two points made above, and the
- lateral buds on the main stem are killed in addition to the three points already mentioned.

In a study conducted by Mann (1991) on a farm near Dalton in the KwaZulu-Natal midlands, the number of frost occurrences was recorded at 10 sites with various altitudes. Results showed significant differences between the numbers of frost occurrences in the valley bottoms, compared with frosts on the sites with the higher altitudes. The study showed a total of 37 frosts in the valley bottom compared to one on the hilltop, over the one year study period in 1990. Sugarcane damage was more prevalent where frost frequency was highest. This finding was similar to that of Roth's (1966), who linked the extent of frost damage to the duration and severity of sub-zero temperatures.

4.3.1 Frost Frequency

In order to determine areas where frost is more likely to occur, analyses were undertaken using the South African temperature database (Schulze and Maharaj, 2004) described in Section 3.3. Two indices of frost were evaluated *viz.*

- the frequency (%) of frost occurrences per annum, and
- the mean number of heavy frosts per annum (minimum temperatures below -2ºC).

The frequency of frost occurrences was computed from the number of times per year when daily minimum temperature dropped to below 0ºC over the 50 year time series from 1950 to

1999. Areas which had fewer than 5 years of frost occurrences out of the 50 year study period were classed as frost free areas. The number of heavy frost occurrences per annum was computed from the mean number of occurrences per annum where the minimum temperature dropped below -2ºC.

4.3.2 Distribution Patterns of Frost over South Africa

In Figure 4.9 the frequency (%) of years, for the time period 1950 to 1999, during which frost occurred, is shown. The distribution patterns indicate frost free zones along the periphery of South Africa. The general trend indicates a progressive increase in the percentage of years with frost with an increase in altitude as one moves inland, with much of the central region of South Africa indicating that 100% of the years had frost occurring. These findings are supported by the information in Table 4.5, which show a higher mean annual number of frost occurrences in the higher altitude, inland provinces of South Africa. In regard to areas in which sugarcane is grown (cf. Figure 3.6), the majority of the KwaZulu-Natal midlands and Swaziland areas indicate that less than 20% of years experienced frost. There were, however, small patches showing between 20% and 40% of years having frost.

The mean number of heavy frosts per annum (Figure 4.10) shows that heavy frost occurrences are generally limited to the higher altitude, inland regions of South Africa. The number of heavy frosts per year ranges from fewer than 10 occurrences around the periphery of South Africa to in excess of 100 occurrences in certain of the highland regions of Lesotho. The central parts of South Africa, including the Free State, show a range of between 10 and 50 heavy frost events per annum. Heavy frost distributions depicted in Figure 4.10 generally do not overlap with areas in which sugarcane is grown. A small area in the Lebombo mountain region in the southeast of Swaziland does, however, indicate a low incidence of heavy frosts per annum; so sugarcane should not be planted here.

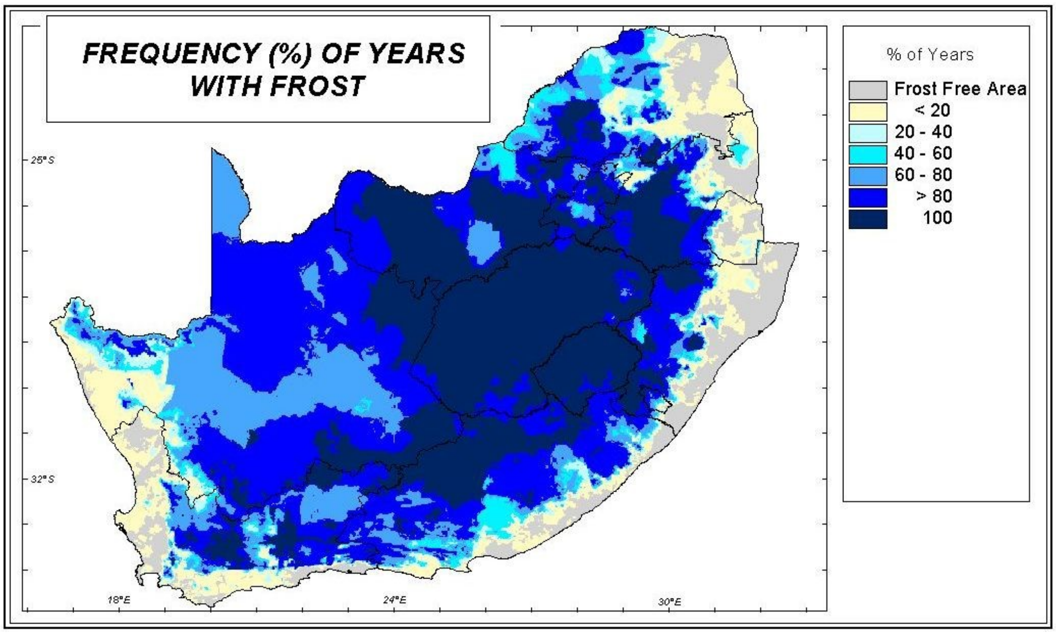

Figure 4.9 Frequencies of frost occurrences (T ≤ 0ºC) over in southern Africa

Table 4.5 Mean number of frost occurrences in southern Africa

Province / Country	**Mean Value**	**CV (%)**	**Maximum Value**	**Minimum Value**	**Exceedence Probability**		
					80%	**50%**	**20%**
Limpopo	27.9	29	57.4	14.9	20.3	27.1	34.5
Mpumalanga	42.2	32	77.2	14.0	31.6	40.3	54.1
North West	36.4	23	59.4	14.9	28.5	37.5	43.8
Northern Cape	32.0	37	96.3	14.0	21.6	29.2	42.0
Gauteng	40.4	32	75.7	13.9	27.9	39.1	53.5
Free State	52.3	25	153.9	15.8	40.6	52.5	63.7
KwaZulu-Natal	36.8	52	161.5	13.0	22.3	31.0	49.3
Eastern Cape	46.7	43	156.8	15.2	28.4	43.7	63.8
Western Cape	30.6	38	105.6	13.5	20.0	28.5	40.4
Swaziland	17.1	17	25.3	10.5	14.8	16.9	19.0
Lesotho	82.5	44	193.5	19.6	48.3	78.8	115.4

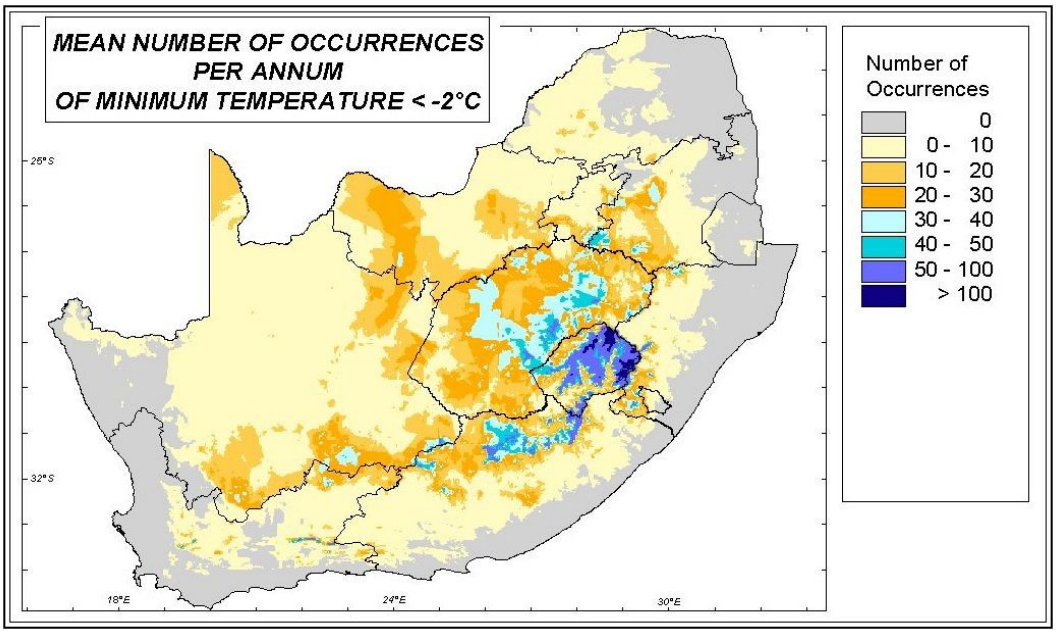

Figure 4.10 Mean number of heavy frosts per annum (T_{min} < -2ºC) over southern Africa

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In this chapter, selected second order derivatives of temperature were mapped. These included heat units and frost. Their distributions may be used to determine, for example, temperature related distributions of specific pests and diseases, as well as determining areas that may or may not be suitable for sugarcane crop production. In the following chapter climate based constraints in regard to pests and diseases are mapped and their distributions evaluated.

5. MAPPING CLIMATE BASED CONSTRAINTS IN REGARD TO PESTS AND DISEASES

5.1 Introduction

The incidence of pests and diseases affecting sugarcane is determined largely by climatic conditions. From this, the distributions of some of the more serious pests and diseases have been mapped according to specific climate related parameters. The pests and diseases mapped in this project include eldana, chilo and rust, each of which will be addressed in this chapter.

5.2 The *Eldana saccharina* Stalk Borer

The eldana stalk borer (*Eldana saccharina* Walker), indigenous to South Africa, is one of the most serious pests in the sugarcane industry, causing substantial annual losses in sugarcane yield (Carnegie *et al.,* 1976). It is for this reason that this pest has been the focus of much research by scientists from SASRI and other institutions, and is included in this dissertation. For more background information regarding the eldana stalk borer pest *per se*, refer to Section 2.2.1.

5.2.1 Determination of Distribution Patterns of *Eldana saccharina*

Way (1994) established that temperature was one of the main drivers of eldana activity, affecting mating success, adult longevity, oviposition and egg development. By understanding the specific temperature thresholds which limit certain life stages of the eldana pest, it is possible to develop algorithms and create distribution patterns of the pest within sugarcane growing areas, based on these thresholds.

The ambient minimum temperature threshold required for eldana mating is 15°C (Atkinson, 1981; Leslie, 2006). In addition to this, the time period during which eldana have been found to mate coincides with the first 3 hours after sunset (Atkinson 1981; Leslie, 2006). By combining these two requirements, a mating index was formulated whereby the number of hours, during the first 3 hours after sunset, was accumulated for each day on the condition that the temperature was above 15°C. This was used to map possible distribution patterns of a mating index for eldana.

Prior to the calculation of the eldana mating index, it was necessary to derive hourly temperatures. This was done by disaggregating daily temperature values from the South African temperature database (described in Section 3.3) into hourly temperatures, using the procedures which are described in Section 3.3.4.

A variety of distribution patterns were mapped at a 1' x 1' resolution (i.e. ~1.7 x ~1.7 km) using the mating index as described above. The first was the mean number of accumulated mating hours per annum from 1950 to 1999. This time period was then divided into two equally long 25 year time periods, 1950 to 1975 and 1976 to 1999, in order to establish whether there where any potential changes in the distribution patterns of eldana, resulting from possible changes in temperature patterns during this time period. Maps showing the mean numbers of accumulated mating hours for both the summer (October – March) and the winter (April – September) season were also created in order to ascertain differences in distribution patterns between the two major seasons.

5.2.2 Distribution Patterns of *Eldana saccharina* over Southern Africa

The values shown in Figure 5.1 of the mean annual number of eldana mating hours, range from fewer than 500 hours in the cooler inland regions of South Africa to in excess of 1 000 hours in the eastern parts of the country, including the coastal and northern parts of KwaZulu-Natal, eastern Mpumalanga and the eastern parts of the Limpopo province bordering on Mozambique. The distribution of areas showing with 750 to 1 000 mating hours include much of the region on the periphery of the borders of South Africa. Finger-like extensions, extending inland from the coastal regions of KwaZulu-Natal are noted, these are the result of higher temperatures within the valleys of some of the major river systems in this province (Schulze and Maharaj, 2007a). Most of the central regions of South Africa have between 500 and 750 mating hours per year, with the majority of Lesotho as well patches in the north-eastern Free State, KwaZulu-Natal, Northern Eastern and Western Cape provinces showing values of fewer than 500 mating hours.

A comparison of the number of eldana mating hours was made between the earlier 25 years of the available temperature database, from 1950 to 1974 (Figure 5.2) and the later 25 years from 1975 to 1999 (Figure 5.3), with the differences between the two shown in Figure 5.4. No significant regional trends of either a marked increase or a decrease in the number of potential eldana mating hours are observed in Figure 5.4. However, patches of both increases and decreases in the number of potential mating hours are noted throughout South Africa.

Significant differences are, however, evident in Figures 5.5 and 5.6 between the summer and winter season distributions of potential mating hours for eldana. These differences are noted especially in the Northern Cape, North West, Limpopo, Mpumalanga, Swaziland and KwaZulu-Natal. In areas of the Northern Cape the number of potential mating hours drops from more than 525 hours in summer to fewer than half of that amount in the winter period. In the North West and Limpopo provinces, during the summer months, the majority of the area is shown to have in excess of 500 potential eldana mating hours. This number, however, drops to fewer than 300 in the winter period. A significant decrease in the areas showing more than 500 potential eldana mating hours is noted in Mpumalanga, Swaziland and KwaZulu-Natal. These distributions are significant in that they indicate areas which are highly to be conducive to the eldana pest mating in the summer months, but not conducive to the pest's mating during the winter months, thereby limiting its potential spread.

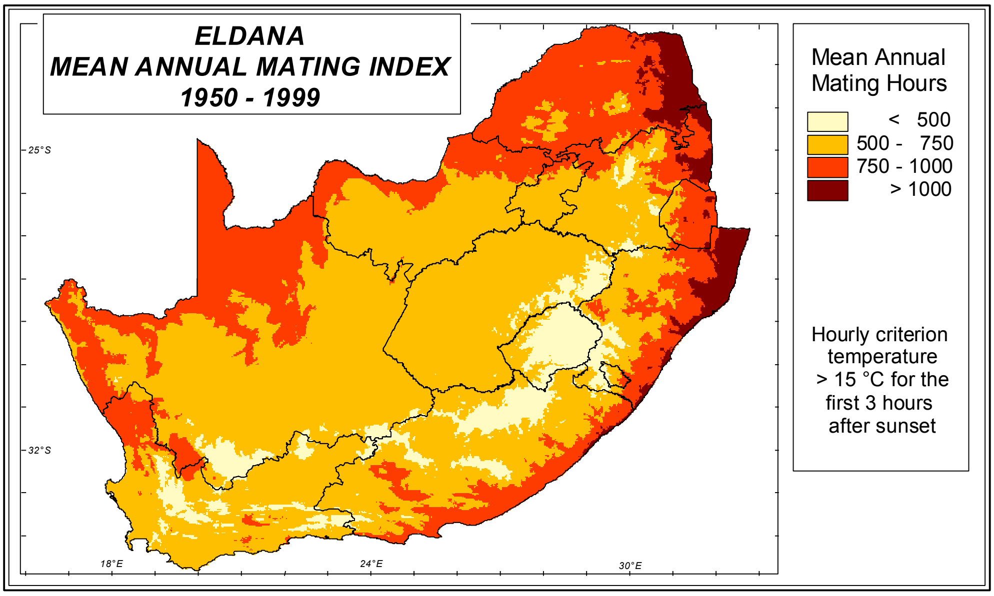

Figure 5.1 Mean annual number of potential eldana mating hours for the 50 year period 1950 -1999

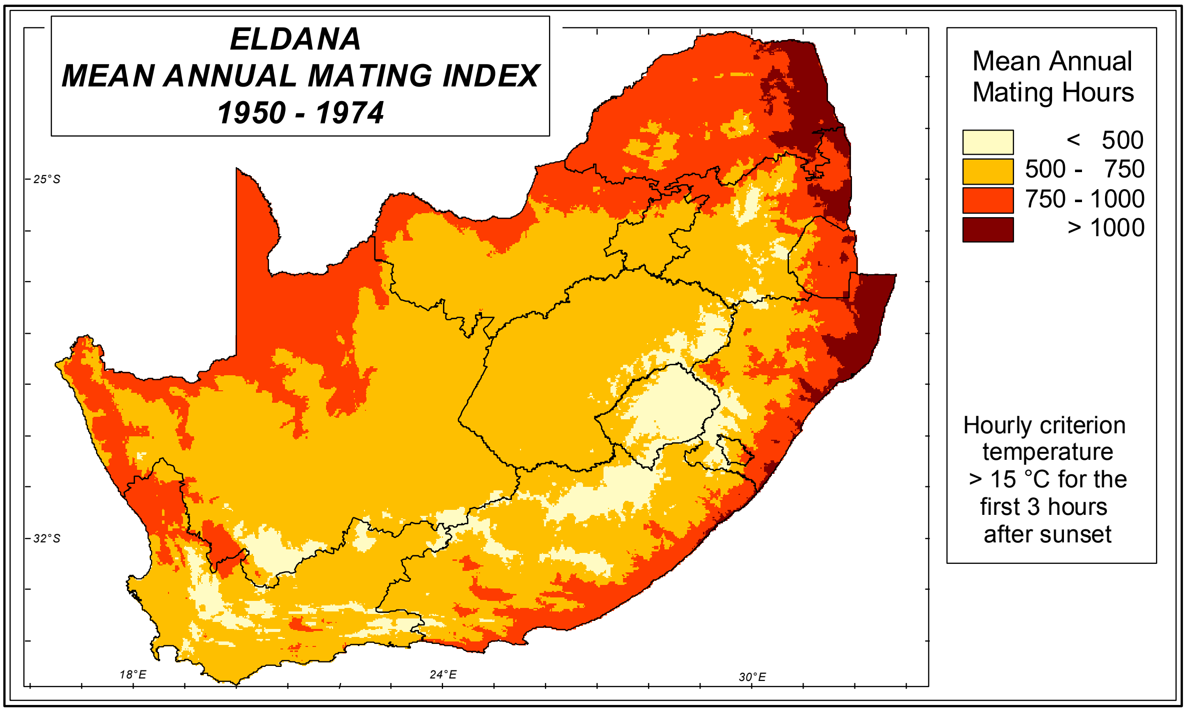

Figure 5.2 Mean annual number of potential eldana mating hours for an earlier 25 year period from 1950 to 1974

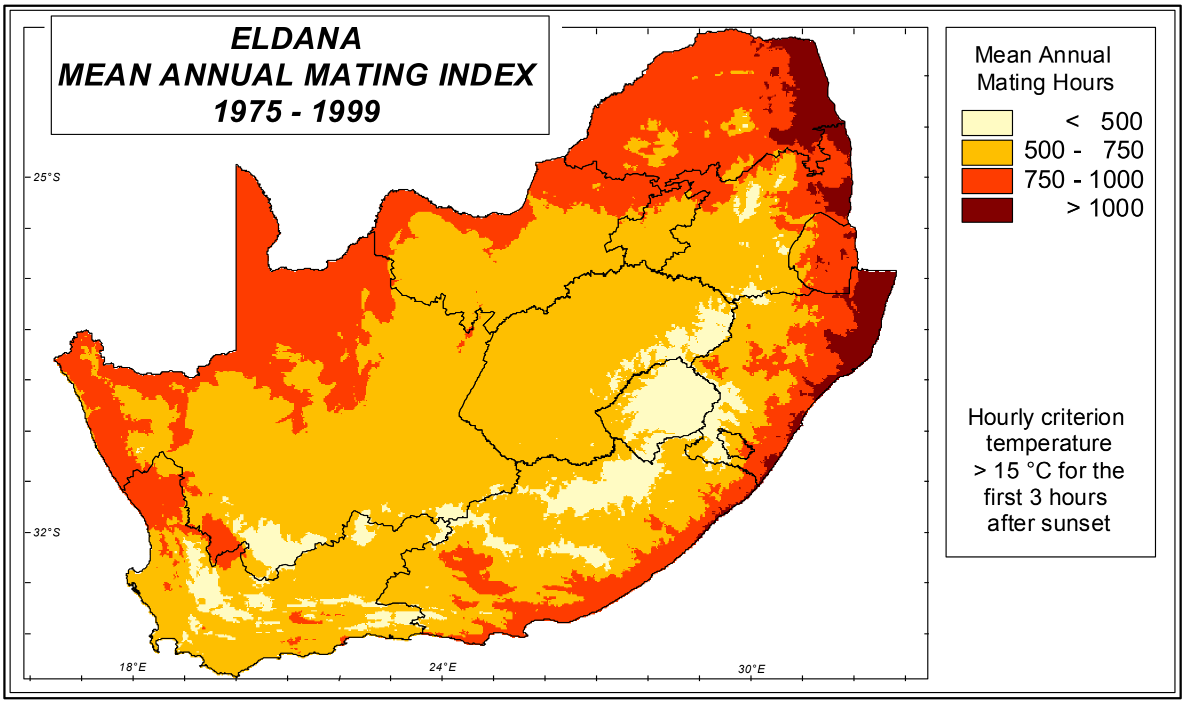

Figure 5.3 Mean annual number of potential eldana mating hours for a later 25 year period from 1975-1999

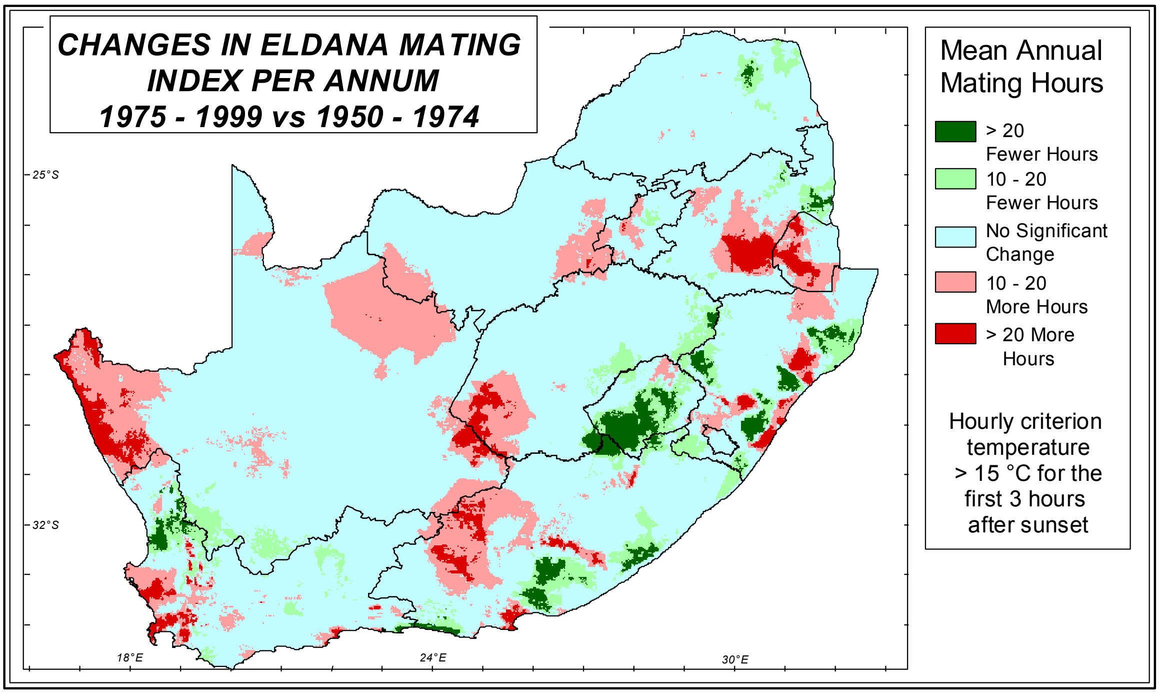

Figure 5.4 Changes in mean annual potential mating hours between the 1975 to 1999 and 1950 to 1974 periods

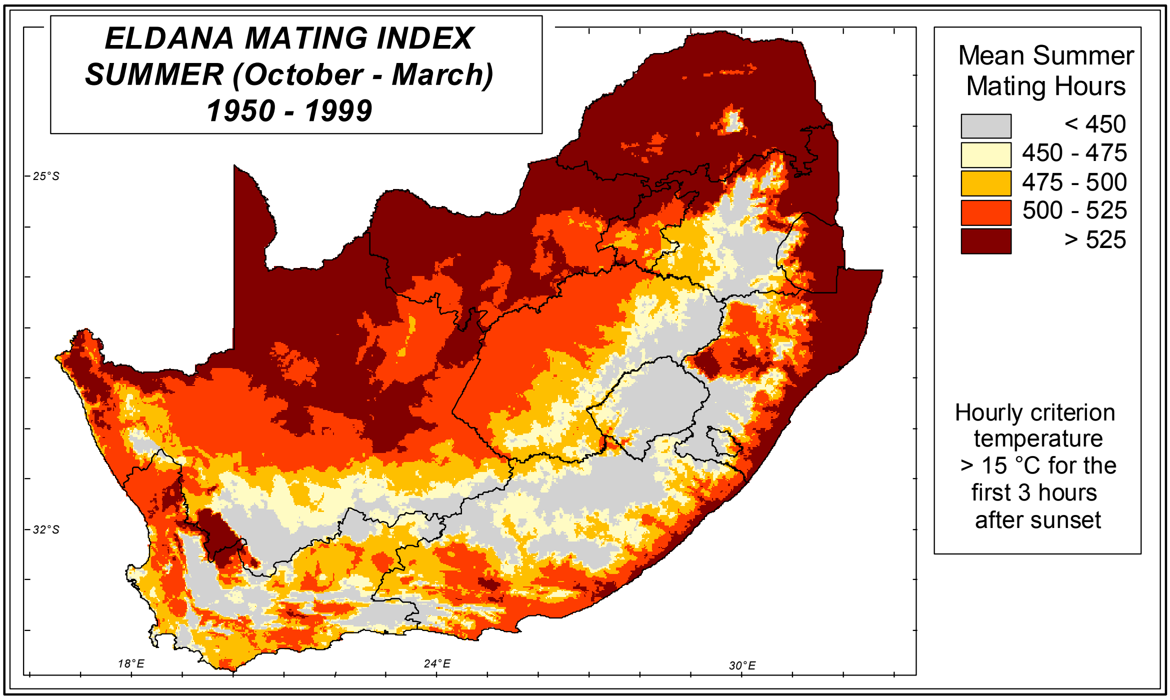

Figure 5.5 Mean number of potential eldana mating hours in the summer season from October to March

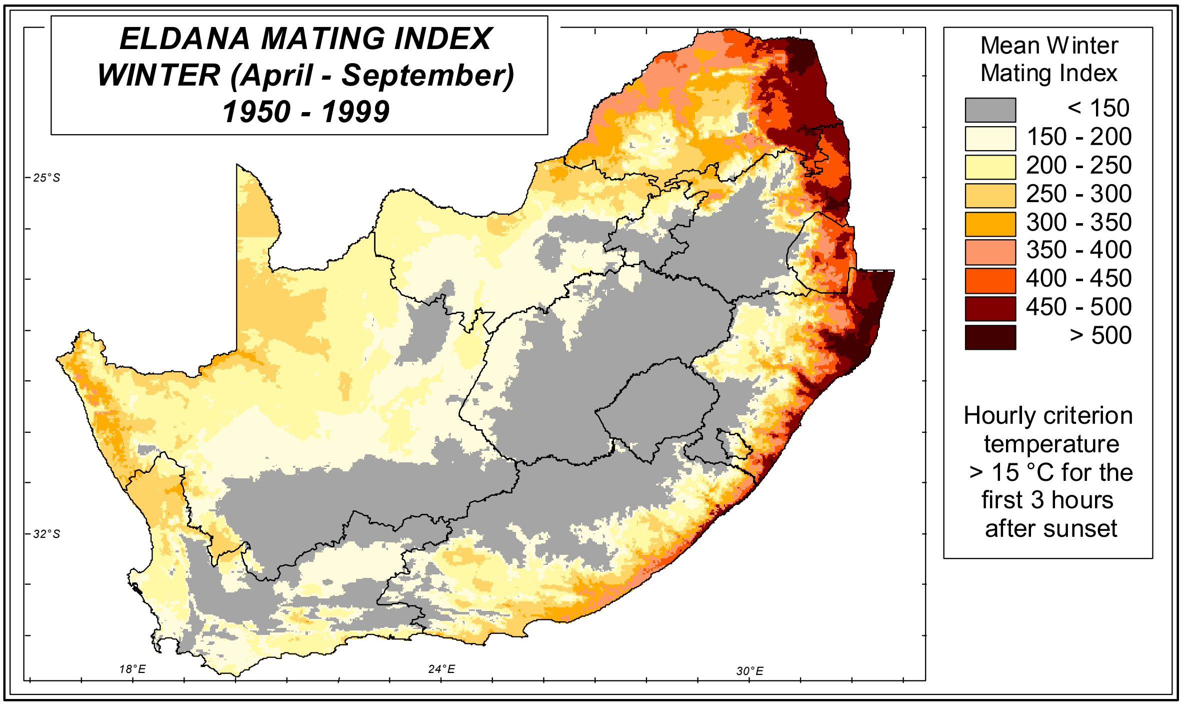

Figure 5.6 Mean number of potential eldana mating hours in the winter season from April to September

From the maps depicted in Figures 5.1 to 5.6, it was found that the eastern parts of southern Africa, particularly the coastal and northern parts of KwaZulu-Natal, Mpumalanga and the Limpopo provinces as well as Swaziland experience climatic conditions that are the most suitable for the reproduction of eldana. These areas largely coincide with the regions in which sugarcane is grown. The results obtained from this research may be used as a tool in strategic decision making. By identifying areas in which eldana may be a problem, specific sugarcane varieties may be planted to reduce the potential damage of the pest. Strategic decisions relating to planting dates may also be made.

5.3 The *Chilo sacchariphagus* Stalk Borer

The chilo sugarcane stalk borer has the potential to cause substantial yield losses to the sugarcane industry (Way and Turner, 1999) and has, therefore, been identified as a potentially serious pest. It is for this reason that chilo has been included in this study. For more background information on the *Chilo sacchariphagus* stalk borer please refer to Section 2.2.2.

5.3.1 Determination of Distribution Patterns of *Chilo sacchariphagus*

Similar to the case of eldana, the distribution patterns of potential chilo infestations are governed by temperature. Studies conducted by Goebel (2006) reveal that eggs laid by chilo will only hatch if the temperature is above 13°C, and that chilo pupae and larvae will only develop at temperatures above 13°C and 12.7°C, respectively. The ambient minimum temperature threshold required for chilo mating is 15°C, while for maintaining active growth and development it is 17°C (Goebel, 2006). The temperature thresholds given above were verified by Goebel (2006) through a series of laboratory experiments conducted at the CIRAD Experiment Station (St-Denis, Réunion) as part of an ongoing research programme on integrated pest management against this pest. In addition to this, it was found that chilo are only able to mate during the night-time (Way and Turner, 1999). From the above-mentioned thresholds the following three indices where formulated in order to map possible distributions of the chilo pest, *viz.*

- a mating index,
- a maintenance index, and
- a mortality index.

The chilo mating index is defined as the average number of accumulated night-time hours when the temperature is above 15°C, according to the above-mentioned thresholds as defined by Goebel (2006) and Way and Turner (1999).

The chilo maintenance index shows distributions of areas in which temperatures are sufficient for the active growth and development of the pest. For this index the number of consecutive days on which the average temperature is below 17°C was calculated. Although 17°C is not the optimum temperature for chilo activity, research undertaken by Goebel (2006) indicates that this temperature is suitable for chilo to grow and develop successfully. Therefore, by considering the number of consecutive days on which this threshold is not exceeded, areas that are not conducive for the growth and development of chilo can be mapped. The higher the number of consecutive days below this threshold, the less likely the pest is to maintain growth and development.

The third index formulated was that of the mortality index, which shows the non-likelihood of chilo survival. Goebel (2006) found that the minimum temperature required for chilo survival was approximately 13°C. This threshold was therefore used to develop an index whereby the mean number of two or more consecutive days during which the minimum temperature was below 13°C would indicate the non-likelihood of chilo survival. The longer the period with minimum temperatures below 13°C, the less likely the pest is to survive.

The above-mentioned indices were mapped at 1' x 1' resolution (i.e. ~1.7 x ~1.7 km), using the South African daily temperature database (Schulze and Maharaj, 2004) as described in Section 3.3. However, prior to the calculation of the three chilo indices, it was necessary to disaggregate daily temperature values into hourly temperatures. The procedures used to disaggregate the daily temperature values have been described in Section 3.3.4.

5.3.2 Distribution Patterns of *Chilo sacchariphagus* over Southern Africa

The distribution patterns of the chilo mating index are shown in Figure 5.7. The number of hours in which chilo is able to mate range from fewer than 2000 per annum for much of the central regions of South Africa to in excess of 3 000 hours in northeastern parts of KwaZulu-Natal, eastern Limpopo and eastern Mpumalanga provinces bordering on Mozambique. Finger like extensions of heightened mating hours inland from the KwaZulu-Natal coast are attributed to higher temperatures within the major incised valleys in this province (Schulze and Maharaj, 2007a). Values of between 2000 and 2400 mating hours are noted for much of the external border regions of South Africa.

The mean annual maintenance index for chilo is shown in Figure 5.8. From this index, the higher the number of consecutive days in which temperature is < 17°C, the less likely the pest is able to maintain growth and development. The distribution of values shown in Figure 5.8 range from < 7 days in the northeastern parts of KwaZulu-Natal, eastern Limpopo and eastern Mpumalanga provinces bordering Mozambique to > 63 days in the central regions of South Africa. Certain areas within the Eastern and Western Cape provinces indicate the potential for chilo maintenance. These numbers are, however, high (when compared to those of KwaZulu-Natal, eastern Limpopo and eastern Mpumalanga provinces bordering Mozambique), therefore indicating the unlikelihood of chilo maintenance. The mortality index depicted in

Figure 5.9, in which lower numbers of two or more consecutive days when the temperature is < 13°C, are indicative of a higher chance of chilo survival, does, however, suggest that chilo would not be able to survive in the majority the areas of the northern and western parts of South Africa. This is also indicated by the other two indices. The mortality index therefore limits potential chilo distributions to the coastal regions of KwaZulu-Natal and the Eastern Cape.

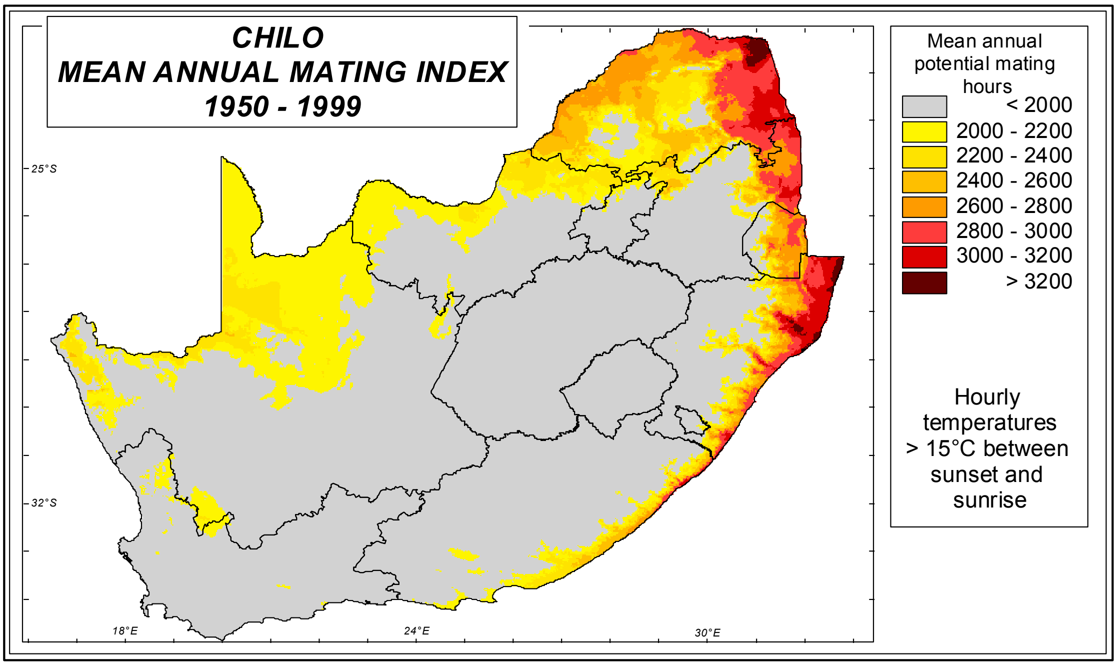

Figure 5.7 Mean annual chilo mating index over southern Africa

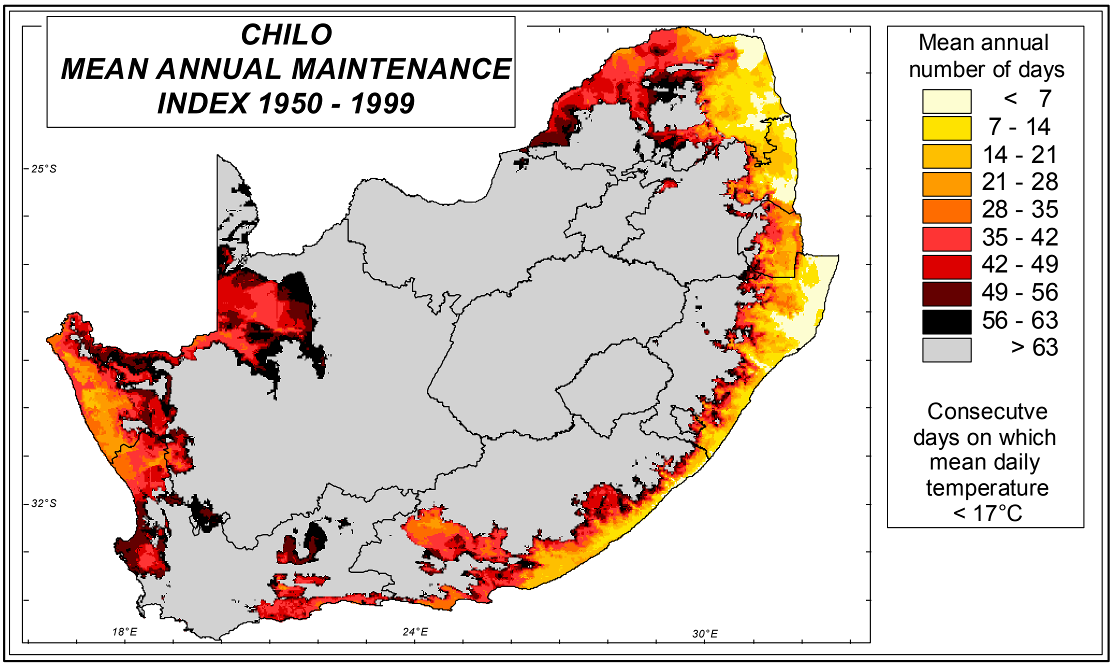

Figure 5.8 Mean annual maintenance index for chilo over southern Africa

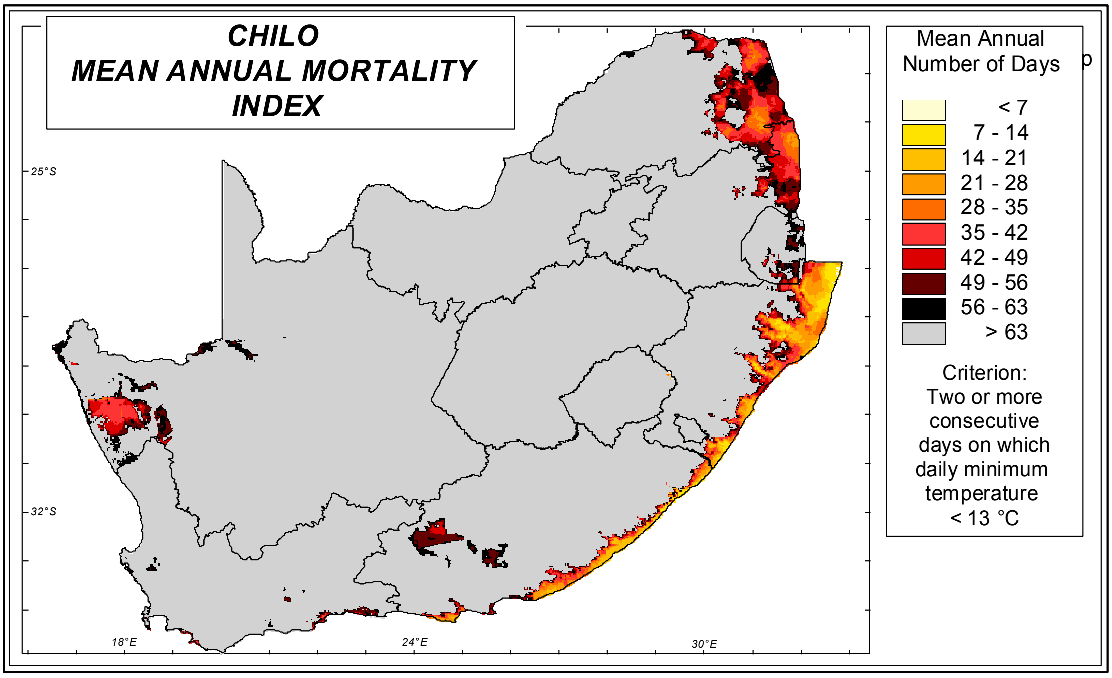

Figure 5.9 Mean annual chilo mortality index over southern Africa

5.4 The Rust Fungus

Common rust, caused by the pathogen *Puccinia melanocephela,* was first recorded in the South African sugar industry in 1941 (Ryan *et al*., 1989). The ease with which rust is able to spread and infect sugarcane makes this one of the more serious diseases affecting sugarcane production in southern Africa. For more background information on the rust fungus, refer to Section 2.2.3.

5.4.1 Determination of Distribution Patterns of Sugarcane Rust, *Puccinia melanocephala*

The distribution and infection of rust is affected by a number of climatic factors which include temperature and humidity parameters as well as wet leaf duration. High temperatures in conjunction with high humidity levels, together with prolonged periods when the plant leaf is wet, have been found to be most conducive for the infection of common rust (Sandoval *et al*., 1983; Webb *et al*., 1997; Magarey *et al*., 2004).

Studies conducted by Sandoval *et al.* (1983) show the temperature ranges most conducive for the infection of *Puccinia melanocephala* include maximum daily temperatures between 30°C and 34°C, median daily temperatures of between 24°C and 27°C, and minimum daily temperatures of between 18°C and 23°C. From these values a rust temperature index was formulated by the author, whereby areas displaying temperatures within the range of the above given temperatures, were considered as rust conducive. This was done by finding the mid-point of each of the temperature ranges, equating to a maximum temperature of 32°C, a median temperature of 25.5°C and a minimum temperature of 20.5°C, and then through a rust temperature index R_t, given in Equation 5.1, obtaining the relative closeness of daily temperatures to those temperature ranges given by Sandoval *et al.* (1983). From this, the lower the rust index, R_t, the more conducive the temperatures are for rust infection.

$$R_t = \sqrt{(T_{max} - 32)^2 + (T_{min} - 20.5)^2 + (\bar{T} - 25.5)^2} \quad \text{..(5.1)}$$

where:

R_t = rust temperature index,

T_{max} = daily maximum temperature,

T_{min} = daily minimum temperature, and

$\bar{T}$ = daily average temperature, computed as $(T_{max} + T_{min})/2$.

The temperature database described in Section 3.1 was used in the derivation of the rust temperature index. The R_t index yielded values ranging from 0-15. Through a series of iterations, it was found that R_t values of less than 4 fell within the temperature ranges defined by Sandoval *et al.* (1983). These values were therefore flagged as rust conducive. The number of days on which R_t values were < 4 were accumulated on an annual basis, and averaged over the 50 year time period over which the daily temperature database covers southern Africa (Schulze and Maharaj, 2004).

In addition to the rust temperature index, an index considering the number of wet leaf days was developed. Research undertaken by Webb *et al.* (1997) shows the infection efficiency of rust increasing substantially as leaf wetness duration is increased.

With regard to rust infection, both the intensity and duration of rainfall are important. Rainfall events with high intensities and long durations are detrimental to the spread and infection of rust owing to such events removing spores from the surface of plant leaves, and therefore reducing the chance for infection (Sache, 2000).

A direct calculation of wet leaf duration was, however, not possible with the information contained in the South African rainfall database (Lynch, 2004), as only daily magnitudes and neither intensities nor durations of rainfall are given. For this reason an index of wet leaf days indicating the number of days on which low amounts of rainfall were recorded, was developed. The maximum threshold decided upon was 5 mm on a rainday, on the assumption that amounts in excess of that would be indicative of either longer duration or high intensity rainfall event. Since the 50 year time series of daily rainfall values are available for South Africa only at the scale of Quaternary Catchments (Schulze *et al*., 2007a) and not on a raster of one arc minute as in the case of temperature, the wet leaf day index could only be mapped at Quaternary Catchments level.

In addition to the two above-mentioned indices, a third index was formulated in which the temperature and wet leaf duration indices were combined. With this index, the mean annual number of days, for the period 1950 to 1999, on which temperature fell within the above-mentioned thresholds (Figure 5.10) and on which it rained, but rainfall was < 5 mm (Figure 5.11), was calculated (Figure 5.12).

5.4.2 Distribution Patterns of Sugarcane Rust Over Southern Africa

Areas most conducive to the formation of rust on sugarcane with respect to temperature are depicted in Figure 5.10. They are limited mainly to the northeast coast of KwaZulu-Natal, eastern Mpumalanga as well as the eastern parts of Limpopo, where there are on average between 100 and 125 rust conducive days per year. A number of areas in Figure 5.10, including parts of the KwaZulu-Natal midlands, do not indicate a high potential occurrence of rust, according to the temperature index, although rust is known to occur in those regions. This may be as a result of other factors such as rainfall, humidity and/or wet leaf duration enabling the infection and development of rust, with temperature possibly playing a secondary role.

The distribution patterns of possible rust infection according to the wet leaf day index, shown in Figure 5.11, indicate no significant trends, as distribution patterns are very patchy. However, the southern half of KwaZulu-Natal is seen as the most conducive to rust as there are no areas in that region showing fewer than 20 conducive days per year. Within this area, the wet leaf day rust index indicates places showing in excess of 60 rust conducive days per year. The northern parts of southern Africa, including Swaziland, eastern Mpumalanga and the eastern parts of Limpopo indicate high possibilities for rust infection according to the temperature index given in Figure 5.10. However, in Figure 5.11 which displays the wet leaf day index, these areas show a very low possibility of rust infection, with fewer than 40 rust conducive days for the majority of these regions.

In Figure 5.12 the distribution patterns of the combined temperature and wet leaf day indices are shown. The numbers of rust conducive days according to this index range from fewer than 4 days per annum, covering the majority of the inland parts of South Africa, to between 16 and 20 days in patches of the eastern parts of southern Africa. The overall distribution pattern shows the eastern parts of southern Africa as being most conducive, with numbers ranging between 4 and 8 days. Some small patches in the Northern Cape and the North West provinces also show between 4 and 8 days to be rust conducive. The number of days indicated by this rust index is significantly lower than those of the previous two indices. In addition to this, the area shown as rust conducive is reduced. A possible reason for this is that the thresholds used for this index may have been too stringent.

Further analysis and verification of these indexes is required. This, however, falls outside of the scope of this dissertation, as the focus of this study is on the application of previously formulated factors affecting the distribution patterns of the variables considered.

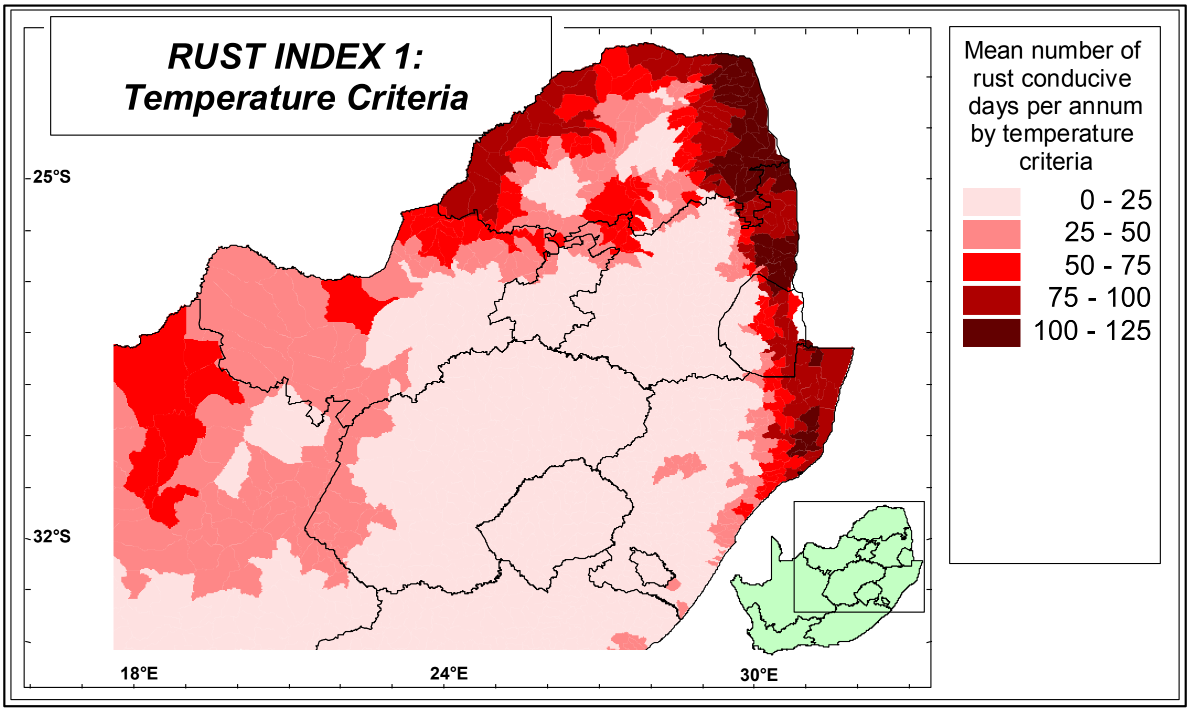

Figure 5.10 Possible distributions of rust according to temperature criteria

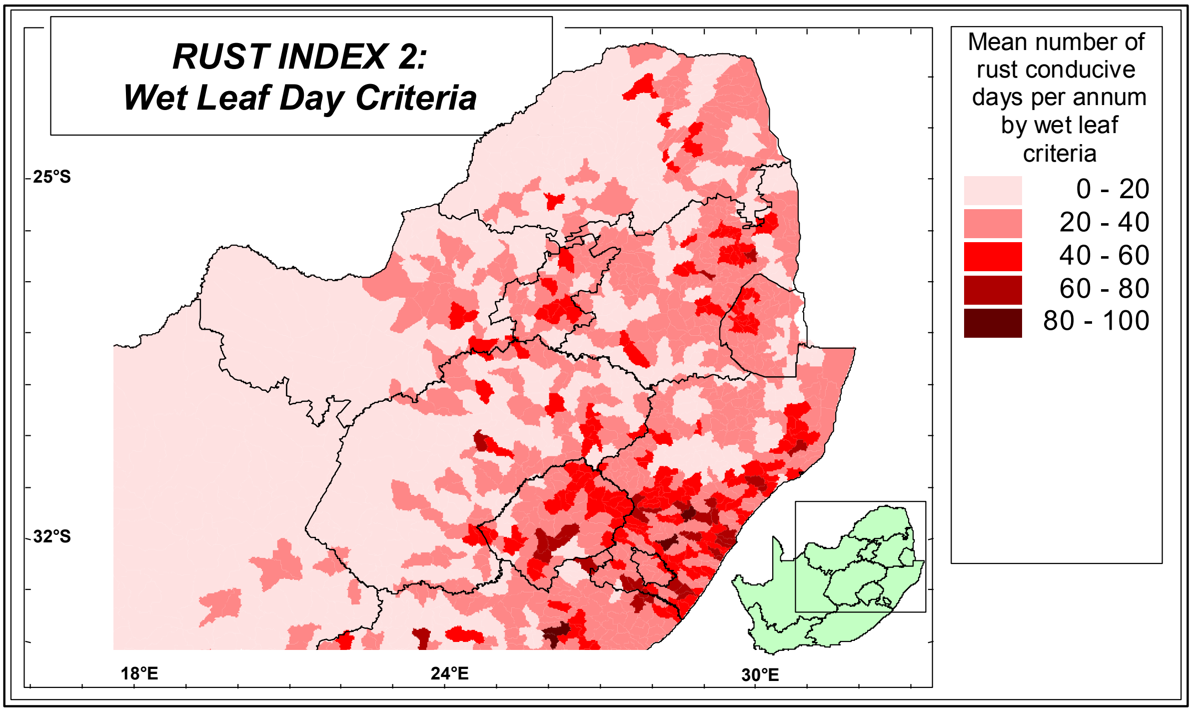

Figure 5.11 Possible distributions of rust according to wet leaf criteria

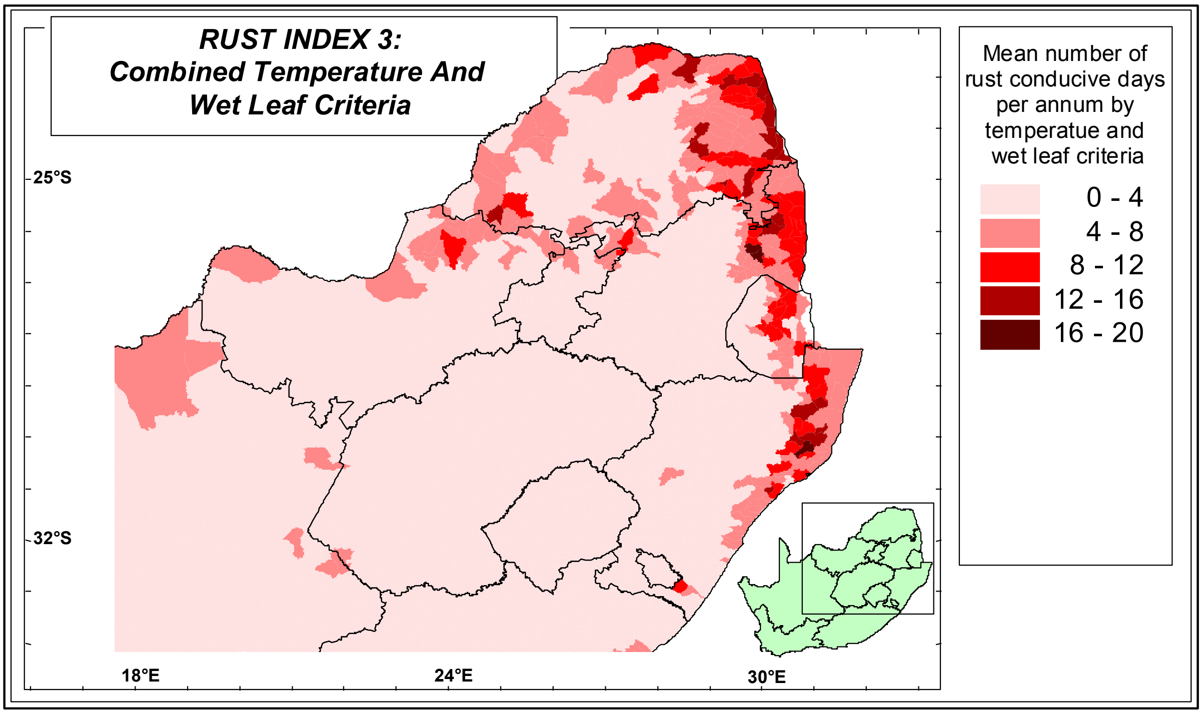

Figure 5.12 Possible distributions of rust according to a combination of temperature and wet leaf criteria

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In this chapter algorithms for three of the pests and diseases which limit the production and yield of sugarcane in southern Africa have been developed and mapped. Although the number of pests and diseases affecting the sugarcane industry are numerous, the three specific ones, *viz*. eldana, chilo and rust, were chosen as they either have the potential to cause significant losses in yield, or have done so in the past. The distributions these pests and diseases may be used in, for example, the selection of sugarcane varieties that are resistant to the infection or infestation of these pests and diseases, especially in those areas highlighted in the maps as being at risk.

In the following chapter soil water related constraints and potentials to sugarcane production in southern Africa are discussed, evaluated and mapped.

6. MAPPING SOIL WATER RELATED CONSTRAINTS AND POTENTIALS OF SUGARCANE PRODUCTION IN SOUTHERN AFRICA

6.1 Introduction

Soil is an essential medium for the growth and production of sugarcane. There are many factors that determine the suitability of a particular soil for crop production. Soil water content affects a variety of sugarcane production issues. The aim of this chapter is to address a number of soil water related issues, including the mapping of soil water content, soil compaction, irrigation water demands, conducive and non-conducive growing conditions and identifying areas that are prone to the flowering of sugarcane.

6.2 Soil Water

The main objective of mapping soil water content was to establish the mean number of days per annum during which the soil water content would exceed, or be below, specific critical thresholds relating to the water requirements of the sugarcane plant. Mapping soil water content is of particular significance in this research as it forms the basis of a number of other studies included in this study, *viz*. soil compaction, irrigation water demands of sugarcane, conducive growing conditions and sugarcane flowering. For a number of studies described below the simulation and mapping was undertaken for the entire region comprising of South Africa, Lesotho and Swaziland.

6.2.1 Definitions and Assumptions Made in Simulations

The *ACRU* model (Schulze, 1995 and updates) was used to simulate daily soil water contents for the entire South Africa, Lesotho and Swaziland at the Quaternary Catchment (QC) scale (refer to Section 3.5 for a description of the *ACRU* model and to Section 3.6 for a definition of Quaternary Catchments). All of the simulations were undertaken at a daily time step spanning the 50 year time period 1950 to 1999, using the temperature and rainfall databases described in Sections 3.2 and 3.3 respectively. Simulations of soil water content were undertaken for two different soil texture classes found typically in sugarcane production areas, using three different, but typical soil profile depths. For each simulation a specific soil texture and soil profile depth was assumed for all QCs covering the defined southern African region.

The different soils selected for simulations were a sandy clay loam (SaClLm) with profile thicknesses of 0.6 m, 0.9 m and 1.2 m and a sandy (Sa) soil with a profile thickness of 1.2 m. For each of these soils four critical conditions of plant water stress were identified and their exceedances/non-exceedances then mapped. These conditions were excess plant water stress, no plant water stress, mild plant water stress and severe plant water stress, as described below and shown schematically in Figure 6.1. The specific values relating to the above-mentioned thresholds are given in Table 6.1.

- **Excess plant water stress:** This is a term given to the condition a plant experiences when soil water content, θ, exceeds that held at the Drained Upper Limit (DUL), i.e. θ_{DUL}, resulting in the soil becoming saturated. The result of this condition is a limit in the plant's ability to transpire at its maximum rate, caused by a state of anoxia (lack of oxygen) which results from conditions of excess soil water (Dijkhuis and Berliner, 1988). Excess plant water stress is thus expressed as:

    - $\theta > \theta_{DUL}$

  on a given day, with the day's total evaporation, E, then reducing to below its maximum, E_m, depending on the amount of excess water, with the potential to reduce total evaporation to 0.3 E_m when the soil is totally saturated (Dijkhuis and Berliner, 1988).

- **No plant water stress**: As the name alludes to, this is a condition where the plant is not under any soil water stress and is therefore able to transpire at its maximum rate, i.e. $E = E_m$ or $E / E_m = 1$, as in Figure 6.1. These conditions occur when the soil water content equals or drops below that at DUL, but equals or exceeds the soil water content at a specified fraction of total Plant Available Water (PAW) at which plant stress commences, *viz*. θ_{fs}, which in this case has been set at 0.5 PAW for sugarcane. Total PAW is defined as the difference between soil water held at DUL, i.e. θ_{DUL}, and that held at the plant's permanent wilting point or Lower Limit, i.e. θ_{LL}. (Dunne and Leopold, 1978) Therefore, the conditions when no plant water stress occurs on a given day is expressed as:

$$\theta_{DUL} \geq \theta \geq \theta_{fs}$$

or $$\theta_{DUL} \geq \theta \geq 0.5(\theta_{DUL} - \theta_{LL}).$$

- **Mild plant water stress:** This is the condition whereby the plant is stressed as a result of the soil water content being below the stress fraction, θ_{fs}, but it is still able to transpire at a rate defined in this study as being equal to, or in excess of, 20% of its maximum evaporation (Schulze *et al.*, 2007b), i.e.

$$\theta_{fs} > \theta \geq 0.2\ E/E_m, \text{ which is computed to be}$$
$$\theta_{fs} > \theta \geq 0.6\ (\theta_{fs} - \theta_{LL}) \text{ for these soils.}$$

- **Severe plant water stress:** This is defined in this study as the soil water content at which the plant is only able to transpire at a rate of below 20% of its maximum evaporation (Schulze, 1995). i.e.

$$\theta < 0.2\ E_m$$

which in this case, with θ_{fs} being at 0.5 PAW, equates to

$$\theta < 0.6\ (\theta_{fs} - \theta_{LL}).$$

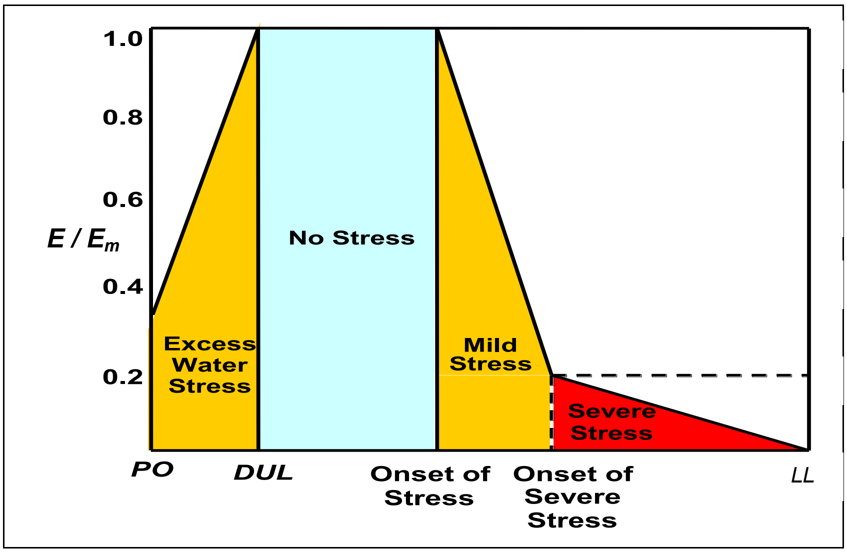

Figure 6.1 Schematic of different levels of plant water stress (Schulze *et al.*, 2007b)

The model's input variables against which the above-mentioned plant stress levels were simulated are given in Table 6.1. The sugarcane crop was assumed to have a crop coefficient of 0.9 for all months of the year (Smithers *et al.,* 1998), i.e. maximum crop evaporation on a day with no soil water stress would equate to 90 % of the reference potential evaporation, E_r, taken in this study to be the daily A-pan equivalent potential evaporation as computed by Schulze (1997). It was also assumed that 80% of the sugarcane plants' roots were in the topsoil (Smithers *et al.,* 1998). In all simulations the topsoil was set to a thickness of 0.3 m. Canopy interception per rainfall event was set at 1.8 mm (De Villiers, 1978), and the coefficient of initial abstraction, which can be described as an index of the soil's ability to infiltrate water, was set at 0.3 for all months of the year. The saturated drainage rates from the topsoil to subsoil and subsoil into the intermediate/groundwater zone (as illustrated schematically in Figure 3.6) were set at 0.5 of the excess water per day for sandy clay loam (SaClLm) soils and a more rapid 0.8 / day for the sandy soil, based on research by Rawls *et al.* (1982).

As mentioned previously, for each simulation, specific soil and crop related assumptions were made for all QCs covering the defined southern African study region. In each new simulation, the soil depth and type were then altered as stated above. The reason for keeping the soil and crop variables uniform throughout southern Africa for each simulation was to enable comparisons of soil water content to be made which were determined solely by climate variations.

Table 6.1 Soil input variables used for simulations of soil water stress levels for the soils used in this study

Variable	Sandy Clay Loam	Sand
Lower Limit	θ = 160 mm.m^{-1}	θ = 50 mm.m^{-1}
Drained Upper Limit	θ = 260 mm.m^{-1}	θ = 115 mm.m^{-1}
Saturation	θ = 435 mm.m^{-1}	θ = 440 mm.m^{-1}
Saturated Drainage Rate	0.5/day of excess soil water/day	0.8/day of excess soil water/day

6.2.2 Distribution Patterns of Soil Water Content Over Southern Africa

Figures 6.2 to 6.5 display distribution patterns of the mean number of days per year on which soil water content exceeds DUL. From Figure 6.2 it is seen that on average there are fewer than 2 days per year in the western quarter of South Africa with soil water content ≥ DUL. This, however, increases to more than 20 days per year in patches over the southwestern parts of the Western Cape, KwaZulu-Natal and the escarpment areas of Mpumalanga and Limpopo provinces. Figures 6.3 and 6.4, which show soil water contents for the same SaClLm soil texture, but for total soil profile depths of 0.9 m and 1.2 m, respectively, display very similar spatial distributions to those seen in Figure 6.2, but with fewer days meeting the criteria. Areas showing higher (10-20) numbers of days per annum with the deeper soils when the soil water content is greater than DUL include the northeastern areas of the Eastern Cape, KwaZulu-Natal, Swaziland and Mpumalanga. A small patch in the south of the Western Cape also indicates 20 days and more on which soil water content was greater than DUL. It appears that the deeper sandy (1.2 m) soils show fewer days than sandy clay loams on which soil water exceed DUL, as noted in Figure 6.5, primarily as a result of sands having higher drainage rates than sandy clay loams (cf. Table 6.1). From these results, the majority of southern Africa is shown to experience less than 3% of the year as having soil water conditions above DUL. This is testament to the arid nature of southern Africa.

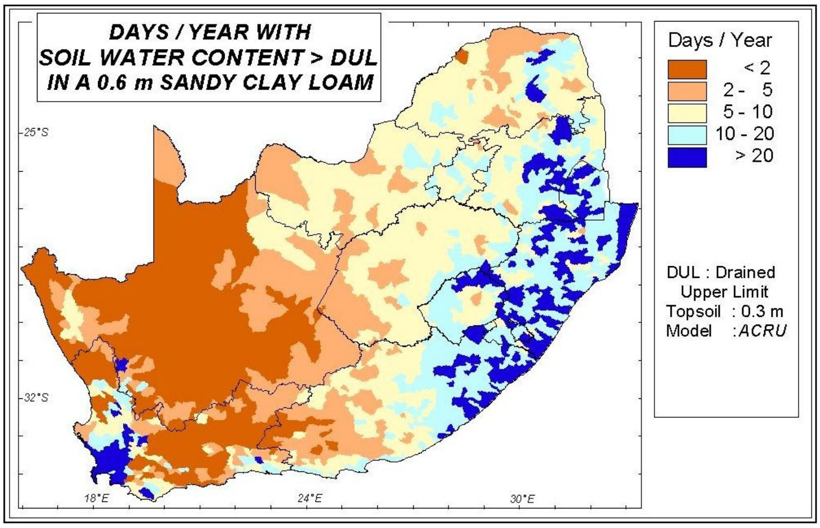

Figure 6.2 Mean number of days / year with soil water content above the drained upper limit for a 0.6 m sandy clay loam soil

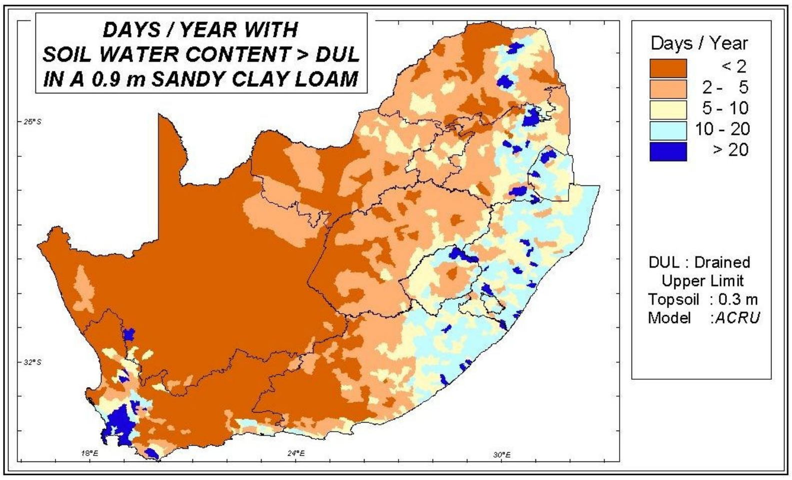

Figure 6.3 Mean number of days / year with soil water content above the drained upper limit for a 0.9 m sandy clay loam soil

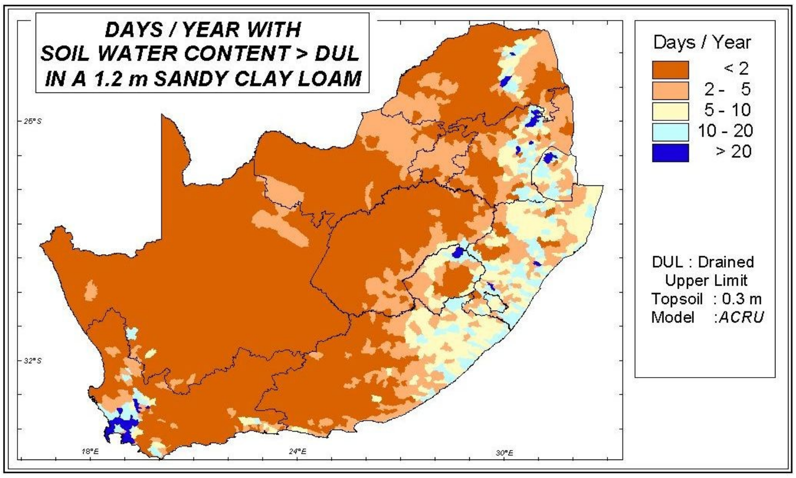

Figure 6.4 Mean number of days / year with soil water content above the drained upper limit for a 1.2 m sandy clay loam soil

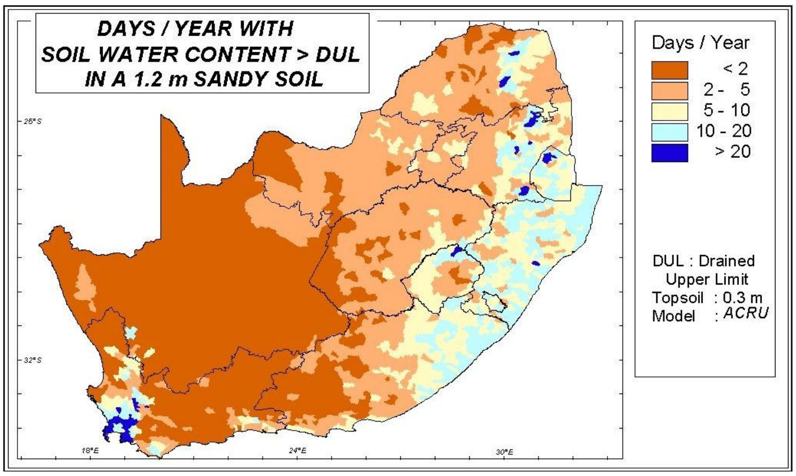

Figure 6.5 Mean number of days / year with soil water content above the drained upper limit for a 1.2 m sandy soil

In Figure 6.6, for a SaClLm soil texture with a thickness of 0.6 m, distribution patterns of the mean number of days per year when the sugarcane plant would not be stressed, indicate that fewer than 20 such days per year occur in the western 20% of South Africa, increasing to greater than 80 days in the northern parts of the Eastern Cape, over much of KwaZulu-Natal and eastern Mupumulanga. The distribution patterns seen in Figures 6.7 and 6.8 for SaClLm soils with respective thicknesses of 0.9 and 1.2 m, of the number of days with no plant water stress, are similar to those in Figure 6.6. A slight increase in the area showing more than 80 days with no soil water stress is noted with increasing soil depths in the central parts of Limpopo, northern KwaZulu-Natal and eastern Swaziland. This shows that the deeper soils are able to retain soil water for longer periods of time. When comparing Figure 6.8 and Figure 6.9, a reduction in the areas showing greater than 80 days of no soil water stress is noted. This is indicative of sandy type soils not being able to retain moisture as well as sandy clay loam type soils.

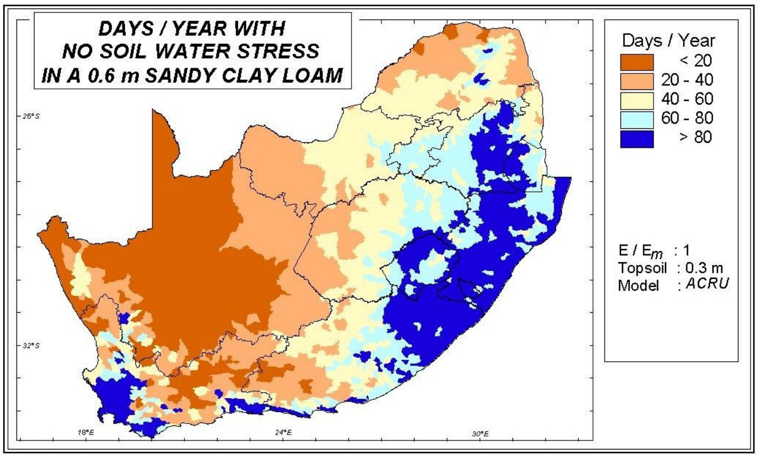

Figure 6.6 Mean number of days / year with no soil water stress for a 0.6 m sandy clay loam soil

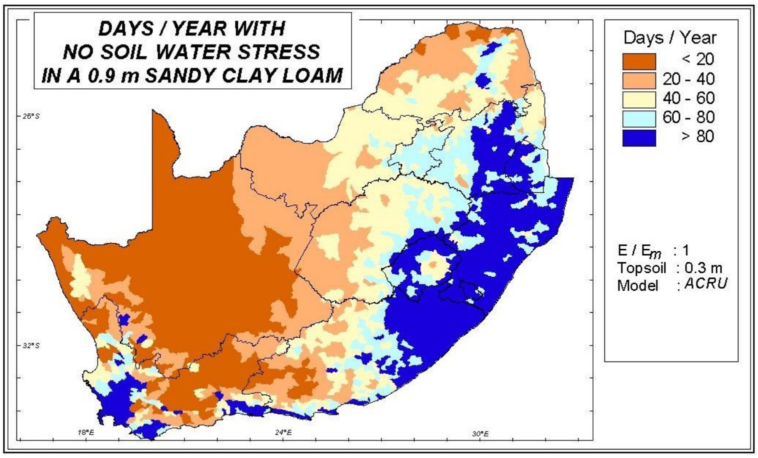

Figure 6.7 Mean number of days / year with no soil water stress for a 0.9 m sandy clay loam soil

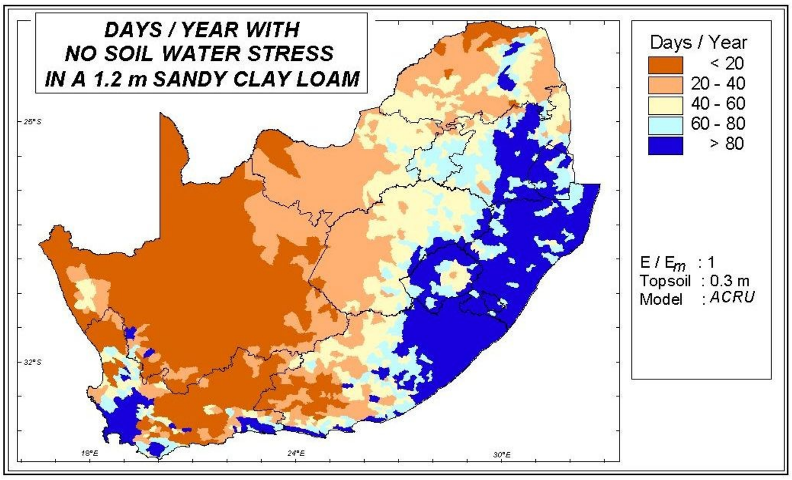

Figure 6.8 Mean number of days / year with no soil water stress for a 1.2 m sandy clay loam soil

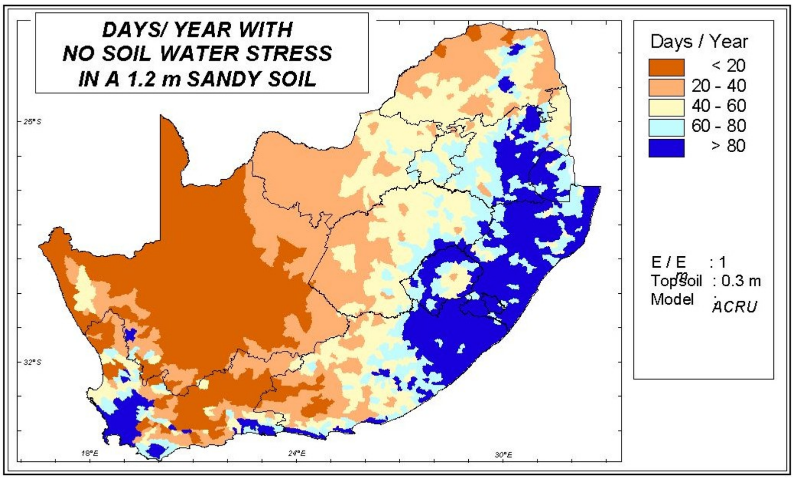

Figure 6.9 Mean number of days / year with no soil water stress for a 1.2 m sandy soil

The map displaying distribution patterns of the mean number of days per year with mild soil water stress for a 0.6 m SaClLm soil, shown in Figure 6.10, indicates less than 20 days per annum of mild stress along the east and south coasts of South Africa. This number increases to greater than 100 days per annum in the western parts of South Africa. From Figures 6.11 and 6.12 it can be seen that with the deeper soils the number of "mild stress days" decreases. In Figure 6.13, for a sandy soil, the range and number of days where the soil is mildly stressed are far lower than the equivalent thickness SaClLm soils, with only between 2 and 20 mild stress days over most of southern Africa. When comparing the number of mild stress days in Figure 6.13 to those of severe stress days seen in Figure 6.17 for the sandy soil, it is seen that for the majority of the year even the deep sandy soil is severely stressed. This shows that a sandy soil is not able to retain soil water very well.

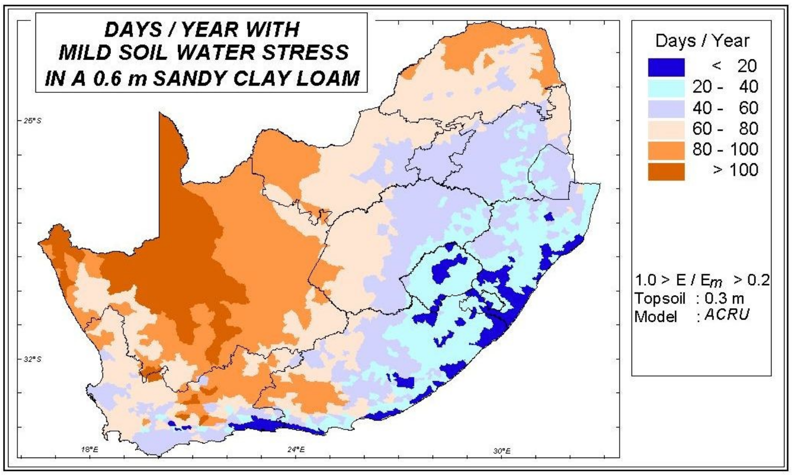

Figure 6.10 Mean number of days / year with mild soil water stress for a 0.6 m sandy clay loam soil

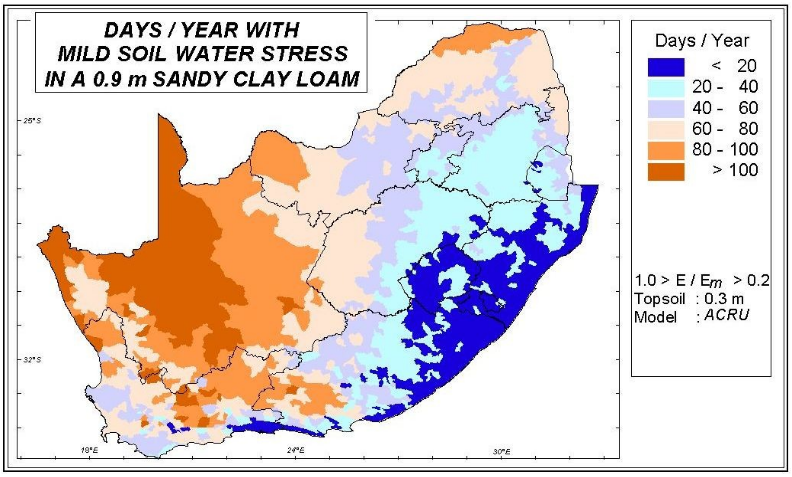

Figure 6.11 Mean number of days / year with mild soil water stress for a 0.9 m sandy clay loam soil

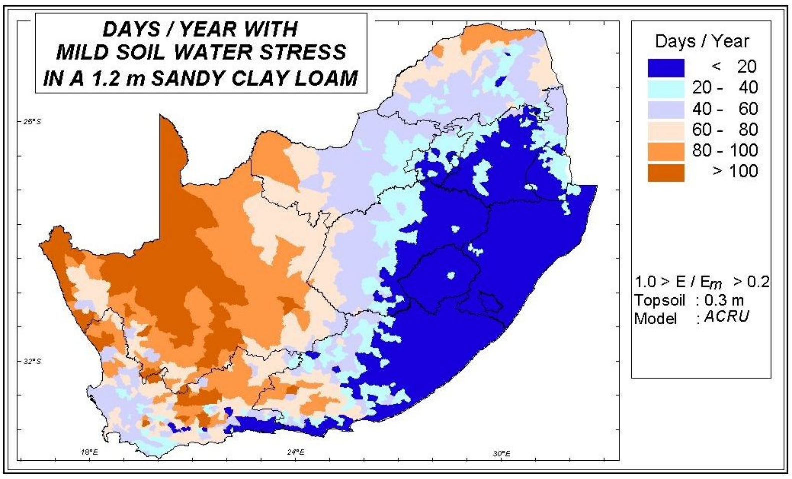

Figure 6.12 Mean number of days / year with mild soil water stress for a 1.2 m sandy clay loam soil

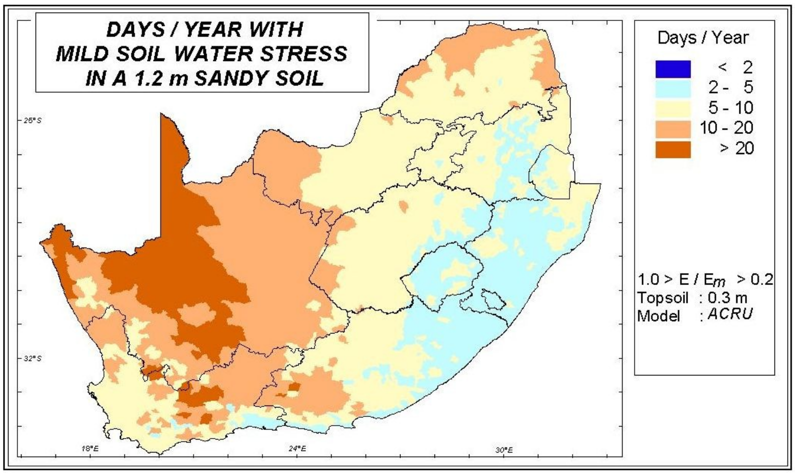

Figure 6.13 Mean number of days / year with mild soil water stress for a 1.2 m sandy soil

The general trend of the mean number of days per year that soils experience severe soil water stress are shown in Figures 6.14 to 6.17. These maps show that this soil water condition is the most common in South Africa, in agreement with the general arid nature of South Africa's climate. This may be seen in Figure 6.14 for a 0.6 m SaClLm, which indicates in excess of 300 days per year (on average) where the soil water status was at a point where plants would be severely stressed in areas of the Northern Cape. This value decreases to small patches of fewer than 150 days in KwaZulu-Natal. When comparing the number of severely stressed days in KwaZulu-Natal for the different soil thicknesses of SaClLm (Figures 6.14, 6.15 and 6.16), it is noted that the number of days decrease with increases in soil depth from 0.6 m to 0.9 m to 1.2 m. As mentioned previously, this is as a result of the ability of deeper soils to retain more soil water. Figure 6.17, for a sandy soil with a thickness of 1.2 m, indicates no areas having fewer than 150 days per year of severe stress, with approximately two-thirds of southern Africa displaying in excess of 300 days with severe stress, due largely to the low soil water holding capacity of sandy soil.

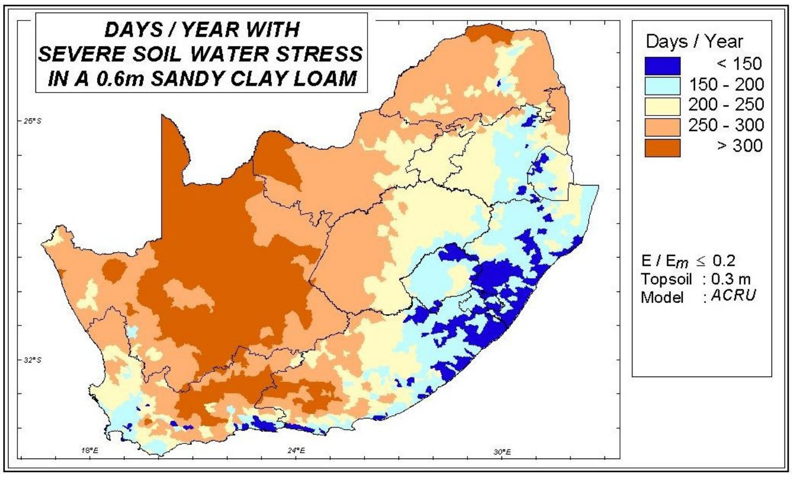

Figure 6.14 Mean number of days / year with severe soil water stress for a 0.6 m sandy clay loam soil

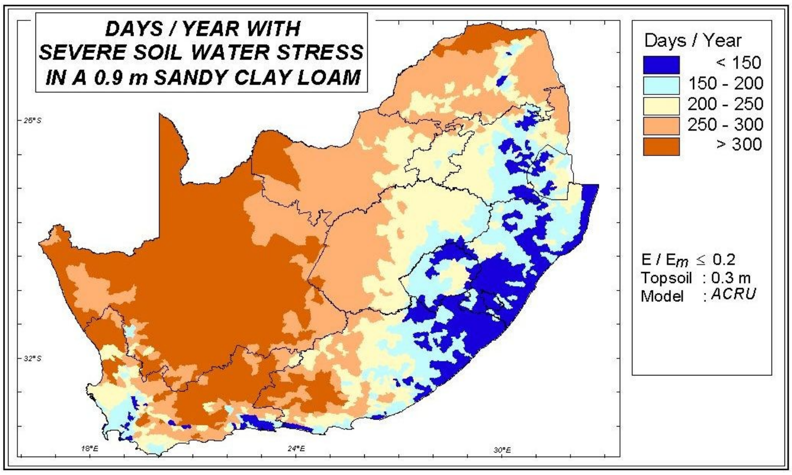

Figure 6.15 Mean number of days / year with severe soil water stress for a 0.9 m sandy clay loam soil

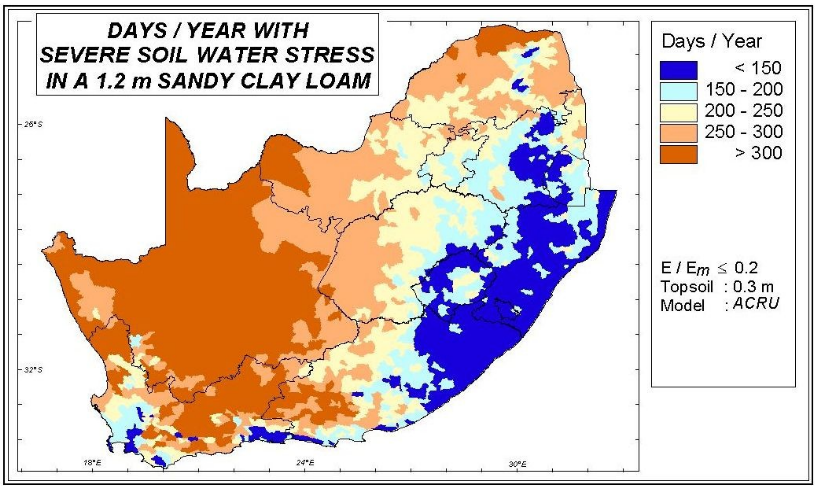

Figure 6.16 Mean number of days / year with severe soil water stress for a 1.2 m sandy clay loam soil

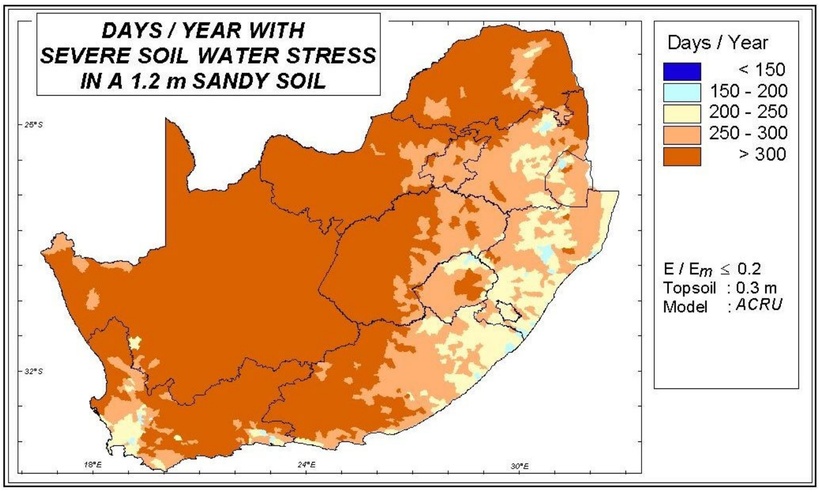

Figure 6.17 Mean number of days / year with severe soil water stress for a 1.2 m sandy soil

From the distribution patterns of soil water content shown in Figures 6.2 to 6.17, it is noted that the most prevalent soil water status, under the assumptions made in this study, is that of severe stress, with the majority of southern Africa showing these soil water conditions to be present for more than 50% of the year. Vast differences between the eastern and western parts of southern Africa are noted. The eastern and southern parts of southern Africa indicate that soil water conditions are far more suitable for crop production, with to this study showing higher numbers of days there during the year in which the soil is not under severe soil water stress.

6.3 Soil Compaction

As described in Section 2.3.1.1, soil compaction is defined as a reduction in the volume of a given mass of soil (McKibben, 1971). The result of this is a reduction in the potential for the soil to support plant growth (Smith, 1999). Owing to the negative impact of soil compaction, and its potential to limit plant growth, the mapping of soil compaction was considered to be important in assessing limitations to sugarcane growth. The aim of mapping soil compaction was to map the times of the year and the mean number of days per year that soils are more prone to soil compaction, and enable one to time harvesting operations.

6.3.1 Assumptions, Tools and Models Used in Soil Compaction Mapping

Soil compaction is affected by a number of factors, including soil water content (e.g. Bezuidenhout *et al.*, 2006) and soil texture (Mitchell and Berry, 2001). Mitchell and Berry (2001) discussed the fact that certain soil textures are more prone to compaction than others in the context of sugarcane production. For example, loamy soils are more likely to compact when compared to sandy or clay type soils. It was also noted that soils become more prone to compaction as the soil water content increases up to DUL (Mitchell and Berry, 2001). Therefore, in order to assess soil compaction, it is important to know both the soil texture and soil water content.

For the purpose of compaction mapping, a scenario was considered whereby a uniform soil profile with the physical properties of a 0.9 m deep SaClLm with a maximum water holding capacity of 234 $mm.m^{-1}$ was assumed. The *SOCOMO* model developed by van den Akker (2004) was used to simulate the depth of plastic deformation of the soil, assuming a load of 2 000 kg and using a reference radial tyre pressure of 200 kPa. The reference soil water content, used in mapping soil compaction, was taken from simulations as described in Section 6.2. Statistics relating to soil compaction were therefore derived for the 50 year time period 1950-1999 for which soil water content simulations were undertaken. Soil compaction was considered critical if the first 80% of the plastic deformation occurred in the top 300 mm of the soil (Bezuidenhout *et al.*, 2006). The statistics used in mapping soil compaction included:

- **start of the traffic season** is described as the average Day of the Year (DOY, with DOY = 1 being 1 January) after which the soil is not at risk to compaction, according to above-mentioned criteria, allowing for infield traffic;
- **duration of the traffic season** is the average number of days in a year during which the soil is not vulnerable to soil compaction;
- **mean risk** is the average number of days, within the reference traffic season, during which soil would be at risk of compaction; and the
- **risk trend** is used to indicate the time of season where soil compaction is more likely, i.e. positive values indicate higher risks towards the end of the traffic season, and negative values indicate higher risk at the beginning of the season.

The above-mentioned scenario, used in this study to map soil compaction, may differ greatly to what is found in reality. This study is therefore useful in identifying general areas and times of the year during which soil compaction may be a problem. For more accurate results, actual soils information relating specifically to an area of concern is necessary.

6.3.2 Distribution Patterns of Soil Compaction Statistics Over the Sugarcane Belt of Southern Africa

Distribution patterns of both the start and the duration of the traffic season are shown in Figure 6.18 (a). The start of the traffic season (DOY, as described above) is depicted by isolines, whereas the surface colours on the map represent the duration of the traffic season. Figure 6.18 (b) shows the percentage risk of soil compaction during the traffic season by isolines, whereas the colours in the legend of the map indicate the associated risk. For example, the traffic season at Noodsberg, indicated on Figure 6.18 (a) by an arrow, starts on DOY 120-150, which corresponds to 8 May, and ends 120-150 days later, between the 5th of September and the 4th of October. From Figure 6.18 (b) it may be seen that on average 30-35% of the time during the traffic season at Noodsberg, indicated by the arrow, the soil will be at risk of compaction beyond critical levels. The risk trend indicates a constant risk throughout the traffic season as it corresponds to values between –0.1 and 0.0.

Figure 6.18 (a) indicates that the traffic season starts predominately around DOY 120-150 for the inland regions of KwaZulu-Natal. In general, a trend of increasing traffic season length is observed with a progression inland and north. The difference in traffic season length between the northern and southern regions is most likely the result of the fact that frontal rainfall does not affect the northern regions as much as it does in the south (Bezuidenhout *et al.*, 2006). The coastal and inland differences in traffic season length are also most likely a result of differences in rainfall amounts between these two regions, with increased rainfall along the coast (Schulze and Lynch, 2007). The general risk of the inland regions, shown in Figure 6.18 (b), is essentially constant, showing risks in the region of about 25%, however, with small patches showing heightened risks of up to 40 %. The predominant trend shown in Figure 6.18 (b) indicates a relatively even risk throughout the season, with some smaller areas showing slightly more risk at the beginning of the season. In the coastal regions, trends of a later and shortened traffic season are observed, with the traffic season only starting as late as DOY 210 and lasting for a short 30 days in the southern and northern coastal regions. The risk trend shown in Figure 6.18 (b) is relatively insignificant, although it does indicate a higher risk for soil compaction at the start of the traffic season along the northern interior and coastal regions.

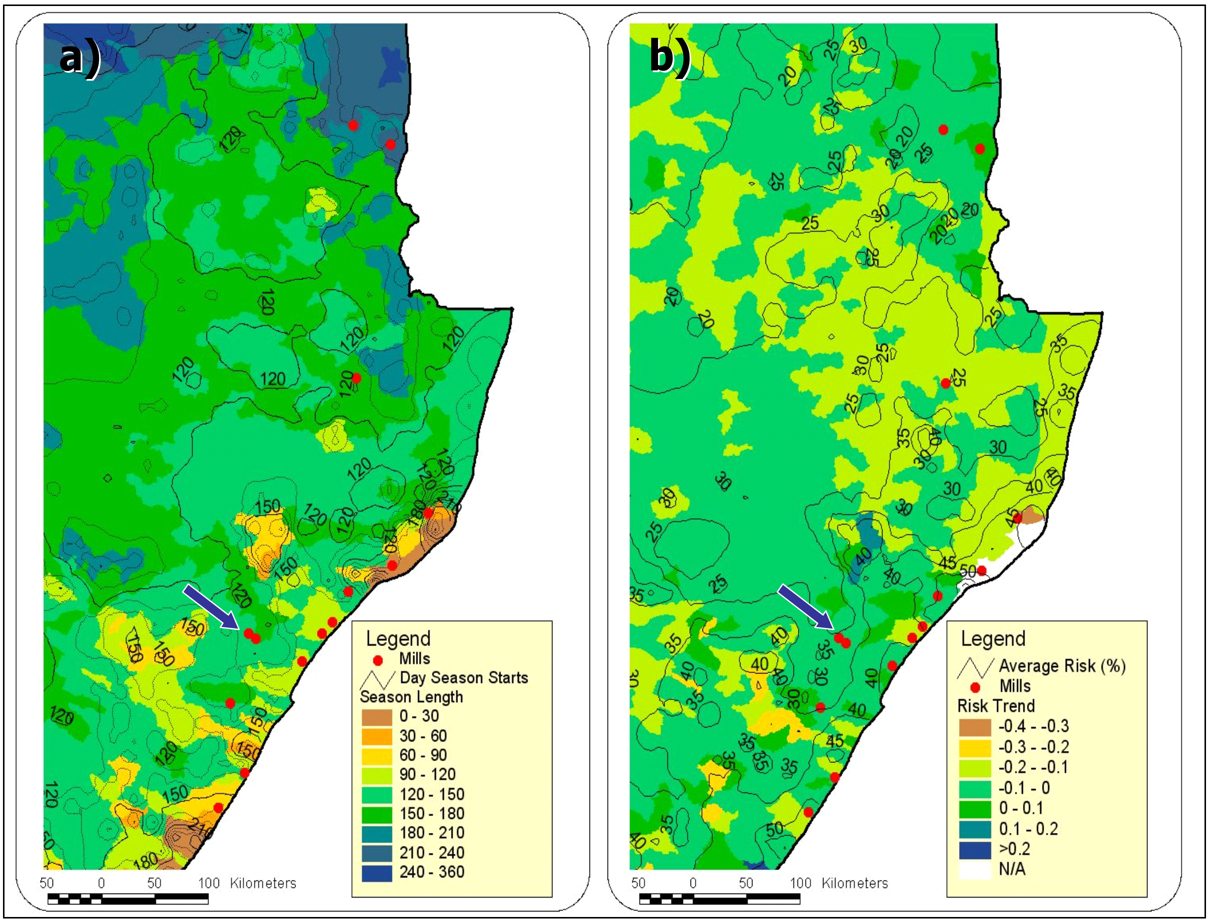

Figure 6.18 (a) The start and duration of a reference traffic season and (b) the risk and risk trend associated with this traffic season (Bezuidenhout *et al*., 2006)

6.4 Irrigation Water Demand

In Southern Africa, generally, there is a shortage of water for agricultural production. For optimum yields irrigation is thus necessary over most regions. When irrigating it is necessary that correct application methods and application rates are used to maximise water use efficiency (Schulze, 2007b). Within this section, various modes of irrigation are evaluated and their respective application amounts mapped.

6.4.1 Assumptions, Tools and Models Used in Irrigation Demand Mapping

The maps presented in this section on irrigation assume a gross irrigation demand. Gross irrigation demand is defined here as the total amount of water extracted from the source of water (i.e. river, dam or canal system) in order to satisfy the irrigated crop's water demand. This therefore includes conveyance, field application and crop interception losses. For all simulations the conveyance losses were set at 10%. Wind/drift spray losses were set at 12% for overhead irrigation and 2% for drip irrigation (Smithers and Schulze, 1995).

Irrigation was applied for all 12 months of the year for a fully grown crop equivalent to sugarcane, with a crop coefficient of 0.9 (Smithers *et al*., 1998). The majority of roots were in the top 0.65 m of the SaClLm type soil, which had an assumed depth of 0.9 m. Soil water contents were set to 0.435 m/m, 0.260 m/m and 0.160 m/m, respectively for saturation, drained upper limit and permanent wilting points for a 0.9 m deep soil. The coefficient of initial abstraction was set at 0.3, and interception loss per rainday and/or overhead irrigation application was set to 1.8 mm/event (De Villiers, 1978). Each of the runs was for 50 years, extending from 1950 to 1999, using the *ACRU* agrohydrological model (see Section 3.5 for a description of the daily time step physical-conceptual *ACRU* agrohydrological model).

Four different modes of irrigation scheduling were simulated in assessing irrigation water demands over southern Africa (Schulze and Hull, 2007a). These have been described in Section 2.3.1.2. The modes of irrigation scheduling were demand irrigation, deficit irrigation, drip irrigation and fixed amount / fixed cycle irrigation. Demand irrigation was initiated when plant available water (PAW) dropped to below 50%, i.e. by 45 mm (50% of (234 mm – 144 mm)), at which point irrigation was applied to refill until the soil reached DUL (234 mm). The same inputs were used for deficit irrigation with the only difference being that when 50% of PAW was reached, irrigation was applied to 20 mm below DUL, allowing for possible rainfall to infiltrate into the soil and not be "wasted" through deep percolation or stormflow. The third mode of irrigation application evaluated was that of drip irrigation. The difference between previously mentioned irrigation modes and drip irrigation is that with drip irrigation there are no interception losses (of 1.8 mm/event) and wind/spray drift losses are lower, set at 2% compared to 12% for overhead type systems. Another difference is that with drip irrigation the soil is assumed to be refilled to DUL daily, which is not the case with previously mentioned modes.

Fixed amount / fixed cycle irrigation was simulated for three different irrigation scheduling amounts, these being 15 mm / 7 day cycle, 20mm / 7 day cycle and 35 mm / 7 day cycle. These equate to ~ 2 mm, ~3 mm and ~5 mm of irrigated water available to the crop per day. In the case of a 15 mm / 7 day cycle, if a rainfall event exceeding 20 mm occurred the irrigation cycle was skipped. The same was assumed for the 20 mm / 7 day cycle and 35 mm / 7 day cycle if 35 mm and 50 mm fell, respectively. For each of the simulations the conveyance losses were assumed to be 10%, wind/spray losses were set to 12% and canopy interception losses were input as 1.8 mm per event.

6.4.2 Distribution Patterns of Irrigation Demand Over Southern Africa

Mean annual gross irrigation demands, under these soil, crop and loss assumptions, for southern Africa range from ~ 1400 mm to ~ 2400 mm per year. This range may be seen in Figure 6.19 in which, as expected, the gross irrigation requirements in higher rainfall areas such as the east and south of the region were significantly lower than those in lower rainfall areas of the west, north and central regions of the country.

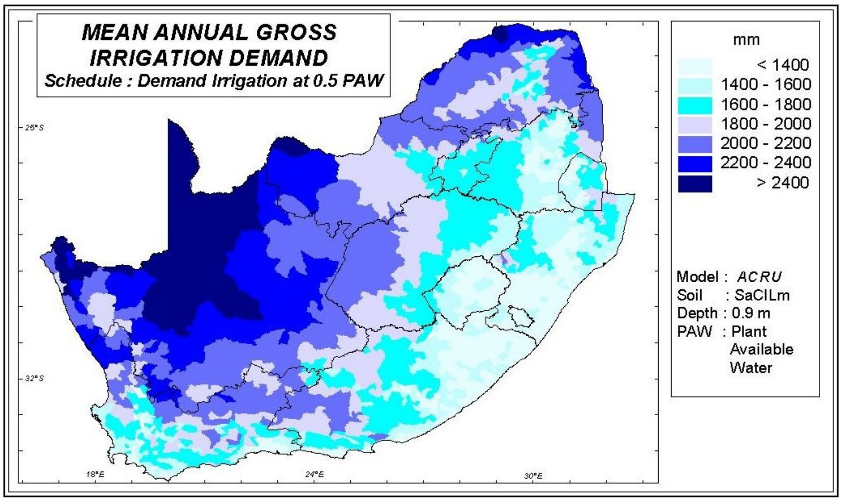

Figure 6.19 Mean annual gross irrigation requirement based on demand irrigation with a 0.9 m SaClLm soil, irrigated at 0.5 PAW

Notable differences in annual application amounts were evident for the four different modes of scheduling. The most efficient mode of irrigation was found to be drip irrigation, shown in Figure 6.20. The reason for this is that wind/spray drift losses are virtually eliminated and interception losses are cut out entirely, as water is irrigated directly to the soil surface, thereby ensuring a highly efficient use of applied water. This is shown in Figure 6.20 by the relatively large area with relatively low mean annual gross irrigation demand. The second most efficient type of irrigation was found to be that of deficit irrigation, shown in Figure 6.21. This may be attributed to the fact that with this mode of irrigation the soil profile is not filled to DUL, but part of the soil's storage capacity remains unsaturated, allowing for any additional rainfall to infiltrate the soil profile. The difference in the annual irrigation water requirement between demand and deficit irrigation was between 100 – 200 mm per annum.

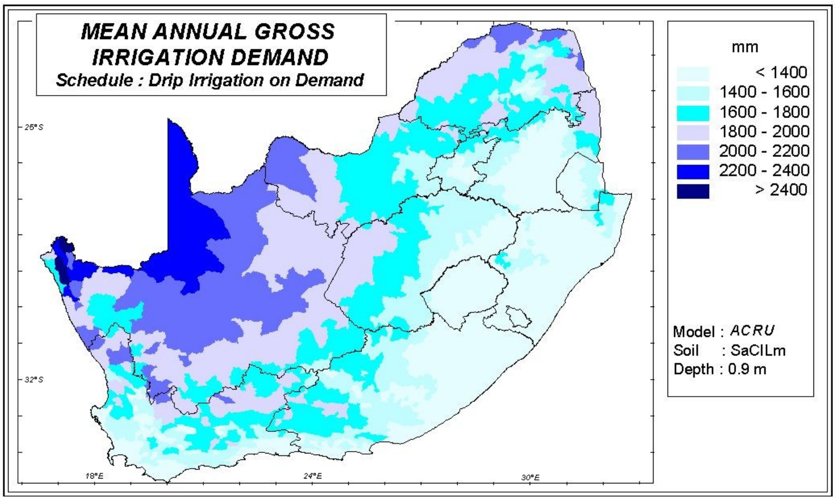

Figure 6.20 Mean annual gross irrigation demand for drip irrigation on a 0.9 m SaClLm soil

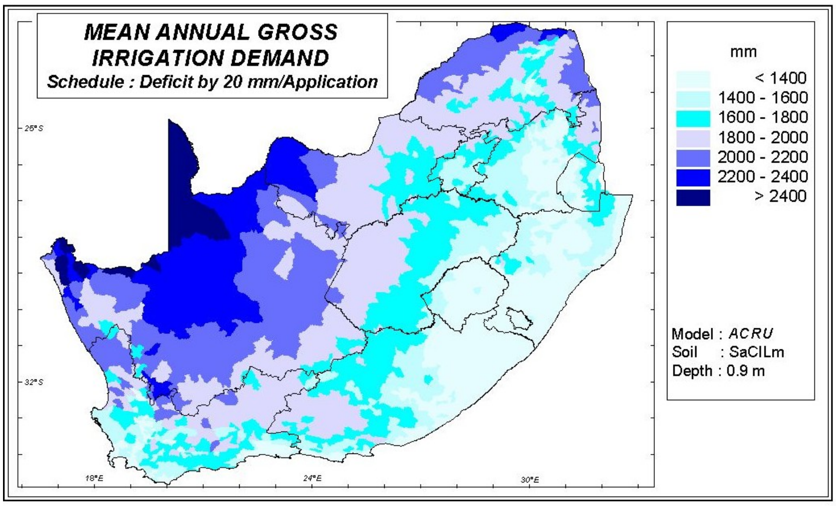

Figure 6.21 Mean annual gross irrigation demand based on deficit irrigation on a 0.9 m SaClLm soil

Figures 6.22 to 6.24 show the distribution patterns of the mean annual gross irrigation demands for application amounts of 15 mm / 7 day cycle, 20 mm / 7 day cycle and 35 mm / 7 day cycle. With the lower application rate of 15 mm / 7 day cycle, annual application amounts varied from ~ 700 mm to ~ 950 mm over South Africa. However, with the higher application rate of 35 mm / 7 day cycle, the amount of irrigated water applied increased to between ~ 1400 mm and ~ 2400 mm. This significant increase in the amount of water applied suggests that the higher application rate may lead to waste, due to over-irrigation. These findings are confirmed by Schulze (2007c), who found that percolation losses for the study region of southern Africa were to be in excess of 150 mm per year for a 35 mm/7 day cycle.

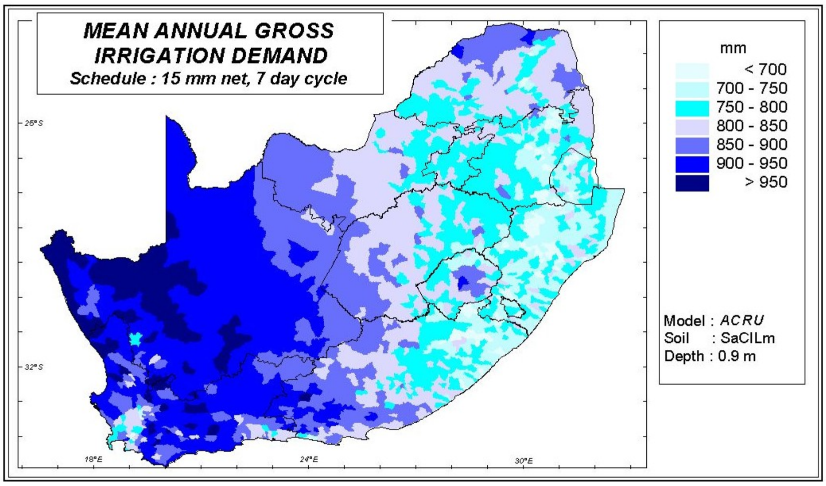

Figure 6.22 Mean annual gross irrigation demand for a 15 mm / 7 day cycle on a 0.9 m SaClLm soil

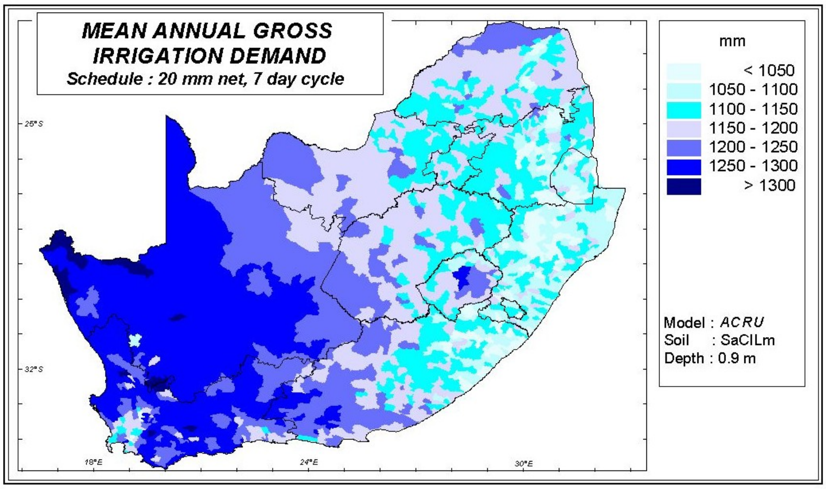

Figure 6.23 Mean annual gross irrigation demand for a 20 mm / 7 day cycle on a 0.9 m SaClLm soil

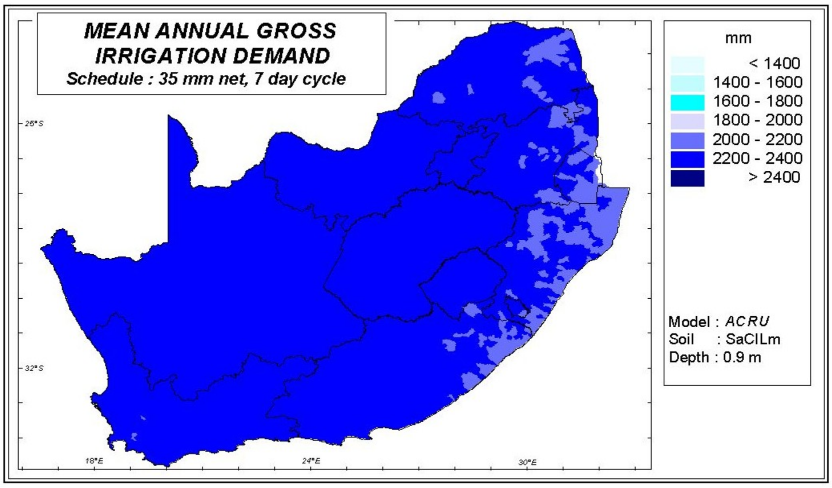

Figure 6.24 Mean annual gross irrigation for a 35 mm / 7 day cycle on a 0.9 m SaClLm soil

Maps depicting both summer and winter irrigation applications were represented by the months of January and June respectively. From Figures 6.25 and 6.27, which illustrate demand and drip irrigation requirements during the month of January, it may be seen that the values are very similar, varying from 125 –150 mm in the east to approximately 250 mm in the more arid western regions, except that the map of demand irrigation shows, on average, application rates approximately 25 mm higher for the month. During the winter months evaporation rates are lower, which therefore implies that irrigation demands should be lower than in summer. This may be seen in Figures 6.26 and 6.28 for demand and drip irrigation in June. The general distribution patterns for these modes of irrigation are very similar. These patterns show that less than 50 mm of irrigation is required in the southern regions of South Africa during July, as this time period coincides with the winter rainfall season. These values then increase northwards, where demands are between 100 – 125 mm for July.

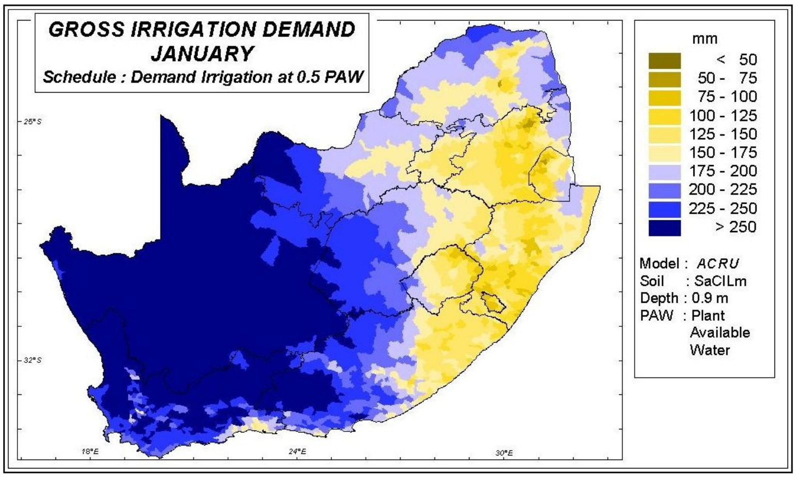

Figure 6.25 Gross irrigation demand in January for demand irrigation on a 0.9 m SaClLm soil, irrigated at 0.5 PAW

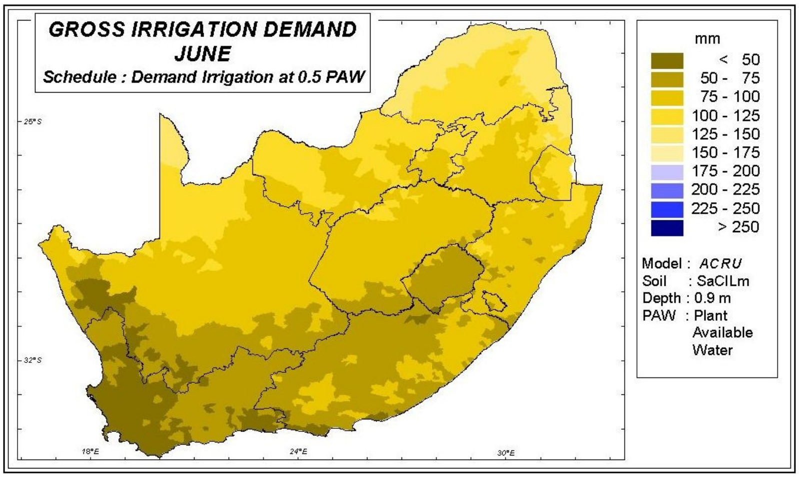

Figure 6.26 Gross irrigation demand in June for demand irrigation on a 0.9 m SaClLm soil, irrigated at 0.5 PAW

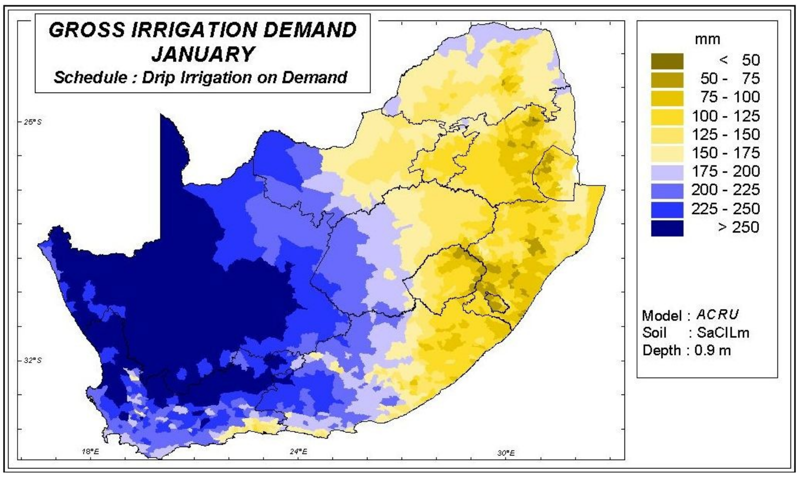

Figure 6.27 Gross irrigation demand in January for drip irrigation on a 0.9 m SaClLm soil

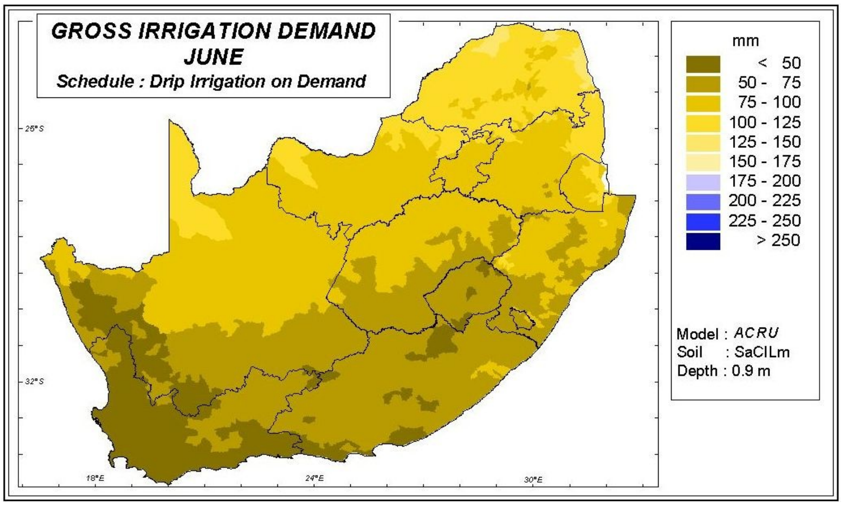

Figure 6.28 Gross irrigation demand in June for drip irrigation on a 0.9 m SaClLm soil

In Figures 6.29 to 6.34, maps of different fixed amount / fixed cycle modes of scheduling are displayed. Comparisons were made according to the amount of irrigated water applied, bearing in mind that irrigation cycles were skipped in the simulations if specific rainfall thresholds were exceeded, as mentioned previously in Section 6.4.1.

In Figure 6.29, which illustrates patterns for a fixed amount of 15 mm / 7 day cycle for January, applications vary from less than 50 mm in the east, to between 50 – 75 mm in the central regions and between 75 – 100 mm able to be applied in January in the more arid west. The distribution patterns shown in Figure 6.31 for the 20 mm per 7 day application for January indicate, in general, an increase of approximately 25 mm from those seen in Figure 6.29 for the 15 mm / 7 day cycle. Figure 6.33 illustrates the application amounts for the 35 mm / 7 day cycle and shows an almost uniform 175 – 200 mm application over South Africa for the month of January, with some areas in the east indicating a slight reduction to 150 – 175 mm. These high values would suggest that significant amounts of water would be wasted, due to over-irrigation, as shown previously in Figure 6.29 for the mean annual gross irrigation demand for this application rate. However, application rates of 15 mm and 20 mm / 7 day cycle show far more effective usages of water and limited wastage.

In the winter months (June), for the fixed amount / fixed cycle schedules, application rates were essentially at a maximum of what could have been applied under the specific irrigation cycle. The reason for this is that during the dry winter months the rainfall thresholds were seldom exceeded, except for small areas in the south and southwest of South Africa, which receive rainfall predominantly during the winter months. With the fixed amount / fixed cycle amount of 15 mm / 7 day cycle a relatively uniform amount of between 75 – 100 mm was required for June, as seen in Figure 6.30. With the application rates of 20 mm / 7 day cycle and 35 mm / 7 day cycle the distributions were relatively uniform for the whole of South Africa, with application rates of 100 – 125 mm and 175 – 200 mm respectively, as shown in Figures 6.32 and 6.34. The reason for irrigation demands being greater than that which may be applied to the field within a particular month, according to the given application rates, is due to the fact that gross irrigation is assumed. This therefore includes conveyance and application losses, which results in inflated irrigation demands.

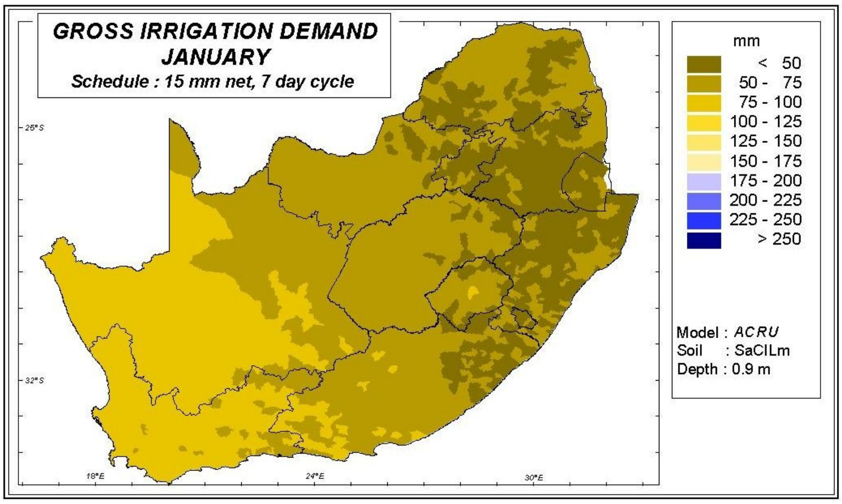

Figure 6.29 Gross irrigation demands in January for a fixed application of 15 mm / 7 days on a 0.9 m SaClLm soil

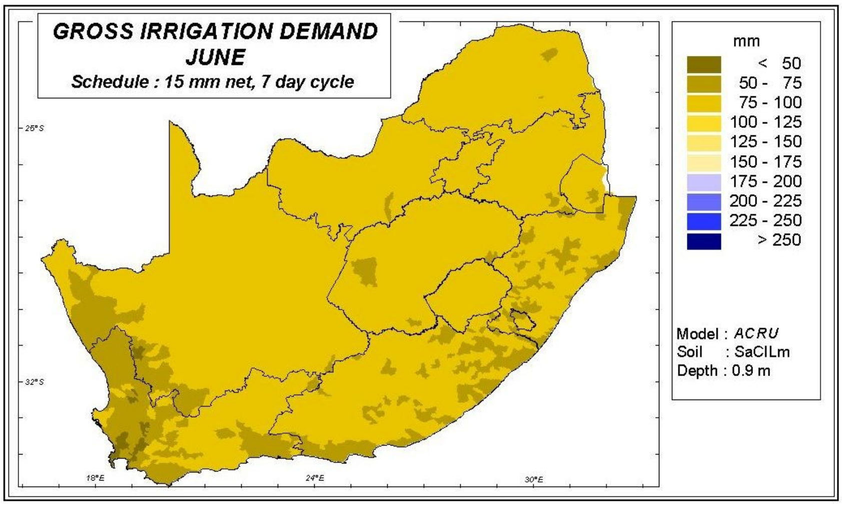

Figure 6.30 Gross irrigation demand in June for a fixed application of 15 mm / 7 days on a 0.9 m SaClLm soil

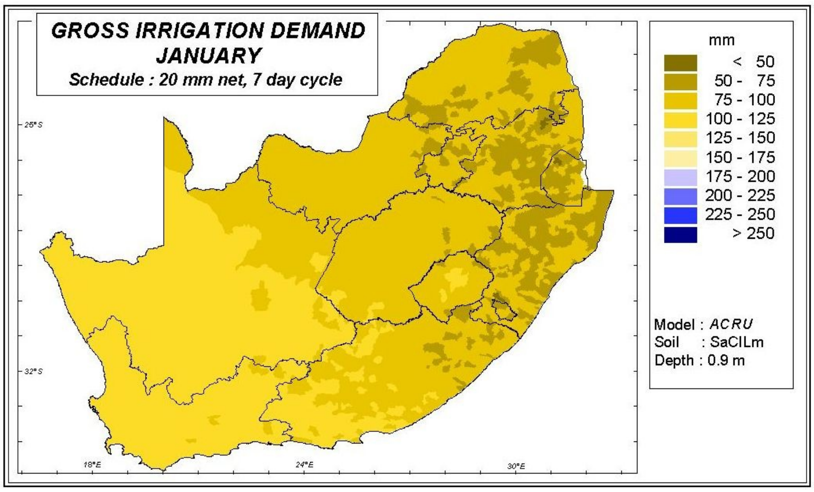

Figure 6.31 Gross irrigation demand in January for a fixed application of 20 mm / 7 days on a 0.9 m SaClLm soil

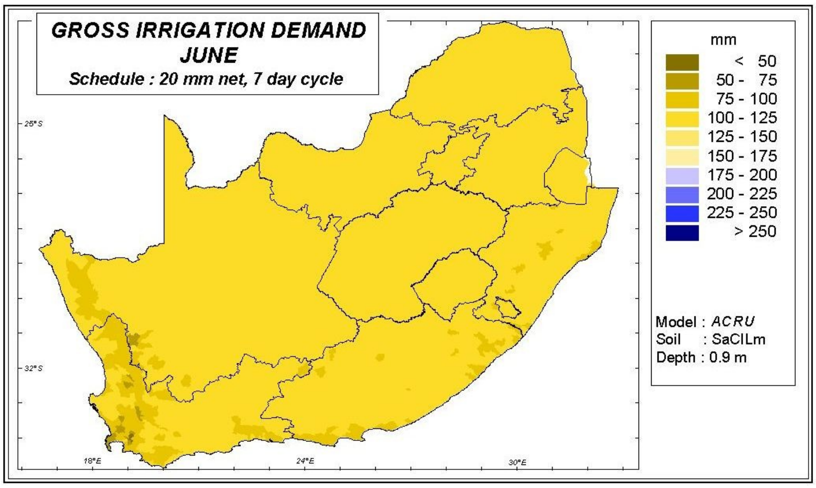

Figure 6.32 Gross irrigation demand in June for a fixed application of 20 mm / 7 days on a 0.9 m SaClLm soil

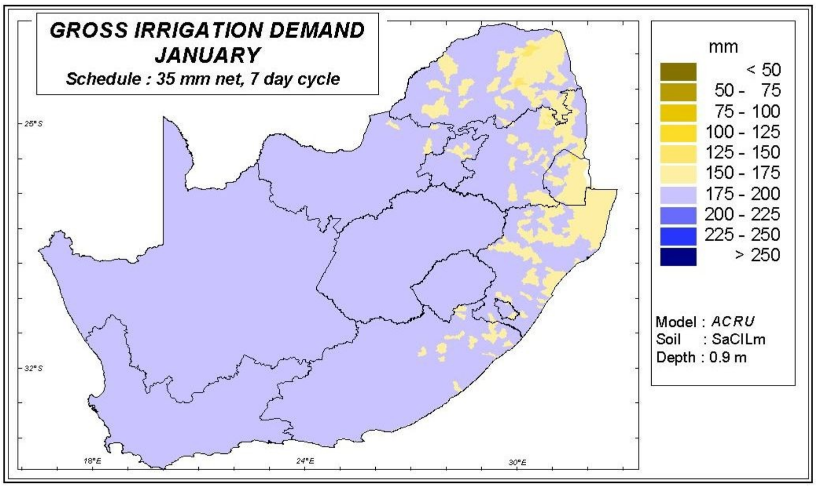

Figure 6.33 Gross irrigation demand in January for a fixed application of 35 mm / 7 days on a 0.9 m SaClLm soil

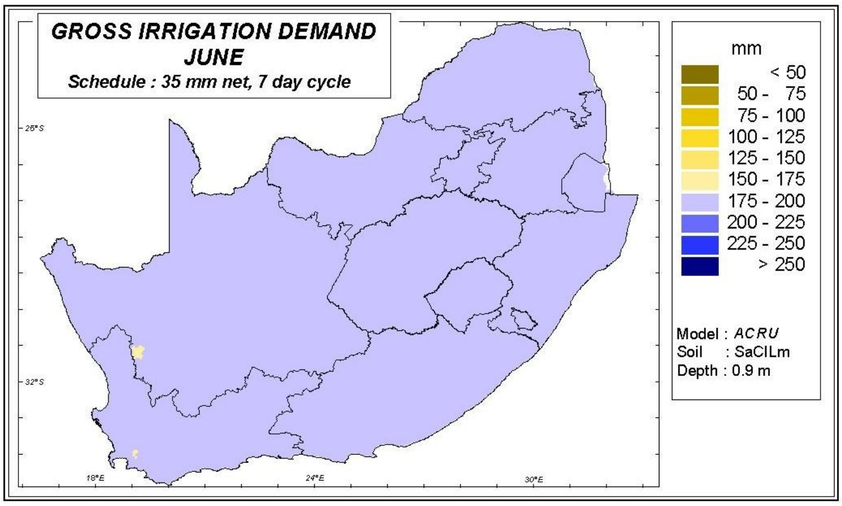

Figure 6.34 Gross irrigation demand in June for a fixed application of 35 mm / 7 days on a 0.9 m SaClLm soil

6.5 Conducive and Non-Conducive Growing Conditions

Conducive growing conditions are defined as the accumulated number of heat units on the basis that plant growth is not restricted, or inhibited, by either temperature or soil water stress, as defined below in Section 6.5.1. Non-conducive growing conditions are therefore the opposite of this, whereby growth is restricted, or inhibited, owing to a lack of soil water or temperature. Distributions of conducive growing conditions enable the identification of areas where, according to water availability and temperature, sugarcane growth is most viable. For more information on conducive and non-conducive growing conditions refer to Section 2.3.1.3.

6.5.1 Methods and Assumptions Used in Mapping Conducive and Non-Conducive Growing Conditions

A number of assumptions were made in order to map conducive and non-conducive growing conditions. These included:

- first, that sugarcane does not produce new biomass at temperatures below 10ºC (Zhou *et al.,* 2003);
- secondly, when soil water content drops to below 50% of total PAW, sugarcane growth is inhibited (Singels *et al.,* 1998); and

- thirdly, that for purposes of comparison a uniform soil profile with the water holding and drainage properties of a 0.9 m deep SaClLm was considered for the whole of southern Africa.

The calculation of conducive growing units is therefore the accumulation of daily heat units for a base temperature of 10ºC, only when the soil water content on that day excelled 50% of total PAW. Conversely, non-conducive units are the accumulation of daily heat units with a base temperature of 10ºC, on the condition that soil water content for that day was less than 50% of total PAW. Plant available water was calculated for a SaClLm soil assuming a Drained Upper Limit (DUL) of 234 $mm.m^{-1}$ and a Lower Limit (PWP) of 144 $mm.m^{-1}$ for a 0.9 m deep soil profie. Daily soil water content was estimated as in Section 6.2, using the *ACRU* agrohydrological model (described in Section 3.5).

6.5.2 Distribution Patterns of Conducive and Non-Conducive Sugarcane Growth Conditions

Maps of conducive and non-conducive growing conditions were produced for the months of January and June, in order to represent summer and winter conditions, respectively, and for the entire year. In Figure 6.35, showing conducive cane growth units for the month of January, the majority of conducive growing conditions are found in the eastern half of the country, with values ranging from approximately 60 units to in excess of 240 units. Regions showing the greatest potential for sugarcane growth, according to these criteria, include the central and southern coast areas of KwaZulu-Natal, central Swaziland, Mpumalanga and the central Limpopo provinces. The distribution patterns shown in this map may be attributed to the fact that soil water contents in these areas, at this time of year, are largely in excess of 50% PAW, therefore allowing for the accumulation of heat units. The opposite is true for the western half of the country, where temperature conditions would be conducive, but the lack of soil water would result in sub-optimal growing conditions for sugarcane.

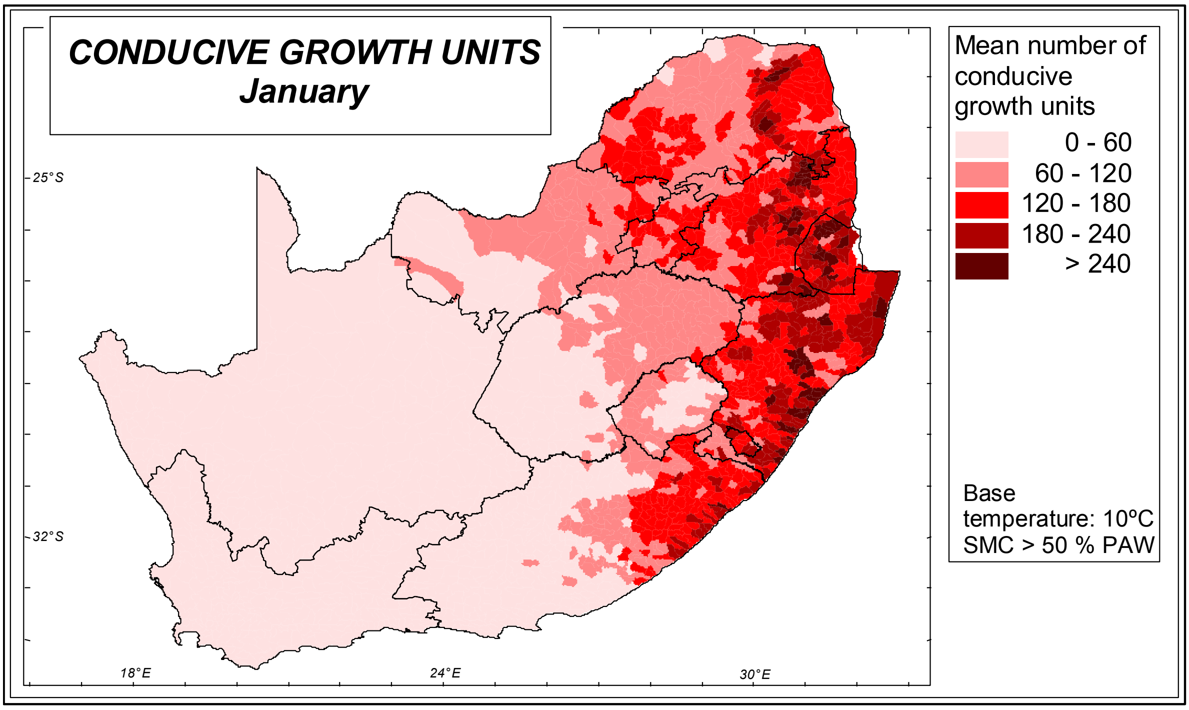

Figure 6.35 Mean number of conducive growth units for the month of January

The distribution patterns shown in Figure 6.36 are vastly different to those for January. In June the majority of conducive growth units is limited to the coastal areas, with the Western Cape indicating the largest area in which conditions are favourable for growth. The number of conducive growth units for these regions range between 25 and 75, which is significantly lower to those of January. For the winter period, soil water contents and temperature are both too low for optimal sugarcane growth in the inland regions of South Africa, resulting in the low number of optimal heat unit accumulations. Parts of the Eastern Cape may have sufficient soil water content (cf. Figures 6.3 and 6.11), but owing to the low winter temperatures there is only a low accumulation of optimal growth heat units (cf. Figures 4.1 to 4.8). When comparing the distribution patterns shown in Figure 6.35 with those in Figure 6.36, it may be seen that, although some areas in the summer months may show optimal growing conditions for sugarcane, it is not possible to grow sugarcane in these areas owing to lack of optimal growing conditions in the winter.

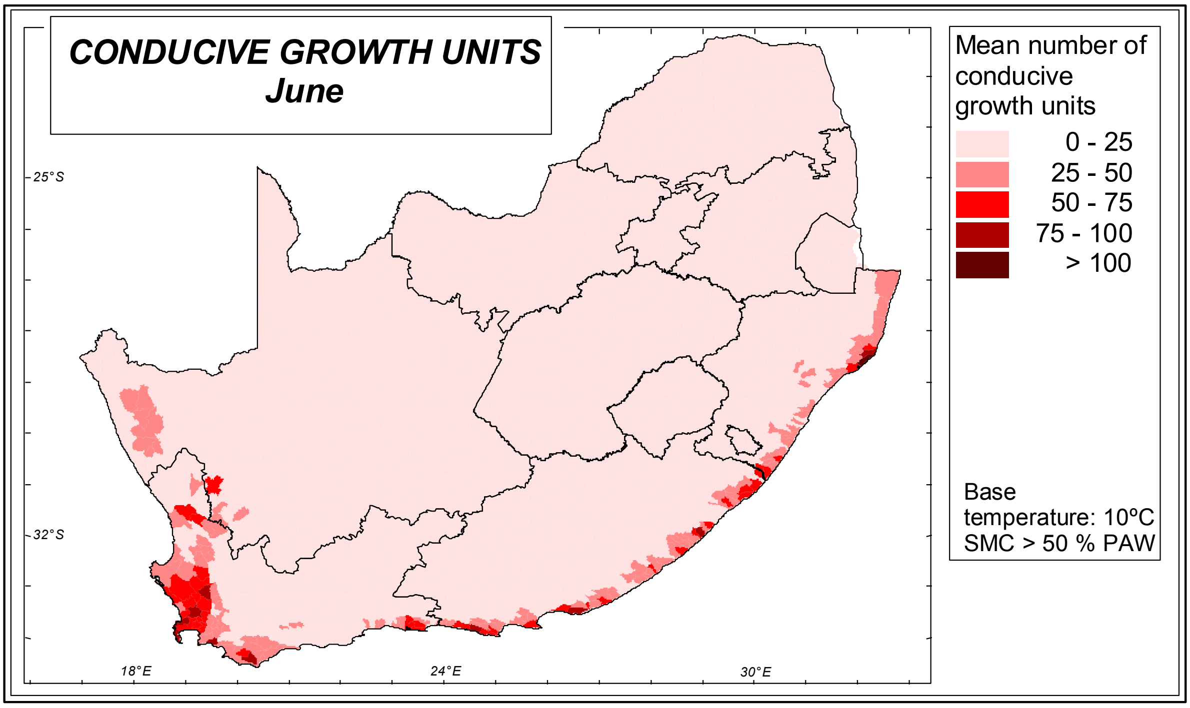

Figure 6.36 Mean number of conducive growth units for the month of June

Figure 6.37 shows the distribution patterns of non-optimal heat units for the month of January. These range from less than 125 units in areas of the eastern parts of South Africa to between 500 and 625 heat units in the central and northern regions of South Africa. The relatively high numbers of heat units found in the central and northern parts of South Africa may be attributed to the high temperatures in combination with relatively low rainfall amounts during this time of the year. Figure 6.37 confirms the results shown in Figure 6.35, in that during summer months, the northern parts of the Eastern Cape, KwaZulu-Natal, central Swaziland, Mpumalanga and central Limpopo show conditions that are conducive to sugarcane growth. The patterns shown in Figure 6.38 of non-conducive heat units for the month of June show a very different pattern to those shown in Figure 6.37. The majority of non-conducive heat units are concentrated around the coastal and northeastern regions of southern Africa. The total number of accumulated heat units varies from fewer than 50 units in the central and southeastern parts of southern Africa, to in excess of 200 units in the northeastern regions of southern Africa. The relative lack in the number of heat units, especially in the central areas of southern Africa, may be attributed to the low temperatures during this time of the year, which results in the reduced number of accumulated units.

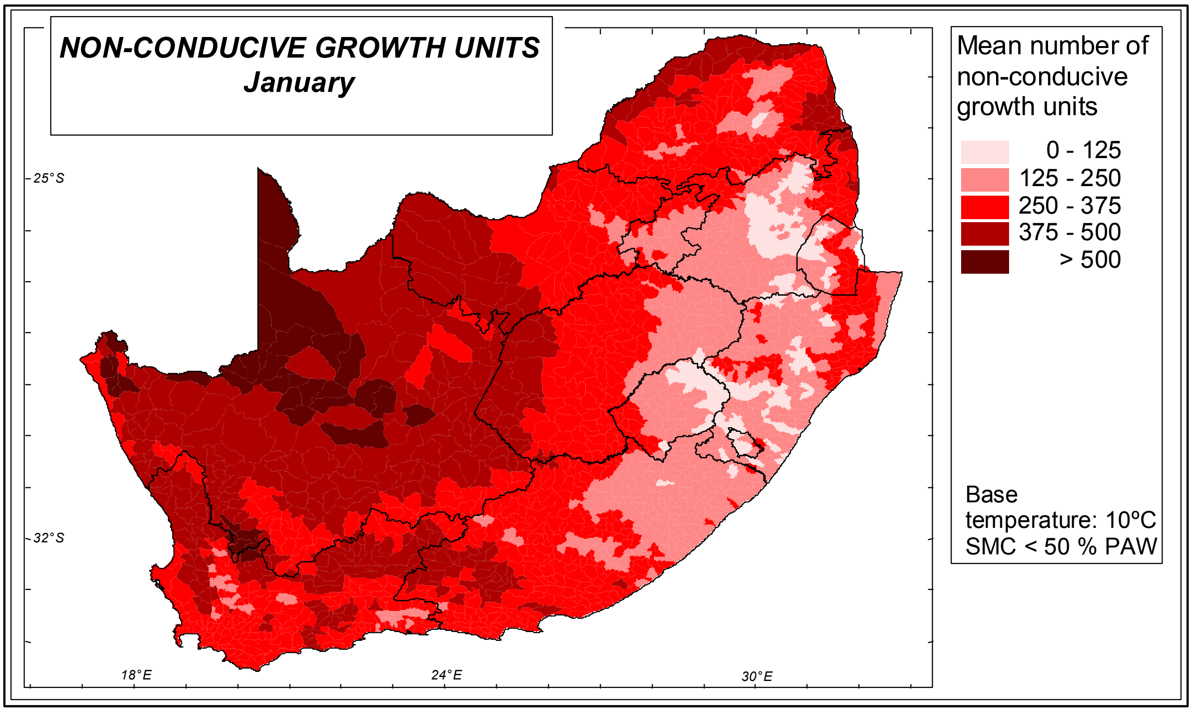

Figure 6.37 Mean number of non-conducive growth units for the month of January

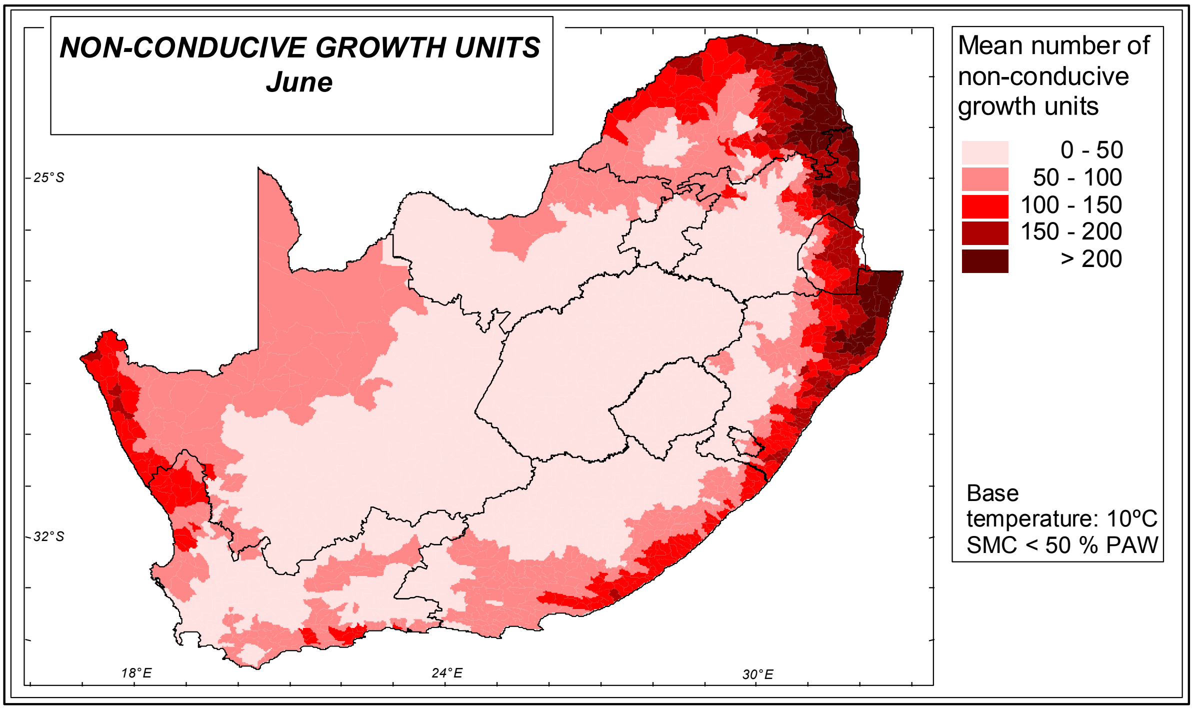

Figure 6.38 Mean number of non-conducive growth units for the month of June

Distribution patterns of mean annual conducive and non-conducive growth units for southern Africa are shown in Figures 6.39 and 6.40 respectively. In Figure 6.39, the majority of conducive growth units are found in the eastern half of southern Africa. Regions showing the greatest potential for sugarcane growth include the northeatern parts of the Eastern Cape, coastal and midland regions of KwaZulu-Natal, central Swaziland, Mpumalanga and parts of Limpopo province, where values ranged between 1000 and 1750 growth units. These distribution patterns may be attributed to higher incidences of moist soil conditions as a result of higher magnitudes of mean annual precipitation, as depicted by Schulze and Lynch (2007). The mean annual non-conducive growth units, shown in Figure 6.40, depict the coastal, northern and north-eastern parts of southern Africa as having the highest numbers of non-conducive growth units, with numbers ranging from ~ 1500 units to > 3750 units. The high number of non-conducive growth units is evidence of the generally hot and arid nature of much of southern Africa. The distribution patterns of non-conducive growth units follow very closely to the distribution patterns of mean annual temperature as depicted by Schulze and Maharaj (2007a), which shows the distribution of non-conducive growth units is largely affected by temperature through its influence on heat units.

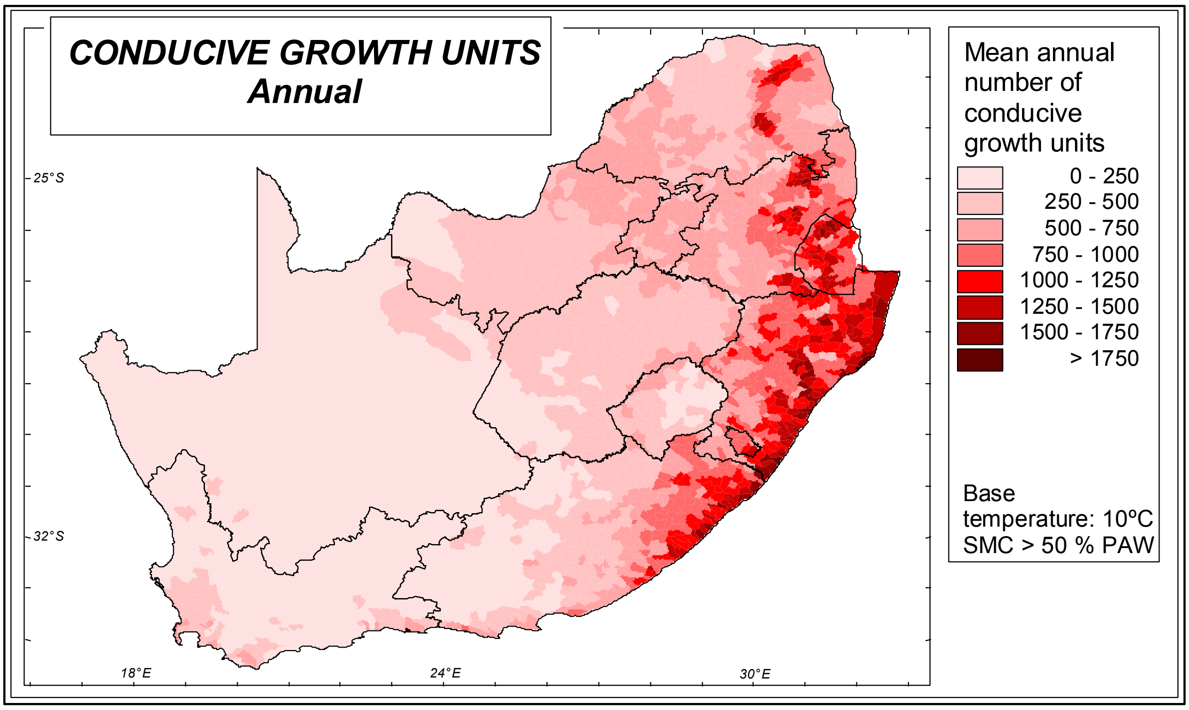

Figure 6.39 Mean annual number of conducive growth units for southern Africa

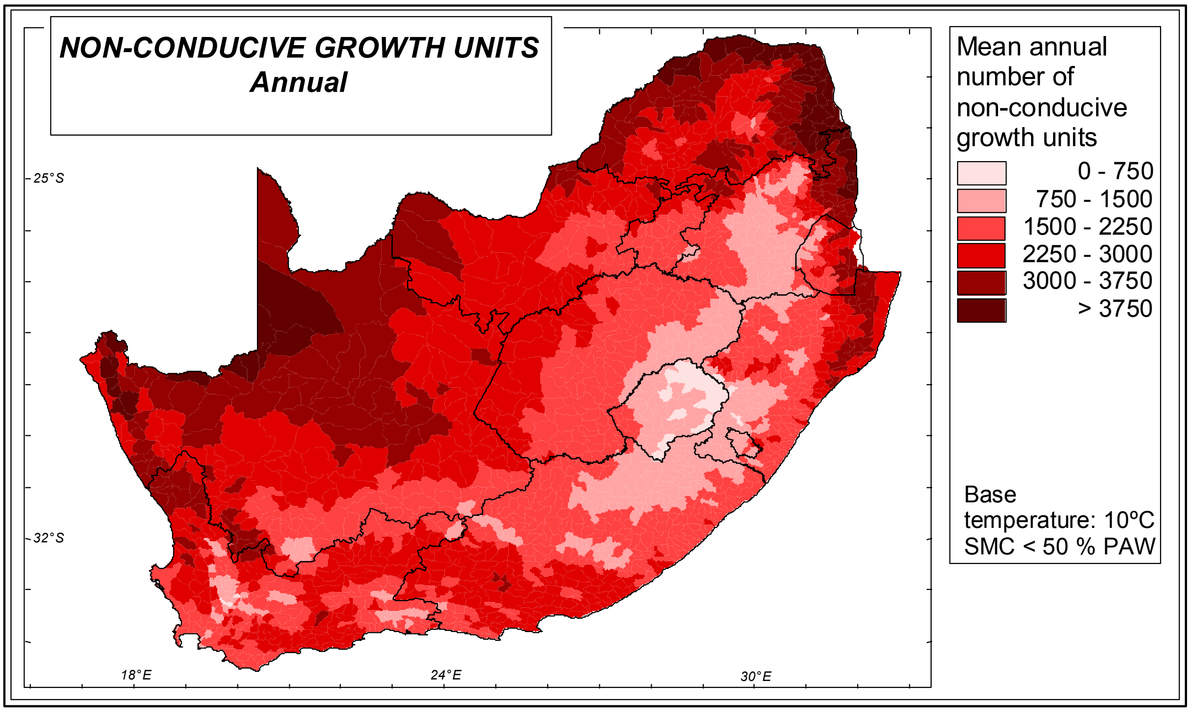

Figure 6.40 Mean annual number of non-conducive growth units for southern Africa

6.6 Flowering in Sugarcane

Flowering of sugarcane is the result of a number of complex physiological processes, triggered by specific environmental conditions (Julien, 1972; Coleman, 1969; Gosnel, 1973; Moore, 1987; Nayamuth *et al.*, 2003, Donaldson and Singels, 2004). Flowering results in a reduction in sugarcane yield; however, only if it impacts on the harvesting cycle. The aim of mapping the flowering of sugarcane is to identify areas in which conditions are most suitable to flower initiation. For more information on flowering of sugarcane refer to Section 2.3.5.

6.6.1 Methods and Assumptions Used in Mapping Flowering of Sugarcane

Studies conducted by Donaldson and Singels (2004) on the environmental requirements for sugarcane flowering formed the basis upon which assumptions were made in order to map areas that may be prone to sugarcane flowering. According to Donaldson and Singels (2004), in order for flowering to occur, specific day lengths (Moore, 1987), temperatures (Coleman, 1968) and soil water contents (Gosnel, 1973; Moore, 1987) are required, *viz.*

- no soil water stress (Gosnel, 1973; Moore, 1987),
- a day length shorter than 12.5 hours (Ethirajan, 1987), and
- daily maximum and minimum temperatures of approximately 28°C and 23°C, respectively (Heinz, 1987).

It was also found by Coleman (1968) that at temperatures below 18°C, flower initiation and/or emergence were significantly reduced. The time period during which sugarcane flowering is initiated coincides with 22 days from the time when day length shortens to less than 12.5 hours (Ethirajan, 1987). In order to calculate the commencement and duration of this time period, a number of latitudinal points along the current sugarcane growing regions (cf. Figure 3.6) were taken, and the associated day when day length shortened to below 12.5 hours calculated. These time periods coincided largely with the first three weeks of March.

From the above-mentioned factors an index was developed whereby, for the 22 day period calculated from the beginning of March, the average number of days over the 50 year period spanning 1950 to 1999 on which soil water content for the day was > 50% PAW (to account for non-stress conditions), and daily minimum temperature was above 18°C, were accumulated. The South African temperature database described in Section 3.2, and the derivation of soil water contents as described in Section 6.2 for a SaClLm textured soil with a profile thickness of 0.9 m, were used in the calculations of the above-mentioned thresholds.

6.6.2 Distribution Patterns of Sugarcane Flowering in Southern Africa

The sugarcane flowering index, mapped in Figure 6.41, indicates the east coast of southern Africa to be most prone to sugarcane flowering. Parts of the central and north coast areas of KwaZulu-Natal display an average of between 8 and 12 days out of a total possible 22 that meet the conditions to induce flowering. Areas along the east coast and extending inland of KwaZulu-Natal, some of the northern coastal parts of the Eastern Cape, central Swaziland, the lowveld of Mpumulanga and the Limpopo province show between 4 and 8 days per annum which meet the condition for flowering. Between 2 and 4 conducive days are found on the peripheries of these areas. Although the above-mentioned numbers seem low, it is important to note that they are an average over a 50 year period (1950 to 1999), and that flowering does not generally occur every year, but rather more sporadically. Therefore, it is very unlikely that the index would indicate all 22 possible days of a year as meeting the flowering conditions. Bearing this in mind, areas showing between 8 and 12 conducive days indicate a high risk of sugarcane flowering. This index therefore provides some indication of long-term flowering risk. Further research is needed to also quantify the inter-annual variability of the flowering index.

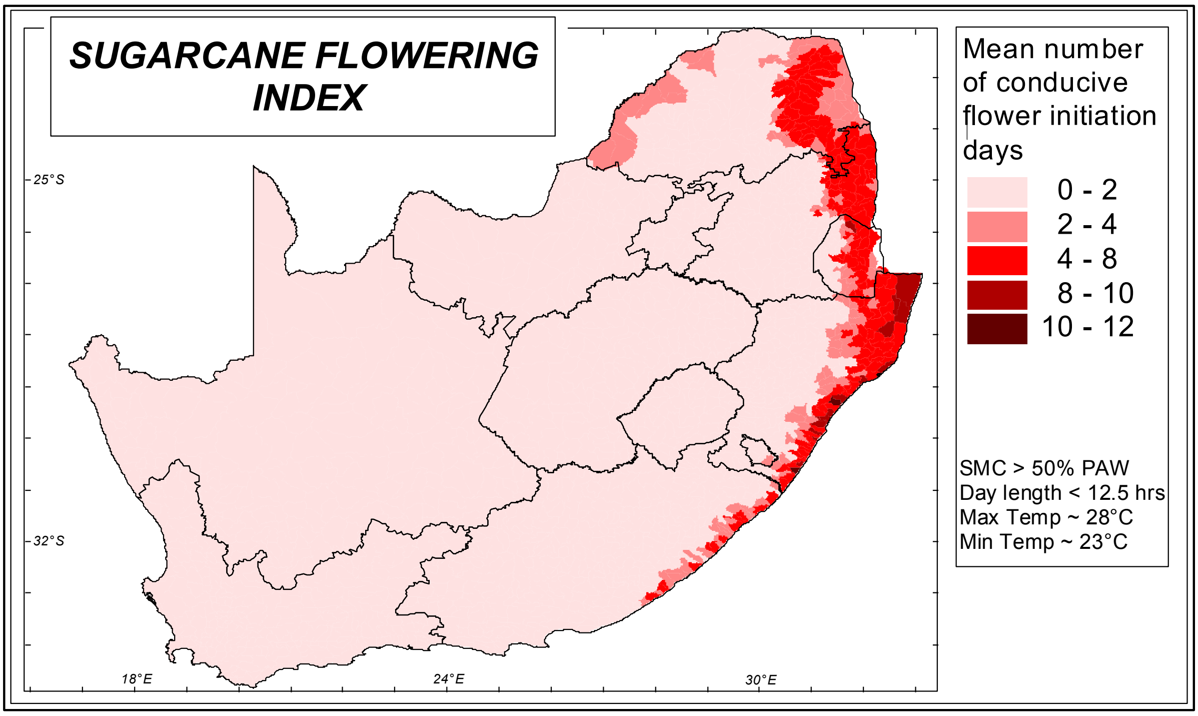

Figure 6.41 Mean annual number of days prone to the flowering of sugarcane

* * * * * * *

In this chapter a number of the factors which affect the growth and production of sugarcane, and which are related to soil water, were evaluated. These factors included soil water content, soil compaction, irrigation water demands, conducive and non-conducive growing units and, finally, sugarcane flowering. The objective of mapping of soil water content was to allow for comparisons of soil water to be made between the various soil types and depths, as well as to identify specific areas in which soil water may be a limiting factor to sugarcane growth. These maps may potentially be used in strategic planning, by extension officers or farmers in general. Mapping soil compaction included estimating the start of the infield traffic season as well as their associated length and risk. Through these maps, theoretical time periods were identified as to when the risk of soil compaction is reduced. These maps may be used as a guideline to, for example, plan planting and harvesting dates, so that the risk of soil compaction may be minimised. Irrigation water demands were mapped to allow for comparisons to be made between the various modes of irrigation, based on a 0.9 m SaClLm soil. The objective of this was to enable users to identify which specific irrigation mode and application rate would be most suited to a particular region. Conducive growth units were mapped according to the temperature and soil water criteria, and these show up areas most suitable for sugarcane growth. The intended purpose of these maps was to identify potentially new areas in which sugarcane may be grown successfully. Non-conducive growth units depicted the areas in which the sugarcane plant is more likely to become stressed, owing to a lack of soil water and increased temperatures. Flowering in sugarcane may potentially result in losses in sugarcane yield. It is for this reason that areas that may be prone to sugarcane flowering were identified. The application of these maps may be found in strategic planning, for example, by selecting flowering resistant varieties of sugarcane in areas shown to be prone to it occurring. The chapter which follows covers the mapping of yield estimates for both dryland and irrigated sugarcane.

7. ESTIMATES OF SUGARCANE YIELDS

7.1 Introduction

In the sugarcane industry there are a number of benefits associated with accurate crop yield estimation. Through sugarcane yield estimation, informed decisions involving mill operations, planning and management as well as agronomic practices at a farm scale may be made. There are a variety of techniques available for yield estimation, including rules of thumb, neural network analysis, statistical modelling, remote sensing and more deterministic simulation modelling (Lumsden *et al*., 1998). For this study the *ACRU* agrohydrological simulation model was used to simulate sugarcane yields under dryland conditions for a range of season lengths, in order to determine:

- areas suitable for sugarcane growth,
- optimum season length at different locations, and
- potential sugarcane yields.

In addition to this, the estimation of sugarcane yield increments per 100 mm of irrigated water, using various modes of irrigation, was calculated using the *ACRU* model.

7.2 Estimates of Optimal Sugarcane Season Lengths and Associated Dryland Yields in Southern Africa

Owing to the variability of the southern African climate, the optimal season lengths and yields of sugarcane differ greatly from location to location and year to year. In this section, optimal season lengths and the associated dryland cane yields are estimated. Sugarcane yields for varying season lengths are estimated with the degree day driven crop coefficient research version of the *ACRU* model, developed by Lumsden (2000). Those climate derived crop coefficients are then used to model accumulated actual evapotranspiration, which is the variable used to estimate sugarcane yield with the Thompson (1976) equation, but for user defined varying season lengths. The equations are given in Section 3.5.2.2. Prior to using the above-mentioned version of the *ACRU* model to simulate sugarcane yield, the recently developed *CANEGROW* model (Moult, 2005) was considered. It was, however, found that the input requirements of this model were too detailed for the scale at which this study was undertaken.

7.2.1 Model Inputs When Estimating Sugarcane Yields

The above-mentioned research sugarcane module (as against the downloadable general user version) of the *ACRU* agrohydrological model was developed by Lumsden (2000) and caters for estimating yields with different growing cycle lengths, harvest dates and ratoons. This version was used to simulate sugarcane yields with varying season lengths of 12, 15, 18, 21 and 24 months. For all simulations only a typical sandy clay loam (SaClLm) textured soil with a total depth of 0.9 m and a topsoil thickness of 0.3 m was considered for all QCs. Soil water contents at the lower limit, the drained upper limit and saturation were assumed to be at 160 mm.m^{-1}, 260 mm.m^{-1}, and 435 mm.m^{-1} respectively. The crop coefficient for sugarcane was input at 0.9 for all months of the year and interception losses were set at 1.8 mm per rainday (De Villiers, 1978).

When mapping sugarcane yields, a number of climatic and economic criteria/constraints were used to define potentially viable sugarcane growing areas, *viz*.

- mean harvest cycle accumulated heat units (base 12°C) had to exceed 3 300 degree days, which relates to the heat requirements of the sugarcane plant for maturity to be reached (Inman-Bamber, 1995);
- mean accumulated heat units (base 12°C) had to be below 4 500 degree days, as above this value no significant increase in yield accrues (Hughes, 1992), therefore resulting in a loss in annualised profit beyond this heat unit threshold;
- the means of daily July minimum temperature had to be in excess of 5°C, which relates to the cold/frost constraints of the sugarcane plant (Smith, 1998); and
- areas with annualised cane yield less than 30 t/ha were considered not economically viable for sugarcane production (Schulze *et al.,* 2007c).

7.2.2 Verification of Dryland Sugarcane Yields over Southern Africa

In order to verify the yields obtained by the *ACRU* model, comparisons between simulated and actual yields were undertaken. Industry production data from 1982 to 2002 were used to calculate mean sugarcane yield per harvest season for various mills throughout the sugarcane growing areas of South Africa (Bezuidenhout and Singels, 2007). Simulated yields were taken from the corresponding Quaternary Catchments that were considered to largely represent a mill supply area. From Table 7.1, which gives means of actual sugarcane yields per annum from various mills and the corresponding means of annualised simulated sugarcane yields, an average overestimation of 18.4 t/ha is noted, compared with an overestimation of 29.8 t/ha by Bezuidenhout and Singels (2007). This overestimation is a common phenomenon amongst crop yield models (Bezuidenhout and Singels, 2007), and is most likely due to certain factors that affect sugarcane yield in reality, but are not taken into account in simulations. Such factors include, for example, pests and diseases and different levels of management. However, from these results it may be concluded that simulated yields are representative of those that occur in the industry. The bias-corrected root mean square error of average simulated yield at a QC scale was 9.4 t.ha (14.8%). The mean of the simulation bias was 18.4 t/ha, compared with 29.8 t/ha, found by Bezuidenhout and Singels (2007). These results therefore engender confidence in the approach taken, and in the results which follow.

Table 7.1 Mean actual and simulated sugarcane yields for various milling stations throughout the South African sugar industry

Mill name	**Means of actual sugarcane yields (t/ha) per annum**	**Means of simulated sugarcane yields (t/ha)**
Komati	84.1	92.6
Pongola	76.2	91.4
Umfolozi	68.6	69.7
Entumeni	42.1	60.4
Felixton	60.0	69.7
Darnall	49.3	84.5
Noodsberg	68.8	95.0
Eston	60.5	93.4
Sezela	56.4	81.6
Umzimkulu	70.2	81.7

7.2.3 Distribution Patterns of Dryland Sugarcane Yields Over Southern Africa for Various Season Lengths

The distribution patterns of dryland sugarcane yields for a 12 month growing season, shown in Figure 7.1, display a range of between 30 to 40 t/ha/annum in the northeastern parts of southern Africa, including the eastern parts of Mpumalanga and Limpopo, to in excess of 70 t/ha/annum in an area of the northeastern part of KwaZulu-Natal. The northeastern region of KwaZulu-Natal shows the greatest potential for dryland sugarcane production with a 12 month growing season, indicating in excess of 50 t/ha/annum for most of this region.

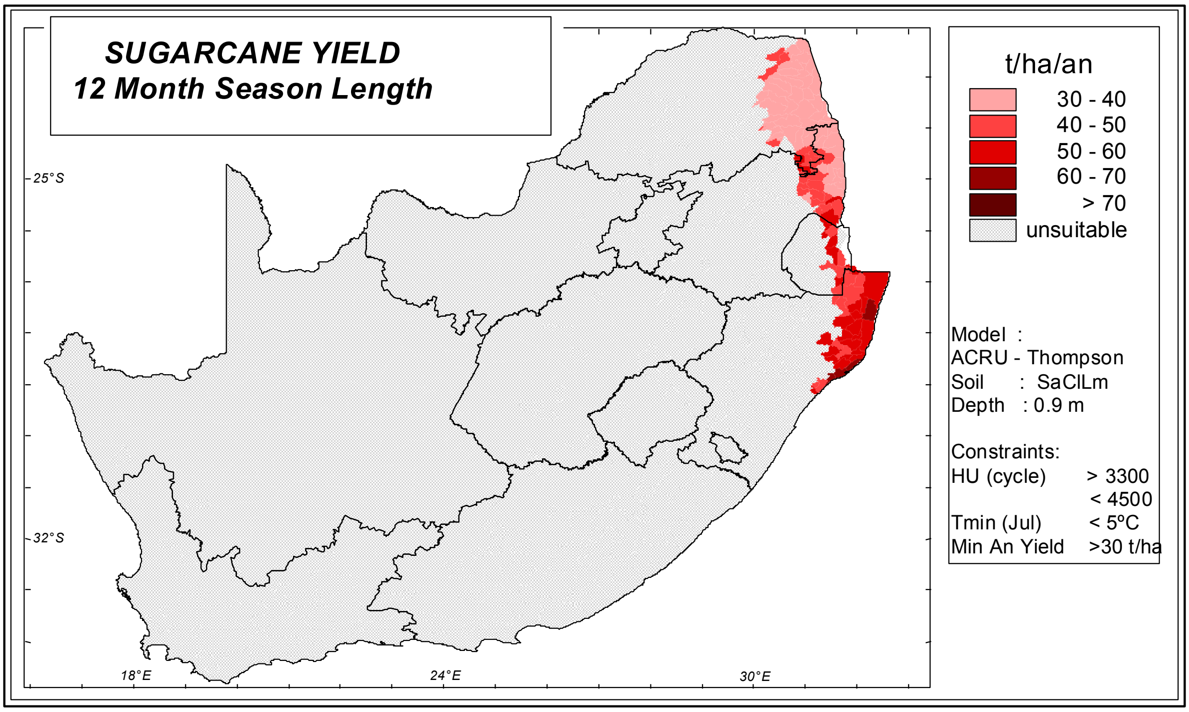

Figure 7.1 Distribution patterns of estimated sugarcane yields for a 12 month season length

Figure 7.2 shows the distribution patterns of sugarcane yield for a 15 month growing season. With the extended season length, the area which is shown to be viable for sugarcane production increases, and shifts inland to the more central higher lying parts of northern KwaZulu-Natal, Mpumalanga and Limpopo. The yields calculated for a 15 month season length are generally higher than those of the 12 month season, with the majority of areas showing between 60 and 75 t/ha being harvested. However, the map of annualised sugarcane yield for a 15 month crop, given in Figure 7.3, allows for comparisons to be made, and shows very similar annual yields to those seen for the 12 month season length. Areas previously shown to be viable in the northeastern parts of KwaZulu-Natal, Mpumalanga and Limpopo no longer show up as viable sugarcane production areas for this particular season length. The reason for this is that the upper limit of 4 500 HUs is exceeded for these regions. This suggests that the economic benefits of having a growth season of this length would be negligible, as possible increases in sugarcane yield for the increased season length would be low.

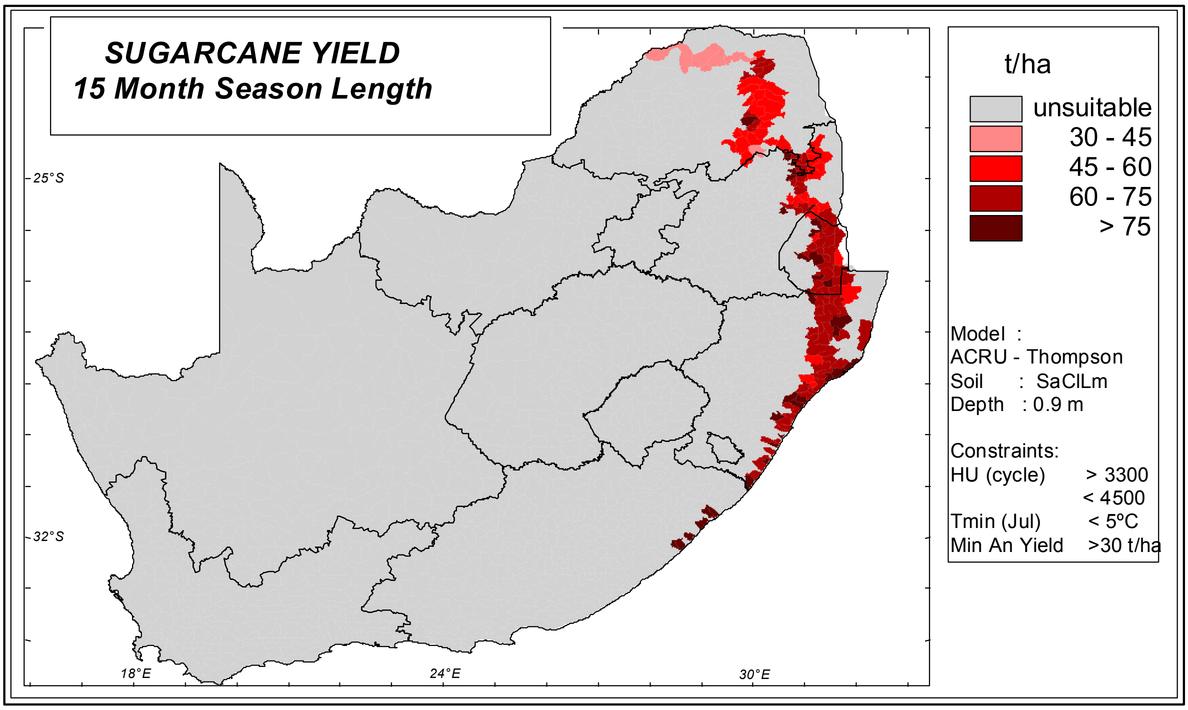

Figure 7.2 Distribution patterns of estimated sugarcane yields for a 15 month season length

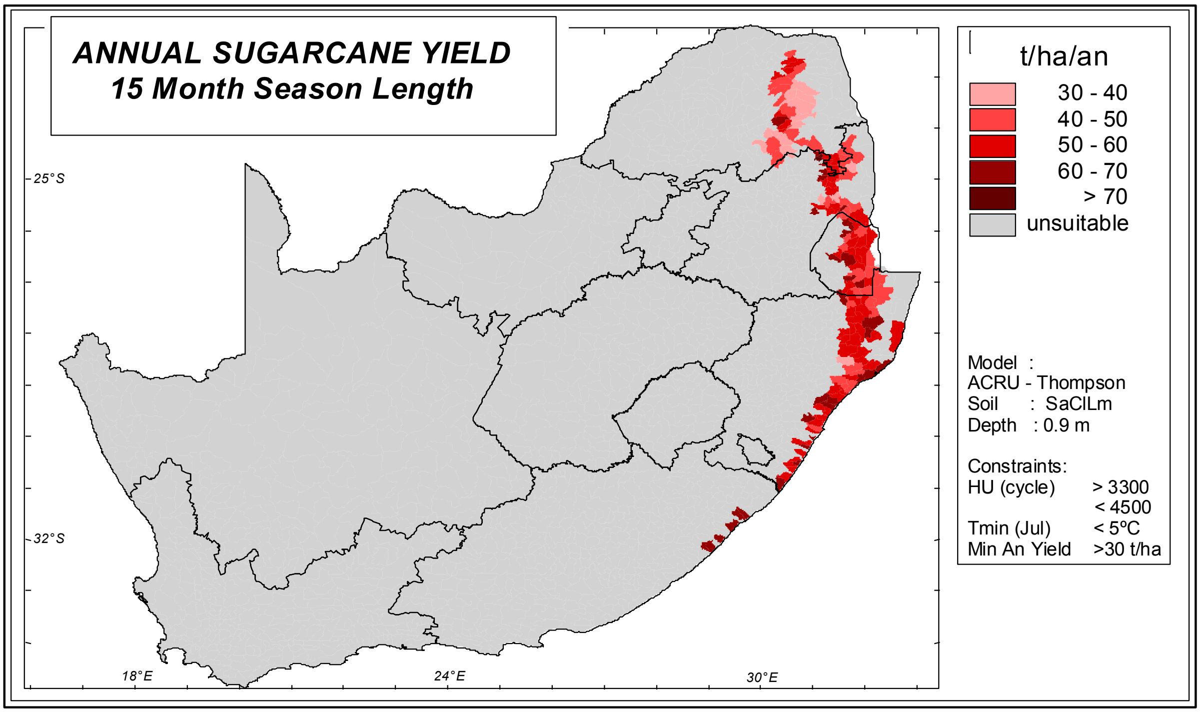

Figure 7.3 Estimates of annualised sugarcane yields for a 15 month season length

The distribution patterns of the total as well as annualised yields for an 18 month sugarcane growing season are shown in Figures 7.4 and 7.5, respectively. A shift in the areas in which sugarcane production is viable is noted in Figure 7.4, with areas further inland and south, extending into the Eastern and Western Cape indicating the potential for sugarcane production. The northeastern parts of the Eastern Cape, as well as the central and southern midlands KwaZulu-Natal and Swaziland show the greatest potential for sugarcane production at this season length, with potential yields of more than 70 t/ha over the 18 month season, or an annualised yield of in excess of 50 t/ha/annum. The central parts of Mpumalanga and Limpopo indicate, for the most part, a potential yield of between 50 and 70 t/ha over the 18 month growing season. However, the annualised yield values for these regions, shown in Figure 7.5, indicate a low annual potential yield of only between 30 and 40 t/ha/annum in those regions. In Figure 7.4, small areas in the Western Cape indicate a potential for sugarcane production. These estimated potential yields are, however, relatively low. This is confirmed in Figure 7.5 which shows the annualised potential yields, and which indicates a more conservative distribution of potential sugarcane growing areas in the Western Cape. These low annual potential yields show that planting sugarcane in these areas may not be viable in the long term.

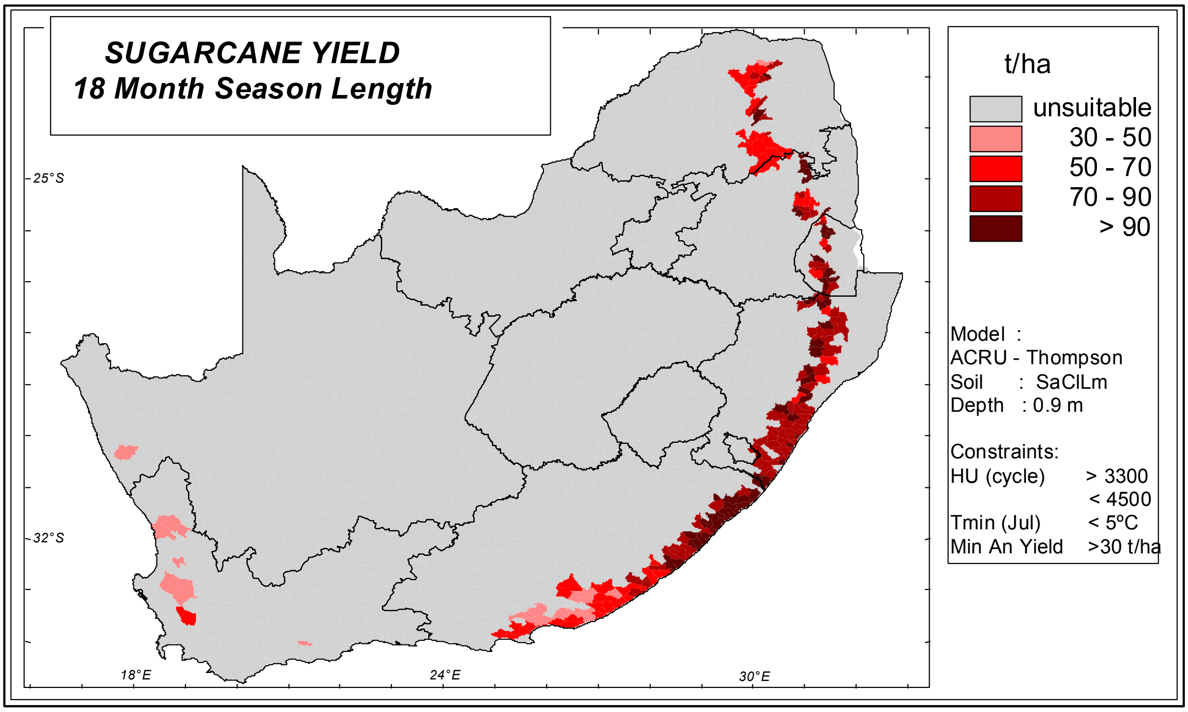

Figure 7.4 Distribution patterns of estimated sugarcane yields for an 18 month season length

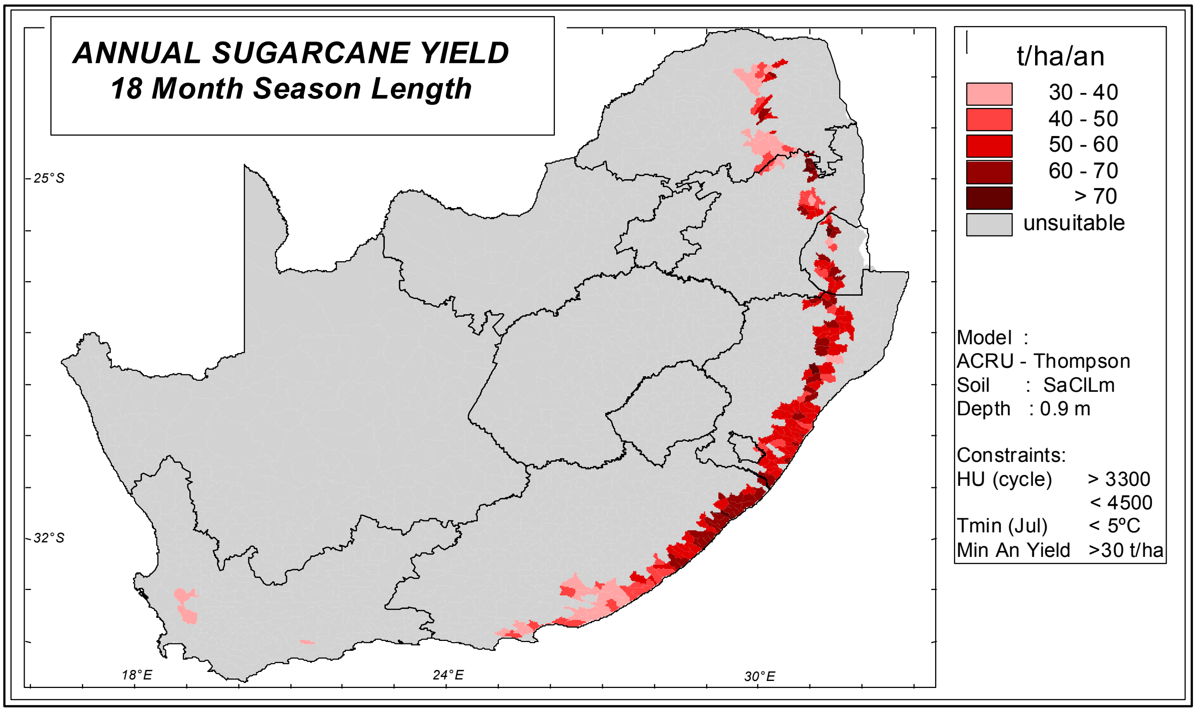

Figure 7.5 Estimates of annualised sugarcane yields for an 18 month season length

In Figures 7.6 and 7.7, areas showing the potential sugarcane production for a season length of 21 months include the inland regions of KwaZulu-Natal, coastal parts of the Eastern Cape, as well as small patches in the Western Cape, western parts of Swaziland, central

Mpumalanga and Limpopo. The central inland regions of KwaZulu-Natal and the northern parts of the Eastern Cape indicate the greatest potential for sugarcane production for a 21 month harvest season, showing patches of potential yields exceeding 100 t/ha over the 21 month season. In Figure 7.7 of the annualised potential sugarcane yields, the majority of regions indicated in KwaZulu-Natal, Swaziland and the Eastern Cape show potential annual yields of more than 50 t/ha/annum. Similar to the distribution patterns shown in Figure 7.5, a reduction in the area shown to be viable in the Western Cape is noted in Figure 7.7.

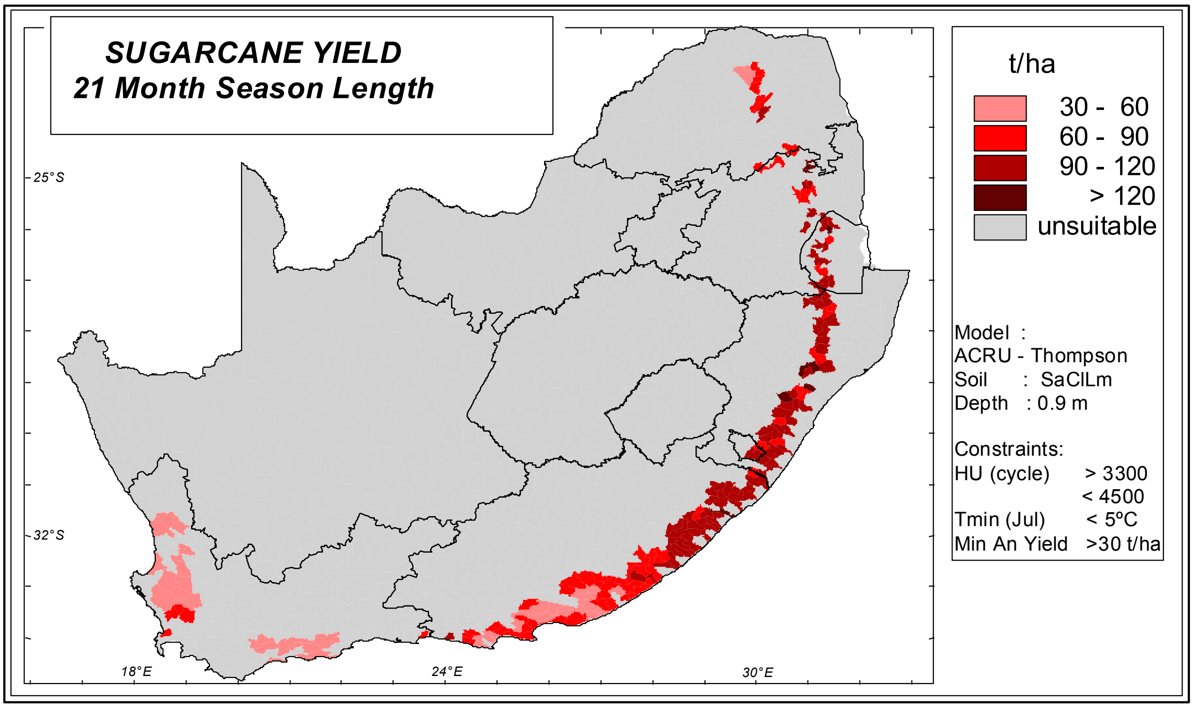

Figure 7.6 Distribution patterns of estimated sugarcane yields for a 21 month season length

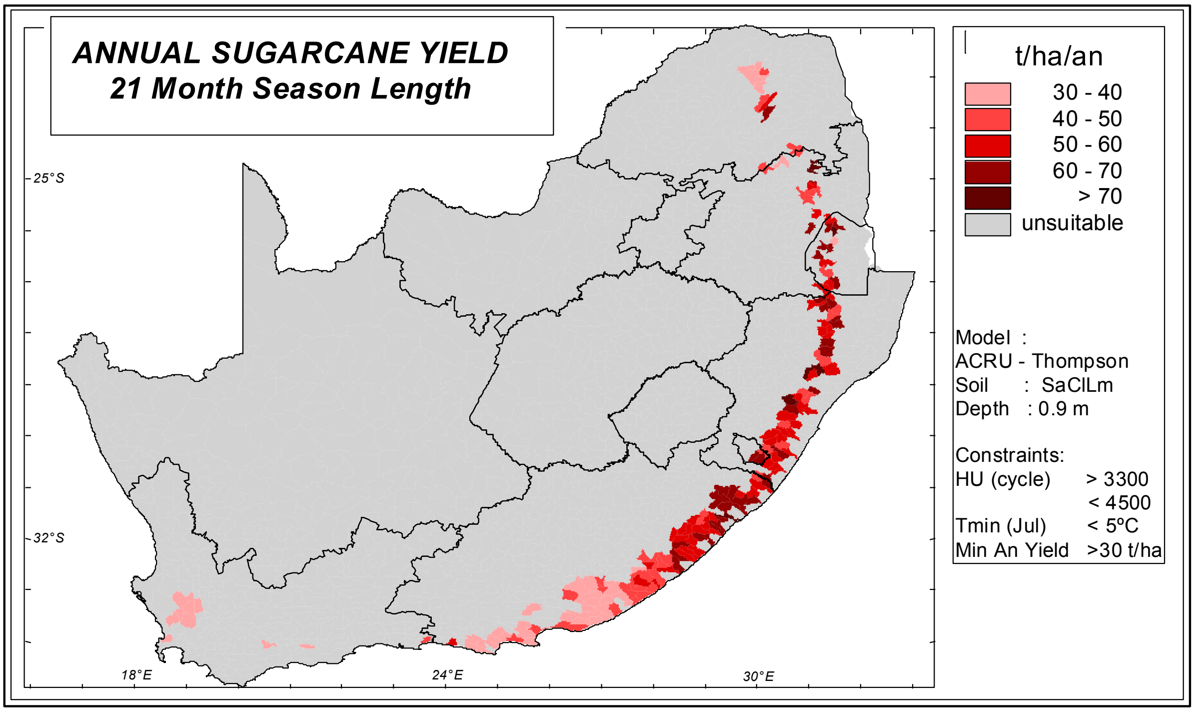

Figure 7.7 Estimates of annualised sugarcane yields for a 21 month season length

The distribution patterns shown in Figures 7.8 and 7.9 of potential sugarcane yields for a 24 month growing season are limited largely to the cooler inland regions of KwaZulu-Natal, the Eastern Cape, Western Cape, Swaziland and small patches of the central regions of Mpumalanga and Limpopo. The annualised yield estimates for the areas indicated in Figure 7.9 are generally above 50 t/ha/annum, apart from areas in the Western Cape, where yields of between 30 and 40 t/ha/an are shown.

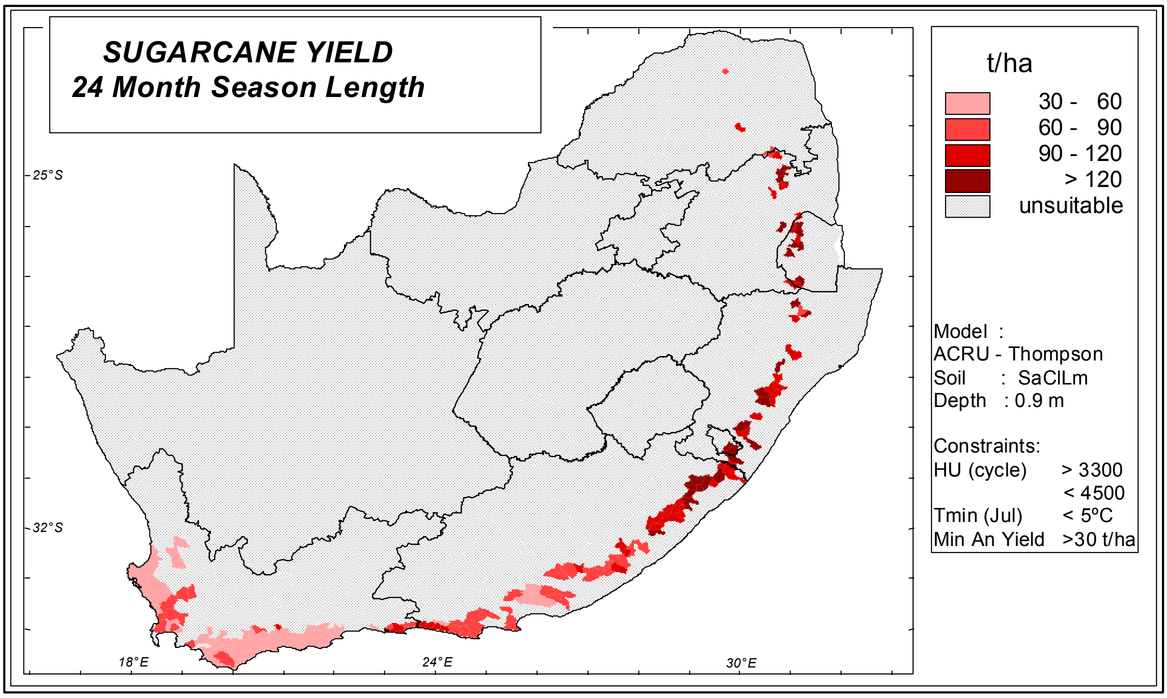

Figure 7.8 Distribution patterns of estimated sugarcane yields for a 24 month season length

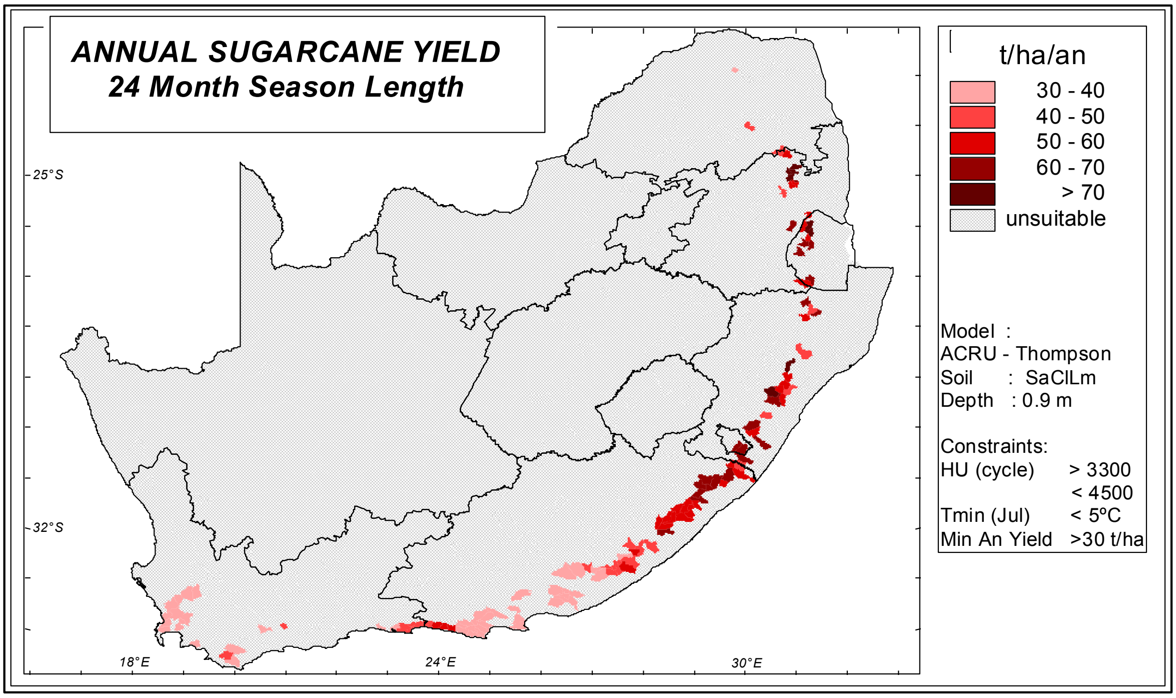

Figure 7.9 Estimates of annualised sugarcane yields for a 24 month season length

Figure 7.10 shows the distribution patterns of optimal season lengths for southern Africa. These distributions were obtained by mapping the harvest season length for which the highest yield is simulated,, given the criteria described in Section 7.2.1. From this map, shorter harvest seasons are most optimal in the northern coastal regions of KwaZulu-Natal, eastern

Mpumalanga and eastern Limpopo province. Areas showing more optimal yields with longer growing seasons include the more inland and higher altitude regions of Limpopo, Mpumalanga, Swaziland and KwaZulu-Natal regions, as well as the coastal and inland regions of the Eastern and Western Cape. The longer growing periods may be attributed to the reduced temperatures in the higher altitude regions and the cooler southern parts of South Africa. These distribution patterns are confirmed in Figure 7.11, which show the distribution patterns of dryland sugarcane harvest cycle lengths, determined by Schulze (2007f), based on algorithms developed by Smith (1998).

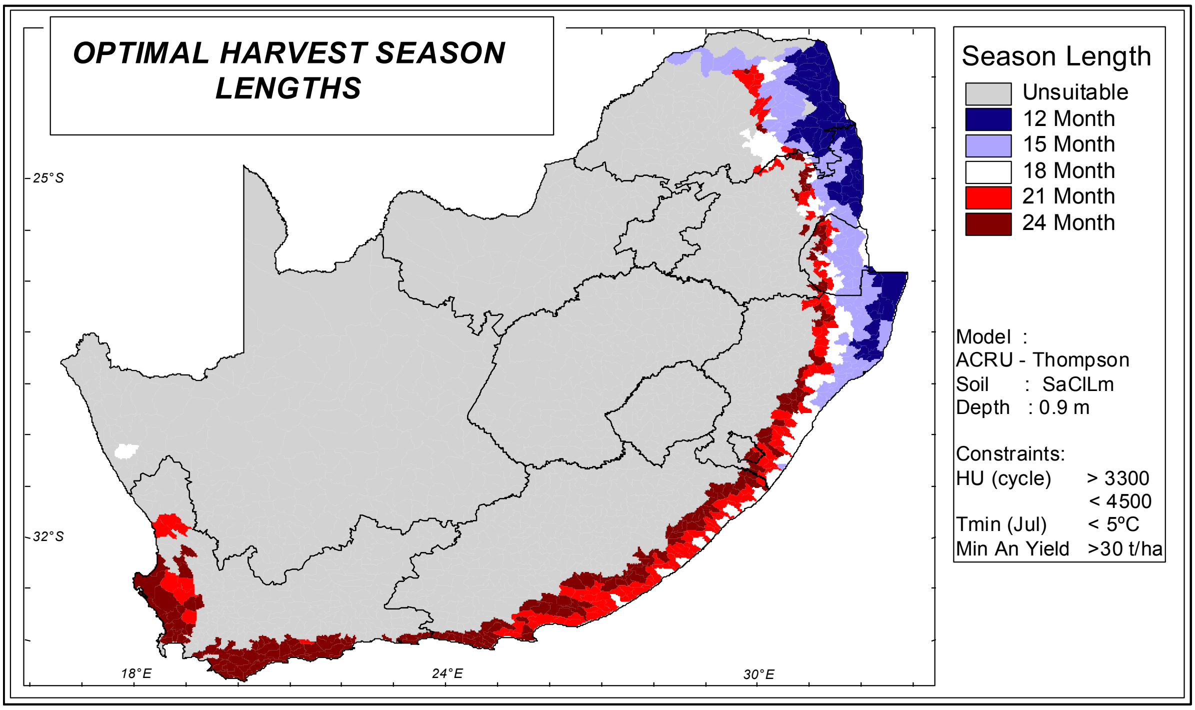

Figure 7.10 Optimal season lengths for sugarcane growth over southern Africa

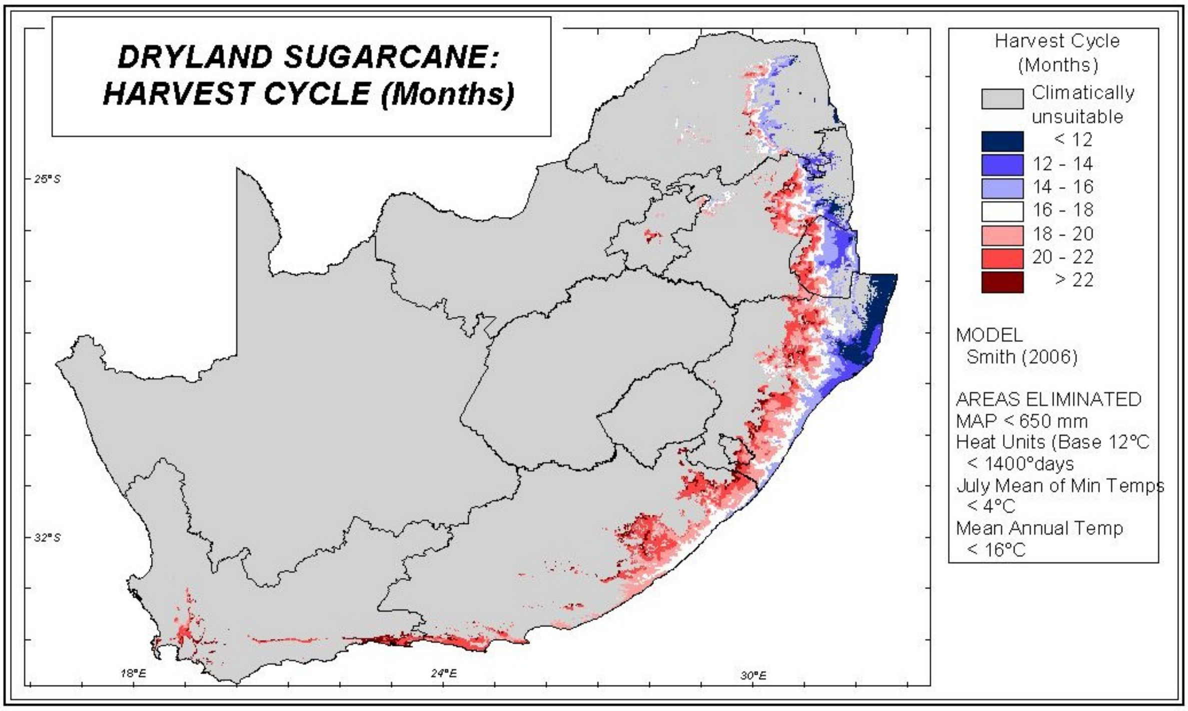

Figure 7.11 Length of the harvest cycle (months) over southern Africa of dryland sugarcane based on the Smith (2006) model (Schulze, 2007f)

From the distribution patterns of sugarcane yields with varying season lengths shown in Figures 7.1 to 7.9, and summarised in Figure 7.10, it was found that areas viable for sugarcane production with short growing seasons are limited to the hotter coastal and northeastern parts of KwaZulu-Natal, as well as the eastern parts of Swaziland, Mpumalanga and Limpopo. However, with an increase in season length, a shift in the areas shown to be viable for sugarcane production to inland locations at higher altitudes, as well as more southern parts of South Africa, are noted.

7.3 Sugarcane Yield Increments per Unit of Irrigation Water Application

In overall irrigation planning it is important to know what the gain in yield, over and above yields attained under rainfed conditions, would be per unit of irrigation water applied. The incremental sugarcane yield, per 100 mm of gross irrigated water applied, was therefore calculated for each of the Quaternary Catchments making up the southern African study region.

7.3.1 Definitions and Assumptions Made in Simulations

Simulations were run with the *ACRU* model (Schulze, 1995) for each of the 1 946 QCs in the defined study region of southern Africa (Schulze and Hull, 2007b). For simulation purposes a sandy clay loam textured soil of 0.9 m depth was assumed, as was a crop coefficient of 0.9 for all months of the year, and 100% surface mulch cover. Gross irrigation requirements included 10% conveyance losses, wind/spray drift losses of 12% for overhead irrigation and 2% for drip irrigation (Smithers and Schulze, 1995). Interception losses were set as 1.8 mm per irrigation/rainfall event (De Villiers, 1978). As mentioned previously, annualised sugarcane yields were estimated with the *ACRU* model using a relationship between evapotranspiration and cane yield, developed by Thompson (1976), as described in Section 3.5.2.2. From the yields obtained from the *ACRU* model simulations, yield increments were calculated using Equation 7.1, as shown below.

$$\text{Sugarcane Yield Increment} = \frac{\text{Irrigated Sugarcane Yield - Dryland Sugarcane Yield}}{\text{100 mm Gross Irrigation Demand}} \quad \text{......(7.1)}$$

Gross irrigation demand is defined here as the total amount of water extracted from the source of water (i.e. river, dam or canal system) in order to satisfy the irrigated crop's water demand. This therefore includes conveyance, field application and crop interception losses, as mentioned above. Various modes of irrigation were used in the calculation of gross irrigation demand, including demand irrigation, deficit irrigation, drip irrigation and fixed amount fixed cycle irrigation comprising of 15 mm, 20 mm and 35 mm / 7day cycle, as described in Sections 2.3.1.2, and 6.4.

7.3.2 Distribution Patterns of Sugarcane Yield Increments per 100 mm of Irrigation Water Application Over Southern Africa

Distribution patterns of sugarcane yield increments per 100 mm of gross irrigation water application may be seen in Figures 7.12 to 7.17 for various modes of irrigation. Increments range from < 6 t/ha/annum per 100 mm to > 11 t/ha/annum per 100 mm across southern Africa. The lower yield increments of approximately 6 t/ha/annum per 100 mm of irrigated water are generally found in the high rainfall areas of the eastern parts of southern Africa, with the increment increasing to approximately 11 t/ha/annum in the semi-arid west, where precipitation amounts are significantly less. Very little difference in yield increments is noted between the different modes of demand (Figure 7.12), deficit (Figure 7.13) and drip (Figure 7.14) irrigation. Differences in yield increments per 100 mm of irrigated water are, however, noted between the fixed cycle schedules for amounts of 15 mm (Figure 7.15), 20 mm (Figure 7.16) and 35 mm (Figure 7.17) per 7 day cycle. In the eastern parts of KwaZulu-Natal, Swaziland and Mpumalanga, increases in the areas showing increments of between 8 and 11 t/ha/an are noted with the higher application rates.

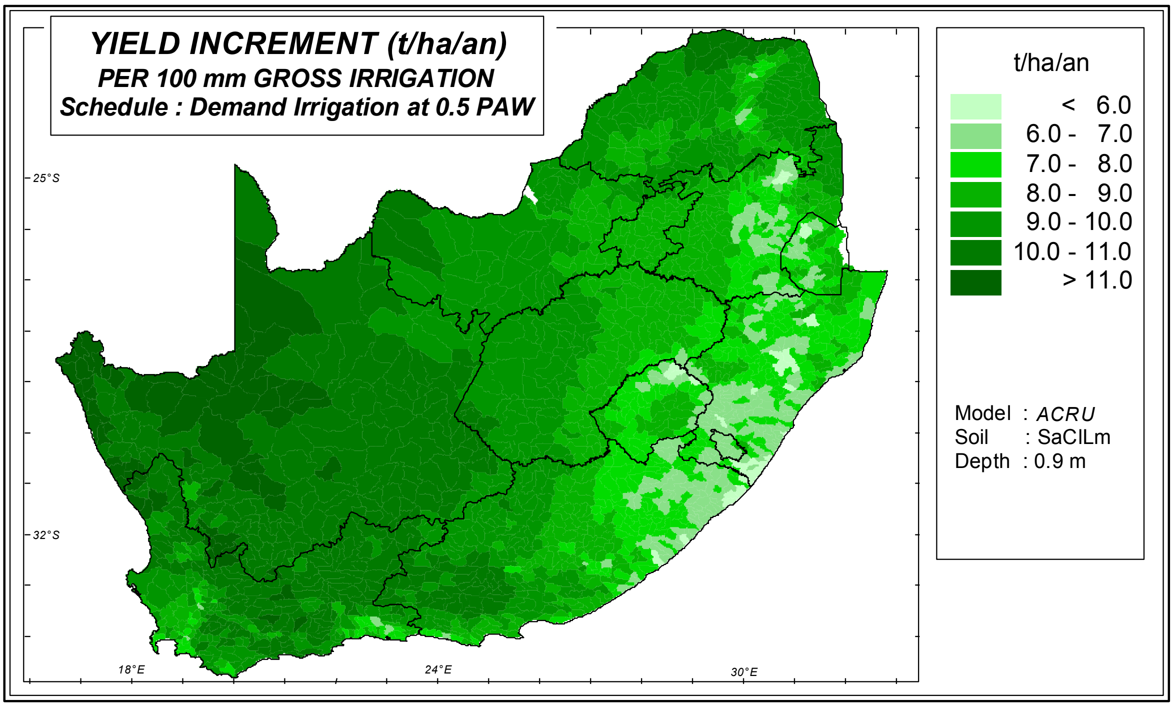

Figure 7.12 Sugarcane yield increments per 100 mm of gross irrigation water application by demand irrigation

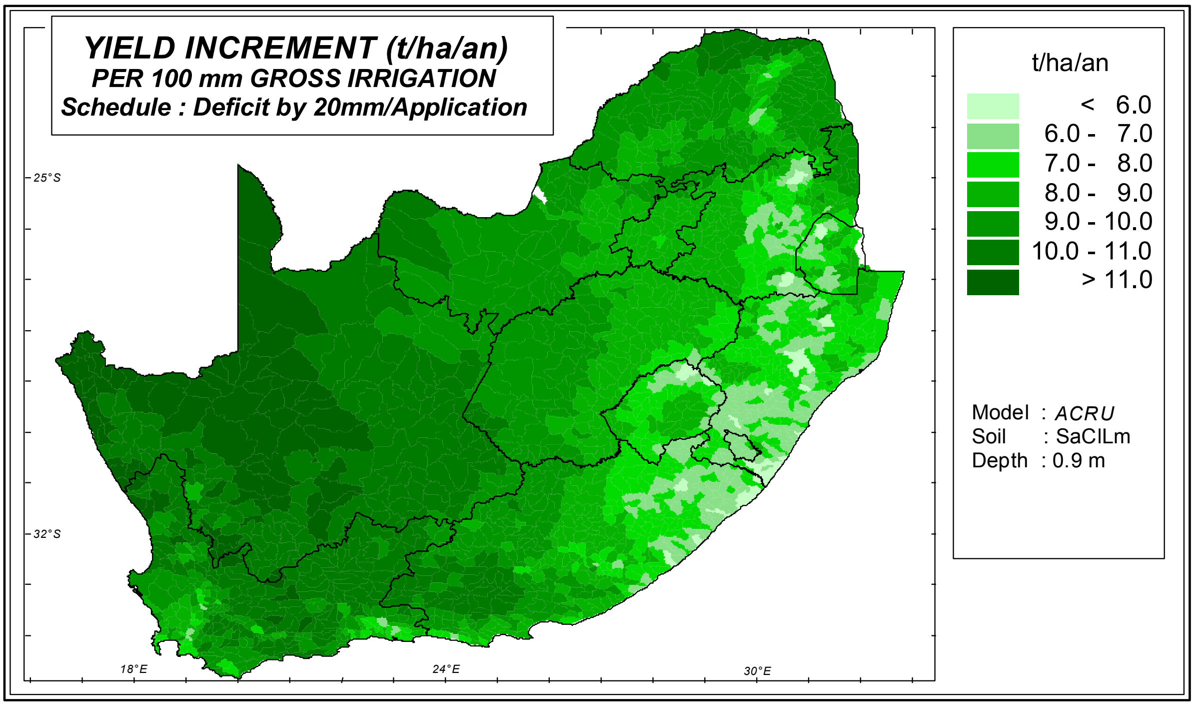

Figure 7.13 Sugarcane yield increments per 100 mm of gross irrigation water application by deficit irrigation

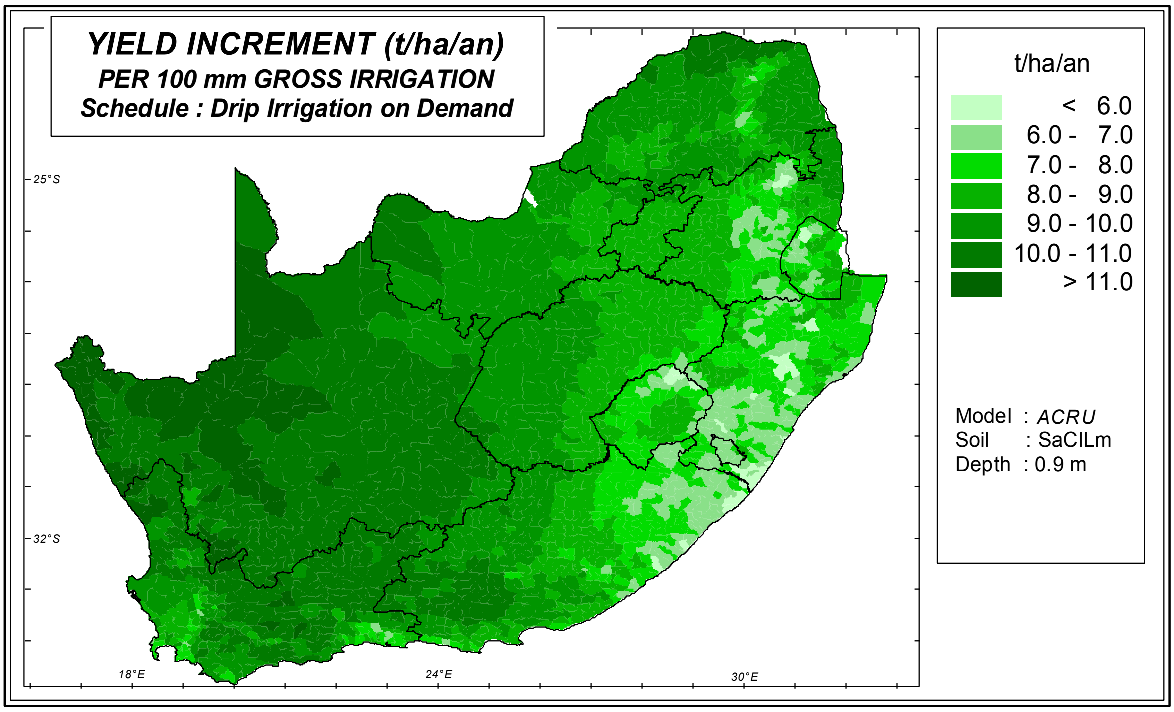

Figure 7.14 Sugarcane yield increments per 100 mm of gross irrigation water application by drip irrigation

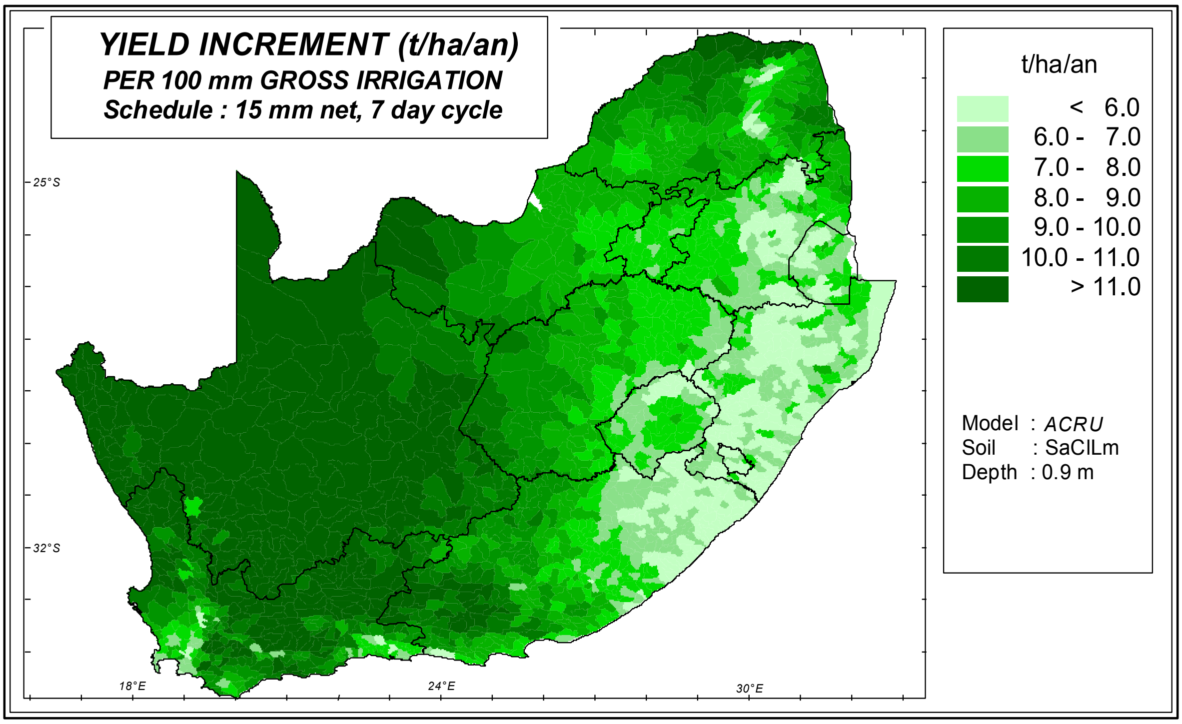

Figure 7.15 Sugarcane yield increments per 100 mm of gross irrigation water with a 15 mm application in a 7 day cycle

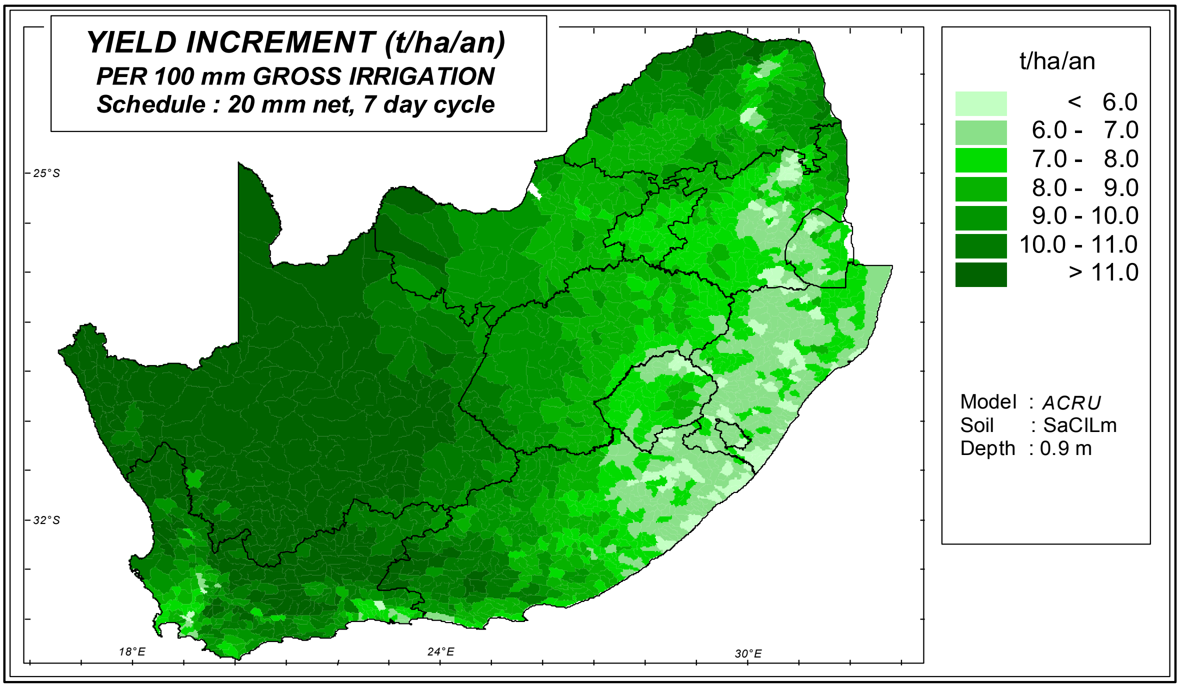

Figure 7.16 Sugarcane yield increments per 100 mm of gross irrigation water with a 20 mm application in a 7 day cycle

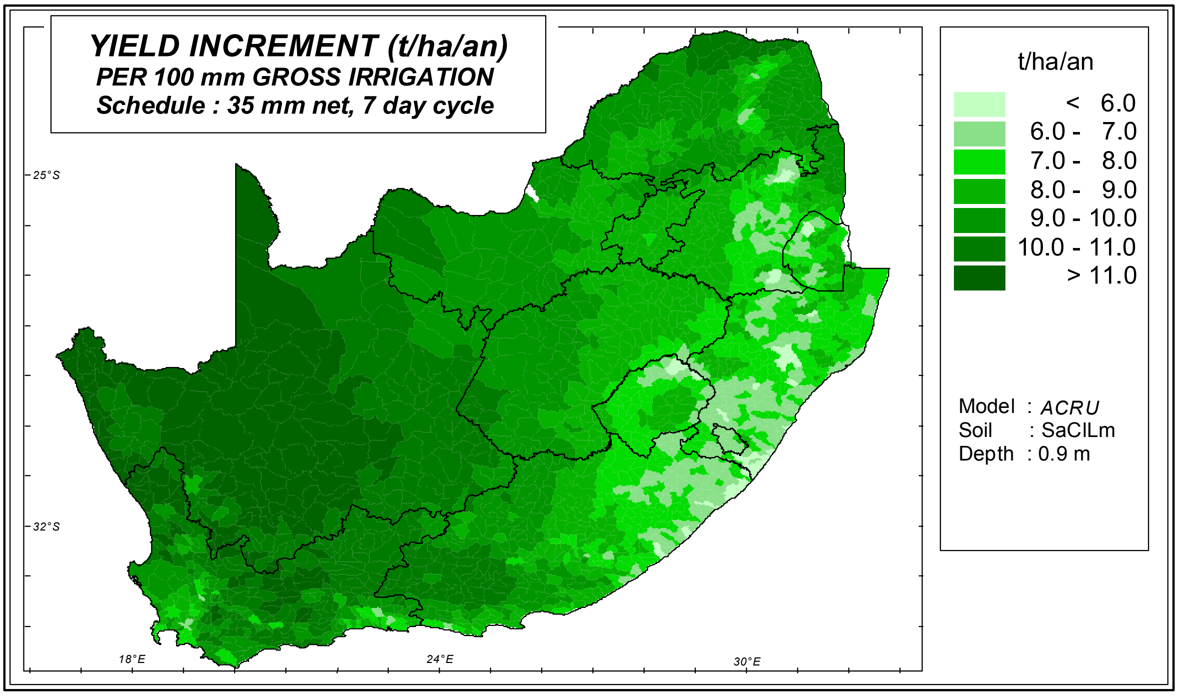

Figure 7.17 Sugarcane yield increments per 100 mm of gross irrigation water with a 35 mm application in a 7 day cycle

* * * * * * *

In this chapter maps were presented of dryland sugarcane yields simulated with the *ACRU* model for various season lengths. In addition, yield increments per 100 mm of irrigation water application were mapped for southern Africa in order to assess the potential benefits of irrigating sugarcane. The following chapter contains the discussion and conclusions pertaining to this dissertation.

8. DISCUSSION AND CONCLUSIONS

In this chapter, the aims and objectives stated in Chapter 1 will be revisited by examining all of the variables which were defined in this study, as affecting sugarcane production in South Africa. Thereafter conclusions are drawn as to whether the aims and objectives were met. Possible applications of this work will be discussed and recommendations for future research will be made.

8.1 Aims and Objectives Revisited

The objectives of this research were to:

- identify a number of important variables that affect sugarcane production,
- employ suitable models to represent these variables, and
- simulate and map the extent and severity of these variables at a high spatial resolution over southern Africa.

The major variables affecting sugarcane production in southern Africa, selected for this study, included the *Eldana saccharina* stalk borer, the *Chilo sacchariphagus* stalk borer, sugarcane rust fungus, heat units for a range of base temperatures, frost, soil water content, soil compaction, irrigation water demand, conducive and non-conducive growing conditions, flowering proficiencies for sugarcane, sugarcane yields and yield increments per unit of irrigation. The above-mentioned variables were placed into four different categories, as follows:

- second order derivatives of temperature,
- climate based constraints to sugarcane production in regard to pests and diseases,
- soil water related constraints and potentials of sugarcane production, and
- sugarcane yield estimations.

Second order derivatives of temperature included mapping heat units for a range of base temperatures, as well as mapping the distribution of frost occurrences over southern Africa.

The southern African temperature database of daily maximum and minimum temperatures (Schulze and Maharaj, 2004) was used in the computation the above-mentioned second order derivatives of temperature. The representative base temperatures used in mapping heat units each had specific relevance to not only sugarcane growth, but also to various temperature requirements of a variety of pests and diseases. Two different methods were used to map the distribution patterns of frost, *viz*, the frequency of frost events over the 50 year time period 1950 to 1999, and the percentage of years in which frost occurred over the same time period. These maps indicated that frost occurrences are predominantly limited to the higher altitude inland areas of southern Africa, with only a small probability of frost occurring in patches of KwaZulu-Natal and Swaziland where sugarcane is currently being grown.

Climate based constraints to sugarcane production with regard to pests and diseases included the mapping of the *Eldana saccharina* stalk borer, the *Chilo sacchariphagus* stalk borer and the sugarcane rust fungus. Algorithms relating chilo, eldana and rust indices to specific maximum and minimum temperature thresholds, based on previous research, were applied with the 50 year daily maximum and minimum temperature database. Maps showing the distribution patterns of eldana indices were prepared for both annual and seasonal time periods. In addition to these, maps were compiled to depict the changes in the distribution patterns of eldana indices over the period 1950 to 1999. No distinct patterns, or shifts, in the distribution of eldana indices were noted between the above-mentioned time periods. From the map of the annual distribution of the eldana mating index, it could be concluded that the eastern and northern parts of southern Africa, including the coastal and northern parts of KwaZulu-Natal, most of Swaziland, eastern part of Mpumalanga and most of the Limpopo provinces presented the most suitable conditions for eldana reproduction. Distribution patterns during the summer months were found to be far more extensive compared to those of the winter months, owing to the higher temperatures.

Chilo index distributions were mapped according to specific threshold temperatures relating to its ability to mate, maintain healthy growth and development as well as its ability to survive. Similar to the distribution patterns of eldana, the areas that are most conducive for the reproduction, development and survival of chilo are the eastern parts of southern Africa including coastal and northern parts of KwaZulu-Natal, most of Swaziland, the eastern border of Mpumalanga and a large part Limpopo province. These results may be used in planning, for example, to plant eldana resistant varieties of sugarcane in areas in which eldana may be a problem.

Distribution patterns of the sugarcane rust fungus were mapped from temperature thresholds, wet leaf conditions and a combination of the two. The map depicting areas in which temperature conditions were likely to favour the infection of rust, highlighted the northeastern parts of KwaZulu-Natal, Swaziland, eastern parts of Mpumalanga, large parts of Limpopo, and some areas of the NorthWest and the Northern Cape provinces. However, the wet leaf parameters indicated the southern midlands and coastal regions of KwaZulu-Natal to have the most favourable climates for the rust fungus. The distribution patterns were, however, patchy and no significant other regional trends could be identified. The map showing a combination of the two indices highlighted the northeastern parts of South Africa along the north coast of KwaZulu-Natal, Swaziland, the lowveld parts of Mpumalanga and Limpopo province as being most favourable, although the index displayed was low. The distribution patterns displayed from these three indices were, however, inconclusive. Either incorrect or ineffective temperature and/or wet leaf thresholds used in mapping, as well as the inability to take into consideration and make use of other factors affecting rust distribution, may be the cause of this.

Soil water related constraints and potentials affecting sugarcane production in South Africa included soil water content, soil compaction, irrigation water demand, conducive and non-conducive growing conditions and flowering proficiencies for sugarcane. Soil water content and irrigation water demands were estimated with the *ACRU* agrohydrological model. Four different levels of soil water stress were mapped, *viz*. excess plant water stress, no plant water stress, mild and severe plant water stress. From these maps it was found that the most prevalent soil water condition in South Africa was severe plant water stress. Various modes of irrigation application were used in the assessment of irrigation water demands in southern Africa, these including deficit, demand and drip irrigation as well as various quantities of fixed amounts for a 7 day cycle. The drier western parts of South Africa displayed the highest irrigation water demand. In regard to water use demands, drip irrigation proved to be the most effective of the modes of irrigation in southern Africa as a result of the relatively low losses associated with this irrigation mode. The application of these results may be found in determining the most effective irrigation mode for a particular region, although more specific and detailed site related information is necessary for any particular region of concern to confirm these results.

Soil compaction was computed using the *SOCOMO* model in conjunction with the mapped values of soil water content. The start and duration of the infield traffic season and its associated risk were mapped. Longer traffic seasons with lower associated risk were noted for in the inland regions of KwaZulu-Natal, compared to the coastal regions, where shorter soil compaction season lengths with higher risks were found, owing to increased amounts of precipitation in these areas. Through these maps, theoretical time periods when the risk of soil compaction is reduced were identified. These maps may be used as a guideline to, for example, plan planting and harvesting dates, so that the risk of soil compaction may be minimised.

Conducive and non-conducive growth unit maps portray the accumulation of heat units with a base temperature of 10ºC when the soil water content is either unstressed (conducive) or stressed (non-conducive). From these maps it may be deduced that the eastern half of southern Africa, particularly the coastal and northern parts of KwaZulu-Natal, central parts of Swaziland, eastern Mpumalanga and the Limpopo province are most conducive for dryland sugarcane growth.

Sugarcane flowering proliferation was mapped using algorithms in which, for a specific time period, certain temperatures and soil water content thresholds had to be met. The map depicting sugarcane flowering indicates the coastal and northern regions of KwaZulu-Natal as having the highest probabilities for sugarcane flowering during approximately the first three weeks of March.

Sugarcane yields were estimated using the *ACRU* agrohydrological model for various season lengths. In addition to this, yield increments per 100 mm of irrigation water application were computed. In estimating sugarcane yields for different season lengths, the northern areas of KwaZulu-Natal, parts of Swaziland, Mpumalanga and the Limpopo province were found to be viable with a short (i.e. 12 month) sugarcane growing season. With an increase in season length, areas shown to be viable for sugarcane production shifted inland and southwards. Yield increments per 100 mm of irrigated water showed the greatest benefits of irrigation to be in the drier areas of South Africa, with lower yield increments in the eastern parts of South Africa where sugarcane is actually produced.

It may be concluded from the above summary of results that the objectives stated in Chapter 1 were met. The distribution patterns of the above-mentioned variables relied greatly upon the various models employed to represent them, as well as the accuracy of the temperature and rainfall databases to which the various models were applied.

8.2 Possible Applications of This Research

The results obtained from this research may, in the future, be used as a tool in strategic decision making in the sugar industry by extension officers and farmers in general. By identifying areas which, for example, are particularly prone to the infestation of certain pests or diseases, sugarcane varieties that are resilient to those pests and diseases may be developed and planted. In addition, strategic decisions relating to, for example, the times of the year when the soil is not generally at risk of compaction due to infield traffic, or the potential benefits of implementing irrigation, may be made. Potential future sugarcane growing areas may be identified from the maps which show sugarcane yields to be viable for a given harvest cycle. Results obtained from this study may also be used as a basis for further research relating to the variables selected in this study. In addition to this, work completed in this project may trigger new ideas or challenges among other researchers.

8.3 Recommendations for Future Research

The applicability of this research depends largely upon the resolution at which the different variables were mapped. Improvements to the resolution of those maps prepared at the Quaternary Catchment level may be made in future, as the recently developed Quinary Catchments (i.e. fifth level) database contains climate and soils data at a finer spatial scale representing far more homogeneous land segments than those of QCs. The incorporation of detailed actual soils information covering the entire study region may significantly improve the accuracy of the distribution patterns of the variables selected.

Improvements to the mapping of pests and diseases, particularly rust, may be made by incorporating more climatological and/or environmental factors into the models used to identify the distribution patterns of these pests and diseases. The incorporation of humidity thresholds and the accurate prediction of the formation of dew on leaves of plants in, for example, the mapping of the rust fungus may significantly improve the predictions of distribution patterns of this disease. By incorporating not only climatological parameters into the models used to map the distribution patterns of eldana and chilo, but also linking them to other factors such as soil water content, more accurate predictions on the distribution patterns of these pests may possibly be made in future.

Climate change has, in recent times, been the topic of much scientific research. The incorporation of possible effects of climate change on the distribution patterns of the above-mentioned variables may greatly assist in future strategic planning. The integration of the latest results from downscaled Global Circulation Models (GCMs) as possible scenarios representing expected future climates could indicate potential shifts in the areas in which sugarcane can be produced, possible changes in yields, as well changes in the distribution patterns of pests and diseases affecting sugarcane production.

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