CHAPTER 1

GENERAL INTRODUCTION

1.1 RATIONALE

Irrigation uses about 62% of South Africa's surface and ground-water resources (DWAF, 2004). Irrigated agriculture is facing fierce competition for this substantial share of water as the water demand for industrial, domestic, municipal and other activities are increasing rapidly. There is a need to increase water (and land) productivity, to meet the increasing demand for animal protein as human populations increase and diets become more affluent (Smil, 2002). Natural veld cannot fulfil this need alone and must be supplemented with irrigated and fertilised planted pastures. This requires intensive use of fertilisers and water, which leads to a higher cost of production and a greater risk of environmental pollution. Thus, farmers are under pressure to decrease their share of water and fertiliser usage, whilst at the same time, produce sufficient pasture for animal production to supply the protein demand of a growing population more efficiently.

In South Africa, returns generated from animal production enterprises make pastures one of the highest value crops produced under irrigation. It is estimated that the total area utilized for irrigated pasture production is approximately 16% of the total area under irrigation. Annual ryegrass (Lolium multiflorum) is one of the most common irrigated pastures in the pasture based dairy industries (Dickinson *et al.*, 2004). It has high nutritional qualities, palatability, digestible energy, protein and mineral contents (Theron and Snyman, 2004). It plays an essential role in supplying good quality grazing between the winter and summer seasons, thereby dramatically improving fodder flow options in the dairy industry (Eckard *et al.*, 1995).

Management of dairy farming has now attained unprecedented levels of technology, largely due to the availability of user friendly equipment. In spite of this, there are still trends to rely on experience and tradition for managing irrigation and nitrogen (N) fertilisation. Irrigation water and N are resources that can be optimised by selecting an appropriate irrigation system, scheduling technique and pasture (i.e. N fixing legumes and/or species with high water use efficiency). For sustainable pasture production, the best possible fertiliser and water management is required in order to attain high biomass yield with minimum inputs, which maximises profit whilst minimising impact on the environment. The most appropriate and cost effective management strategy would therefore be to integrate irrigation and N inputs, since N and water cannot be managed independently (Rawnsley *et al.,* 2009).

A number of experiments have been done throughout the country on the effect of N on yield and quality of grass pastures (Eckard, 1994); however, there is a lack of reliable information and data pertaining to annual ryegrass water requirements as affected by N to facilitate efficient irrigation and fertilisation management. Many researchers have worked on the modelling of grass production but the integration of water and nitrogen in relation to irrigation strategies and fertiliser management have not been totally addressed. Despite recent developments in the latest fertiliser and irrigation application equipment and scientifically based guidelines, it can be seen that there are still knowledge gaps between research and farming practice. The challenge is to accurately understand and describe the interaction between water and N in addressing the gaps with alternative methods to the current practice. Practical on-farm equipment and/or models are required to accurately recommend the correct amount of water and N, thereby minimizing N leaching and maximising production and quality at lowest cost. Therefore, the focus of this study is to integrate both irrigation and N management in order to improve the efficiency of both resources.

The Water Research Commission initiated and funded a five-year study on irrigation and N management of planted pastures under different management conditions (WRC K5/1650). The main objectives were to develop irrigation, N and other management guidelines of irrigated planted pastures for the major pasture growing areas of South Africa. Hence, field experiments were conducted in 2007 and 2008 at Cedara and Hatfield as case studies using annual ryegrass for testing selected on-farm equipment (FullStop® wetting front detector) and model (Soil Water Balance) and managing N and irrigation.

1.2 IRRIGATED PASTURE PRODUCTION IN SOUTH AFRICA

More than 80% of South Africa is arid to semi-arid, with unreliable rainfall. This makes most of the country unsuitable for intensive agriculture such as dairy farming under dryland conditions (Gertenbach, 2006). Grasses are often grown under dryland conditions, however, there is a trend towards greater use of irrigation by farmers to improve the reliability of yield of pastures. It is estimated that the total area utilized for irrigated pasture production is approximately 16% of the total area under irrigation in South Africa. The most common irrigated pastures are ryegrass, kikuyu (*Pennisetum clandestinum*) and lucerne (*Medicago sativa*). Irrigated ryegrass and dryland kikuyu with supplemental irrigation, are the primary sources of feed in the pasture based dairy industry and are mostly grown in the relatively higher rainfall areas, particularly in the Natal Midlands, the Eastern Highveld, the Eastern Cape and in the winter rainfall areas of South Africa (Dickinson *et al.*, 2004).

Annual ryegrass is divided into two different types, namely Westerwolds and Italian. Westerwolds are true annuals and in South Africa they are generally planted in autumn, as rising temperatures and increased day length in spring causes seed set. When Italian ryegrass is sown in autumn, it normally extends the growing season by as much as four weeks longer than Westerwolds into the early summer. This characteristic of Italian ryegrass types plays an essential role in supplying better quality material between winter and summer grazing. Italian (annual) ryegrass is usually selected over perennial ryegrass due to its high forage yield during winter and its good quality for the dairy industry. Moreover, perennial ryegrass also has a problem of persistency (Eckard, 1994).

Plant growth is determined by the accumulation of dry matter as affected by the environment. Three important processes regulating the growth of plants are uptake of water, photosynthesis (i.e. radiant dependent reduction of carbon dioxide from air) and uptake of nutrients (Dovrat, 2003). Primary pasture cultural management practices (irrigation, fertilisation, and defoliation) which affect growth and development of grasses, have direct effects on the water use efficiency of annual ryegrass (Reeves *et al*., 1996; Peyraud and Astigarraga, 1998). In South Africa, many dairy farmers are applying New Zealand principles of pasture management which are based on perennial pastures (Findlay, 2005). The reason for this is that there are not enough accurate local data on water requirements, water use and rooting depth of irrigated annual ryegrass pasture.

1.2.1 Irrigation guideline

In semiarid regions, water is the primary contributor to grassland production (Whitney, 1974). The development of well-established pasture requires favourable growing conditions with no water stress. This leads to higher yields and good nutritive valued pasture. In some situations, irrigation may give little or no advantage, especially in humid areas. Under hot climatic conditions, water deficits, even for short periods, limit metabolic processes, which may reduce growth rates. Therefore, the aim of irrigation management is to maintain a favourable supply of water within the root zone between the extremes of excessive dryness or wetness.

In South Africa, as a general rule of thumb, annual ryegrass needs about 1200 mm of water for a growing season (Dickinson *et al*., 2004). In summer rainfall regions a rate of 25 mm per week of water is used, and this was calculated from class A pan which is typically 3 to 4 mm per day in the winter (Tainton, 2000). Jones (2006) also recommended 25 mm per week for the production of annual ryegrass in KwaZulu Natal. Regardless of differences in climatic and soil factors, most agriculturalists recommend 25 mm irrigation per week (minus rainfall), when reporting management factors of annual ryegrass to avoid drought (Goodenough *et al*., 1984; Van Heerden, 1986; Eckard, 1989; Harris and Bartholomew, 1991; Le Roux *et al*., 1991). However, according to Steynberg *et al.* (1993), there is a 20% variation in production potential of temperate species between seasons due to weather and rainfall distribution. Therefore, a single set of irrigation norms to schedule irrigation for pastures was clearly insufficient (Steynberg *et al.*, 1993).

Annual ryegrass is characterised by a shallow root system which make it susceptible to rapidly developing soil-water deficits (Dovrat, 1993). When soil water status is used as criterion for irrigation, the rooting depth of a particular pasture should be determined. In South Africa a shallow rooting depth of 0.3 m was used to determine irrigation requirement for planted pasture (Green, 1985). Under water stressed conditions, annual ryegrass has a large concentration of roots in the upper 0.25 m horizon, with a substantial reduction in root density with depth (Gonzalez-Dudo *et al.,* 2005). For annual ryegrass, effective rooting depths and soil water extractions ranging between 0.6 - 1.5 m were reported (Steynberg *et al*., 1994; Theron and Van Rensburg, 1998; Theron and Snyman, 2004; Gonzalez-Dudo *et al*., 2005). In general, annual ryegrass absorbed most water from 0.1 to 0.4 m and in some cases from 0.7 m when soil was relatively dry. One way of ascertaining effective rooting depth of a species, is to establish the depth to which soil is drying without the crop experiencing significant stress (Crosby, 2003). In addition, soil texture is very important to decide on how much and when to irrigate. Irrigation management, however, is one aspect that is seldom monitored and measured.

1.2.2 Water use efficiency

Water use efficiency (WUE) can be defined as harvestable biomass per volume of water used (Wallace, 2000). It includes the total amount of water needed for plant growth, including water lost through evapotranspiration from the soil and plant surfaces (Van Vuuren, 1997). Atmospheric demand, soil water availability and other cultural practices such as fertilisation, different cultivation practices and defoliation methods can influence water use of pasture. Nevertheless, water use of grasses is strongly affected by growth rate, length of season and soil surface coverage.

Most experiments conducted using annual ryegrass report a WUE of 10 - 22 kg DM ha^{-1} mm^{-1} (Johns and Lazenby; 1973; Steynberg *et al*., 1993; Theron and Van Rensburg, 1998; Callow *et al*., 2000) with optimum cultural practices. Water use efficiencies increased from 12 to 22 kg DM ha^{-1} mm^{-1} when N fertiliser applications increase from 150 to 450 kg N ha^{-1} $year^{-1}$ (Theron and Van Rensburg, 1998). Smika *et al.* (1965) report that if natural grazing is fertilized well, it will have a WUE of 10 kg DM ha^{-1} mm^{-1}. Planted pastures, therefore, have the potential to utilize water more efficiently than natural grazing, depending on species and environmental factors.

1.2.3 Nitrogen guidelines

Nitrogen fertiliser continues to be a major input influencing yield and quality of irrigated annual ryegrass in South Africa. Improved productivity has been reported with the application of N fertiliser in high rainfall areas and under irrigation in low rainfall areas. It has been increasingly used on pastures as an effective and flexible management tool to help farmers meet the feed requirements of livestock (McKenzie *et al*., 2003; Abassi *et al*., 2005). According to the Food and Agriculture Organisation (FAO), N fertiliser use has increased 7-fold from 1960 to 2000 (Tilman *et al.,* 2002). Commercial fertilisers are normally used as sources of N in pasture production, but because of increasing energy costs and international demand (Smil, 2002), N prices continue to escalate.

Current N recommendations for annual ryegrass in South Africa are based on the target yield, maximising forage yield per unit area, with little focus on quality and without considering environmental concerns (Eckard *et al.,* 1995). Van Vuuren (1997) recommended N application in small frequent amounts. Nitrogen application increases yield, mainly due to an increase in number of tillers and as a result of leaf expansion. Pasture growers usually split the annual recommended N equally into the number of cuts, regardless of soil and environmental variations between growth cycles (Eckard *et al.,* 1995; Miles; 2007). As the amount of N applied per cut increases, so does the water use of the pasture. With the same rate of N, water use was higher when N was applied every month than once every two months (Eckard, 1994).

According to Miles (2007), optimum N for maximum yield of annual ryegrass was between 200 to 400 kg N ha^{-1} $year^{-1}$. Marais *et al.* (2003) applied N fertiliser at a rate of 50 kg ha^{-1} for each cut. Nitrogen application rates of 300 to 350 kg N ha^{-1} $year^{-1}$ were found to be optimum for growth of annual ryegrass (Eckard, 1989; Eckard *et al.,* 1995). However, economical optimum levels of dry matter production may require much less N than those for maximum yield.

1.2.4 Effects of excessive N fertiliser

Farmers usually apply high N rates (at least 50 kg ha^{-1} $cycle^{-1}$) to ensure maximum forage yield (Miles, 2007). In addition to being wasteful, high fertiliser N application can lead to:

- Forage yield imbalances (optimum growth in some growth cycles and deficiency in others) (Eckard, 1990; Eckard *et al*., 1995).

- Excessive forage crude protein (CP) concentrations, leading to an increased non-protein N content (Reeves *et al*., 1996). For ruminants, a minimum CP concentration of 12% is required for microbial digestion (Peyraud and Astigarraga, 1998) and 17% is optimum for milk production. At CP concentration levels greater than 17%, almost 80% of the additional CP is lost from the rumen and excreted in urine (Van Vuuren, *et al*., 1992; Tas *et al*., 2006). Crude protein concentrations greater than the maximum of 22% may drastically increase nitrate levels in forage which leads to nitrate and ammonia toxicity, imbalances in mineral metabolism (Coombe and Hood, 1980) and metabolic disorders.

- Reduced intake (Marais *et al*., 2003) and milk yields (Tas *et al*., 2006), as energy is used to digest excess protein at the expense of milk production. Nash *et al.* (2008) reported better energy production per unit dry matter yield with 30 kg N ha^{-1} $cycle^{-1}$ than with 60 kg ha^{-1} $cycle^{-1}$, even if the highest biomass yield was obtained at the higher rate. Available energy is more important than forage biomass, and new quality parameters such as non-structural carbohydrates or metabolisable energy are becoming more useful (Hoekstra *et al.,* 2007).

- Reduced palatability, usually due to reduced dry matter content (high moisture content) as a result of high N application (Theron and Van Rensburg, 1998). Even if N fertiliser effects on annual ryegrass were not significant there is a trend by animals to reject pastures with high N content.

- Soil acidification and the pollution of water resources by increasing the risk of N losses (Miles and Hardy, 1999; Monaghan *et al*., 2007).

1.2.5 Nitrogen use efficiency

The effectiveness of applied N in increasing pasture production is usually expressed as the N fertiliser use efficiency (NUE). The NUE in pasture systems is commonly measured as the amount of forage DM produced for each unit of applied N (Zemenchik and Albrecht, 2002), and thus is also referred to as the magnitude of pasture response to N fertiliser. This magnitude is dependent on the severity of the N shortage in the soil, pasture species, climate, N fertiliser application rate, soil type and other factors that influence plant growth (Abassi *et al.,* 2005).

Nitrogen use efficiencies reported under South African conditions vary significantly, and range from 10 to 80 kg DM kg N^{-1} depending on N rates, defoliation practices (cutting or grazing) and N management strategies. NUEs decreased from 60 to 38 kg DM kg N^{-1} when N fertiliser applications increased from 150 to 450 kg N ha^{-1} $year^{-1}$ (Theron and Van Rensburg, 1998). Eckard (1994) reported 25-34 kg DM kg N^{-1} at different sites in KwaZulu Natal when 200 kg N ha^{-1} $year^{-1}$ was applied. Morrison *et al.* (1980) used a NUE threshold of 10 kg DM kg N^{-1} as economical to asses an optimum N rate for pastures.

Applied N not taken up by plants or immobilised in the soil organic pool is vulnerable to losses from runoff, leaching and volatilisation (Sumanasena *et al.,* 2004). These losses of N are of serious environmental concern. Elevated N concentrations in surface waters are believed to be a major contributing factor to the increasing eutrophication of waterways (Tarkalson *et al.,* 2006). So, with N fertiliser providing considerable benefit to agriculture, but also having a substantial impact on the environment, it is important to have a balance between economic benefit and environmental risk.

1.3 HOW CAN NITROGEN AND IRRIGATION EFFICIENCIES BE IMPROVED?

Due to a shortage of irrigation water, an ever increasing cost of N fertilisers and environmental concerns, current irrigation and N guidelines need to be improved. Considerable research in irrigation and N management strategies has been conducted to improve irrigation water and N efficiency, reduce losses and increase harvestable yield and quality (Wallace, 2000). Possible strategies are: 1) improving irrigation practice with better irrigation scheduling (Sumanasena *et al.,* 2004), 2) accounting for N carryover between harvests and/or accounting for mineralisable N (Collins and Allinson, 2004; Miles, 2007), 3) adaptive management using simple tools to manage both water and fertiliser (Stirzaker *et al.,* 2010; Hyytiäinen *et al.,* 2011), and 4) use of modelling to integrate the effects of weather, soil, crop and management practices (Rawnsley *et al.,* 2009).

1.3.1 Irrigation scheduling

Irrigation scheduling is the decision of when and how much water to apply (Johns and Lazenby, 1973). The aim is to determine the amount of irrigation water to apply and the time for application, thereby maximising irrigation efficiencies. Accurate irrigation scheduling plays an important role in deciding the income of a dairy enterprise by affecting pasture yield and quality; irrigation and nutrient input and energy usage; and environmental pollution. Appropriate irrigation scheduling can lead to increased profits without compromising the environment by increasing productive water use and by reducing run-off, deep percolation below the root zone with nutrient leaching and soil water evaporation. Several irrigation scheduling techniques of varying levels of sophistication based on soil, plant and atmospheric measurements are recommended worldwide to address the shortage of irrigation water and maximise yield (Stevens *et al.,* 2005).

Farmers are able to get optimum forage yield and quality and improve NUE (reduce N leaching and runoff) by applying the right amount of water at the right time by selecting an appropriate irrigation technique. Direct on-farm techniques (soil, plant or atmospheric) are the best ways to schedule irrigation. However, according to a survey conducted by Stevens *et al*. (2005) most South African farmers (about 72%) were not using objective irrigation scheduling. Instead they were using past experience. The main reasons given to Stevens *et al*. (2005) for South African farmers not using irrigation scheduling techniques were: 1) failure to appreciate the net benefit from irrigation scheduling and the lack of reliable user-friendly irrigation scheduling techniques; 2) high cost of equipment; 3) information collecting and processing was time consuming; and 4) some of the equipment needed more technical knowledge.

An irrigation calendar is a simple guideline or chart that indicates when and how much to irrigate. Calendar based irrigation scheduling provides irrigators with an inexpensive and convenient strategy to estimate irrigation timing and amount. Such calendars allow irrigators to minimise effects of over or under-irrigation by matching water application to pasture water requirements (Whitfield and Qassim, 2004). Moreover, with intensive pastures and rotational grazing management, the farm must be divided into plots or paddocks to facilitate efficient fodder flow for the animals throughout the season. Hence, installing irrigation scheduling tools in all paddocks may not be economical. Using irrigation calendars, therefore, may yield extra benefit in pasture as compared to water management in other crops.

Deficit irrigation scheduling was reported to be successful for pastures to reduce irrigation water inputs and reduce N leaching, thereby increasing water and N use efficiencies and income (Sumanasena *et al.,* 2004; Rawnsley *et al.,* 2009). Neal *et al*. (2011) were successful in achieving maximum forage yields with deficit irrigation for a range of tropical and temperate pastures. In another experiment, Rawnsley *et al.* (2009) used mild deficit irrigation to increase irrigation use efficiency and reduce N leaching. Sumanasena *et al.* (2004) used a range of deficit irrigation strategies to reduce N and P leaching from mixed pasture.

1.3.2 Allowances for nitrogen mineralisation and carryover

Recent studies have shown that N availability is extremely dynamic and is associated with weather, soil water and rate of mineralisation (Collins and Allinson, 2004; Hatfield and Prueger, 2004). In warm weather, soil N availability is usually high because of rapid mineralisation, while in cold weather mineralization is slow, and N less available. In wet seasons N can be leached because nitrates dissolve easily in soil water, and N can be lost to the atmosphere by denitrification. This makes it hard to know how much N is actually needed at any given stage (growth cycle) and reduces farm profits and causes potentially high environmental losses to both surface and ground-water (nitrate leaching) and to the atmosphere (ammonia volatilization and denitrification). Applying the current recommended N (50 kg ha^{-1} per growth cycle) could be deficient in some years (growth cycles), whilst in others the same amount of fertiliser could be adequate or excessive (Andraski and Bundy, 2002; Collins and Allinson, 2004; Miles, 2007).

A fertilisation strategy that takes into account the nutrients currently available in the soil can provide economic benefits as compared to one in which the amount of fertiliser is fixed at the beginning of each growth cycle. This more flexible nutrient regime can reduce unnecessary fertilisation when the soil is rich in nutrients and increase the growth potential of a crop when nutrients in the soil are inadequate.

A range of N management strategies has been investigated to improve N efficiency, reduce losses and increase harvestable yield and quality. Some of these strategies are to avoid applying N during winter (Eckard, 1994), or account for N carryover between harvests and/or account for mineralisable N (Collins and Allinson, 2004; Miles, 2007). The strategy of no N application during winter (June and July), however, has been criticised, as pasture is critically dependent on N fertiliser for growth and survival (Eckard, 1994) due to very low rates of mineralisation in winter. These strategic N applications are mainly dependent on environmental effect on crop growth rate and N release from mineralisation. According to Miles (2007), N fertiliser application could be reduced between 85 to 174 kg ha^{-1} per year (depending on soil carbon content), by including mineralisable soil N inputs in N recommendations for pastures.

1.3.3 Adaptive management

Adaptive management is generally considered to be the best approach for managing systems with high uncertainty, or where it is impossible or impractical to collect all the necessary information (Holling, 1978; Walters, 1986; Lee, 1993). Adaptive management is the process of refining a management strategy in response to evaluating its success. It requires field measurement data and observations for local conditions, and evaluates success based on scientific principles and local experience (Walters, 1986). It is a learning process, so that the grower is able to adopt practices that make sense for his own specific conditions to increase profits and reduce environmental impacts at the same time (Lee, 1993). On-farm adaptive management programmes encourage farmers to implement management actions, monitor to observe the results of those actions, and use the results to update knowledge and adjust future management actions accordingly (Walters, 1986; Lee, 1993). Since monitoring is expensive, farmers seek a measurement that can integrate many of the processes involved in the soil water balance and N cycle (Stirzaker *et al.,* 2010; Fessehazion *et al*., 2011; Hyytiäinen *et al.,* 2011). The challenge is to find tools which allow effective implementation of adaptive management strategy.

The dynamic nature of pasture systems increases the uncertainty of using generalised recommendations. Another means to reduce uncertainty about the yield obtained in response to input use is to apply fertiliser or irrigation based on monitoring the soil water and N balance.

However, improving N and water management at field level with frequent sampling (components of N and water balance) is expensive, complex, time consuming and impractical. A robust, on-farm monitoring indicator which is relatively simple, cost effective and readily adopted by farmers, is the FullStop® wetting front detector. It can be simultaneously used for managing irrigation water and observing N by monitoring depth of wetting and nitrate concentration of the passing wetting fronts (Stirzaker *et al.*, 2010). The challenge will be to develop useful robust guidelines from such observations.

1.3.4 Modelling

Generally radiation, temperature, water and nutrients are the most important environmental factors that influence growth and quality of pastures (Dovrat, 1993). Nitrogen and irrigation recommendations are typically developed based on field experiments conducted for few years (2-3). However, there is always high uncertainty using the results from field experiments for other sites, soils and seasons. With advances in computer technology, numerical models have been used widely to analyse and solve resource management problems such as the scheduling of irrigation and fertilisation management (Bahera and Panda, 2009). A wide range of crop simulation models have been used extensively to quantify the change in yield potential at different levels of management and climatic variability. It was also shown that simulation studies can supplement field studies in decision making (Van der Laan *et al.*, 2011). Models can predict quite accurately the growth, development and yield of crops by incorporating complex processes with the help of soil, daily weather and management inputs, to assist growers to select best management options. A modelling approach can therefore be a lot more locally accurate than the current rigid generalised irrigation and N recommendations. Once satisfied with the validation process, a model can provide a much lower cost than other scheduling tools.

Results acquired from computer simulation can be used in conjunction with data collected from field experiments to better understand systems and to extrapolate findings in time and space

(Annandale *et al*., 2000). This can save money and time required for conducting long-term intensive field experiments for gathering information on potential pasture production with different resources. In the absence of monitoring methods, models can also be used to explore better irrigation management strategies in order to increase irrigation and N use efficiency and determine site specific irrigation requirements and calendars. Considering the use of a large number of data sets and time consuming determination of input parameters required for pasture specific models, relatively simple generic crop models (such as SWB) may be more useful. According to Stevens *et al.* (2005), the major problem with the adoption of models by farmers is their complexity. Therefore, there should be a trade-off between accuracy and simplicity.

The SWB model is used locally in South Africa to simulate crop growth and the soil water balance of several cereal, vegetable and tree crops. It is probably better to use a model which is known locally by farmers and consultants instead of introducing another new model. The model is available on the web and can be downloaded free of charge.

1.4 HYPOTHESIS AND OBJECTIVES

In South Africa, irrigation water and N fertiliser are the two most important inputs controlling the productivity of irrigated annual ryegrass. To increase production, there has been a tendency to adopt high application rate of fertiliser and irrigation water, often concomitantly. Besides the high cost of production, degradation of water and soil quality owing to overuse of these resources is a matter of global concern. Therefore, water and N fertiliser inputs should be carefully managed to avoid losses.

The main hypotheses formulated to be tested in this study were linking that N and water management could:

1) Increase forage quality without significant forage yield reduction;
2) Improve nitrogen and water use efficiencies, and
3) Reduce potential N leaching

The overall objectives of the study were:

1) To test whether adaptive N and water management approaches could improve the current fixed N application rate guideline;
2) To study the response of annual ryegrass forage yield and quality parameters to N application and determine the trade-offs between yield and quality;
3) To parameterise and calibrate the SWB model for annual ryegrass and to evaluate its performance under varying N levels and irrigation regimes, and.
4) To assess potential irrigation management strategies for annual ryegrass, estimate water requirement and develop site-specific irrigation calendars for major ryegrass growing regions of South Africa using the SWB model.

The approaches used to test the hypotheses and address objectives are presented in separate chapters. With this background, comprehensive field investigation (Chapters 2 and 3) and modelling (Chapters 4, 5 and 6) were undertaken using annual ryegrass. The chapters are presented in article format and are prepared according to the South African Journal of Plant and Soil authors' guidelines.

In Chapter two, adaptive irrigation and N management strategies are used to reduce N fertiliser and irrigation inputs without significant yield reduction and improved yield whilst reducing potential environmental pollution (N leaching). In Chapter three, responses of annual ryegrass forage yield and forage quality parameters are determined by applying different N fertiliser application rates. In Chapter four, the simple irrigation scheduling version of the SWB

(SWB-Calendar) model is calibrated and validated and calendars are developed for selected sites and soil types. In Chapter five, the scientific version of the SWB (SWB-Sci) model is calibrated and validated for a range of N fertiliser levels and irrigation regimes. In Chapter six, a range of irrigation strategies were compared with apparent current farmers' irrigation practice using the SWB-Sci model. Finally, in Chapter seven, general conclusions and recommendations are presented.