CHAPTER 4

IMPROVING WATER MANAGEMENT OF IRRIGATED ANNUAL RYEGRASS USING THE SWB-PRO MODEL

4.1 INTRODUCTION

Water availability is considered to be the main factor limiting pasture production in South Africa (Aucamp, 2000). About 62% of South Africa's surface and ground water resources (at 98% assurances) are used for irrigation (DWAF, 2004). This substantial amount of water assigned to irrigated agriculture is facing fierce competition as the water demand of industrial, domestic and other activities increase. Thus, farmers are facing pressures to decrease their share of water usage, while at the same time producing sufficient pasture to supply the milk demand of the growing population. Clearly, therefore, innovations are needed to increase the efficiency of irrigation and water use.

Unfortunately, knowing how much water to apply through irrigation and how often is no trivial matter. In addition, nutrient management, especially N, is inextricably linked to water management, as over-irrigation leaches valuable nitrates from the profile out of reach of the growing pasture. As energy, fertiliser and water costs increase and profit margins narrow, farmers are realising the necessity of improved irrigation scheduling to obtain maximum yields for the lowest financial investment. Ideal pasture management is the production of economically optimum forage yield and quality without compromising the environment. Accurate irrigation scheduling plays an important role in deciding the income of a dairy enterprise by affecting yield and quality; irrigation input and energy usage; and environmental pollution. Improved knowledge of irrigation timing and amount can also be of great value in scheduling other cultural operations.

Annual ryegrass is one of the most widely grown irrigated winter pastures in South Africa. It has high nutritional quality, is very palatable, and is high in digestible energy, protein and minerals

(Dickinson *et al.,* 2004; Theron and Snyman, 2004). Annual ryegrass plays an essential role in supplying good quality grazing between the winter and summer seasons, thereby dramatically improving fodder flow options (Eckard *et al*., 1995). However, it is a high user of water and its performance is less than optimum under drought or adverse environmental and/or management conditions (Theron and Snyman, 2004).

Irrigation technologies may be adapted by commercial and emerging rural farmers for more-effective and wiser use of limited water supplies. Irrigation scheduling is the main component of water management by which irrigators decide when and how much water to apply (Hoffman *et al*., 1992). Proper scheduling can lead to increased profits without compromising the environment, by increasing productive water use and reducing unproductive water loss through 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). However, the tools required are relatively expensive and complicated making the implementation of irrigation scheduling for the average farmer difficult (Orloff and Carlson, 1997). Some monitoring tools may also not provide the most reliable method of scheduling due to soil spatial variability or by giving little information either on the amount or when water is to be applied (Hillel, 1990; Hoffman *et al.,* 1992). Using irrigation monitoring tools, however, provides reasonable and quantitative information for irrigation scheduling. A combination of one or more monitoring approaches would improve the accuracy of recommended timing and amount of irrigation to be applied.

In the last four decades, various computer models, which integrate the soil, plant and atmospheric approaches by estimating soil water balance components, have been developed for different purposes (Joyce and Kivkert, 1987; Bahera and Panda, 2009; Allen *et al*., 2011). The Soil Water Balance model (Annandale *et al*., 1999), a real-time, generic crop growth, soil water balance and irrigation scheduling model, is one of these. 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. This can save money and the time required for conducting long-term intensive field experiments for gathering information on potential crop production with different resources. In the absence of monitoring, models can also be used to explore better irrigation management strategies in order to increase irrigation use efficiency and determine site specific irrigation requirements or calendars.

Considering the use of a large number of data sets and time consuming determination of input parameters required for the pasture specific models, relatively simple models (such as the SWB) may be more applicable. According to Stevens *et al.* (2005), the major problems with adoption of models by the farmers is their complexity, therefore, there should be trade-offs between accuracy and simplicity. The SWB model is being used to simulate crop growth and soil water balance of several cereals, vegetable and tree crops (Annandale *et al.,* 2000; Jovanovic *et al.*, 1999; Geremew *et al.,* 2008; Beletse *et al.,* 2008; Singels *et al.,* 2010). Therefore, it is better to use a model which is locally known by farmers and consultants instead of introducing another new model.

The current irrigation guidelines of most temperate grasses, including ryegrass is 25 mm of irrigation water per week (Jones, 2006; Macdonald, 2006). Evaporative demand differs between locations and over time for a specific location, and as crop canopy cover varies. Therefore, a rigid guideline of 25 mm per week will lead to over or under irrigation. There is a need to determine irrigation requirements of annual ryegrass by developing site specific irrigation calendars which are simple guidelines or charts that indicate when and how much to irrigate. Calendar based irrigation scheduling, provides irrigators with an inexpensive strategy to estimate irrigation timing and amount. The irrigation requirements developed can be flexible by deducting real time measured rainfall since the last irrigation event.

The objectives of the study were to parameterise the SWB model for ryegrass and evaluate its performance under different levels of irrigation. Once satisfied with the model's water requirement prediction capability, the model can be used to develop site specific irrigation calendars for major ryegrass growing regions of South Africa.

4.2 MODEL DESCRIPTION

SWB model was developed based on the NEWSWB (Campbell and Diaz, 1988). Simulations can be done with two approaches: 1) an FAO based model that calculates canopy cover from an empirical crop factor and 2) a mechanistic simulation of crop growth. The FAO approach simulates crop water use and growth relatively simply using crop coefficients for various growth stages (Jovanovic and Annandale, 1999). On the other hand, the crop growth model simulates dry matter production more mechanistically. The mechanistic crop growth model has the capability to simulate the effect of water stress on canopy size (Jovanovic and Annandale, 2000), which cannot be done by the simple FAO approach. However, this requires more detailed crop specific model parameters.

SWB estimates crop growth and water balance fluxes and storage using weather, soil and crop units. A detailed description is available in Annandale *et al.* (1999). The weather unit of SWB calculates the Penman-Monteith grass reference daily evapotranspiration (ETo) according to FAO 56 recommendations (Allen *et al.,* 1998). Water movement in the soil profile is simulated using a cascading or finite difference approach.

In the crop unit, SWB calculates a daily dry matter increment as either being radiation or water limited. SWB estimates phenological development, growth and yield of a crop from emergence to maturity based on soil water status and environmental conditions. Transpiration is assumed to be equal to crop water uptake, which is a function of soil water potential, leaf water potential and root conductance. The use of thermal time in mechanistic growth model negates the need to specify length of developmental stages as crop factors modelling approach to express crop development, which varies for different planting dates and regions (Oliver and Annandale, 1998). Hence in the growth model, water-limited growth is calculated using parameters that directly limit biomass accumulation including a crop stress index and leaf water potential (Annandale *et al.,* 2000). In addition, the growth model enables an accurate description of deficit irrigation strategies, where water use is supply limited (Annandale *et al.,* 1999).

The model was parameterised and extensively tested for many crops (Annandale *et al.,* 2000; Beletse *et al.,* 2008; Geremew *et al.,* 2008; Jovanovic *et al*., 1999; Singels *et al.,* 2010). To improve applicability for ryegrass pasture various defoliation practices including fixed date, thermal time and accumulated forage biomass were included in the SWB model.

4.3 MATERIALS AND METHODS

4.3.1 Site description and crop management

Data collected from an open field and rainout shelter during the 2007 and 2008 growing seasons were used to calibrate and validate the model. The open field experiment was conducted at the Cedara Experimental Farm of the Department of Agriculture Research Station (altitude 1076 m, 29°32'S; 30°17'E) in the Midlands of KwaZulu-Natal. The rainout shelter experiment was conducted at the Hatfield Experimental Farm (altitude 1327 m, 25°45'S; 28°16'E) of the University of Pretoria, Pretoria. The soil at Cedara was a deep, red, kaolinitic Hutton soil with a heavy clay loam texture to a depth 0.4 m, and heavier clay soil from 0.4 to 1.0 m (Soil Classification Working Group, 1991) while that of Hatfield was a sandy loam. The irrigation systems were dragline sprinklers at Cedara and dense grid drip at Hatfield.

At both sites, annual ryegrass cultivar "Agriton" was planted in rows at a seeding rate of 30 kg ha^{-1} and spacing of 15 mm between rows. At planting 20 kg P ha^{-1} was applied while 60 kg N ha^{-1} and 25 kg K ha^{-1} was applied for each growth cycle. Access tubes were installed in each plot to monitor soil water content to a depth of 1.0 m. A large fraction of ryegrass' active root system is located in the top 0.60 m, thus root zone soil water deficit and irrigation scheduling for both sites was conducted to the 0.60 m soil depth.

4.3.2 Treatments

Two different approaches were used. The first used different irrigation strategies for growth analysis and forage yield determination and the second used micrometeorological techniques for measuring total evaporation under well watered conditions. The data were used for model calibration and validation.

4.3.2.1 Irrigation strategies

At Cedara, plots were 12 m wide and 36 m long, with a 12 m spacing between plots. Each plot had its own sprinkler lines to allow the application of independent irrigation amounts. In 2007, deficit (growth cycles one to three) and frequency (growth cycles four to eight) irrigation scheduling strategies were used (Table 4.1). For the first three growth cycles, plots were irrigated to 100% (**W1**) or 60% of plant available water (field capacity – wilting point) (**W2**) weekly. For the next five growth cycles (fourth to eighth) plots were irrigated every 7 days (**W1**) or 14 days (**W2**) to field capacity. In 2008, well watered treatment plots were irrigated once a week during autumn, spring and summer; and once every two weeks in winter to field capacity (**W1**). In both years, in summer 15 mm soil deficit was left after irrigation as “room for rain”. In 2008, water stressed plots were irrigated only after harvest when N and K fertilisers were applied (**W2**).

At Hatfield, plots were 3.0 m^2 (1.5 m x 2.0 m) with an interspacing of 0.5 m between each plot. Plastic sheeting was inserted to a depth of 1.2 m in the interspaces to limit the movement of water between plots. Plots were irrigated twice a week (**W1**), weekly (**W2**) or once every two weeks (**W3**) to field capacity (Table 4.1). In both sites and years, treatments were replicated three times and were assigned in a randomised complete block design.

Table 4.1 Treatments used for calibration and validation of the SWB model

Site	Year	Planting date	Treatments	Defoliation	Growth cycles	Modelling objective
Cedara	2007	06/03/2007	W1 W2	3 leaf stage	8	Validation
	2008	25/03/2008	W1	3 leaf stage	7	Calibration
		17/04/2008	W2	3 leaf stage	5	Validation
Hatfield	2007	05/06/2007	W1 W2 W3	28 days	4	Validation
	2008	23/04/2008	W1 W2 W3	28 days	4	Validation

4.3.2.2 Evapotranspiration measurement using the shortened energy balance method

Evapotranspiration (ET) under well watered conditions was estimated using the surface renewal technique to obtain the sensible heat flux and the latent heat flux (ET) obtained as the residual of the shortened energy balance equation (Savage *et al.,* 2010). To allow for adequate fetch a large field (120 m x 50 m) with a dominant wind direction from the South East during the study period was planted with annual ryegrass in April. The measurements of surface renewal (SR) (Paw *et al*., 2005) were conducted for three growth cycles (11th September to 6th of November 2008). An eddy covariance system (EC) was also installed from 2nd October to 6th November. The primary use of the EC was for calibrating the α factor for the surface renewal system (Mengistu and Savage, 2010).

Wind velocity and temperature (0.75 m above the ground) were measured using a three dimensional sonic anemometer (model 81000, RM Young, Michigan, USA). Sampling frequency of the three components of wind velocity, *u, v, w,* and sonic temperature *T* was 10 Hz. The two-minute averages of eddy covariance between *u, v, w* and *T* and wind direction ε = arctan v/u were calculated and stored for further analysis. For the surface renewal method, two unshielded type-E fine wire chromel-constantan thermocouples (75 µm diameter) were used to measure high frequency air temperature 0.25 m above the crop surface. The height of the thermocouples was adjusted twice a week to maintain a constant 0.25 m height above the pasture canopy .

The eddy covariance and surface renewal measurements were used for estimating sensible heat flux (H). The NR-LITE net radiometer (Kipp & Zonen, Delft, The Netherlands) placed 1.0 m above the soil surface was used to measure net irradiance (R_n). Soil heat flux (G) was measured using two soil heat flux plates (model HFT-S, REBS, Seattle, USA) placed 80 mm below the soil surface. For measuring the soil heat stored above the soil heat flux plates, thermocouples were installed at depths of 20 and 60 mm. A CS616 water content reflectometer (Campbell Scientific, USA) was used for measuring the volumetric water content of the top 80 mm soil layer.

4.3.3 Data collection

At both experimental sites, weather data, including daily values of minimum and maximum air temperature and humidity, wind speed, incoming solar radiation and precipitation, were collected from automated weather stations. Soil water contents were measured using a Diviner-2000 probe (Sentek®, Australia) at Cedara and a neutron water meter model 503 DR CPN Hydroprobe (Campbell Pacific Nuclear, California, USA) at Hatfield. Irrigation amounts were measured with manual raingauges at Cedara and with water meters at Hatfield.

At both sites, leaf area and above ground biomass were measured every 7 to 14 days by harvesting plant material from an area of 0.25 x 0.25 m to a height of 50 mm from the soil surface. The samples were hand separated into leaf and stem material. The leaf area index (LAI) was determined using an LI 3100 belt driven leaf area meter (LiCor, Lincoln, Nebraska, USA). For forage yield determination, grass was harvested at the 2 to 3 leaf stage (1 m^2) at Cedara, and every 28 days (0.0625 m^2) at Hatfield using a manual grass mower to a 50 mm stubble height. At Cedara, after sampling for forage yield and stubble biomass, the whole field was harvested to a height of 50 mm with a tractor drawn mower. Forage dry matter was determined by oven drying samples at 70℃ to constant mass.

4.3.4 Model reliability test

The statistical evaluation parameters used to test the accuracy of the model were the coefficient of determination (r^2), Willmott (1982) index of agreement (D) and mean absolute error of measured values (MAE). For accurate model predictions, r^2 and D should be greater than 0.8, while MAE should be less than 20% (De Jager, 1994).

4.3.5 Model application

Four major milk producing areas of South Africa including the KwaZulu-Natal Midlands (Cedara), Eastern Highveld (Ermelo), Eastern Cape (Queenstown) and Southern Cape (George) were selected. Long-term (50 years: 1950 to 2000) rainfall and reference evapotranspiration (ETo) of the selected sites are presented in Figure 4.1. The sites showed seasonal variations in rainfall and ETo which clearly motivate the need to develop site specific irrigation calendars.

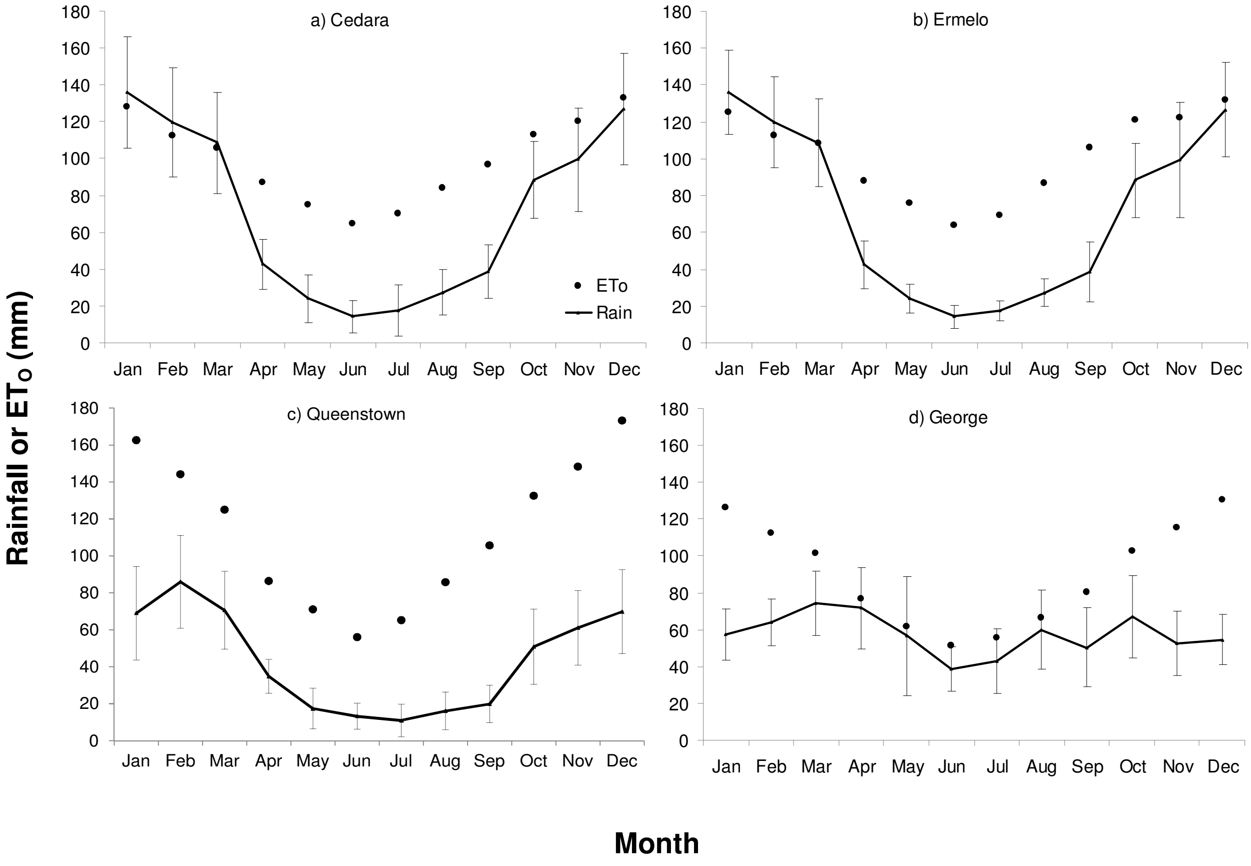

Figure 4.1 Monthly long-term means (1950-2000) of reference evapotranspiration (ETo) and precipitation in four ryegrass growing areas (vertical bars are standard deviation)

Long-term historical weather data (1950 to 2000) including minimum and maximum temperatures of representative sites were used for estimating water requirements and irrigation calendars of annual ryegrass. Water requirements were estimated for 50 years while calendars were developed using the daily mean of the long-term weather data. The maximum soil depth was set to 0.4 m because most pastures are planted on marginal soils. Simulations were preformed from 1st March to 6th November (eight harvests). The first defoliation was simulated 60 days after planting and after this first harvest, the pasture was defoliated at four week intervals, in autumn and winter and three week intervals in spring. The virtual crop was "irrigated" with a sprinkler irrigation system and the initial soil water content at planting for all the layers was set to field capacity. This assumption was made because planting is at the end of the rainy season and it is usually safe to assume the soil profile is wet. This can be also supported from the high rainfall received during the month of February (Figure 4.1).

Irrigation calendars are simple guidelines or charts that indicate when and how much to irrigate. Site specific and monthly irrigation calendars were developed by excluding rain as examples, to illustrate how farmers can develop their own crop and site specific calendars. Site specific irrigation calendars were developed for four major milk producing areas of South Africa for a sandy (low water holding capacity), sandy loam (medium water holding capacity) and clay (high water holding capacity) soil textural classes. The pasture was irrigated when 50% of the plant available water was depleted which was equivalent to 16 mm for sandy, 21 mm for sandy loam and 28 mm for clay loam. Monthly general irrigation calendars were also developed for a deep, well drained and fertilised, medium textured soil using a common “recipe” of 25 mm per irrigation event, but scheduling the timing according to long-term water requirement.

4.4 RESULTS AND DISCUSSION

4.4.1 Model calibration

Field data collected during 2008 from Cedara under well watered conditions were used to estimate crop specific parameters of ryegrass. Ryegrass growth parameters which were determined by Annandale *et al.* (1999) were refined in order to account for pasture specific management and cultivar differences. Crop specific growth parameters including radiation extinction coefficient, vapour pressure deficit, corrected dry matter water ratio, radiation use efficiency, specific leaf area, leaf stem partitioning parameter, growing degree days for different development stages, leaf water potential at maximum transpiration, maximum crop height and root depth (Table 4.2) were determined according to the procedure described by Jovanovic and Annandale (1999). Parameters that could not be estimated experimentally were obtained from the literature or estimated by calibrating the model against measured field data.

Table 4.2 Specific crop input parameters of ryegrass used for SWB model calibration

Parameter	Value	Unit	Source
Extinction coefficient for solar radiation	0.53	-	Annandale *et al.* (1999)
Dry matter water ratio	3.8	Pa	Measured
Radiation conversion efficiency	0.0013	kg MJ^{-1}	Annandale *et al.* (1999)
Base temperature	4	℃	Akmal and Janssens (2004)
Temperature for optimum light limited growth	15	℃	Annandale *et al.* (1999)
Cut off temperature	25	℃	Annandale *et al.* (1999)
Emergence day degrees	50	d ℃	Measured
Day degrees at the end of vegetative growth	3000	d ℃	Adjusted with calibration
Day degrees for maturity	3500	d ℃	Adjusted with calibration
Transition period day degrees	300	d ℃	Annandale *et al.* (1999)
Day degrees for leaf senescence	600	d ℃	Annandale *et al.* (1999)
Maximum crop height	0.5	m	Measured
Maximum root depth	0.6	m	Measured
Fraction of TDM translocated to heads	0.01	-	Annandale *et al.* (1999)
Leaf water potential at maximum transpiration	-1500	kPa	Annandale *et al.* (1999)
Maximum transpiration	8	mm d^{-1}	Measured
Specific leaf area	25	m^{2} kg^{-1}	Measured
Leaf-stem partition parameter	0.91	m^{2} kg^{-1}	Measured
Fraction of total dry matter partitioned to roots	0.15	-	Measured
Root growth rate	4	m^{2} kg^{-1}	Annandale *et al.* (1999)
Stress index	0.95	-	Annandale *et al.* (1999)
Total dry matter at emergence	0.0005	kg m^{-2}	Adjusted with calibration
Total dry matter after harvest	0.075	kg m^{-2}	Measured
Leaf area index after harvest	0.50	-	Measured

In Figures 4.2 to 4.7, model simulation output is displayed as lines, whilst measured data are presented in symbols given with error bars if available. Simulation generally agreed well with the measured data for all parameters during model calibration (Figure 4.2). In addition to the visual similarity between simulated and measured values, all the statistical parameters ($r^2 > 0.79$, $D > 0.80$ and MAE < 20%) imply calibration of the model was satisfactory (Table 4.3).

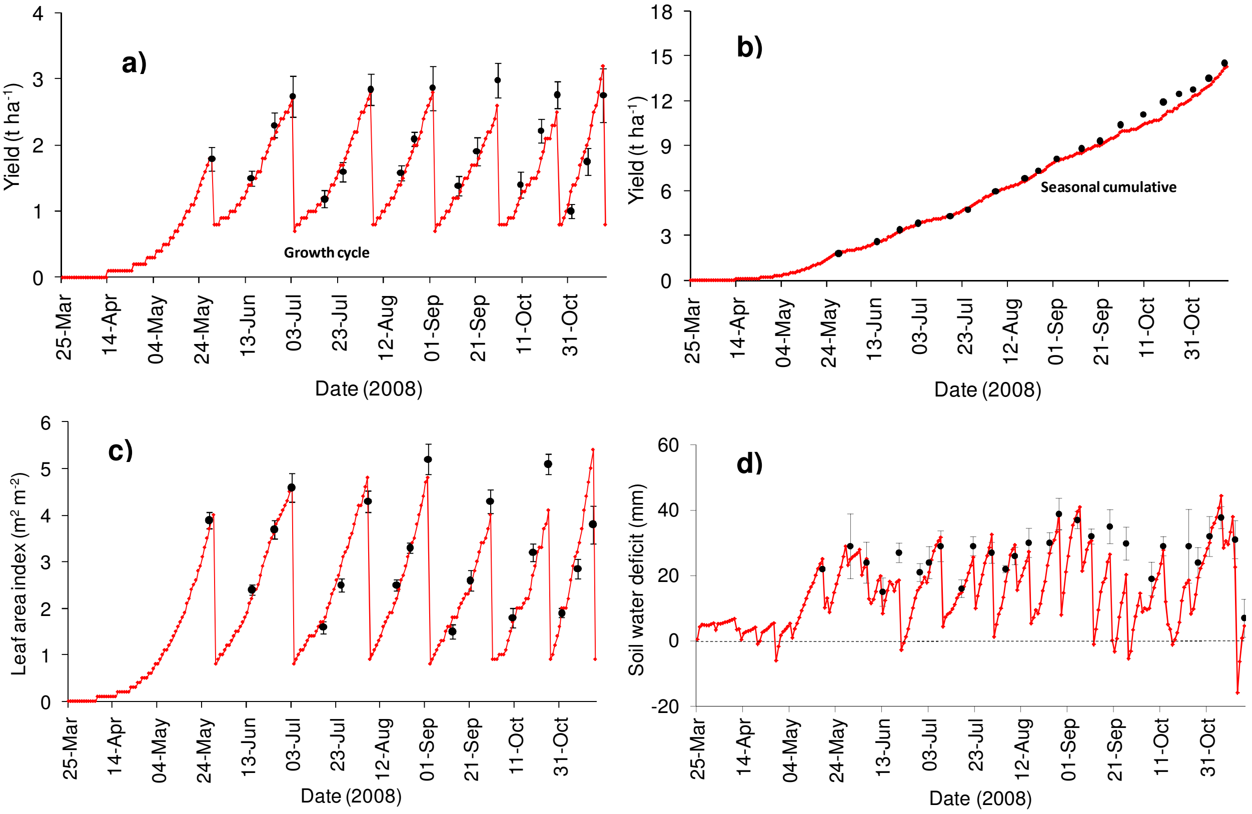

Figure 4.2 Simulated (lines) and measured data (symbols) of above ground dry matter for a) growth cycles and b) from whole season, c) leaf area index and d) soil water deficit to field capacity for model calibration of ryegrass at Cedara during the 2008 growing season (Vertical bars are the standard deviation of measured data)

Simulated and measured pasture growth (leaf area index and above ground biomass) were in good agreement (r^2 and $D > 0.80$ and MAE < 20%) (Figure 4.2). The accuracy of the agreement between measured and simulated forage yield was improved when the model was used to simulate forage biomass yield for seasonal cumulative forage production, rather than for individual growth cycles (Table 4.3). The model tended to overestimate forage yield slightly at the end of the season. This was likely due to a reduced number of vegetative tillers and start of flowering and seed formation towards the end of the growing season (Marais *et al.,* 2003). These parameters are not simulated by the SWB generic crop growth model. However, the model simulated forage yield quite accurately for the active vegetative growing season (March to October- 26 weeks), when the quality and productivity of annual ryegrass was high. The model was also able to predict profile soil water content deficit to field capacity adequately, with most parameters within acceptable ranges with r^2 and D > 0.80 and MAE < 20% (Table 4.3).

Table 4.3 Statistical parameters used for evaluation of model performance of predicted forage yield, leaf area index, soil water deficit during calibration

Parameter	N	r^2	D	MAE (%)
Forage yield (cycles)	21	0.88	0.97	8.99
Forage yield (cumulative)	21	0.99	0.99	3.80
Leaf area index	21	0.81	0.95	10.89
Soil water deficit	33	0.79	0.96	16.25

(N: number of observations; r^2: coefficient of determination; D: Willmott index of agreement; MAE: mean absolute error)

4.4.2 Model validation

Independent data from water stressed treatments collected from Cedara in the 2007 and 2008 and Hatfield for 2007 and 2008 were used for validating the SWB model,. Model predictions were compared with measured forage yield for individual growth cycles and cumulatively for the whole season for leaf area index, root zone soil water deficit to field capacity and evapotranspiration. The statistical parameters used to evaluate the accuracy of model validation simulations are presented in Table 4.4.

Table 4.4 Statistical evaluation between observed and predicted values of forage yield and leaf area index during model validation in 2007 and 2008 seasons

Parameter	N treatment	Growth cycle yield			Cumulative yield			Leaf area index		
		r^2	D	MAE (%)	r^2	D	MAE (%)	r^2	D	MAE (%)
Cedara 2007-2008	W1-2007	0.77	0.93	12.7	0.99	0.99	2.2	0.76	0.93	14.8
	W2-2007	0.73	0.92	14.3	0.99	0.96	3.5	0.72	0.92	16.1
	W2-2008	0.92	0.97	9.7	0.99	0.99	2.7	0.90	0.93	12.3
Hatfield 2007	W1	0.95	0.97	9.0	0.99	0.99	4.9	0.91	0.95	12.8
	W2	0.94	0.95	12.9	0.99	0.98	6.8	0.94	0.96	12.1
	W3	0.88	0.96	12.1	0.97	0.98	12.2	0.90	0.90	16.3
Hatfield 2008	W1	0.98	0.98	8.1	0.99	0.98	7.0	0.80	0.92	14.8
	W2	0.92	0.95	5.3	0.99	0.99	8.6	0.81	0.94	14.0
	W3	0.86	0.85	11.6	0.95	0.97	11.3	0.77	0.86	16.2

r^2: coefficient of determination; D: Willmott index of agreement; MSE: mean standard error; MAE: mean absolute error

4.4.2.1 Forage yield and leaf area index

The simulated and measured values of forage yield for well watered and water stressed treatments during model validation periods are shown in Figure 4.3 for individual growth cycles and in Figure 4.4 for the whole season. The overall accuracy was satisfactory with all the statistical parameters within acceptable limits. Forage yield in the last growth cycle was overestimated by the model for all sites and treatments. This could be due to the onset of flowering and reduction in the number of tillers as mentioned previously. On the other hand, the model slightly underestimated forage yield in some growth cycles under water stressed conditions (Figure 4.3).

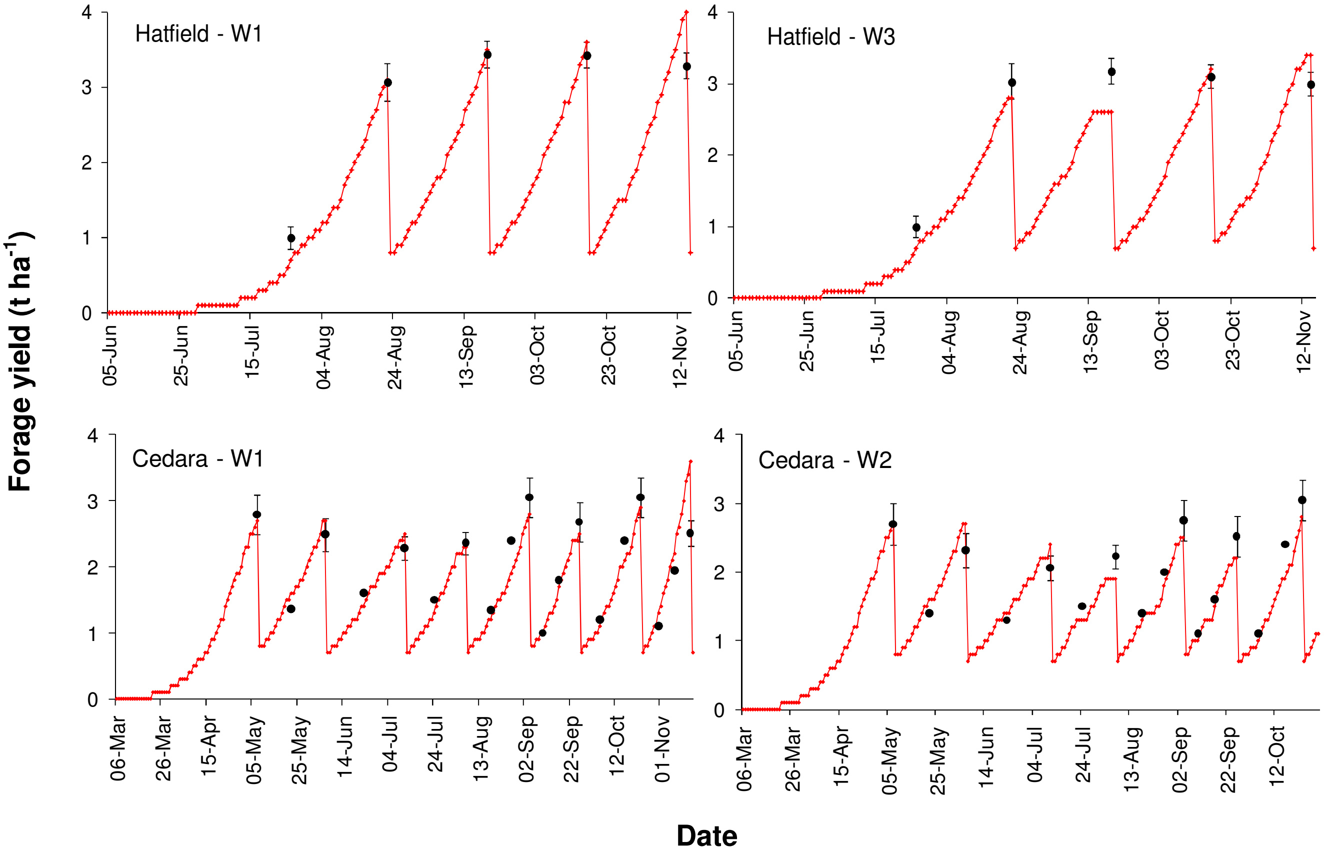

Figure 4.3 Simulated (solid lines) and measured (symbols) forage yield for individual growth cycles for the well watered (W1) and water stressed (W2 for Cedara; W3 for Hatfield) treatments during the 2007 growing season

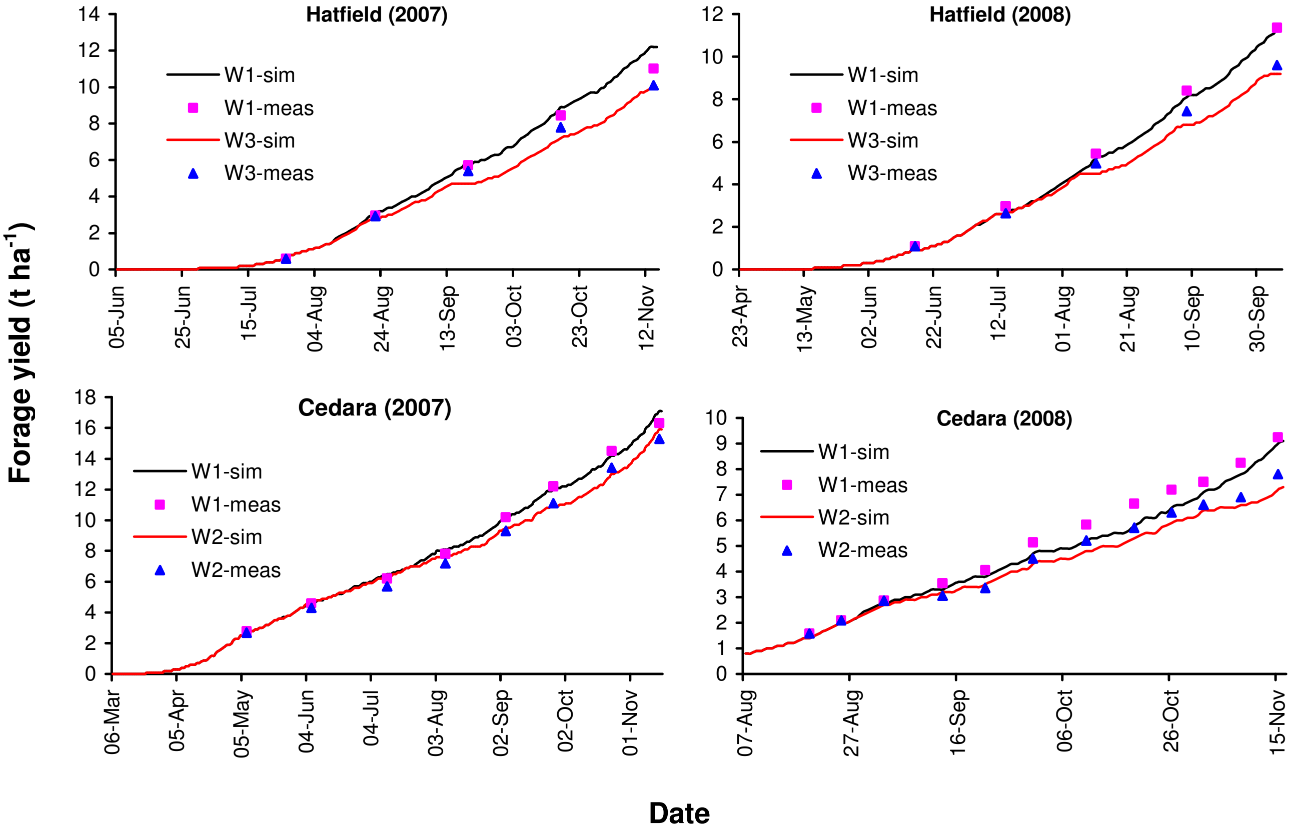

Figure 4.4 Simulated (solid lines) and measured (symbols) seasonal cumulative forage yield for the well watered (W1) and water stressed (W2 for Cedara; W3 for Hatfield) treatments during the 2007 and 2008 growing seasons

The maximum simulated and measured LAIs were in the range of measured data (4.0 - 6.5 m^{-2} m^{-2}) reported in the literature by Akmal and Janssens (2004). Generally, the model simulated LAI well, as the statistical parameters between modelled and observed LAIs showed good accuracy(Table 4.4), with all statistical performance evaluation parameters within the acceptable range (r^2: 0.72-0.94; D: 86-96; and MAE less than 20%). However, there the model under estimated LAI under water-stressed treatments in some growth cycles (Figure 4.5).

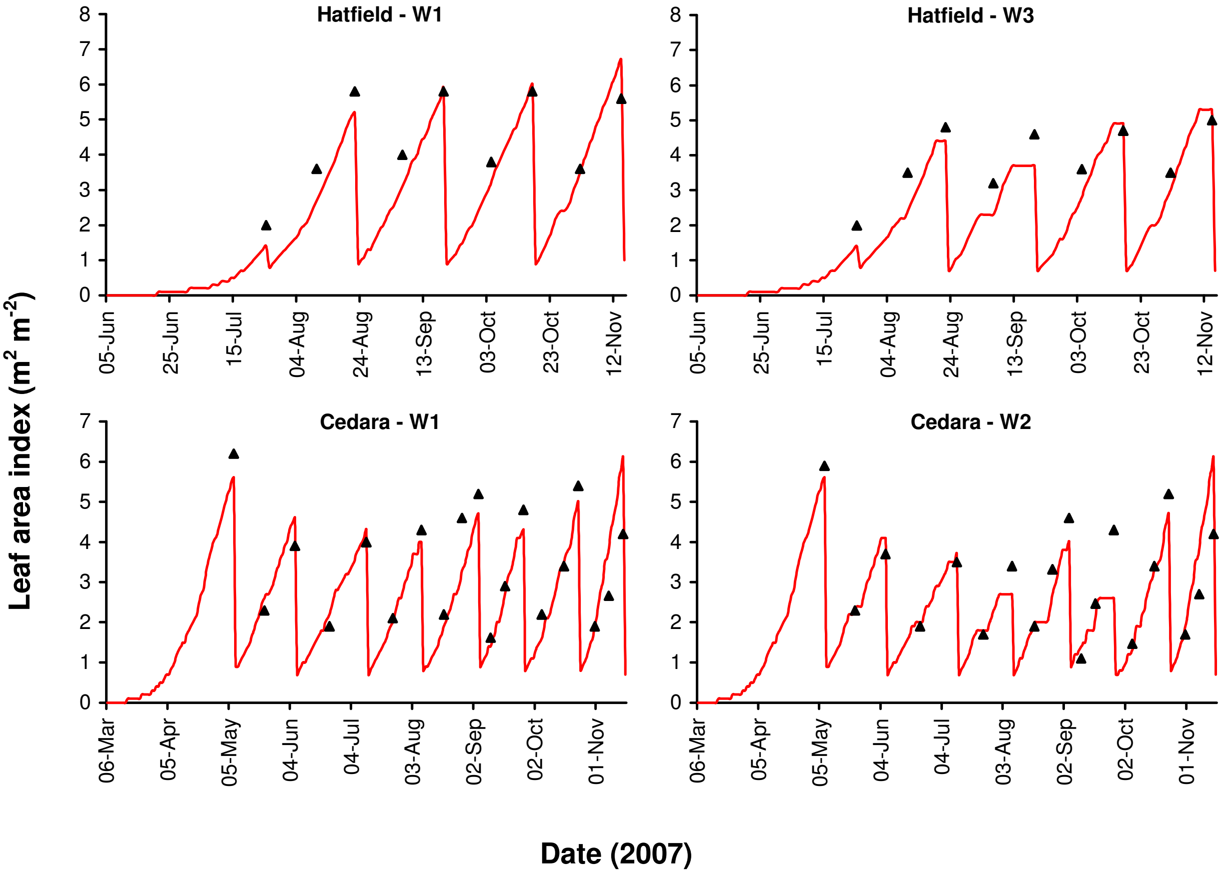

Figure 4.5 Simulated (solid lines) and measured (Symbols) leaf area index for the well watered (W1) and water stressed (W2 for Cedara; W3 for Hatfield) treatments during the 2007 growing season

4.4.2.2 Soil water deficit

Soil water deficit to field capacity (FC) predictions were less accurate (r^2: 0.30 - 0.75; D: 0.73 - 0.89; MAE: 14.19-22.64%) compared to other simulated parameters (Table 4.5), but still with reasonable agreement between measured and simulated values, especially for well-watered treatment (Figure 4.6). The lower accuracy is typical for this parameter (Todorovic *et al.,* 2009), and could be due to soil variability and inaccuracies resulting during calibration of water content measuring sensors. Considering the simplicity of the input data required to run a cascading soil water balance it can be concluded that the model simulated soil water content satisfactorily.

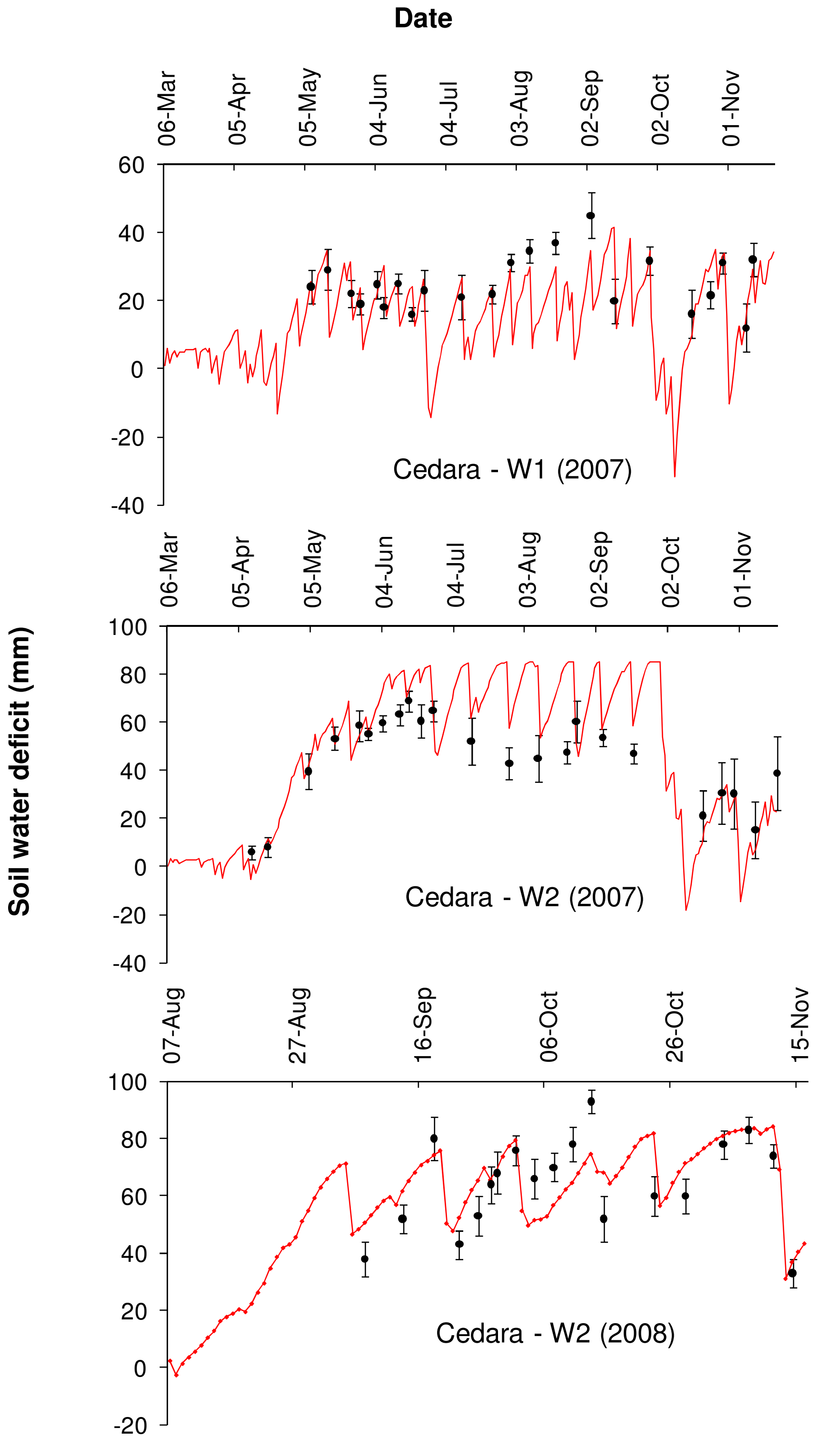

Figure 4.6 Simulated (solid lines) and measured (symbols) of the soil water deficit for the well watered (W1) and water stressed (W2) treatments for Cedara during the 2007 and 2008 growing seasons

Table 4.5 Statistical evaluation between observed and predicted values of soil water deficit to field capacity and evapotranspiration during model validation in the 2007 and 2008 seasons

Parameter		Treatment	r^2	D	MAE (%)
Soil water deficit	Cedara 2007-2008	W1-2007	0.30	0.73	22.64
		W2-2007	0.75	0.89	21.55
		W2-2008	0.52	0.83	14.19
Evapotranspiration	Cedara 2008	Well-watered	0.69	0.98	25.83

r^2: coefficient of determination; D: Willmott index of agreement; MAE: mean absolute error

4.4.2.3 Evapotranspiration

Cumulative actual ET for the three well watered growth cycles was 161 mm compared to whilst that of during the experimental period 152 mm for the simulated ET. The values of the simulated daily ET of well watered pasture were similar to the measured ones (Figure 4.7). The model, however, systematically predicted higher ET compared to measured values when ET was less than 1 mm. However, overall the model predicted ET reasonably well (Table 4.5).

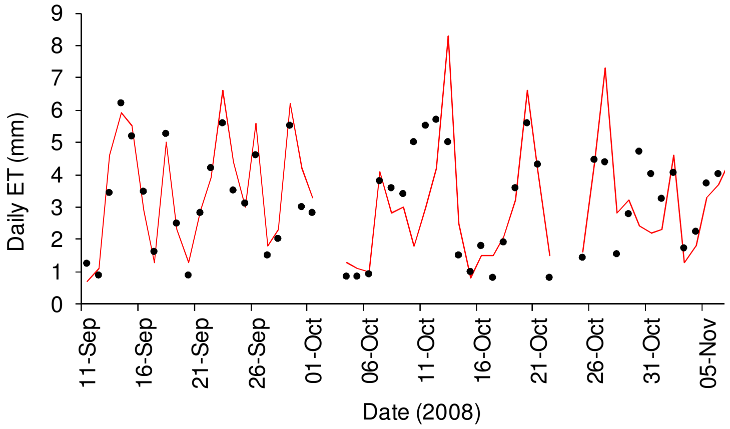

Figure 4.7 Simulated (lines) and measured (symbols) evapotranspiration of ryegrass for the Cedara site during the 2008 growing season for well watered conditions

4.4.3 Model application

The good agreement between observed and simulated data for different sites and irrigation regimes, gives confidence that the SWB model can be used to predict long-term pasture growth and water use under different irrigation management scenarios. In this study, the SWB growth model was used to estimate irrigation requirements of ryegrass in four major milk producing areas of South Africa with different irrigation scheduling strategies.

4.4.3.1 Water requirement

Model simulations showed variation in water use of ryegrass between years (Figure 4.8). Daily water use ranged from an average of 1.5 mm in winter (June) to 5.5 in summer (November). Long-term water use of ryegrass in the Southern Cape was relatively lower than that of the other sites.

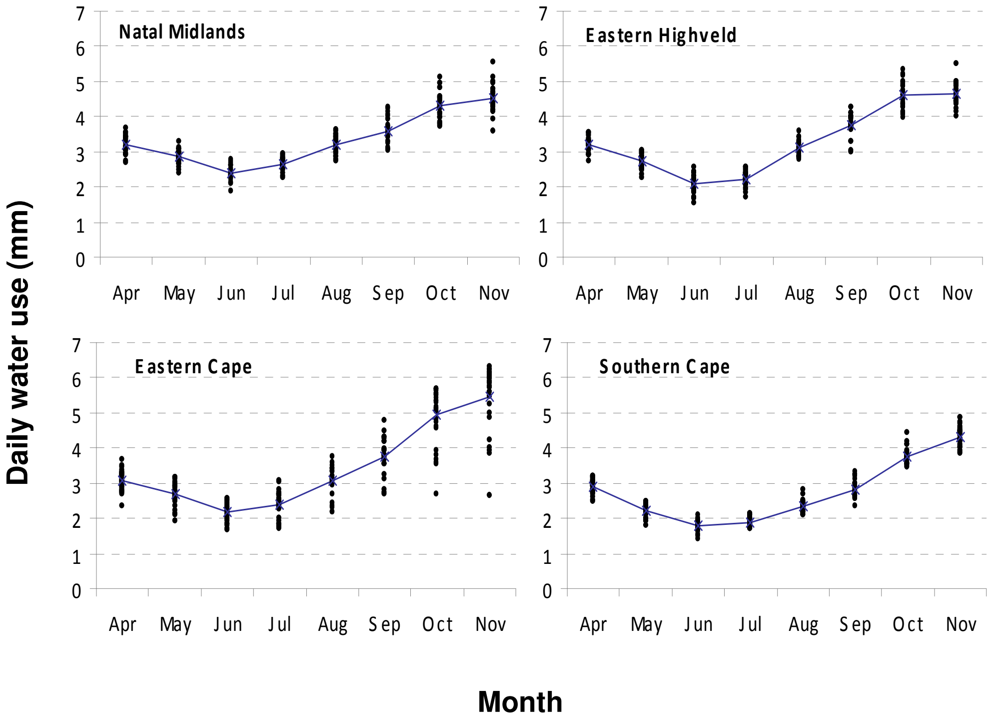

Figure 4.8 Simulated mean long-term daily water use of ryegrass for major milk producing areas of South Africa (points show individual season simulated water use)

There were variations in forage yields, irrigation requirements and irrigation use efficiency of ryegrass simulated using the SWB growth model (Table 4.6). In spite of the lowest irrigation applications (581 mm), simulated forage yields were highest in the Southern Cape, which lead to the highest irrigation use efficiency (Table 4.6). The seasonal water requirement for annual ryegrass according to current guideline (Jones, 2006) (with a fixed amount of 25 mm a week for 35 weeks) is 875 mm. Model outputs using the strategy "irrigate to field capacity when the soil deficit exceeded 25 mm" and "irrigate a fixed amount of 25 mm weekly" produced the same yield. However, the irrigation applications were higher by 131 (Eastern Cape) to 294 mm (Southern Cape) when the pasture was irrigated with a fixed amount of 25 mm a week. This would certainly be a source of water loss through runoff and deep percolation below the root zone, and leaching of nutrients would lead to yield reduction and deterioration of water quality.

Table 4.6 Seasonal forage yield, irrigation application and irrigation use efficiency (IUE) for the long-term simulation for four major milk producing areas of South Africa

	Yield ($t\ ha^{-1}$)	**Irrigation (mm)**		**IUE ($kg\ ha^{-1}\ mm^{-1}$)**	
		FC	**Farmer**	**FC**	**Farmer**
Natal Midlands	15.8 (0.89)	720 (33)	875	21.9 (1.62)	18.1 (1.01)
Eastern Highveld	14.4 (0.87)	707 (27)		20.4 (1.41)	16.5 (0.99)
Eastern Cape	13.9 (0.85)	744 (30)		18.6 (1.22)	15.9 (0.97)
Southern Cape	16.6 (1.09)	581 (22)		28.5 (2.04)	19.0 (1.24)

FC: irrigate to field capacity when the soil deficit exceeded 25 mm. Farmer: irrigate a fixed amount of 25 mm (875 mm per season). Values in brackets are standard deviations.

As expected, in all regions irrigation efficiencies were higher using “irrigate to field capacity when the soil deficit exceeded 25 mm” than “irrigate a fixed amount of 25 mm per week” (Table 4.6). Therefore, there could be opportunities to improve irrigation use efficiency of irrigated pastures by using the rainfall strategically when rainfall is high and deficit irrigation when VPD is low, in areas such as the Southern Cape (Figure 4.9).

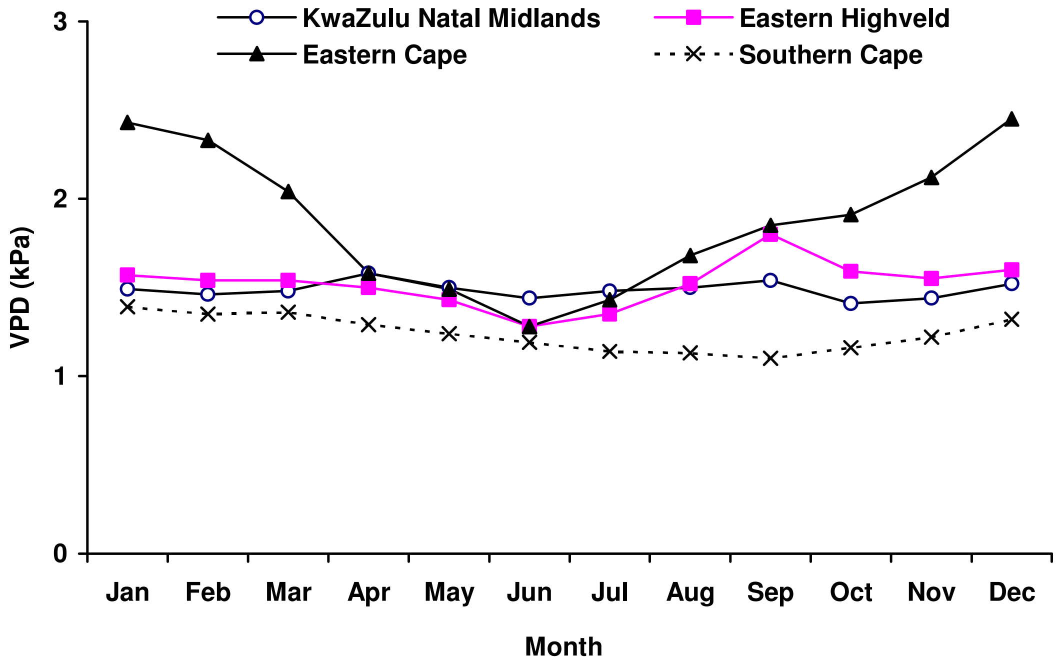

Figure 4.9 Mean monthly vapour pressure deficit (VPD) for long-term (1950-2000) for major milk producing areas of South Africa

4.4.3.2 Irrigation calendars

Site specific irrigation calendars developed for four major milk producing areas of South Africa including the KwaZulu-Natal Midlands, Eastern Highveld, Eastern Cape and Southern Cape using three soil textural classes are presented in Tables 4.7 to 4.9. These calendars were developed as examples by excluding rainfall. For more specific cases, irrigators can develop their own site and crop specific calendars using the user friendly SWB model.

Table 4.7 Simulated site specific irrigation calendars for a sandy soil for four major ryegrass growing areas of South Africa

Events	**KwaZulu Natal Midlands**		**Eastern Highveld**		**Eastern Cape**		**Southern Cape**	
	Date	mm	Date	mm	Date	mm	Date	mm
1	03-Apr	13	04-Apr	13	04-Apr	12	05-Apr	16
2	09-Apr	16	10-Apr	15	11-Apr	16	11-Apr	16
3	14-Apr	17	15-Apr	17	16-Apr	16	17-Apr	18
4	19-Apr	18	20-Apr	18	21-Apr	17	23-Apr	18
5	24-Apr	18	25-Apr	18	26-Apr	17	29-Apr	18
6	29-Apr	18	30-Apr	17	01-May	16	07-May	16
7	05-May	16	07-May	15	10-May	16	15-May	17
8	12-May	17	13-May	16	16-May	16	22-May	17
9	18-May	18	19-May	17	22-May	17	29-May	17
10	23-May	16	25-May	18	28-May	16	07-Jun	15
11	28-May	16	31-May	18	05-Jun	16	17-Jun	16
12	03-Jun	17	10-Jun	16	15-Jun	16	25-Jun	16
13	12-Jun	17	18-Jun	16	23-Jun	16	03-Jul	15
14	19-Jun	17	25-Jun	16	01-Jul	17	14-Jul	16
15	25-Jun	17	02-Jul	16	13-Jul	16	22-Jul	16
16	01-Jul	17	13-Jul	16	21-Jul	16	29-Jul	17
17	11-Jul	17	21-Jul	17	28-Jul	17	07-Aug	16
18	18-Jul	17	27-Jul	16	04-Aug	16	15-Aug	16
19	24-Jul	18	01-Aug	15	13-Aug	17	21-Aug	16
20	29-Jul	16	10-Aug	17	19-Aug	17	27-Aug	17
21	03-Aug	16	16-Aug	17	25-Aug	18	02-Sep	17
22	10-Aug	16	21-Aug	17	30-Aug	17	10-Sep	17
23	15-Aug	16	26-Aug	19	05-Sep	16	16-Sep	18
24	20-Aug	18	30-Aug	16	11-Sep	17	21-Sep	18
25	25-Aug	18	04-Sep	16	15-Sep	16	27-Sep	17
26	30-Aug	19	10-Sep	18	19-Sep	17	03-Oct	18
27	04-Sep	16	14-Sep	17	23-Sep	18	07-Oct	16
28	10-Sep	17	18-Sep	18	29-Sep	16	11-Oct	16
29	14-Sep	16	22-Sep	19	03-Oct	16	15-Oct	16
30	18-Sep	17	27-Sep	16	07-Oct	18	21-Oct	17
31	22-Sep	18	02-Oct	18	11-Oct	19	26-Oct	18
32	27-Sep	15	06-Oct	18	15-Oct	20	30-Oct	17
33	02-Oct	17	10-Oct	20	20-Oct	17		
34	06-Oct	17	14-Oct	20	24-Oct	17		
35	10-Oct	19	18-Oct	17	28-Oct	19		
36	14-Oct	18	23-Oct	17	31-Oct	17		
37	18-Oct	17	27-Oct	18				
38	23-Oct	16	31-Oct	20				
39	27-Oct	18						
40	31-Oct	19						

Table 4.8 Simulated site specific irrigation calendars for a sandy loam soil for four major ryegrass growing areas of South Africa

Events	**KwaZulu Natal Midlands**		**Eastern Highveld**		**Eastern Cape**		**Southern Cape**	
	Date	mm	Date	mm	Date	mm	Date	mm
1	07-Apr	23	08-Apr	23	07-Apr	19	07-Apr	22
2	14-Apr	23	15-Apr	23	15-Apr	22	15-Apr	23
3	20-Apr	22	22-Apr	25	22-Apr	24	23-Apr	24
4	27-Apr	25	29-Apr	24	29-Apr	24	01-May	23
5	04-May	22	09-May	23	10-May	23	14-May	23
6	13-May	22	17-May	22	19-May	23	24-May	23
7	21-May	24	25-May	24	28-May	24	03-Jun	22
8	29-May	24	02-Jun	23	10-Jun	22	18-Jun	23
9	09-Jun	22	15-Jun	22	23-Jun	23	29-Jun	22
10	19-Jun	23	26-Jun	23	05-Jul	22	15-Jul	22
11	27-Jun	22	09-Jul	23	19-Jul	23	26-Jul	23
12	08-Jul	23	21-Jul	23	29-Jul	23	06-Aug	22
13	18-Jul	23	30-Jul	24	10-Aug	22	17-Aug	23
14	26-Jul	24	10-Aug	23	19-Aug	23	25-Aug	22
15	02-Aug	23	18-Aug	23	27-Aug	25	02-Sep	22
16	12-Aug	23	25-Aug	25	03-Sep	23	12-Sep	23
17	19-Aug	23	31-Aug	23	11-Sep	22	19-Sep	23
18	26-Aug	25	09-Sep	24	17-Sep	24	26-Sep	22
19	01-Sep	22	15-Sep	24	22-Sep	22	04-Oct	24
20	10-Sep	24	20-Sep	23	30-Sep	23	10-Oct	24
21	16-Sep	24	25-Sep	22	06-Oct	25	16-Oct	24
22	22-Sep	26	02-Oct	24	11-Oct	23	24-Oct	23
23	30-Sep	23	07-Oct	24	16-Oct	24	30-Oct	25
24	06-Oct	25	12-Oct	25	23-Oct	23		
25	11-Oct	23	17-Oct	24	28-Oct	25		
26	16-Oct	23	24-Oct	24	01-Nov	22		
27	23-Oct	22	29-Oct	24				
28	28-Oct	23						

Table 4.9 Simulated site specific irrigation calendars for a clay soil for four major ryegrass growing areas of South Africa

Events	**KwaZulu Natal Midlands**		**Eastern Highveld**		**Eastern Cape**		**Southern Cape**	
	Date	mm	Date	mm	Date	mm	Date	mm
1	09-Apr	29	10-Apr	29	11-Apr	28	09-Apr	29
2	18-Apr	31	19-Apr	31	20-Apr	29	19-Apr	30
3	26-Apr	29	28-Apr	31	29-Apr	30	29-Apr	29
4	05-May	28	10-May	30	13-May	30	14-May	29
5	16-May	29	20-May	29	24-May	30	27-May	30
6	26-May	31	30-May	29	07-Jun	29	13-Jun	29
7	06-Jun	28	15-Jun	28	23-Jun	29	28-Jun	29
8	19-Jun	29	28-Jun	28	10-Jul	29	17-Jul	29
9	30-Jun	31	15-Jul	29	25-Jul	30	30-Jul	29
10	15-Jul	29	27-Jul	28	08-Aug	29	15-Aug	29
11	25-Jul	29	08-Aug	28	20-Aug	31	26-Aug	30
12	03-Aug	28	18-Aug	28	29-Aug	29	06-Sep	28
13	15-Aug	30	26-Aug	29	09-Sep	29	16-Sep	29
14	24-Aug	32	03-Sep	30	17-Sep	31	24-Sep	28
15	01-Sep	29	12-Sep	29	24-Sep	30	04-Oct	29
16	11-Sep	29	19-Sep	30	03-Oct	30	12-Oct	32
17	18-Sep	29	26-Sep	30	10-Oct	32	20-Oct	29
18	25-Sep	30	04-Oct	31	16-Oct	28	28-Oct	30
19	04-Oct	31	10-Oct	29	24-Oct	29		
20	11-Oct	31	16-Oct	28	30-Oct	32		
21	18-Oct	32	25-Oct	30				
22	26-Oct	30	31-Oct	30				
23	02-Nov	33						

Monthly irrigation calendars developed for a deep, well drained, medium textured soil (using the current guideline application rate of 25 mm irrigation event) for major milk producing areas of South Africa are presented in Figure 4.10. These monthly calendars are general (because they are same for all soil types and only weather is considered) but simple and can be used in the absence of site specific irrigation calendars.

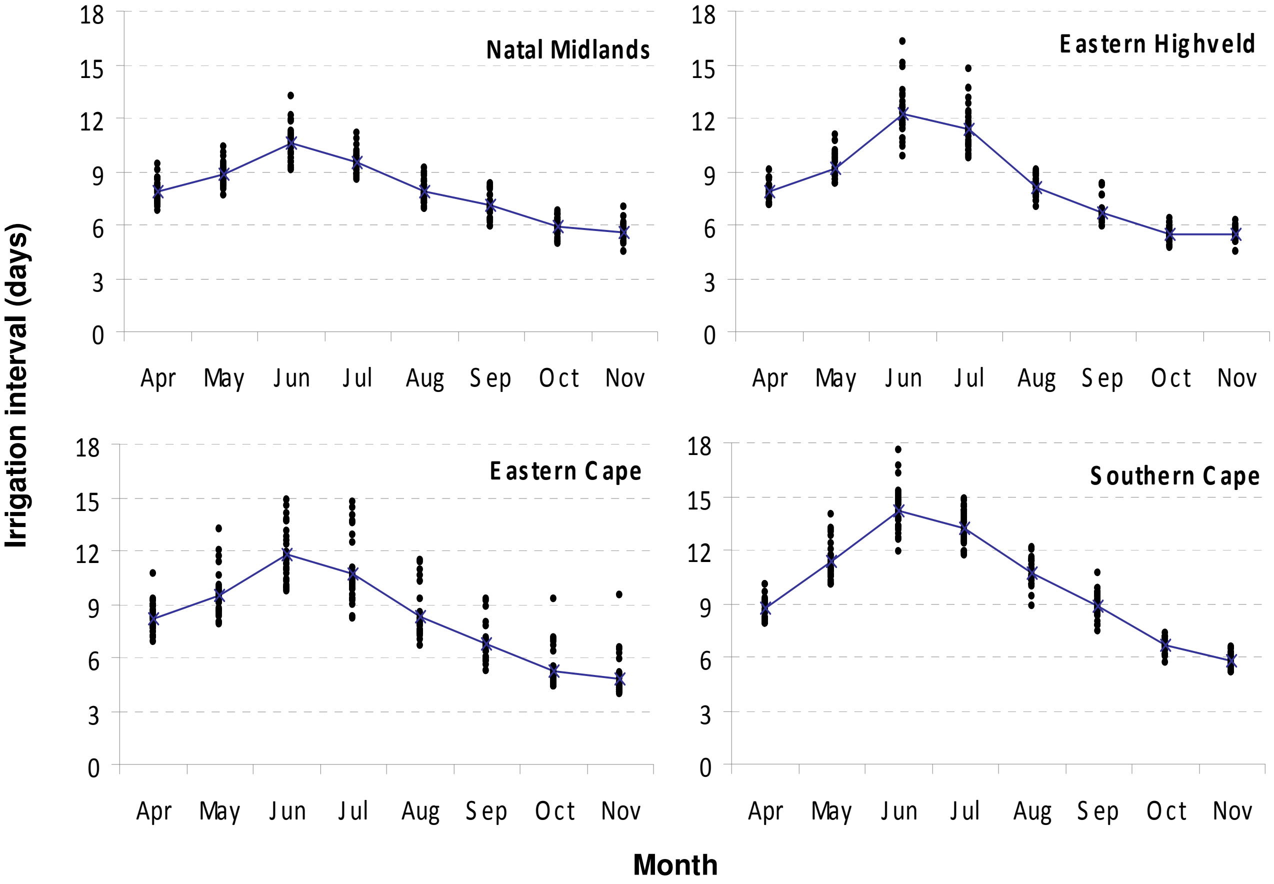

Figure 4.10 Example monthly recommended irrigation intervals (25 mm per event) for milk producing areas of South Africa (points show long-term irrigation intervals)

The model can be used by farmers or consultants to develop their own calendars with relatively few and simple inputs. The minimum inputs required for developing calendars are: 1) Weather data including location of the farm and long-term weather data including minimum and maximum of nearest weather station; 2) soil root depth and textural class (i.e. sand, sandy clay loam, clay loam) and 3) irrigation management including irrigation system, timing and refill options. A range of irrigation systems can be selected including farrow, sprinkler, pivot, micro, drip and subsurface drip. Irrigation timing can be based on three strategies; namely to irrigate at a fixed time interval, when a fixed amount is depleted or when a certain depletion level has been reached. For example: a) Farmers who receive water allocations on specific days (such as those participating in irrigation schemes), usually follow a fixed time interval (eg. every 7 days). b) Farmers use a fixed irrigation amount due to practical on-farm limitations (such as the limited capability of the irrigation system, storage capacity of reservoirs, etc) and usually initiate irrigation when soil deficit reaches a fixed threshold. c) Farmers could also prefer variable timing and amount to avoid crop water stress (depletion level strategy whenever a certain predetermined percentage of plant available water is depleted from the root zone). Refill options can be to field capacity, deficit, leave room for rain or use leaching fractions. Therefore, irrigators can follow different strategies for making a decision on when and how much to irrigate depending on particular situations.

4.5 CONCLUSIONS

The SWB model was evaluated at two sites for different irrigation treatments in two ryegrass growing seasons. Simulated forage yield, leaf area index, root zone soil water deficit and daily evapotranspiration agreed well with observed values. The model was used for predicting water requirement and developing irrigation calendars using annual ryegrass as an example. The main strength of the SWB model is that it requires fewer crop input parameters than more detailed models but still predicts crop growth and soil water balance reasonably well.

The model can be used for managing irrigation scheduling, predicting yields and estimating water requirements of ryegrass under different climatic conditions. If available, accurate site specific measurements using soil water sensors that represent the whole field could be preferable over model predicted irrigation requirements. In the absence of such measuring devices, farmers or consultants can develop site specific calendars using the model without considering rainfall. These calendars can also be modified by farmers when rain falls by subtracting rainfall from the recommended irrigation requirement. These calendars can also be supported with the help of some simple irrigation scheduling tools such as the wetting front detector (WFD). A WFD informs the irrigator when the required wetting front has been reached but it does not tell when to irrigate (Stirzaker, 2003; Geremew *et al.,* 2008). Therefore, combining the calendars (when to irrigate) and using a WFD (how much) can be more beneficial than using calendars developed using a model alone. However, these calendars are clearly superior to the common ‘recipe’ of 25 mm per week.