Performance of simple irrigation scheduling calendars based on average weather data for annual ryegrass

Melake K Fessehazion[1,2]*, John G Annandale[1], Colin S Everson[1,3], Richard J Stirzaker[1,4], Michael van der Laan[1], Wayne F Truter[1] and Amanuel B Abraha[1]

[1]Plant Production and Soil Science, University of Pretoria, Pretoria, South Africa

[2]Current address: Agricultural Research Councilï Vegetable and Ornamental Plant Institute, Pretoria, South Africa

[3]Bioresources Engineering and Environmental Hydrology, University of KwaZulu-Natal, Pietermaritzburg, South Africa

[4] CSIRO Land and Water, Canberra, Australia

* Corresponding author, e-mail: fessehazionm@arc.agric.za

Poor irrigation management in pastures can lead to yield and quality reduction as well as loss of income through extra pumping and leaching of nitrate fertiliser. A number of irrigation scheduling techniques of varying levels of sophistication have been developed over the years to address limited irrigation water availability and maximise productivity. Despite this, the adoption of irrigation scheduling tools by farmers remains low. The objective of this study was to assess the use of simple irrigation scheduling calendars based on average weather data to improve irrigation management in ryegrass. The calibrated Soil Water Balance (SWB) model was used to generate simple irrigation calendars and assess effectiveness for different scenarios by mechanistically simulating water dynamics and pasture growth. Scheduling irrigation using the calendars gave similar irrigation applications, water losses and yields compared to a more scientific real-time scheduling (in response to soil water depletion by the crop). While site-specific irrigation scheduling calendars can easily be generated by consultants and irrigators, even simpler monthly estimates of average daily water use can also be useful. Application of calendars by farmers is encouraged

Key words: Site specific irrigation calendar, Soil Water Balance (SWB) model, planted pastures, water requirement

1 INTRODUCTION

South Africa has an average annual rainfall of 497 mm, which is far below the world annual average of 850 mm, with two-thirds of the country receiving less than 500 mm (Backeberg et al. 1996). The uneven distribution of rainfall is significant in limiting natural range production potential throughout the year. As a result, natural range alone is not enough to support livestock production, but must be supplemented with planted pastures to meet the rising demand for food (meat and milk) as human populations increase (Aucamp 2000). Planted pastures play an important role in livestock production by providing roughage throughout the year, improving fodder flow, the carrying capacity of the farm and the performance of individual animals when the quantity and/or quality produced by natural veld is inadequate (Botha et al. 2008; Neal et al. 2011).

In South Africa out of the total 1.2 million ha land under irrigation, only 300 000 ha is planted to pastures (Backeberg et al. 1996). As with many other regions around the world, limited availability of irrigation water limits the production of pasture biomass. This has resulted in a shift of milk-producing enterprises from the central part of the country to the high rainfall areas of the KwaZulu-Natal midlands and the Cape coastal regions (Dickinson et al. 2004). In these regions, however, irrigation water scarcity is still considered to be one of the main limiting resources for pasture production (Gertenbach 2006), motivating farmers to schedule irrigation in order to optimise production.

Annual ryegrass (Lolium multiflorum) is one of the most widely grown irrigated winter pastures (Dickinson et al. 2004). 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). This crop 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). It is a high water user, however, and its performance is suboptimal under drought or adverse environmental and/or management conditions (Theron and Snyman 2004). For example, in South Africa, the current farmersô irrigation scheduling recommendation for most temperate grasses, including ryegrass, is 25 mm of irrigation water per week minus cumulative rainfall over the previous week (Macdonald 2006). This was calculated from class A pan evaporation, which is typically 3ï 4 mm dī 1 in the winter (Steynberg et al. 1993; Tainton 2000). Evapotranspiration (ET) demand can differ between locations and seasons as a result of varying weather and growing conditions, and is also closely related to the extent of crop canopy. Therefore, there is a need to mechanistically simulate water dynamics and pasture growth in order to develop irrigation guidelines for representative pasture-growing regions (WRC 2006).

More accurate irrigation scheduling that includes innovative irrigation management strategies, such as leaving room for rain in the wet season, can lead to increased profits as a result of saved water and electricity costs. This is also beneficial to the environment, as nutrient export via runoff and deep drainage losses is potentially reduced (Tamminga 1992). In the last five decades, several irrigation scheduling techniques of varying levels of sophistication, based on soil, plant and atmospheric measurements, have been recommended to improve water use efficiency and maximise yield (Stevens et al. 2005). For example, various computer models, which integrate soil, plant and atmospheric approaches by estimating soil water balance components, have been developed for improving irrigation scheduling (Hillel 1990; Annandale et al. 2011). The Soil Water Balance (SWB) model (Annandale et al. 1999), a real-time, generic crop growth, soil water balance and irrigation scheduling model, is one of these. The model was calibrated and validated for different pastures under a range of management conditions (Annandale et al. 1999; Beletse et al. 2008; Fessehazion et al. 2012).

Site-specific calendar-based irrigation scheduling, accounting for local weather conditions and soil characteristics, could provide irrigators with an inexpensive yet reliable strategy to estimate irrigation timing and amount, especially when farmers are not using other tools, such as soil water sensors. Even simpler monthly calendars, which provide information on site-specific daily crop water use, may help farmers in their irrigation management. Recommended irrigation applications can be modified by deducting measured rainfall since the last irrigation event.

The objectives of the study were (1) to evaluate the performance of the SWB model to simulate annual ryegrass water use and growth, (2) to generate site-specific calendars and alternative monthly daily water use calendars, which can easily be used by pasture farmers and (3) to test the effectiveness of these calendars compared to standard irrigation scheduling (refilling to field capacity when a predetermined soil water deficit is reached without stressing the pasture) in two major ryegrass growing regions of South Africa, as an example.

2 MATERIALS AND METHODS

2.1 Model description

SWB is a mechanistic, real-time, generic, crop growth, soil water balance and irrigation scheduling model, which has a user friendly interface (Annandale et al. 1999, Singles et al. 2010). It is based on the NEWSWB model of Campbell and Diaz (1988). SWB calculates reference daily evapotranspiration (ETo) according to FAO 56 recommendations (Allen et al. 1998). For limited weather data, the model calculates ETo from minimum and maximum temperatures according to Annandale et al. (2002). Water movement in the soil profile is simulated using either a cascading or finite difference approach. The model simulates dry matter production by calculating a daily dry matter increment as being either radiation or water limited. Phenological development, growth and yield of a crop from emergence to maturity are estimated based on soil water availability and environmental conditions. Water-limited growth is calculated using parameters that directly limit biomass accumulation including a crop stress index (Annandale et al. 2000). In addition, the model enables an accurate description of deficit irrigation strategies, where water use is supply limited (Olivier and Annandale 1998). To adapt the model for irrigated pastures, three commonly used cutting options were included, based on accumulated biomass, accumulated thermal time (growing degree days) or variable timing (user defined dates). A detailed description is available in Annandale et al. (1999) and Fessehazion (2011).

2.2 Site description and crop management

Data collected from a rainout shelter in the 2007 and 2008 growing seasons and an open field during the 2008 growing season were used to validate the model. The rainout shelter experiment was conducted at the Hatfield Experimental Farm (25°45ôS; 28°16ôE 1327 masl) of the University of Pretoria, South Africa. The open field experiment was conducted at the Cedara Experimental Farm (29°32ôS; 30°17ôE; 1076 masl) of the Department of Agriculture in the KwaZulu-Natal Midlands, South Africa. The soil at Hatfield is a sandy loam while that of Cedara is a deep, red, kaolinitic Hutton soil with a heavy clay loam texture to a depth of 0.4 m, and heavier clay soil from 0.4 to 1.0 m (Soil Classification Working Group 1991). A dense-grid dripper line system was used for irrigation at Hatfield, and dragline sprinklers were used at Cedara. At both sites, annual ryegrass cultivar óAgritonô was planted in rows at a seeding rate of 30 kg ha^{-1} and spacing of 0.15 m between rows. At planting, 20 kg P ha^{-1} was applied, and thereafter, 60 kg N ha^{-1} and 25 kg K ha^{-1} was applied for each growth cycle.

2.3 Treatments

Hatfield

Plots had an area of 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. In both years, plots were irrigated twice a week (**W1**) or once every two weeks (**W2**) to field capacity. Treatments were replicated three times and were assigned in a randomised complete block design.

Cedara

Well-watered treatment plots were irrigated weekly to field capacity during autumn, spring and summer, and once every two weeks in winter (**W1**). Water stressed plots were irrigated only at the start of growth cycles when N fertiliser was applied (**W2**). ET was also measured for three growth cycles using an energy balance approach in a large field (120 m x 50 m) of well-watered ryegrass to allow for adequate fetch.

2.4 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 recorded using automated weather stations. Soil water content to a depth of 1.0 m was measured using a neutron water meter model 503 DR CPN Hydroprobe (Campbell Pacific Nuclear, USA) at Hatfield and Diviner-2000 probe (Sentek®, Australia) at Cedara. Root zone soil water deficit calculations for irrigation scheduling was made to a 0.60 m soil depth as 90% of ryegrassô active root system is within this depth (Fessehazion et al. 2012). For forage yield determination, grass was harvested every 28 days at Hatfield and at the 2 to 3 leaf stage at Cedara from an area of 1 m^2 using a manual grass mower to a 50 mm stubble height above the soil surface. Forage dry matter was determined by oven drying samples at 70°C to constant mass.

At Cedara, evapotranspiration (ET) was estimated using energy balance method. The surface renewal (SR) technique was used to obtain the sensible heat flux (H) and measurements of SR (Paw U et al. 2005) were conducted over three ryegrass growth cycles (11th September to 6th November 2008). Measurements using an eddy covariance (EC) system were also conducted from 2nd October to 6th November 2008. The primary use of the EC measurements was for calibrating the surface renewal system (Paw U et al. 2005). Wind velocity and air temperature were measured 1 m above the ground using a three dimensional sonic anemometer (model 81000, RM Young, Michigan, USA). Sampling frequency of the three components of wind velocity, and sonic temperature (*T)* was 10 Hz. 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 EC and SR measurements were used to estimate sensible heat flux. The NR-LITE net radiometer (Kipp and 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. Latent heat flux (λT) or ET was obtained as the residual of the shortened energy balance equation (Savage et al. 2010).

2.5 Model parameterisation and reliability test

Ryegrass model input parameters were obtained from literature (Beletse et al. 2008, Fessehazion 2011). A forage yield of 0.75 t ha^{-1} and LAI of 0.5 m^2 m^{-2} were used for initialising the crop after each harvest. 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).

2.6 Model application

Once the model was successfully tested, it was used to estimate ryegrass water requirements, develop irrigation calendars and determine crop response to different irrigation scheduling practices for two sites representative of the major milk producing areas in South Africa (KwaZulu-Natal, Cedara and Western Cape, George). Water requirements and irrigation calendars were developed by excluding rain so that irrigators can account for actual rainfall by adjusting irrigation application rates.

The simulated crop was irrigated with a sprinkler irrigation system and the initial soil water content at planting for all soil layers was set to field capacity. This is justified by the high rainfall received during March (Table 1). Planting dates for this crop in South Africa falls between mid-February and mid-April, and the pasture grows until mid-October to mid-December each year. Long-term simulations were run for 50 years from March to November each year (eight harvests), with a fallow period between seasons. The first harvest was simulated 60 days after planting, followed by harvests at four week intervals in autumn and winter and three weeks in spring and early summer.

[Table 1]

2.6.1 Generation of irrigation calendars

Site-specific calendars

Site-specific calendars were developed using the daily average of the long-term weather data and local soil characteristics. Calendars were developed for sand, loam and clay textured soils representing low, medium and high water holding capacities. A soil depth of 0.40 m was selected because pastures are usually planted on relatively marginal, shallow soils, which are not suitable for most agronomic crops. For the calendar-generating simulation, the pasture was irrigated when 50% of the plant available water was depleted, which was equivalent to 17 mm for the sand, 26 mm for loam and 33 mm for clay soils.

Monthly irrigation calendar (daily water requirement for each month)

Site-specific calendars generated using the model have date and amount of irrigation as output. However, for farmers who usually move their sprinkler irrigation system from paddock to paddock, it will not always be practical to stick to a single site specific calendar for all paddocks. To cater for this, a monthly irrigation calendar was developed from simulated long-term estimates of water requirements of annual ryegrass. This calendar gives the daily water requirement of ryegrass for each month and farmers can simply multiply the water requirement by the number of days since the last irrigation. For example, if the daily water requirement of ryegrass is 2.5 mm in June for an application rate of 25 mm, then the irrigation interval will be 10 days (25 mm / 2.5 mm d^{-1}). If there is rainfall before the next planned irrigation the amount of rainfall can be subtracted to keep the same interval or the next irrigation can be delayed. For example, if rainfall is 10 mm, either the irrigation could be reduced to 15 mm (25 mm - 10 mm) or the next irrigation can be extended by 4 days (10 mm rain /2.5 mm d^{-1} water use).

2.6.2 Testing irrigation calendars

Once the calendars are developed using a long-term average weather data, they need to be tested using real weather data of individual years for medium texture (loam) soils. Therefore, the ability of calendars to accurately inform irrigation scheduling was tested using simulations with historical daily weather data (1950-1999). More scientific real time scheduling, irrigating in response to soil water depletion by the crop, was compared to calendar-based irrigation scheduling strategies. Three irrigation management scenarios described below were tested.

1. Scientific practice **(Standard)** i.e. refill to field capacity when 50% of the plant available water was depleted.

2. Site-specific calendar **(Site-specific calendar)** developed using the SWB model based on average weather data.

3. Simple monthly calendar **(Monthly calendar)** with fixed 25 mm application amount, which is same as the commonly used farmersô irrigation guideline of 25 mm per irrigation, but with a variable irrigation interval according mean daily water requirement for a specific month.

The generated site-specific (2) and monthly calendars (3) developed using long-term average weather data were re-run for all years using real time weather data (1950-1999) by subtracting the rainfall from the irrigation requirements between irrigations. Rainfall events of 3 mm or less (between two irrigations) were not considered to contribute to crop water availability and were therefore ignored (Macdonald 2006).

3 RESULTS AND DISCUSSION

3.1 Model evaluation

Simulations generally agreed well with measured data for all variables tested (Figure 1a). All statistical parameters imply validation of the model was satisfactory (Table 2). Agreement between measured and simulated forage yield was better for seasonal cumulative forage production, rather than for individual growth cycles. Forage yield in the last growth cycle was overestimated for all sites and treatments. This was likely due to a reduced number of vegetative tillers at the start of flowering and seed formation towards the end of the growing season (Marais et al. 2003).

[Table 2]

[Figure 1]

Soil water deficit from field capacity simulations were less accurate (r^2: 0.63-0.91; D: 0.67- 0.82; MAE: 15.9-29.5%) compared to other simulated variables (Table 2), but were still within reasonable agreement between measured and simulated values. The lower accuracy is typical for this variable (Todorovic et al. 2009, Annandale et al. 2000), and could be due to soil variability and soil water sensor inaccuracies. Considering the simple cascading soil water balance approach used in the model, it can be concluded that the model simulated soil water content satisfactorily (Figure 1b).

For the well watered ryegrass during the period when ET was measured using the energy balance method (three growth cycles) cumulative measured ET was 161 mm whilst the simulated ET was 152 mm. Simulated daily ET rates of well-watered pasture were similar to measured values (Figure 1c). The model systematically predicted higher ET compared to measured values when ET was less than 1 mm day^{-1}, on cloudy and rainy days. However, overall the model predicted ET well with an r^2 of 0.69, a D value of 0.91 and an MAE 25.8 (Figure 1c).

3.2 Generated irrigation calendars

Site-specific calendars

Site-specific irrigation calendars developed for two major milk producing regions of South Africa (KwaZulu-Natal Midlands-Cedara and Western Cape-George) for two different soil textures are presented in Table 3.

[Table 3]

Monthly calendars

Generated monthly irrigation calendars are presented in Figure 2. Daily mean water requirements of ryegrass for each month for the active ryegrass growing season ranged from 1.8 mm in June (mid-winter) to 4.5 in November (early summer). These monthly calendars are general (because they are the same for all soil textural classes and only weather is considered), but simple, and can be used in the absence of site specific irrigation calendars.

[Figure 2]

For example, in both regions considered, using the monthly irrigation calendar reduced irrigation interval in winter and increased it in summer compared to the current farmersô irrigation of 25 mm every week (Table 4). For an irrigation application rate of 25 mm, irrigation intervals were increased to 12-14 days in winter and reduced to 5-6 days in summer. For the current commonly used irrigation guideline, however, a fixed amount of 25 mm per week would apply (Macdonald 2006). Therefore, a rigid guideline of 25 mm per week would definitely lead to over- or under-irrigation.

[Table 3]

For site-specific and monthly irrigation calendars, it is important to remember that irrigation applications need to be frequent to ensure seedling emergence and vigorous stand establishment. Generally, 5-8 mm of irrigation every 2-3 days during seedling emergence and 10-12 mm every 3-4 days during early establishment is sufficient.

3.3 Testing generated calendars

Variations in simulated irrigation requirements and unwanted water losses due to deep drainage losses resulting from different irrigation strategies at the two sites are presented in Figure 3. Since there was no water stress all irrigation strategies produced the same virtual mean yield of 14.4 t ha^{-1} for Cedara and 16.7 t ha^{-1} for George over the year the model was re-run using scientific real time irrigation strategy (refilling to field capacity when a predetermined soil water deficit is reached without stressing the pasture), irrigation sites specific or monthly calendars. Higher irrigation requirements were simulated for Cedara compared to George (Figure 3), unwanted water loss was, however, similar in both regions.

Irrigation requirements were similar when irrigation scheduling was conducted using site specific irrigation calendars and standard irrigation to field capacity strategies (Figure 3). Irrigation applications using monthly calendars were, however, higher by 10-20% and 15-26% when compared to the standard irrigation and site specific irrigation calendars respectively. In spite of higher irrigation applications the monthly calendars can allow farmers to adjust their irrigation interval and amount at their own convenience to match their grazing management strategies according to mean daily water requirement of each month given in Figure 3. The monthly calendars can also benefit farmers with limited irrigation system, who usually move their irrigation system from paddock to paddock.

Generally, the lowest unwanted losses due to drainage were observed when the standard irrigation to field capacity strategy was followed and were similar to the calendar-based irrigation scheduling used in this study as examples. These water losses which resulted from excessive irrigation application would certainly be accompanied by leaching of nutrients and also may lead to yield reduction and deterioration of water quality. Considering the forecast for 2010 (Whitehead and Archer 2009), for ryegrass production in South Africa, 25% of production cost was allocated to irrigation, and 55% to fertilization. Therefore, using calendar-based irrigation scheduling strategies could have a big impact in saving pumping costs and minimising leaching of nutrients and chemicals. Using the cost savings made from reduced fertilisers, water and energy, a farmer could expand his pastures depending on the availability of land and improve his profits.

4 CONCLUSIONS

The SWB model was successfully used for predicting water requirement and generating and testing irrigation calendars using annual ryegrass as an example. If available, accurate soil water measurements that represent the whole field are preferable to a model predicted soil water balance. In the absence of such measuring devices, farmers or consultants can generate site-specific calendars (soil and weather, irrigation system and management specific) using models such as SWB. In addition to site-specific calendars, monthly irrigation calendars can also be used. These calendars can also be used in conjunction with other simple irrigation scheduling tools in a way that can be more beneficial than using the calendars alone (Stirzaker 2003).

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 SWB) may be more applicable. The minimum inputs required for developing site specific calendars are: 1) weather data including location of the farm and long-term weather data including minimum and maximum temperature of nearest weather station; 2) soil depth and textural class (i.e. sand, loam, clay) and 3) irrigation management including irrigation system, timing and refill options. A range of irrigation systems can be selected including flood, sprinkler and pivot. 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 using 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 and c) farmers may 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 are to field capacity, a deficit, a strategy leaving some room for rain or to apply leaching fractions. Therefore, irrigators can follow different irrigation management strategies for generating calendars. Adoption of a more objective irrigation scheduling by farmers, such as the one recommended in this paper, will result in increased profitability to farmers while reducing environmental impact. The model is available on the web (www.up.ac.za/upwi/swb; click on ósoftwareô) and can be downloaded free of charge.

Acknowledgements

We gratefully acknowledge the Water Research Commission for initiating, funding and managing the Project 1650 óGuidelines for irrigation management in pasture productionô from which this paper was emanated. Dr Michael Mengistu for his assistance during micro-met evapotranspiration measurement.

REFERENCES

Allen RG, Pereira LS, Raes D, Smith M. 1998. Crop evapotranspiration. Guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper No. 56. Rome: FAO.

Annandale JG, Benade N, Jovanovic NZ, Steyn JM, Du Sautoy N. 1999. Facilitating irrigation scheduling by means of the soil water balance model. WRC Report No. 753/1/99. Pretoria: Water Research Commission.

Annandale JG, Campbell GS, Olivier FC, Jovanovic NZ. 2000. Predicting crop water uptake under full and deficit irrigation. An example using pea (*Pisum sativum* cv. Puget). *Irrigation Science* 19: 65-72.

Annandale JG, Jovanovic NZ, Benade N, Allen RG. 2002. Software for missing data error analysis of Penman-Monteith reference evapotranspiration. *Irrigation Science* 21:57-67.

Annandale JG, Stirzaker RJ, Singels A, Van Der Laan M, Laker MC. 2011. Irrigation scheduling research: South African experiences and future prospects. *Water SA* 37: 751-763.

Aucamp AJ. 2000. The place and role of cultivated pastures in South Africa. In: Tainton N (ed), *Pasture Management in South Africa*. Pietermaritzburg: University of Natal Press.

Backeberg GR, Bembridge TJ, Bennie ATP, Groenewald JA, Hammes PS, Pullen RA, Thompson H. 1996. Policy proposal for irrigated agriculture in South Africa, WRC Report no KV96/96. Pretoria: Water Research Commission.

Beletse YG, Annandale JG, Steyn JM, Hall I, Aken ME. 2008. Can crops be irrigated with sodium bicarbonate rich CBM deep aquifer water? Theoretical and field evaluation. *Journal of Ecological Engineering* 33: 26-36.

Botha PR, Meeske R, Snyman HA. 2008. Kikuyu over-sown with ryegrass and clover: dry matter production, botanical composition, nutritional value. *African Journal of Range and Forage Science* 25:93-101.

Campbell GS, Diaz R. 1988. Simplified soil water balance models to predict crop transpiration. In: Bidinger FR, Johansen C (eds). *Drought Research Priorities for the Dryland Tropics*. India: ICRISAT. pp 15-26.

De Jager GM. 1994. Accuracy of vegetation evaporation ratio formulae for estimating final wheat yield. *Water SA* 20: 307-315.

Dickinson EB, Hyam GFS, Breytenbach WAS, Metcalf WD, Bassoon WD, Williams FR, Scheepers LJ, Plint AP, Smith HRH, Smith PJ, Van Vuuren PJ, Viljoen JH, Archibald KP, Els JN. 2004. Pasture Handbook. Maanhaarrand: Kejafa Knowledge Works.

Eckard RJ, Bartholomew PEB, Tainton NM. 1995. The yield response of annual ryegrass *Lolium multiflorum* to varying nitrogen fertiliser application strategies. *South African Journal of Plant and Soil* 13: 112-116.

Fessehazion MK. 2011. Using adaptive management and modelling to improve nitrogen and water use efficiency in crop production: A case study using annual ryegrass. University of Pretoria PhD thesis, Pretoria, South Africa.

Fessehazion MK, Stirzaker RJ, Annandale JG, Everson CS. 2011. Improving nitrogen and irrigation water use efficiency through adaptive management: a case study using annual ryegrass. *Agriculture, Ecosystems and Environment* 141: 350-358.

Fessehazion MK, Annandale JG, Everson CS, Abraha AB, Truter WF. 2012. Irrigation guidelines for annual ryegrass pasture. WRC Report no. TT521/12. Pretoria: Water Research Commission.

Gerterbach W. 2006. Dairy farming in South Africa ï where to now?

http://www.fao.org/es/ESC/common/ecg/186/en/18_William_Gertenbach__paper.pdf. [accessed 30 September 2013].

Hillel D. 1990. Role of irrigation in agricultural systems. In: Stewart et al. (eds), *Irrigation of Agricultural Crops*. Madison: American Society of Agronomy.

Macdonald CI. 2006. Irrigation of pastures. Cedara Agricultural Development Institute available online http://agriculture.kzntl.gov.za/portal/AgricPublications/ProductionGuidelines/PasturesinKwaZuluNatal/IrrigationofPastures/tabid/313/Default.aspx [accessed 30 September 2013].

Marais JP, Goodenough DCW, de Figueiredo M, Hopkins C. 2003. The development of a *Lolium multiflorum* cultivar with a low moisture content and an increased readily digestible energy to protein ratio. *Australian Journal of Agricultural Research* 54: 101-106.

Neal JS, Fulkerson WJ, Hacker RB. 2011. Differences in water use efficiency among annual forages used by the dairy industry under optimum and deficit irrigation. *Agricultural Water Management*, 98:759-774.

Olivier FC, Annandale JG. 1998. Thermal time requirements for the development of green pea (*Pisum sativum* L.). *Field Crops Research* 56: 301-307.

Paw U KT, Snyder RL, Spano D, Su HB. 2005. Surface renewal estimates of scalar exchange. In: Hatfield JL, Baker JM (eds), *Micrometeorology in Agricultural Systems*. Agronomy Monograph. No. 47. pp. 455-483.

Savage MJ, Odhiambo GO, Mengistu MG, Everson CS, Jarmain C. 2010. Measurement of grassland evaporation using a surface-layer scintillometer. *Water SA* 36: 1-8.

Singels A, Annandale JG, De Jager JM, Schulze RE, Inman-Banber NG, Durand W, Van Rensburg LD, Van Heerden PS, Crosby CT, Green GC, Steyn JM. 2010. Modelling crop growth and crop water relations in South Africa: Past achievements and lessons for the future. *South African Journal of Plant and Soil* 27: 49-65.

Soil Classification Working Group. 1991. Soil classification. A Taxonomic System for South Africa. Memoirs of Natural Agricultural Resources of South Africa, No 15. Department of Agricultural Development, Pretoria.

Stevens JB, Duvel GH, Steyn GJ, Marobane W. 2005. The range, distribution and implementation of irrigation scheduling models and methods in South Africa. WRC report No. 1137/1/05. Pretoria: Water Research Commission.

Steynberg RE, Nel PC, Rethman NFG. 1993. Waterverbruik en waterverbruiksdoeltreffendheid van gematigde aangeplante weidings onder besproeiing. WRC Report No. 257/1/94.

Stirzaker RJ. 2003. When to turn the water off: scheduling micro-irrigation with a wetting front detector. *Irrigation Science* 22:177ï 185.

Tamminga S. 1992. Nutrition management of dairy cows as a contribution to pollution control. *Journal of Dairy Science*, 75:345-357.

Tainton NM. 2000. Pasture Management in South Africa, University of Natal Press, Pietermaritzburg.

Theron JF, Snyman HA. 2004. The influence of nitrogen and defoliation on digestibility and fibre content of *Lolium multiflorum* cv. Midmar. *African Journal of Range and Forage Science* 21: 21-27.

Todorovic M, Albrizio R, Zivotic L, Abisaab MT, Stöckle C, Steduto P. 2009. Assessment of AquaCrop, CropSyst, and WOFOST models in the simulation of sunflower growth under different water regimes. *Agronomy Journal* 101:508-521.

Water Research Commission. 2006. Guidelines for irrigation management in pasture production. Knowledge Report.

Whitehead ENC, & Archer CG. 2009. COMBUD pasture and livestock budgets 2009/2010. KwaZulu Natal Department of agriculture, Environment and rural Development, Cedara.

Willmott CJ. 1982. Some comments on the evaluation of model performance. *Bulletin of the American Meteorological Society* 64: 1309-1313.

Table 1 Long-term (1950-2000) monthly mean minimum (T_{min}) and maximum (T_{max}) temperature, vapour pressure deficit (VPD), total precipitation and reference evapotranspiration (ETo) for two major annual ryegrass growing areas of South Africa

Year	Parameter	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.
Cedara	T_{min} (°C)	13.8	10.4	6.3	2.9	3.1	5.3	8.7	10.6	12.5
	T_{max} (°C)	24.6	22.9	21.0	19.0	19.5	20.7	22.4	22.4	23.4
	VPD (kPa)	1.48	1.58	1.50	1.44	1.48	1.50	1.54	1.44	1.41
	Rain (mm)	105	50	26	12	15	29	50	90	105
	ETo (mm)	106	87	75	65	70	84	98	113	120
George	T_{min} (°C)	13.9	11.3	9.2	8.0	6.9	7.0	8.3	9.8	11.8
	T_{max} (°C)	23.7	21.6	20.4	19.3	18.6	18.4	19.1	20.0	21.6
	VPD (kPa)	1.36	1.29	1.24	1.19	1.14	1.13	1.10	1.16	1.22
	Rain (mm)	81	72	58	44	42	74	62	71	61
	ETo (mm)	101	77	61	51	55	67	80	103	116

Table 2 Statistical evaluation between observed and predicted values of forage yield (per growth cycle and cumulative) and soil water deficit during model evaluation

Site	Water treatment	Growth cycle yield			Cumulative yield			Soil water deficit to field capacity		
		r^2	D	MAE (%)	r^2	D	MAE (%)	r^2	D	MAE (%)
Cedara 2008	W1[β]	0.88	0.97	8.9	0.99	0.99	3.8	0.82	0.96	16.3
	W2	0.92	0.97	9.7	0.98	0.99	2.7	0.52	0.83	14.2
Hatfield 2007	W1	0.95	0.97	9.0	0.99	0.99	4.9	0.91	0.82	29.5
	W2	0.88	0.96	12.1	0.97	0.98	12.2	0.77	0.73	15.9
Hatfield 2008	W1	0.98	0.98	8.1	0.99	0.98	7.0	0.74	0.70	25.3
	W2	0.86	0.85	11.6	0.95	0.97	11.3	0.63	0.67	20.1

[β] Well-watered treatment used for calibration. W1: well watered treatment; W2: water stressed treatment: r^2: coefficient of determination; D: Willmottôs index of agreement; MAE: mean absolute error

Table 3 Simulated site-specific irrigation calendars of ryegrass for sand, loam and clay soils for the summer (Cedara) and winter (George) rainfall areas of South Africa

Cedara						**George**					
Sand		**Loam**		**Clay**		**Sand**		**Loam**		**Clay**	
Date	mm	Date	mm	Date	mm	Date	mm	Date	mm	Date	mm
23-Mar	11	23-Mar	18	23-Mar	16	22-Mar	11	22-Mar	18	22-Mar	18
29-Mar	10	30-Mar	16	05-Apr	31	29-Mar	12	28-Mar	16	01-Apr	26
04-Apr	15	07-Apr	28	16-Apr	35	05-Apr	18	04-Apr	24	12-Apr	34
10-Apr	19	16-Apr	29	26-Apr	36	12-Apr	19	13-Apr	28	24-Apr	36
16-Apr	20	24-Apr	29	11-May	35	18-Apr	18	22-Apr	28	09-May	34
22-Apr	21	03-May	28	24-May	35	25-Apr	21	02-May	29	25-May	36
28-Apr	21	17-May	29	10-Jun	35	02-May	20	18-May	29	15-Jun	34
06-May	18	27-May	29	26-Jun	36	13-May	18	30-May	28	04-Jul	34
15-May	20	11-Jun	28	16-Jul	35	22-May	20	18-Jun	27	25-Jul	34
22-May	21	24-Jun	29	29-Jul	34	30-May	19	03-Jul	27	13-Aug	34
29-May	20	09-Jul	28	15-Aug	36	13-Jun	19	22-Jul	28	27-Aug	36
09-Jun	19	22-Jul	28	26-Aug	37	23-Jun	18	04-Aug	27	11-Sep	34
18-Jun	19	01-Aug	28	07-Sep	35	03-Jul	18	19-Aug	28	22-Sep	36
26-Jun	20	15-Aug	28	18-Sep	37	17-Jul	19	29-Aug	27	06-Oct	37
05-Jul	18	24-Aug	29	29-Sep	34	26-Jul	19	11-Sep	28	15-Oct	36
16-Jul	19	01-Sep	29	09-Oct	37	04-Aug	18	20-Sep	29	27-Oct	35
24-Jul	21	13-Sep	29	17-Oct	35	15-Aug	19	01-Oct	28	04-Nov	34
31-Jul	20	20-Sep	28	28-Oct	36	23-Aug	20	09-Oct	30		
10-Aug	18	30-Sep	28	04-Nov	34	30-Aug	20	16-Oct	27		
17-Aug	19	08-Oct	30			09-Sep	19	26-Oct	28		
23-Aug	20	15-Oct	31			16-Sep	20	02-Nov	30		
29-Aug	22	25-Oct	29			22-Sep	22				
05-Sep	19	31-Oct	28			01-Oct	20				
12-Sep	20					07-Oct	21				
17-Sep	19					12-Oct	20				
22-Sep	21					17-Oct	19				
30-Sep	20					24-Oct	18				
05-Oct	19					29-Oct	20				
10-Oct	21					03-Nov	22				
15-Oct	22										
22-Oct	19										
27-Oct	20										
31-Oct	19										
04-Nov	19										
26-Oct	20										
30-Oct	19										
03-Nov	19										
Total	**713**		**696**		**679**		**587**		**594**		**598**

Table 4 Simulated daily water use and an example of monthly calendars (fixed irrigation amount of 25 mm application with variable irrigation interval for each month) generated from daily water use of ryegrass for the summer (Cedara) and winter (George) rainfall areas of South Africa

Month	**Cedara**		**George**	
	Daily water requirement (mm)	Irrigation interval (days)	Daily water requirement (mm)	Irrigation interval (days)
Mar.	3.6	-	3.2	-
Apr.	3.2	8	2.9	9
May	2.8	9	2.2	11
Jun.	2.4	11	1.8	14
Jul.	2.5	10	1.9	13
Aug.	3.1	8	2.3	11
Sep.	3.6	7	2.8	*9*
Oct.	4.2	6	3.8	7
Nov.	4.6	5	4.3	6

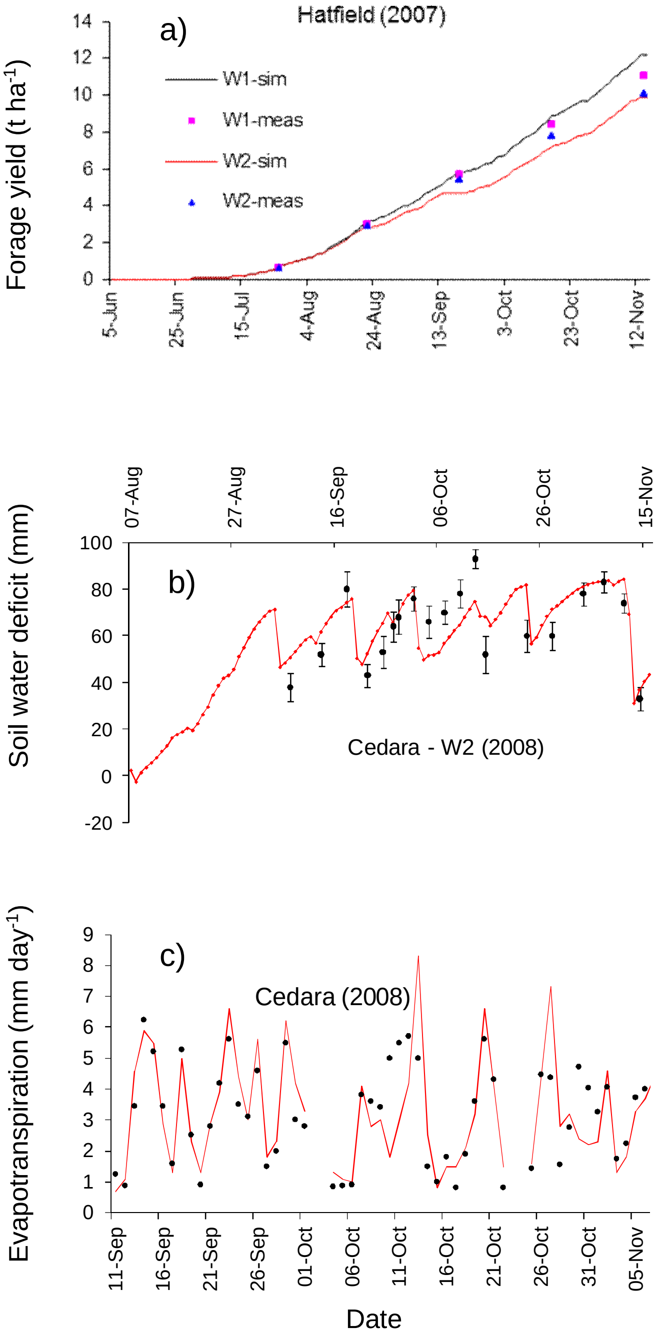

Figure 1 Simulated (solid lines) and measured (symbols) a) cumulative forage yield b) soil water content deficit to field capacity and c) evapotranspiration for well watered (W1) and water stressed (W2) ryegrass

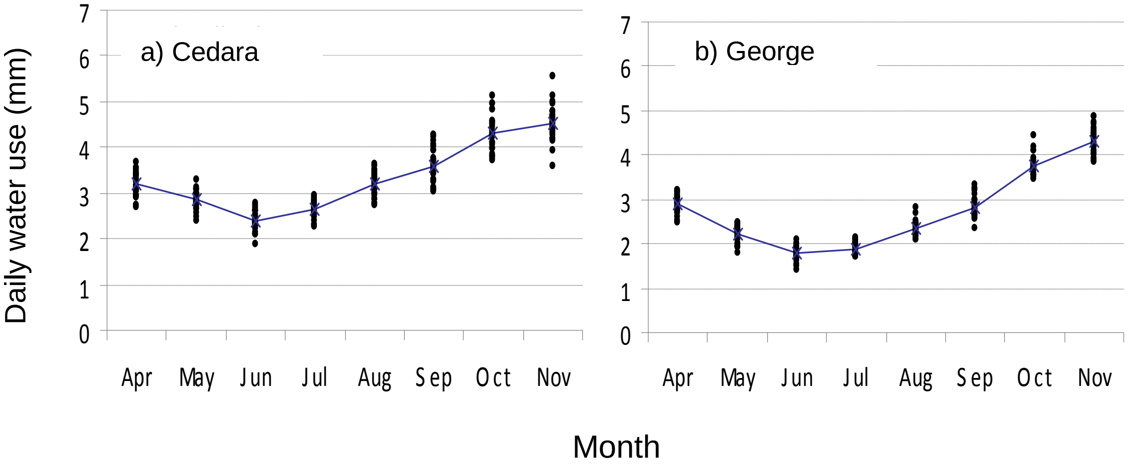

Figure 2 Simulated mean long-term daily water use of ryegrass a) Cedara (KwaZulu Natal Midlands) and b) George (Western Cape) of two major ryegrass producing areas of South Africa (points show water use of individual seasons and the line shows long-term average water use)

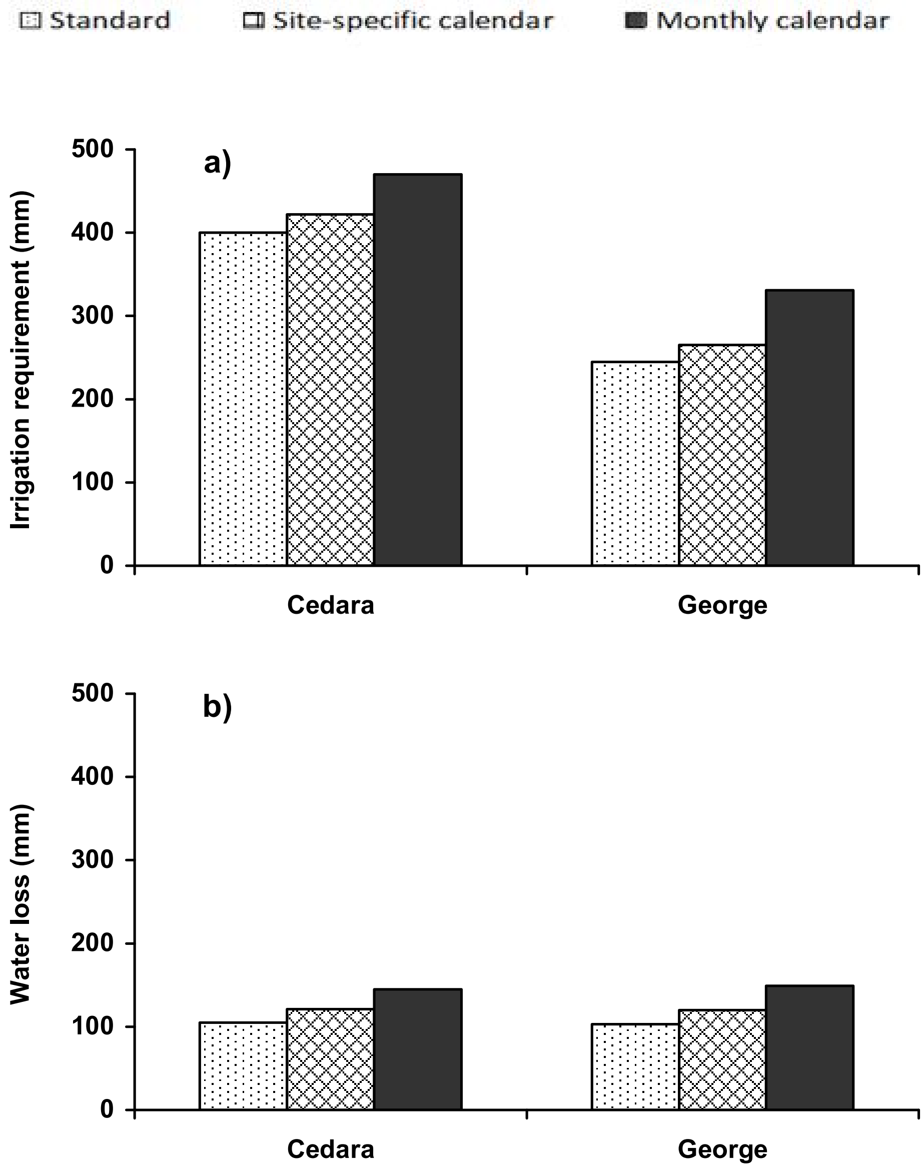

Figure 3 Simulated ryegrass seasonal mean irrigation water requirement and unwanted water losses for medium textured loam soil for a) Cedara and b) George