CHAPTER 6

EXPLORING POTENTIAL IRRIGATION MANAGEMENT STRATEGIES FOR ANNUAL RYEGRASS USING THE SWB-SCI MODEL

6.1 INTRODUCTION

Cultivated pastures play an important role in livestock production by providing roughage throughout the year, improving fodder flow, carrying capacity of the farm and performance of individual animals. Input costs in the pasture based systems are much lower than with a total mixed ration system (Gertenbach, 2006). However, availability of irrigation water for producing pastures may limit the pasture based system. Hence, there has been a movement of milk producing enterprises from the central part of the country to the high rainfall areas of the KwaZulu-Natal Midlands, and the Southern, Eastern and Western Cape Coasts (Dickinson *et al.*, 2004). In these regions, however, there are still limitations to pasture based systems due to irrigation water availability (Gertenbach, 2006).

Annual ryegrass (*Lolium multiflorum*) pasture is one of the most widely utilised irrigated pastures in South Africa and is noted for its ability to provide winter grazing in the intensive dairy industry (Dickinson *et al.*, 2004). It is a high yielding pasture and possesses a high nutrient content under favourable environmental growing conditions (Theron *et al.*, 2002; Theron and Snyman, 2004). Its production requires intensive management of N fertiliser and irrigation to ensure maximum yield and optimum quality. However, irrigation water scarcity and increasing N fertiliser prices, concerns on excessive forage crude protein concentrations and environmental pollution necessitates prudent N and irrigation management in pasture production.

Most experiments conducted using annual ryegrass were to maximise forage yield per unit area by focusing on mainly N application with little consideration for irrigation water and environmental risk (Eckard *et al.,* 1995). Generally, for temperate grasses, including annual ryegrass, 25 mm of irrigation water per week is a common practice (Jones, 2006; Macdonald, 2006). However, evaporative demand differs between locations and over time for a specific location and crop requirements also change as crop canopy cover varies. Hence, the current irrigation practice of 25 mm per week may cause: a) forage yield and quality imbalances between harvests (Eckard, 1990; Eckard *et al.,* 1995), b) reduced water use efficiency by increasing unproductive water losses due to surface runoff and deep drainage (Chapter 4) and c) detrimental effects on soil and water resources due to nutrient leaching (Pervanchon *et al.,* 2005; Monaghan *et al.,* 2007). Overall, this will reduce profitability of the enterprise.

In the last few decades, several mathematical computer models have been developed to better understand nutrient and water dynamics of cropping systems. Models can supplement experimental data where long-term experiments are limited or not possible. Moreover, other alternative strategies can be explored under different conditions including soils, regions and irrigation and N management strategies. The scientific version of the Soil Water Balance (SWB-Sci) model, a locally developed mechanistic, crop growth, soil water and N balance irrigation-scheduling model, was calibrated and tested successfully for a range of irrigation regimes and N application rates of annual ryegrass at different sites (Chapter 5). This model can therefore be used with confidence to extrapolate irrigation and N requirements of annual ryegrass to other areas. It can also be used to improve N and irrigation water use efficiencies by assessing potential irrigation and fertilisation management strategies.

The objectives of this chapter are therefore, to test the hypotheses that an irrigation scheduling tool can 1) improve forage yield, 2) improve water use efficiency by decreasing unproductive water losses and 3) minimise nitrate leaching.

Hence, a range of irrigation management strategies including calendar based irrigation scheduling developed with the simple SWB-Pro model, deficit irrigation and “room for rain” were evaluated using the SWB-Sci model for major annual ryegrass growing areas of South Africa.

6.2 MATERIALS AND METHODS

6.2.1 Model description

SWB-Sci is a locally developed mechanistic crop growth, soil water and N balance, irrigation-scheduling model. Details of the sub-models of SWB-Sci are presented elsewhere (Annandale *et al.,* 1999, Annandale *et al*., 2004; Tesfamariam, 2009; Van der Laan, 2009).

6.2.2 Model modification

To adopt the model for long-term simulation, three commonly used defoliation practices were included into SWB-Sci. These are based on accumulated biomass, accumulated thermal time (growing degree days) and variable timing (user defined dates).

6.2.3 Model input parameters

The weather unit of SWB-Sci calculates the Penman-Monteith grass reference daily evapotranspiration (ETo) according to FAO 56 recommendations (Allen *et al.,* 1998). Weather data including daily values of minimum and maximum air temperature and humidity, wind speed, incoming solar radiation and precipitation are used to run the model. For limited data the model can also calculate ET_O from minimum and maximum temperatures according to Annandale *et al.* (2002). Long-term weather data (1950-2000), including precipitation, minimum and maximum temperatures for major crop growing sites of South Africa are available in the SWB-Sci database.

Soil inputs of the model include parameters for runoff curve number, drainage factor, maximum drain rate of the soil profile, root depth limit, standing and surface biomass, cultivation depth and bypass coefficient. In each soil layer, input parameters including soil texture (sand and clay percentage), layer thickness, initial soil water content, water content at field capacity, water content at permanent wilting point, bulk density, soil cation exchange capacity, pH, organic carbon, inorganic N (ammonium and nitrate) and crop residue are required. Soil initial C fractions for N mineralisation transformation inputs can be categorised for the top cultivation layer (0.3 m) and deep sub-soil (below 0.3 m).

Crop input specific parameters representing different crops can be selected from the crop file database. Each crop has a database of crop parameters for phenology (thermal time requirements to reach specific growth stages and photoperiod), morphology (root depth, specific leaf area and other parameters defining canopy and root characteristics), growth (maximum transpiration, extinction coefficient for solar radiation, water use efficiency normalized by VPD, stress response parameters, etc.) and N parameters (defining crop N demand and root uptake).

The model has different N fertilisation application amounts, source (organic or inorganic), type (organic or inorganic) and method (broadcast or incorporated). Users can choose from a range of commercially available organic or inorganic N fertilisers with their respective N concentrations. In ‘tillage management”, users can select the depth and equipment used. The model has a database of different farm tillage equipment with their mixing and incorporation efficiencies from which a user can select. The model requires crop and type of residue (standing or surface) of the previous year, and relevant fractions (fast or slow cycling and lignified) of selected crop residue can be accessed from the database.

6.2.4 Model output parameters

The simulated output parameters from SWB-Sci include irrigation application, forage yield, water use, unproductive water loss (through soil evaporation, deep drainage and runoff), N uptake and N leaching.

6.2.5 Scenario simulation analyses

The model was used to determine how the crop reacts to different irrigation scheduling practices. Hence, to predict long-term pasture growth and yield, soil water balance and N loss (leaching) under different irrigation application strategies were simulated. Six irrigation management scenarios were tested (see Table 6.1 for full description). For the most common irrigation practice, rainfall of 3 mm and less was ignored (Macdonald, 2006). As a result for scenarios (2 and 3) small rainfall events (< 3 mm) were ignored for the site specific and general calendars. The seanrous

Table 6.1 Irrigation management scenarios tested in four major milk producing areas of South Africa

Irrigation strategies	Abbreviation	Detailed description
Field capacity	1. FC100	Common scientific practice - refill to field capacity when the soil water deficit to field capacity in the root zone exceeds 25 mm
Mild deficit irrigation	2. FC80	Irrigate 80% of FC20 (20 mm)
	3. FC60	Irrigate 60% of FC20 (15 mm)
Room for rain	4. RR20	Leaving 20 mm deficit to field capacity after irrigation as a buffer for rain (Pastures were irrigated when 60% plant available water was depleted)
common farmers' practice	5. WK25	The common farmers' practice of 25 mm irrigation per week (WK25) minus rainfall (> 3 mm) received within the week
General monthly calendar	6. Gen-cal	General monthly calendar guideline developed using the simple SWB-Pro model minus rainfall (> 3 mm) received from the last irrigation event
General monthly calendar	7. Site-cal	Site specific calendar developed using the simple SWB-Pro model minus rainfall (> 3 mm) received from the last irrigation event
Zero irrigation	8. I0	No irrigation or only rainfall scenario was included for calculating irrigation use efficiency

Long-term daily weather data (1950-2000) of precipitation, minimum and maximum temperatures for major annual ryegrass growing sites in South Africa were selected from the SWB-Sci weather database. Representative sites in four main annual ryegrass growing regions were selected. These were in the KwaZulu-Natal Midlands (Cedara), Eastern Highveld (Ermelo), Eastern Cape (Queenstown) and Southern Cape (George) (Figure 6.2). Measured long-term mean rainfall, minimum and maximum temperatures and vapour pressure deficit (estimated from temperature) of the sites are presented in Table 6.1.

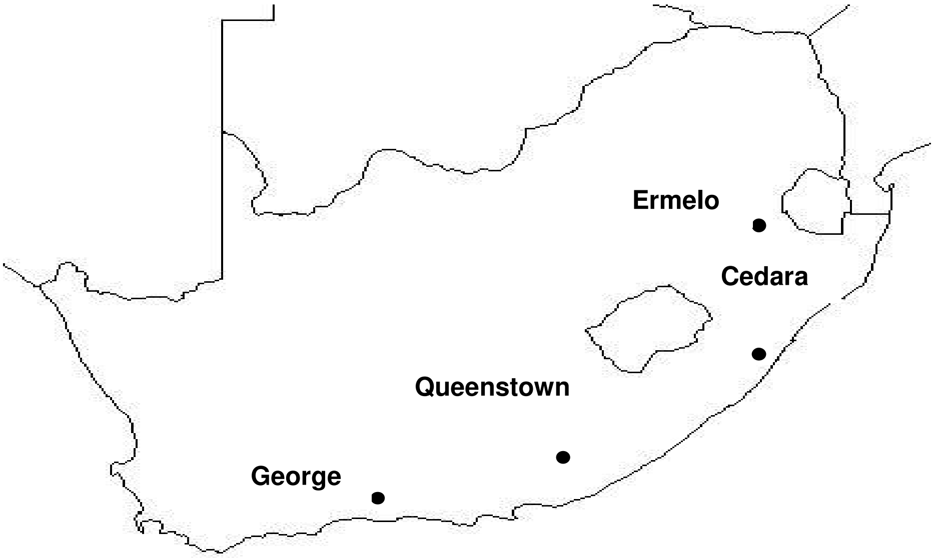

Figure 6.1 Main annual ryegrass growing areas of South Africa used to develop site specific and general irrigation calendars

Soil input parameters from the Cedara site described in Chapter 2 were used for all regions. The profile was a deep, red, kaolinitic Hutton soil with a heavy clay loam texture to a depth of 0.4 m, with a heavier clay texture from 0.4 to 1.0 m. 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 (Table 6.2).

Table 6.2 Long-term (1950-2000) monthly mean minimum (T_{min}) and maximum temperature (T_{max}), vapour pressure deficit (VPD) and total precipitation for the major annual ryegrass growing areas of South Africa

Year	Parameter	Mar.	April	May	June	July	Aug.	Sept.	Oct.	Nov.
Cedara (KwaZulu Natal Midlands)	T_{max} (°C)	24.6	22.9	21.0	19.0	19.5	20.7	22.4	22.4	23.4
	T_{min} (°C)	13.8	10.4	6.3	2.9	3.1	5.3	8.7	10.6	12.5
	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
Ermelo (Eastern Highveld)	T_{max} (°C)	23.6	21.5	19.2	16.5	17.0	19.5	22.7	23.2	23.4
	T_{min} (°C)	11.4	8.1	3.7	0.1	0.1	2.9	6.8	9.5	11.2
	VPD (kPa)	1.54	1.50	1.43	1.28	1.35	1.52	1.80	1.59	1.55
	Rain (mm)	74	43	14	8	8	13	31	91	125
Queenstown (Eastern Cape)	T_{max} (°C)	26.8	22.5	20.2	17.5	18.6	20.9	23.6	24.4	26.8
	T_{min} (°C)	12.9	8.5	5.0	2.4	2.2	4.1	7.6	9.5	12.0
	VPD (kPa)	2.04	1.58	1.49	1.28	1.43	1.68	1.85	1.91	2.12
	Rain (mm)	69	38	20	14	10	18	24	46	57
George (Southern Cape)	T_{max} (°C)	23.7	21.6	20.4	19.3	18.6	18.4	19.1	20.0	21.6
	T_{min} (°C)	13.9	11.3	9.2	8.0	6.9	7.0	8.3	9.8	11.8
	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

Common management and cultivation practices followed by farmers were simulated. Annual ryegrass planting date is between mid-February and mid-April, and the pasture grows until mid-October to mid-December each year. Annual ryegrass seedlings are very sensitive to heat and may die if sown too early during periods of high temperature, while forage yields in the winter may be reduced significantly if planting is too late. Long-term simulations were run for 30 years from 01 March to 06 November (eight harvests), with a fallow period between pastures. 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 and early summer.

Pasture growers usually split the annual recommended N equally into the number of growth cycles (cuts). Generally, a 50 kg N ha^{-1} per growth cycle is the recommend application rate used by farmers. The virtual N application rate used was, therefore, the same as that of the current farmers' guideline of 50 kg N ha^{-1} per cycle (400 kg N per year for eight growth cycles), applied one month after planting for the first harvest and immediately after each cut for the rest of the harvests.

Forage yield, unproductive water losses due to deep drainage plus runoff, and nitrate leaching below the root zone (0.6 m) were simulated. Water use efficiency (WUE) and marginal irrigation use efficiency (MIUE) were calculated according to Rawnsley *et al.* (2009) using:

$$\text{Water use efficiency (WUE)} = \text{Yield/ ET} \qquad (6.1)$$

$$\text{MIUE} = (\text{Yield with irrigation} - \text{Yield without irrigation})/\text{Irrigation} \qquad (6.2)$$

For all regions, simulated and calculated parameters were analysed using the Statistical Analysis System (SAS) program for Windows v9.2 (SAS, 2002) by considering irrigation strategies as treatments and years as replications. Where there was significance, means were separated using the least significant difference at the 5% confidence level.

6.3 RESULTS AND DISCUSSION

6.3.1 Forage yield and water use

In all regions there were significant yield differences among irrigation strategies (Table 6.3). The current common farmers' guideline of 25 mm a week (WK25) produced the lowest yields compared to the rest of the strategies except for the water stressed FC60. Calendar based irrigation scheduling Gen-cal and Site-cal simulated significantly higher yields than WK25. In all three regions except the Southern Cape, the lowest yields were obtained from the FC60 strategy. In the Southern Cape, yields between FC100 and the deficit irrigation strategies (FC80 and FC60) were not significantly different, while for the other three regions yields of FC60 differed significantly from FC100 and FC80. In the Southern Cape, the non-significant differences in yields between most irrigation strategies and FC60 were because of high mean annual rainfall (462 ± 109) during the growing seasons.

Table 6.3 Seasonal forage yield (t ha^{-1}) for the long-term simulation for seven irrigation strategies in four major milk producing areas of South Africa

Irrigation strategies	KwaZulu-Natal Midlands	Eastern Highveld	Eastern Cape	Southern Cape
FC100	13.7(1.3) [§]ab[β]	14.5(0.8)ab	13.2(1.5)a	13.7(2.1)b
FC80	14.0(1.1)a	13.9(0.6)bc	13.0(1.4)ab	14.7(2.1)ab
FC60	11.5(1.3)c	11.0(0.8)d	10.0(1.5)c	14.0(1.5)ab
RR20	14.3(1.3)a	14.9(0.6)a	13.8(1.4)a	15.0(1.7)a
WK25	12.6(1.7)bc	13.5(1.4)c	11.9(1.9)b	11.8(2.1)c
Gen-cal	13.8(1.7)a	14.3(1.1)ab	13.3(1.5)a	14.5(2.4)ab
Site-cal	14.0(1.9)a	14.5(0.9)ab	13.4(1.5)a	14.5(2.2)ab
I0	6.6(1.6)[NA]	5.6(1.0)[NA]	4.5(1.6)[NA]	10.0(2.3)[NA]

[§] Values in the brackets are standard deviations. [β] Values followed by the same letter within a column are not significantly different. [NA] is not applicable to the treatment.

In the Eastern Cape and KwaZulu-Natal Midlands the yield in the first growth cycle was lower compared to the Eastern Highveld and Southern Cape (Figure 6.2). Yield reduction could be due to higher deep drainage (Figure 6.4) which leads to nutrient leaching (Figure 6.5). In autumn and spring, the WK25 strategy produced similar yields to the highest yielding irrigation strategy. However, the yields were lower in the winter months of June and July (for the third and fourth growth cycles) when the WK25 strategy was used (Figure 6.2). This was due to lower growth rate and water use of annual ryegrass in winter as a result of unfavourable weather (Table 6.1) i.e. low minimum temperatures (from about 0°C in Eastern Highveld to 7.0 °C in Southern Cape).

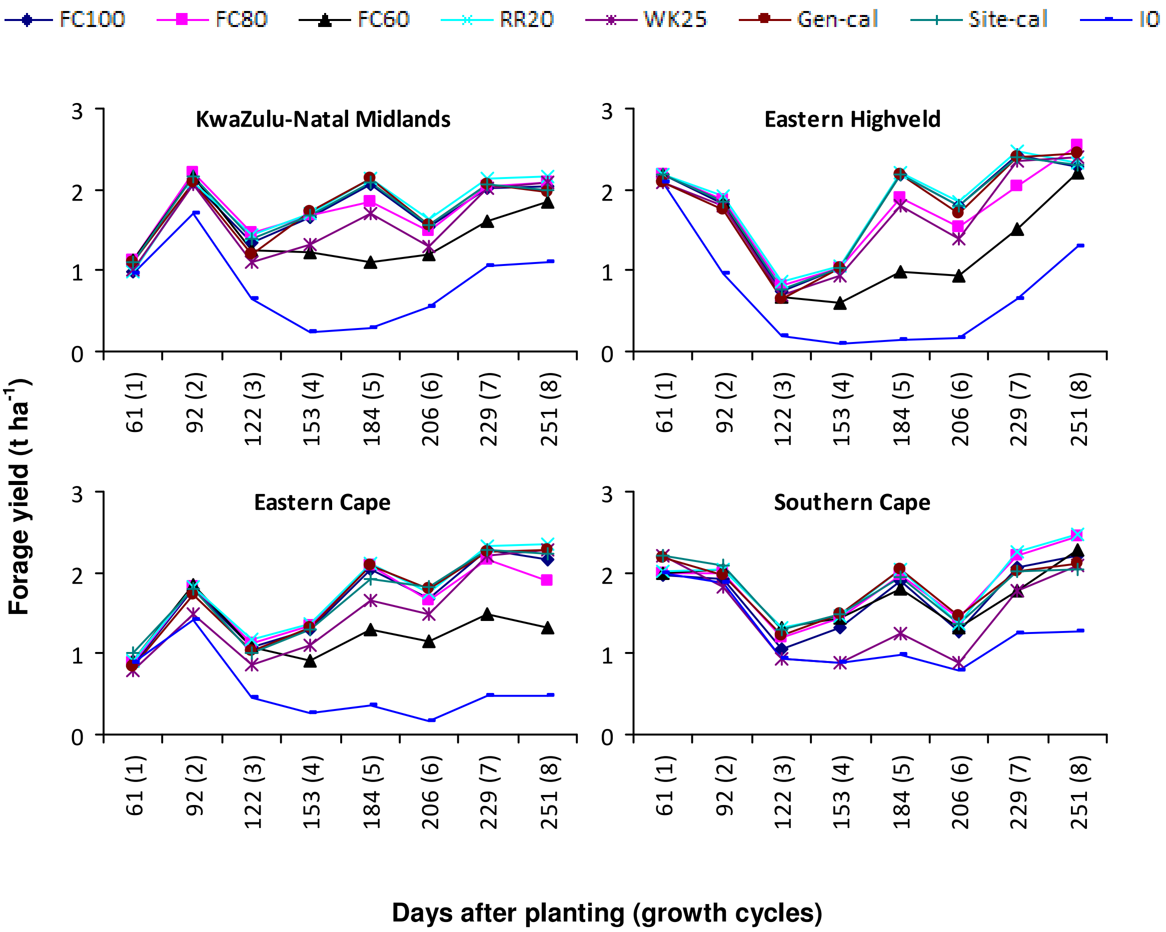

Figure 6.2 Growth cycle forage yield of annual ryegrass (average long-term simulation for seven irrigation strategies and dryland) in four major milk producing areas of South Africa. X-axis bracketed values represent the number of the cutting cycle

There were variations in irrigation requirements (Figure 6.3) between different regions, years, irrigation strategies and growth cycles. As expected, for all irrigation strategies except WK25, in the summer rainfall areas (KwaZulu-Natal Midlands, Eastern Highveld and Eastern Cape) the highest irrigation applications were in late winter and late spring (70 - 90 mm per growth cycle), whilst in the winter rainfall area (Southern Cape) the highest irrigation applications were in autumn and early summer (60 -70 mm per growth cycle) (Figure 6.3). This was due to differences in rainfall distribution between the different sites (Table 6.1).

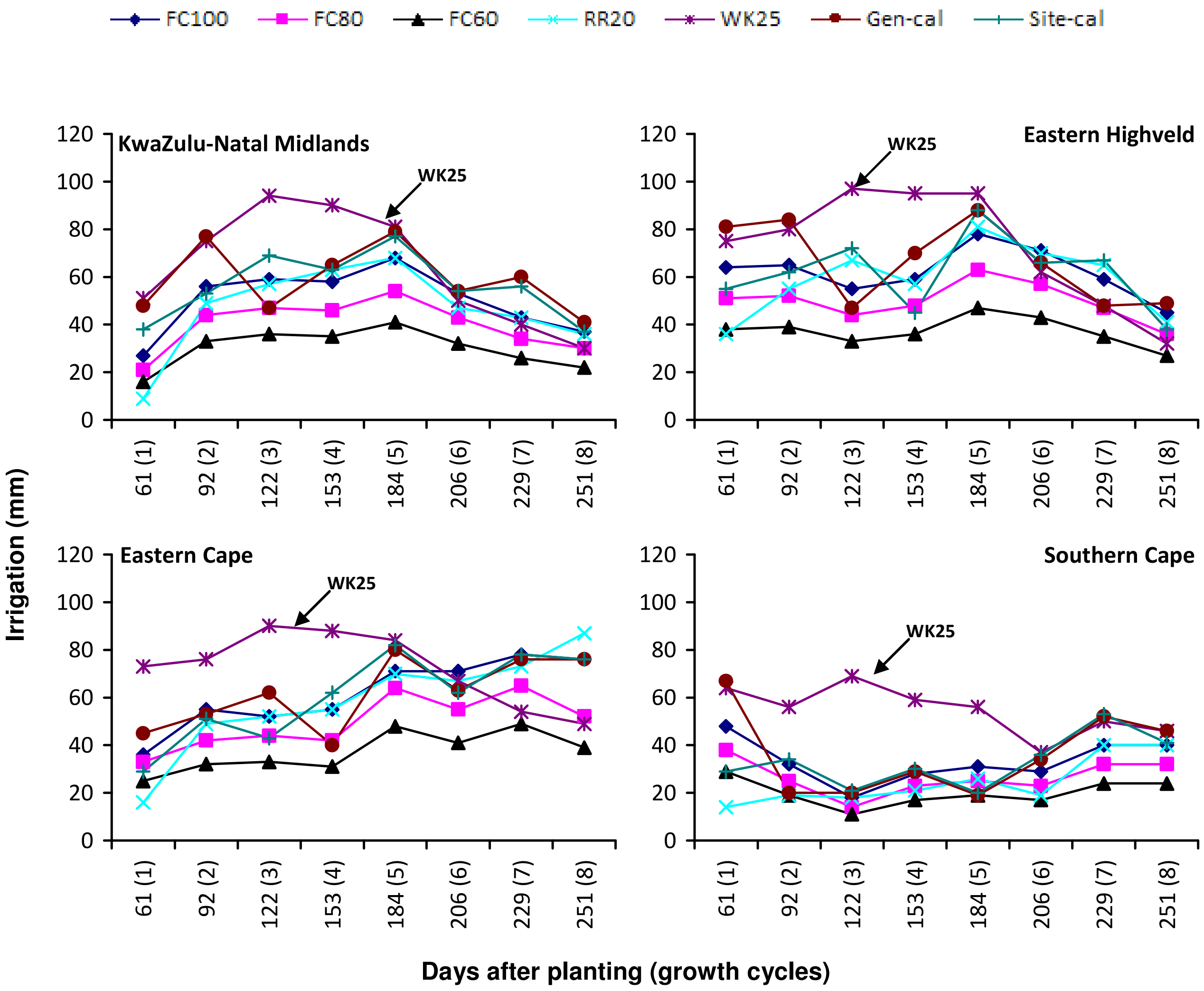

Figure 6.3 Growth cycle irrigation applications of annual ryegrass (long-term simulation for seven irrigation strategies) in four major milk producing areas of South Africa. X-axis bracketed values represent the number of the cutting cycle

All regions with the exception of the Southern Cape showed similar irrigation requirements in each irrigation strategy (Table 6.4). Generally, irrigation applications for the WK25 strategy were significantly higher than the other strategies. In all regions, in spite of similar yields for the FC100 and RR20 strategies (Table 6.2), irrigation requirements of the "room for rain" (RR20) strategy were lower than the FC100 strategy. For example, in Southern Cape irrigation requirement of annual ryegrass using the RR20 (196 mm) was lower than the FC100 (266 mm) strategy by as much as 26%, where significant rainfall is experienced during the growth season (Table 6.4).

Table 6.4 Seasonal rainfall and irrigation application (long-term simulation for seven irrigation strategies) in four major milk producing areas of South Africa

Irrigation strategies	KwaZulu-Natal Midlands	Eastern Highveld	Eastern Cape	Southern Cape
FC100	401(60)[§]c[β]	496(36)bc	495(77)b	266(70)b
FC80	321(48)e	397(29)d	396(62)c	213(56)bc
FC60	241(36)f	298(22)e	297(46)d	160(42)d
RR20	371(61)d	471(51)c	469(99)b	196(71)cd
WK25	511(42)a	581(29)a	580(41)a	434(37)a
Gen-cal	471(43)b	534(25)ab	497(51)b	290(35)b
Site-cal	450(40)b	493(30)bc	481(48)b	263(35)b
Rainfall	392(97)[NA]	265(62)[NA]	270(103)[NA]	462(109)[NA]

[§] Values in the brackets are standard deviations. [β] Values followed by the same letter within a column are not significantly different. [NA] is not applicable to the treatment.

To illustrate, the current irrigation guideline for annual ryegrass pasture in KwaZulu-Natal is 650 mm over a dry season of 26 weeks with an average of 25 mm per week (Jones, 2006). The total mean water application is 1042 mm (650 mm irrigation + 392 mm rain). This is higher than the model's long-term mean estimated water application of 903 mm (511 mm irrigation + 392 mm rain) when the current farmers' practice of 25 mm per week strategy was used. This was due to inefficiencies in irrigation scheduling. There was over-irrigation in the cold winter and under irrigation during the warm spring and early summer seasons when WK25 was used (Figure 6.3). With good irrigation scheduling a mean irrigation amount of 191 mm (36%) for the KwaZulu-Natal Midlands, 110 mm (19%) for the Eastern Highveld, 184 mm (32%) for the Eastern Cape and 274 mm (61%) for the Southern Cape could have been saved as compared to the common farmers' practice, without significantly reducing the forage yield.

Deep drainage plus surface runoff losses showed differences among irrigation strategies (Table 6.5). Generally, the lowest losses were observed when the FC60 strategy (18 - 69 mm) was followed, however, for this strategy, yields were significantly reduced compared to other strategies (Table 6.2). In all regions, using calendar based irrigation scheduling (Gen-cal and Site-cal) and the RR20 (when 20 mm as room for rainfall was reserved in the profile) strategies, reduced water loss due to drainage and runoff by 40 - 70% compared to WK25 (Table 6.5), without significant yield reduction (Table 6.3).

Table 6.5 Seasonal water loss due to drainage plus runoff (mm) for the long-term simulation of seven irrigation strategies and dryland in four major milk producing areas of South Africa

Irrigation strategies	KwaZulu-Natal Midlands	Eastern Highveld	Eastern Cape	Southern Cape
FC100	89(61)[§]cd[β]	36(37)c	62(53)bc	106(80)b
FC80	64(57)d	21(24)c	45(40)bc	86(90)bc
FC60	61(56)d	18(18)c	42(38)c	69(85)c
RR20	73(68)d	28(26)c	46(43)bc	71(77)c
WK25	195(89)a	138(53)a	186(84)a	256(114)a
Gen-cal	127(92)b	69(53)b	73(56)b	113(108)b
Site-cal	116(91)b	40(47)c	63(66)bc	101(113)bc
I0	58 (57)[NA]	16 (17)[NA]	39 (77)[NA]	48(77) [NA]

[§]Values in the brackets are standard deviations. [β]Values followed by the same letter within a column are not significantly different. [NA] is not applicable to the treatment.

Generally, for all regions over 80% of the water loss (drainage plus runoff) was due to drainage (data not shown). In summer rainfall areas (especially in the KwaZulu-Natal Midlands and Eastern Cape) most of the deep drainage occurred in the first growth cycle (Figure 6.5). This was because planting was in late summer (March) when rainfall was in excess of plant requirements (Figure 6.1). There was also drainage and runoff in the I0 (no irrigation) strategy at the beginning of the season when canopy cover was sparse. In the winter rainfall area (Southern Cape), however, the highest drainage was observed in late winter and early spring when rainfall increased to over 70 mm per month.

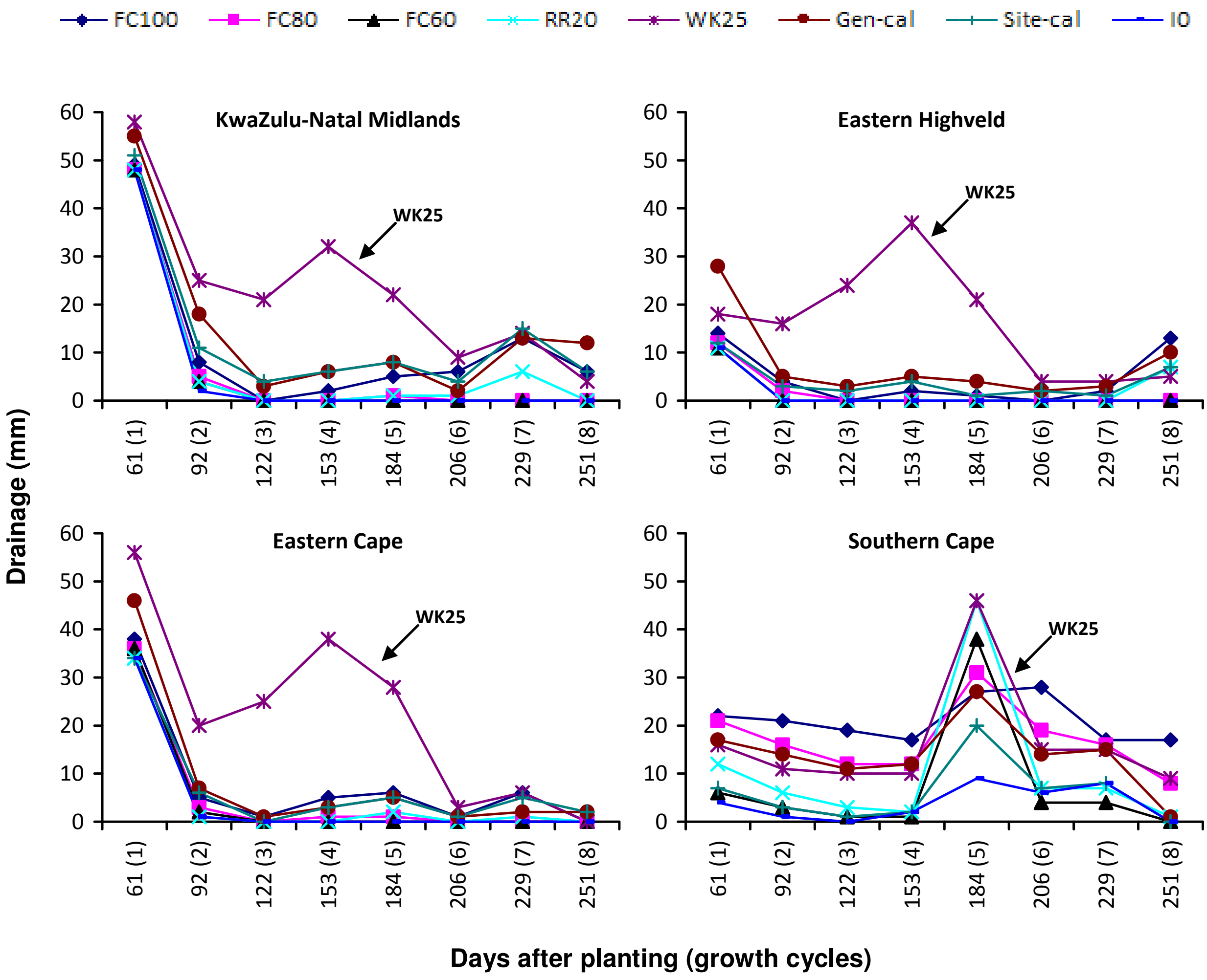

Figure 6.4 Deep percolation from annual ryegrass growth cycles (long-term simulation for seven irrigation strategies and dryland) in four major milk producing areas of South Africa. X-axis bracketed values represent the number of the cutting cycle

6.3.2 Water and irrigation use efficiency

Generally for all irrigation scenarios, the lowest (mostly lower than 20 kg ha^{-1} mm^{-1}) water use efficiencies (WUEs) were observed in the Eastern Cape (Table 6.6). This could be due to higher vapour pressure deficits (VPD) resulting from higher maximum temperatures during autumn (March) and summer (November). For these months, VPD for Eastern Cape was greater than 2.0, however, for the other sites VPD ranged between 1.2 and 1.6 (Table 6.1). The RR20 strategy showed the highest WUEs compared to other irrigation strategies used. Site-cal also revealed similar results in all sites except in the Southern Cape. High WUEs were due to higher yields and reduced losses of water through drainage and possibly reduced leaching of nutrients. In most regions, all the irrigation scenarios with the exception of severe deficit (FC60) showed superior WUEs to the WK25 strategy. For example, in KwaZulu-Natal Midlands WUEs were greater than 20.0 kg ha^{-1} mm^{-1} for all strategies (except FC60) whilst for the WK25 strategy the WUE was 18.7 kg ha^{-1} mm^{-1}.

Table 6.6 Seasonal water use efficiency (WUE: kg ha^{-1} mm^{-1}) for a long-term simulation of seven irrigation strategies and dryland in four major milk producing areas of South Africa

Irrigation strategies	KwaZulu-Natal Midlands	Eastern Highveld	Eastern Cape	Southern Cape
FC100	21.3(1.8) §ab$^{\beta}$	21.6(0.7)ab	19.9(1.8)a	24.5(2.8)bc
FC80	21.3(1.5)a	21.3(0.9)ab	19.9(1.8)a	25.8(2.6)ab
FC60	19.6(1.6)cd	19.5(1.3)c	17.7(1.9)b	25.1(2.2)abc
RR20	21.7(1.8)a	21.9(0.8)a	20.4(1.9)a	26.6(2.3)a
WK25	18.7(2.2)d	19.6(1.1)c	17.4(2.3)b	19.8(2.8)d
Gen-cal	20.0(2.0)bcd	20.8(0.7)b	19.3(1.8)a	24.0(2.9)c
Site-cal	20.5(2.2)abc	21.3(1.8)ab	19.3(1.7)a	24.1(2.8)bc
I0	17.9(2.4)^{NA}	20.0(60)^{NA}	15.1(2.7)^{NA}	22.7(5.3)^{NA}

§Values in the brackets are standard deviations. $^{\beta}$Values followed by the same letter within a column are not significantly different. ^{NA} is not applicable to the treatment.

Neal *et al.* (2011) reported ranges of WUEs similar to the current study for different annual temperate pastures using a range of deficit irrigation strategies. For the KwaZulu-Natal Midlands, the calculated WUE from the current farmers' irrigation practice (750 mm of irrigation) for the highest target yield (12 t ha^{-1}) of annual ryegrass is 16.0 kg ha^{-1} mm^{-1} which is lower than the ranges (18.7 to 21.7 kg ha^{-1} mm^{-1}) calculated from the irrigation strategies used in this study. Because evaporative demand changes throughout the season, it may be possible to limit or eliminate irrigation in the months of excessively high evaporative demand or VPD, and produce annual ryegrass only in periods of low evaporative demand. Simulations were conducted using a well-drained soil, therefore caution should be exercised in the selection of the correct soil type (water holding capacity) before using the deficit (FC80) and room for rain (RR20) strategies as choosing the wrong soil type could result in under-irrigation (especially sandy soil).

Marginal irrigation use efficiency (MIUE) explains the forage biomass produced per mm of irrigation application. WUE gives an indication of physiological capability of a particular species, whilst MIUE is more relevant in comparing the pros and cons of irrigation applied compared to dryland production (Rawnsley *et al.,* 2009). In all regions, the highest MIUEs were observed when deficit irrigation strategies were used (Table 6.7). In the Southern Cape, the highest MIUE (23.0 kg ha^{-1} mm^{-1}) was obtained using FC60, while for the other three regions FC80 showed the highest MIUEs (21.0 - 23.0 kg ha^{-1} mm^{-1}). In the Southern Cape, approximately 80 mm of water was saved when FC60 deficit irrigation strategy was used. When using FC80 strategy about 80 mm in the KwaZulu-Natal Midlands, 100 mm in the Eastern Highveld and 120 mm in the Eastern Cape water was saved. In all regions, the RR20 strategy also gave similar, but non-significant MIUEs compared to the most efficient irrigation strategies.

Table 6.7 Seasonal marginal irrigation use efficiency (MIUE: kg ha^{-1} mm^{-1}) for a long-term simulation of seven irrigation strategies in four major milk producing areas of South Africa

Irrigation strategies	KwaZulu-Natal Midlands	Eastern Highveld	Eastern Cape	Southern Cape
FC100	17.5(4.0)§bc^{β}	17.7(1.7)b	17.2(3.2)b	11.5(7.0)d
FC80	23.0(2.8)a	20.9(1.0)a	21.4(2.4)a	19.4(7.3)abc
FC60	20.5(2.6)ab	17.9(1.1)b	18.7(1.9)ab	23.0(3.8)a
RR20	21.5(3.6)ab	19.7(1.2)ab	19.8(2.4)ab	22.5(4.7)ab
WK25	11.6(4.3)d	13.4(3.0)c	12.5(4.5)c	13.9(7.3)e
Gen-cal	15.2(4.9)c	16.1(2.8)bc	17.5(3.8)b	15.0(9.9)cd
Site-cal	16.4(5.6)c	18.0(2.4)bc	18.2(4.3)b	16.7(9.8)bcd

§Values in the brackets are standard deviations. ^{β}Values followed by the same letter within a column are not significantly different.

6.3.3 N leaching

For all regions the greatest N leaching occurred in the WK25 strategy (Table 6.8). N leaching was highest in the Southern Cape and lowest in the Eastern Highveld. This was due to difference in the amount and distribution of rainfall between regions. Site specific (Site-cal) and general (Gen-cal) calendar based irrigation scheduling simulated less leaching than WK25, but similar to that of the FC100 simulation. Deficit (FC80) and room for rain (RR20) strategies gave the lowest leaching next to dryland (I0), without compromising yield (Table 6.3). For example, in KwaZulu-Natal Midlands N the use of site specific (Site-cal) and general (Gen-cal) calendar based irrigation scheduling reduced N leaching by up to 30-40% (90-103 kg N ha^{-1}) compared to the WK25 strategy (153 kg ha^{-1}).

Table 6.8 Seasonal N leaching (kg ha^{-1}) for long-term simulations of seven irrigation strategies and dryland in four major milk producing areas of South Africa

Irrigation strategies	KwaZulu-Natal Midlands	Eastern Highveld	Eastern Cape	Southern Cape
FC100	81(45)§b^{β}	34(39)bc	62(57)bc	94(65)b
FC80	46(39)c	11(21)cd	39(39)bcd	63(72)cd
FC60	43(38)c	7(16)d	36(39)d	49(69)d
RR20	53(47)c	15(21)cd	37(46)cd	51(63)d
WK25	153(52)a	104(44)a	148(64)a	176(51)a
Gen-cal	103(58)b	55(54)b	64(58)b	82(75)bc
Site-cal	90(61)b	30(43)cd	55(62)bcd	70(78)bcd
I0	7(4)^{NA}	9(15)^{NA}	33(39)^{NA}	29(61)^{NA}

§Values in the brackets are standard deviations. ^{β}Values followed by the same letter within a column are not significantly different. ^{NA} is not applicable to the treatment.

In all regions, N leaching was highest at the beginning of the season (first growth cycle) during establishment. This was because there was high soil N mineralisation, N carryover from previous seasons, high rainfall, poorly established root systems and a sparse canopy cover. For example, for KwaZulu-Natal Midlands in the first growth cycle, all strategies including I0 (dryland) showed high N leaching (greater than 35.0 kg ha^{-1}) (Figure 6.5). In the remaining growth cycles, however, significant N leaching was observed only when the WK25 strategy was followed (Figure 6.5). When using WK25 strategy about 20.0 kg ha^{-1} was lost compared 0 - 10 kg ha^{-1} in the other irrigation strategies (Figure 6.5).

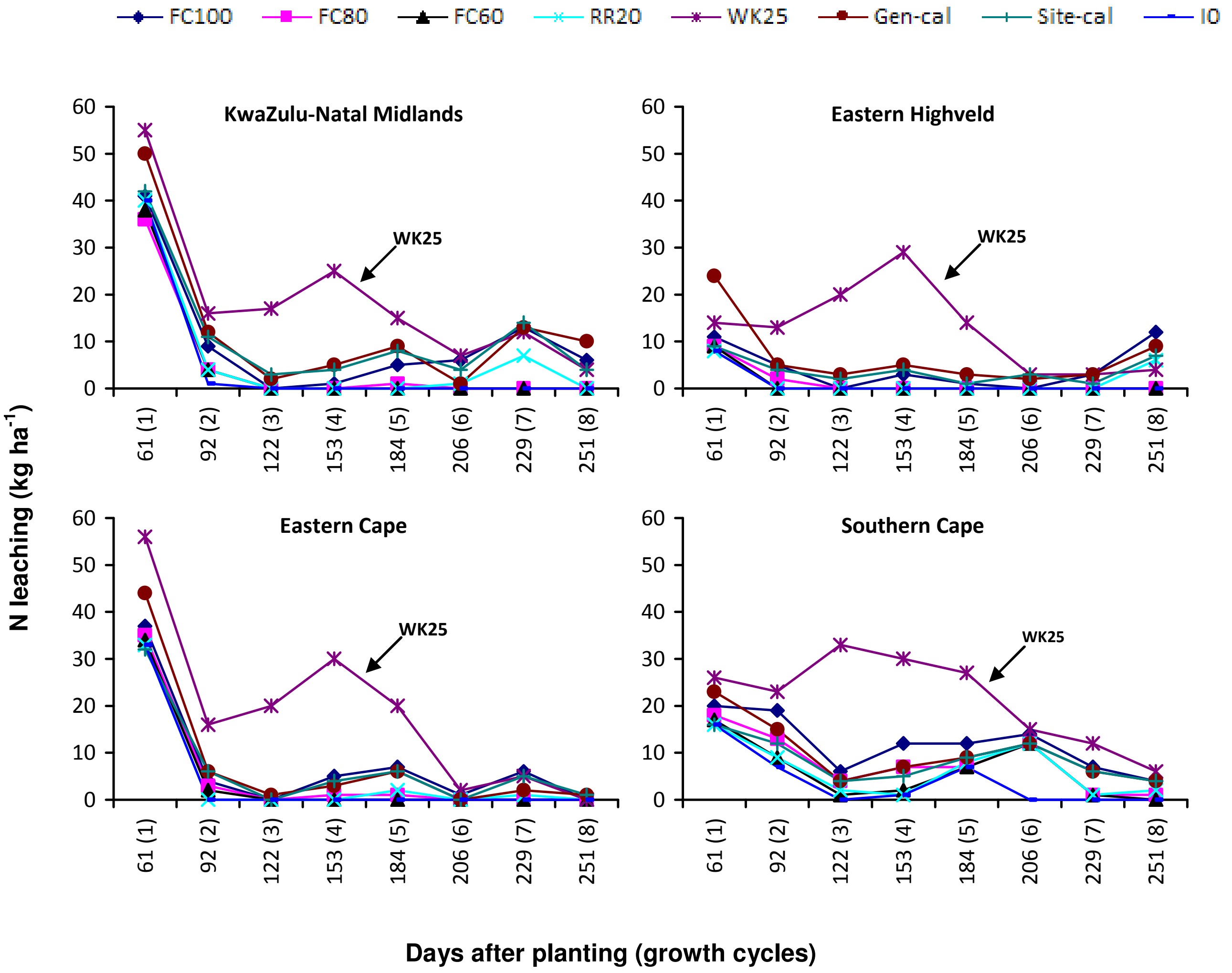

Figure 6.5 Growth cycle N leaching (kg ha^{-1}) below the active root zone (0.6 m) of annual ryegrass (long-term simulation of seven irrigation strategies and dryland) in four major milk producing areas of South Africa. X-axis bracketed values represent the number of the cutting cycle

Model output trends for mobile soil nitrate concentrations in draining soil solutions during the long-term simulation were similar reaching a maximum of 200 mg L^{-1}. For example, during a ten year simulation exercises (1971-1980) for the KwaZulu-Natal Midlands (Figure 6.6), the occurrence of leaching events were less frequent when using a site specific calendar (Site-cal) compared to following the WK25, Gen-cal or FC100 strategies.

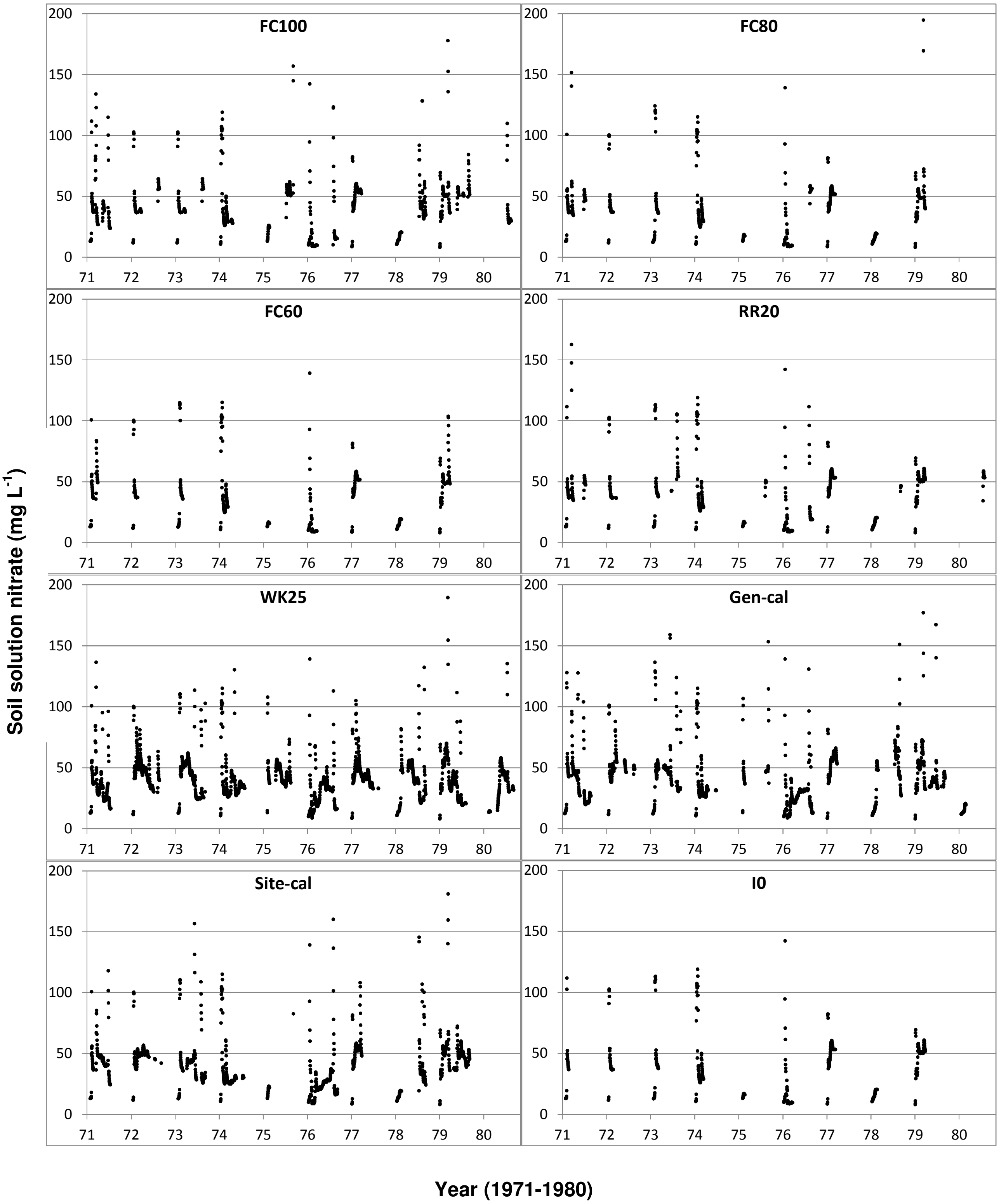

Figure 6.6 Leaching of mobile soil nitrate (mg L^{-1}) concentrations simulated using the model for a range of irrigation strategies for the KwaZulu-Natal Midlands

6.4 CONCLUSIONS

Intensive production of pastures such as annual ryegrass requires high inputs for land preparation, fertilisation and irrigation. Considering these costs, severe deficit irrigation (a deliberate reduction of irrigation) may not be cost-effective. Hence in this study, the main objective was to explore tactical irrigation (e.g. leave room for rain) scheduling and mild deficit irrigation options, where irrigation amount could be reduced without significantly affecting forage yield. The modelling exercise in this study showed that there may be opportunities to improve irrigation use efficiency of irrigated pastures by using rainfall strategically (RR20 or mild deficit of FC80). These strategies can have increased practical implications for medium to heavy soils (with relatively high water holding capacity) in the high rainfall areas of South Africa, especially in the Southern Cape and KwaZulu-Natal Midlands. Because evaporative demand changes throughout the season, it may be possible to limit or eliminate irrigation in months of high evaporative demand or VPD (towards the end of the growing season) and produce annual ryegrass only in periods of low evaporative demand.

Selecting an irrigation strategy depends on climate and availability, type and accuracy of irrigation scheduling equipment such automatic weather station, soil water monitoring probes, WFDs. However, in the absence of irrigation monitoring equipment, simple site specific irrigation calendars (developed using SWB-Pro in Chapter 4) can be used, as these give similar results to the common scientific (FC100) irrigation strategies. Most importantly, deficit irrigation or room for rain refill options can be employed while using calendar-based irrigation scheduling (e.g. by keeping the timing the same, but reducing the amount).

In 2010, of the total annual ryegrass production costs in South Africa, 25% was allocated to irrigation and 55% to fertilisers (Whitehead and Archer, 2009). Therefore, these strategies could also improve nutrient use efficiencies and protect the environment by reducing pollution (leaching of nutrients and chemicals) and soil erosion (surface runoff). Hence, using the cost savings made from reduced fertilisers, water and energy, pasture growers could expand their pastures and improve profits. This study demonstrated that the most appropriate management strategy for farmers is to integrate irrigation and N inputs, since N and water cannot be managed independently. In order to optimise yield and quality, and reduce N leaching, irrigation should be managed based on the wetness of the soil and nitrate concentration in the deep root zone, with the aid of tools such as the wetting front detectors (presented in Chapter 2).