UNIVERSITY OF SOUTHERN QUEENSLAND

Strategies for Maximising Sugarcane Yield with Limited Water in the Bundaberg District

A Dissertation submitted by
Craig Baillie, B Eng

For the award of
Master of Engineering
2004

ABSTRACT

Sugarcane farmers in Bundaberg have had limited access to irrigation water over the last ten years. The district has the potential of growing 3.8 million tonnes of sugarcane. However, a series of dry seasons saw this reduce to 2.1 million tonnes in 2002. Compounding the effects of both dry seasons and limited water supplies has been a 30% reduction in the sugar price over this period. The irrigation requirement of sugarcane in the Bundaberg area is 8 ML/ha. The original allocated volume for sugarcane production in this area was 4.5 ML/ha (based on 1970 production areas). However, as the area under production has increased and announced allocations in each year has reduced, this allocation is now equivalent to an application volume of about 2 ML/ha

A change from the traditional practice of full irrigation is required as water supplies become depleted. As there were no clear guidelines on how growers could respond to diminishing water supplies, this research investigated opportunities to fine tune irrigation practices and the performance of irrigation systems (ie. low cost solutions) that would assist growers to maximise sugarcane yield. A grower survey was initially conducted to identify current practice and opportunities for change. Field investigations focused on the performance of water winch and furrow irrigation systems, which make up 91% of the irrigated area in the district. As most of these application systems have insufficient capacity to meet crop demands opportunities to schedule irrigations were limited to start up after rain.

Improvements in irrigation system performance were found to provide the greatest potential to increase sugarcane yield under conditions of limited water. Investigations identified that irrigation performance could be significantly improved through relatively minor adjustment.

Field trials found that wind speed and direction significantly influenced the performance of travelling gun irrigators. Although growers were generally aware of the effects of wind, meteorological data suggested that the opportunity to operate water winches in low wind conditions is limited. Changing to a taper nozzle under moderate to high wind conditions will reduce the effect of wind on performance. This practice was found to improve the uniformity (measured by Christiansen's Uniformity Coefficient, CU) by 16%. The grower survey indicated that there was no preference towards the use of taper nozzles in windy conditions. Additional trial work developed a relationship between the variation in water applied to the field through non uniformity and sugarcane yield. An 8% reduction in yield was determined for a 10% reduction in CU. This indicated that changing to a taper nozzle could potentially increase sugarcane yield by 15% in high wind conditions. Other settings, which also influenced uniformity, included lane spacing and gun arc angle

Simple changes to the operation of furrow irrigation systems were also found to dramatically improve irrigation performance. Field measurements in combination with simulation modelling of irrigation events using SIRMOD II identified that current irrigation performance ranged in application efficiency from 45 to 99% (mean of 79%) and a distribution uniformity from 71 to 93% (mean of 82%). Both application efficiency and distribution uniformity were increased to greater than 90% and 84% respectively, except on a cracking clay soil. Improvements in application efficiency and distribution uniformity were achieved by adjusting furrow flow rate (cup size), turning the irrigation off at the right time (ie. just as it reached the end of the field) and banking the end of the field. Growers had a good understanding of the correct cut off time and were attentive to reducing run off through either banking ends or tail water return. However, growers had a poor understanding of the significance of furrow flow rate. Other opportunities to improve irrigation performance on high infiltration soils included alternate furrow irrigation and shallow cultivation practices which maintained compaction in the interspace and reduced infiltration.

Soil moisture and crop growth measurements indicated that sugarcane yield could be maximised by starting the irrigation rotation earlier after rainfall (ie. at a deficit equal to the irrigation amount). These observations were modelled using the crop simulation model APSIM sugar to assess the strategy over a longer time interval and the influence of seasonal variation. Simulation modelling showed that final sugarcane yields were not sensitive to irrigation start-up strategies. Yields for the start-up strategies modelled varied by less than 5 tc/ha. This minor difference occurred as the crop yield was driven by the total amount of water available to the plant. The limited amount of irrigation water available to the plant (2 to 3 ML/ha) had only a minor effect on the water balance and no significant change to effective rainfall between strategies. The greatest difference in yield occurred between irrigation treatments when water was left over at the end of the season (9.2 tc/ha). Starting irrigation earlier after rainfall events (on a 14 day rotation) provided the greatest opportunity to use all of the available irrigation supply. By comparison, delaying the application of the first irrigation after rainfall resulted in some of the irrigation water not being applied in 30% of years.

CERTIFICATION OF DISSERTATION

I certify that the ideas, experimental work, results, analyses and conclusions reported in this dissertation are entirely my own effort, except where otherwise acknowledged. I also certify that the work is original and has not been submitted for any other award, except where otherwise acknowledged.

Signature of Candidate	Date

ENDORSEMENT

Signature of Supervisor	Date

ACKNOWLEDGEMENTS

I would like to acknowledge those people and organisations who have contributed to this project in one way or another.

Research to determine irrigation strategies for limited water first commenced on Bundaberg Sugar Ltd farms in response to low announced water allocations in 1999. The majority of field work contained in this dissertation was conducted through a secondment to the Bureau of Sugar Experiment Stations (BSES) and the Rural Water Use Efficiency (RWUE) Initiative. The broad aims of both the local RWUE Initiative project and this research work were to assist growers to maximise sugarcane yields with limited water. Field work and activities conducted within the local RWUE Initiative project were directed with this common interest in mind and with the additional rigour required for a research degree. I would like to thank Bundaberg Sugar Ltd for financially supporting this research and the BSES and CANEGROWERS Bundaberg for the opportunity to work on the RWUE Initiative.

I would like to acknowledge the role that others have had in assisting in the collection, analysis and presentation of both the grower survey to benchmark grower practices and field data measuring the performance of travelling guns (water winches). The grower survey was developed in consultation with Danni Stehlik and Kerry Mummery from the Centre for Social Science Research at Central Queensland University (CQU) and presented by the CQU team as part of a benchmarking activity for the RWUE initiative. Glen Gordon provided technical assistance in the collection of the field performance evaluation data for the travelling guns and subsequently presented part of this work for his final year thesis (BENG, Agricultural) at the University of Southern Queensland.

I would also like to thank those growers who participated in the trial work and through discussion helped develop strategies for maximising sugarcane yield with limited water. Additionally, I would like to acknowledge and thank Sandra Dennis for her technical assistance and support and Steven Raine for his energy and direction throughout this process. Most of all I would like to thank my family, particularly Jus, who has helped make this happen.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABREVIATIONS

AE	Application Efficiency
CU	Christiansen’s Uniformity Coefficient
DU	Distribution Uniformity
ET_0	Reference Evapotranspiration
fasw	Fraction of Available Soil Water
PAWC	Plant Available Water Content
RAW	Readily Available Water
tc/ha	Tonnes of Cane per Hectare
tvd	Top Visible Dewlap

1 INTRODUCTION

From the early stages of the Australian sugar industry the need for irrigation was recognised as a means to stabilise yields in various districts and provide a management strategy to minimise the effects of droughts. The need for irrigation was noted in Bundaberg as early as 1870 when small scale irrigation was carried out from shallow wells. In 1885, pumps were installed at Bingera on the Burnett River to irrigate cane land and supply water to Bingera Mill. By 1901 a small irrigation scheme was developed by James Gibson (Bingera Mill) to irrigate 237 hectares of cane land. Droughts during 1902 to 1904 were pivotal in confirming the need for irrigation (Kerr, 1983).

Formal research into the benefit of irrigation in the Bundaberg region can be traced back as far as 1931 when trials were conducted to determine the potential yield benefits of irrigation (Kingston, 2000). In the Bundaberg District, supplementary irrigation is estimated to provide an increase in yield of 22.6 tonnes of cane per hectare or 3.6 tonnes of sugar per hectare (Holden, 1998).

Today, approximately 60% of the annual Australian sugarcane crop is produced by either full or supplementary irrigation. This equates to approximately 40% of the sugarcane growing area throughout Australia (Ham, 1994). In recent years, significantly lower rainfall and major expansion in cane land has placed a strain on irrigation water resources (Shannon et al., 1996). Ridge (2001) suggested that the optimum irrigation strategy will vary depending on water availability. A change in the availability of water resources therefore requires a shift in the strategies for best use. To improve irrigation efficiency under limited water supplies, irrigation practices need to be adjusted.

1.1 SUGARCANE PRODUCTION IN THE BUNDABERG AREA

Sugarcane in Bundaberg is produced from a harvested area of 37 000 hectares, which is nearly all irrigated. Sugarcane is supplied to three regional mills (Fairymead, Bingera and Millaquin) which in 1999 crushed a record crop of 3.8 million tonnes of cane. However, production fell to 2.1 million tonnes in 2002 (Table 1-1) as a result of dry seasons and reduced water allocations. Low sugar prices have also compounded the effects of low production. The value of sugar produced from the Bundaberg district has fallen from $170 million in 1997 to approximately $107 million dollars in 2000. The influence that irrigation has on production and ultimately the value of sugar produced is significant.

Table 1-1 District Production and Sugar Price

Season	District Tonnes of Cane (x 10^6)	Sugar Price $/Tonne of Sugar
1997	3.4	339
1998	3.0	355
1999	3.8	252
2000	3.0	252
2001	2.7	332
2002	2.1	270

1.2 IRRIGATION WATER SUPPLY

1.2.1 Water Sources

Irrigation water supplies in the Bundaberg district include surface water from the Bundaberg Water Supply Scheme and ground water from the Bundaberg Subartesian Area. Surface water provides the most significant proportion of the supply with 74% of nominal allocations. The total annual nominal allocation for irrigation is approximately 250 000 ML with 185 000 ML supplied from the Burnett Water Supply Scheme (DNR&M, 2003) and 65 000 ML from ground water. (Ridge, 2000)

The Bundaberg Water Supply Scheme has a total storage capacity of 637 420 ML and includes the catchments of the Kolan River and the Burnett River. Water is primarily supplied from Fred Haigh Dam (on the Kolan River) which has a capacity of 562 000 ML (Figure 1-1). Down stream from Fred Haigh Dam water is regulated by Bucca Weir (11 600 ML) and the Kolan Barrage (4 020 ML). Water can be diverted from Fred Haigh Dam into the Burnett River where Walla Weir (29 500 ML) and the Ben Andersen Barrage (30 300 ML) regulate supply (DNR&M, 2003).

Figure 1-1 Fred Haigh Dam

Water is distributed to non-riparian growers from the Kolan and Burnett Rivers via pipeline, open channels, balancing storages, relift pump stations and reservoirs. The distribution system is an “on demand” delivery system which automatically controls supply to growers through float gates and electronic control of pumps stations supplying channels or storage reservoirs.

1.2.2 Irrigation Allocations and Water Availability

There has been a dramatic shift in the irrigation water resources available since 1989 (Table 1-2). From 1989 to 1995, water supply was largely unrestricted. However, since 1995, water supplies have been dramatically reduced.

Table 1-2 Surface water and ground water announced allocations

(Ridge, 2000)

Water Year	Bundaberg Water Supply Scheme		Ground Water System	
	Starting Announced Allocation (%)	Final Announced Allocation (%)	Starting Announced Allocation (%)	Final Announced Allocation (%)
1988/89	150	150		106
1989/90	150	150		115
1990/91	160	200		106
1991/92	150	200		115
1992/93	170	200		116
1993/94	120	180		96
1994/95	110	110		87
1995/96	35	71	47	71
1996/97	50	75	51	66
1997/98	15	51	62	77
1998/99	22	77	58	73
1999/2000	29	59	61	75
2000/01	24	81		

The Bundaberg Water Supply Scheme was designed in 1970 as a supplementary irrigation scheme. Water from the scheme was initially allocated to growers on an area basis at 4.5 ML/ha of cane assigned land. Based on a typical crop rotation of 70% of the assigned cane area, the amount of water available for irrigation was effectively 6 ML/ha. The irrigated area within the Bundaberg Water Supply Scheme has increased from 40 070 ha in 1970 to 55 300 ha in 1994. Considering both this expansion and reduced water supplies in the last five years, the amount of water currently available for irrigation is approximately 50% of the full water supply allocated to growers in 1970. In addition, growers have often had to make decisions based on much less water as the announced allocation at the start of each season has ranged from 15 to 30% which is effectively 0.5 to 1.0 ML/ha of irrigation water.

Allocations for the ground water system have generally been similar to the surface water scheme in the last 5 years (except for some areas directly along the coast). The ground water system has the advantage of starting the water year with a higher amount of water but with little chance of this dramatically increasing during the season. Starting allocations for groundwater users during this period have ranged from 50 to 60 %. Table 1-2 indicates that during the season groundwater allocation increases aren’t as large as for surface water supplies.

1.3 CROP WATER REQUIREMENTS

The crop response to irrigation is both seasonally and spatially variable due to climatic differences from year to year and between districts within the Australian sugar industry (Table 1-3). In Bundaberg, the annual crop water requirement of sugarcane is 1360 mm with 580 mm normally supplied by effective rainfall and 780 mm (7.8 ML/ha) required by irrigation (Holden, 1998).

Benchmark figures suggest that for a fully irrigated crop, 100 mm of irrigation would normally produce an additional 10 tonnes of cane per hectare (Tilley and Chapman, 1999). However, the response to irrigation diminishes as the amount of water applied to the crop is increased (Figure 1-2). In Bundaberg, the marginal increase in sugarcane yield from a nett irrigation amount of 6 to 7 ML/ha is similar to the irrigation costs. Hence, allowing for application inefficiencies, the economic returns are maximised at approximately 8 ML/ha.

Table 1-3 Irrigation requirements in sugarcane across districts

(Holden, 1998)

District	Annual crop water use (mm)	Effective rainfall (mm)	Irrigation requirement (mm)	Level of irrigation
Ord	1960	550	1410	Full
Cairns	1630	1360	270	Limited supplementary
Mareeba / Dimbulah	1550	405	1145	Full
Atherton	1170	760	410	Moderate supplementary
Tully / Babinda	1310	1500	Nil	Nil
Herbert	1350	1100	250	Limited to moderate supplementary
Burdekin	1520	450	1070	Full
Mackay / Proserpine / Sarina	1490	630	860	Moderate to extensive supplementary
Bundaberg / Maryborough	1360	580	780	Extensive supplementary
Moreton	1100	1180	Nil	Nil
Rocky Point	1150	990	160	Limited supplementary
Northern NSW	1200	1000	200	Limited supplementary

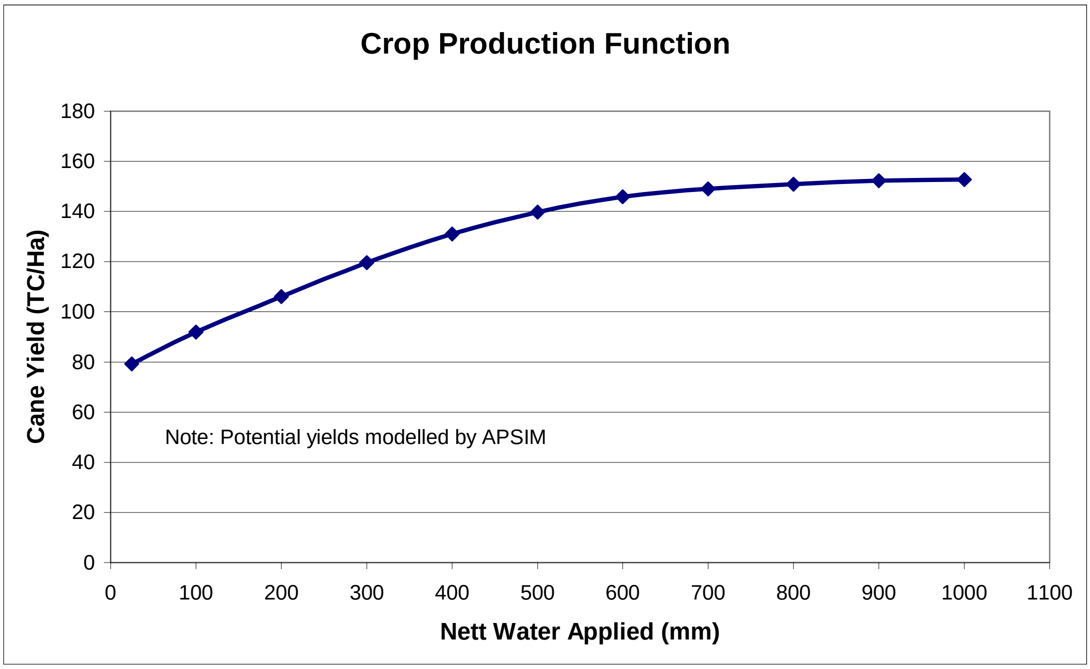


Figure 1-2 Crop response to irrigation

(Inman-Bamber, Unpublished data)

Full irrigation is traditionally applied where the aim is to meet the full water demands of the crop. An irrigation is initiated when the soil moisture is depleted to a level which avoids any yield reduction (tc/ha) from water stress. In ideal conditions and temperatures above 24^0C, sugarcane has been recorded to grow at rates of 40 mm / day (Holden, 1998). As soil moisture is depleted, growth rates decline in response to moisture stress.

While irrigating to maintain high growth rates produce more tonnes of cane, the sugar content or the economic component of the crop is reduced. Full irrigation in the context of a sugarcane crop infers irrigating to 85% of crop water requirements (at full canopy) to impose a slight moisture stress so that cane production and sugar production are maximised.

The irrigation refill point for sugarcane is determined by the soil moisture deficit at which stem elongation reduces to 50% of maximum growth, measured to the top visible dewlap as per Figure 1-3 (Holden, 1998). The soil moisture deficit at this point is termed readily available water (RAW).

Figure 1-3 Measuring height to the top visible dewlap

Crop water use is determined as a percentage of evaporation from a class A evaporation pan depending on canopy development (Table 1-4). Typical water use for sugarcane in Bundaberg at peak demand is approximately 6 mm/day (based on long term average Class 'A' evaporation records).

Table 1-4 Sugarcane crop factors

(Holden, 1998)

Canopy cover	Class 'A' pan crop factor
Bare ground	0.3
¼ canopy	0.5
½ canopy	0.6
¾ canopy	0.7
Full canopy	0.85
Maturing crop	0.65

1.4 IRRIGATION APPLICATION SYSTEMS

There are three major irrigation application systems in use within the Bundaberg district: travelling gun irrigators (water winches), furrow and drip. Other minor systems include boom, lateral move and centre pivots. The proportion of these systems varies across the district with notably more furrow systems and less water winches being located in the Millaquin area (Table 1-5). Winch and furrow systems represent the majority of irrigation application systems used within the district. Collectively these systems irrigate approximately 91% of the district.

Table 1-5 Irrigation application systems used in the Bundaberg area

(Bundaberg Sugar Ltd, 2000)

Type of Irrigation System	Proportion of systems in each Mill Area (%)		
	Fairymead	Millaquin	Bingera
Water Winch	67.5	27.6	67.9
Boom	0.6	0.0	0.3
Lateral Move	0.8	0.0	0
Centre Pivot	0.0	0.3	0.7
Furrow	24.6	57.0	26.9
Drip	6.5	15.1	4.2

1.5 PROJECT AIMS

Announced allocations over the last 10 years indicate dramatic differences in the availability of water (Table 1-2). From 1989 to 1995, irrigation resources were virtually unlimited supporting full irrigation practices. From 1995, irrigation resources have been restricted and district productivity has dramatically reduced. Hence, the aim of this project was to develop practical strategies to maximise the use of limited water for sugarcane production.

The strategies included on-farm solutions to improve productivity using the existing irrigation systems by finetuning practices rather than introducing new irrigation infrastructure or management systems. This resulted in the need for a broad approach to take advantage of all aspects of irrigation on-farm. A multidisciplinary approach, incorporating engineering and agronomic aspects was employed. A variety of techniques were used including a grower survey, on-farm monitoring, targeted irrigation testing and analysis, and crop modelling.

Factors influencing the optimum use of irrigation water have been reviewed (Chapter 2) and a grower survey to benchmark current irrigation performance was conducted (Chapter 3). The performance of the major irrigation systems used in the district (ie.

water winches and furrow irrigation comprising 91% of irrigated area) was evaluated using in field measurements and opportunities for improvement were identified (Chapters 4 and 5). Similarly, crop responses to irrigation practices were measured at field sites and strategies to improve these practices were identified and / or simulated using the crop simulation model APSIM Sugar (Chapter 6). Recommendations to maximise the use of limited water in the Bundaberg district are proposed based on surveyed grower practices, infield observations and crop simulations (Chapter 8).

2 SYSTEM PERFORMANCE AND CROP RESPONSE

2.1 INTRODUCTION

Improving the performance of the irrigation system is a simple and effective strategy to maximise the beneficial use of limited water supplies. Higher irrigation efficiency means more water is beneficially used by the crop. If water losses are large or uniformity is poor, overall irrigation performance will be low. With limited irrigation, Lee et al. (1985) concluded that it was more economical to improve the application efficiency of the current system than to move from one system to another. The benefit of moving from furrow to sprinkler or drip did not outweigh the capital investment, increased training and increased operating and maintenance costs.

Robertson et al. (1997) reported that despite the opportunity to improve the performance of irrigation systems, there is little evidence in the Australian sugar industry of the performance being measured so that irrigation practices can be fine tuned. An investigation by Shannon et al. (1996) in the Bundaberg district found the application efficiency of water winches ranged from 70 – 85%, furrow systems from 10 – 90% and drip systems from 30 – 90%. This indicates a significant opportunity to improve system performance. In Bundaberg, targeting the improvement of winch and furrow systems provides the greatest opportunity as these systems represent 91% of the irrigated area (Table 1-5).

The optimum use of irrigation water during the season will vary depending on water availability. Due to seasonal variation no single irrigation strategy will consistently be the best in every season. A change in the availability of water resources requires a shift in the strategies for best use while understanding the seasonal influences. To improve irrigation efficiency under limited water supplies, irrigation practices need to be adjusted and developed as appropriate.

With limited access to irrigation water supplies, irrigation strategies change from full irrigation practices to deficit irrigation. Deficit irrigation exposes the crop to water stress during either a particular growth period or throughout the whole of the growing season (Kirda and Kanber, 1999). The objective is to maximise the yield per unit of water by maximising the quality of the economic component of the crop, improving the effectiveness of rainfall, or reducing the likelihood of water logging or deep drainage. The general underlying principle is that the application of a controlled water stress will not cause significant yield reduction.

2.2 WATER WINCH IRRIGATORS

A large proportion of the Queensland sugar crop is irrigated by water winches. In most irrigation districts water winches represent approximately 60% of the irrigation systems in use (Tilley and Chapman, 1999). In Bundaberg approximately 55% of the irrigation systems in use (by area) are water winches. Water winches were introduced to the Bundaberg district in the early 1970s as a labour saving alternative to hand shift sprinklers.

The key component of a water winch (Figure 2-1) is a high pressure irrigation gun (operating up to 650 kPa) mounted on a moving cart. The gun produces a wetted circle from a single water jet as a knocker arm rotates the gun. The throw distance of the water jet is commonly 50 metres however some machines in still air can throw up to 70 metres.

Water is supplied to the irrigator via a flexible hose, which trails the cart. The hose is connected to a hydrant usually located half way down the field. Water winches operate along tow paths which are regularly spaced according to manufacturer’s specifications. The specified distance between tow paths is a fraction of the guns wetted diameter. Tow paths are usually 400 m in length. Some machines operate on runs up to 600 m long.

The water winch cart is moved down the field by a cable, anchored at the far end of the field, which is wound onto a drum. The drive mechanism which powers the drum is either a turbine or piston that diverts water from the gun. For piston driven machines the water displaced by the piston is exhausted through walker jets, back onto the field. Water passing through the turbine is diverted back to the main stream of the gun. A combination of nozzle size, nozzle type, operating pressure and travel speed determines the application rate. Application rates can be varied from 10 to 110 mm per irrigation.

Water winches are employed on a range of soil types and topography and tend to be operated under a range of conditions. The performance of water winches is greatly affected by windy conditions which reduce uniformity. Water winches require low capital costs to install but require high operating costs to run. This combination suggests they are limited to areas of supplemental irrigation (Ross and Williamson, 1990). Many systems have insufficient capacity to meet crop demand and are operated in less than optimum conditions.

Figure 2-1 Traveling Gun Irrigator (Water Winch)

2.2.1 Measuring Performance of Water Winches

The performance of overhead irrigation systems is a function of uniformity. The uniformity of overhead irrigation systems is measured by Christiansen's Uniformity Coefficient, CU as proposed by Christiansen (1941). The Christiansen coefficient was originally developed for sprinkler irrigation and remains the most widely used uniformity measure for that purpose (Smith et al., 2002). Well designed sprinkler systems are designed to operate at a CU of >85%. Christiansen's Uniformity Coefficient, CU is expressed in the following terms.

$$CU = 100\left(1 - \frac{m}{X}\right) \qquad \textbf{Eqn 1}$$

where m is the mean absolute deviation of the applied depths x_i and is given by:

$$m = \frac{\sum \left| x_i - X \right|}{n} \qquad \textbf{Eqn 2}$$

X is the mean applied depth, and n is the number of depth measurements.

2.2.2 Factors Influencing Performance of Water Winches

Despite the significant use of water winches in the Australian sugar industry, only limited work has been conducted into their performance in the field. Performance is influenced by a number of factors including wind (speed and direction), lane spacing and machine settings. Similar to all overhead irrigation systems, high uniformity is dependant on adequate overlap of the sprinkler pattern.

Wind Speed and Direction

Wind speed and direction has the most significant impact on uniformity by reducing both the throw distance of the water jet from the gun and the wetted diameter of the sprinkler pattern. As the wetted diameter reduces, the uniformity of the application is also reduced through insufficient overlap. High wind speeds particularly in the travel direction of the irrigator has the greatest effect on reducing the throw distance from the gun. The sprinkler pattern perpendicular to the wind direction is narrowed whilst downwind the pattern is elongated.

Jensen (1983) noted that testing by various researchers had been conducted to determine the effects of wind speed and direction on the irrigation uniformity of travelling gun irrigators. The average CU cited from these studies ranged from 70 to 75% at wind speeds of approximately 16 km/h. BSES (1984) measured the performance in Bundaberg of different nozzle types in stationary radial leg tests and found the CU ranged from 31 to 70%. It was also observed that uniformity increased from 55 to 70% when wind reduced from 16.7 km/h to 10.6 km/h. Bell (1991) reported adequate distribution from travelling guns at wind speeds up to 10 to 15 km/h. However, for wind speeds greater than 20 km/h, the performance of the irrigator dramatically reduced.

Jensen (1983) recommended that irrigation using travelling irrigators be restricted to wind speeds less than 16 km/h and preferably at night, when low wind is more common. Recommendations in relation to the wind direction included positioning lane ways perpendicular to the prevailing wind direction and to cease irrigating when the wind direction is parallel to the travel direction.

Lane Spacing

Poor uniformity can also occur due to insufficient overlap as a result of inappropriate lane spacing. Travelling guns have long been known to apply water to the field non-uniformly, particularly when lane spacing is excessive and under windy conditions (Smith et al., 2002). Considering that the wetted diameter of the irrigator is reduced under windy conditions, allowances can be made (during the design of the system) to maintain overlap by reducing the lane spacing. John et al. (1985) reported CUs ranging from 19 to 82% for travelling guns and suggested that inappropriate lane spacing was a major factor contributing to poor performance. Similarly, Wigginton and Raine (2001) found poor uniformity was related to excessive lane spacing.

Lane spacing is a function of the no wind wetted diameter of the sprinkler pattern and likely wind conditions experienced in a particular area. Irrigation texts suggest a lane spacing of 65% of the wetted diameter in low wind conditions reducing to 40% in high wind conditions (Jensen, 1983; Solomon, 1990). Specifications for lane spacing by different machine manufacturers range from 65 to 80%. Newell et al. (2002) suggests that the larger lane spacings recommended by machine manufacturers has resulted in the poor performance of these machines in the past.

Machine Settings

There are several settings on the machine which can alter performance. These include the trajectory angle of the gun, gun rotation angle, nozzles (type and size) and the operating pressure of the irrigator.

Gun trajectory angles commonly used by manufacturers, range from 21 to 27 degrees. Maximum throw distances in still conditions are produced at angles ranging from 24 to 28 degrees. Trajectory angles of 21 and 24 degrees perform better in windy conditions where the throw distance from guns with angles greater than 25 degrees are countered by the influences of wind (von-Bernuth, 1988).

Reducing the gun rotation angle has the effect of placing more water on the extremities of the sprinkler pattern. A greater volume of water on the edges of the sprinkler pattern has benefits in maximising overlap and improving uniformity. Wigginton and Raine (2001) increased uniformity by reducing gun rotation angles to between 240 and 270 degrees (from 360). Work by Cseko and Lelkes (1995), Al-Naeem (1993) and Grose (1999) suggest that the optimum angle is between 220 and 240 degrees.

There are two types of nozzles available on travelling irrigators. These include ring and taper nozzles. Taper nozzles provide the greatest stream integrity and maximum throw distance in windy conditions. Ring nozzles provide better stream break up for delicate crops at lower operating pressures and give a greater degree of flexibility in nozzle sizes (Nelson, 1980).

Despite the manufacturer’s qualitative assessment of ring and taper nozzles, only minimal technical data is available. This data doesn’t indicate the difference in performance between ring nozzles and taper nozzles under varying conditions. The manufacturer’s data suggests that taper nozzles will performance better in windy conditions by having a greater wetted diameter which will help maintain overlap. Merriam and Keller (1978) suggested uniformity in windy conditions could be improved by using a taper nozzle.

Increasing nozzle size increases the discharge and throwing distance of the jet. Larger nozzles were recommended by BSES (1984) to improve uniformity in windy conditions. Increasing the nozzle size produced a larger wetted diameter which maximised performance. Merriam and Keller (1978) also suggested the use of larger nozzles in windy conditions.

2.3 FURROW IRRIGATION

Furrow irrigation is the second most prominent irrigation system used in the Bundaberg district (Table 1-5). Furrow irrigation is predominately used in districts which have full irrigation requirements such as the Burdekin and Tablelands. Significant irrigation research has been conducted on furrow irrigation particularly in the Burdekin district. Within the Bundaberg district, furrow irrigation has been practiced for over 30 years although the majority of systems are approximately 20 years old.

Furrow irrigation systems in use across the Bundaberg district are generally less than 400 metres in length. Water is applied by either gated aluminium pipe (52%) or thin walled plastic fluming referred to as layflat (48%). Aluminium gated pipe is normally 100 mm or 125 mm in diameter and is used in situations where water is pumped. Gated pipe in most cases has been converted from hand shift sprinkler pipes. Layflat is commonly used in situations where water is supplied at low head such as from the surface water scheme. Layflat ranges from 200 to 300 mm in diameter with the most common being 250 mm.

Water is distributed down each furrow through outlets spaced along the aluminium pipe or layflat opposite each furrow. The amount of water applied to the field can be controlled by the furrow flow rate. The flow rate down each furrow is controlled by the opening of the outlet. This is achieved with screw type gates on aluminium pipe or cups inserted into layflat with cut or moulded holes. Adjustable plastic gates are also available for layflat.

In some situations growers have sufficient pressure at scheme outlets to avoid the need for pumping. Typically furrow systems operate at low heads in the order of 1 metre. Water in most cases is conveyed around the farm through pipe work. There is virtually no water distributed around farms through open channels except for a few of the larger farms.

Figure 2-2 Furrow irrigation using layflat

2.3.1 Measuring Performance of Furrow Irrigation

The performance of furrow irrigation systems is measured by both the efficiency (which is governed by evaporative, deep drainage and runoff losses) and the uniformity of water applied to the root zone of the crop. The most commonly used measures of performance include Application Efficiency (AE) and Distribution Uniformity (DU), which are defined as:

$$AE = \frac{\text{mean depth applied to the root zone}}{\text{mean depth applied to the field}} \qquad \textbf{Eqn 3}$$

$$DU = \frac{\text{mean of the lower ¼ applied depths in the field}}{\text{mean depth applied to the field}} \qquad \textbf{Eqn 4}$$

2.3.2 Factors Influencing Performance of Furrow Irrigation

The performance of surface irrigation is a function of field design, infiltration characteristics of the soil and irrigation management practices (Raine et al., 1998). Relatively high efficiencies are possible with furrow irrigation (>80%) with typical performance expected to range from 60 to 75% (Solomon, 1993). Efficiencies reported by Raine and Bakker (1996b) suggest that under commercial conditions efficiencies can be much lower and highly variable. It was reported that application efficiencies of sugarcane in the Burdekin (for individual irrigations) ranged from 10% to 90%. Similar performance of furrow irrigation was measured in Bundaberg by Shannon et al. (1996).

Substantial improvement can be made to the performance of furrow irrigation systems through field design and improved management techniques. Field design principally includes field length. Management techniques include operation practices during irrigation and management of the field (cultural practices). Operational practices include appropriate furrow flow rate, irrigation cut-off times, consistency of flow between furrows and irrigating every furrow or alternate furrow. Cultural practices include banking furrow ends, tail water return and cultivation practices.

Field Design

Furrow length is dependant on a range of factors including the soil characteristics, slope and furrow flow rate. Raine and Bakker (1996b) reported application efficiency with changes in row length for two soils in the Burdekin. For an alluvial soil application efficiencies reduced from 73% to 42% as the row length increased from 300 to 700 metres. For a cracking clay, application efficiencies only changed marginally from 76% to 73% as row length increased from 300 to 1 200 metres. Benami and Ofen (1984) suggest run lengths of 250 to 400 metres for medium to heavy textured soils with slopes less than 0.2% as a general guide for setting up furrow irrigation. These conditions are similar to those where furrow irrigation is practiced in Bundaberg.

Furrow Flow Rate and Cut-off Time

One of the most effective methods of varying the performance of surface irrigation systems is to alter the inflow rate of the water application (Alazba and Fangmeier, 1995). Altering furrow flow rate changes the speed that water moves down the furrow. This in turn controls the amount of water applied to the field by varying the opportunity time for water to infiltrate into the soil.

The duration of the irrigation or the cut off time is also an important factor when maximising the performance of furrow irrigation systems. Excessively long irrigation events will lead to significant losses from runoff or deep drainage. Alternatively an irrigation event which is not run for long enough will suffer from under irrigation at the tail end of the field.

Poor performance of furrow irrigation systems in Bundaberg has been found to be due to inappropriate furrow flow rate and irrigation duration (Linedale, 2001). Low furrow flow rates and excessive irrigation duration, typically cause excessive infiltration leading to deep drainage. In Bundaberg on three sites, application efficiency was improved from 57 to 99%; 56 to 63% and 45 to 73%. This was achieved by increasing furrow flow rates and controlling cut-off times so that the irrigation just reached the end of the field (Linedale, 2001). Raine and Bakker (1996a) reported that application efficiency in some cases could be improved by 10 to 20% by turning the water off at the correct time.

Variability of the flow rate in different furrows is also important when matching furrow flow rates and cut-off times. The precision at which the irrigation can be operated is reduced if furrows advance at different rates. This makes the system hard to manage with different cut-off times for individual furrows. Other impacts include variation of applied depth between furrows reducing overall field uniformity or distribution uniformity (DU).

Linedale (2001) reported significant variation of inflow between furrows for both layflat and gated pipe. Variability was reduced by 69% by using moulded cups over hand cut cups on layflat. Significant variation in the furrow flow rate along gated pipe was also reported. This was due to significant pressure differences along the pipe and the sensitivity of flow rate to small changes in the opening of the gate.

Banked Furrow Ends

In the absence of tail water recycling, banking the end of the field reduces runoff. Tilley and Chapman (1999) reported that many growers (without tail water recycling) continue to irrigate after the water has reached the end of the field to ensure that the root zone is completely recharged. Banking the end of the field allows the irrigation to be shut off earlier as water draining from the top of the field recharges the end. Linedale (2001) found that banked ends in combination with controlled cut-off times maximised irrigation performance.

Tail Water Return

Tail water return systems reduce runoff losses by recycling the water that runs off the field from irrigation. Water is collected in a recycling pit where it is pumped to the top end of the field (or other fields) for irrigation. Tail water return is becoming increasingly popular in furrow irrigated areas such as the Burdekin and Tablelands. Growers prefer tail water recycling to changing farm layout and management practices, particularly on heavy clay soils where most losses occur as a result of runoff (Tilley and Chapman, 1999). In the Burdekin, improvements in application efficiency of approximately 20% have been demonstrated through tail water recycling (Raine and Bakker, 1996a).

Irrigating Alternate Furrows

Irrigating alternate furrows can be a useful management practice for reducing the amount of water applied to the field. Alternate furrow irrigation is particularly effective at reducing deep drainage in highly infiltrating soils. Coupled with higher furrow flow rates, irrigating alternate furrow reduces the wetted surface area of the field which reduces infiltration. The successful use of alternate furrow depends on soil properties that enable movement of water from the furrow to the cane stool (row).

Linedale (2001) reported that alternate furrow irrigation could be effectively used to improve irrigation efficiency in Bundaberg. In cases where modified practices of conventional furrow were not effective, alternate furrow irrigation improved performance significantly. Application efficiencies of greater than 75% were achieved using alternate furrow irrigation. Similarly other researchers have reported water savings of up to 50% by adopting alternate furrow irrigation in a variety of crops including sugarcane (Raine et al. 1997).

Cropping Practices

Cultivation practices can significantly influence irrigation performance by altering the infiltration characteristic of the soil (Raine et al., 1996). For example, deep cultivation practices can improve surface infiltration on soils with poor penetration. Light cultivation or no cultivation maintains soil compaction, which reduces the infiltration rate of freely draining soils.

Changes in furrow shape associated with cultivation practices can also alter the infiltration characteristics of the furrow. A "V" shaped furrow controls infiltration by smearing or compacting the bottom of the furrow. Other influences include less surface area for water infiltration. By comparison, a "U" shaped furrow is less compacted and has a greater surface area to promote infiltration.

Cultivation has been found to double the infiltration of the soil and improve water penetration. Conversely surface compaction in narrow furrows has resulted in water savings of up to 37% while also improving distribution uniformity (Raine and Bakker, 1996b).

Crop residues can also improve irrigation performance by assisting water infiltration. Crop residues increase the resistance to water flow along each furrow which causes the depth of flow and opportunity time to increase (Evans, 1987; Raine and Bakker 1996b).

2.4 CROP RESPONSE TO IRRIGATION

Crop simulation modelling by various researchers within the Australian sugar industry (Robertson et al., 1997; Ridge, 2001; Hardie, 2000; Inman-Bamber et al., 2002) have highlighted that no single irrigation strategy will consistently be the best in every season. A combination of seasonal variation and water availability influences the optimum strategy adopted.

2.4.1 Irrigation Deficits

Turner (1990) stated that many crops are watered when the soils moisture deficit reaches 50% of Plant Available Water Content (PAWC). However, 75% of PAWC can be used before the rate of crop transpiration decreases. This is important in sugarcane as sucrose accumulation occurs whenever the crop is transpiring. Inman-Bamber and Jager (1988) suggested that although cane yield may decrease when the readily available water has been consumed, sugar yield may substantially increase during consumption of the remaining soil water. Inman-Bamber et al. (1998) reported that most soils in the Queensland sugar industry have been characterised for

Readily Available Water (RAW). However, with limited water resources, the crop is commonly required to extract to much greater deficits and in this context the RAW values reported may not be useful.

Early irrigation research of sugarcane in Bundaberg identified crop response to significant soil moisture deficits. Droughts in the Bundaberg area during 1964, 1965 and 1969 were the precursor to a period of irrigation research conducted in the late 1960's to the mid 1970s into irrigation scheduling. An irrigation scheduling experiment (Leverington et al., 1970) was initiated at Bundaberg in the autumn of 1967 to obtain information on the growth patterns and yields of sugarcane subjected to two different irrigation treatments and a rain fed treatment.

Results from the trial work (Kingston, 1972) suggest that irrigating at a moderate soil moisture stress (soil moisture tension of 400 kPa at 23 cm depth), although slightly reducing cane yield, increased sucrose and sugar yield when compared to a more frequently irrigated treatment (soil moisture tension of 100 kPa at 23 cm depth). This work also identified that a severely moisture stressed crop (soil moisture tension equal to or greater than 983 kPa) was reported to take up to 8 days to recover. If irrigation was applied before severe soil moisture stress set in (i.e. soil moisture stress not exceeding 312 kPa) then normal growth resumed almost immediately.

Over 4 irrigation seasons, the difference between the sucrose yields of the two irrigation treatments was either small or non significant. A water saving of approximately 50% in the 400 kPa treatment was achieved when compared to the 100 kPa treatment. Kingston and Chapman (1975) suggested that the 400 kPa regime was close to the optimum supplementary irrigation schedule for sugar production.

Kingston and Chapman (1975) suggested that the 400 kPa regime could be achieved by using a class A pan management factor of 0.68. For a rooting depth of 0.9 m, a soil moisture deficit for the 100 kPa and 400 kPa regimes of 51% and 76% of Plant Available Water Capacity (PAWC) was determined. Data presented by Kingston and Ham (1975) equates the 100 and 400 kPa regimes to a soil moisture deficit at which 50% and 25% of maximum stem elongation occurs.

Recent work by Ridge (2001) reported similar results to the earlier trial work conducted in Bundaberg. Ridge suggested that 50% stalk growth rate corresponded to 65 to 75% of PAWC and that a 30% growth rate corresponded to a 70 to 80% PAWC. Crop modelling results indicated that with limited irrigation supplies, the soil moisture deficit before irrigation could be increased to 80% PAWC. Ridge (2001) reported that from overseas experience, this related to a Class A pan factor of 0.64.

Using the APSIM crop model Ridge (2001) suggested that where adequate water supplies were available, irrigating at 50% PAWC (similar to 50% stem elongation) produced the highest yields. Alternatively for restricted water supplies irrigating at 80% PAWC (similar to 30% stem elongation) achieved the highest yields. Similar results were reported by Hardie (2000).

Ridge (2001) suggested that a trigger point for irrigation of 50% stem elongation was not achievable with limited water in Bundaberg. Stem elongation could be reduced to 30% of maximum which is equivalent to 75% depletion of PAWC. Hardie (2000) also suggested that scheduling based on a stem elongation of 30% is more appropriate for limited water supplies in the Bundaberg district.

Irrigation of the entire farm as opposed to fully irrigating part of the farm was found by Ah-Koon et al. (2000) to maximise yields. Partitioning the farm so that part was fully irrigated and other parts drastically limited, yielded 73 tc/ha over the enterprise. When water was applied at 0.5 ET_0 over a greater area, the average farm yield was 90 tc/ha.

2.4.2 Crop Response to Irrigation during the Season

The crop response to irrigation varies during the season. Applying irrigation during the most responsive stages of crop development maximises the benefits of limited water supplies. From the earlier work conducted in Bundaberg, Kingston (1972) suggested that supplemental irrigation policy should be directed towards preventing cane fields from reaching a state of severe moisture stress, particularly during the summer months when peak growth occurs. Pene and Edi (1999) found that sugarcane was less sensitive to water stress at the tillering stage than during stem elongation. The recommended use of limited water was to omit irrigation at tillering as soon as the crop has been successfully established and hold water over to the stem elongation period.

Kingston and Ham (1975) found that stalk elongation rates increased rapidly once mean day temperatures exceeded 24^{o}C. Hence, a mean daily temperature of 24^{o}C was used as an index of the peak growth period (stem elongation) in Bundaberg. This was found to occur between November and March. Average irrigation cycle times were derived from November through the peak growth period to April. For the 400 kPa regime, Kingston and Ham (1975) noted that the irrigation interval on average was every 20 days for 72 mm of nett irrigation (providing rainfall didn’t exceed 89 mm).

Ridge (2001) also reported that increased soil moisture stress levels can be tolerated outside of the main growth period before growth rates are reduced. This allows a delay in irrigation during this period without affecting yields. Ridge and Hillyard (2000) found that the strategy of saving water early in the season and adopting an irrigation schedule linked to rainfall events in the peak growth period resulted in a high irrigation water use efficiency of 22.8 tonnes of cane / ML for the application of 2.4 ML / ha of irrigation to plant cane. The strategy of splitting limited water allocation between maintenance of crop early in the season and growth at full canopy development proved successful.

An irrigation scheduling strategy was developed by Ellis and Lankford (1990) to optimise sugar production for limited water supplies. The results showed that the early tillering phase was not sensitive to water stress. Similarly Langlier (1988) measured the sensitivity of sugarcane to water stress at various growth stages and found that the crop was least sensitive to water stress during tillering with the critical growth stage occurring during rapid growth.

Inman-Bamber and Jager (1988) investigated the variation of water use efficiency during the crop cycle and the effect of water stress during different stages of crop development. For a crop ratooned in early July, water use efficiency after November rose to nearly 0.4 t/ha/mm in unstressed cane during summer. This was approximately three times the water use efficiency over the entire season. Results indicated that there was a much greater potential for yield loss during stem elongation or rapid growth due to water stress.

To make the best use of limited water, Langlier (1988) also looked at the relative irrigation efficiency of each growth stage throughout the season with the aim of applying the limited water that was available to the most efficient stages. By concentrating on those periods where the applied water could be used more efficiently, overall water use efficiency was maximised. Results indicated that this occurred during the periods of peak growth.

2.4.3 Full vs. Limited Irrigation Supplies

Despite the work conducted in the 1970s, irrigation practices promoted in the Queensland sugar industry have focused on full irrigation. A state-wide extension campaign “Watercheck” (Shannon et al., 1996) was initiated to improve irrigation practices by extending previous research and knowledge to growers. Shannon et al. (1996) reported that much of the previous irrigation research conducted within the Australian sugar industry hadn’t been adopted by cane growers.

In Bundaberg, the focus of the Watercheck project was to improve irrigation efficiency through irrigation scheduling. It was perceived amongst extension staff that growers were applying more water than the soil could hold. The principal method of reducing over watering was to match the irrigation amount to the soil storage capacity and by having a better understanding of crop water use, determine an appropriate irrigation frequency.

Soils were characterised according to readily available water or the soil water holding capacity down to a refill point at which 50% of maximum stem elongation occurs. Irrigation strategies promoted through the Watercheck project were consistent with full irrigation which is reflective of the water resources available in Bundaberg at the time (refer to Section 1.2). Given that limited adoption of irrigation research had occurred prior to Watercheck and that irrigation practices promoted within the Queensland sugar industry have focused on full irrigation, further work is required to assist growers in developing and implementing strategies for limited water.

2.5 DEVELOPING STRATEGIES FOR LIMITED WATER

A review of the literature identified significant opportunities to improve the use of limited water. The literature highlighted the potential to maximise production by improving irrigation practice through adopting a broad multidisciplinary approach. Specifically the key opportunities to maximise the use of limited water are associated with improving irrigation system performance and maximising crop response.

Currently there is limited data available on the infield performance and operation of irrigation systems used in the Bundaberg district. While a number of strategies have been investigated in the literature for managing supplementary irrigation supplies (Section 2.4), these have typically focused on scheduling practices for a single field and have failed to identify clear and effective irrigation scheduling practices which consider the constraints imposed at a whole farm scale. Similarly, there has been a failure to identify opportunities to improve the efficiency of irrigation application systems and investigate the associated agronomic benefits (Sections 2.2 and 2.3)

Hence to develop strategies to maximise the use of limited water for sugarcane production it will be necessary to conduct an integrated research program which includes:

- Benchmarking current irrigation practices at the field and farm level via surveys;
- Undertaking on-farm irrigation performance evaluations and crop growth measurements; and
- Using crop growth models to investigate the production responses associated with alternate irrigation management strategies.

These strategies will target opportunities to maximise sugarcane yield by improving irrigation system performance and maximising crop response.

2.5.1 Irrigation System Performance

Improving the performance of the irrigation system is a simple and effective strategy to maximising the beneficial use of limited water supplies (Section 2.1). Higher irrigation efficiency means more water is beneficially used by the crop. Despite the significant use of both water winches and furrow irrigation systems in the Bundaberg District (91% of the irrigated area, Table 1-5) there is a lack of detailed information on the performance of these systems under commercial conditions. Hence there is a need to:

- Review current practices in relation to the operation of these systems;
- Compare current practices to operational settings which influence performance;
- Assess the performance of water winch and furrow irrigation systems in the field under commercial conditions; and
- Identify management practices which can be used to improve irrigation performance.

2.5.2 Maximising Crop Response

Irrigation strategies are dependant on the amount of water available for irrigation. Irrigation practices previously promoted within the Australian sugar industry have focused on full irrigation supplies. With limited water availability, a shift away from the traditional practice of full irrigation to deficit irrigation is required.

For limited irrigation supply irrigating to a deficit of 75% PAWC is promoted in the literature, which is equivalent to a soil moisture deficit at which 25 to 30% maximum stem elongation occurs. Trial results in Bundaberg indicated similar sugar yields could be obtained with up to 50% less irrigation water applied. With limited water supplies the literature also suggests irrigating during the main growth period, will maximise production.

Previous work has concentrated on the irrigation of a particular block and is removed from the context of multiple fields which make up a farm. Other considerations which must be taken into account are on farm constraints which influence irrigation practice. Hence there is a need to:

- Review current practices in relation to scheduling of irrigations for whole systems;
- Compare current practices to current knowledge;
- Relate current practices in the field to crop response; and
- Identify irrigation strategies which can be used to improve crop response with limited water supplies by considering the management of multiple blocks within an irrigation system and any associated constraints.

3 BENCHMARKING IRRIGATION PRACTICES

3.1 INTRODUCTION

There is little documented information regarding on-farm irrigation practices in the Bundaberg area. Hence, current irrigation practices were benchmarked from a grower survey to assist in identifying opportunities and develop irrigation strategies for limited water. Questions relating to general farming practice, irrigation management, the operation of irrigation systems and irrigation scheduling were included in the survey questionnaire. The grower survey included 91 growers across the district and using a range of irrigation application systems. The aim of the survey was to benchmark and evaluate irrigation practices so that opportunities to develop irrigation strategies for limited water could be identified.

3.2 METHODOLOGY

3.2.1 Survey Methodology

The grower survey was developed to benchmark irrigation practices across the Bundaberg district (see Stehlik and Mummery, 2000). Over 115 questions relating to irrigation practices were developed covering:

- Farm Size and Practice;
- Management of Irrigation;
- Irrigation Systems;
- Irrigation Type;
- Irrigation Scheduling; and
- Service and Information Support.

To evaluate irrigation performance, information was extracted from data specifically relating to irrigation management, irrigation systems, irrigation type and irrigation scheduling. The irrigation management section included monitoring of water use and cropping practices. The irrigation systems section included questions on the irrigation water supply and the application systems in use. The irrigation type section included specific questions relating to how irrigation systems were being operated. The irrigation scheduling section obtained information on the adoption of irrigation scheduling tools as well as the grower's understanding of soil water holding characteristics and crop water use.

The survey questionnaire was scripted into teleform software suitable for high speed scanning.   A pilot survey was conducted for feedback prior to completion of the final survey draft. Based on this feedback changes were made to the questionnaire before the final survey was undertaken.

The survey was designed using a stratified random sample based on mill area and irrigation system. A list of potential survey participants was stratified into mill areas and the irrigation systems that they used. Survey participants were then randomly selected from the stratified sample.   Individual surveys were conducted on the grower's property at a time and date that suited them. Each question was asked as written, to maintain the integrity and accuracy of the survey information and the response noted on the survey pro forma. Survey data was transferred from the survey pro forma into electronic form using high speed scanners.

3.2.2 Data Analysis

To assess how well irrigation management practices met crop demands, the equivalent daily irrigation application rate was calculated from machine settings (water winches) and the operating hours per day obtained in the grower survey. Current practice was then compared to the recommended crop water requirements for supplementary water supply (Section 2.4.1). The equivalent daily irrigation application rate for water winches was determined from the nozzle output, walking speed of the winch, operating hours and irrigation interval (rotation). For furrow systems, application data could not be extracted directly from the survey data, however the area furrow irrigated by a grower was obtained. For the original design of the Bundaberg Water Supply Scheme, the flow rate of irrigation off take outlets was based on area therefore it is reasonable to assume that flow rate characteristics per unit area for water winch and furrow systems are similar. The average flow rate per unit area calculated for water winch systems was applied to furrow systems. Over the area furrow irrigated, an equivalent daily application rate was then determined by accounting for the daily operating hours of furrow systems (which was recorded in the survey).

The engineering performance of water winches and furrow irrigation was assessed by comparing current practices to the factors discussed in Sections 2.2.2 and 2.3.2. For water winches these factors included wind (speed and direction), lane spacings, gun settings, nozzles and operating pressure. For furrow systems, field length, furrow flow rate, cut-off times, runoff, alternate furrow irrigation and cropping practices were reported to influence irrigation performance.

3.3 RESULTS AND DISCUSSION

In total 91 growers were surveyed, which represented 13% of irrigating cane farmers in the Bundaberg district. Growers commonly irrigated with more than one irrigation system on their farm. Of the 91 growers who were involved in the grower survey, 70 responded to the section on water winch irrigation and 53 responded to the section on furrow irrigation.

3.3.1 Operation of Water Winches

Wind Speed and Direction

Growers demonstrated an understanding of the effects of wind speed and direction (Section 2.2.2) on the performance of a water winch (Figure 3-1). Growers were asked to identify the maximum wind speeds and wind direction they would operate their systems.

Overall the majority of growers operating water winches (89%) preferred to irrigate when the wind direction was across the row (Figure 3-1). In comparison, only 37% of growers irrigated when the wind direction was parallel to the row. At wind speeds greater than 15 km/h, only 3% of growers irrigated when the wind was parallel to the row compared to 10% when the wind was across the row. At wind speeds between 10 and 15 km/h (upper limits for operating), 7% of growers irrigated when the wind was parallel to the row compared to 19% when the wind direction was across the row.

A large percentage of growers ceased irrigating at relatively low wind speeds. At wind speeds less than 5 km/h, and when the wind direction was across the row, 50% of the growers ceased operation. Whenever the wind direction was parallel to the row for all wind speeds, 52% of growers decided not to start.

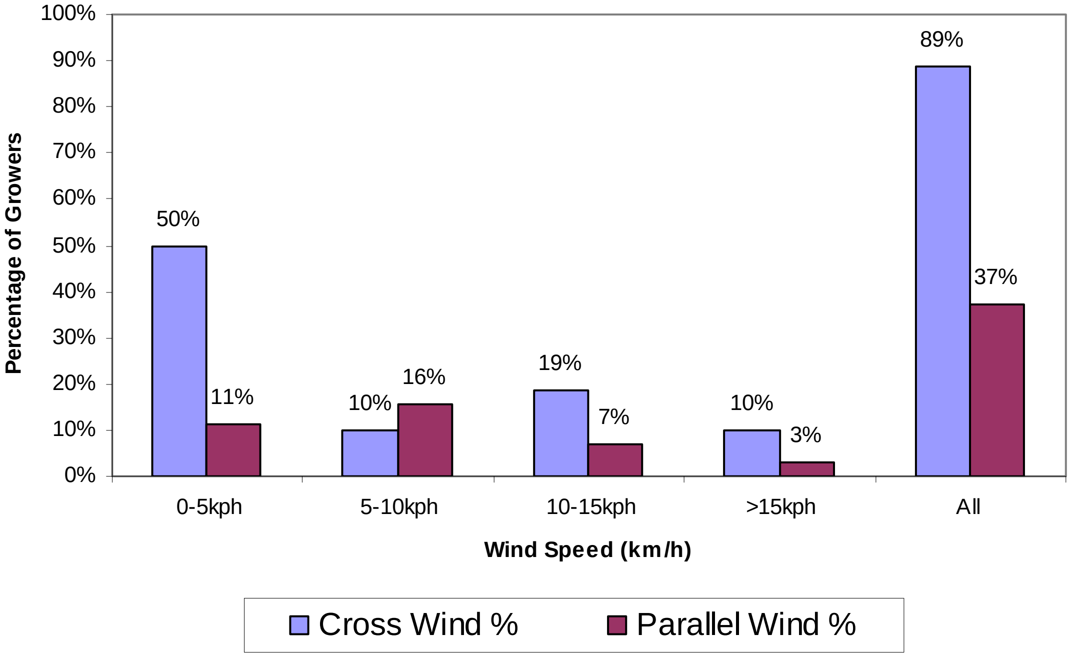


Figure 3-1 Maximum operating wind speed for water winches

In reality, low wind conditions would only represent a small proportion of a 24 hour period suggesting that growers would be forced to irrigate in less than ideal conditions, despite best intentions. Weather data for 1997/1998 recorded at Fairymead, north of Bundaberg was used to determine typical operating hours per day. Figure 3-2 is a cumulative distribution frequency graph of wind speed over a 24 hour period. From Figure 3-2, 40% of the daytime wind speed is greater than 15 km/h. During the evening this reduces to 15% of the time and in the morning to 5%.

This information indicates that the operation of water winches in low wind conditions is restricted during a 24 hour period. The best operating times for winches is during the morning and evening when there is a greater chance that the wind will be less than 15 km/h.

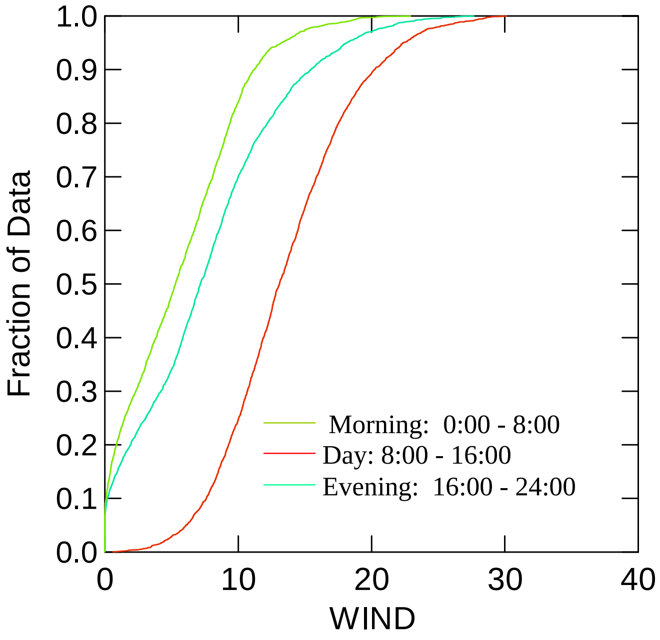


Figure 3-2 Wind Distribution (Fairymead 1997-1998)

Lane Spacing

Recommended lane spacings for water winches are 65% of the wetted diameter in low wind conditions and 40% in high wind conditions (Section 2.2.2). In no wind conditions, the wetted diameters of the machines generally range from 90 to 110 metres. Based on these recommendations lane spacings approximately 60 to 70 metres would be required under low wind conditions and less than 60 metres as wind speed increases.

From the survey information (Figure 3-3), most growers (76%) were operating water winches with lane spacings greater than 70 metres. Even for low wind conditions, most systems had lane spacing in excess of the recommendation. This suggested that further investigations were needed to evaluate current practice and to provide more appropriate lane spacings for the local conditions.

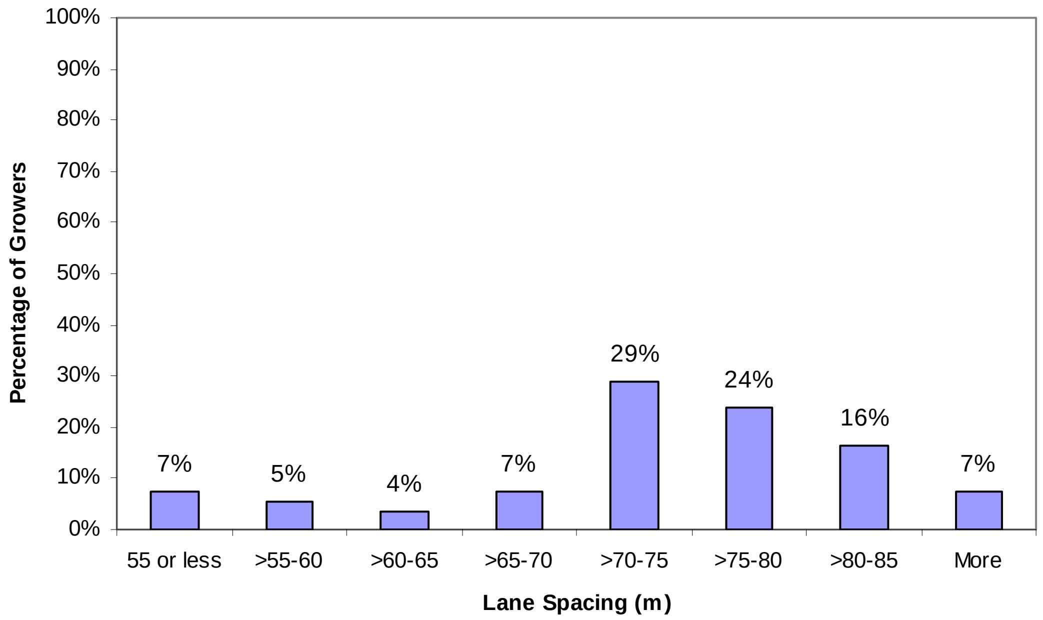


Figure 3-3 Lane spacing used for water winches

Gun Arc Angle

Only 24 % of growers operated at a gun arc angle within the optimum angle of 220 and 270 degrees (Figure 3-4). A large percentage (43%) of growers operated at arc angles less than 220 degrees and 32% of growers operated at more than 270 degrees. This suggests that a large percentage of machines could be fine tuned by changing gun arc angles but further work is required to determine the optimum gun arc angle.

Gun Trajectory Angle

From the grower survey (Figure 3-5) 66% of growers operated winches with trajectory angles of either 21 or 24 degrees. In still conditions, a trajectory angle of 24 to 28 degrees produces the greatest wetted diameter from the gun. In windy conditions, the wetted diameter is maximized at trajectory angles of 21 to 24 degrees. Hence, the results indicated that the majority of water winches had been setup with guns for windy conditions. However, a large percentage of growers weren't aware of their gun trajectory angle.

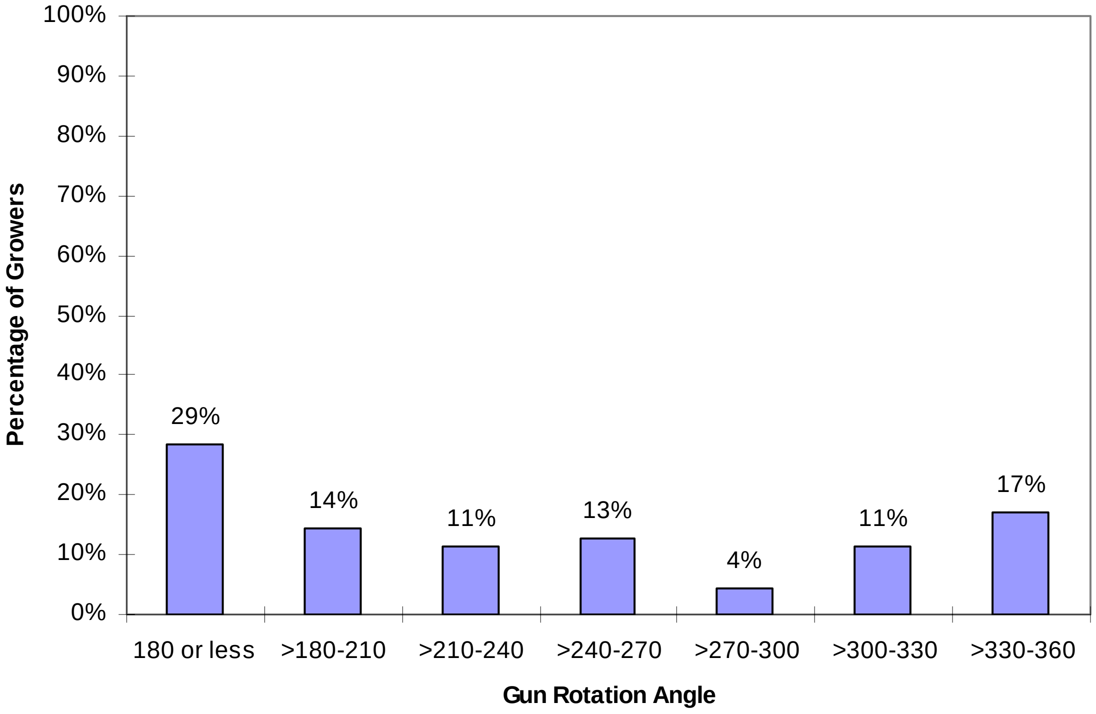


Figure 3-4 Gun rotational settings used on water winches

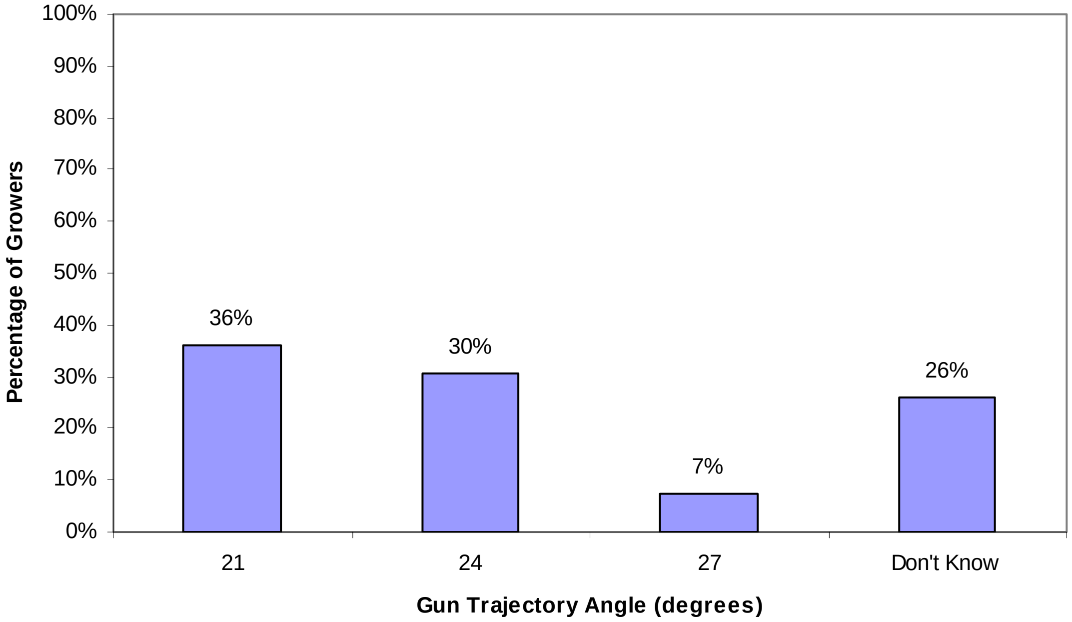


Figure 3-5 Gun trajectory angles used on water winches

Nozzle Type and Size

There are two types of nozzles available for travelling irrigators. Taper nozzles provide the greatest stream integrity and maximum throw distance in windy conditions while ring nozzles provide better stream break up. Overall the use of ring nozzles was much more common than taper nozzles (Table 3-1). At higher wind speeds (>10 km/h) the difference between ring and taper nozzles was less, however ring nozzles were more commonly used.

When the wind direction was across the row and wind speeds were greater than 10 km/h, 16% of growers used ring nozzles as opposed to 12% of growers using taper nozzles. Similarly 9% of growers used ring nozzles when the wind was parallel to the row compared to 1% of growers using taper nozzles. These results suggest limited awareness of the benefits of using taper nozzles at higher wind speeds. The common use of ring nozzles at higher wind speeds suggest that the performance of the winch could be improved by changing nozzles. This needs to be investigated further.

The most commonly used nozzle sizes were the 1.46" and 1.56" ring nozzles and the equivalent 1.2” and 1.3” taper nozzles sizes. From the results there didn’t appear to be any increase in use of the larger nozzles at higher wind speeds. The potential benefits of increasing nozzle size also needs further investigation.

Table 3-1 Percentage of growers* using specific nozzle types and sizes at various wind speeds and direction

Cross wind				
	Wind Speed km/h			
Nozzle Size & Type	0-5km/h	5-10km/h	10-15km/h	>15km/h
1.05”T	3%	1%	3%	1%
1.2”T	9%	1%	3%	0%
1.3”T	4%	1%	3%	0%
1.4”T	1%	0%	3%	0%
1.29”R	13%	3%	1%	1%
1.46”R	10%	1%	3%	4%
1.56”R	7%	0%	1%	3%
1.66”R	3%	1%	1%	0
Taper Nozzles (total)	17%	4%	11%	1%
Ring Nozzles (total)	33%	6%	7%	9%
All Nozzles (total)	50%	10%	19%	10%
Parallel Wind				
	Wind Speed km/h			
Nozzle Size & Type	0-5km/h	5-10km/h	10-15km/h	>15km/h
1.05”T	7%	0%	0%	0%
1.2”T	0%	3%	0%	0%
1.3”T	0%	1%	0%	0%
1.4”T	0%	1%	1%	0%
1.29”R	3%	3%	1%	0%
1.46”R	1%	6%	3%	1%
1.56”R	0%	1%	0%	1%
1.66”R	0	0	1%	0
Taper Nozzles (total)	7%	6%	1%	0%
Ring Nozzles (total)	4%	10%	6%	3%
All Nozzles (total)	11%	16%	7%	3%

** Percentage of growers operating water winches*

Pressure

The recommended operating pressure at the gun is typically between 75 and 85 psi. From Figure 3-6, only 37% of growers operated the gun within this range. Half of the growers operated the winch at a pressure less than 75 psi. The performance of water winches in relation to nozzle pressures needs further investigation.

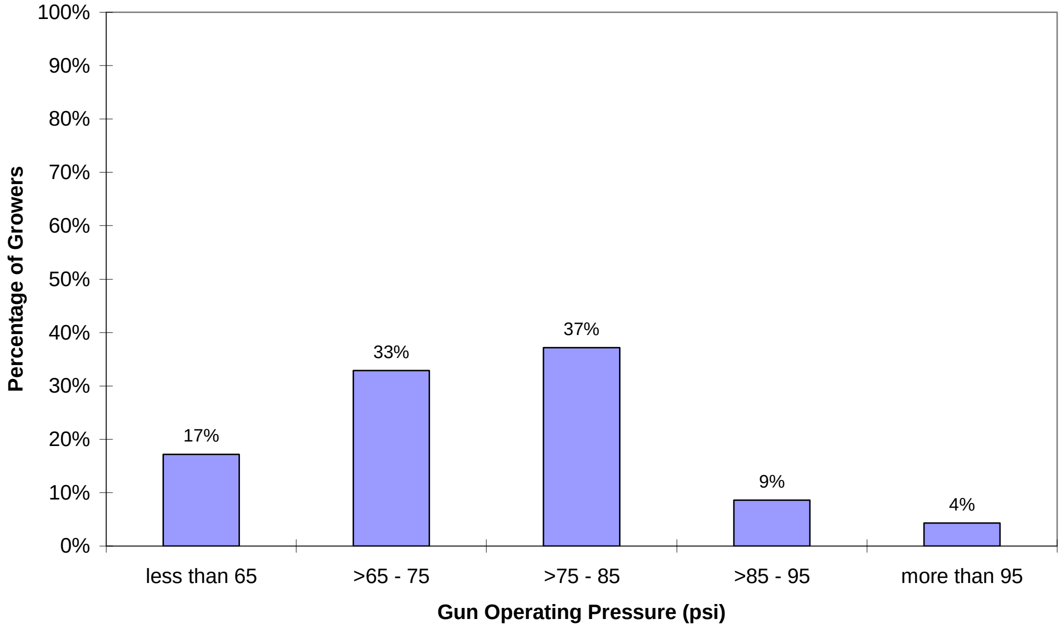


Figure 3-6 Gun operating pressures used on water winches

3.3.2 Operation of Furrow Irrigation

Field Design

As a general guide, maximum row lengths for medium to heavy textured soils were presented in Section 2.3.2 Depending on soil, maximum field lengths ranged between 250 and 400 metres. Only 4% of fields furrow irrigated had row lengths longer than 400 m (Figure 3-7). Results indicated that field lengths for furrow irrigation in Bundaberg were appropriate to maximise irrigation performance.

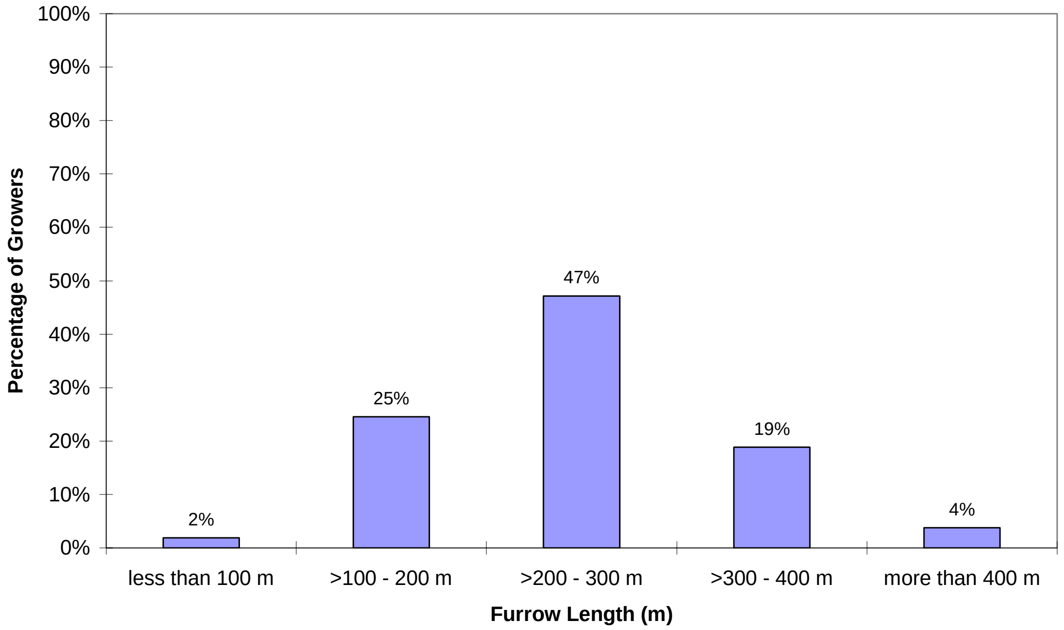


Figure 3-7 Furrow length in use

Furrow Flow Rate and Cut-off Times

Furrow flow rate controls the amount of water applied to the field. Significant increases in irrigation performance of furrow systems can be achieved by altering furrow flow rate. Despite this, only 5% of growers surveyed knew the furrow flow rate of their system. Opportunities to fine tune the performance of furrow systems by changing furrow flow rate needs to be further investigated.

The duration of the irrigation or the cut-off time is also an important factor in maximising irrigation performance. Broad recommendations for appropriate cut-off times include turning the water off just as the water reaches the end of the field or even before this time if irrigating with high furrow flow rates. Results from the grower survey (Figure 3-8) suggest a very good understanding of this concept. From the survey 83% of growers either turned the water off at the end of the field or before. Only 17% of growers soaked the end of the field and of these, 90% had tail water return or banked the end of the field.

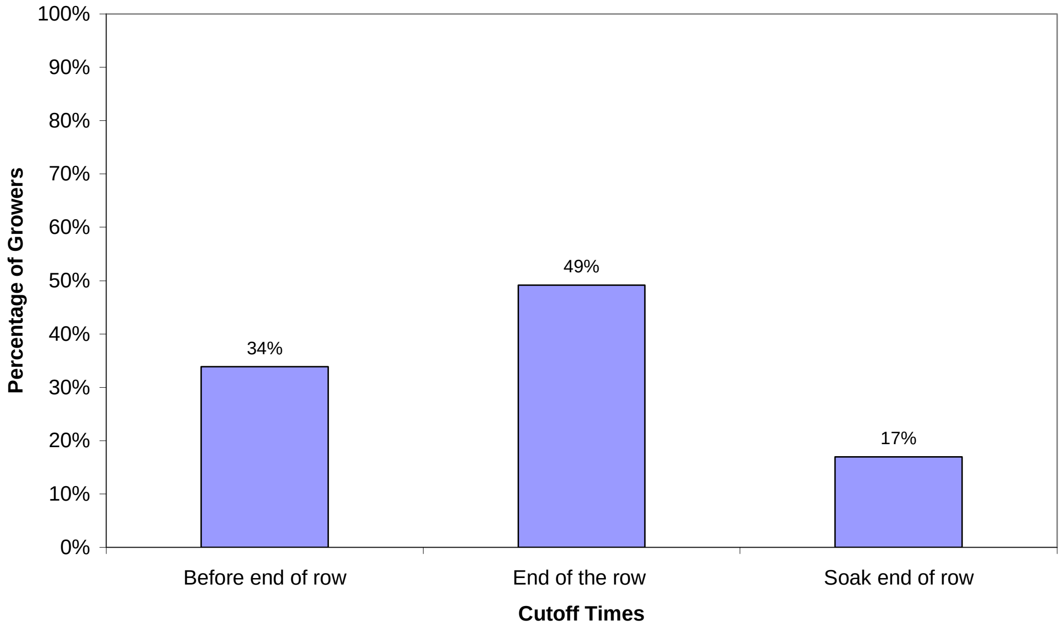


Figure 3-8 Irrigation cutoff times used by growers

Consistent inflow between furrows is vital to accurately control cut-off times. The precision at which the irrigation can be operated is reduced if furrows advance at different times. Variation of furrow inflow can occur with both layflat and gated pipe (Section 2.3.2). Consistent furrow inflows, using layflat, are a function of uniform outlet size. Hand cut cups and adjustable cups can cause significant variation in flow due to uneven aperture size. This is dramatically reduced using moulded orifice cups.

From the survey (Figure 3-9) only 10% of furrow irrigation systems using layflat were operated with moulded cups. The use of moulded cups provides a simple solution to assisting improvements in the performance of the irrigation system by maximising the effects of other operational changes such as inflow and cut-off times.

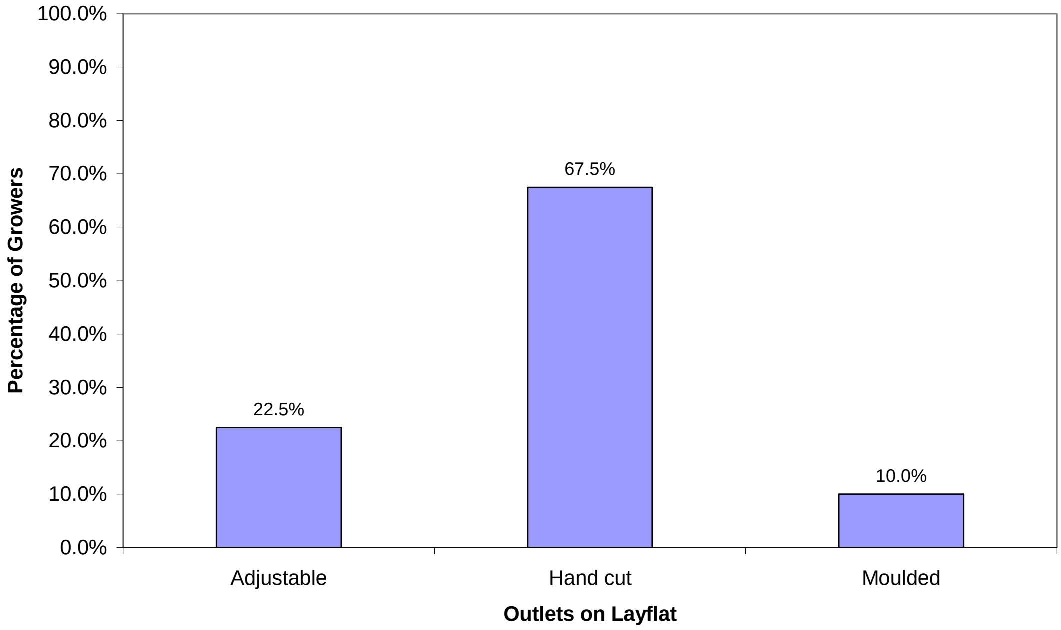


Figure 3-9 Outlet types used on layflat

Banked Furrow Ends and Tailwater recycling

Banking furrow ends reduces runoff by effectively damming the end of the field. This allows the irrigation to be shut off earlier as surface water from the top of the field drains to the bottom of the field. The grower survey (Figure 3-10) indicated 55% of growers banked ends.

Tail water recycling reduces runoff by collecting and recycling the water that runs off the field during irrigation. Results from the grower survey (Figure 3-10) indicated 43% of growers have tail water recycling systems. Overall, growers applied appropriate practices in relation to the prevention of runoff.   A significant proportion (81%) of growers reduced runoff by either banking the end of the field and/or tail water recycling.

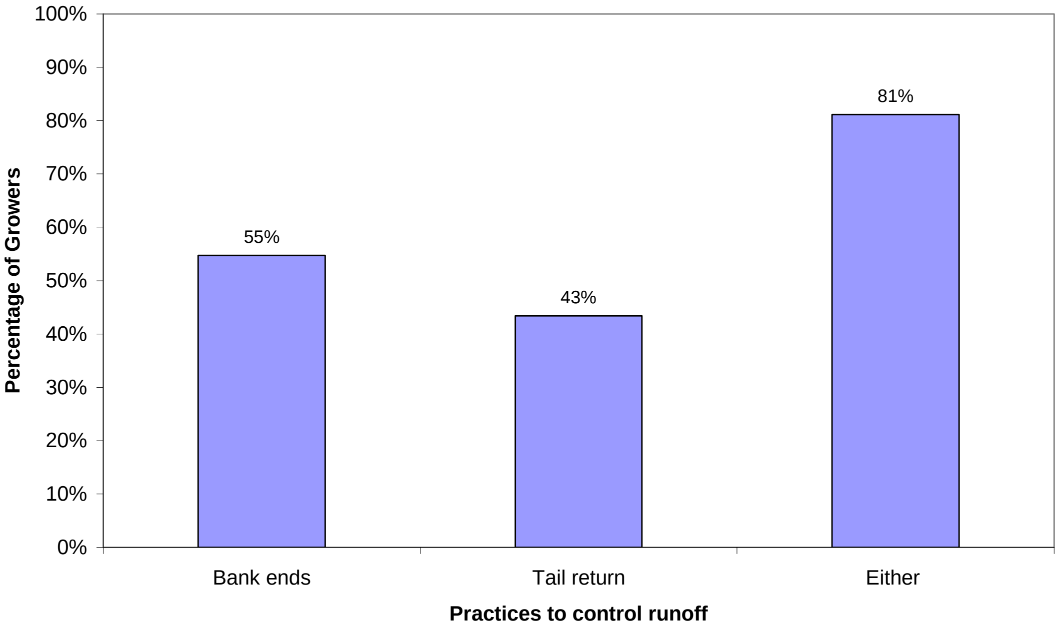


Figure 3-10 Use of banked ends and tail water return

Irrigating Alternate Furrows

Irrigating alternate furrows can be a useful management practice to reduce the amount of water applied to the field. Alternate furrow irrigation is particularly effective at reducing deep drainage on high infiltration soils. From the grower survey, 13% of furrow irrigators practiced alternate furrow irrigation. This is supported by information collected by Bundaberg Sugar Ltd which reports that 12% of furrow systems (by area) are operated as alternate furrow.

The survey results indicate a significant use of alternate furrow irrigation already in the Bundaberg district. Based on the potential benefits of alternate furrow irrigation, particularly on highly infiltrating soils, alternate furrow irrigation provides an opportunity to improve irrigation performance on these soil types.

Cropping Practices

Cropping practices which can influence irrigation performance include cultivation, crop residues and furrow shape. Cultivation improves water infiltration where soils are hard setting and water penetration is poor. Crop residues can also improve irrigation performance by assisting water infiltration. Changing furrow shape can also alter the infiltration characteristics of the field. A “V” shaped furrow reduces infiltration while a “U” shaped furrow promotes infiltration (Section 2.3.2).

From the grower survey, 53% of furrow irrigators cultivate to improve water penetration while 62% of the area farmed by furrow irrigators is trash blanketed. A large percentage of growers (72%) altered furrow shape to improve irrigation efficiency. Although these figures are not indicative of irrigation performance they do suggest that cropping practices are recognised by growers as influencing irrigation performance. How these practices may influence irrigation performance needs further consideration. For example, where soils infiltrate rapidly, cultivation and crop residues may enhance deep drainage due to excessive infiltration. Minimum tillage on these soils may maintain compaction in the furrow which reduces infiltration and deep drainage. Cropping practices can have a significant impact on irrigation performance and further investigation is necessary.

3.3.3 Irrigation Management

Current Practices

Over 60% of growers surveyed were operating their water winch and furrow irrigation systems in a manner similar to the recommended crop requirements for supplementary irrigation supplies (Section 2.4.1). Under limited water, irrigation requirements reduce from 6 mm/day to 5 mm/day as the pan factor is reduced from 0.85 to 0.65 (Section 2.3.1). Figure 3-11 displays the equivalent daily volume of water applied by growers based on how the irrigation systems were being operated.

The largest percentage of irrigation systems were operated to supply the equivalent of 5 mm/day. Based on current practices, 29% of growers using water winches and 37% of furrow irrigators applied the equivalent of 5 mm/day. A significant percentage of growers also applied 4 and 6 mm/day. Equivalent daily application rates ranging from 4 to 6 mm/day represented 69% of growers using water winches and 63% using furrow irrigation.

Under current operating practices, the majority of growers were unlikely to be over irrigating (Figure 3-11). From the data, 65% of winch and 63% of furrow systems applied the supplementary irrigation requirements or less (ie. ≤ 5mm/day). For full irrigation practices, which allows for a slight moisture stress, (6 mm/day ie. pan factor = 0.85) 18% of winch and 26% of furrow irrigators had application rates higher than 6 mm/day. Only 12% of winch irrigators and 15% of furrow irrigators had application rates higher than the peak transpiration of the crop (7 mm/day ie. pan factor = 1.0).

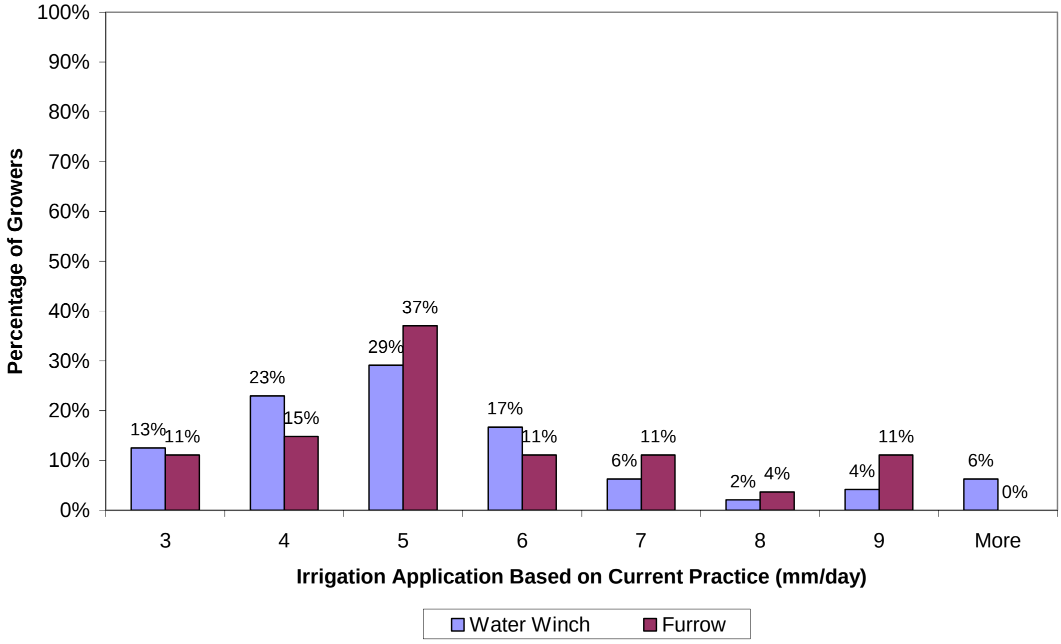


Figure 3-11 Daily application rates for water winch and furrow irrigation

Opportunities to Better Meet Crop Demand

The volumes applied by water winches, although similar to furrow systems, were slightly skewed to less than 5 mm/day. Figure 3-12 and Figure 3-13 display the operating hours per day and the irrigation rotation. A larger percentage of furrow systems operate for a greater number of hours per day. This is reflected by the irrigation rotation. Overall these differences result in furrow systems being able to apply more water and better meet the demands of the crop. The results also suggest that there is potential for winch systems operating below 5 mm/day to better meet crop demands by operating for longer periods during the day. However, this would be dependant on having suitable wind conditions for irrigation.

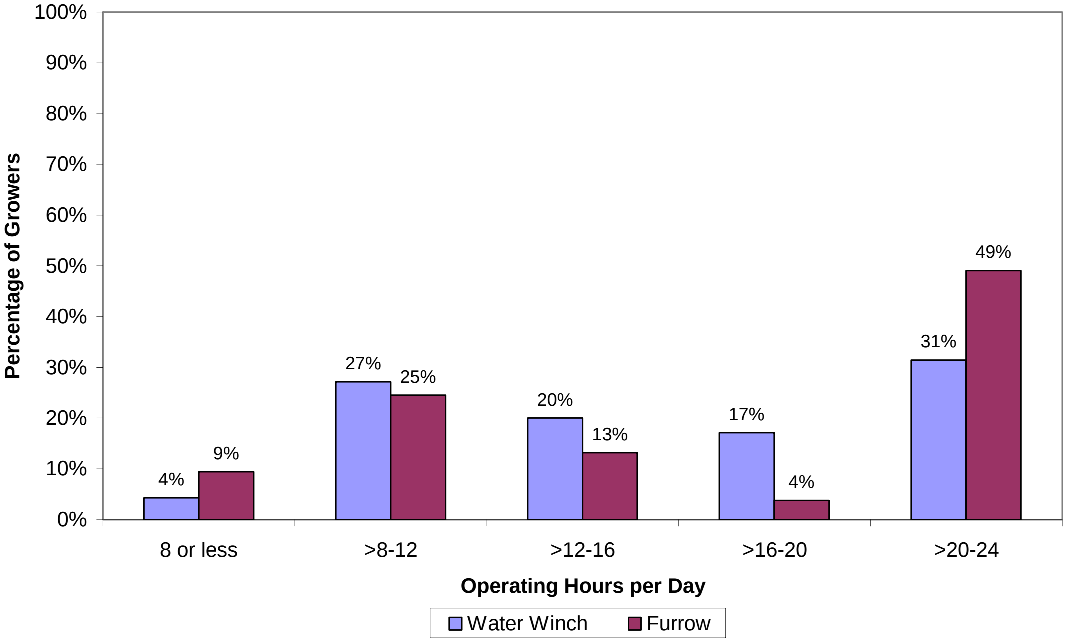


Figure 3-12 Daily operating hours of water winch and furrow irrigation

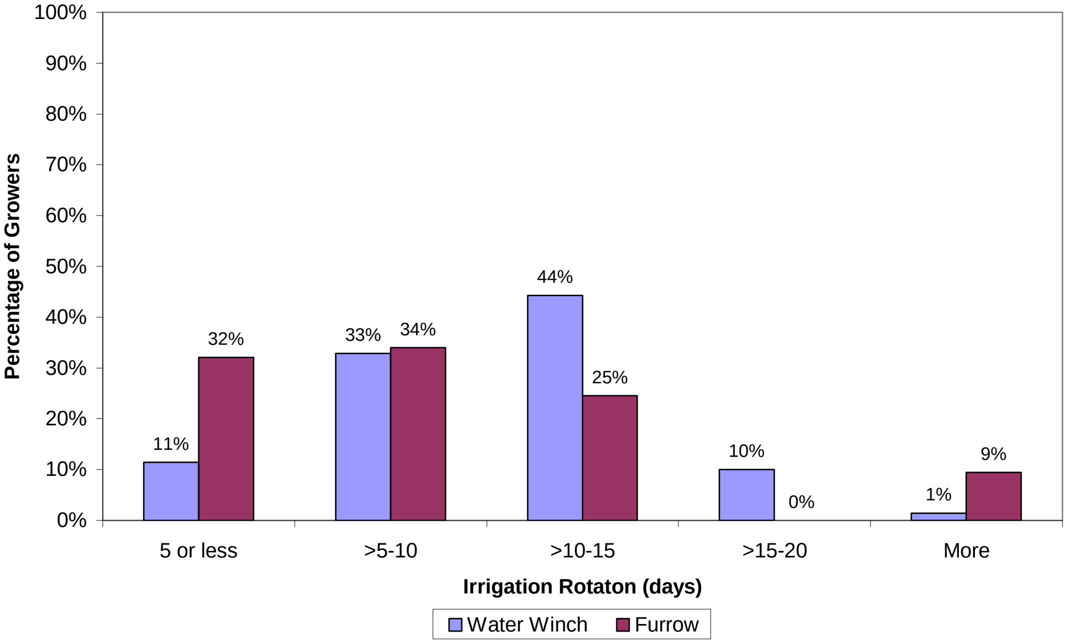


Figure 3-13 Irrigation rotation of water winch and furrow irrigation

Irrigation Scheduling

Grower responses to the survey did not demonstrate a high level of understanding in relation to the principles of irrigation scheduling and the implementation of supplementary irrigation recommendations. Irrigation scheduling was not widely adopted with only 16% of growers using irrigation scheduling tools. These tools included evaporation data, soil moisture monitoring equipment and crop growth measurements. In addition, growers demonstrated a limited understanding of soil water holding characteristics and crop water use. Only 34% of growers had an appreciation of how much water their soils held while only 22% of growers were able to relate irrigation amounts to equivalent days of crop water use. However, considering that most irrigation systems are not able to meet the crop demands, irrigation scheduling would only be required at critical times such as start-up after rain or earlier in the season where the crop demands are less.

Starting Irrigation after Rain

Although recommendations for irrigation with supplementary irrigation supplies were identified in the literature, the translation of these recommendations to the management of multiple blocks on start-up after rain is not clear. From the grower survey, start up after rain commonly occurred 5, 7, 10, and 14 days after rainfall (Figure 3-14). The most common practice was to start irrigating 14 days after rain followed by 10, 7 and 5 days. A significant number of growers decided to irrigate after 14 days. Given that most of the systems were unable to meet crop water use requirements, a critical aspect of managing limited water resources appears to be start-up after rain. Hence, identifying a clear strategy for start-up after rain requires further investigation.

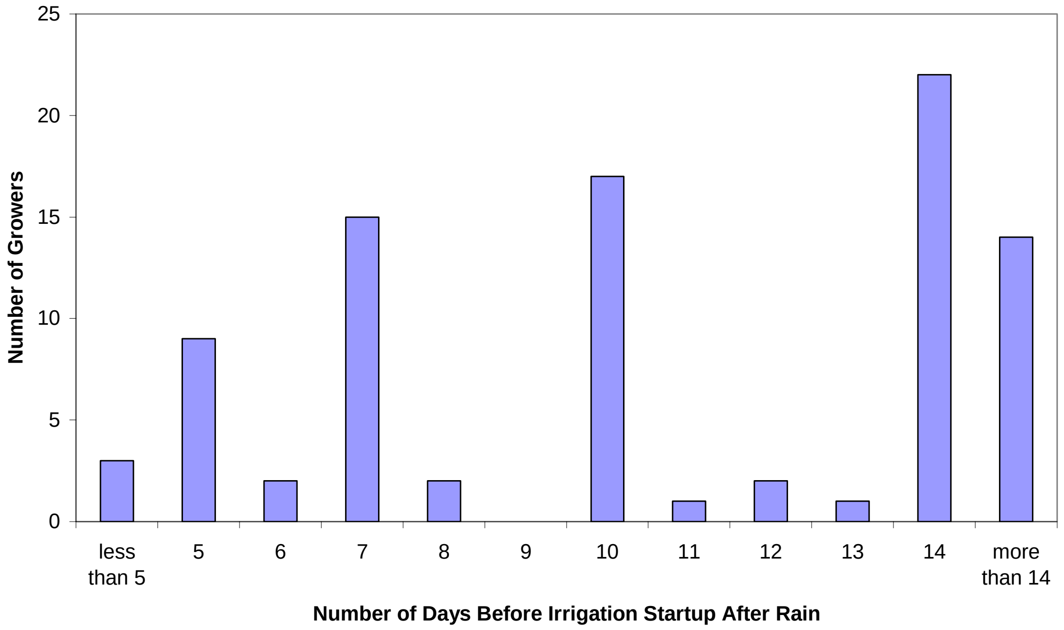


Figure 3-14 Days before irrigation is applied after rainfall

3.4 CONCLUSION

Current irrigation practices were benchmarked and evaluated in relation to the recommendations discussed in Chapter 2. From the evaluation of current practices opportunities were identified to improve irrigation performance.

Improving Water Winch Performance

Most growers currently using water winches were aware of the effects that wind can have on irrigation performance. This was reflected in the results of the survey where growers opted to irrigate under low wind conditions. Opportunities to irrigate in these conditions are limited suggesting that growers would be forced to irrigate in less than ideal conditions.

Strategies to improve the performance of water winches in windy conditions need to be developed. The use of taper nozzles and increased nozzle sizes for example were reported to improve irrigation performance under windy conditions. The survey results didn’t indicate a preference to use either taper nozzles or larger nozzles sizes in windy conditions. Other factors which influence irrigation performance include lane spacing, gun arc angles and operating pressures. The majority of growers were operating outside of the recommendations for these settings. The impact that these settings have on irrigation performance needs to be evaluated under local conditions so that strategies for improvement can be developed.

Improving Furrow Irrigation Performance

The results from the survey indicated that the field length of most furrow systems was appropriate to maximise irrigation performance. Growers typically had an understanding of correct cut-off times and attention to reducing runoff with 81% of growers banking ends or tail water recycling.

From the survey results strategies for improving the performance of furrow irrigation systems should be focused towards fine tuning furrow flow rates. Most growers were unaware of the flow rate that their system was setup for, suggesting a poor understanding of the impacts on irrigation performance. Significant gains in irrigation efficiency could be made by changes to furrow flow rate (section 2.3.2). The other aspect of furrow flow rate requiring improvement was consistency of flow between rows. This is a function of uneven cup sizes which could be overcome by using moulded orifice cups (section 2.3.2). The survey results indicated only a small percentage of growers (10%) were using moulded cups.

Alternate row irrigation has been suggested (section 2.3.2) as a method to improve irrigation efficiency on high infiltration soils. Already, 13% of growers have adopted these practices. Cropping practices were considered by growers to influence irrigation performance and there maybe scope to improve performance by better matching cropping practices to soil infiltration (eg. shallow cultivation on high infiltration soils to reduce deep drainage).

Management of Limited Water

Current irrigation practices for water winch and furrow irrigation indicated that over 60% of growers were operating their irrigation systems similar to the recommended crop requirements for supplementary irrigation supplies. This was despite only a limited adoption of irrigation scheduling tools and knowledge of plant and soil water relationships. Under current operational practices the capacity of these systems barely met the full crop water requirements for the majority of growers. This indicated that due to these constraints, irrigation scheduling was dictated by the capacity of the system. Furrow systems had more capacity due to longer operating hours per day which shortened the irrigation rotation. This suggested that opportunities may exist to modify winch operation to better match supplementary irrigation demands.

Strategies for the management of limited water also need to focus on when irrigation is applied after rain. Considering that most irrigation systems were unable to meet the crop water demands, the major opportunity to improve the management of limited irrigation supplies was irrigation start-up after rain. Although recommendations for irrigation with supplementary irrigation supplies were identified in the literature, the translation of these recommendations to the management of multiple blocks on start-up after rain is not clear. The majority of growers started irrigating 14 days after rainfall events. However, other significant periods were 10 and 7 days after rain. Clearly this needs to be investigated further so that appropriate strategies can be developed.

4 PERFORMANCE OF TRAVELLING GUN IRRIGATORS

4.1 INTRODUCTION

Water winches were introduced to the Bundaberg District in the 1970s as a labour saving alternative to hand shift sprinklers. Presently 55% of the Bundaberg District is irrigated by travelling gun irrigators. The operation of travelling gun irrigators was examined to identify how the machine could be fine tuned to maximise yield. The performance of these machines and the impacts of various settings on performance were examined in field trials. These trials examined the uniformity of the system, measured by Christiansen's Uniformity Coefficient (CU) as a key indicator of performance. Atmospheric losses were also examined as an indicator of application efficiency.

4.2 METHODOLOGY

Trials were conducted to measure the uniformity of travelling gun irrigators over a range of conditions. The trial work identified how changes to the settings on these machines could improve overall performance. Testing was conducted on the most common type of water winch gun in the Bundaberg District, a Nelson P200 gun with a 21^{o} trajectory angle. The travel speed of the cart was set at 20 metres/hour (approximately 1 chain per hour). The actual machine used for testing was a Trailco Traveller T450-2. All trial work was conducted on Bundaberg Sugar farms.

Simple changes to machine settings were evaluated to determine their impact on performance over a range of conditions. The machine settings that were tested included:

- nozzle size and type (ring, R vs. taper, T) - 1.46"R, 1.56"R, 1.2"T & 1.3"T);
- pressure – 515, 550, 585 kPa (75, 80, 85 psi); and
- gun arc angle settings of 330, 270 and 240 degrees.

The uniformity of the sprinkler pattern was measured using catch cans arranged in transects either side of the winch track, known as a standing leg test. Catch cans were made from 90 mm PVC pipe with caps glued into the ends (Figure 4-1). The cans were spaced at 5 metre intervals and raised 900 mm above the ground to avoid interference with the crop (Figure 4-2). To simulate the distribution pattern at the soil surface a stand pipe was used to raise the nozzle by 900 mm. Three tests were conducted with cans raised 3 metres above the ground to simulate interception from a mature crop. These tests were also conducted with cans at the lower height.

Figure 4-1 Catch can - 90 mm PVC pipe with glued end caps

Other measurements included hydraulic pressure at the gun, flowrate and wind speed and direction.   Pressure was measured using a new factory calibrated pressure gauge taped into the gun. Flowrate was recorded using an inline flowmeter that had been calibrated to +/- 3%. Wind speed and direction data were recorded by an automatic weather station.

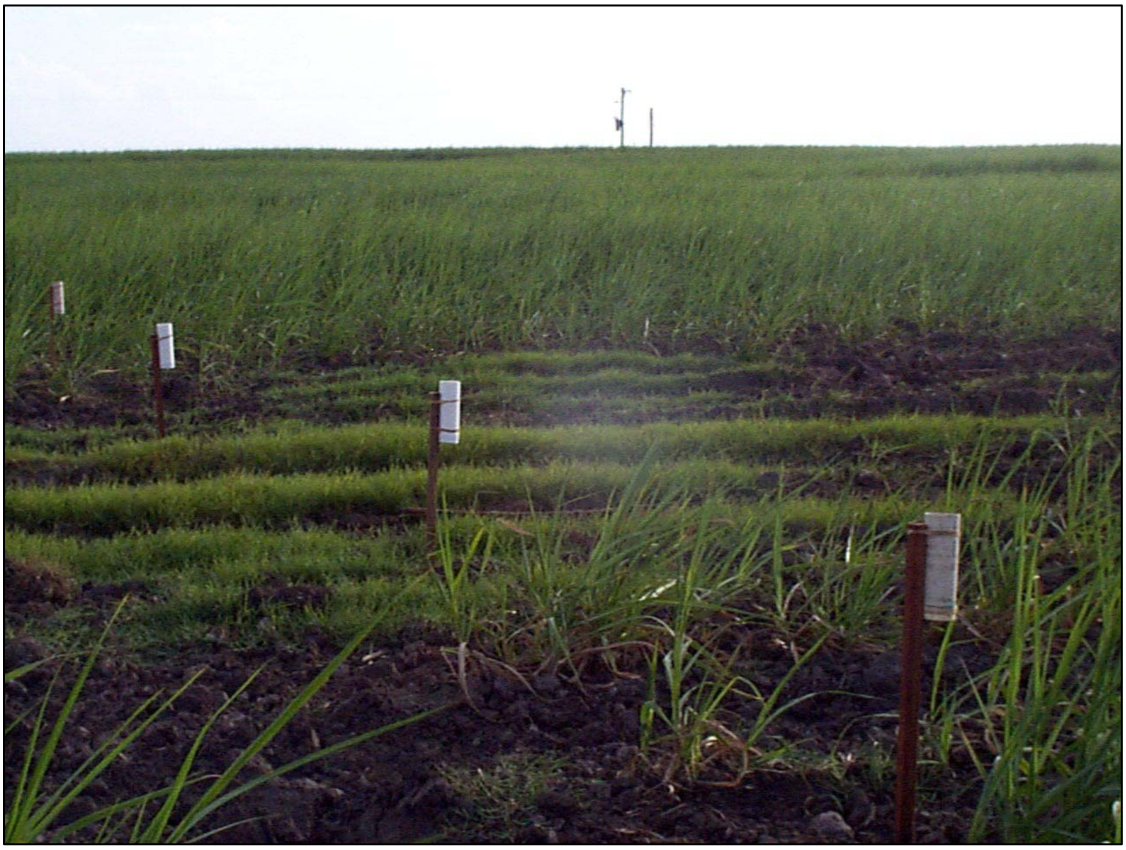


Figure 4-2 Catch cans arranged in a standing leg test

4.3 RESULTS AND DISCUSSION

Initially 22 tests were conducted and the Christiansen's Uniformity Coefficient (CU) was calculated for each test using a 75 metre lane spacing. A summary of the results is presented in Table 4-1 while the full data set was presented by Gordon (2000).

The CU ranged from 48% to 84% (with a mean of 73%) which was poor given a CU of 84 to 86% is traditionally considered acceptable (Smith et al., 2002).   A further 2 tests were conducted to evaluate the effect of gun arc angles on spray patterns (Table 4-2). Optimum lane spacings were also determined by manipulating overlap to simulate different lane spacings. The mean depth of water applied by the winch for each test was determined from catch cans and the flowmeter to identify atmospheric losses (and application efficiency).

Table 4-1 Christiansen's Uniformity Coefficient (CU) for water winch trials

Trial No.	Nozzle	Gun Pressure (kPa)	Wind Speed (km/h)	Wind Direction	Mean applied depth (mm) *flowmeter*	Mean applied depth (mm) *catch cans*	CU (%) 75 m lane spacing	Optimum lane spacing (m)	Atmospheric Loss	Application Efficiency
1	1.2T	550	7.1	parallel	60	47.3	84.2	65	21%	79%
2	1.2T	550	14.3	cross	60	41.8	79.6	75	30%	70%
3	1.2T	515	3.8	cross	60	35.1	77.8	85	42%	58%
4	1.2T	585	15.1	parallel	64.8	40.7	73.1	65	37%	63%
5	1.46R	550	14.1	parallel	60	38.1	48.3	55	28%	72%
7	1.46R	515	12.4	parallel	60	42.6	56.5	55	29%	71%
8	1.46R	585	14.9	parallel	68.64	54.2	69.6	65	21%	79%
9	1.3T	515	4.5	cross	68.64	59.5	80.5	55	13%	87%
10	1.3T	550	8.9	cross	70.56	47.7	84.5	75	32%	68%
11	1.56R	585	9.3	cross	72.72	54	77.2	65	26%	74%
12	1.3T	550	11.6	cross	70.56	52.9	78.6	55	25%	75%
13	1.3T	515	10.6	parallel	68.64	58.6	83.5	65	15%	85%
14	1.2T	550	12.3	parallel	60	52.7	79.1	65	12%	88%
16	1.46R	550	13.8	parallel	64.8	44.5	60.9	65	20%	80%
17	1.2T	585	17	parallel	63.12	40	48.8	55	32%	68%
18	1.2T	515	13	cross	58.56	32.4	67.1	55	45%	55%
19	1.46R	515	14.5	cross	61.44	37.3	66.8	55	39%	61%
20	1.46R	550	13.3	cross	64.8	49	80	85	24%	76%
21	1.46R	585	22.2	cross	64.8	46.5	70.8	65	28%	72%
22	1.2T	515	13.3	parallel	57.12	54	72.3	65	5%	95%

4.3.1 Application Patterns

An example of the distribution patterns from one pass of a water winch at low wind speed (trial 3) and at high parallel wind (trial 4) is shown in Figure 4-3. The main features of the sprinkler patterns include:

- A wetted diameter of approximately 100 metres;
- Peaks either side of the winch track due to the walker jets; and
- Peaks about 30 m either side of the winch track from the 330 degree rotation angle / arc angle of the gun.

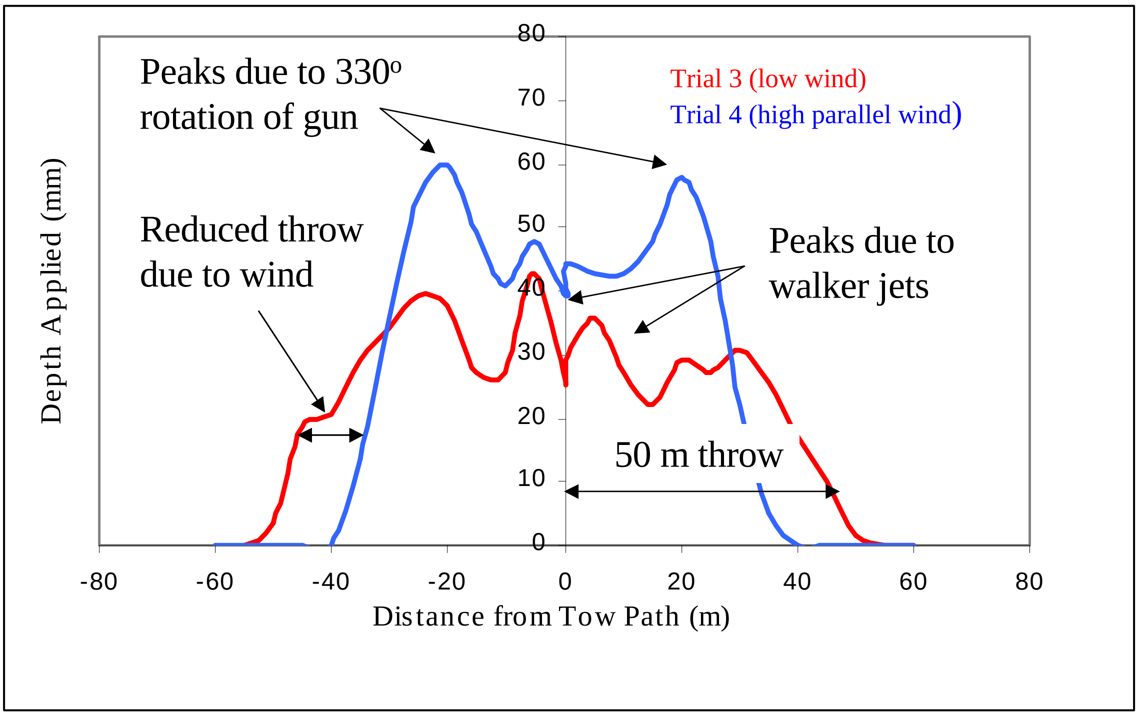


Figure 4-3 Spray pattern characteristics

The final distribution of water applied to the field for trial 3 is shown in Figure 4-4. The applied depths are a result of two adjacent passes of the machine. The applied depths between both winch tracks were determined by overlapping two sprinkler patterns 75 metres apart (ie. typical spacing between winch tracks).

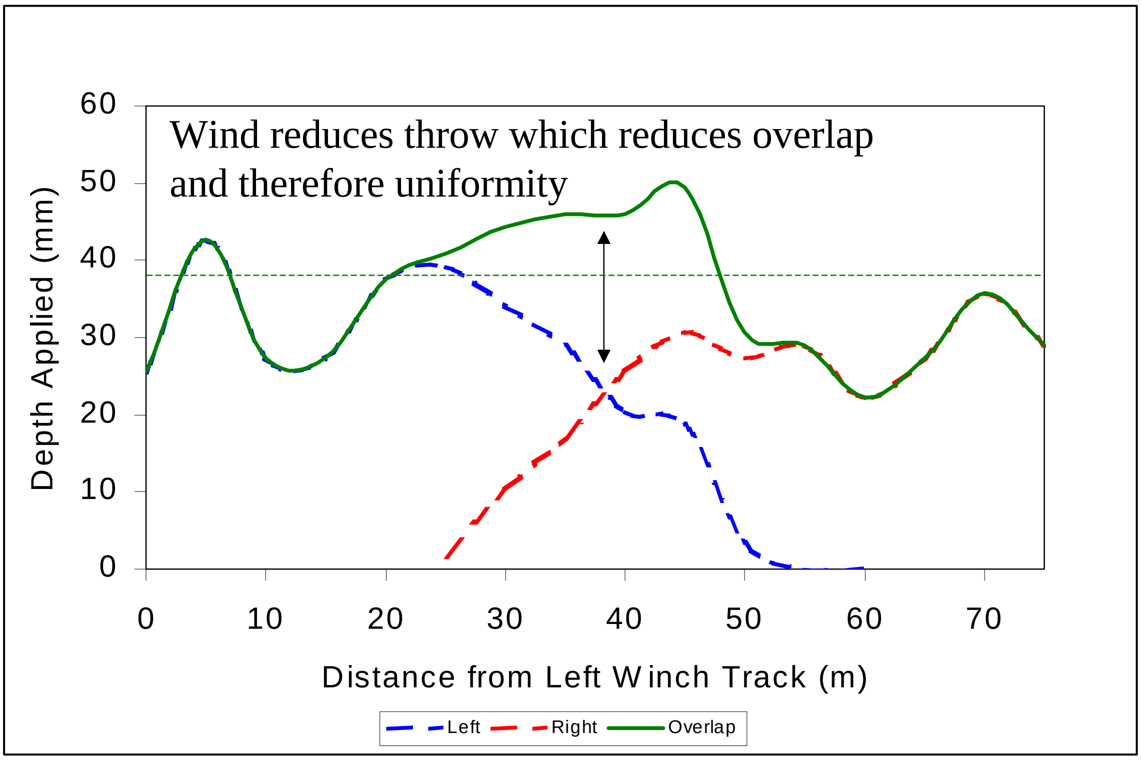


Figure 4-4 Sprinkler overlap and uniformity

The mean depth of the application is 35.1 mm however the applied depth varies from 25 to 51 mm. In this case, the CU of the irrigation event was calculated as 77.8% which is poor when compared to the recommendations in the literature of 84 to 86% CU for acceptable performance.

4.3.2 Wind Speed and Direction

Wind speed and direction had the most significant influence on irrigation performance. Uniformity decreased with increasing wind speed, particularly when the wind direction was parallel to the travelling direction of the winch. This was due to the considerable reduction in throw distance across the field, which reduced the wetted diameter of the sprinkler pattern, resulting in less overlap.

The wetted diameter of the gun was typically 90 to 110 metre in low wind conditions. However, in the most extreme case high parallel winds reduced the wetted diameter to approximately 60 metres. Under these conditions a 10 metre section of the field was left unwatered as the sprinkler patterns from adjacent tow paths didn't meet, resulting in a CU of 48%.

Observations were consistent with the recommendations in the literature (Section 2.2.2) to cease operating at wind speeds greater than 16 km/h or when the wind direction is parallel to the travelling direction of the winch. For parallel winds at speeds from 10 to 15 km/h, CU decreased from approximately 80% to 50% (Figure 4-5). This compared to cross wind conditions where the reduction in CU was less and reduced from approximately 80% to 65% (Figure 4-6). The variation in CU for parallel winds was consistent with the range reported by BSES (1984). For a cross wind, the CU at wind speeds approaching 16 km/h was consistent with trials reported by Jensen (1983). The variation between test results for similar wind speeds was greater for high parallel wind conditions (40%) compared to the same wind speeds for a cross wind (20%).

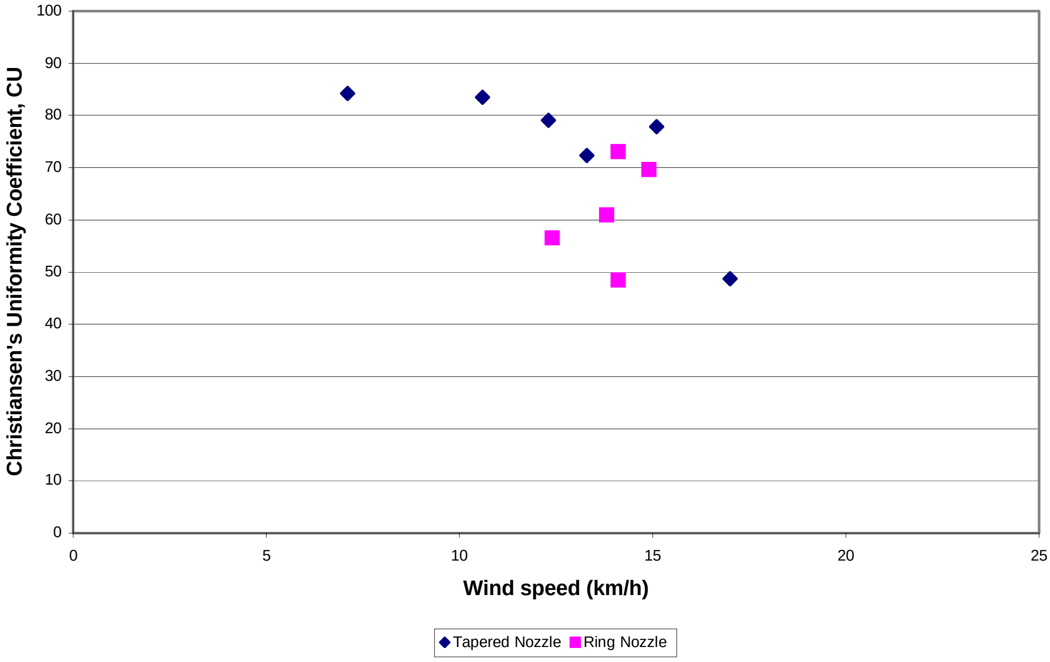


Figure 4-5 Performance of taper and ring nozzles in a parallel wind

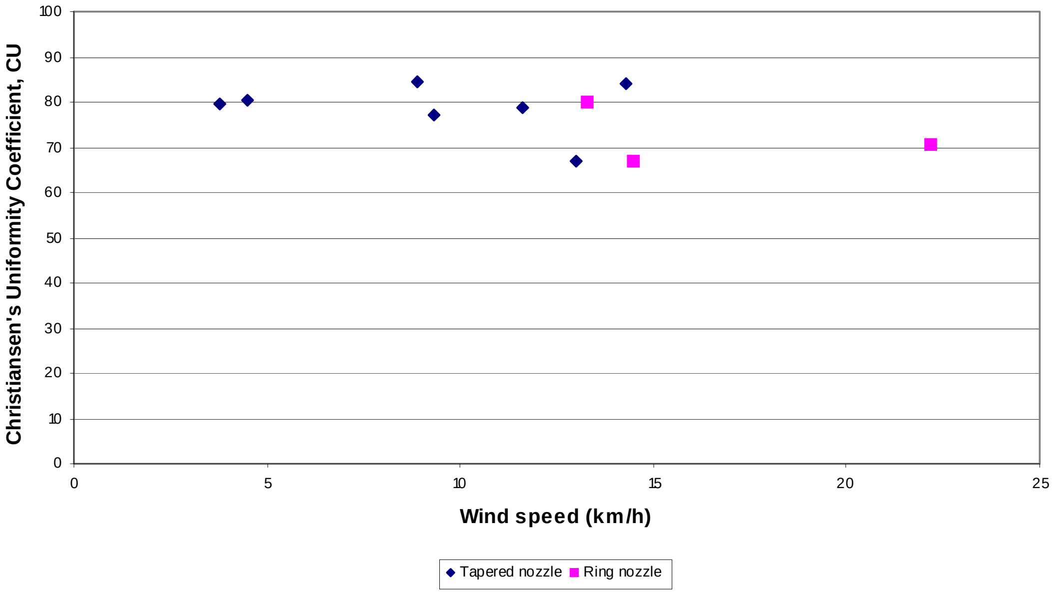


Figure 4-6 Performance of taper and ring nozzles in a cross wind

4.3.3 Lane Spacing

Apart from trials 2, 3 and 10 which occurred at low wind speeds, the performance of water winches would be greatly improved by reducing the lane spacing. Lane spacings of 75 to 80 metres are adopted locally. These lane spacings equate to approximately 70 to 90% of the wetted diameter. Optimum lane spacings of 55 to 65 metres were calculated. This was achieved by manipulating the data to simulate various overlap of the distribution patterns (Table 4-1) to maximize CU. Lane spacings of 55 to 65 metres equate to 50 to 70% of the wetted diameter.

Lane spacings recommended by manufacturers using Nelson P200 guns range from 65 to 80% of wetted diameter. Jensen (1983) made general recommendations of 65% wetted diameter reducing to 40% in high wind conditions. The optimal lane spacings calculated in the trials are consistent with these recommendations. For many growers with established irrigation systems, changing lane spacing would be impractical. Under these circumstances other strategies need to be adopted to improve irrigation uniformity.

4.3.4 Nozzle Type

Taper nozzles were found to maintain a greater wetted diameter by throwing the water jet further under windy conditions. The performance of taper nozzles was superior to ring nozzles in parallel winds at speeds approaching the maximum operating limit ie. between 10 to 15 km/h (Figure 4-5).

In a parallel wind direction at high wind speeds (10 to 15 km/h), CU for a taper nozzle was 16% higher than for a ring nozzle. The performance of ring nozzles was highly variable compared to taper nozzles in tests conducted under high wind parallel to the row direction. Between 10 to 15 km/h, CU varied by 10% for taper nozzles compared to 25% for ring nozzles. At high wind speeds when the wind direction was across the row, little difference in performance was recorded between ring and taper nozzles (Figure 4-6).

At wind speeds greater than 15 km/h the performance of the gun reduced despite the use of taper nozzles. The results agreed with current recommendations to cease operation in wind speeds greater than 15 km/h. Only a small number of growers operated at winds speeds in this order.

4.3.5 Gun Arc Angle

A marginal gain in CU from 78% to 81% was achieved by decreasing the gun arc angle from 330 degrees to 240 degrees (Table 4-2). Winch sprinkler patterns (Figure 4-7) showed that by reducing the gun arc angle from 330 degrees to 240 degrees, more water was thrown to the extremity of the sprinkler pattern. This should assist in combating the effect of wind by maintaining the wetted diameter of the sprinkler pattern and maximising uniformity. However the benefits of reducing gun arc angle are expected to be greater under higher wind conditions and further work is required.

Table 4-2 Variation of Christiansen's Uniformity Coefficient (CU) with gun arc angles

Trial No.	Gun Arc Angle	Pressure	Wind Speed	Mean Applied Depth (mm)	CU (%) (75 m lane spacing)
3	330^0	515	< 5 km/h	35.1	77.8
23	270^0	550	< 5 km/h	38.1	79.1
24	240^0	550	< 5 km/h	45.9	80.8

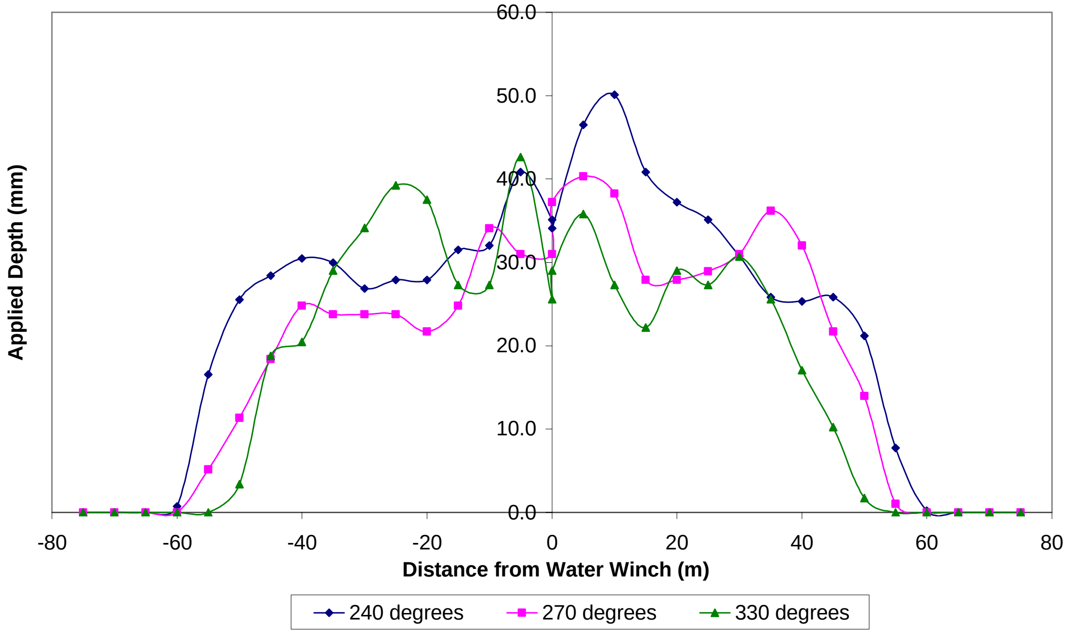


Figure 4-7 The effect of changing gun arc angle on sprinkler pattern

4.3.6 Other Settings

Nozzle size and operating pressure over the ranges investigated had no apparent effect on the performance of the machine. The effect of wind had a much greater influence on machine performance and masked the influence of these settings. To understand the importance that these settings have on overall performance further testing would be required for low wind conditions.

4.3.7 Atmospheric Losses

For mean application amounts of 57 to 73 mm (Table 4-1), atmospheric losses calculated as the difference between metered applications and catch can recovery, ranged from 5% to 46%. Most trials had losses between 20 to 30%. Assuming that runoff and deep drainage was insignificant (Section 6.3.2), then atmospheric losses largely determine the application efficiency of the machine. This meant that water winches were operating at application efficiencies ranging from 54% to 95% with an average of 73%. This compared to a range of 60 to 70% reported by Solomon (1993) and 70 to 85% reported by Shannon et al. (1996).

Test data didn't reveal any trend of increased atmospheric losses as wind speed increased. However, high cross winds tended to consistently have a higher loss than high parallel winds. This is because in high crosswinds the atmospheric losses are moved out of the specific irrigated area while with high parallel winds some of the losses are moved within this area.

4.4 CONCLUSION

Opportunities were identified to improve the performance of water winches under commercial conditions. Wind speed and direction had the most significant influence on irrigation performance. Irrigation uniformity reduced as wind speed increased, particularly when the wind direction was parallel to the row. Operational settings and system changes were identified which reduce the effects of wind and maximised the performance of the machine in less than ideal operating conditions.

At wind speeds approaching 15 km/h and parallel to the row direction, taper nozzles were found to improve the uniformity of the machine by maintaining overlap (ie. maximising the wetted diameter). Overall, trial results were consistent with the recommendations in the literature. Results suggested that water winches could be operated effectively up to a maximum wind speed of 15 km/h providing taper nozzles were used when the wind direction was parallel to the row. At wind speeds approaching 15 km/h taper nozzles were found to improve CU by 16%. For all wind speeds where the wind direction was across the row, ring and taper nozzles gave similar performance.

Reducing the gun arc angle marginally improved CU at low wind speed. From the distribution pattern it was observed that more water was thrown to the extremity of the sprinkler pattern which would better combat the effects of wind. Greater differences in uniformity would be expected at higher wind speeds. Further testing is required at higher wind speeds to confirm this effect.

Nozzle size and operating pressure had no apparent effect on the performance of the machine over the range measured. Hence the effects of wind speed and direction were far greater than the influence of these parameters.

Lane spacings of 75 metres were found to be excessive for local wind conditions. From the results, lane spacings would need to be reduced to between 55 and 65 metres to optimise irrigation uniformity. Large scale changes to the irrigation system such as these aren’t considered practical, especially considering that irrigation performance can be improved through simple operational changes such as changing nozzle type.

Atmospheric losses resulted in a reduction of application efficiencies ranging from 20 to 30% for most tests. These results were consistent with the performance of overhead irrigation systems of 60 to 70% reported in the literature. It was also considered that by reducing the application amount, application efficiency would decrease. This would occur as a result of the atmospheric losses making up a greater percentage of the water applied to the field.

5 PERFORMANCE OF SURFACE IRRIGATION

5.1 INTRODUCTION

The performance of furrow irrigation systems was examined under commercial conditions to identify management practices which could be used to improve irrigation performance locally. Field trials at seven sites were conducted to investigate opportunities to improve the application efficiency and distribution uniformity of an irrigation event. The surface irrigation model SIRMOD II (Walker, 1996) was used to measure current irrigation performance and optimise operational settings including furrow flow rate and cut-off times. Banking the end of the field, irrigating alternate furrow and the influence of different cultivation practices on soil infiltration were also evaluated.

5.2 METHODOLOGY

5.2.1 Description of Field Sites

Seven surface irrigated field sites (Table 5-1) were monitored across the Bundaberg district to assess the performance of surface irrigation systems and identify management practices to improve irrigation performance. The field sites were spatially distributed across the district to incorporate the range of on-farm influences when operating commercial furrow irrigation systems.

Table 5-1 Characteristics of surface irrigated field sites

Site	Soil Type	Typical RAW at 0.7*PAWC (mm)	Field Length (m)	Field Slope (m/m)	System Type
1	Red Dermosol	90	255	0.0011	Layflat
2	Black Vertosol	80	305	0.0014	Gated pipe
3	Black Vertosol	90	371	0.0060	Gated pipe
4	Red Kandasol	70	458	0.0022	Layflat
5	Red Dermosol	90	286	0.0068	Layflat
6	Red Kandasol	80	310	0.0063	Layflat
7	Red Dermosol	90	318	0.0047	Layflat

5.2.2 Field Measurements

A range of measurements were undertaken at each of the field sites to calculate field infiltration characteristics, evaluate irrigation performance and enable irrigation optimisation. The measurements obtained included:

- furrow flow rate;
- irrigation advance (the time taken for water to reach various points along the field);
- irrigation duration (cut-off time);
- length of the field;
- slope of the field;
- furrow geometry; and
- row width.

Furrow flow rate was measured using a bucket and a stop watch. Some difficulty was encountered measuring low flows (ie. hard to place bucket under water stream) or when outlets into the furrow were close to the ground. In these situations the water flow in the furrow was measured through a 50mm flowmeter installed in a PVC tube.

Furrow advance data was collected at each site using Irrimate sensors (Figure 5-1). The Irrimate sensors are connected to a datalogger, which monitors the advance time for a number of furrows at a specific distance along the field. The Irrimate records the arrival of the advance as the water bridges an open circuit between 2 pins (3 mm apart) wired to the logger. Each set of pins are located in the bottom of the furrow. A maximum of 8 furrows can be monitored at one time by the Irrimate. A palm top computer downloads the data via an infrared connection.

Figure 5-1 Irrimate furrow advance timers

A minimum of three sets of Irrimate sensors were used to record the irrigation advance. All dataloggers were synchronised and reset prior to installation. The first sensor was used to identify when the irrigation commenced and was positioned at the start of the furrow. The other sensors were located at halfway along the field and the end of the field. Additional sensors were used at some sites to better define the advance. These were positioned at 0.25 and 0.75 of the length of the field.

In all cases the irrigation duration (ie. when the irrigation was started and stopped) was recorded by the grower. Slope of the field was determined by measuring the length of the field with a trundle wheel and elevation measured using an automatic level. Furrow shape was determined by measuring the top, middle and bottom widths and the depth of the furrow with a tape measure.

5.2.3 Determining Field Infiltration Characteristics

Infiltration of water along the furrow length was calculated using the two point technique (Elliott and Walker, 1982) to solve the Kostakov-Lewis equation which is of the form:

$$Z = kt^a + f_0 t \qquad \textbf{Eqn 5}$$

where:

Z = cumulative infiltration (m^3/m/m)

t = intake opportunity time (min)

k & a = empirical fitting parameters

f_o = basic (final) intake rate of the soil (m^3/m/m/min)

For this work, f_o was neglected, effectively reducing Equation 5 to an unmodified Kostakov equation. This was primarily due to the minor effect of f_o during the initial phase of infiltration (provided the modelling is not extrapolated for significantly longer than the measured data) and that strategies developed will not be influenced by including the f_o term. Neglecting the f_o term is somewhat corrected in the model through the computation of the a and k parameters.

Determining the basic infiltration rate of the soil, f_o requires the irrigation event to be run long enough for a steady state to be reached between furrow inflow and outflow. In most cases the irrigation was cut off well before this occurred. The relative difficulty in obtaining these measurements (ie. setting up flumes or weirs to measure furrow ouflow) in lieu of the final outcomes, discussed above, would have unnecessarily complicated field work.

Using furrow advance data for multiple rows at each site, a power regression curve was fitted through the data to determine an average advance curve. From this curve the advance times for the end of the field and the half way point were used in SIRMOD II to calculate the infiltration parameters a and k (ie. using the two point method). SIRMOD II is a surface irrigation model which simulates the hydraulics of surface irrigation systems in the field.

Once the infiltration parameters a and k are determined, SIRMOD II is calibrated to match the field measured advance by adjusting Mannings roughness coefficient (ie. Mannings n) within the model. Mannings n effectively increases or slows the advance of water down the furrow within the model by reducing / increasing the roughness of the furrow. Mannings n can be determined from field measurements however as this is changed to calibrate the model an initial Mannings n of 0.04 (typical of bare soil) was used. The calculation of the parameters a and k within SIRMOD II are influenced by Mannings n, therefore as the simulated advance was calibrated to meet the measured advance a and k were recalculated. Further fine tuning of the model by altering Mannings n was done without recalculating a and k.

The model was calibrated for each site to ensure the simulated advance matched the measured advance. Obtaining an advance point at the end of the field was critical in accurately determining the infiltration characteristics of the field. Using advance points other than the last point (ie. at sites where more that 2 advance points were recorded) in the 2 point calculations resulted in large differences between the simulated advance at the end of the field and that measured. From this observation it was concluded that when using the two point technique to calculate the infiltration characteristics of the field the last point is critical.

5.2.4 Modelling Irrigation Performance

Irrigation events and performance were simulated using the surface irrigation model SIRMOD II (Walker, 1999). SIRMOD II simulates the depth and variation of water applied to the field via surface irrigation systems. Based on field measurements during an irrigation event SIRMOD II was used to:

- simulate the actual irrigation event and evaluate irrigation performance in terms of Application Efficiency (AE) and Distribution Uniformity (DU); and
- optimise operational parameters such as furrow flow rate and cut-off times to maximise AE and DU.

To calculate application efficiency, SIRMOD II requires the target depth of water held within the root zone (ie. Z required). It was assumed that Z required was equal to the soil moisture deficit at the refill point. For this work, Z required was assumed to be 0.7 of PAWC as measured by Donnallan et al. (1998).

A "trial and error" approach was used to adjust operational parameters such as furrow flow rate, irrigation cut-off times and banking the ends of the furrow to identify optimal values which maximised AE. Altering the furrow flow rate also requires changing the irrigation cut-off time. Both settings were altered in combination to achieve the highest AE. The model was also used to evaluate the benefit of free draining or banked ends on furrows.

5.3 RESULTS and DISCUSSION

Irrigation performance varied significantly between sites (Table 5-2). Application Efficiency (AE) ranged from 45 to 99% (with a mean of 79%) while Distribution Uniformity (DU) ranged from 71 to 93% (with a mean of 82%). Optimal irrigation practices identified using SIRMOD II were compared to the measured irrigation performance (Table 5-2). Substantial opportunities to improve irrigation performance by simple changes to the operation of the irrigation system were identified.

Table 5-2 Measured (Meas.) and Optimised (Opt.) Results

Site	Flow rate (L/s)		Cutoff time (minutes)#		Presence of Banked ends		Application Efficiency (%)		Distribution Uniformity (%)	
	Meas.	Opt.	Meas.	Opt.	Meas.	Opt.	Meas.	Opt.	Meas.	Opt.
1a	1.0	3.5	77	-55	n	y	45	90	72	100
1b	3.0	3.5	557	-27	n	y	42	96	90	87
2	1.5	4.0	-2	-25	n	n	51	59	90	92
3	1.2	3.0	113	-5	n	y	75	98	84	87
4	1.0	1.0	175	0	n	y	88	100	83	84

5	1.2	1.2	14	0	n	n	96	97	93	93
6	1.8	1.8	11	26	n	y	99	100	71	100
7	1.2	1.2	-2	18	n	y	99	100	82	91

[#] Cut-off times relative to time water reached the end of the furrow.

5.3.1 Furrow Flow Rate

Despite soil type differences, furrow flow rate was similar at each of the monitoring sites. Furrow flow rate ranged from 1.0 to 1.5 L/s with the exception of site 6 and site 1b. Site 6 and 1b were purposely included in the monitoring sites to assess the influence of higher flow rates on irrigation performance.

Modelled results indicated that increased flow rates improved AE on high infiltration soils by reducing the applied depth. This occurred at sites 1a and 3 where AE was improved from 45% to 90% and 75 to 98%, respectively. The furrow flow rate at these sites was increased to 3.5 L/s (site 1a) and 3.0 L/s (site 3). The measured results from site 6 also showed that a higher flow rate reduced the applied depth and therefore achieved a high AE.

Increasing the flow rate at site 2 (a cracking clay soil with substantial cracks) had minimal impact on AE (Table 5-2). Furrow flow rate was increased from 1.5 to 4.0 L/s with only a minor improvement in AE (ie. from 51% to 59%). Improving AE on the same soil type was achieved by irrigating prior to cracking. This was seen at site 3 where AE improved from 75 to 98%.

At sites 4 to 7, a measured AE greater than 88% was achieved with a furrow flow rate ranging from 1.0 to 1.2 L/s. Flow rates in this range were appropriate for soils without excessive infiltration rates.

Overall the results indicated that a flow rate of approximately 1 L/s was a suitable starting point for most soils and operating conditions in the Bundaberg district. However, furrow flow rates on high infiltration soils need to be increased to between 3 and 4 L/s. Measuring the volume of water applied to the field in relation to the soil water holding characteristics will indicate if flow rates need to be adjusted. Comparing measurements between sites 2 and 3 suggest that cracking clay soils should be irrigated before cracking occurs.

5.3.2 Cutoff Time

Simulated modelling of irrigation events at each site identified that the optimum cut-off time coincided with water just reaching the end of the field (Table 5-2) when the field had banked ends. At higher furrow flow rates (3 to 3.5 L/s), the irrigation should be turned off before the water reaches the end of the field. After the irrigation is turned off, drainage water from the top of the field should be sufficient to reach the end of the field.

The simulated results were confirmed in practice at sites 5, 6 and 7 where cut-off times were similar to when the advance reached the end of the field. At sites 1, 3 and 4 the irrigation was run for significantly longer resulting in reduced AE due to excessive runoff and deep drainage.

With the presence of banked ends the results strongly suggest that irrigation cut-off time should be managed so that the water just reaches the end of the furrow. Running the irrigation for a longer period reduces irrigation performance. In circumstances with high furrow flow rates (ie. ~3 L/s) cut-off should occur earlier providing there is sufficient drainage to reach the end of the field.

5.3.3 Banked Ends

Banked ends generally increased AE by reducing runoff and improved DU by increasing infiltration at the end of the field. Despite the benefit to irrigation performance, the ends of the field were not banked for the sites monitored. From the simulations all sites except for sites 2 and 5 benefited from banking the end of the field when furrow flow rate and cut-off time were optimised.

Sites 2 and 5 demonstrated similar soil infiltration characteristics. The advance curve at both sites indicates rapid initial infiltration that virtually ceased as the water moved down the furrow. At site 2, this characteristic can be explained by a cracking clay soil which had cracked prior to irrigation. As the cracks filled the soil sealed and infiltration ceased. At site 5, the high infiltration properties were characteristic of the soil type. However, a suspected plough pan at depth, due to shallow cultivation practices, was believed to limit total infiltration at this site.

As most of the infiltration at sites 2 and 5 occurred in the initial moments as water moved down the furrow, banking the end of the field provided no benefit to DU. Simulations with the presence of banked ends indicated that it was difficult to avoid ponding at the end of these fields due to the very low final infiltration rates.

Although the results generally suggest that banking the end of the field should be adopted to maximise irrigation performance, banking should not be adopted on soils with low final infiltration rates and where ponding is likely to occur.

5.3.4 Alternate Furrow Irrigation

Alternate furrow irrigation (AFI) was found to improve AE on a high infiltration soil at site 1 (Table 5-2). AFI in combination with a high furrow flow rate (3 L/s) improved AE by reducing the depth of water applied to the field and eliminating deep drainage (site 1b). By shutting off the irrigation just prior to the advance reaching the end of the field, the simulated AE was improved from 45% to 89%. Simulations indicated that this could be further improved to 96% by increasing the furrow flow rate to 3.5 L/s. However, during the trials a lower AE of 42% was measured as a result of excessive runoff. This occurred as the irrigation continued to run for 557 minutes after the advance reached the end of the field.

AFI (with high furrow flow rate) provides a useful solution to improving the AE on high infiltration soils. Other opportunities for the use of AFI include situations where the depth of water applied to the field is purposely reduced to partially fill the root zone and improve capture of rainfall during the season. However, the adoption of AFI will also be dependent on adequate soakage of water across the furrow to the root zone of the crop.

5.3.5 Cultivation Practices

Cultivation practices significantly influenced irrigation performance. For example, a large difference in irrigation performance was measured between sites 1c and 5 despite similarities between soil type, field characteristics and irrigation operating parameters (Table 5-3). This difference was largely due to deep drainage. To isolate the runoff component the field was simulated so that the cutoff time occurred 14 minutes after water reached the end of the field (ie. the same as site 5). The AE of 58% was improved to 68% however this compared to 96% obtained at site 5. The major difference between both sites was the depth at which tillage operations were conducted. Site 1a was deep ripped at the start of each season while only shallow cultivation practices were conducted at site 5.

Shallow cultivation practices were found to be an effective management strategy to reduce water infiltration at site 5 by producing a plough pan. By comparison, infiltration at site 1a was very difficult to control with dramatic increases in furrow flow rate and alternate furrow irrigation being required to improve AE. Although the irrigation efficiency can be altered through the set up of the irrigation system, this site demonstrated that changing cultivation practices should be considered for improving irrigation efficiency.

Table 5-3 Impact of cultivation practices

Site	Cultivation Practices	Application Efficiency (%)	Distribution Uniformity (%)	Flow rate (L/s)	Cut-off time relative to advance (minutes)	Banked ends
1c	Deep Ripped	58 (68#)	76 (70#)	1.2	158	n
5	Shallow Cultivation	96	93	1.2	14	n

 # Modelled AE and DU where the cutoff time relative to advance reaching the end of the field was equal to 14 minutes (site 5).

5.3.6 Uniformity between Furrows

Advance timers indicated significant differences in time between the fastest and slowest furrows at sites 1, 2 and 3 (Table 5-4). The largest difference between furrows was 572 minutes (9.5 hrs) recorded at site 3. Two sensors per furrow were used at sites 1 and 2 to check the validity of the advance information. Both lots of sensors recorded the same advance times, which provided more confidence in the advance data.

Sites with the highest variation in advance times were also sites at which the irrigation performance improved by increasing furrow flow rates. This indicated that non uniform furrow advance times were more pronounced where furrow flow rates were inappropriate for soil conditions. Differences in furrow flow rates between furrows weren’t recorded and this aspect of improving the performance of furrow irrigation systems needs further investigation.

Table 5-4 Uniformity of furrow advance data

Site	Range in advance times between fastest and slowest furrows (minutes)	Difference in advance times between fastest and slowest furrows (minutes)
1a	1286 - 1357	71
1b	368 – 743	375
1c	358 – 761	403
2	706 – 1062	356
3	686 – 1258	572
4	370 – 565	195
5	469 – 531	62
6	47 – 123	76
7	771 - 836	65

5.4 CONCLUSION

Substantial opportunities exist to improve the performance of furrow irrigation in the Bundaberg District. Except when cracking clay soils had cracked prior to irrigation, the operation of furrow irrigation systems could be manipulated to perform at high application efficiencies (ie. greater than 90% application efficiency). Similarly, distribution uniformity could also be increased to greater than 84%. Simple practices such as changing furrow flow rate, controlling cut-off times and banking furrow ends were identified. Other practices which improved performance on high infiltration soils included irrigating alternate furrows and manipulating the infiltration of the soil through cultivation practices.

The results indicated that furrow flow rates need to be adjusted specifically for soil type and field conditions. Although flow rates of 1 L/s appear to be appropriate for most furrow irrigation in this region, flow rates should be increased to between 3 and 4 L/s on soils with high infiltration rates. A simple rule of thumb for appropriate cut-off times is to turn off the irrigation so that water just reaches the end of the furrow. At low flow rates this occurs just as the advance reaches the end of the furrow. At high flow rates this occurs before the advance reaches the end of the furrow.

Banking the end of the field in most circumstances improved both the application efficiency (by reducing runoff) and distribution uniformity (by improving infiltration at the end of the field). The exception for banking the end of the field was in the situation where soil exhibited an initial rapid infiltration which then quickly reduced to zero. In these situations, banking ends didn’t improve DU and ponding occurred at the end of the field for some time.

Other operational practices such as using alternate furrow irrigation and maintaining surface compaction in the furrow to limit infiltration were found to reduce excessive infiltration and deep drainage on high infiltration soils.

Although the uniformity of inflow between furrows was questioned in response to uneven advance rates between furrows at a few sites, it was also noticed that the same sites also had inappropriate flow rates for the field conditions. It was highlighted that poor uniformity between furrows may be a result of inappropriate furrow flow rate.

6 IDENTIFYING CROP RESPONSES TO IRRIGATION

6.1 INTRODUCTION

Irrigation scheduling strategies identified in the literature (Section 2.4) are focused towards the optimum timing and volume of irrigation for a particular block. How these strategies are applied in practice while managing multiple fields irrigated by a single irrigation system is unclear. Under the commercial constraints identified in Section 3.3.3, most irrigation systems in the Bundaberg area are unable to meet crop demand, therefore opportunities for irrigation scheduling are effectively limited to start up after rainfall.

Previous field work (Chapters 4 and 5) assessed the performance of both water winch and furrow irrigation systems and identified how these systems could be fine tuned to improve performance. Increases in application efficiency can be related to a nett increase in water applied to the crop and the resulting yield increase can be determined from the production function in Figure 1-2. However, the potential yield benefit of improving irrigation uniformity is unknown and needs to be determined.

Opportunities to maximise crop yield by improving irrigation practices and system performance were focused on irrigation start up after rain and the potential for yield increases by improving irrigation uniformity. Field measurements in combination with crop simulation modelling were used to develop and evaluate various strategies.

6.2 FIELD MEASUREMENTS

6.2.1 Field Sites

Six field sites were monitored over two irrigation seasons to obtain an understanding of how the crop responded during the season to the management of limited water and the effects of irrigation performance. Announced irrigation allocations at the start of these water years were 29% (1999 – 2000 water year) and

24% (2000 – 2001 water year). Final announced allocations were 59% and 81%, respectively.

Field sites were spatially distributed across the district and included different soil types, cultural practices and irrigation systems. The field sites (Table 6-1) focused mainly on water winch systems (ie. 4 of the 6 sites) with less priority given to furrow sites to reflect the relative proportion of systems across the district.

Table 6-1 Description of Field Sites

Site No.	Soil Type and Description	Typical RAW at 0.7*PAWC (eff rooting depth)	Irrigation System
1	Fine sandy - silty clay loam and classified as a Brown Sodosol (solodic soil).	52 - 70 mm	Winch
2	Red soil, light to medium clay in texture and classified as a Red Ferrosol (Euchrozem).	70 - 87 mm	Winch
3	Black, medium clay soil over a heavy clay and classified as a Black Vertosol (Black Earth).	87 - 105 mm	Furrow
4	Reddish brown, fine sandy clay soil over a light clay and classified as a Red Kandosol (Red Earth).	70 - 87 mm	Winch
5	Red, light to medium clay soil and classified as a Red Dermosol (Krasnozem)	70 - 87 mm	Furrow
6	Fine sandy - silty clay loam and classified as a Brown Sodosol (solodic soil).	52 - 70 mm	Winch

Soil classifications from Donnollan et al.(1998)

Stem elongation measurements were conducted alongside soil moisture measurements to determine the effects of management practices on crop growth. At field sites 1 and 4, specific field trials were conducted to measure the relationship between irrigation uniformity and sugarcane growth. At these sites, stem elongation measurements were conducted adjacent to catch can measurements to relate the variation in water applied to the field by a water winch to sugarcane growth.

6.2.2 Stem Elongation Measurements

Stem elongation measurements were conducted at sites 1, 4, 5 and 6. Stem elongation measurements were recorded on a daily basis for approximately one month to demonstrate a relationship between crop growth rates and soil moisture. Ten stalks were chosen in close proximity to installed soil moisture probes and marked so that they could be continually monitored.

Short pegs were inserted into the ground at the base of each stalk to provide a benchmark for growth measurements. Stem elongation measurements were determined from the average growth of the 10 stalks, measured to the top visible dewlap of the plant (Figure 1-3). To assist in the measurement of tall cane a telescopic growth stick was made from PVC conduit. The inside conduit was raised when the crop was taller than 1.8 m. This section of the growth stick was marked with numbers in the reverse direction. This allowed height measurements to be read at eye level, which made the task easier and more accurate.

Crop growth measurements were conducted alongside catch can measurements at field sites where the effect of uniformity on cane yield was assessed. At each catch can, the average growth of five cane stalks was used to represent the crop response to water applied at that point in the field. Growth measurements were recorded prior to irrigation. The growth recorded between irrigations was a result of the previous irrigation amount, rainfall and moisture stored in the soil.

6.2.3 Soil Moisture

Soil moisture was monitored down to 1 metre at each site using Enviroscans (Sentek Pty Ltd). The Enviroscan system measures soil moisture by capacitance. The system consists of a central logger with up to 8 probes which have sensors attached. The Enviroscan probes are contained within a PVC access tube inserted into the ground. Access tubes were installed using a slurry technique to ensure no air gaps surrounded the tubes. Installation consisted of auguring an oversize hole, partly filling with a mud slurry and then working the access tube into the hole as the slurry is squeezed up around the tube to ensure soil contact.

The Enviroscan loggers were programmed to record soil moisture every 30 minutes and were configured with 1 metre probes and 4 sensors per probe. Prior to installation sensors were calibrated in air and water however soil moisture readings were determined from factory calibrations. Factory calibrations were used as only relative changes in soil moisture were examined. A comparison of typical RAW characteristics of field sites (Table 6-1) and those determined from Enviroscan measurements (Appendix D and Appendix E) indicated that the factory calibration was reasonably accurate.

Sensors were located at 10 cm, 30 cm, 60 cm and 100 cm below the soil surface. Moisture movement below the 100 cm sensor was assumed to be deep drainage. Probe location varied depending on the irrigation system used. Probes were located where the best sensitivity to irrigation and crop water use was found. This included in the row, when the field was irrigated by a water winch (to allow for water funnelled to the base of the plant from crop canopy) and on the side of the mound when furrow irrigated (lateral movement of water from furrow). Probes were installed in the nearest row 10 metres from a winch track and at least 60 metres from the end of the field. For furrow blocks, probes were installed 10 metres from the headland and the top of the field.

6.2.4 Catch Can Measurements

The uniformity of irrigation events was measured by catch cans arranged in a standing leg test. For a standing leg test, cans are arranged in a line perpendicular to the travelling direction of the irrigator (Figure 6-1). Cans were spaced every third row of cane (approximately every 5 metres) between adjacent towpaths.

Figure 6-1 Catch cans arranged in standing leg test

Triangular Nylex rain gauges were used as catch cans. The rain gauges were attached to 65 mm PVC tube, which slipped over a smaller 50 mm PVC tube in a telescopic arrangement. A hose clamp tightened around the inner tubing was used to set the height of the cans. Each PVC tube was cut to a 1.8 m length, which could be conveniently transported in the back of a utility. The PVC poles were erected by placing them over wooden pegs inserted into the ground.

The telescopic poles allowed the cans to be raised just above the canopy height to obtain accurate measurements of the amount of water received by the crop (Figure 6-2). As the season progressed, the cans were raised in response to crop growth.

Figure 6-2 Telescopic catch can set above canopy height

6.3 CROP REPONSE TO CURRENT PRACTICES

6.3.1 Effect of Soil Moisture on Crop Stress in Terms of Stem Elongation

Daily stem elongation measurements were conducted over one month in the 1999-2000 irrigation season to relate soil moisture to crop stress. Stem elongation was found to be proportionally related to crop water use and soil moisture deficit. An example of this relationship (Site 6) is shown in Figure 6-3. Appendix F includes these relationships for additional sites.

Crop growth is effectively driven by how much water the plant used per day and the suction required by the plant to extract water from the soil. Providing temperature and radiation is similar from day to day, higher growth rates are maintained at higher soil moisture levels. This is shown in (Figure 6-3) where stem elongation and soil moisture measurements demonstrate that crop growths rates were reduced with an increasing soil moisture deficit. Over this same period daily crop water use remained constant also indicating that stem elongation rates reduce before there is any obvious signs of crop stress.

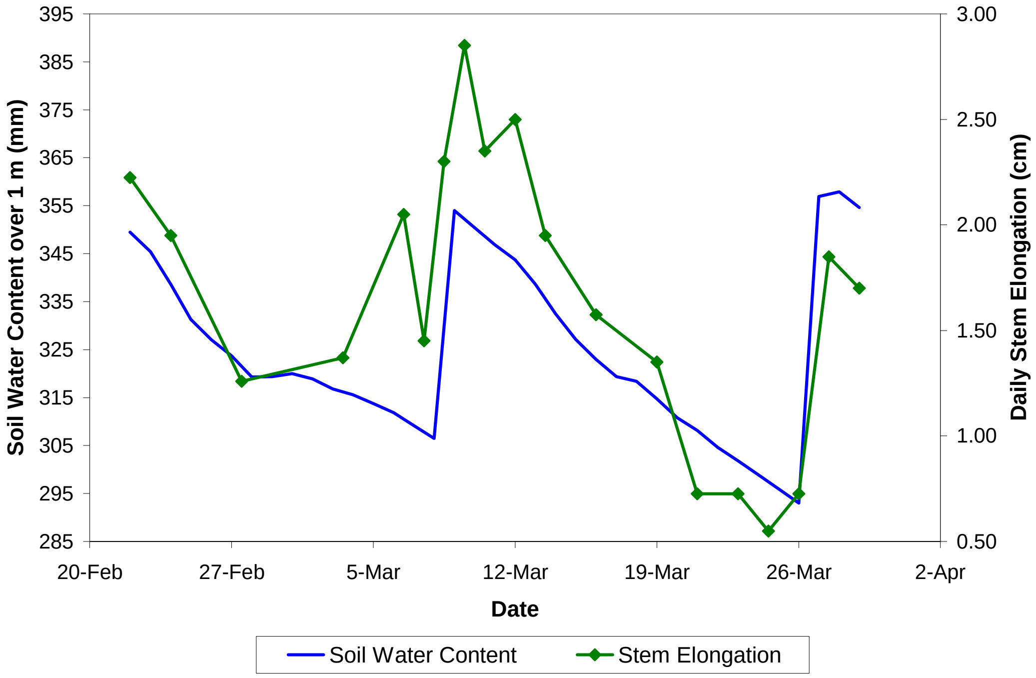


Figure 6-3 Daily Stem Elongation Relative to Soil Water Content (Site 6)

An irrigation event at sites where stem elongation was monitored was applied when stem elongation was close to 30% of maximum stem elongation. This was consistent with the recommendations in Section 2.4. It was observed that the rate of moisture extraction at 30 cm and 60 cm decreased when stem elongation rates reduced to 30% (Appendix F). Hence, refill points at sites where stem elongation measurements weren’t recorded were selected on this basis.

Maximum stem elongation rates were typically 30 mm/day with one site recording growth of up to 39 mm/day. Daily growth rates dropped to between 21% and 43% prior to irrigation (Table 6-2).

Table 6-2 Daily Stem Elongation Rates

Site No.	Maximum Stem Elongation (mm/day)	Growth Rate Prior to Irrigation (mm/day)	Growth Rate Relative to Maximum Stem Elongation
1	28	12	43%
4	32	9	28%
5	39	13	33%
6	29	6	21%

6.3.2 Soil Moisture in Response to Irrigation

Winches

Soil moisture, monitored over two irrigation seasons (Appendices D and E), indicated that water winch systems were typically unable to meet crop demands throughout the season and were operating at a deficit. This confirmed the survey data presented in Section 3.3.3. Figure 6-4 and Figure 6-6 present typical soil moisture data recorded at sites irrigated by water winches.

Once irrigation had commenced, there was little opportunity for reducing the irrigation schedule as the next irrigation was determined by the return interval of the winch. The main irrigation decision was when to start after rainfall. Irrigation applications were generally smaller than the soil moisture deficit at irrigation.

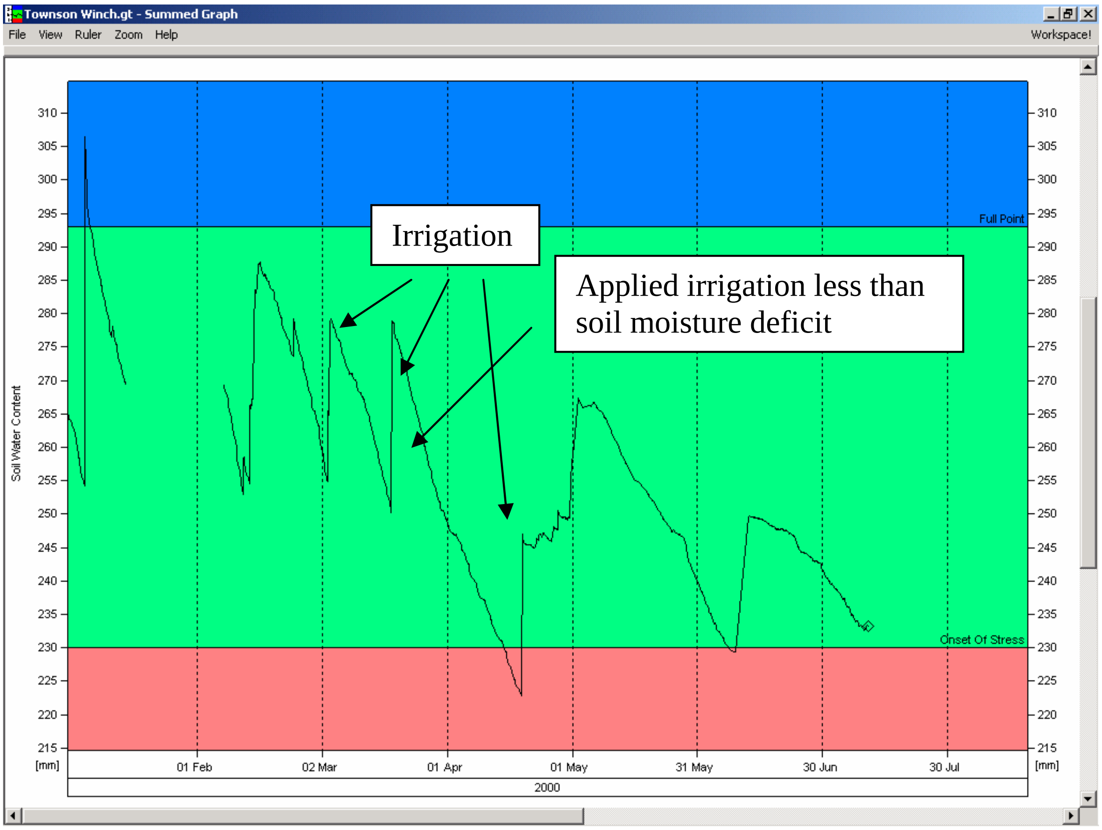
The increasing difference between crop demand and irrigation during the first irrigation season can be seen in Figure 6-5 with the gradual depletion of soil moisture at depth. Soil moisture at depths greater than 60 cm was extracted during the season to make up the difference between crop demand and irrigation. Higher rainfall during the second season supplemented irrigations so that crop demands were better met (Figure 6-7).

The inability of water winches to meet the demands of the crop was highlighted at two sites where the impact of downtime due to break downs was observed. Downtime from pump failure placed greater pressure on the irrigation system to meet crop demands. In effect, the irrigation system was unable to catch up with the crops needs.

Soil moisture readings confirmed application rates were less than the capacity of the soil moisture deficit (Figure 6-4 and Figure 6-6). This meant effective rainfall was maximised due to spare storage capacity of the soil to hold available water for the plant, even immediately after irrigation. During the first season, infiltration from irrigation events reached 60 cm while root extraction occurred down to 1 metre (Figure 6-5). During the second season, water penetration was observed down to 1 metre as soil moisture was maintained at higher levels due to higher rainfall (Figure 6-7). During both seasons, soil moisture changes at 1 metre depths were only minor and deep drainage was believed to be insignificant. Over the two seasons, deep drainage only occurred during major rainfall events.

Soil moisture readings indicated that there was scope to start irrigating earlier after rainfall. Irrigated amounts were commonly less than the soil moisture deficit at the time of irrigation. By starting earlier, soil moisture could be maintained at higher levels for longer. Starting earlier effectively stored irrigation capacity which meant the crop demands were better met and the effect of break downs could be minimised. Stem elongation measurements indicated that maintaining the soil moisture at higher levels for longer would maximise crop yield by minimising crop stress.

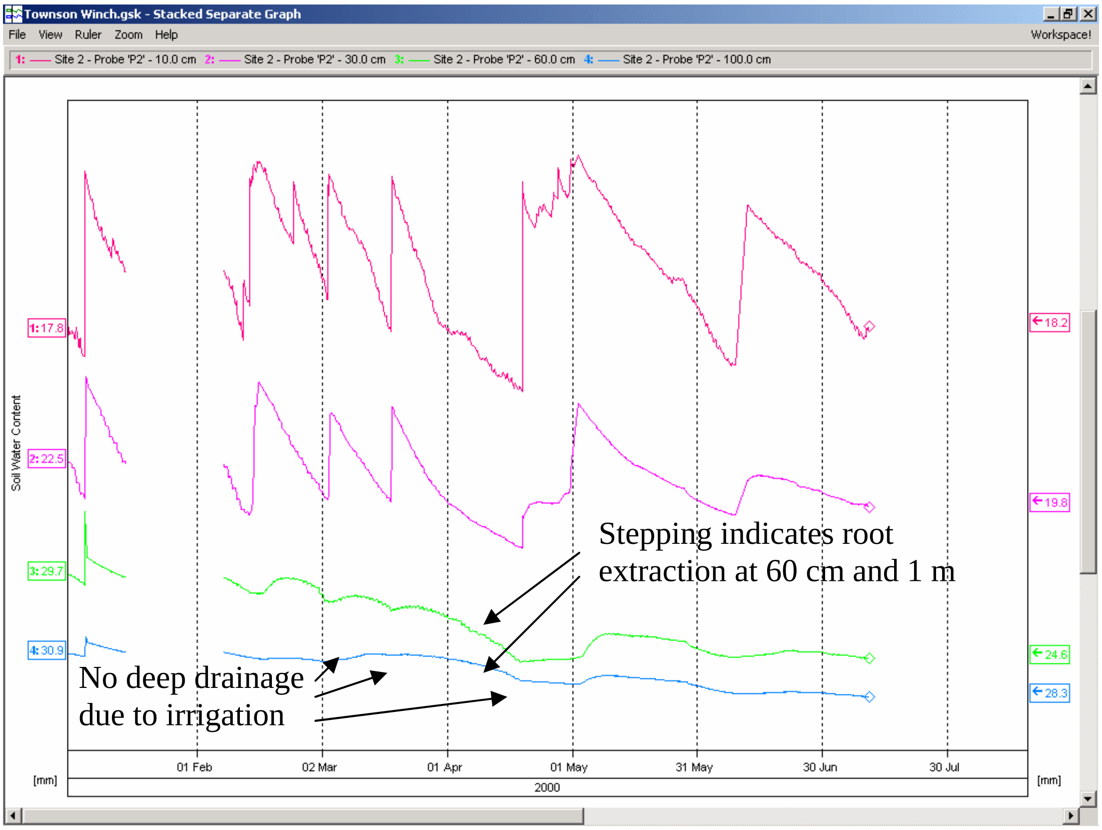
Figure 6-8 and Figure 6-10 present typical soil moisture data recorded at sites irrigated by furrow irrigation systems. Complete soil moisture records for all sites are presented in Appendices D and E.



Irrigation

Applied irrigation less than soil moisture deficit

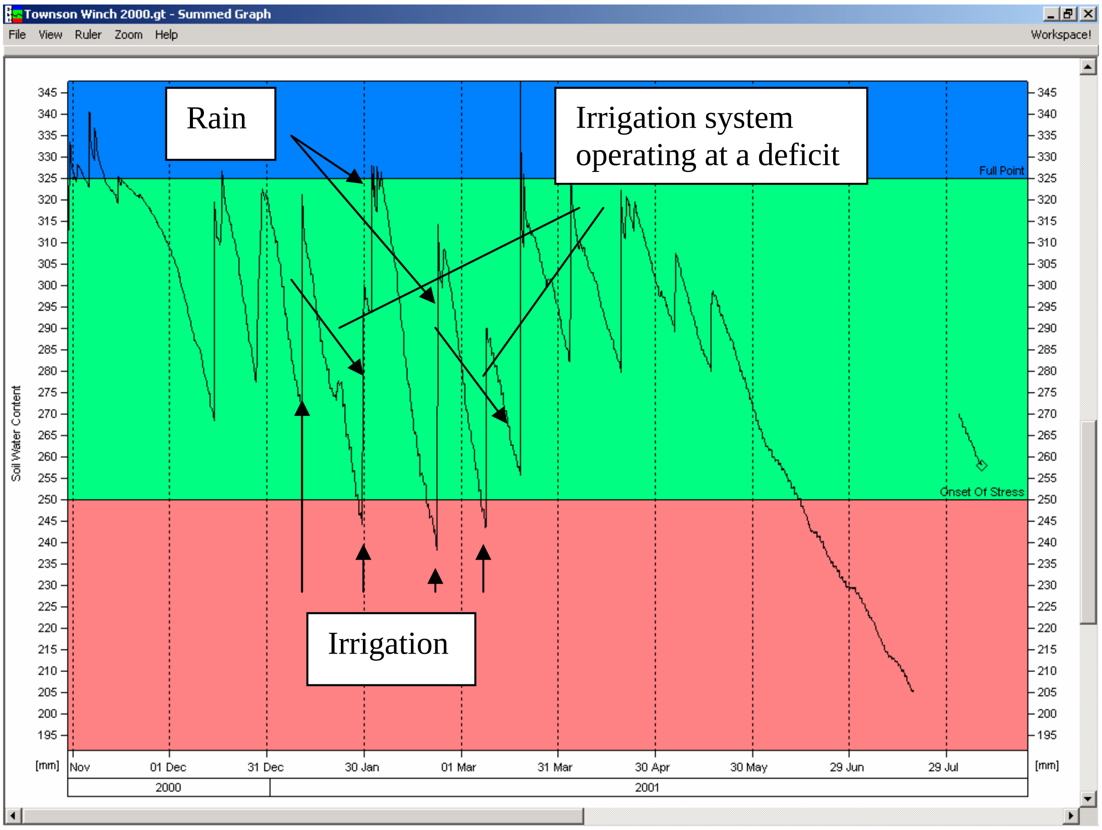
Figure 6-4 Total soil moisture to 1 m depth; site 4; 1999 - 2000



Stepping indicates root extraction at 60 cm and 1 m

No deep drainage due to irrigation

Figure 6-5 Separate level soil moisture (mm / 100 mm); site 4; 1999 – 2000

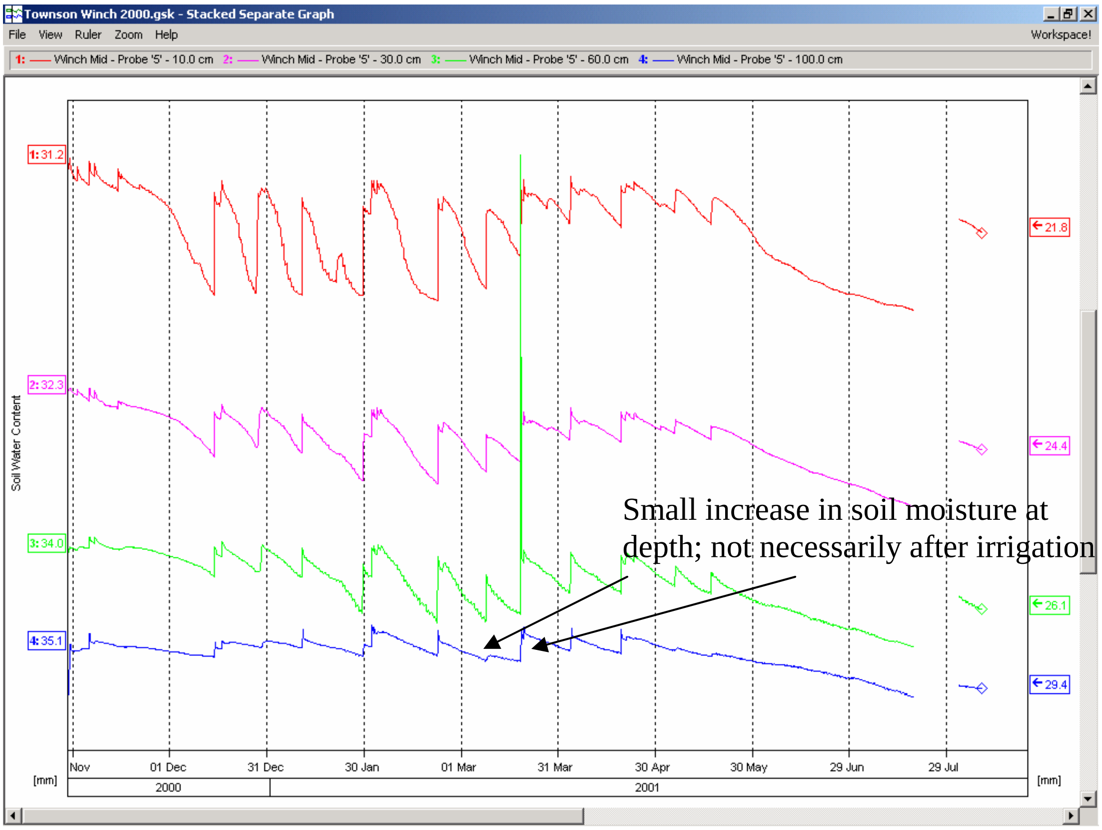


Rain

Irrigation system operating at a deficit

Irrigation

Figure 6-6 Total soil moisture to 1 m depth; site 4; 2000 – 2001



Small increase in soil moisture at depth; not necessarily after irrigation

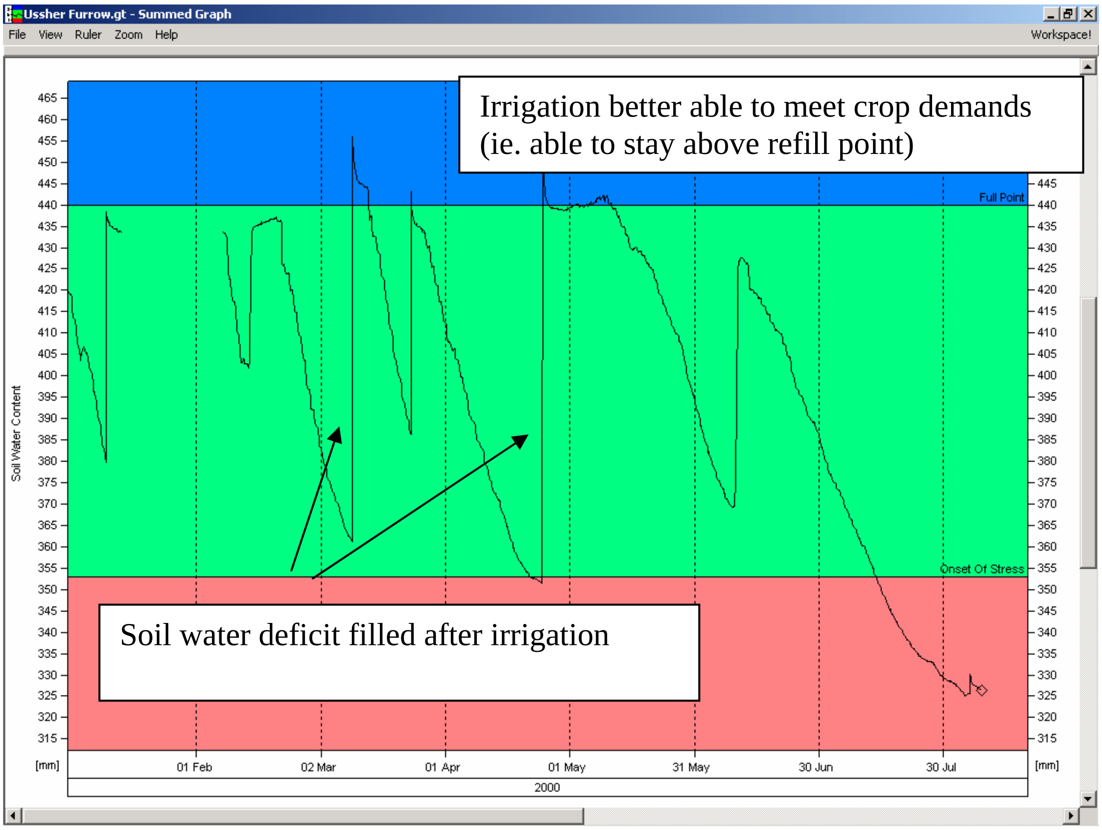
Figure 6-7 Separate level soil moisture (mm/100mm); site 4; 2000 – 2001

Furrow

In comparison to water winches, the furrow systems were better able to meet crop demand and the profile was filled during irrigation. At site 5, irrigation was supplied from an unregulated bore and water supply was virtually unlimited. Prior to irrigation the soil moisture was below the refill point on two occasions. This indicated that those irrigations could have occurred earlier. Generally however, the crop water demand relative to those of the winch systems was better matched. The major difference between winch and furrow systems was the amount of water applied to the field. Furrow systems typically filled the profile during irrigation where as winch systems only partially filled the profile. The potential for deep drainage as a result of higher application rates increased with furrow systems.

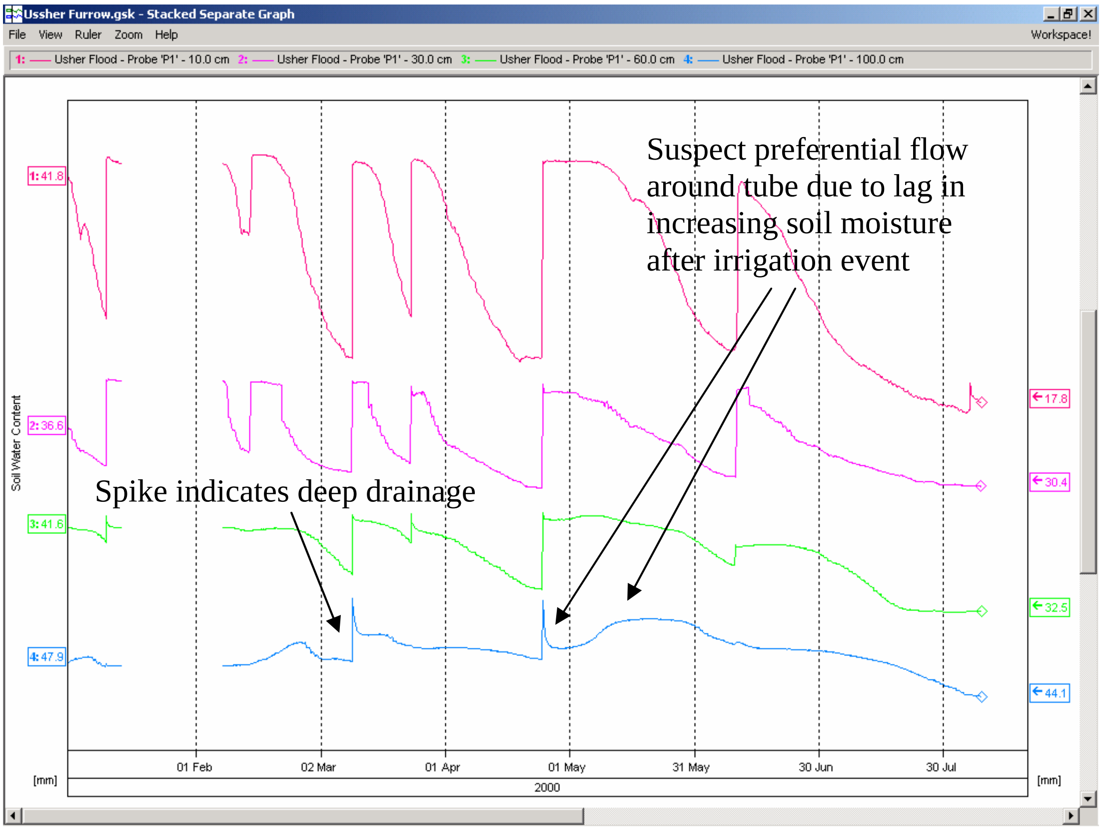
Deep drainage was observed when moisture detected by the bottom sensor (1 metre) of the Enviroscan spiked (Figure 6-9 and Figure 6-11) indicating movement of water to greater than 1 metre in the profile. At both furrow sites root extraction was observed down to one metre as soil moisture was extracted down to the refill point. The effective rooting depth of these soils was considered to be one metre and that water movement past this sensor was most likely deep drainage. Deep drainage occurred at site 5 after each irrigation event, while measurements at site 3 indicated that deep drainage only occurred once after irrigation. On one other occasion at this site, an initial spike of moisture measured by the one metre sensor was suspected to be preferential flow of water alongside the probe tube. A lagged increase in soil moisture a couple of days after the irrigation event was observed indicating that the initial soil moisture response was most likely water movement around the tube. A water table was also suspected at this site due to the sustained high soil moisture content at 60 to 100 cm depth (Figure 6-11).

A comparison of soil moisture measurements between both sites suggested that the operation of furrow systems could be improved by reducing the amount of water applied to the field. This would reduce the potential for deep drainage and potentially create storage capacity for rainfall events.


Irrigation better able to meet crop demands (ie. able to stay above refill point)

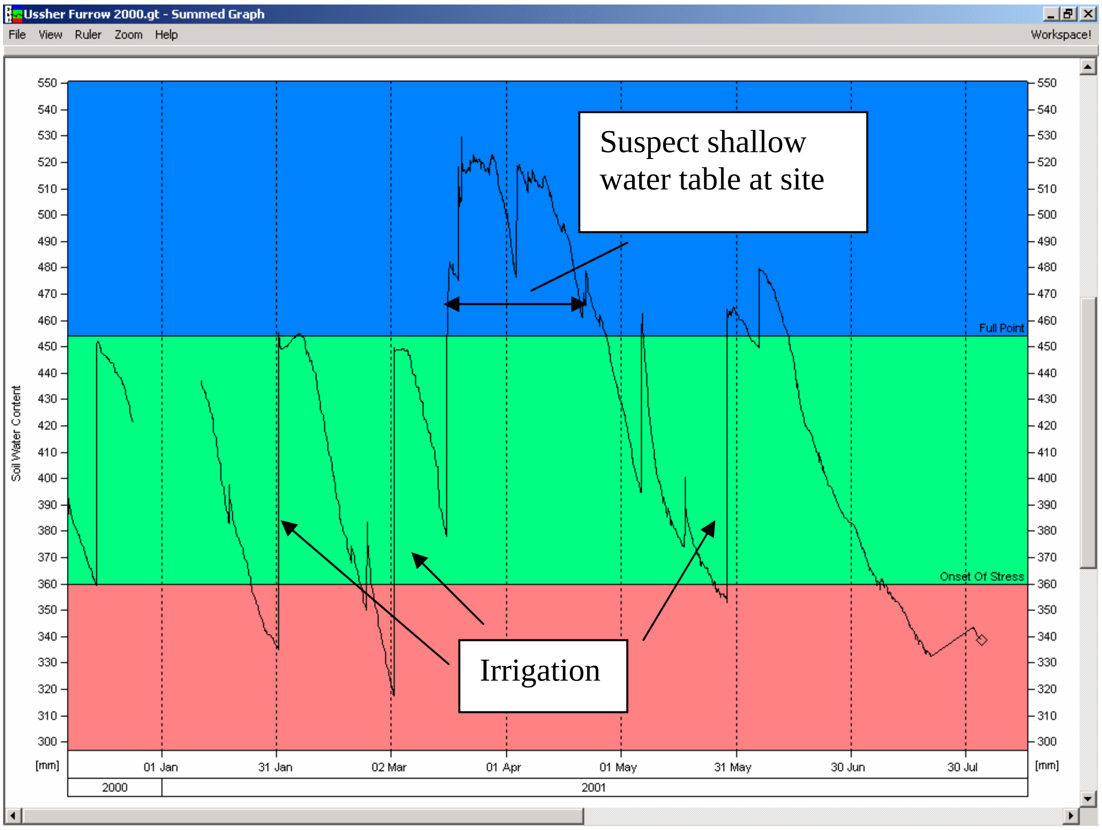
Soil water deficit filled after irrigation

Figure 6-8 Total soil moisture to 1 m depth; site 3 1999 – 2000


Suspect preferential flow around tube due to lag in increasing soil moisture after irrigation event

Spike indicates deep drainage

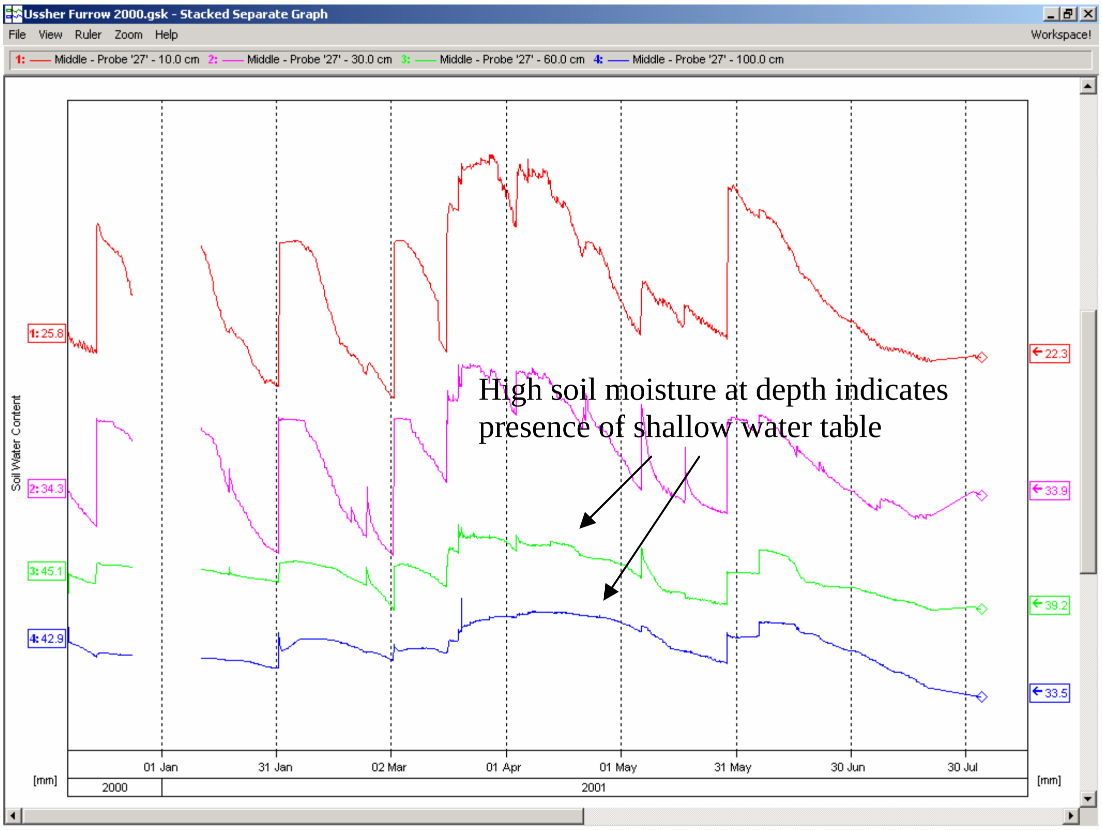
Figure 6-9 Separate level soil moisture (mm / 100 mm); site 3; 1999 – 2000



Suspect shallow water table at site

Irrigation

Figure 6-10 Total soil moisture to 1 m depth; site 3; 2000 – 2001



High soil moisture at depth indicates presence of shallow water table

Figure 6-11 Separate level soil moisture (mm / 100 mm); site 3; 2000 – 2001

6.3.3 Effect on Soil Moisture by Starting Earlier After Rainfall

Soil moisture recorded at the field sites (which included actual irrigation events) was modified to simulate irrigations conducted earlier after rainfall. Actual irrigation events were applied sooner in the spreadsheet model ie. when the soil moisture deficit was equal to the irrigation amount. From the field trials, it was observed that starting irrigation earlier might provide an opportunity for water winch systems operating at a deficit to better meet the demands of the crop. By starting earlier, growers could effectively store irrigation capacity to better match crop demands. The objective was to keep soil moisture as high as possible for as long as possible while accepting that the system was unable to keep up with crop demands. From Section 6.3.1 maintaining the soil moisture at higher levels for longer indicated that crop stress could be minimised and therefore crop yield could be maximised.

To demonstrate the feasibility of this strategy, soil moisture data was modified in a spreadsheet to simulate irrigation start up at a soil moisture deficit equal to the irrigation amount (measured by Enviroscan) after rainfall. This was in most cases a soil moisture deficit of 40 mm except at site 6 where irrigation applications were more than 50 mm. The irrigation interval was constrained to a minimum of 14 days, which matched current constraints of the irrigation systems monitored. When rainfall occurred, irrigation was delayed until the soil moisture deficit was equal to the irrigated amount (for example 40 mm) and allowances for the irrigation interval prior to rain were made.

The results (Figure 6-12 and Appendix G) indicate that irrigations could be started earlier and that soil moisture levels could be maintained higher. Stem elongation measurements also indicated that this would minimise crop stress. However, earlier irrigation start up times need to be evaluated over a longer time frame to test the sensitivity of this strategy against seasonal variation.

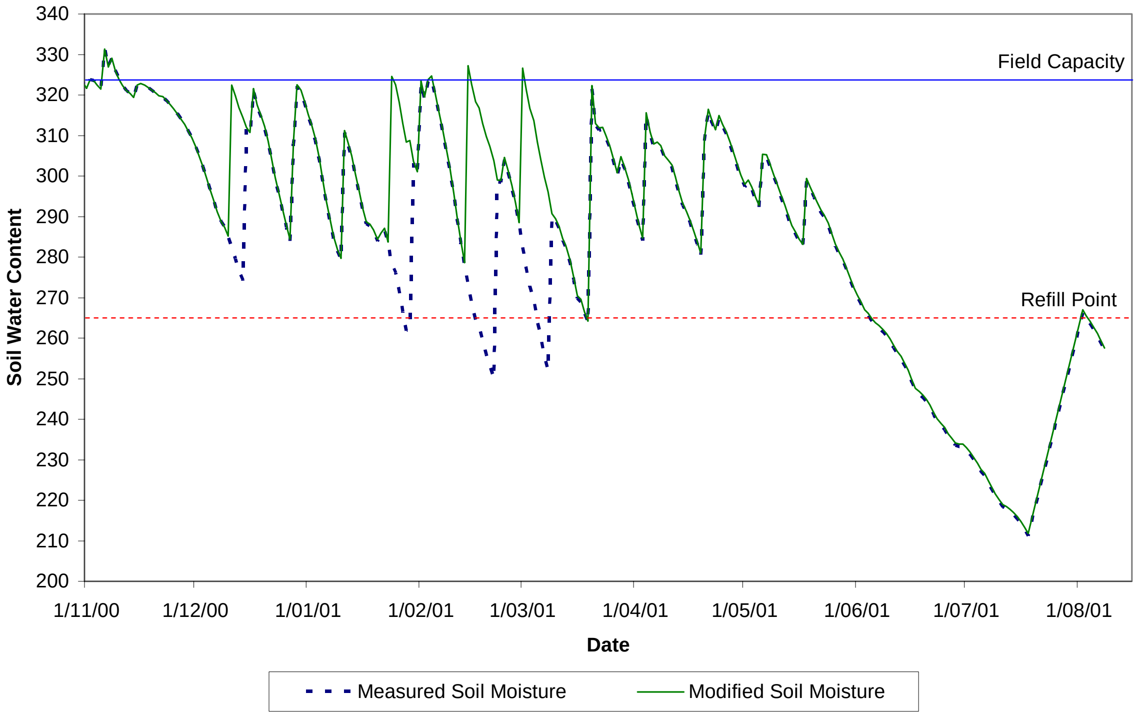


Figure 6-12 Demonstration of early startup (Site 3: 2000 – 2001)

6.4 CROP RESPONSE TO IRRIGATION STARTUP STRATEGIES

The crop simulation model APSIM Sugar, described by Keating et al. (1999), was used to evaluate the impact of different irrigation strategies for starting after rainfall over the whole farm (as opposed to a single field). The APSIM model is a biophysical model and has been validated for a wide range of conditions in Australia and overseas (Keating et al., 1999). The modelling evaluated 3 irrigation strategies which included starting earlier after rainfall (discussed in Section 6.3.3). Crop simulation modelling was conducted over a 10 year period to account for the influence of seasonal variation. Daily climate data for Bundaberg was obtained from the Bureau of Meteorology’s ‘SILO’ database. These records included daily rainfall, radiation and maximum and minimum temperature.

6.4.1 Crop Modelling Process

The modelling was subjected to the constraints of a water winch system, which typically operates at an irrigation deficit. Irrigation applications were applied in 50 mm amounts with an irrigation efficiency of 75%. The irrigation rotation was a minimum of 14 days.

Two soil types were used to simulate a medium water holding soil (Yellow Chromosol) and a high water holding soil (Red Kandasol). The Yellow Chromosol had a PAWC of 88 mm (over the total rooting depth) which had a similar water holding capacity to the field sites that were monitored (Section 6.2.1). The Red Kandasol had a PAWC of 176 mm (over the total rooting depth) and represented the better soils of the Bundaberg region. Irrigation water allocations of 2 ML/ha and 3 ML/ha were simulated for each soil type. A continual 12 month crop was modelled with a crop starting date of September 1. At the start of each 12 month crop, the fraction of available soil water (fasw) was reset to 50% (ie. 0.5 PAWC). The latest possible irrigation date allowed for at least 40 days dry down (approximately 6 weeks) before harvest.

Three irrigation start-up strategies were evaluated by the modelling. These strategies included an early, middle and late start-up strategy. It was identified in the literature (Section 2.4) that the optimum refill point for supplementary irrigation was a deficit of 75% PAWC (25% fasw) and that this closely coincided with a deficit at which 30% maximum stem elongation occurred. This also coincided with the practices at the demo sites where fields were irrigated when the soil moisture deficit was approximately 30%. In this context the early strategy assumed that the irrigation rotation or whole farm was completed at 0.25 fasw. That is the last block in the irrigation rotation was irrigated when the soil moisture deficit was 0.25 fasw. Similarly the middle strategy was halfway through the irrigation rotation at 0.25 fasw; and the irrigation rotation had just started at 0.25 fasw for the late strategy.

Each irrigation strategy was evaluated by combining the yields of three simulated fields (irrigation treatments) which represented the first, middle and last field in the irrigation rotation for that strategy. In total five irrigation treatments were used to determine the 3 irrigation strategies

The start-up strategies (Figure 6-13) included:

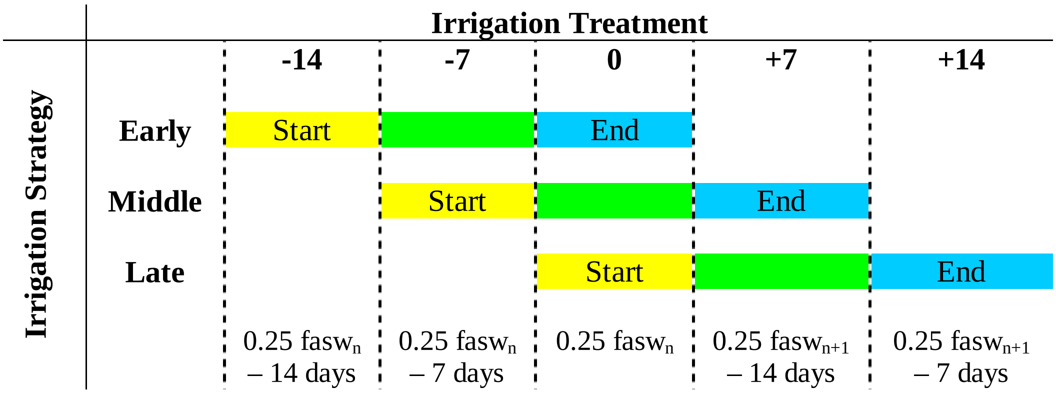
- Early (finish irrigating @ 0.25 fasw): average yield of –14, -7 & 0 days treatments;
- Middle (halfway @ 0.25 fasw): average yield of -7, 0 & +7 days treatments;
- Late (start irrigating @ 0.25 fasw): average yield of 0, +7, & +14 days treatments;

where the irrigation treatments were:

- – 14 days (0.25 fasw$_{n}$ – 14 days)
- – 7 days (0.25 fasw$_{n}$ – 7 days)
- 0 days (0.25 fasw$_{n)}$
- + 7 days (0.25 fasw$_{n+1}$ – 14 days)
- +14 day (0.25 fasw$_{n+1}$ – 7 days)

and n = irrigation number during season.

To conduct the modelling the 0 day treatment was modelled for all years. The irrigation dates for the other treatments where then determined by the 0 day treatment as above. In total five irrigation treatments were modelled for two allocations; two soil types and 10 years of meteorological data.



where n = irrigation number during season

Figure 6-13 Irrigation strategies for an individual irrigation event

6.4.2 Crop Modelling Outcomes

Simulated sugarcane yields are presented for each soil type and water allocation in Table 6-3 and Table 6-4. The effective rainfall for each irrigation treatment and strategy were also determined (Table 6-5 and Table 6-6). Model runs were conducted over a 10 year period however the 1991 to 1992 season was discarded as high rainfall meant that only a limited number of irrigation treatments were able to be imposed in the modelling.

The highest yielding irrigation strategy (shaded yellow in Table 6-3 to Table 6-6) varied from season to season for soils with different water holding capacity and water allocation. The results also suggested an interaction of irrigation strategy with irrigation timing during the season. Sugarcane yields were simulated for each irrigation treatment and combined to simulate an irrigation strategy across the farm.

Variation in sugarcane yield was less than 5 tc/ha between the highest yielding strategy and the lowest yielding strategy in most seasons. The exception was an 18.3 tc/ha increase in yield between the late and early irrigation strategy for the 1992 – 1993 season. This result occurred when modelling the Red Kandasol. In comparison, for the Yellow Chromosol the late treatment only produced an increase in yield of 0.4 tc/ha.

Overall the minor difference in modelled sugarcane yields suggests a significant degree of flexibility for scheduling irrigations after rainfall. This is most likely due to the small amount of irrigation water available, relative to the significantly larger contribution of effective rainfall to meet the crops needs. The total nett application for the 2 ML/ha and 3 ML/ha allocation were 150 mm and 225 mm. This compared to the average effective rainfall of approximately 630 mm for the Yellow Chromosol and 690 mm for the Red Kandasol presented in Table 6-5 and Table 6-6. Manipulating the use of irrigation supplies was insignificant as the effective rainfall across treatments and strategies was virtually the same, regardless of how the water was managed. The effective rainfall between different amounts of water was also very similar indicating a large deficit between irrigation and the crops demands.

Table 6-3 APSIM simulated sugarcane yield (3 ML/ha)

Yellow Chromosol	Irrigation Treatments & Sugar Cane Yield (TC/Ha)					Irrigation Strategies & Sugar Cane Yield (TC/Ha)		
	-14 days	-7 days	0 days	+7 days	+14 days	Early	Middle	Late
92 - 93	61.5	62.3	63.5	69.4	69.2	62.4	65.1	67.4
93 - 94	87.5	87.0	80.4	84.5	78.3	85.0	84.0	81.1
94 - 95	57.5	59.3	59.8	64.4	64.9	58.8	61.1	63.0
95 - 96	55.7	63.4	60.7	64.5	61.7	59.9	62.9	62.3
96 - 97	79.6	79.9	78.4	83.1	74.9	79.3	80.5	78.8
97 - 98	68.5	68.6	70.1	71.6	70.4	69.1	70.1	70.7
98 - 99	81.9	76.7	79.0	75.6	76.4	79.2	77.1	77.0
1999 - 2000	58.0	58.1	57.8	57.4	56.1	58.0	57.7	57.1
2000 - 2001	66.0	65.4	64.0	65.4	64.3	65.1	64.9	64.6
Average	68.5	68.9	68.2	70.6	68.5	68.5	**69.3**	69.1
Red Kandasol								
92 - 93	50.4	50.4	50.4	53.3	55.1	50.4	51.4	52.9
93 - 94	94.0	94.1	86.5	90.4	91.4	91.5	90.3	89.4
94 - 95	61.7	62.9	65.3	69.3	70.8	63.3	65.8	68.4
95 - 96	66.3	69.3	70.2	75.9	75.9	68.6	71.8	74.0
96 - 97	87.4	88.7	81.4	84.4	78.2	85.9	84.8	81.3
97 - 98	66.6	66.1	66.4	66.3	67.7	66.4	66.3	66.8
98 - 99	88.2	89.9	90.4	84.8	85.3	89.5	88.4	86.8
1999 - 2000	52.0	53.6	56.3	58.0	58.9	54.0	56.0	57.7
2000 - 2001	58.1	59.5	60.6	63.8	65.1	59.4	61.3	63.2
Average	69.4	70.5	69.7	71.8	72.0	69.9	70.7	**71.2**

Table 6-4 APSIM simulated sugarcane yield (2 ML/ha)

Yellow Chromosol	Irrigation Treatments & Sugar Cane Yield (TC/Ha)					Irrigation Strategies & Sugar Cane Yield (TC/Ha)		
	-14 days	-7 days	0 days	+7 days	+14 days	Early	Middle	Late
92 - 93	61.0	60.9	60.6	61.3	61.6	60.8	60.9	61.2
93 - 94	72.6	71.9	72.7	77.5	78.3	72.4	74.0	76.2
94 - 95	58.6	58.7	60.2	61.7	63.2	59.2	60.2	61.7
95 - 96	54.9	57.5	57.0	55.5	55.0	56.5	56.7	55.8
96 - 97	64.4	64.6	63.4	69.0	67.5	64.1	65.6	66.6
97 - 98	65.9	66.1	63.4	62.4	58.5	65.1	64.0	61.4
98 - 99	67.9	69.4	71.9	75.6	76.4	69.7	72.3	74.6
1999 - 2000	46.4	46.6	47.5	46.9	46.5	46.8	47.0	46.9
2000 - 2001	55.9	55.3	54.1	55.5	54.4	55.1	55.0	54.7
Average	60.8	61.2	61.2	62.8	62.4	61.1	61.7	**62.1**
Red Kandasol								
92 - 93	40.1	39.3	66.1	67.7	66.5	48.5	57.7	66.8
93 - 94	77.7	77.5	77.5	82.0	83.3	77.6	79.0	81.0
94 - 95	55.2	55.2	55.6	57.2	57.6	55.3	56.0	56.8
95 - 96	69.7	68.9	67.8	66.7	66.4	68.8	67.8	67.0
96 - 97	71.6	73.1	73.4	77.1	78.3	72.7	74.5	76.3
97 - 98	63.4	63.2	63.6	63.6	63.8	63.4	63.4	63.7
98 - 99	72.5	74.0	75.2	76.7	78.2	73.9	75.3	76.7
1999 - 2000	55.3	56.2	56.8	55.6	55.0	56.1	56.2	55.8
2000 - 2001	47.5	48.0	48.8	51.4	52.2	48.1	49.4	50.8
Average	61.4	61.7	65.0	66.4	66.8	62.7	64.4	**66.1**

Table 6-5 APSIM simulated effective rain (3 ML/ha)

Yellow Chromosol	Irrigation Treatments & Effec. Rain (mm)					Irrigation Strategies & Effec. Rain (mm)		
	-14 days	-7 days	0 days	+7 days	+ 14 days	Early	Middle	Late
92 - 93	718.5	718.5	718.7	717.8	718.2	718.6	718.3	718.2
93 - 94	736.8	736.8	736.8	736.7	736.7	736.8	736.8	736.7
94 - 95	540.2	541.3	527.0	540.0	532.6	536.1	536.1	533.2
95 - 96	577.6	565.2	542.5	565.5	542.2	561.8	557.7	550.1
96 - 97	691.4	684.3	660.9	684.4	664.6	678.9	676.5	670.0
97 - 98	701.6	686.9	674.9	677.0	671.2	687.8	679.6	674.4
98 - 99	753.8	753.4	753.0	753.9	753.5	753.4	753.4	753.5
1999 - 2000	401.4	400.6	396.2	400.7	395.7	399.4	399.2	397.5
2000 - 2001	567.5	567.5	567.4	567.5	567.5	567.5	567.5	567.5
Average	632.1	628.3	619.7	627.1	620.3	**626.7**	625.0	622.3
Red Kandasol								
92 - 93	723.6	723.5	717.4	724.9	720.9	721.5	721.9	721.0
93 - 94	824.0	818.8	806.7	825.2	824.1	816.5	816.9	818.7
94 - 95	589.5	594.2	585.8	593.0	585.7	589.8	591.0	588.1
95 - 96	708.8	706.6	706.8	706.0	706.3	707.4	706.5	706.4
96 - 97	748.8	746.3	736.7	746.6	743.8	743.9	743.2	742.3
97 - 98	721.1	720.6	719.5	717.6	715.1	720.4	719.2	717.4
98 - 99	839.1	837.4	838.0	837.7	838.0	838.2	837.7	837.9
1999 - 2000	448.0	446.3	444.1	446.3	444.1	446.1	445.6	444.8
2000 - 2001	645.7	642.8	640.3	643.9	641.8	642.9	642.3	642.0
Average	694.3	692.9	688.4	693.4	691.1	**691.9**	691.6	691.0

Table 6-6 APSIM simulated effective rain (2 ML/ha)

Yellow Chromosol	Irrigation Treatments & Effec. Rain (mm)					Irrigation Strategies & Effec. Rain (mm)		
	-14 days	-7 days	0 days	+7 days	+ 14 days	Early	Middle	Late
92 - 93	717.5	717.8	718.3	718.1	718.6	717.8	718.0	718.3
93 - 94	736.8	736.8	736.8	736.7	736.8	736.8	736.8	736.8
94 - 95	542.2	544.2	538.5	542.3	541.2	541.6	541.7	540.7
95 - 96	585.7	585.6	585.8	583.8	578.2	585.7	585.1	582.6
96 - 97	691.2	684.3	660.9	684.4	664.6	678.8	676.5	670.0
97 - 98	705.8	704.9	703.0	677.0	671.2	704.6	695.0	683.7
98 - 99	753.8	753.4	753.0	753.9	753.5	753.4	753.4	753.5
1999 - 2000	401.8	401.8	401.5	400.7	395.7	401.7	401.3	399.3
2000 - 2001	567.5	567.5	567.4	567.5	567.5	567.5	567.5	567.5
Average	633.6	632.9	629.5	629.4	625.3	**632.0**	630.6	628.0
Red Kandasol								
92 - 93	724.1	723.5	717.3	724.8	720.9	721.6	721.9	721.0
93 - 94	824.0	818.8	806.6	825.1	824.0	816.5	816.8	818.6
94 - 95	597.0	603.9	597.4	601.5	593.6	599.4	600.9	597.5
95 - 96	718.8	717.9	715.3	712.3	709.5	717.4	715.2	712.4
96 - 97	748.8	746.2	736.6	746.7	743.9	743.9	743.2	742.4
97 - 98	720.7	720.3	719.5	718.4	717.4	720.2	719.4	718.4
98 - 99	839.1	837.4	838.5	837.7	838.5	838.3	837.9	838.2
1999 - 2000	449.9	449.5	448.1	446.3	444.1	449.2	448.0	446.2
2000 - 2001	645.6	642.8	640.3	643.8	641.8	642.9	642.3	642.0
Average	696.4	695.6	691.1	695.2	692.6	**694.4**	693.9	693.0

Despite only slight variations in sugarcane yields between irrigation strategies, some patterns emerged in relation to irrigation start-up after rainfall, water allocation and soil type. At 3 ML/ha, modelling showed that the early irrigation strategy produced the highest yield, for the Yellow Chromosol averaged over the simulated period. The early strategy was the highest yielding strategy in 44% of the years modelled due to a combination of better irrigation timing for some years and the greater potential in other years to use all of the available water supply.

The water holding capacity of the Yellow Chromosol was similar to the soils monitored at field sites. Modelled results agreed with observations at field sites from 1999 – 2001 for the Yellow Chromosol, which indicated irrigation practice could be improved by starting irrigation earlier after rainfall to get around the farm.

In comparison, at 3 ML/ha, modelling showed that the late irrigation strategy produced the highest yields for the Red Kandasol averaged over the simulated period. The late strategy was the highest yielding strategy in 67% of years. The late irrigation strategy produced the highest yields except for those years in which the early strategy was able to use all of the available water supplies.

In 33% of the years modelled for both soil types the late irrigation strategy limited the opportunity to apply all of the available water. For example in the 1993 – 1994 season, the +14 day treatment provided opportunity to apply 4 irrigations compared to the -14 day treatment which had opportunity to apply 6 irrigations. This resulted in an increase in yield of 9.2 tc/ha and identified an opportunity to maximise yields on individual blocks by using all of the available water supplies. The nett effect was diluted in the results to less than a 4 tc/ha difference between strategies as the yield increase was averaged across the whole farm.

For an allocation of 2 ML/ha, the late irrigation strategy was the highest yielding strategy for both the Yellow Chromosol (56% of years) and the Red Kandasol (78% of years). All of the available irrigation supply was utilised in each season, therefore yield increases were a result of irrigation start up times.

Modelling indicated an interaction between irrigation treatments and when water supplies were used during the season. Crop yield in most years was higher in the late strategy despite less effective rainfall. This indicated a crop response to when the water was used. Timing after rainfall altered the strategic use of water (ie. when water was used over the whole season) by delaying irrigations and shifting water use to later in the season. The number of days between the -14 days and +14 day irrigation treatments was effectively a lag in irrigations by one month. Each irrigation event was simulated on the same day except for the first and last irrigation events. Effective rainfall, calculated for each strategy indicated that the earlier irrigation treatments in most years obtained the highest effective rainfall. Despite this, sugarcane yield was higher by consistently adopting the late irrigation strategy.

6.5 CROP RESPONSE TO IRRIGATION UNIFORMITY

6.5.1 Crop Growth Response to Applied Water

The response to irrigation timing assumes that water is applied evenly to the entire field. However, in practice this becomes multidimensional due to the non uniformity in which water is applied to the field by the irrigation system. To understand this interaction field trials were conducted which measured crop biomass production relative to the various amounts of water applied across the field due to the non uniformity of an overhead irrigation system.

A relationship between biomass production and water applied to the field was determined from stem elongation and catch can measurements. Biomass produced between irrigations was assumed to be indicative of cane yield. For each of the tests, stem elongation between irrigations was plotted against total water use. The total water available to the crop was determined via a water balance to incorporate rainfall, irrigation and differences in soil moisture between monitoring.

For five of the six tests conducted at Site 4, high irrigation uniformity was achieved, resulting in a low variability of water applied to the field. This effectively reduced the treatment effect of non-uniformity. Significant rainfall between irrigations was sufficient to fill the soil profile to field capacity for one test at both Site 4 and Site 1. This also reduced the treatment effect for these tests.

Despite these set backs, two irrigation events at Site 1 gave a relationship between the water applied to the field and stem elongation (Figure 6-14). For these tests, the crop extracted soil moisture to the same deficit at each irrigation event and no rainfall was recorded. This negated the need to transform catch can readings into soil moisture. A polynomial regression was fitted through the measured field data to develop a relationship between stem elongation and applied water (Figure 6-14).

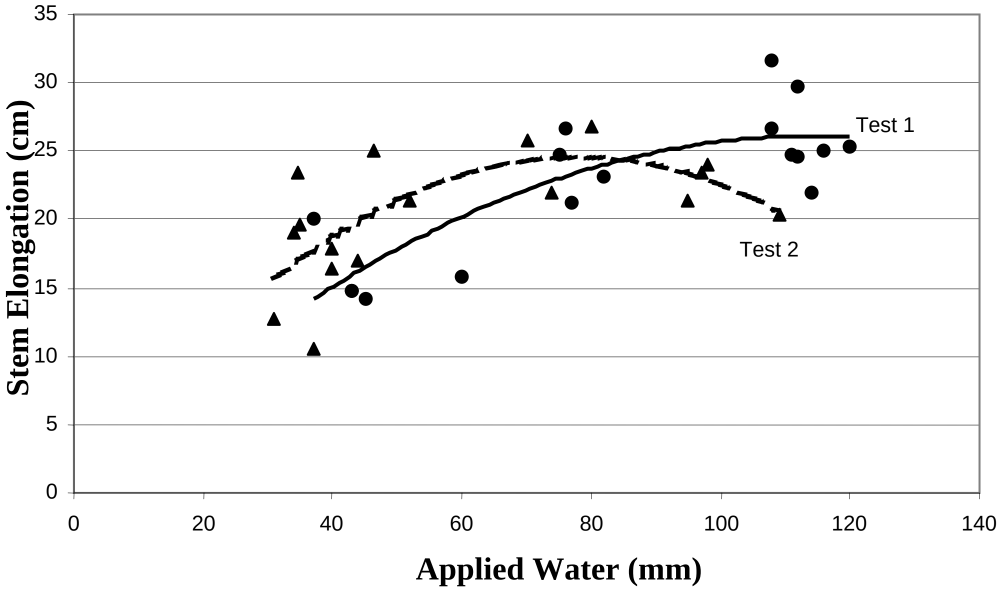


Figure 6-14 Effect of water application on stem elongation

The stem elongation water relationships in Figure 6-14 were then expressed in relative terms. Relative yield (ie. biomass production) is defined as the ratio of actual yield to the maximum yield obtained. The reduction in yield measured in the tests is due to over or under watering from non-uniformity. Under or over watering is expressed as relative water, that is, the amount of water relative to the amount required to maximise yield. It is assumed that the maximum yields obtained in the tests were not constrained by limited water.

Figure 6-15 shows the crop response to water expressed in relative terms for both of the field tests (Figure 6-14). Expressing yield in relative terms filters out other factors which influence absolute yield such as pests, diseases, nutrition, etc. An average response has been fitted to these two tests. Figure 6-15 also shows a comparable relationship for sugarcane derived by Solomon (1990). The similarity of results between the two tests and in comparison with Solomon (1990) provides confidence in the relationship derived, despite the limited data set.

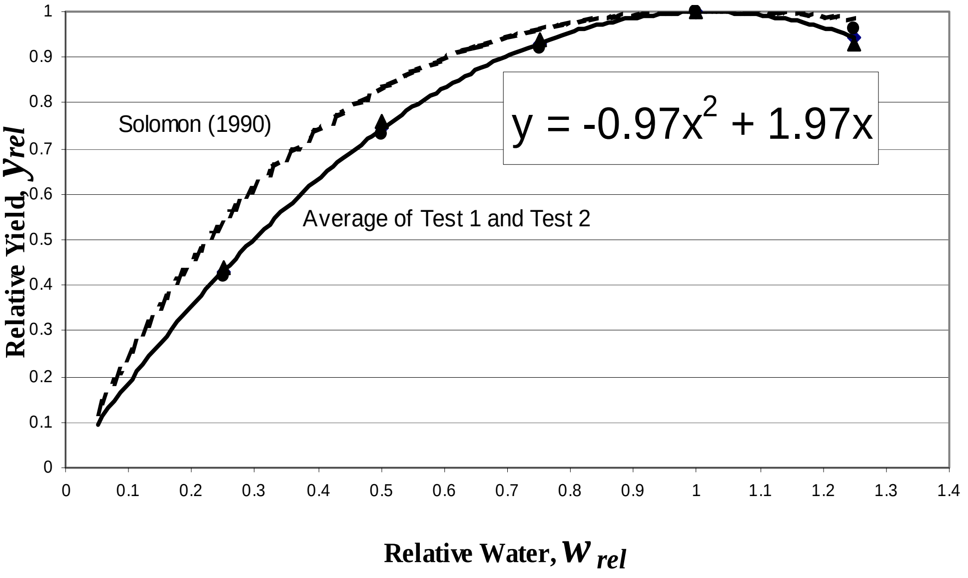


Figure 6-15 Crop response to water expressed in relative terms

6.5.2 Yield Response to Non-Uniformity

The trials conducted by Gordon (2000) consisted of 22 tests, providing a comprehensive data set for examining the impacts of uniformity on yield, based on the relative yield relationship developed above. Each of the distribution patterns reported by Gordon (2000) was expressed as a cumulative distribution of water applied to the field. Yield was calculated by applying the yield water relationship displayed in Figure 6-15 to the cumulative distribution of water across the field for each of the 22 tests. The seasonal distribution of water was assumed to be the same as for the individual irrigation events.

For each test, it was assumed that the mean depth of water applied to the field (X) was sufficient to meet crop demand. The applied depth x_i at a particular point in the field was transformed to relative water, w_{rel_i} by Equation 6 and is graphically shown in Figure 6-16.

$$w_{rel_i} = \frac{x_i}{X} \qquad \textbf{Eqn 6}$$

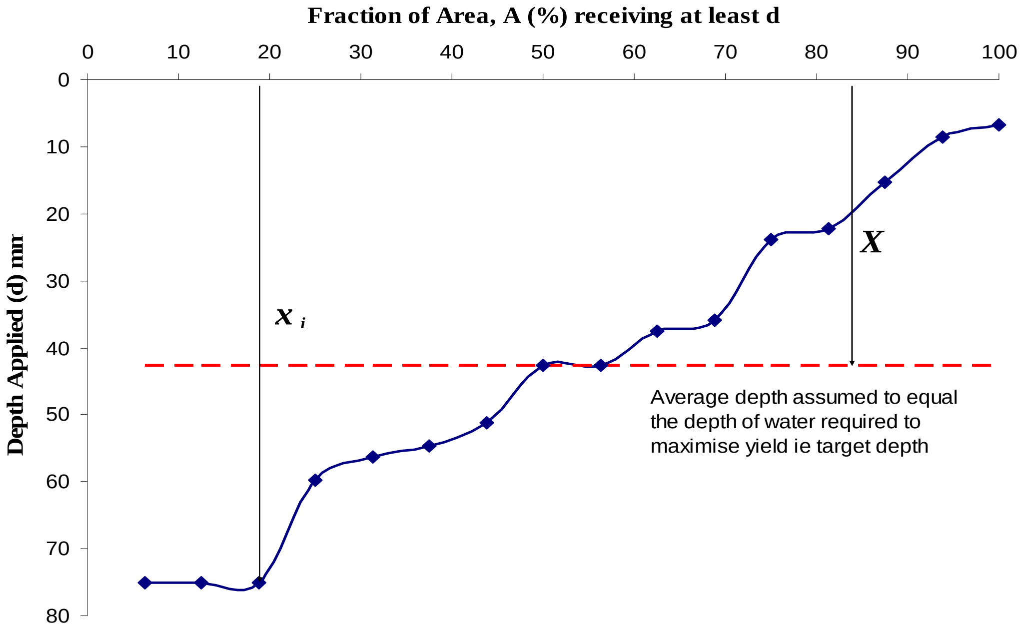


Figure 6-16 Graphical determination of relative water

Relative water was transformed into relative yield, y_{rel_i} using the relationship in Figure 6-15:

$$y_{rel_i} = -0.97 w_{rel_i}{}^2 + 1.97 w_{rel_i} \qquad \textbf{Eqn 7}$$

Total relative yield was then determined for each test by summing the yield response at each catch can according to the percentage area, A_i associated with the applied depth x_i:

$$Y_{rel} = \sum (y_{rel_i} A_i) \qquad \textbf{Eqn 8}$$

The reduction in yield Y_{red} due to non-uniformity was determined by Equation 8 and is graphically shown in Figure 6-17.

$$Y_{red} = 1 - Y_{rel} \qquad \textbf{Eqn 9}$$

Figure 6-17 Graphical determination of total relative yield

For each of the tests, the reduction in yield was plotted against Christiansen's Uniformity Coefficient calculated for each test (Figure 6-18). Similarly for the furrow trials reported in Chapter 5 a reduction in yield was determined by using the infiltrated depths of the furrow irrigation trials. A reduction in yield was also plotted against the Distribution Uniformity calculated for each test (Figure 6-19).

For water winch systems, a linear relationship was fitted between Christiansen's Uniformity Coefficient and yield reduction for the range of tests undertaken by Gordon (2000). An 8% reduction in yield was identified for every 10% reduction in CU (Figure 6-18). Similarly a linear relationship was derived between Distribution Uniformity and yield reduction for the furrow trials reported in Chapter 5. A yield reduction of 1.3% was identified for every 10% reduction in DU (Figure 6-19). It is important to note that the relationships for reduced yield, CU and DU are not directly comparable, but have been reported in the respective uniformity indices for each irrigation system.

Over the range of performances measured in the field, yield reduction due to non-uniformity of furrow irrigation systems wasn’t as significant as for water winches. Maximum yield loss due to non-uniformity of furrow irrigation systems was approximately 7% compared to 35% for water winches.

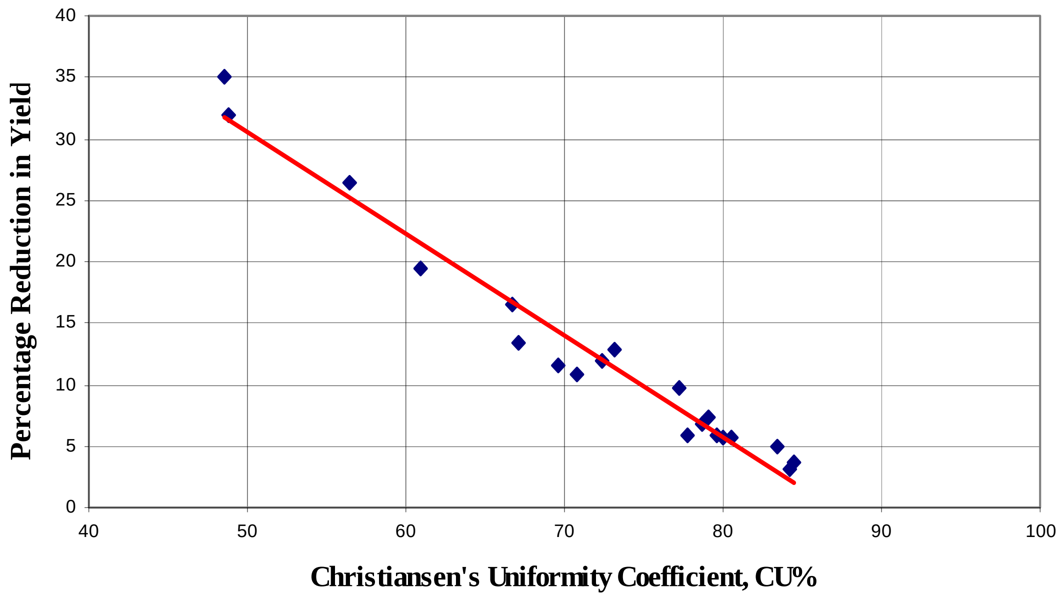


Figure 6-18 Reduction in yield due to non uniformity of water winch systems

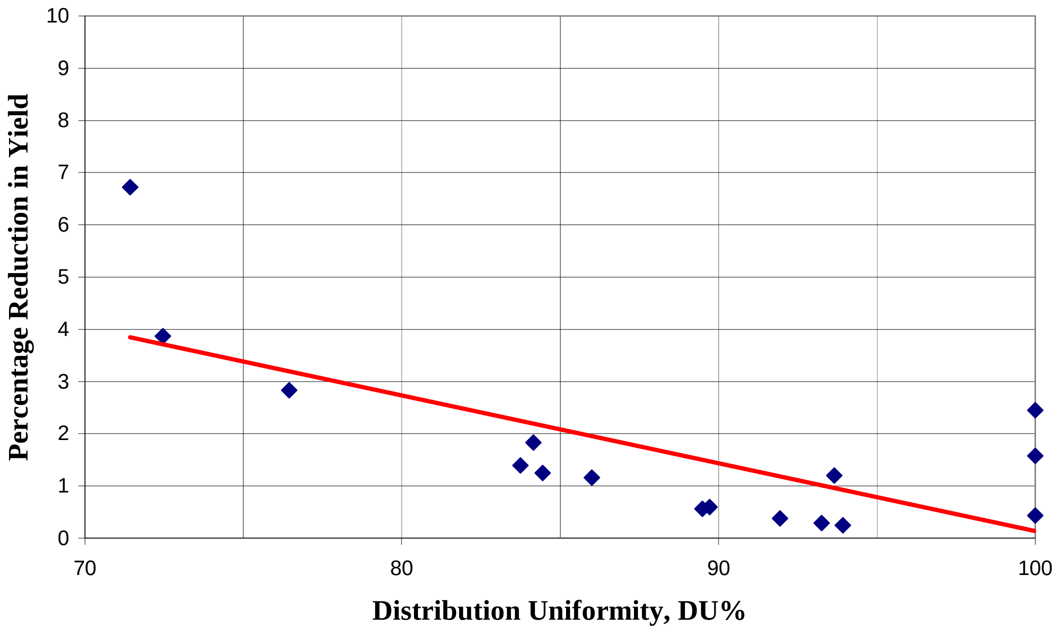


Figure 6-19 Reduction in yield due to non uniformity of furrow systems

6.5.3 Factors Which Influence the Effect of Uniformity

During the trial work, significant rainfall between some of the irrigations filled the soil profile to field capacity, effectively reducing any treatment effect of non-uniformity. This highlighted that in districts with high rainfall or in seasons with high rainfall, the impacts of non-uniformity will be reduced. It also highlights the importance of improving irrigation uniformity as an irrigation strategy in areas with limited water and in dry seasons.

Soil water holding capacity will also influence the effect of non-uniform irrigation. Soils that have a higher water holding capacity will have higher effective rainfall. Crops on lighter soils, which have lower effective rainfall, will be influenced most by non-uniformity.

It should also be noted that the crop sensitivity to water stress at different growth stages may also contribute to overall yield. Hence, where crops are under irrigated during critical growth stages the effect on crop yield may be greater than was determined in this work.

6.5.4 Impacts of Management Practices on Yield for Water Winches

Chapter 4 identified that the major influence on the performance of water winches in the Bundaberg area was the effect of wind. Simple changes to the setup of the irrigator were identified under these conditions to improve uniformity. An example of these changes includes the use of taper nozzles instead of ring nozzles in windy conditions. Taper nozzles were found to maintain throw distance and provide better overlap of the sprinkler pattern, which maximised uniformity. Under high wind speeds, an increase in CU of up to 16% was achieved by changing from ring to taper nozzles (Gordon, 1999). Based on the relationship between yield and applied water (Figure 6-18), a 15% yield increase should be possible with a change in nozzle.

6.6 CONCLUSION

6.6.1 Crop Response to Current Practice

The capacity of water winches to apply more water than the crop demands for supplementary irrigation was found to be limited. Under current operating practices the maximum capacity of these systems was effectively constrained to meeting the demands of supplementary irrigation requirements recommended in the literature. In these circumstances the scheduling of limited water is focused towards starting irrigations after rainfall. Strategies were identified which suggested that irrigation practices could be improved by earlier start up after rainfall (ie. starting irrigation earlier) where systems were operating at a deficit.

6.6.2 Crop Response to Irrigation Startup Strategies

At the farm level, the appropriate use of limited water was found to be dependant on the season, the soil type and the amount of allocation available. Only slight variations in cane yield occurred between the different irrigation strategies modelled. This suggested a significant amount of flexibility between the timing of irrigations after rainfall. The main benefit of irrigating earlier after rainfall was greater opportunity to use all of the available irrigation supply. In 30% of the years modelled, the later irrigation treatment didn’t use all of the available water. Results showed that the difference in yields between individual blocks were greater than 5 tc/ha by holding off too long and not using the full allocation by the end of the season.

Where growers had access to 3 ML/ha, the earlier irrigation strategy returned the highest yields on the Yellow Chromosol while the late irrigation strategy produced the highest yields on the Red Kandasol. By consistently having the same irrigation strategy the late irrigation strategy returned the highest yields over the long term. This suggested that in years where the earlier irrigation strategy returned the highest yield the difference wasn’t as great as those years when the later strategy returned the highest yield.

Where growers had access to 2 ML/ha a slight increase in yield occurred on most occasions by holding off irrigation longer after rainfall. This was more apparent on the heavier soil type (Red Kandasol, 78% of years) than the lighter soil type (Yellow Chromosol, 56% of years). A consistent late irrigation strategy provided the greatest benefit in cane yield over the long term. At the 2ML/ha allocation all of the available irrigation supplies were used regardless of irrigation strategy adopted.

6.6.3 Crop Response to Irrigation Uniformity

Yield decreases of 8% were found for every 10% reduction in CU of water winches. Hence, fine-tuning the operation of the machine to improve uniformity can deliver real yield benefits in improving yields. A yield increase of 15% was calculated from a 16% improvement in CU associated with changing from a ring nozzle to a taper nozzle in windy conditions.

Yield reduction due to non-uniformity of furrow irrigation systems wasn’t as significant as for water winches. Maximum yield loss due to non-uniformity of furrow systems was approximately 7%. A yield reduction of 1.3% was measured for every 10% reduction in DU.

The effect of uniformity on yield was reduced by rainfall between irrigation events. The significance of uniformity would be lower in districts with high rainfall or during wet seasons. However, increasing uniformity is an important strategy for maximising yield in drier areas where water supplies are limited such as Bundaberg, particularly for overhead irrigation systems.

7 GENERAL DISCUSSION

The influence that water has on sugarcane production in the Bundaberg district is significant. Sugarcane production in the Bundaberg district has fallen from 3.8 million tonnes to 2.1 million tonnes due to limited water. Based on this scenario strategies were investigated to maximise sugarcane production with limited water supplies. Current practices and the operation of water winch and furrow irrigation systems were reviewed and evaluated through a grower survey, in-field trials and simulation modelling. Based on these investigations, significant opportunities to improve irrigation performance were identified.

7.1 Winch Irrigation

Water winch systems are the most common irrigation system encountered in the Bundaberg district. The performance of these systems is largely governed by irrigation uniformity. In particular wind speed and direction has the most significant effect on irrigation uniformity. Growers were generally aware of these influences and indicated through the grower survey that they would ideally irrigate in low wind conditions. Growers indicated that they would shut down winches in relatively low wind speeds when the wind is blowing in the row direction (ie. travelling direction of the winch). Meteorological data for the Bundaberg district indicated that growers would be forced to irrigate in less than ideal circumstances as the occurrence of higher wind speeds was common. Additionally, winches are typically unable to apply sufficient water to match the irrigation deficit creating greater pressure on growers to irrigate in less than ideal circumstances. Both these factors confirmed the need to investigate and develop strategies to optimise the performance of water winches under local conditions.

Trial results suggested that water winches could be operated without significant loss of performance up to a maximum wind speed of 15 km/h. However, the wind direction also had a significant effect, particularly when in the row direction. Wind in the row direction reduced the throw distance from the gun reducing the overlap and irrigation uniformity. At winds speeds between 10 to 15 km/hr, taper nozzles were found to improve CU by as much as 16% compared to a ring nozzle at the same wind speed and direction. However, differences between the ring and taper nozzles weren’t significant when the wind direction was across the row.

Reducing the gun arc angle was found to marginally improve CU. However, these tests were conducted at low wind speeds. Larger differences would be expected at higher wind speeds as the reduced arc angle throws more water to the extremity of the sprinkler pattern which better combats the effects of wind.

Atmospheric losses of 20 to 30% were measured. As the volume of these losses is a constant, more frequent irrigation using smaller application amounts would result in increased percentage losses. Similarly, applying larger volumes during each irrigation would reduce the proportional loss. Hence, irrigation efficiency could be improved by applying more water per irrigation.

The current lane spacing of 80 metres was found to be excessive for local conditions. Results suggested that to optimise irrigation uniformity under local conditions, lane spacing would need to be reduced to between 55 and 65 metres. However, this change in lane spacing layout isn’t financially viable and the trial results suggested that larger improvements to winch performance could be more easily achieved through changes in the operational settings.

7.2 Furrow Irrigation

Furrow irrigation is the second most popular form of irrigation in the Bundaberg district. The occurrence across the district varies, with the majority of the Millaquin area irrigated by furrow irrigation. Current levels of application efficiency ranged from 45% to 99% and substantial opportunities to improve irrigation performance were identified. Except when cracking clay soils had cracked prior to irrigation, the operation of furrow irrigation systems could be manipulated to achieve application efficiencies greater than 90% and distribution uniformities greater than 84%. This was achieved in most cases by simply changing furrow flow rate, better control of cut-off times and banking the end of the field.

From the grower survey, most growers were aware of correct cut-off times and the attention to minimising runoff was demonstrated by the large number of tail water recycling systems installed. Similarly, growers were aware that soil infiltration could be influenced through management of tillage practices including furrow formation. However, even though furrow flow rate is used to adjust how much water is applied to the field, only a small proportion of growers (5%) measured their furrow flow.

Furrow flow rates should be adjusted for specific soil and field conditions. Flow rates of approximately 1 L/s were consistently used across all of the field sites that were monitored. However, simulation modelling and field evaluations demonstrated that flow rates should be increased to 3 to 4 L/s on soils with high infiltration rates. Uneven advance between furrows occurred at sites where inappropriate furrow flow rates were selected confirming that furrow flow rates influenced irrigation uniformity.

In general, irrigation cut-off times were controlled so that the irrigation was turned off as water just reached the end of the field. At higher flow rates, the irrigation was turned off earlier as drainage was sufficient for the water to reach the end of the field. In most cases, banking the end of the furrow was found to improve both the application efficiency, by reducing runoff, and the distribution uniformity, by improving infiltration at the end of the field. The exception was in situations where ponding occurred at the end of the field.

Application efficiency on high infiltration soils was maximised by reducing deep drainage. Reducing deep drainage on high infiltration soils was achieved by strategies that included irrigating alternate furrows and using shallow cultivation practices which maintained compaction in the furrow.

7.3 Crop Responses

Crop Response to Start Up Strategies

The grower survey identified that the capacity of irrigation systems in the Bundaberg District (specifically water winches) was insufficient to match fully irrigated crop water requirements. Observations at field sites were consistent with the survey data as soil moisture at field sites were found to progressively decline during the season. Hence, these systems were operating at an irrigation deficit which was similar to the strategies adopted for supplementary water supplies. Once irrigation had commenced the next irrigation was determined by the rotation period of the irrigation system. In effect these systems were self-scheduling. Therefore, a critical aspect of managing these systems was when to start-up irrigation after rainfall.

Soil moisture data recorded at field sites indicated that irrigation practices could be improved and cane yield increased by starting irrigation earlier after rainfall. Crop simulation modelling evaluated three irrigation scenarios (ie. early, middle and late irrigation) relative to the start-up time after rain.

Modelling results indicated that the optimum irrigation strategy was only slight and that it varied between seasons, soil types and available water allocation. The slight increase in yield of the optimum irrigation strategy suggested that irrigation timing after rainfall was reasonably flexible. The insensitivity of irrigation start-up was believed to be due to the small amount of allocation being modelled (ie. 2 & 3 ML/ha relative to the total crop water demand). The calculated effective rainfall for each of the irrigation strategies was almost identical which supported this view.

Some crop yield and water utilisation patterns emerged from the modelling. For example, starting irrigation early after rainfall provided greater opportunity to use all of the water supplies throughout the season. The greatest difference in yield occurred between irrigation treatments when water was left over at the end of the season (9.2 tc/ha). Where the start of irrigation after rainfall was late, the water allocation wasn’t fully utilised in 30 % of the years modelled. The early strategy was the highest yielding strategy for the Yellow Chromosol where 3 ML/ha was available. The late strategy was the highest yield strategy for the Red Kandasol where 3 ML/ha was available. It was also the highest yield strategy for both soils where only 2 ML/ha was available. Modelling suggested that the most important aspect for irrigation scheduling with limited water was to use all of the available water supplies.

Crop Response to Irrigation Performance

Simple changes to improve the performance of the irrigation application system showed greater potential to increase yield than changes to the irrigation start up strategy. This suggested that irrigation strategies for limited water should be focused towards the improvement of irrigation system performance. For water winches, every 10% reduction in CU resulted in a potential reduction in sugarcane yield of 8%. Simple changes to improve irrigation uniformity for winch systems, such as changing nozzle types, were found to increase sugarcane yield by 16%. Similarly, changing the cup size on the layflat for furrow systems was shown to double the nett amount of water applied to the crop (ie. from AE = 45% to AE = 90%) under some circumstances. From the production curve in Figure 1-2 and assuming a gross water allocation of 2 ML/ha this would result in an increased yield of approximately 13 tc/ha.

8 CONCLUSION AND RECOMMENDATIONS

Despite the availability of limited water supplies, opportunities were identified to improve sugarcane yield by fine tuning irrigation practices. Grower practices were reviewed and strategies were developed to improve irrigation system performance and the management of irrigation under commercial conditions. The greatest potential to increase sugarcane yield under conditions of limited water was through the improvement of irrigation system performance. Improving uniformity and application efficiency produced the largest gains. Due to the relatively small amount of irrigation compared to the crops total water demand there was a significant degree of flexibility for irrigation start up after rain. Irrigation strategies that were modelled a month apart had only minor differences in final yields and effective rainfall.

Winch Systems

The uniformity of water winch systems reduced with increasing wind speeds particularly when the wind was parallel to the travelling direction of the winch. Due to the limited capacity of these machines to meet crop demand and the higher winds speeds that occur for most of the day these systems are often forced to irrigate in less than ideal conditions. Minor operational changes such as changing to a different nozzle type were found to result in an increase in potential yield of 16%.

Strategies found to maximise the performance of water winch systems in Bundaberg include:

- Cease operation at wind speeds greater than 15 km/h.
- At wind speeds between 10 to 15 km/h when the wind direction is parallel to the row, use taper nozzles.
- At wind speeds between 10 to 15 km/h for cross winds, nozzle type isn’t critical.
- Maintain current application rates. Reducing application volume to enable more frequent irrigations will increase losses.
- Closer lane spacings should be encouraged for new systems ie. 55 to 65 metres although this wasn’t considered practical for existing systems.

Furrow Systems

Substantial opportunities to improve the performance of furrow irrigation systems were identified. Under commercial conditions each of the furrow systems monitored were manipulated to perform at an AE greater than 90% and a DU of 84%. The exception was at one site which was a heavy clay soil which had cracked prior to irrigating. Simple changes such as changing the cup size (to alter furrow flow rate), turning the irrigation off at the correct time and banking the end of the field significantly increased irrigation performance.

Strategies to maximise the performance of furrow irrigation systems in the Bundaberg area included:

- Increase furrow flow rates to reduce the amount of water applied to the block. A furrow flow rate of 1 L/s is appropriate for most situations with flow rates of up to 3 L/s for a highly infiltrating soil.
- Shut of the irrigation just as water reaches the end of the furrow (or earlier at higher flows).
- Bank the end of the field except for soil with low infiltration rates.
- Irrigate prior to cracking on cracking clay soils.

Alternative strategies identified for high infiltration soils included irrigating alternate furrows and adopting shallow cultivation practices to maintain surface compaction in the interspace and reduce infiltration.

Crop Response to Irrigation

Most irrigation systems in the Bundaberg district were only able to apply equivalent daily application rates similar to the rates reported in the literature for supplementary irrigation. Under these circumstances, the only opportunity for irrigation scheduling was when to start-up after rain. Optimum irrigation strategies varied between soil type, allocation and season with only slight differences in yield between the highest and lowest yield treatment. The result suggested that this degree of flexibility for scheduling irrigation was due to the small amount of water available for irrigation relative to the total demands of the crop. This was demonstrated by the calculation of the same effective rainfall for each treatment which suggests regardless of the deficit at which irrigation was applied there was a big enough buffer in the soil to maximise rainfall.

Subtle differences between irrigation scheduling treatments suggested the following strategies for managing limited water:

- The emphasis should be on using all of the available water supplies. The most significant difference in yield occurred when water was left over at the end of the season.
- The early irrigation strategy provided the greatest opportunity to use all of the available water supplies (plus opportunity for additional announced allocation). In 30% of years the late strategy didn’t use all of the available water supplies.
- The early strategy produced the highest yield on the medium water holding soil (PAWC of 88 mm) with an allocation of 3 Ml/ha. These results were consistent with field observations.
- On a high water holding soil (PAWC of 176 mm) a more conservative irrigation strategy would produce the highest yield regardless of allocation (ie. 2ML/ha or 3ML/ha).

9 REFERENCES

Ah-Koon, D., Ng Cheong, L. R., Teeluck, M., Ratna, D. and Muthy, K. 2000, 'Strategies for deficit irrigation of sugarcane in Mauritius', *International Sugar Journal,* vol. 102, no. 1224, pp. 648 - 650.

Alazba, A. A. and Fangmeier, D. D. 1995, 'Hydrograph shape and border irrigation efficiency', *Journal of Irrigation and Drainage Engineering,* vol. 121, pp. 452 - 457.

Al-Naeem, M. A. H. 1993, *Optimisation of Hosereel Rain Gun Irrigation Systems in Wind: Simulation of the Effect of Trajectory Angle, Sector Angle, Sector Postion and Lane Spacing on Water Distribution and Crop Yield*, PhD Thesis, Silsoe College, Cranfield University.

Baillie, C. P., Gordon, G. and Smith, R. J. 2001, 'Performance of travelling gun irrigators', in *Proceedings of Australian Society of Sugar Cane Technologists,* p. 469.

Bell, I. 1991, ‘Boom Versus Gun Irrigator Optimisation and Comparison Trial’, *in Water Force – Irrigation Australia*, Spring, pp 22 – 34.

Benami, A. and Ofen, A. 1984, *Irrigation Engineering,* Faculty of Agricultural Engineering, Technion - Israel Institute of Technology, Technion City, Haifa, Israel.

BSES 1984, 'Comparative Big Gun Sprinkler Tests at BSES Bundaberg', (unpublished), Bureau of Sugar Experiment Stations, Bundaberg.

Bundaberg Sugar Ltd 2000, *Annual Cane Supply Report - Bundaberg Regional Mills,* Bundaberg Sugar Ltd, Internal Report.

Christiansen, J. E. 1941, 'Hydraulics of sprinkling systems for irrigation.' *Transactions American Society of Civil Engineers,* vol. 107, pp. 221 - 237.

Cseko, G. and Lelkes, J. 1995, 'Water Application by Travelling Gun Sprinklers in Windy Circumstances', *Irrigation Farming - Soils and Fertilisers,* vol. 59, no. 11, pp. 31-43.

DNR&M 2003, *Burnett Basin Resource Operations Plan,* Queensland Government, QNRM03147.

Donnollan, T., Wilson, P. R., Zund, P. R. and Irvine, S. A. 1998, *Soils and Irrigated Land Suitability of the Bundaberg Area, South East Queensland,* Queensland Department of Natural Resources, DNRQ980142.

Elliot, R. L. and Walker, W. R. 1982, Field evaluation of furrow infiltration and advance functions, *Trans ASAE 396-400*

Ellis, R. D. and Lankford, B. A. 1990, 'Tolerance of sugarcane to water stress during its main development phases', *Agricultural Water Management,* vol. 17, no. 1-3, pp. 117 - 128.

Evans, R. G., Aarstad, J. S., Miller, D. E. and Kroeger, M. W. 1987, 'Crop residue effects on surge furrow irrigation hydraulics', *Transactions American Society of Agricultural Engineers*, vol. 30, pp. 424 - 429.

Gordon, G. 2000, *Performance of travelling gun irrigators*, Honours Dissertation, University of Southern Queensland.

Grose, D. J. 1999, *Mathematical Modelling and Simulation of Irrigation Sprinklers*, PhD Thesis, Silsoe College, Cranfield University.

Ham, G. J. 1994, *Irrigation and Drainage - a Queensland Perspective*, 41st Annual General Meeting, Australian National Committee on Irrigation Drainage, Kununarra.

Hardie, M. A. 2000, *APSIM Based Determination of Irrigation Attributes and Best Use of Limited Water in Supplementry Irrigation Areas of the Australian Sugar Industry.*, Bureau of Sugar Experiment Stations, Proserpine, Technical Report TE00001.

Hoffman, G. J. and Martin, H. L. 1993, 'Engineering systems to enhance irrigation performance', *Irrigation Science,* vol. 14, pp. 53 - 63.

Holden, J. R. (ed.) 1998, *Irrigation of Sugarcane*, Bureau of Sugar Experiment Stations, Brisbane, Queensland.

Inman-Bamber, N. G., Baillie, C. and Willcox, J. 2002, 'Tools for improving efficiency of limited water in sugarcane', in *Irrigation: Conservation or Conflict*, ed. B. G. Sutton, Irrigation Association of Australia, Sydney, pp. 251 - 259.

Inman-Bamber, N. G. and Jager, J. M. 1988, 'Effect of water stress on cane growth and water use of sugarcane', *S Afr. J. Plant Soil 1988*, vol. 5, no. 2.

Inman-Bamber, N. G., Muchow, R. C., Holden, J. R., Robertson, M. J. and Ham, G. J. 1998, 'Soil Water Extraction by Sugar Cane Beyond the Readily Available Limit.' in *Proceedings of Australian Society of Sugar Cane Technologists* pp. 112-117.

Jensen, M. E. (ed.) 1983, *Design and operation of farm irrigation systems,* ASAE Monograph 3, St Joseph, MI.

John, P. H., Lees, D. M. and English, G. M. 1985, *Application performance of travelling irrigators.*, New Zealand Agricultural Engineering Institute, Lincoln College, NZ, Project Report No 35.

Keating, B. A., Robertson M. J., Muchow R. C. and Nuth, N. I., 1999, Modelling sugarcane production systems. I Development and performance of the APSIM sugarcane module. *in Field Crop Res*. 61:253-72

Kerr, J. 1983, *Southern Sugar Saga - A History of the Sugar Industry in the Bundaberg District,* Bundaberg Sugar Ltd, Bundaberg, Queensland.

Kingston, G. 2000, ‘An Overview of Irrigation in the Australian Sugar Industry’, *Limited Irrigation Strategies Workshop,* Childers, Queensland.

Kingston, G. 1972, 'An Experiment in Irrigation Scheduling - Further Comments', in *Proceedings of Australian Society of Sugar Cane Technologists* pp. 143 - 150.

Kingston, G. and Chapman, L. S. 1975, 'Water Requirements and Irrigation Scheduling of Sugar Cane in Queensland - II Irrigation scheduling of sugar cane in Queensland', in *Proceedings of Australian Society of Sugar Cane Technologists* pp. 69 - 76.

Kingston, G. and Ham, G. J. 1975, 'Water Requirements and Irrigation Scheduling of Sugar Cane in Queensland - I Water requirements of sugar cane in Queensland', in *Proceedings of Australian Society of Sugar Cane Technologists* pp. 57 - 64.

Kirda, C. and Kanber, R. 1999, ‘Water, no longer a plentiful resource, should be used sparingly in irrigated agriculture.’ i*n Crop yield response to deficit irrigation*, C. Kirda, P. Mountonnet, C. Hera, and D.R. Neilsen (eds). Kluwer Academic Publishers, Dordrecht.

Langlier, P. 1988, 'Irrigation Management - water efficiency and actual requirements', in *Proc 4th International Micro-Irrigation Congress 1988, p5B/2.*

Lee, J. C., Ellis, J. R. and Lacewell, R. D. 1985, 'Valuation of improved irrigation efficiency from an exhaustible groundwater source', *American Water Resources Association Water Resources Bulletin 21*, pp. 441 - 447.

Leverington, K. C., Kingston, G. and Skinner, S. O. 1970, 'An Experiment in Irrigation Scheduling', in *Proceedings of Australian Society of Sugar Cane Technologists* pp 51 - 56.

Linedale, A. I. 2001, *A Participatory Approach to Improving Furrow Irrigation Efficiency*, Final Report SRDC Project BSS206, SD01013, Bureau of Sugar Experiment Stations, Brisbane, Queensland.

McMahon, G. G. 1996, *A summary of district irrigation practices, research and extension for sub-program 3.1.2*, A Report for the Cooperative Research Centre for Sustainable Sugar Production by the Bureau of Sugar Experiment Stations, Brisbane, Queensland.

Merriam, J. L. and Keller, J. 1978, *Farm Irrigation System Evaluation: A Guide for Mangement*, Agricultural and Irrigation Engineering Department, Utah State University, Logan, Utah.

Nelson 1980, *Nelson Big Gun Sprinklers*, Nelson Irrigation Corporation, Walla Walla, U.S.A.

Newell, G., Foley, J. and Smith, R. 2002, *Travelling Gun and Boom Irrigation Machines: Review of Machine Characteristics, Performance Data and Machine Issues 179764/1*, National Centre for Engineering in Agriculture Publication, USQ, Toowoomba.

Pene, C. B. G. and Edi, G. K. 1999, 'Sugarcane yield response to deficit irrigation in two growth stages', in *Crop yield response to deficit irrigation*, eds. C.Kirda, et al., Kluwer Academic Publishers, Dordrecht.

Raine, S. R., Bakker, D. and Robertson, M. J. 1997, 'Alternate furrow irrigation improves water use efficiency', In *Australian Sugarcane*, October-November Vol., pp. 6 - 7.

Raine, S. R. and Bakker, D. J. 1996a, 'Increased furrow irrigation efficiency through better design and management of cane fields', in *Proceedings of Australian Society of Sugar Cane Technologists* pp. 119-124.

Raine, S. R. and Bakker, D. M. 1996b, *Increased productivity through better design and management of cane fields*, Sugar Research and Development Corporation, BS90S Final Report.

Raine, S. R., Ham, G. J. and Shannon, E. L., 1996, ‘Soil management practices to improve the efficiency of surface irrigation in the Burdekin’. in Soil Science: raising the profile., *Proc. ASSI National Soil Conference, 27-29th* April, Brisbane p311-7

Raine, S. R., McClymont, D. J. and Smith, R. J. 1998, 'The effect of variable infiltration on design and management guidelines for surface irrigation', in *Proc. ASSSI National Soils Conference*, Brisbane, pp. 311-317.

Ridge, D. R. 2000, *Assessment of Irrigation Demand for Sugar Cane in the Bundaberg Area*, Bundaberg 2000+ Project.

Ridge, D. R. 2001, *Assessment of Irrigation Strategies for Best Use of Limited Water - A Review of Relevant Research to Date.*, Bundaberg.

Ridge, D. R. and Hillyard, J. 2000, 'Varietal Response to Irrigation Amount and Method in the Bundaberg Area', in *Proceedings of Australian Society of Sugar Cane Technologists* pp. 256 - 263.

Robertson, M. J., Inman-Bamber, N. G. and Muchow, R. C. 1997, 'Opportunities for Improving the Use of Limited Water by the Sugarcane Crop', in *Intensive Sugarcane Production: Meeting the Chalenges Beyond 2000*, eds. B. A. Keating and J. R. Wilson, CAB International, Wallingford, UK, pp. 287 - 302.

Robertson, M. J. and Muchow, R. C. 1997, 'Variation in the Effectiveness of Rainfall Meeting Crop Water Requirements in the Australian Sugar Industry', in *Proceedings of Australian Society of Sugar Cane Technologists* pp 229 - 236.

Ross, H. S. and Williamson, A. J. P. (eds.) 1990, *Irrigation For Profit Water Force Queensland*, Irrigation Association of Australia, Brisbane, Queensland.

Shannon, E., McDougall, A., Kelsey, K. and Hussey, B. 1996, 'WATERCHECK - A Co-ordinated Extension Program for Improving the Irrigation Efficiency of Australian Canegrowers', in *Proceedings of Australian Society of Sugar Cane Technologists* pp 113 - 118. .

SKM 2000, *The Efficiency of Water Use in the Burnett Region - Final Report*.

Smith, R. J. 1990, 'The Distribution of Water from Rigid and Layflat Gated Pipe', in *Proceedings of Australian Society of Sugar Cane Technologists*, pp. 56 - 64.

Smith, R. J., Baillie, C. P. and Gordon, G. 2002, 'Performance of Travelling Gun Irrigation Machines', in *Proceedings of Australian Society of Sugar Cane Technologists* pp 235 - 240.

Solomon, K. H. 1990, 'Irrigation Systems and their water application efficiencies', In *Agibusiness Worldwide*, July / August 1990 Vol., pp. 16 - 24.

Solomon, K. H. 1993, 'Irrigation Systems and Water Application Efficiencies', *Irrigation Australia*, no. Autumn, pp. 6 - 12.

Stehlik D. and Mummery K. 2000, *Rural Water Use Efficiency Initiative Sugar Cane Industry Benchmarking Survey,* Final Report for the Bureau of Sugar Experiment Stations, Department of Natural Resources and Canegrowers, Brisbane, Queensland

Tilley, L. and Chapman, L. S. 1999, *Benchmarking Crop Water Index for the Queensland Sugar Industry, Irrigation Audit 1999*, Burea of Sugar Experiment Stations and Canegrowers, Brisbane, Queensland.

Turner, N. C. 1990, *Plant Water Relations and Irrigation Management*, Agricultural Water Management, 17:1-3.

von-Bernuth, R. D. 1988, 'Effect of Trajectory Angle on Performance of Sprinklers in Wind', *Journal of Irrigation and Drainage Engineering*, vol. 11, no. 4, pp. 579 - 587.

Walker, W. R. 1999, *SIRMOD II Surface Irrigation Simulation, Evaluation and Design - User's Guide and Technical Documentation*, Utah State University, Logan.

Wigginton, D. W. and Raine, S. R. 2001, 'Irrigation system performance on dairy farms in the Mary River catchment.' in *Irrigation Association of Australia Regional Conference 2001*, Toowoomba.

Appendix A Furrow Irrigation Field Data

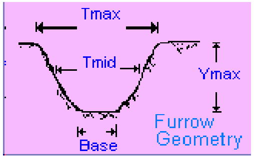
Table A-1 Furrow irrigation field data site 1a

Site 1a

Field & Irrigation Details

Furrow flowrate, Q	1.00 L/s
Time of Cutoff (min)	1415
Length of Field (m)	255
Slope of Field	0.0011
Banked Ends	N

Furrow Characteristics



Tmax	1.14 m
Tmid	0.94 m
Base	0.76 m
Ymax	0.15 m

Raw Data

Dist. (m)	Sensor 1 (min)	Sensor 2 (min)	Sensor 3 (min)	Sensor 4 (min)	Sensor 5 (min)	Sensor 6 (min)
0	455	455	455	455	454	454
85	592	601	911	759	639	794
170	1294	972	1348	1252	1260	1464
255	1740	1912	1775	1763	1811	
	Same Row		Same Row		Same Row	

Advance

Start Time 454

Dist	Advance Times (min)						Regressed Adv.
0	0	0	0	0	0	0	0
85	138			305	185		201
170		518		798	806		668
255	1286			1309	1357		1348

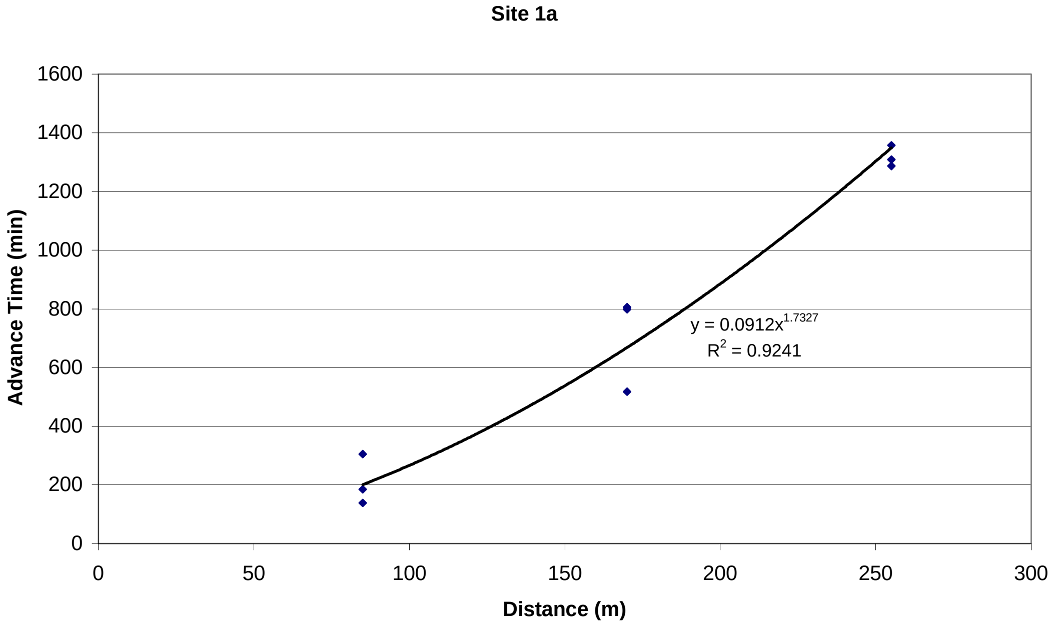


Figure A-1 Furrow Advance site 1a

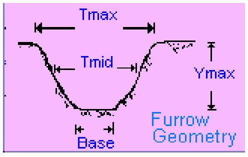
Table A-2 Furrow irrigation field data site 1b

Site 1b

Field & Irrigation Data

Furrow Flowrate, Q (L/s)	3
Time of Cutoff (min)	1005
Length of Field	255
Slope of Field	0.0011
Banked Ends	N

Furrow Characteristics



Tmax	1.14 m
Tmid	0.94 m
Base	0.76 m
Ymax	0.15 m

Raw Data

Dist. (m)	Sensor 1 (min)	Sensor 2 (min)	Sensor 3 (min)	Sensor 4 (min)	Sensor 5 (min)	Sensor 6 (min)	Sensor 7 (min)	Sensor 8 (min)
0	1725	1725	0	not used	1725	1725	1725	1725
64	276	1760	1761		1767	1767	1767	1767
127.5	1819	1819	1819		1849	1850	1850	1497
191	1912	1912	1912		2031	2032	2031	2031
255	2100	2093	2093		2468	2467	2467	2466
	same row				same row			

Advance

Start Time	1725

Dist	**Advance Times (min)**							**Regressed Adv.**
0	0	0	0		0	0	0	0	0
64		35	36		42	42	42	42	35
127.5	94	94	94		124	125	125		125
191	187	187	187		306	307	306	306	264
255	375	368	368		743	742	742	741	448

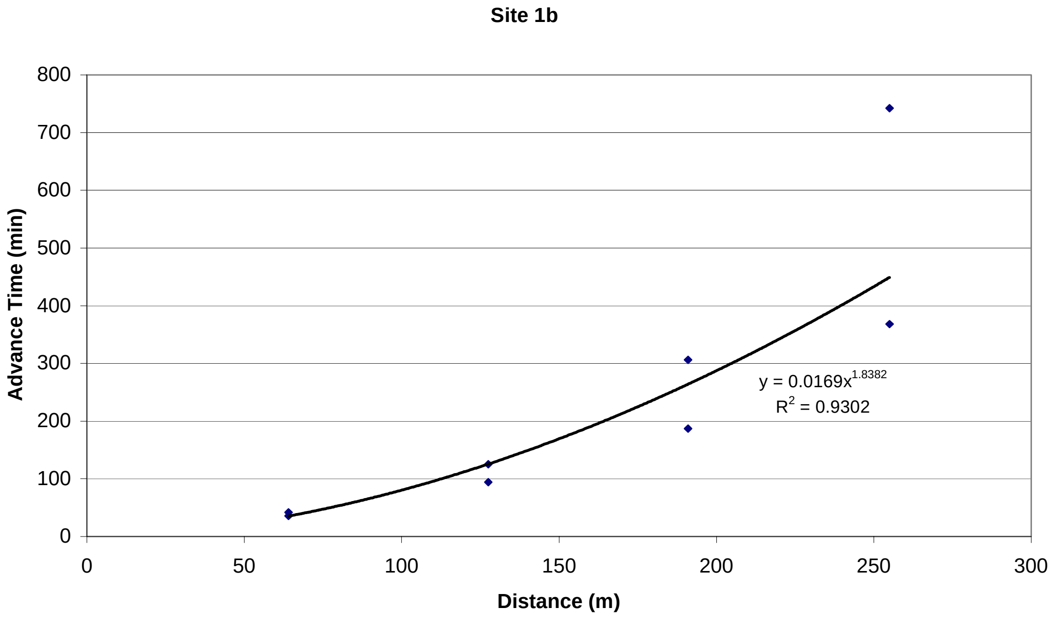


Figure A-2 Furrow advance site 1b

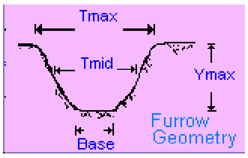
Table A-3 Furrow irrigation field data site 1c

Site 1c

Field & Irrigation Data

Furrow Flowrate, Q (L/s)	1.2
Time of Cutoff (min)	900
Length of Field	255
Slope of Field	0.0011
Banked Ends	N

Furrow Characteristics



Tmax	1.14 m
Tmid	0.94 m
Base	0.76 m
Ymax	0.15 m

Raw Data

Dist. (m)	Sensor 1 (min)	Sensor 2 (min)	Sensor 3 (min)	Sensor 4 (min)	Sensor 5 (min)	Sensor 6 (min)	Sensor 7 (min)	Sensor 8 (min)
0	128	215	176	3	202	201	287	201
64	276	275	668	275	302	260	359	302
127.5	50	446	551	571	451	478	445	381
191	550	550	0	745	957	730	551	371
255	568	477	345	971	33	971	0	0
	R1 flowrate = 1.2 l/s		R2 flowrate = 1.1 l/s		R3 flowrate = 1.1 l/s		R4 flowrate = 1.2 l/s	

Advance

Start Time 201

Dist	Advance Times (min)								Regressed Adv.
0	0	0	0	0	-	-	-	-	0
64	65	65	50	92	-	-	-	-	68
127.5	236	341	241	171	-	-	-	-	224
191	340	535	520	341	-	-	-	-	450
255	358	761	761		-	-	-	-	742

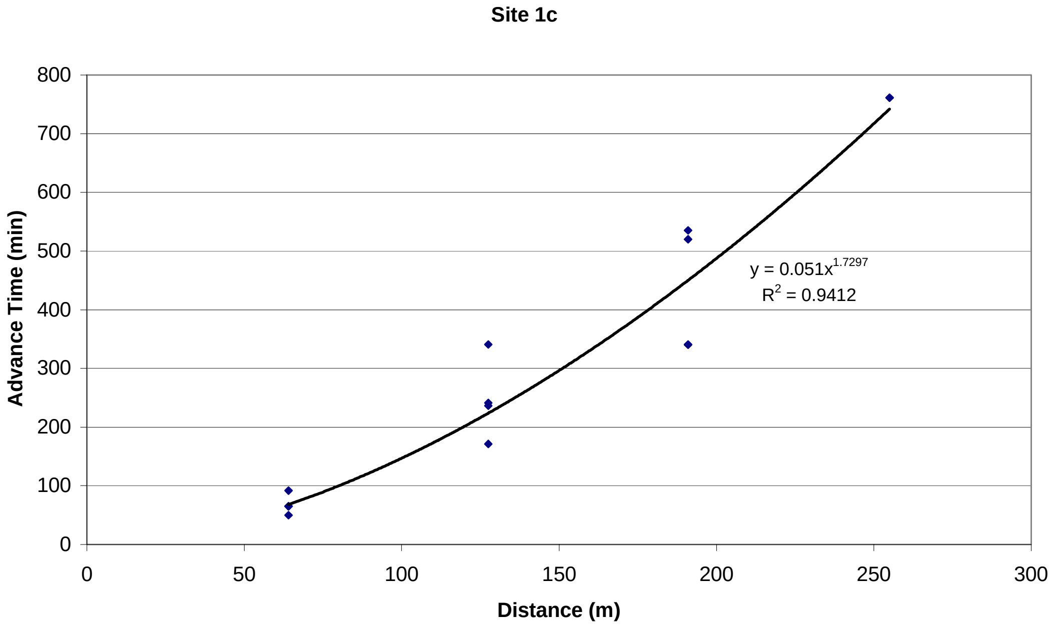


Figure A-3 Furrow advance site 1c

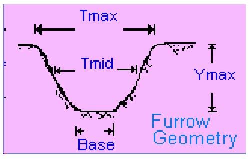
Table A-4 Furrow irrigation field data site 2

Site 2

Field & Irrigation Data

Furrow Flowrate, Q (L/s)	1.45
Time of Cutoff (min)	820
Length of Field	305
Slope of Field	0.0014
Banked Ends	N

Furrow Characteristics



Tmax	0.70 m
Tmid	0.50 m
Base	0.32 m
Ymax	0.15 m

Raw Data

Dist. (m)	Sensor 1 (min)	Sensor 2 (min)	Sensor 3 (min)	Sensor 4 (min)	Sensor 5 (min)	Sensor 6 (min)	Sensor 7 (min)	Sensor 8 (min)	
0	42	42	42	42	42	42	42	42	
76	202	202	205	205	218	218	228	228	
152.5	404	403		404	411	411	435	434	
229	640	627	633	633	645	650	664	664	
305	748	749	796	792	827	870	1104	1104	Avg Flowrate
	R1 flowrate = 1.14 l/s		R2 flowrate = 1.42 l/s		R3 flowrate = 1.32 l/s		R4 flowrate = 1.9 l/s		1.4

Advance

Start Time 42

Dist	Advance Times (min)								Regressed Adv.
0	0	0	0		0	0	0	0	0
76	160	160	163	163	176	176	186	186	170
152.5	362	361		362	369	369	393	392	374
229	598	585	591	591	603	608	622	622	593
305	706	707	754	750	785	828	1062	1062	819

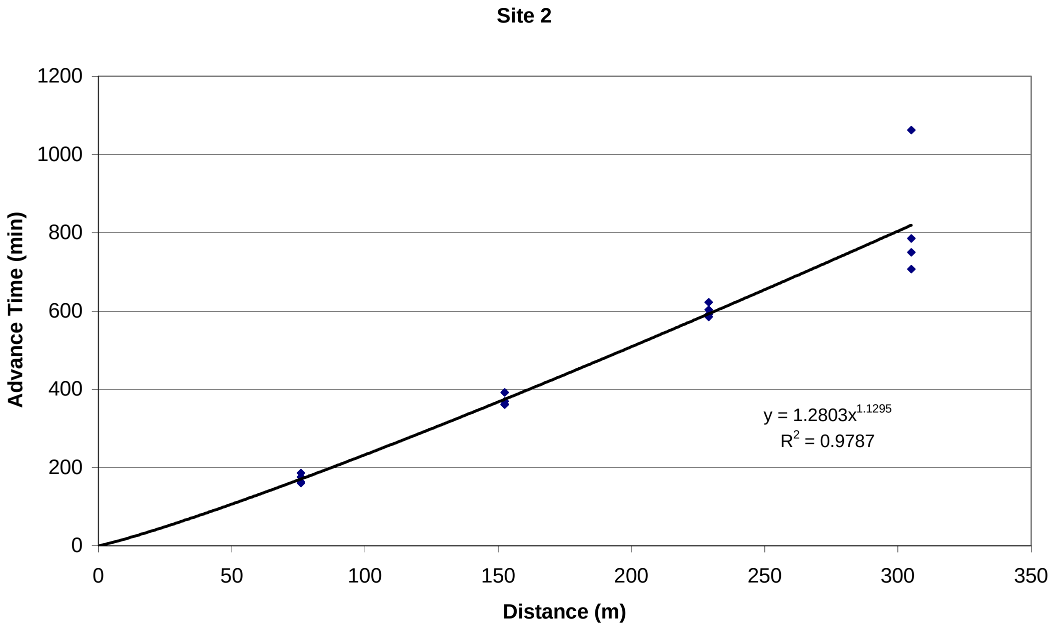


Figure A-4 Furrow advance site 2

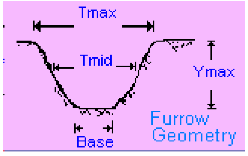
Table A-5 Furrow irrigation field data site 3

Site 3

Field & Irrigation Data

Furrow Flowrate, Q (L/s)	1.2
Time of Cutoff (min)	1111
Length of Field	371
Slope of Field	0.006
Banked Ends	N

Furrow Characteristics



Tmax	0.90 m
Tmid	0.55 m
Base	0.30 m
Ymax	0.13 m

Raw Data

Dist. (m)	Sensor 1 (min)	Sensor 2 (min)	Sensor 3 (min)	Sensor 4 (min)	Sensor 5 (min)	Sensor 6 (min)	Sensor 7 (min)	Sensor 8 (min)
0								
185.5	157	126	140	81	203	66	292	121
371	825	800	743	475	988	416	930	788

Irrigation started 8.30am and timers were reset at 1.00pm, so 1st point discarded and 270 minutes added to times.

Advance
Start Time "+270"

Dist	Advance Times (min)								Regressed Adv.
0	0	0	0		0	0	0	0	0
185.5	427	396	410	351	473	336	562	391	413
371	1095	1070	1013	745	1258	686	1200	1058	996

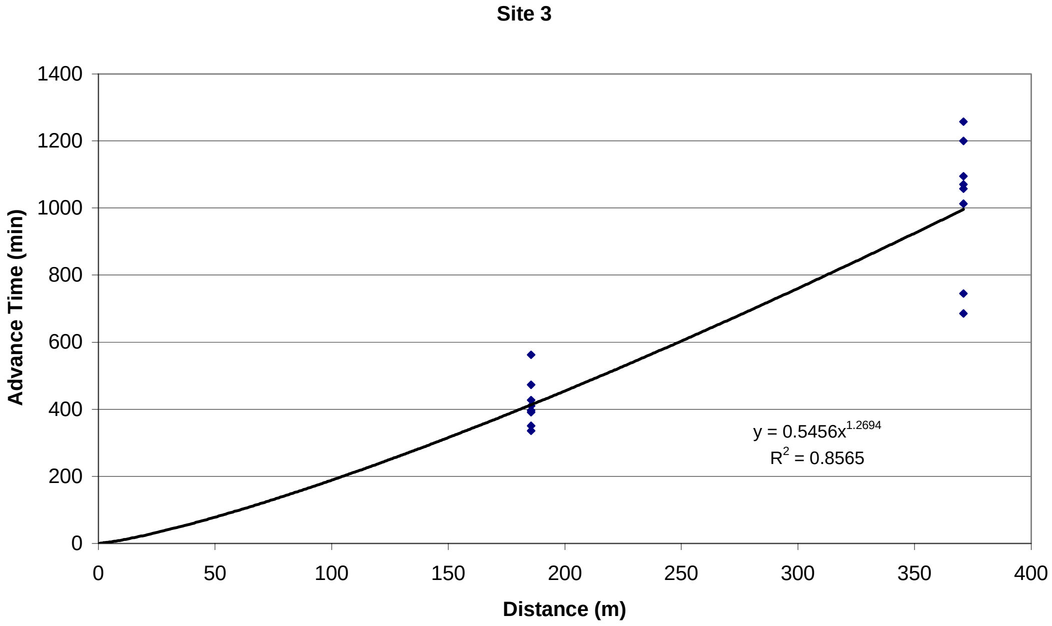


Figure A-5 Furrow advance site 3

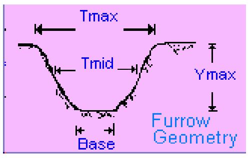
Table A-6 Furrow irrigation field data site 4

Site 4

Field & Irrigation Data

Furrow Flowrate, Q (L/s)	1
Time of Cutoff (min)	595
Length of Field	458
Slope of Field	0.0022
Banked Ends	N

Furrow Characteristics



Tmax	0.66 m
Tmid	0.43 m
Base	0.36 m
Ymax	0.18 m

Raw Data

Dist. (m)	Sensor 1 (min)	Sensor 2 (min)	Sensor 3 (min)	Sensor 4 (min)	Sensor 5 (min)	Sensor 6 (min)	Sensor 7 (min)	Sensor 8 (min)
0	1068	1069	1068	1068	1068	1068	1068	1068
114.5	1105	1124	1277	1104	1097	1114	1107	1117
229	1133	1195		1164	1148	1196	1254	1224
343.5	1213	1612		1293	1388	1316		
458	1438	1470	1633	1541	1611	1594	1577	1565

Advance

Start Time	1068

Dist	**Advance Times (min)**							**Regressed Adv.**
0	0	0	0	0	0	0	0	0	0
114.5	37	56		36	29	46	39	49	38
229	65	127		96	80	128	186	156	126
343.5	145			225	320	248			255
458	370	402	565	473	543	526	509	497	419

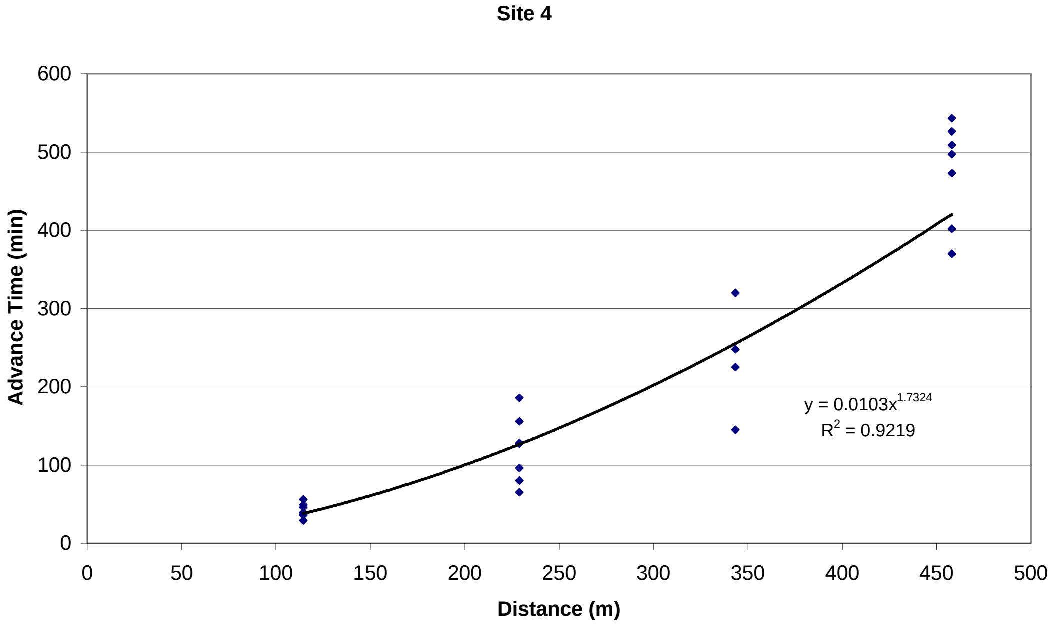


Figure A-6 Furrow advance site 4

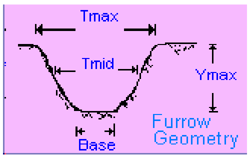
Table A-7 Furrow irrigation field data site 5

Site 5

Field & Irrigation Data

Furrow Flowrate, Q (L/s)	1.24
Time of Cutoff (min)	520
Length of Field	286
Slope of Field	0.0068
Banked Ends	N

Furrow Characteristics



Tmax	1.10 m
Tmid	0.80 m
Base	0.45 m
Ymax	0.10 m

Raw Data

Dist. (m)	Sensor 1 (min)	Sensor 2 (min)	Sensor 3 (min)	Sensor 4 (min)	Sensor 5 (min)	Sensor 6 (min)	Sensor 7 (min)	Sensor 8 (min)
0	360	360	360	360	360	360	360	360
71.5	460	481	459	479	471	466	504	485
143	566	618	566	596	575	567	630	62
214.5	738	771	737	750	691	708	772	735
286	2	868	891	862	871	829	213	862

Advance

Start Time 360

Dist	Advance Times (min)								Regressed Adv.
0	0	0	0	0	0	0	0	0	0
71.5	100	121	99	119	111	106	144	125	113
143	206	258	206	236	215	207	270		238
214.5	378	411	377	390	331	348	412	375	368
286		508	531	502	511	469		502	502

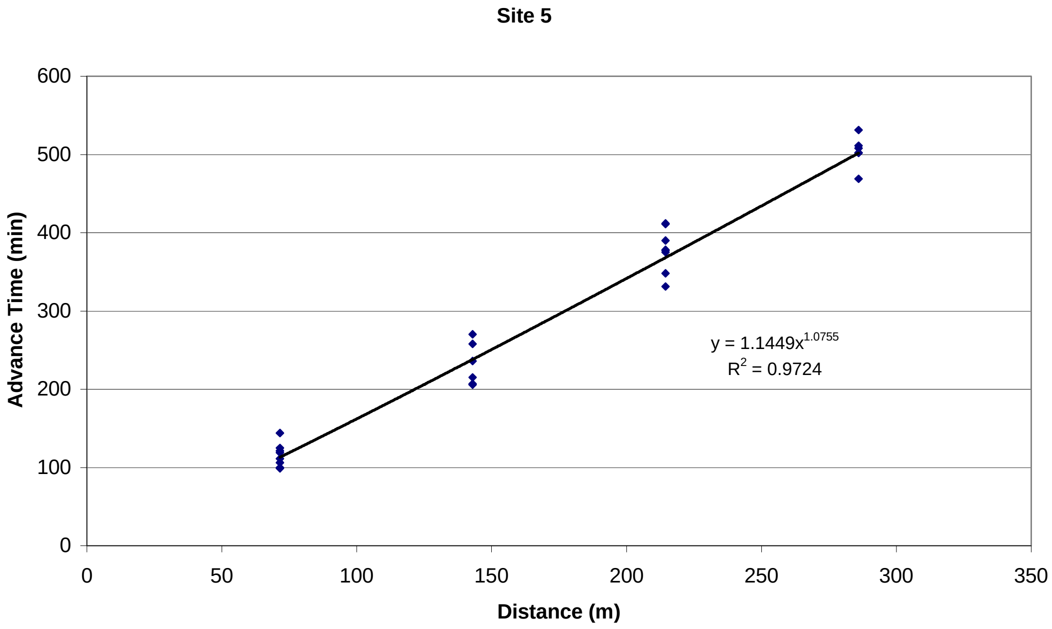


Figure A-7 Furrow advance site 5

Table A-8 Furrow irrigation field data site 6

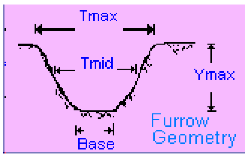
Site 6

Irrigation shutoff just as water reached the end. Last advance times determined from clock (ie. last timers didn't go off)

Field & Irrigation Data

Furrow Flowrate, Q (L/s)	1.8
Time of Cutoff (min)	165
Length of Field	310
Slope of Field	0.0063
Banked Ends	N

Furrow Characteristics



Tmax	1.10 m
Tmid	0.75 m
Base	0.45 m
Ymax	0.20 m

Raw Data

Dist. (m)	Sensor 1 (min)	Sensor 2 (min)	Sensor 3 (min)	Sensor 4 (min)	Sensor 5 (min)	Sensor 6 (min)	Sensor 7 (min)	Sensor 8 (min)
0	2	2	2	2	2	2	2	2
77.5	14	10	9	9	11	12	8	11
155	50	33	34	37	43	38	33	45
231	125	47	49	64	94	60	50	123
310	165	165	165	165	165	165	165	165

Advance

Start Time 2

Dist	**Advance Times (min)**								**Regressed Adv.**
0	0	0	0	0	0	0	0	0	0
77.5	12	8	7	7	9	10	6	9	9
155	48	31	32	35	41	36	31	43	36
231	123	45	47	62	92	58	48	121	84
310	163	163	163	163	163	163	163	163	154

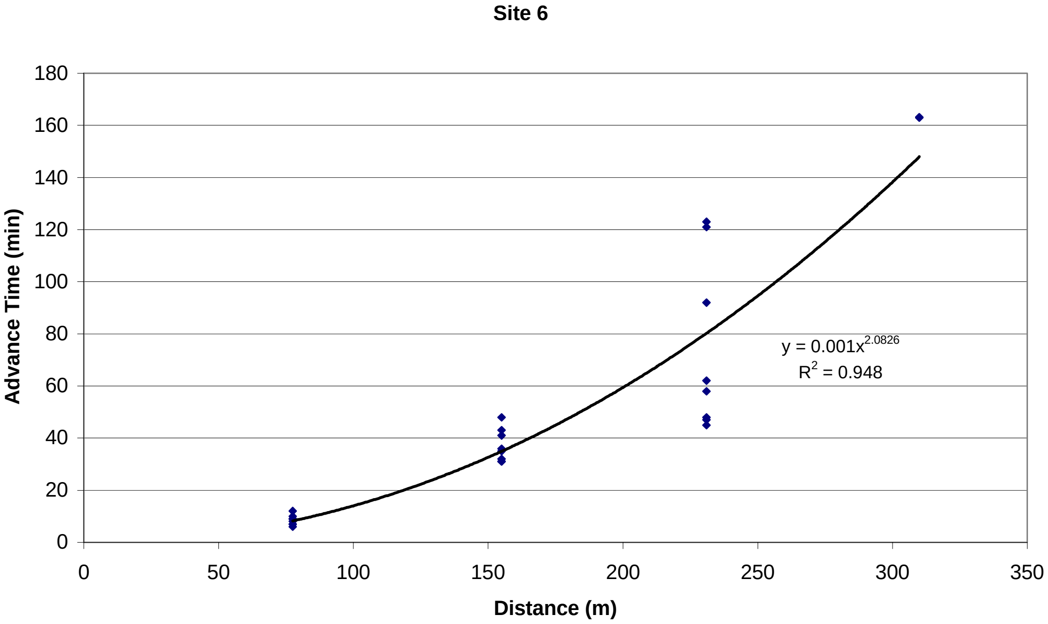


Figure A-8 Furrow advance site 6

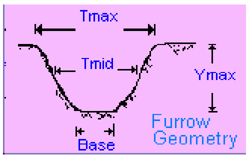
Table A-9 Furrow irrigation field data site 7

Site 7

Field & Irrigation Data

Furrow Flowrate, Q (L/s)	1.2
Time of Cutoff (min)	850
Length of Field	318
Slope of Field	0.0047
Banked Ends	N

Furrow Characteristics



Tmax	1.00 m
Tmid	0.70 m
Base	0.34 m
Ymax	0.16 m

Raw Data

Dist. (m)	Sensor 1 (min)	Sensor 2 (min)	Sensor 3 (min)	Sensor 4 (min)	Sensor 5 (min)	Sensor 6 (min)	Sensor 7 (min)	Sensor 8 (min)
0	981	1092	0	1093	1092	2201	1091	1091
64	1155	1314	0	1297	0	1221	0	1140
126	1393	1348	1591	1409	1385	1386	0	1375
190	1580	1544	3770	1580	1584	1544	3353	1553
252	1722	1674	0	1761	1805	1815	0	1711
318	1885	1862	1911	1927	1924	1899	1919	1863

Advance

Start Time 1091

Dist	Advance Times (min)								Regressed Adv.
0	0	0	0	0	0	0	0	0	0
64	64	223		206		130		49	120
126	302	257	500	318	294	295		284	275
190	489	453		489	493	453		462	454
252	631	583		670	714	724		620	641
318	794	771	820	836	833	808	828	772	851

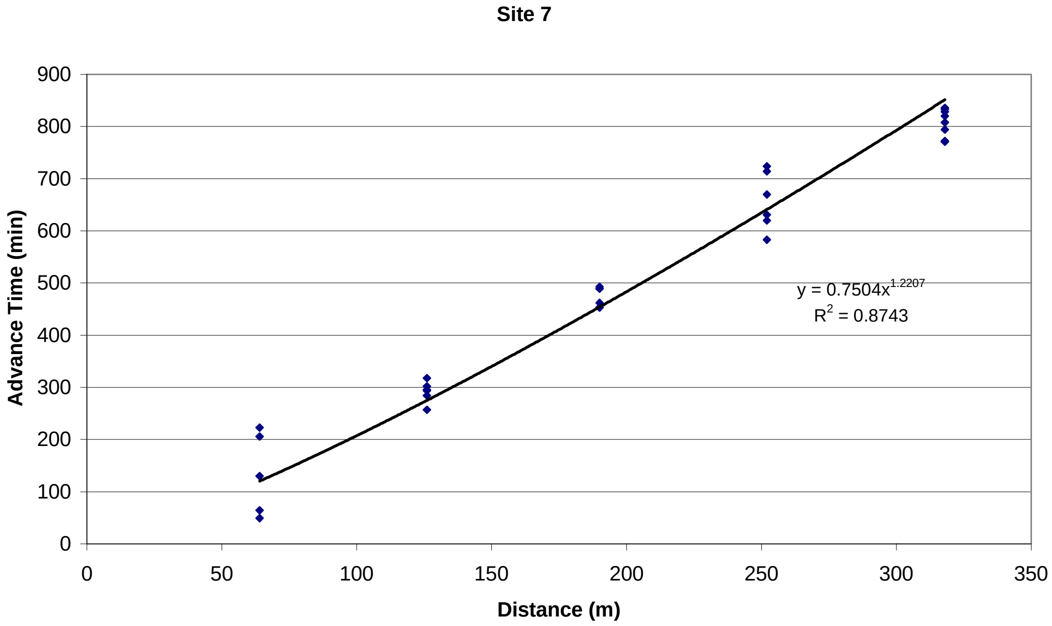
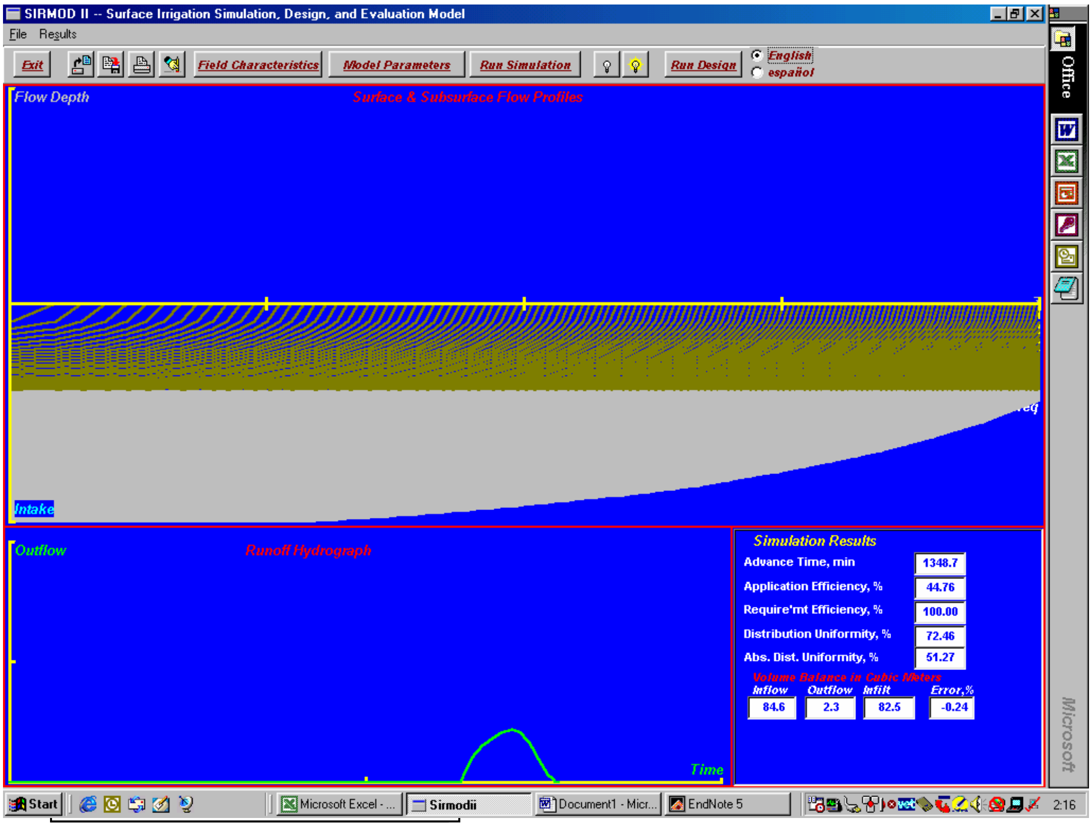


Figure A-9 Furrow advance site 7

Appendix B Simulations of Furrow Irrigation Systems (SIRMOD II)



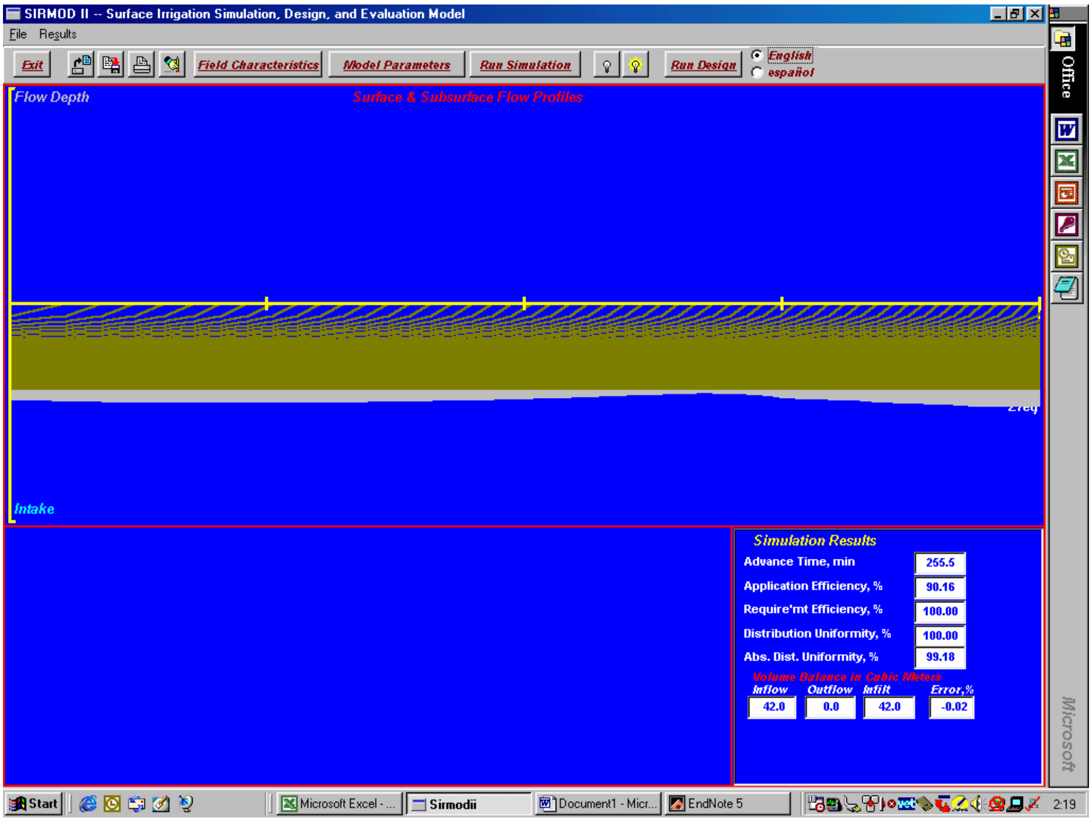
Simulation Results

Advance Time, min	1348.7
Application Efficiency, %	44.76
Require'mt Efficiency, %	100.00
Distribution Uniformity, %	72.46
Abs. Dist. Uniformity, %	51.27

Volume Balance in Cubic Meters

Inflow	Outflow	Infilt	Error,%
84.6	2.3	82.5	-0.24

Figure B-1 Measured irrigation performance site 1a



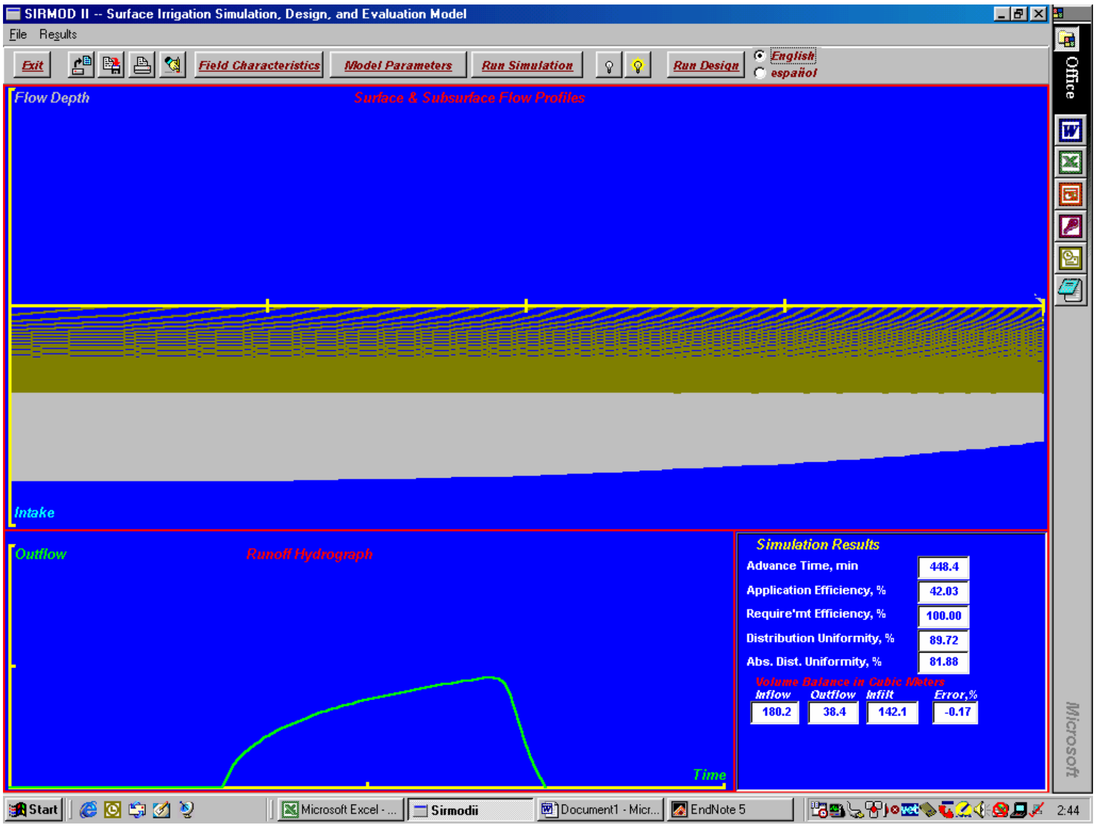
Simulation Results

Advance Time, min	255.5
Application Efficiency, %	90.16
Require'mt Efficiency, %	100.00
Distribution Uniformity, %	100.00
Abs. Dist. Uniformity, %	99.18

Volume Balance in Cubic Meters

Inflow	Outflow	Infilt	Error,%
42.0	0.0	42.0	-0.02

Figure B-2 Optimised irrigation performance site 1a



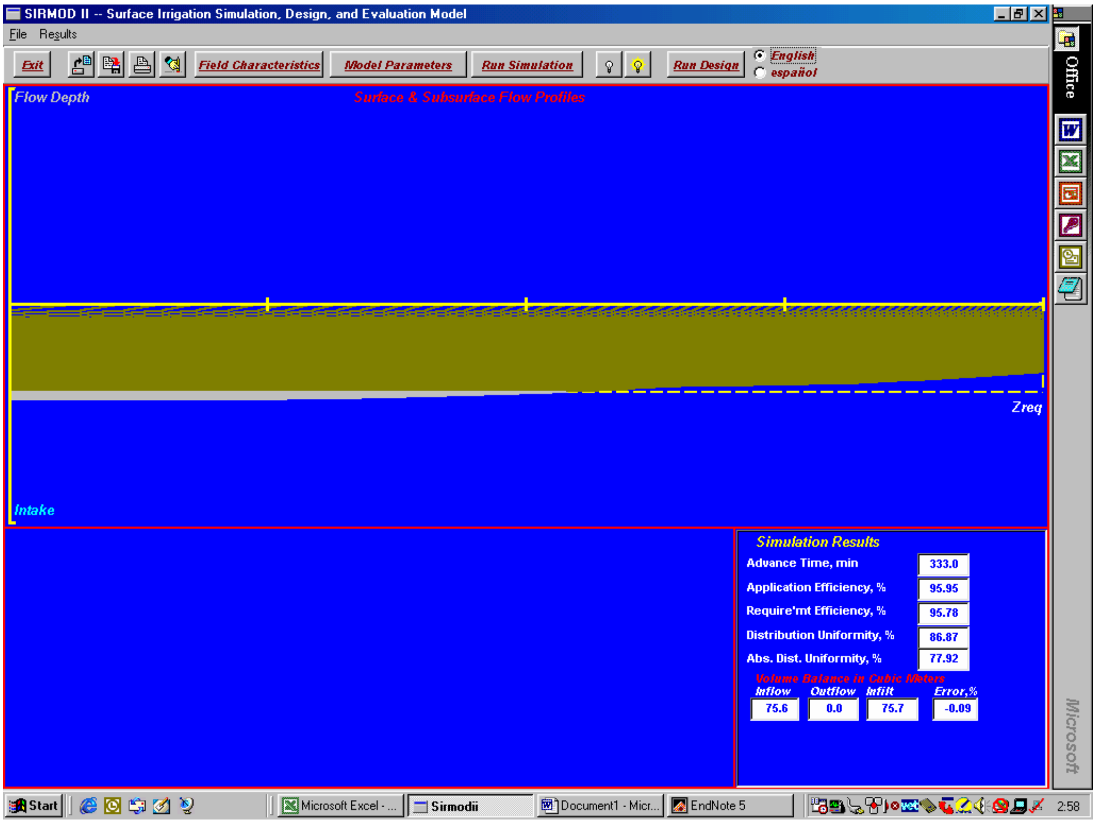
Simulation Results

Advance Time, min 448.4
Application Efficiency, % 42.03
Require'mt Efficiency, % 100.00
Distribution Uniformity, % 89.72
Abs. Dist. Uniformity, % 81.88

Volume Balance in Cubic Meters

Inflow	Outflow	Infilt	Error,%
180.2	38.4	142.1	-0.17

Figure B-3 Measured irrigation performance site 1b



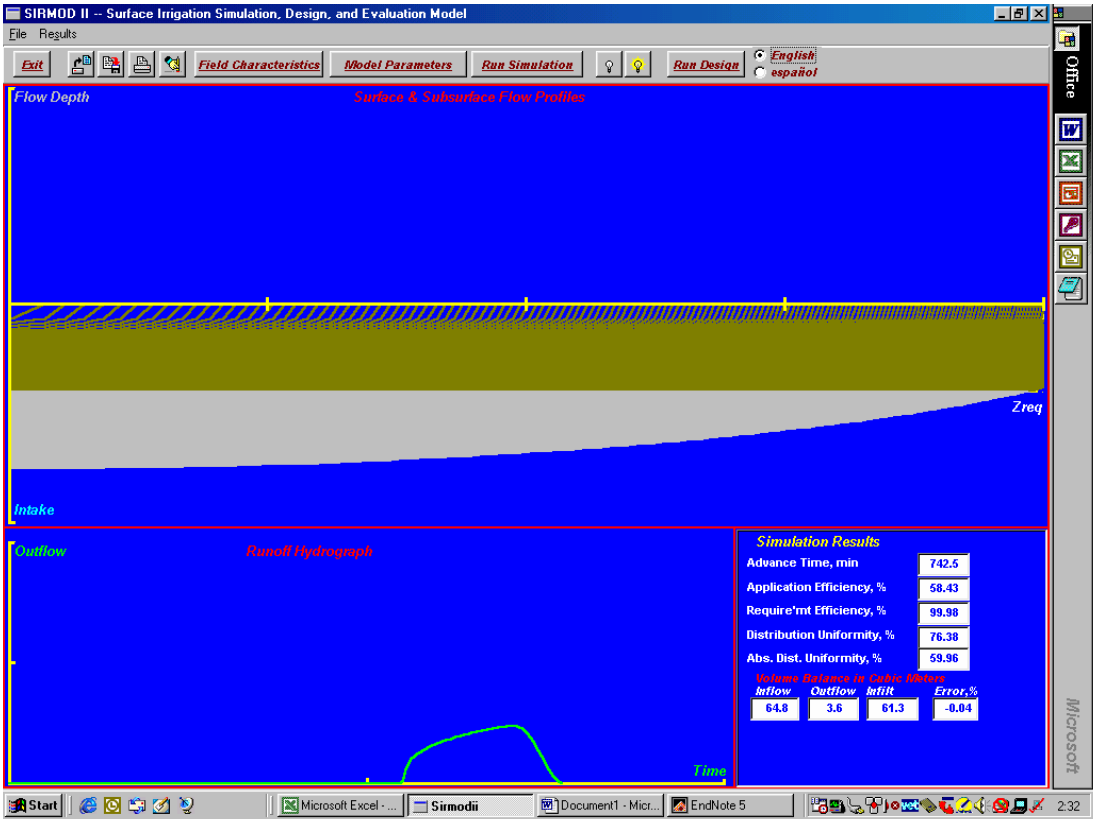
Simulation Results

Advance Time, min 333.0
Application Efficiency, % 95.95
Require'mt Efficiency, % 95.78
Distribution Uniformity, % 86.87
Abs. Dist. Uniformity, % 77.92

Volume Balance in Cubic Meters

Inflow	Outflow	Infilt	Error,%
75.6	0.0	75.7	-0.09

Figure B-4 Optimised irrigation performance site 1b



SIRMOD II -- Surface Irrigation Simulation, Design, and Evaluation Model

Simulation Results

Advance Time, min 742.5

Application Efficiency, % 58.43

Require'mt Efficiency, % 99.98

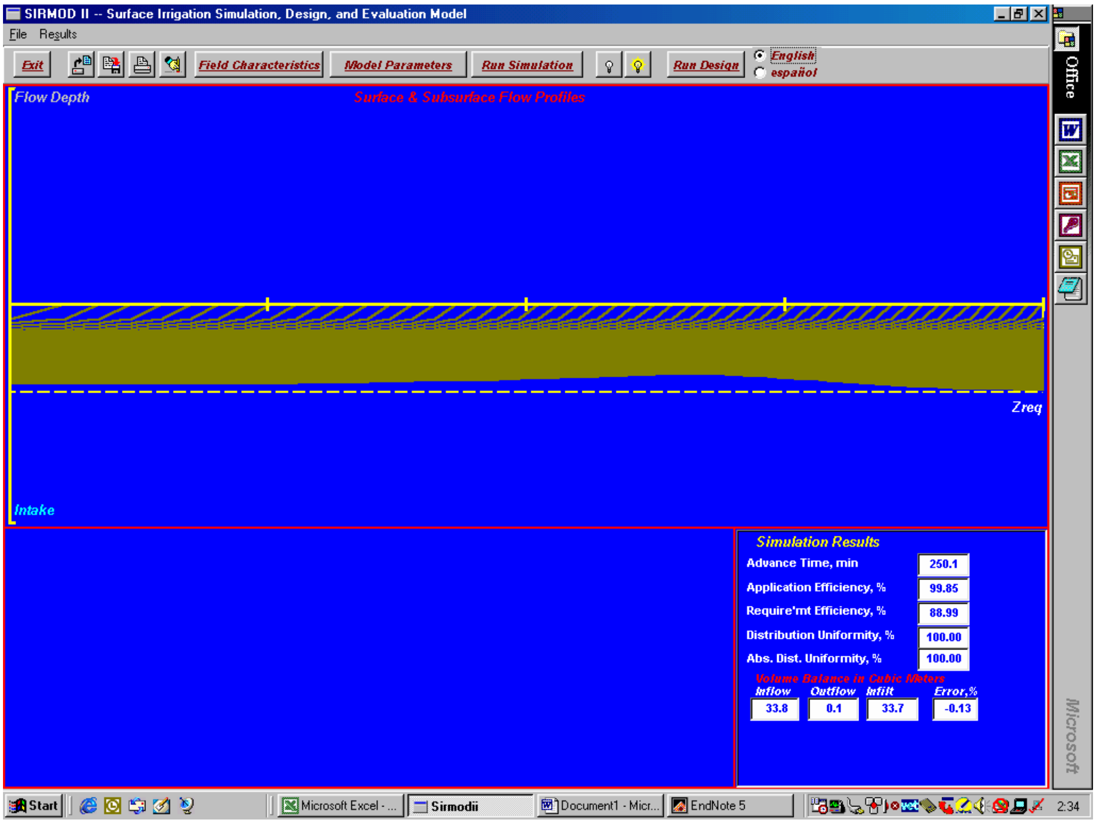
Distribution Uniformity, % 76.38

Abs. Dist. Uniformity, % 59.96

Volume Balance in Cubic Meters

Inflow	Outflow	Infilt	Error,%
64.8	3.6	61.3	-0.04

Figure B-5 Measured irrigation performance site 1c



SIRMOD II -- Surface Irrigation Simulation, Design, and Evaluation Model

Simulation Results

Advance Time, min 250.1

Application Efficiency, % 99.85

Require'mt Efficiency, % 88.99

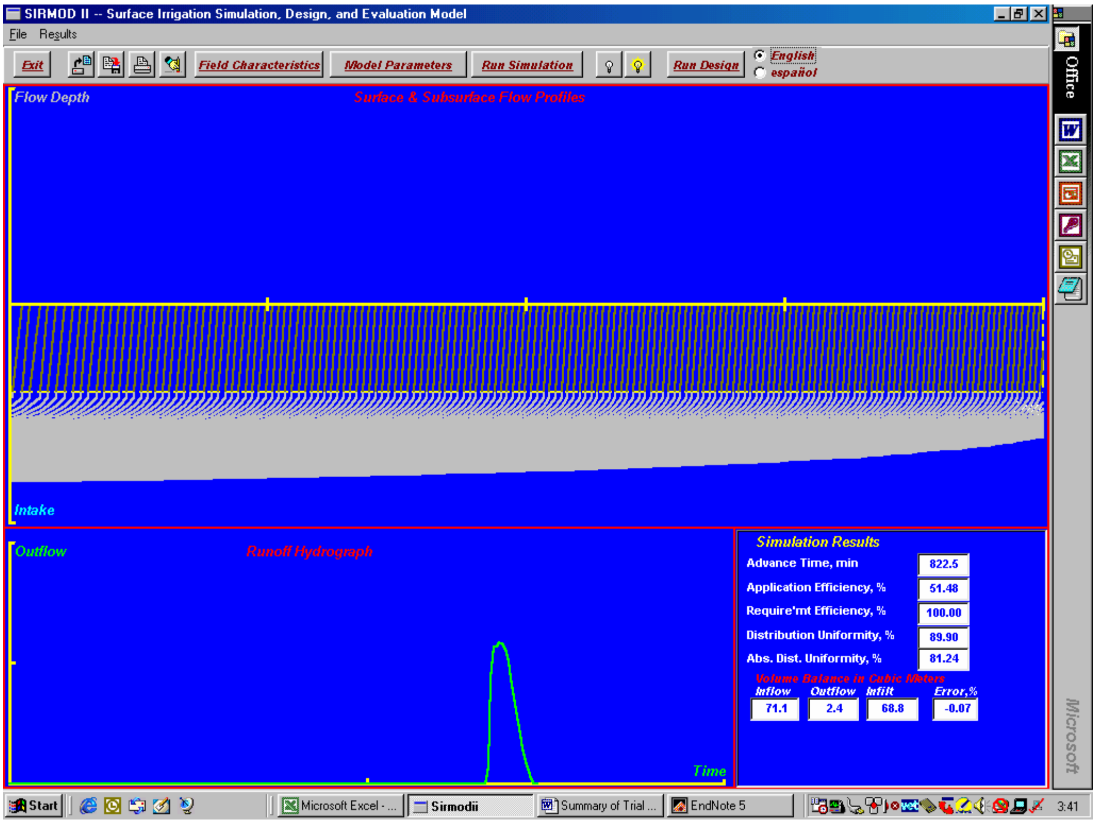
Distribution Uniformity, % 100.00

Abs. Dist. Uniformity, % 100.00

Volume Balance in Cubic Meters

Inflow	Outflow	Infilt	Error,%
33.8	0.1	33.7	-0.13

Figure B-6 Optimised irrigation performance site 1c



SIRMOD II -- Surface Irrigation Simulation, Design, and Evaluation Model

Simulation Results

Advance Time, min 822.5

Application Efficiency, % 51.48

Require'mt Efficiency, % 100.00

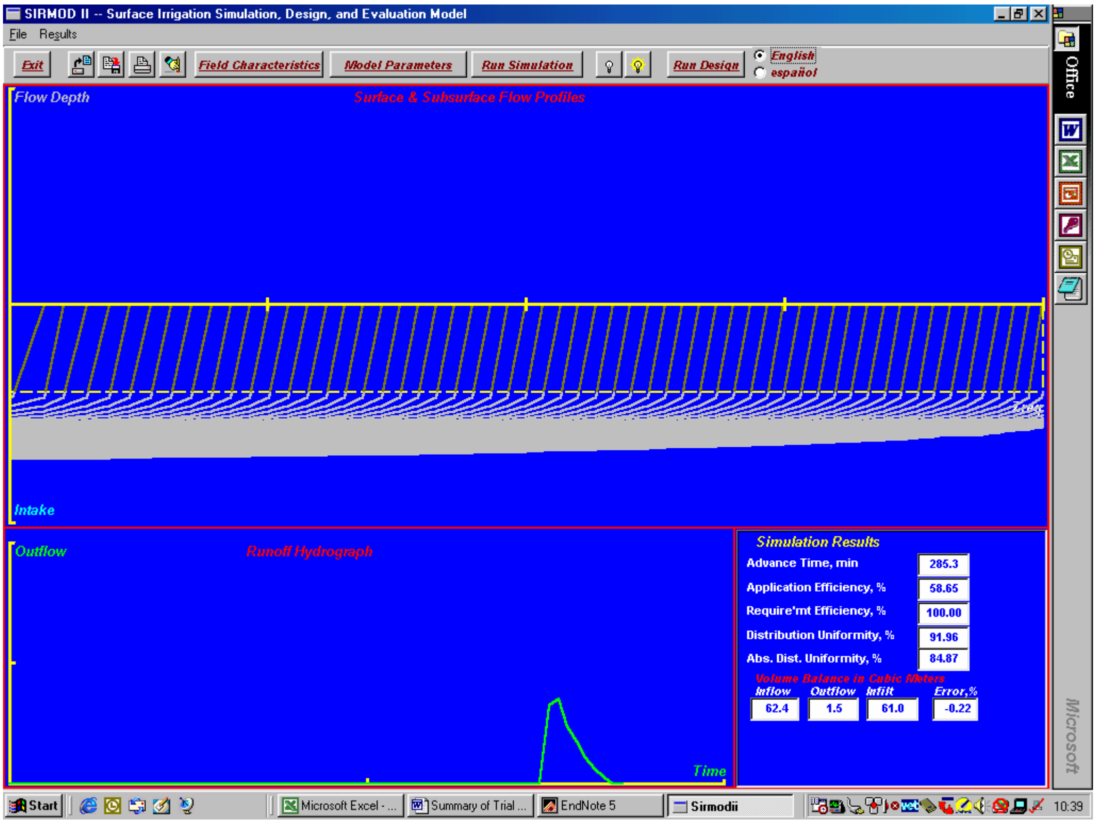
Distribution Uniformity, % 89.90

Abs. Dist. Uniformity, % 81.24

Volume Balance in Cubic Meters

Inflow	Outflow	Infilt	Error,%
71.1	2.4	68.8	-0.07

Figure B-7 Measured irrigation performance site 2



SIRMOD II -- Surface Irrigation Simulation, Design, and Evaluation Model

Simulation Results

Advance Time, min 285.3

Application Efficiency, % 58.65

Require'mt Efficiency, % 100.00

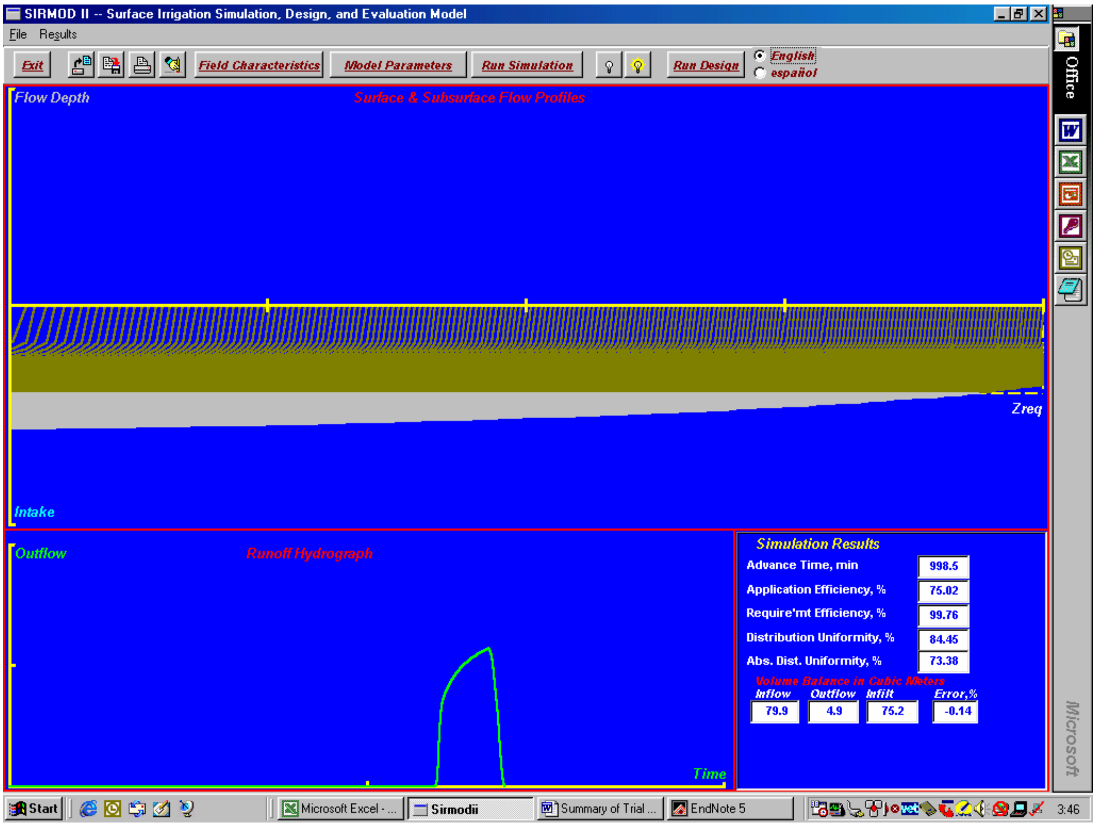
Distribution Uniformity, % 91.96

Abs. Dist. Uniformity, % 84.87

Volume Balance in Cubic Meters

Inflow	Outflow	Infilt	Error,%
62.4	1.5	61.0	-0.22

Figure B-8 Optimised irrigation performance site 2



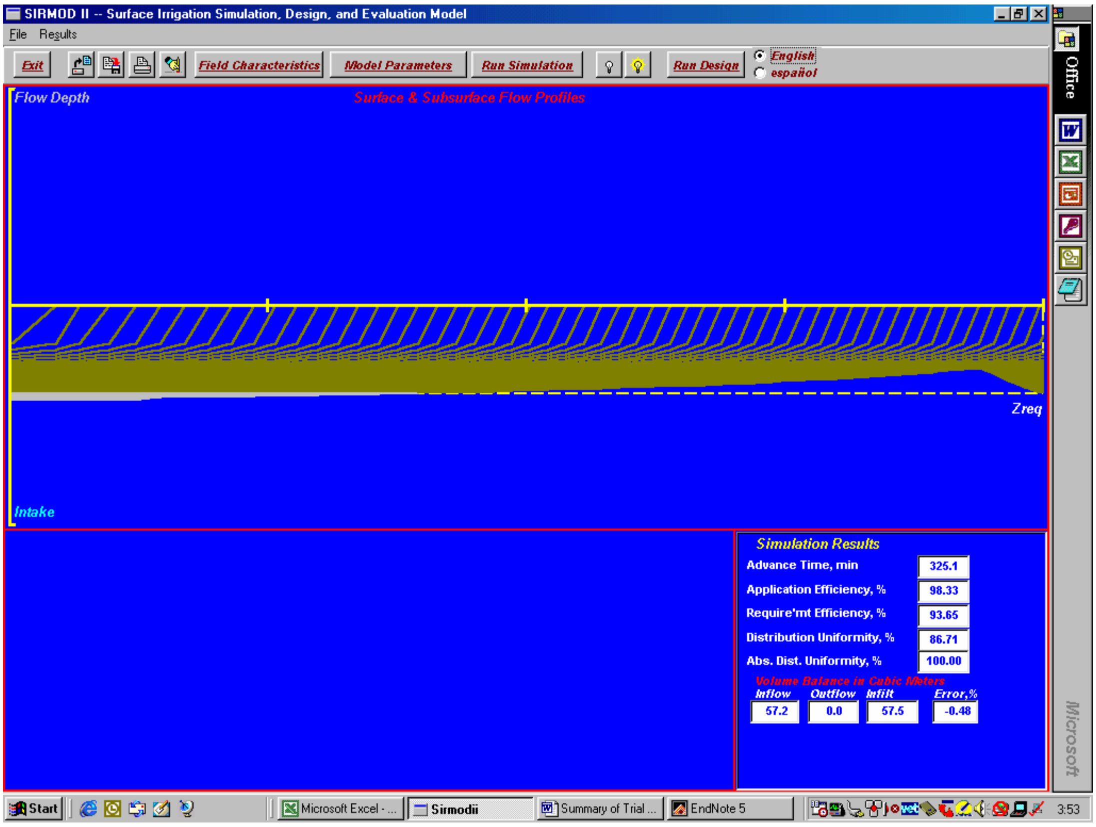
Simulation Results

Advance Time, min 998.5
Application Efficiency, % 75.02
Require'mt Efficiency, % 99.76
Distribution Uniformity, % 84.45
Abs. Dist. Uniformity, % 73.38

Volume Balance in Cubic Meters

Inflow	Outflow	Infilt	Error,%
79.9	4.9	75.2	-0.14

Figure B-9 Measured irrigation performance site 3



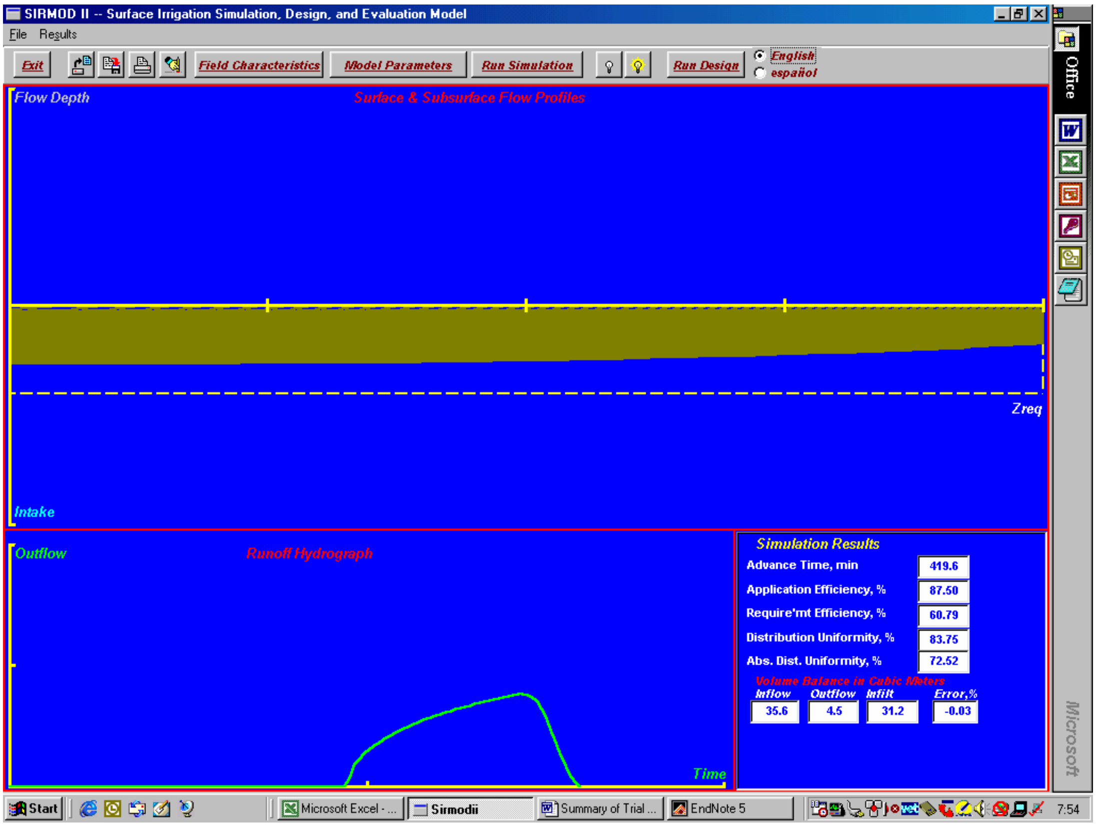
Simulation Results

Advance Time, min 325.1
Application Efficiency, % 98.33
Require'mt Efficiency, % 93.65
Distribution Uniformity, % 86.71
Abs. Dist. Uniformity, % 100.00

Volume Balance in Cubic Meters

Inflow	Outflow	Infilt	Error,%
57.2	0.0	57.5	-0.48

Figure B-10 Optimised irrigation performance site 3



Simulation Results

Advance Time, min 419.6

Application Efficiency, % 87.50

Require'mt Efficiency, % 60.79

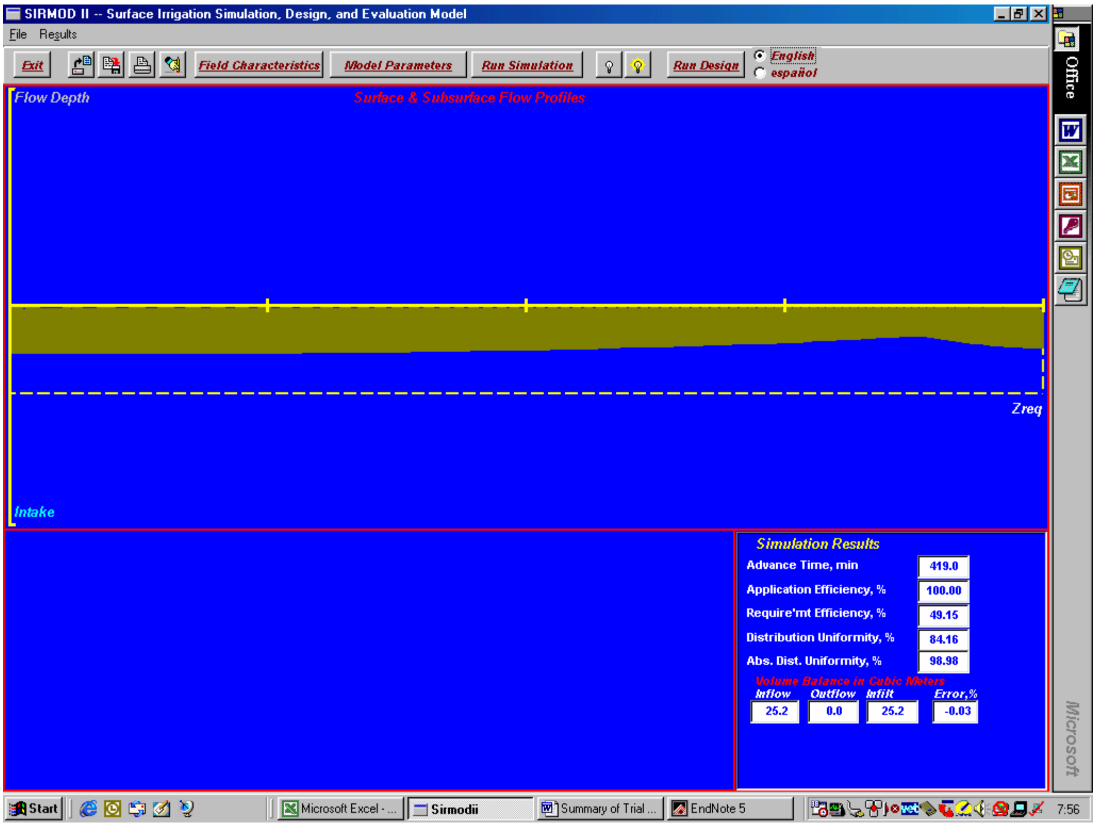
Distribution Uniformity, % 83.75

Abs. Dist. Uniformity, % 72.52

Volume Balance in Cubic Meters

Inflow	Outflow	Infilt	Error,%
35.6	4.5	31.2	-0.03

Figure B-11 Measured irrigation performance site 4



Simulation Results

Advance Time, min 419.0

Application Efficiency, % 100.00

Require'mt Efficiency, % 49.15

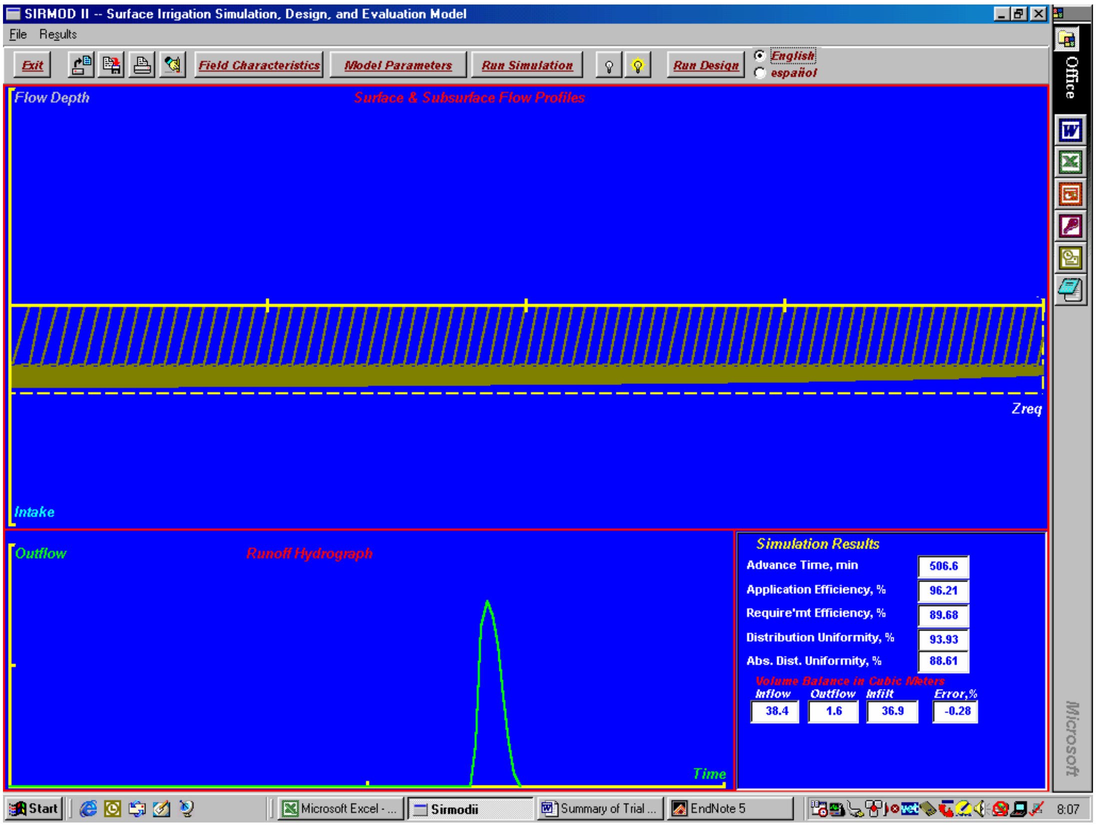
Distribution Uniformity, % 84.16

Abs. Dist. Uniformity, % 98.98

Volume Balance in Cubic Meters

Inflow	Outflow	Infilt	Error,%
25.2	0.0	25.2	-0.03

Figure B-12 Optimised irrigation performance site 4



Simulation Results

Advance Time, min 506.6

Application Efficiency, % 96.21

Require'mt Efficiency, % 89.68

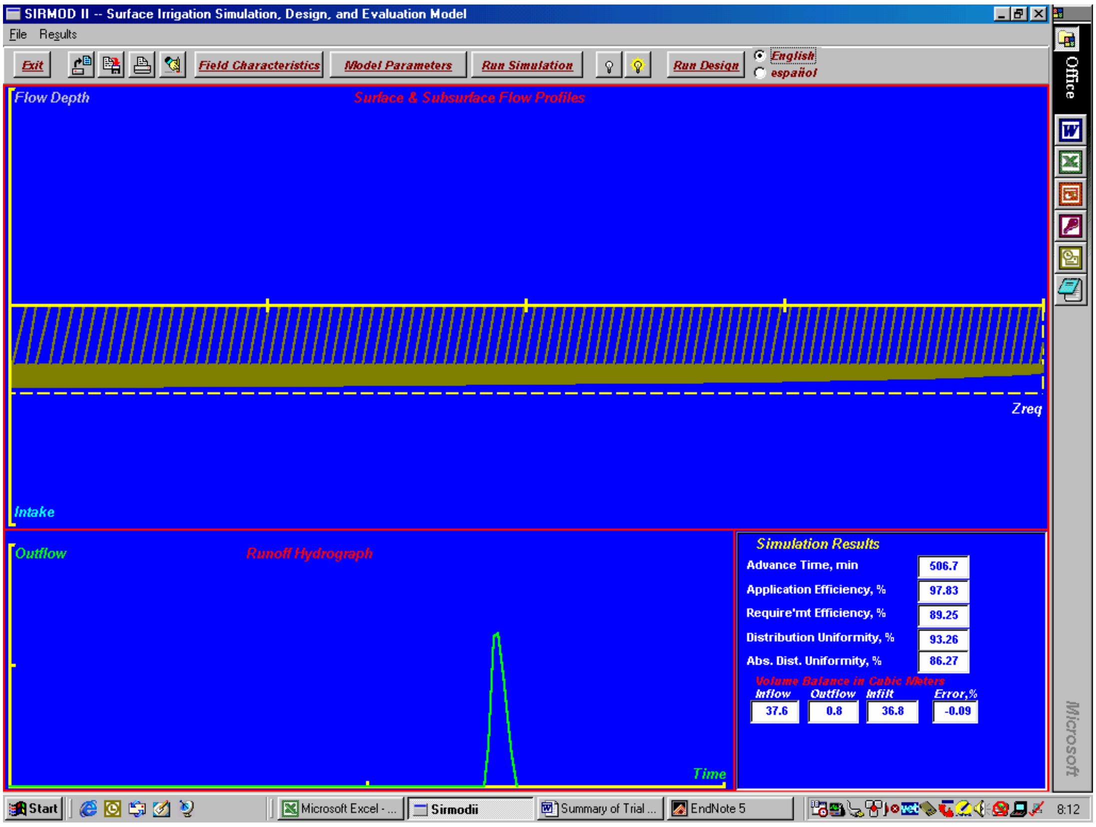
Distribution Uniformity, % 93.93

Abs. Dist. Uniformity, % 88.61

Volume Balance in Cubic Meters

Inflow	Outflow	Infilt	Error,%
38.4	1.6	36.9	-0.28

Figure B-13 Measured irrigation performance site 5



Simulation Results

Advance Time, min 506.7

Application Efficiency, % 97.83

Require'mt Efficiency, % 89.25

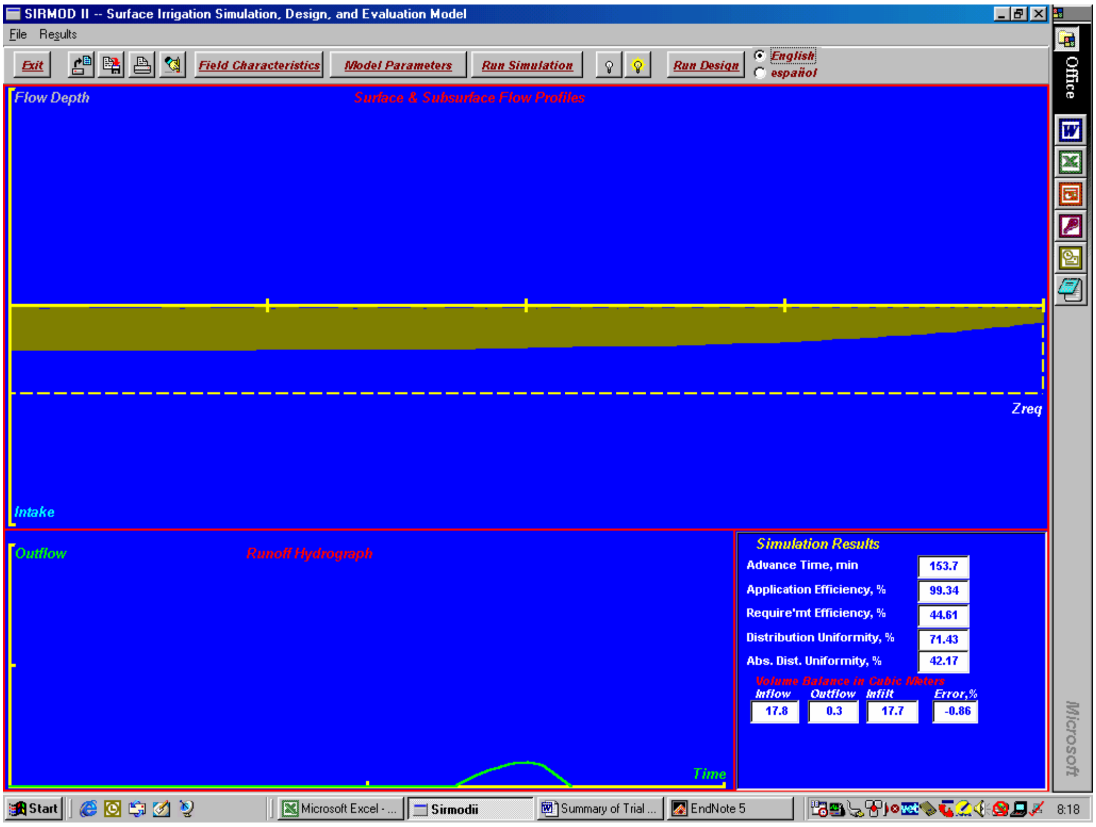
Distribution Uniformity, % 93.26

Abs. Dist. Uniformity, % 86.27

Volume Balance in Cubic Meters

Inflow	Outflow	Infilt	Error,%
37.6	0.8	36.8	-0.09

Figure B-14 Optimised Irrigation performance site 5



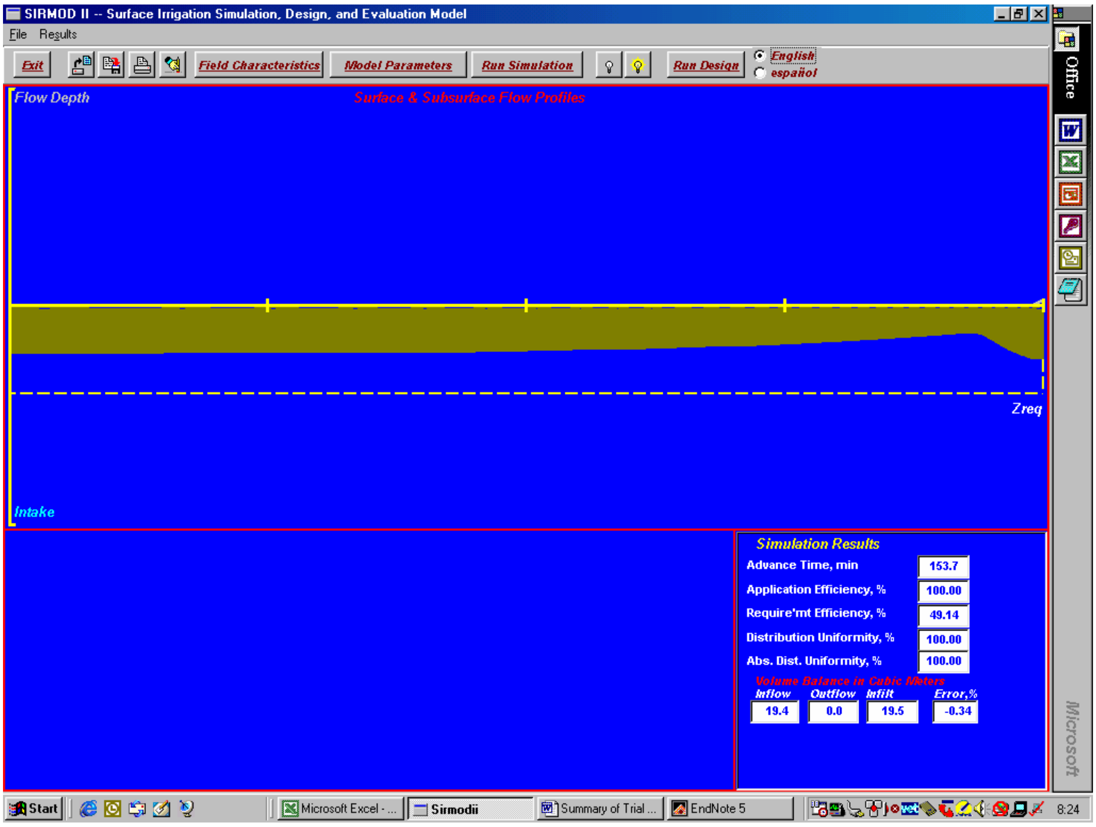
Simulation Results

Advance Time, min: 153.7
Application Efficiency, %: 99.34
Require'mt Efficiency, %: 44.61
Distribution Uniformity, %: 71.43
Abs. Dist. Uniformity, %: 42.17

Volume Balance in Cubic Meters

Inflow	Outflow	Infilt	Error,%
17.8	0.3	17.7	-0.86

Figure B-15 Measured irrigation performance site 6



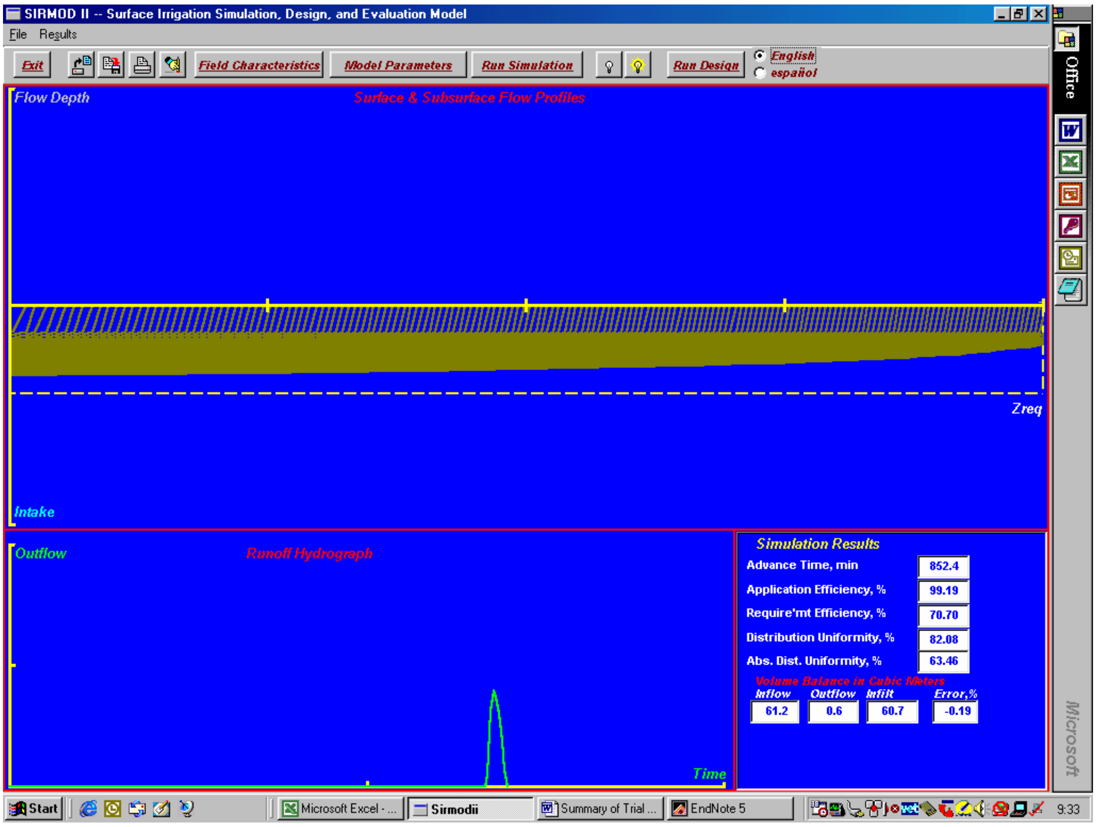
Simulation Results

Advance Time, min: 153.7
Application Efficiency, %: 100.00
Require'mt Efficiency, %: 49.14
Distribution Uniformity, %: 100.00
Abs. Dist. Uniformity, %: 100.00

Volume Balance in Cubic Meters

Inflow	Outflow	Infilt	Error,%
19.4	0.0	19.5	-0.34

Figure B-16 Optimised irrigation performance site 6



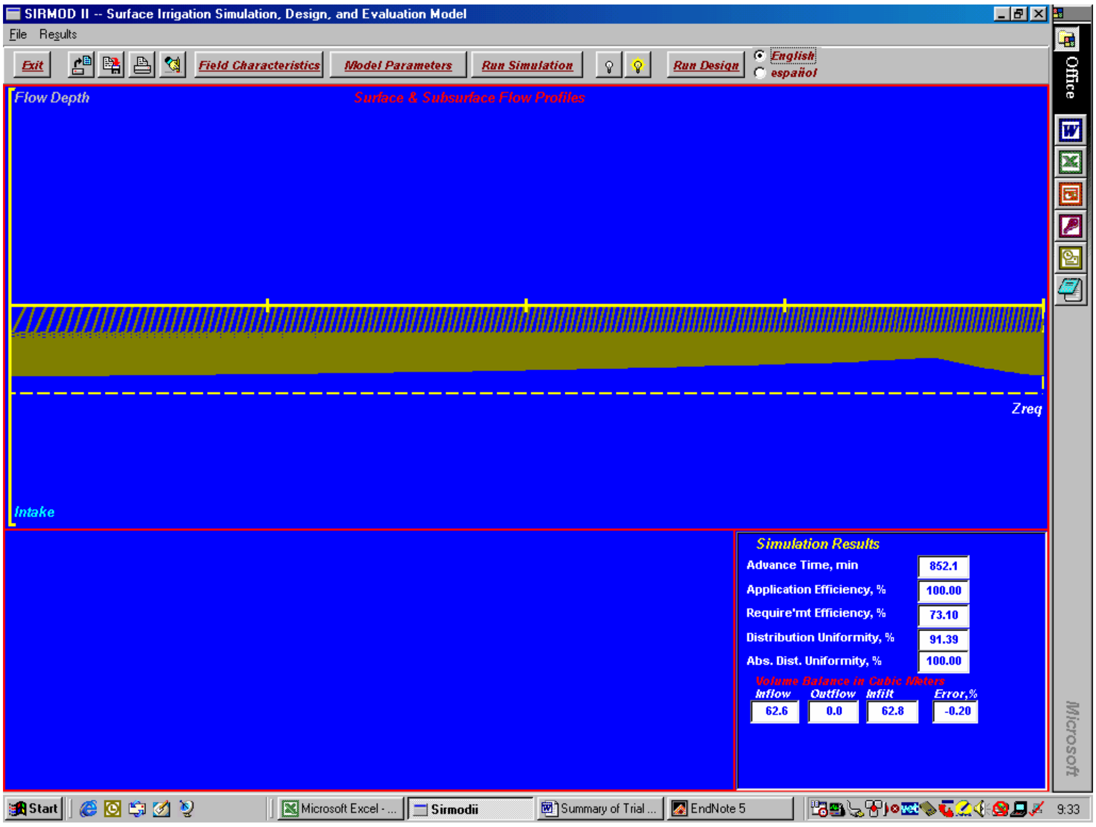
Simulation Results

Advance Time, min: 852.4
Application Efficiency, %: 99.19
Require'mt Efficiency, %: 70.70
Distribution Uniformity, %: 82.08
Abs. Dist. Uniformity, %: 63.46

Volume Balance in Cubic Meters

Inflow	Outflow	Infilt	Error,%
61.2	0.6	60.7	-0.19

Figure B-17 Measured irrigation performance site 7



Simulation Results

Advance Time, min: 852.1
Application Efficiency, %: 100.00
Require'mt Efficiency, %: 73.10
Distribution Uniformity, %: 91.39
Abs. Dist. Uniformity, %: 100.00

Volume Balance in Cubic Meters

Inflow	Outflow	Infilt	Error,%
62.6	0.0	62.8	-0.20

Figure B-18 Optimised irrigation performance site 7

Appendix C Irrigation Dates at Field Sites

Irrigation Dates at Field Sites

Field Site No.	1999 - 2000	2000-2001
1	15/12/1999	12/01/2001
	26/01/2000	13/02/2001
	11/02/2000	28/02/2001
	24/02/2000	12/03/2001
	17/03/2000	17/04/2001
	3/06/2000	5/05/2001
		4/06/2001
2	15/12/1999	1/12/2000
	19/01/2000	9/01/2001
	4/02/2000	31/01/2001
	15/03/2000	16/02/2001
	31/03/2000	13/03/2001
		1/05/2001
3	19/01/2000	15/12/2001
	4/02/2000	1/02/2001
	9/03/2000	3/03/2001
	23/03/2000	29/05/2001
	25/04/2000	
4	7/12/1999	15/12/2000
	28/01/2000	12/01/2000
	3/03/2000	30/01/2000
	19/03/2000	20/02/2000
	20/04/2000	13/03/2000
		20/04/2000
		26/07/2000
5	1/12/1999	15/12/2000
	18/01/2000	12/01/2001
	10/02/2000	30/01/2001
	3/03/2000	20/02/2001
	22/03/2000	13/03/2001
	17/04/2000	20/04/2001
		26/07/2001
6	9/02/2000	27/01/2001
	8/03/2000	23/02/2001
	26/03/2000	25/03/2001
	25/05/2000	21/04/2001

Appendix D Soil Moisture Data Recorded at Field Sites 1999 – 2000

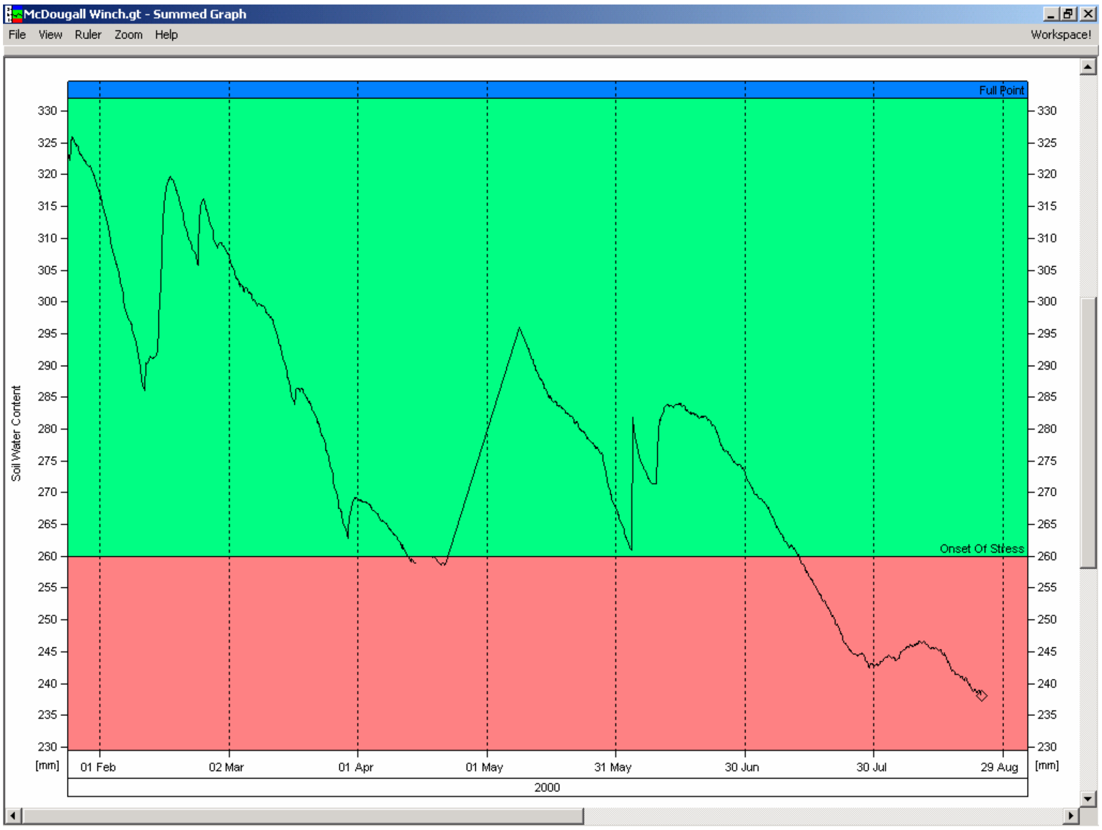


Figure D-1 Summed soil water content down to 1 m at field site 1

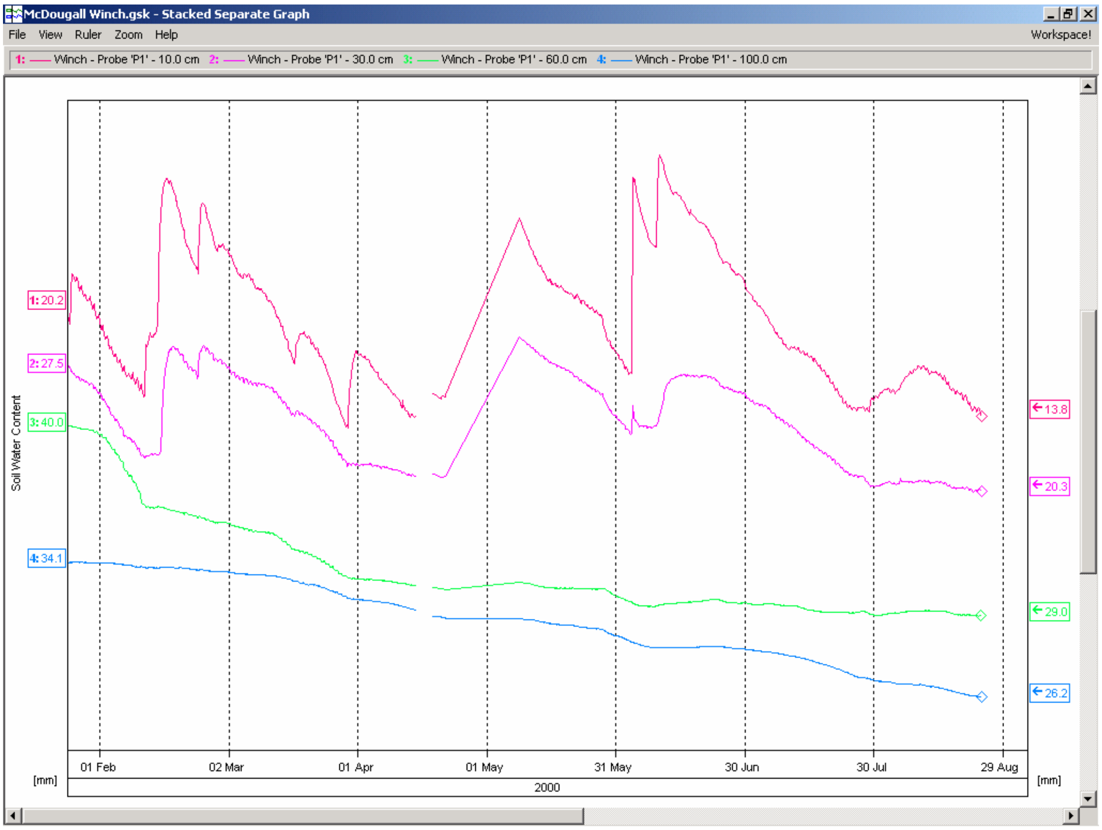


Figure D-2 Separate level soil water content at field site 1

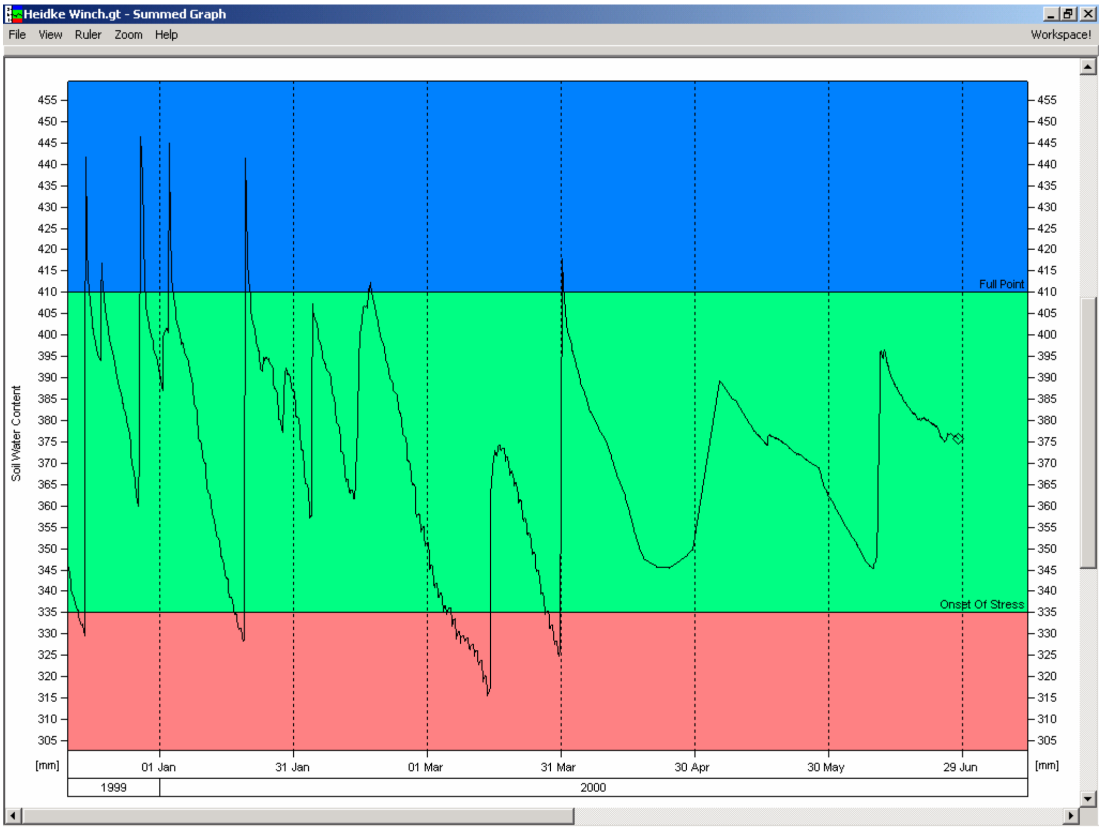


Figure D-3 Summed soil water content down to 1 m at field site 2

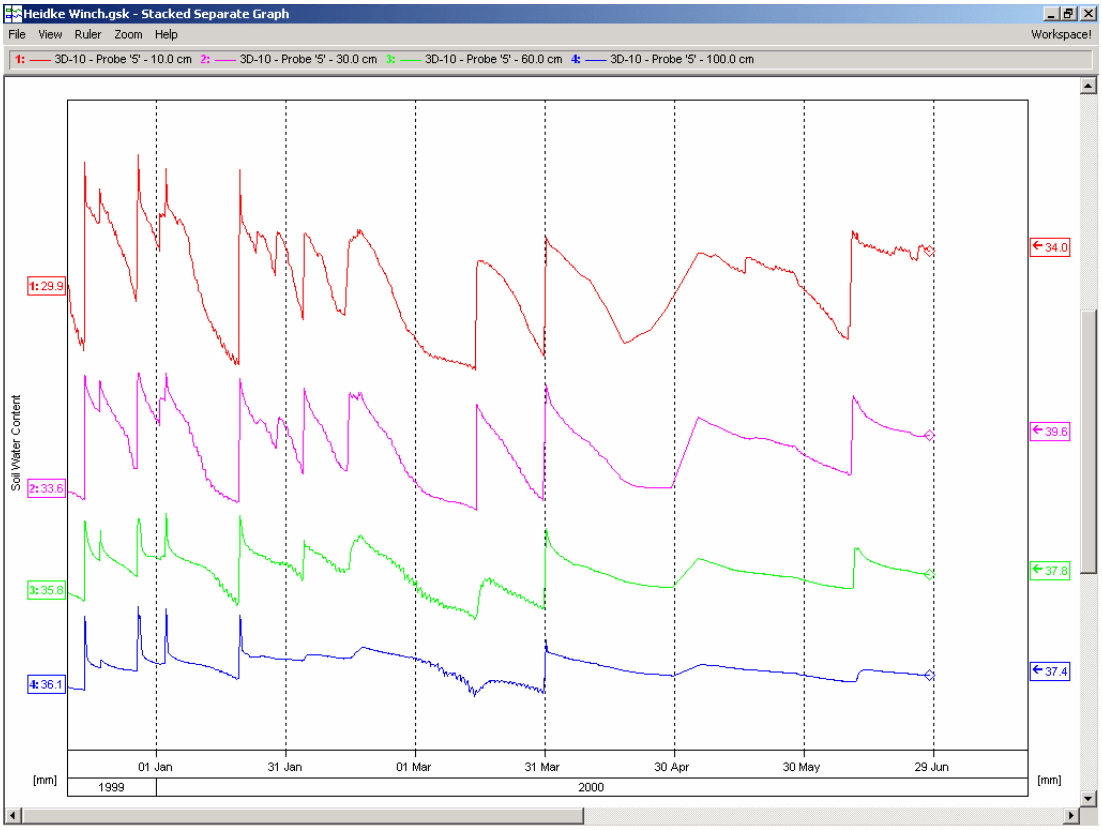


Figure D-4 Separate level soil water content at field site 2

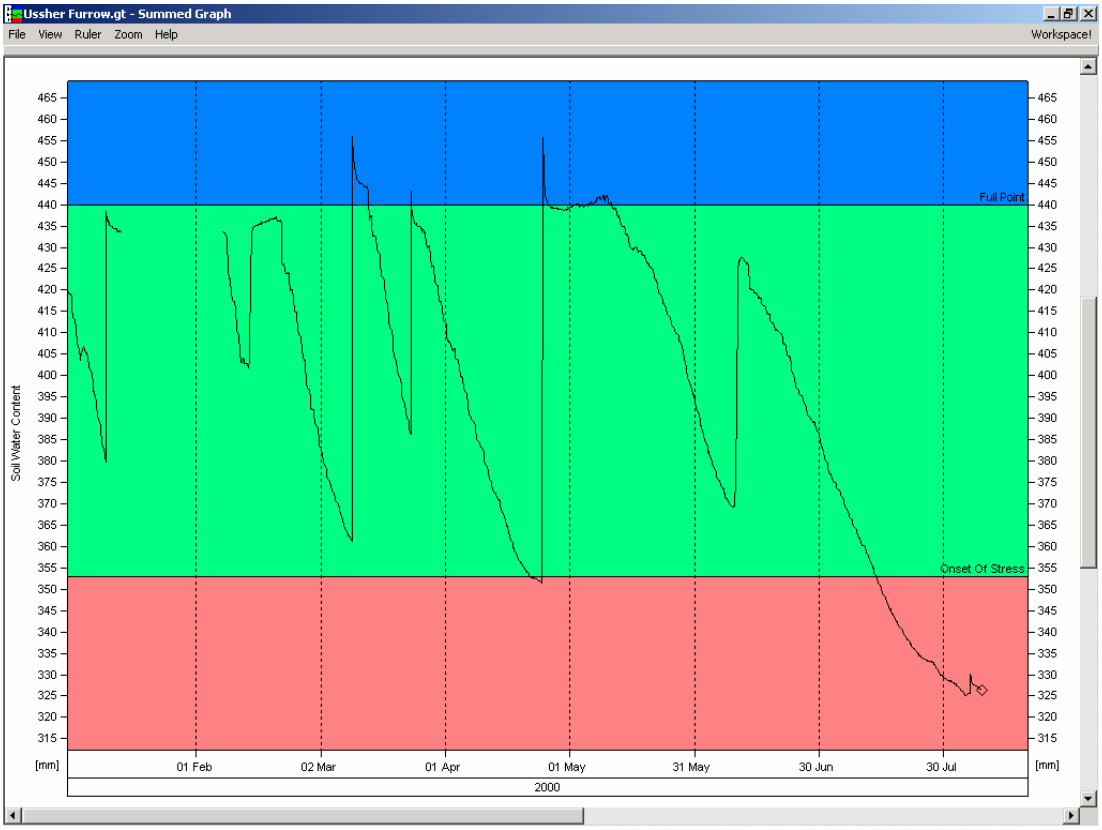


Figure D-5 Summed soil water content down to 1 m at field site 3

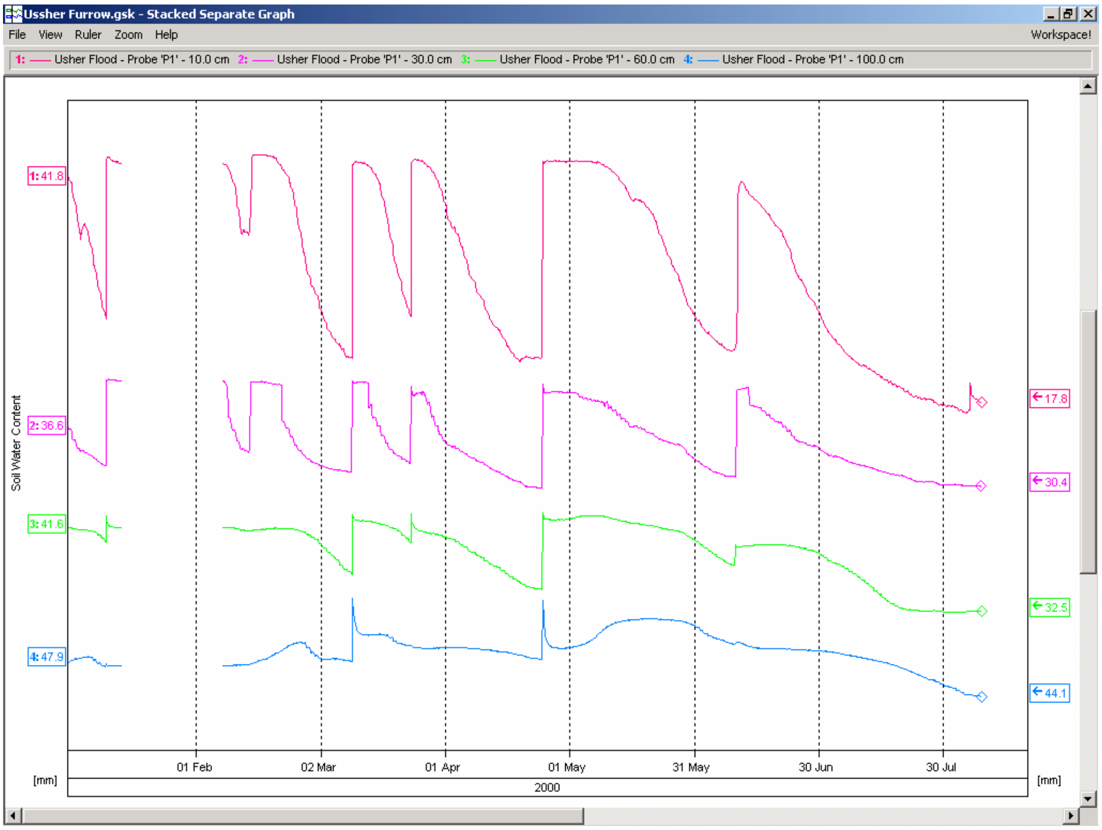


Figure D-6 Separate level soil water content at field site 3

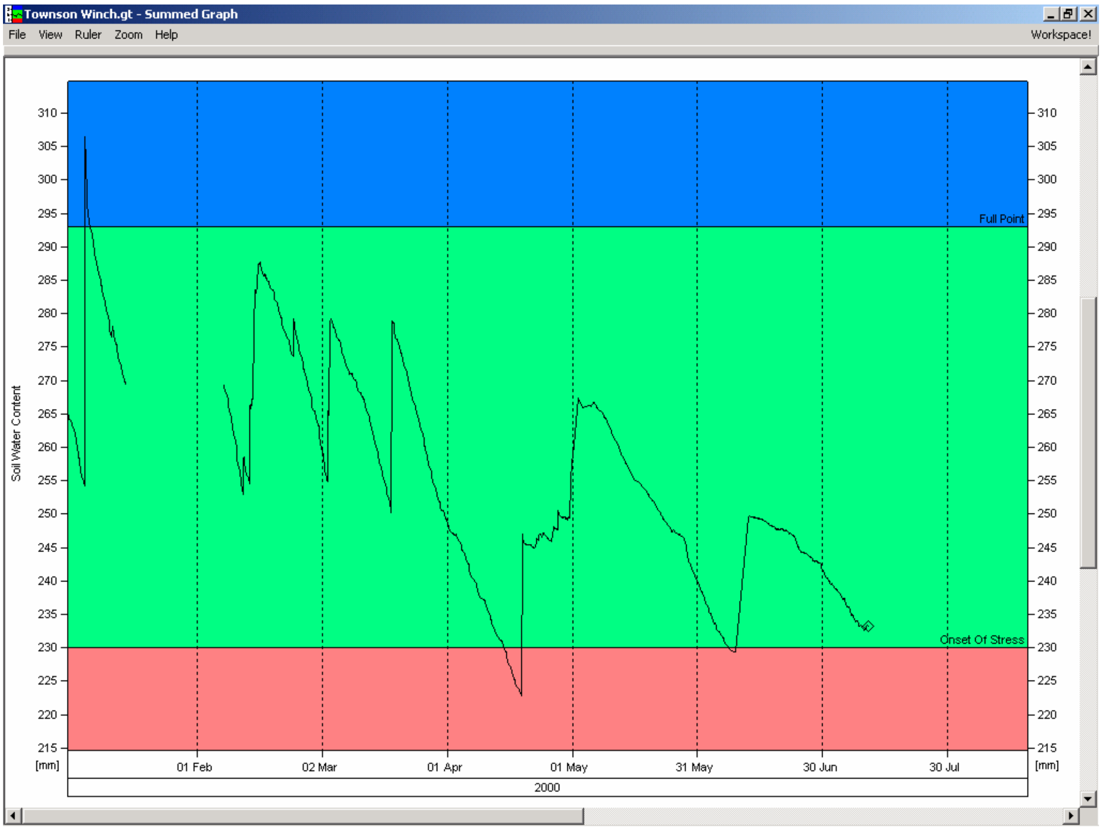


Figure D-7 Summed soil water content down to 1 m at field site 4

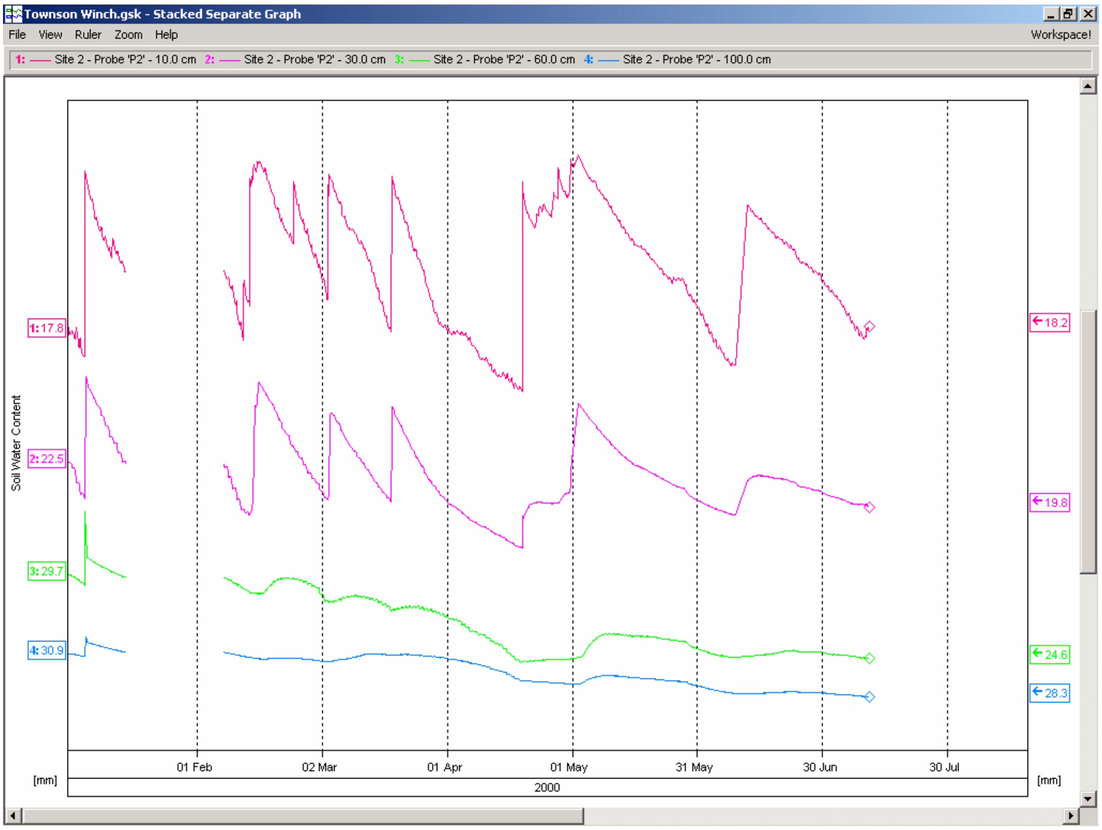


Figure D-8 Separate level soil water content at field site 4

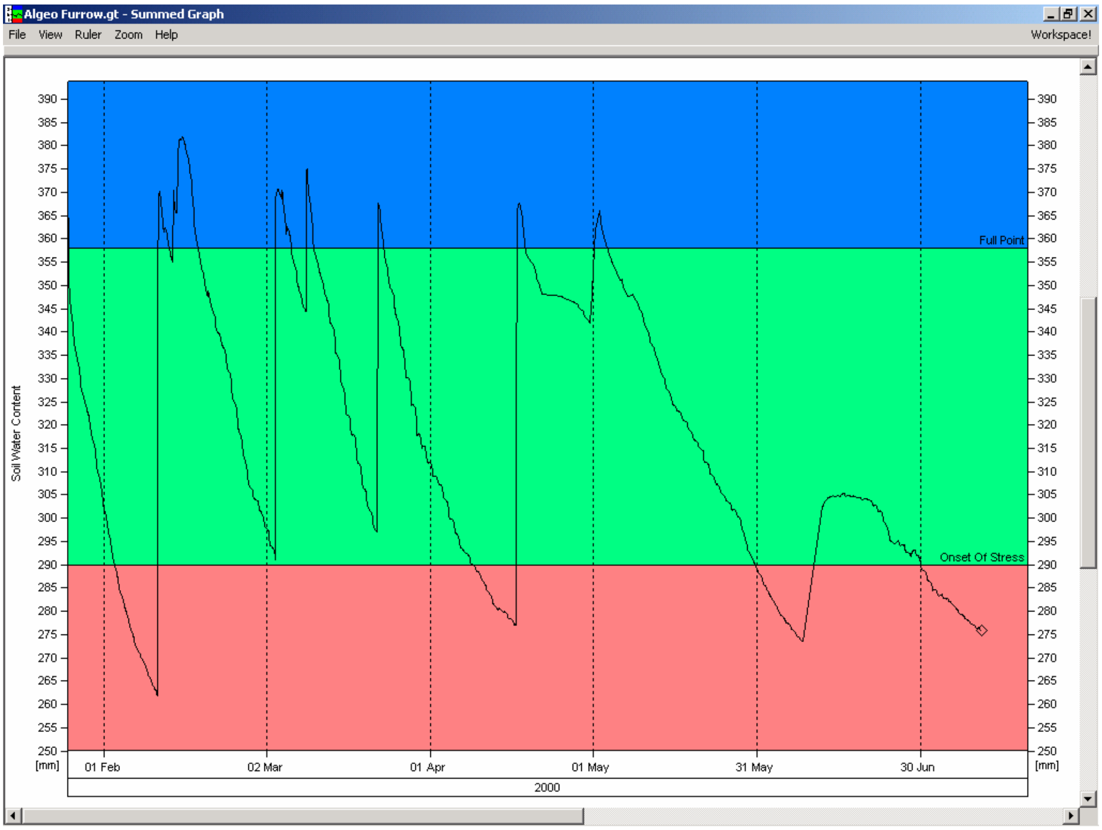


Figure D-9 Summed soil water content down to 1 m at field site 5

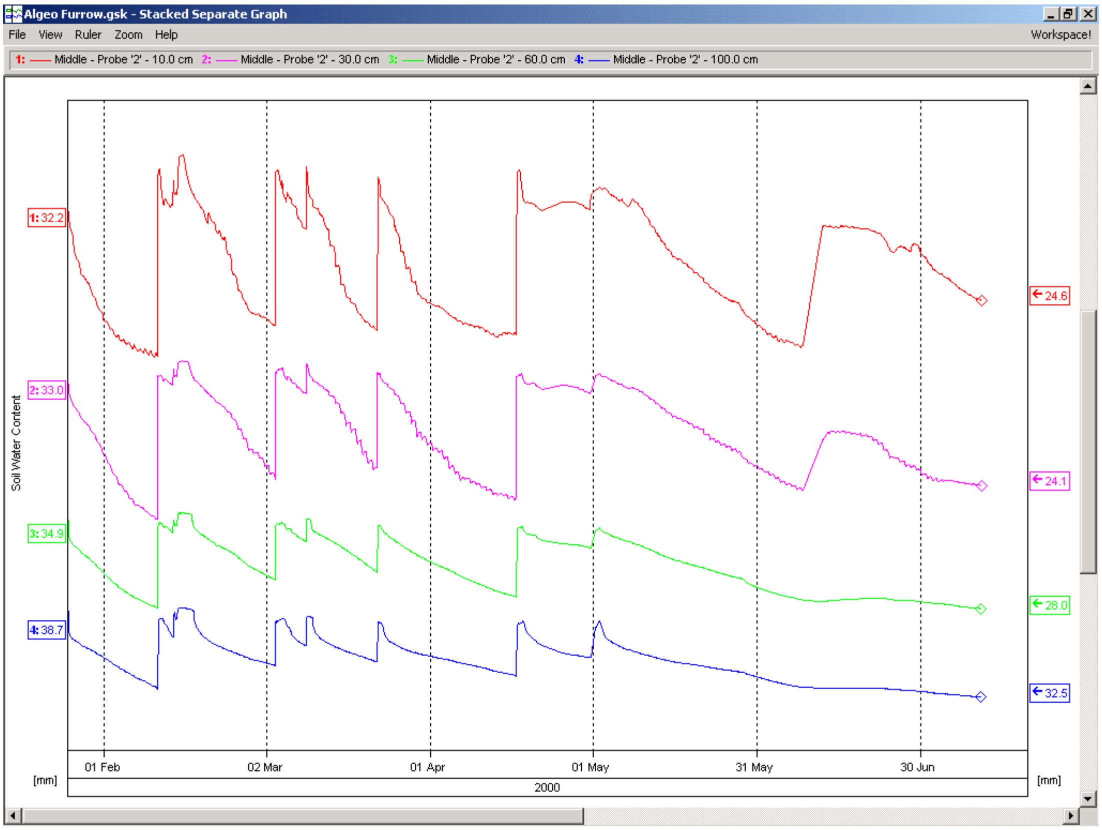


Figure D-10 Separate level soil water content at field site 5

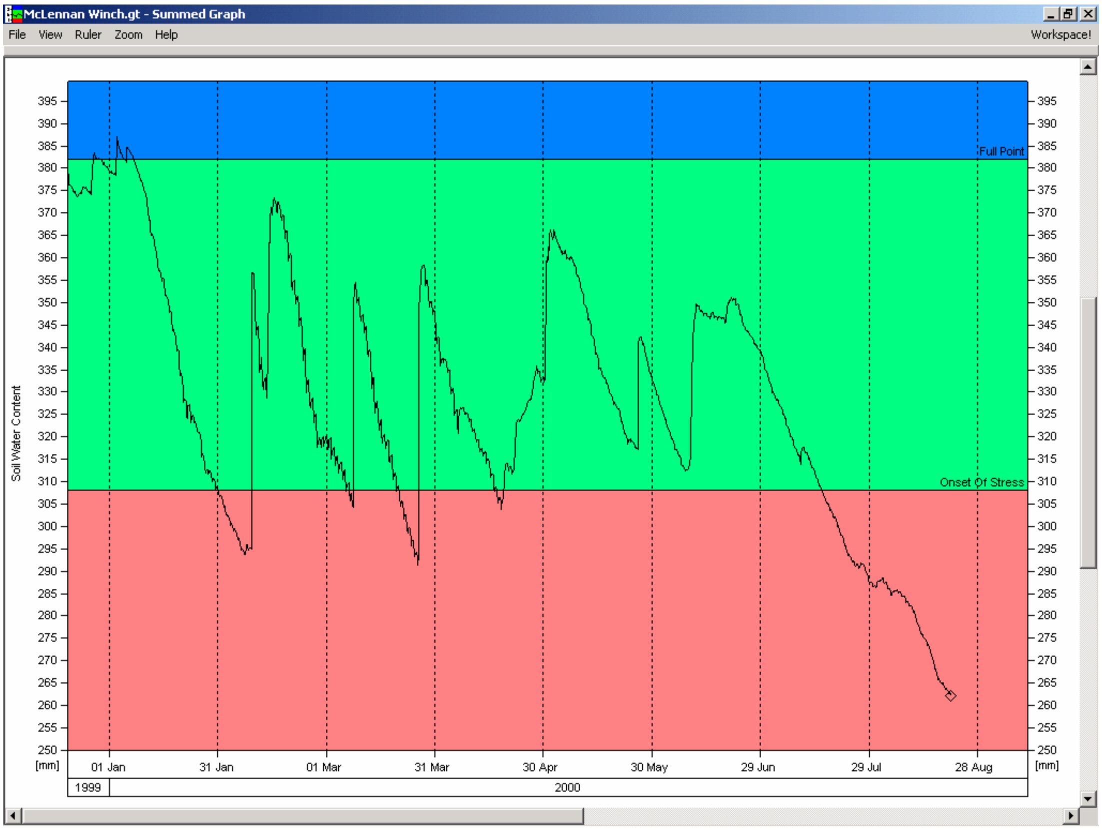


Figure D-11 Summed soil water content down to 1 m at field site 6

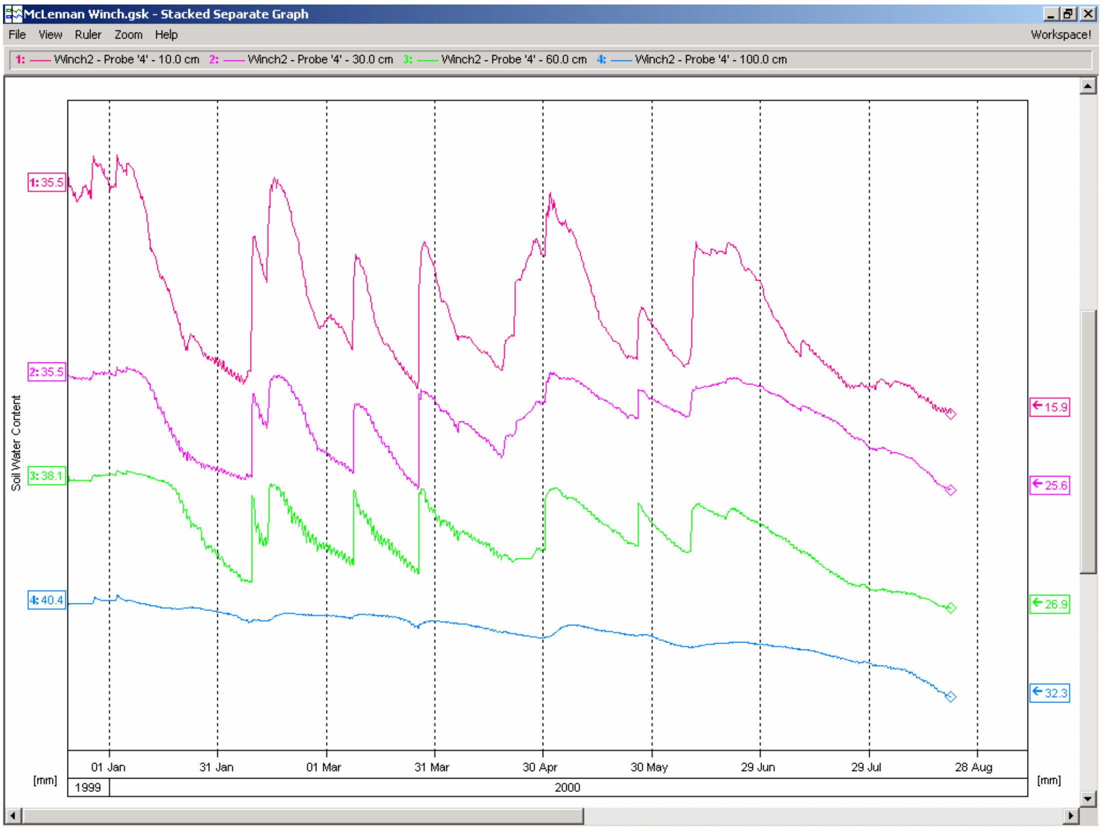


Figure D-12 Separate level soil water content at field site 6

Appendix E Soil Moisture Data Recorded at Field Sites 2000 – 2001

Figure E-1 Summed soil water content down to 1 m at field site 1

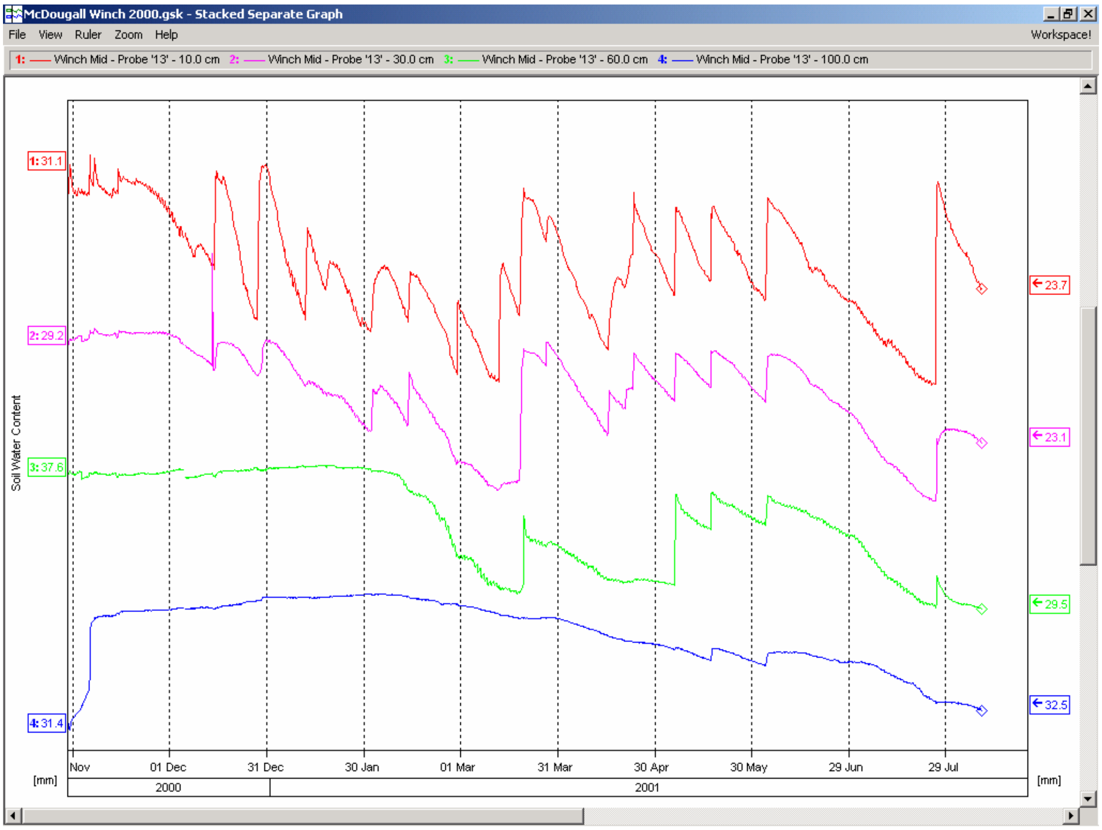


Figure E-2 Separate level soil water content at field site 1

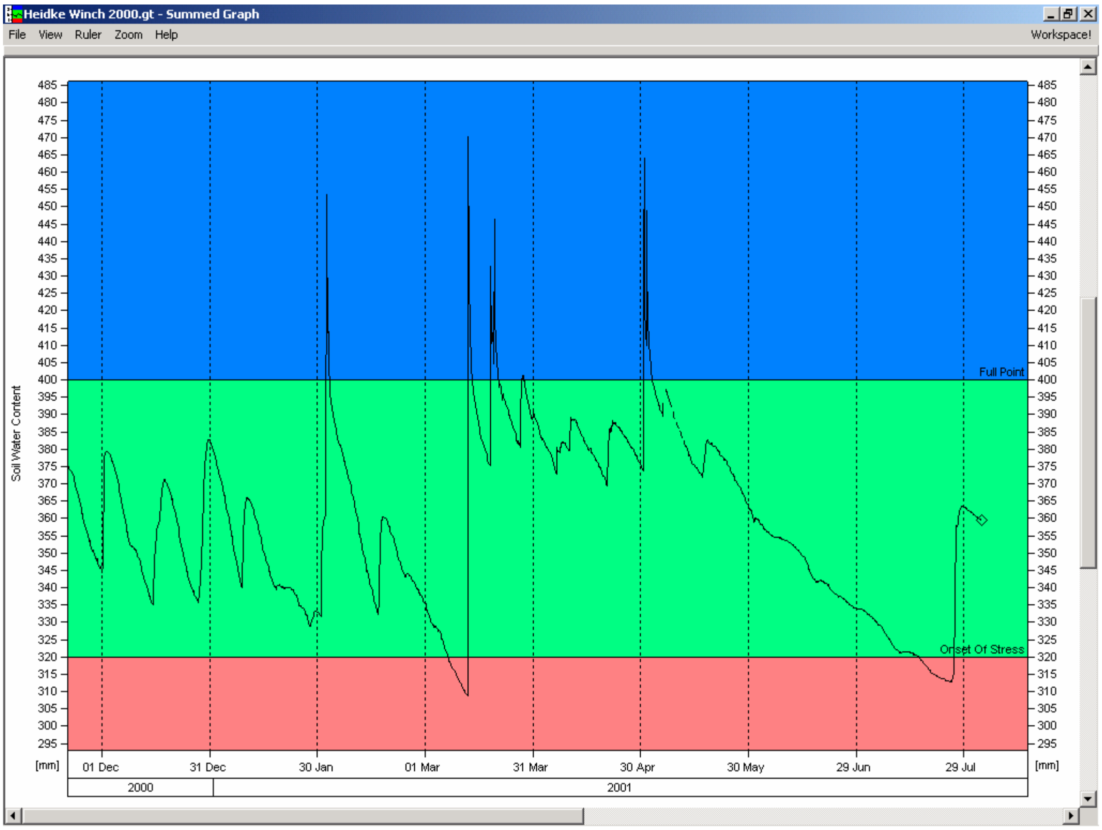


Figure E-3 Summed soil water content down to 1 m at field site 2

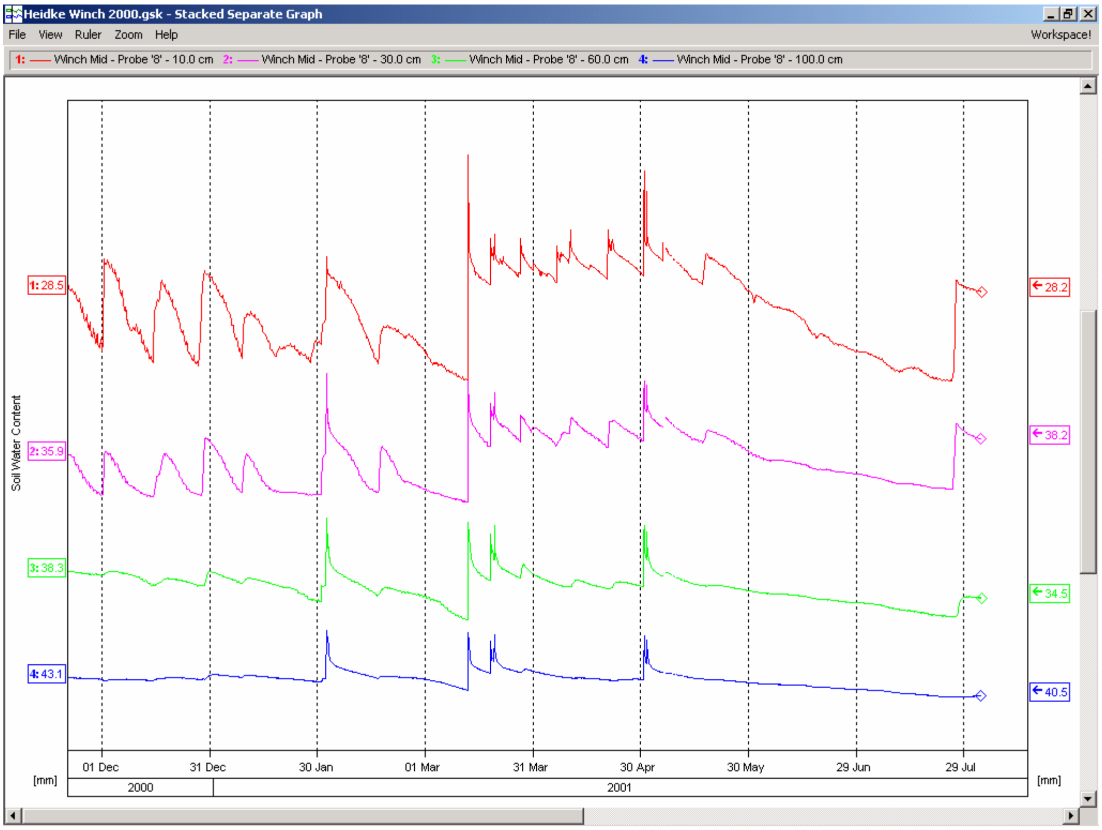


Figure E-4 Separate level soil water content at field site 2

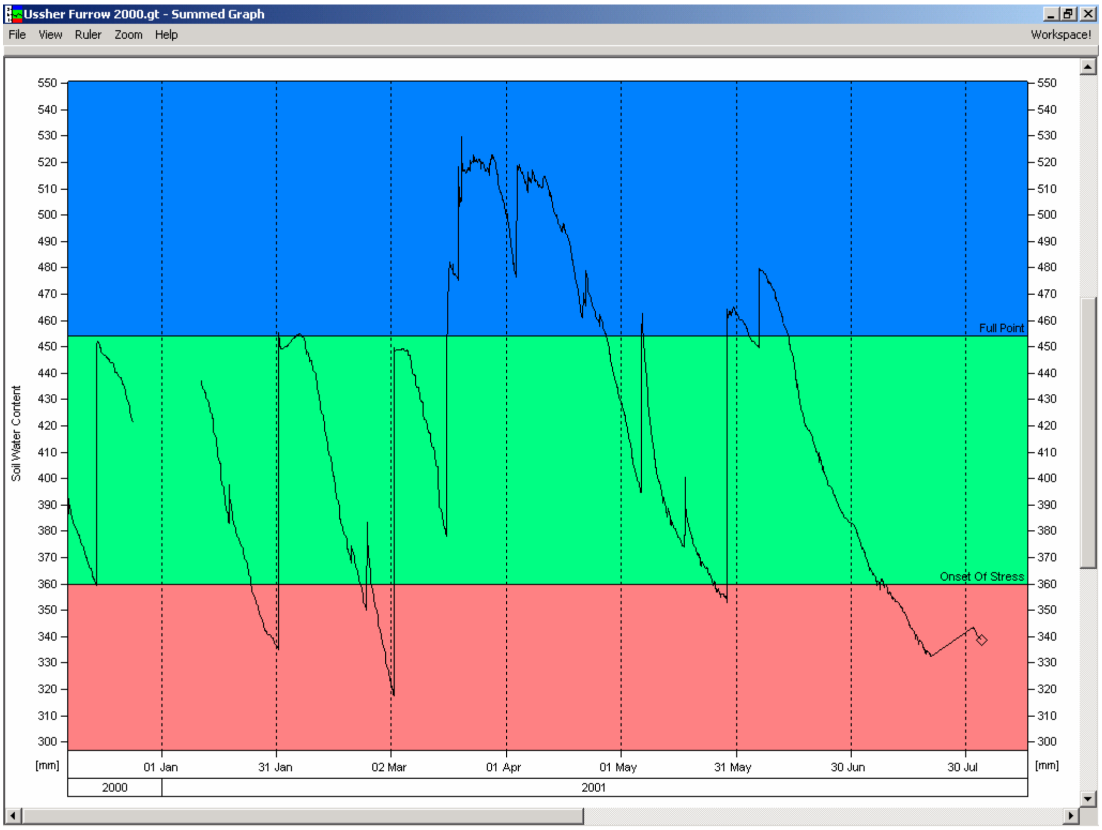


Figure E-5 Summed soil water content down to 1 m at field site 3

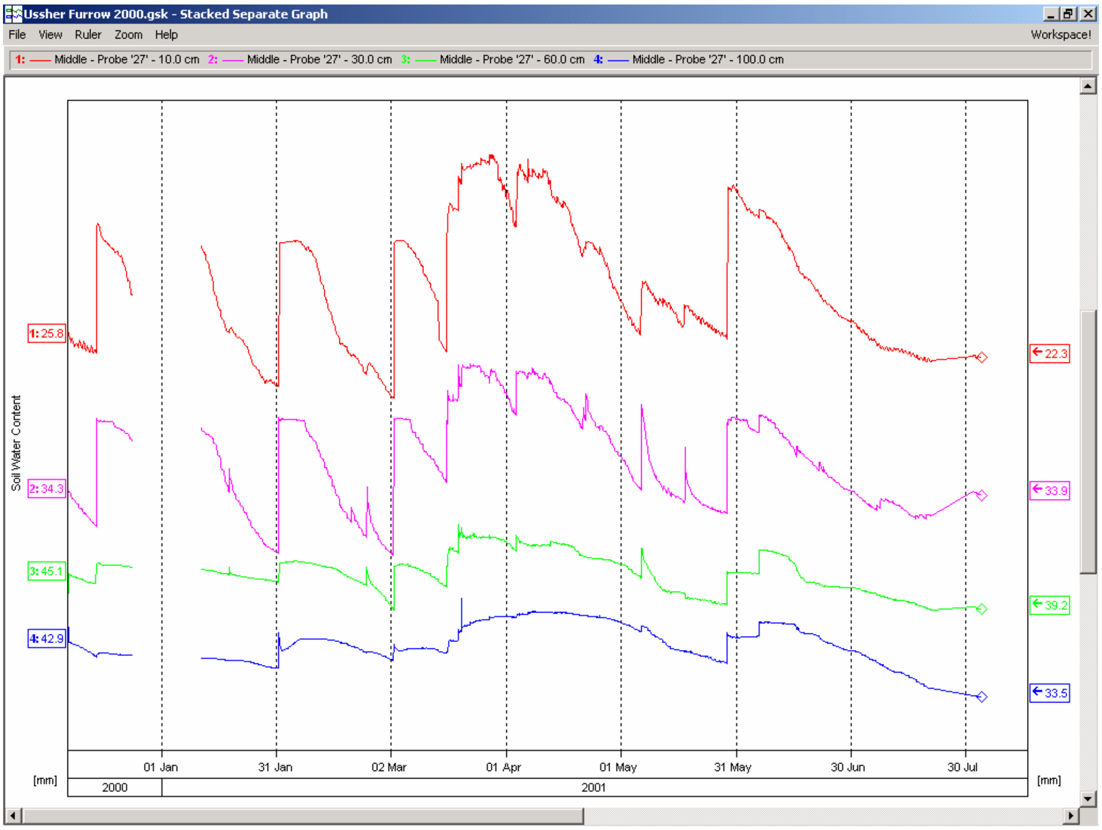


Figure E-6 Separate level soil water content at field site 3

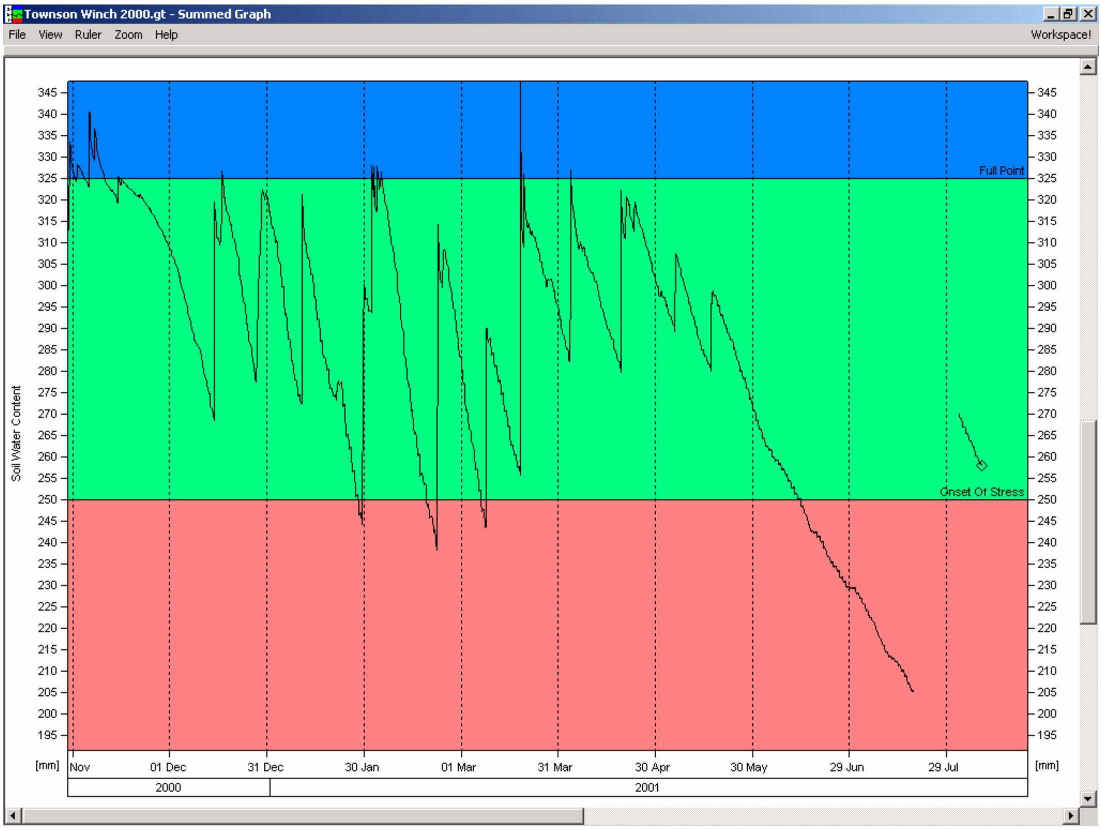


Figure E-7 Summed soil water content down to 1 m at field site 4

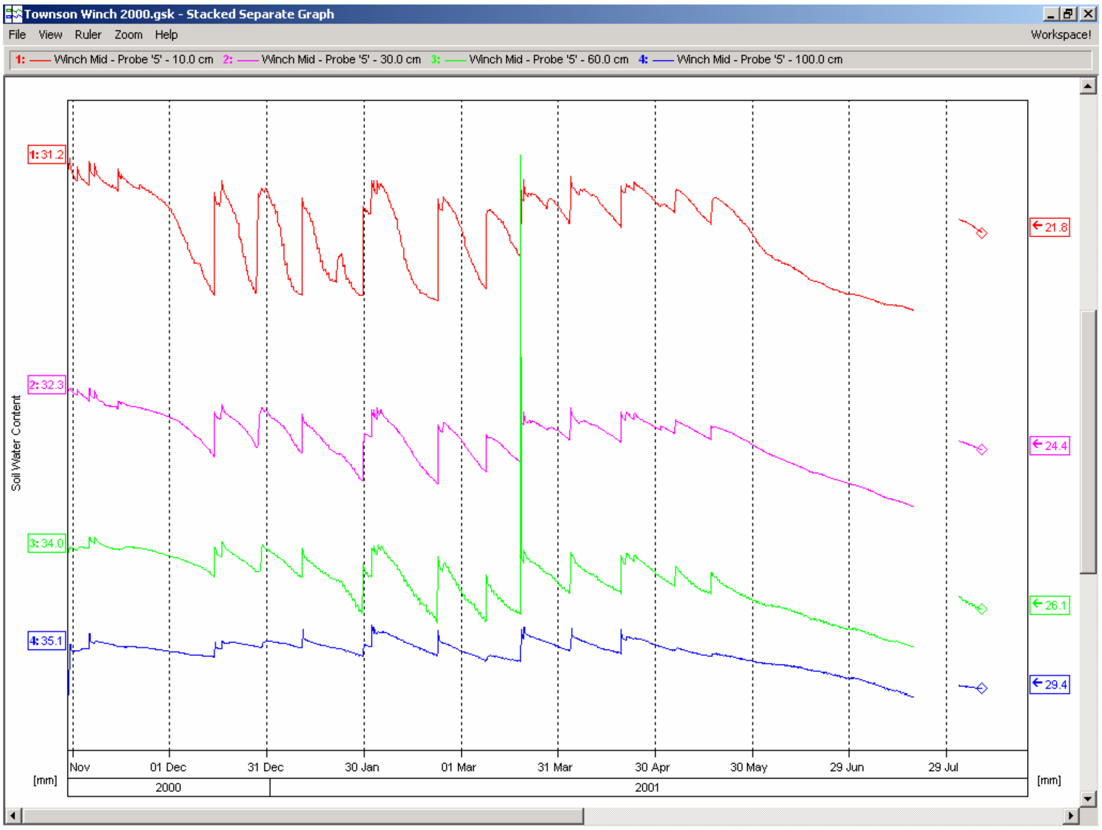


Figure E-8 Separate level soil water content at field site 4

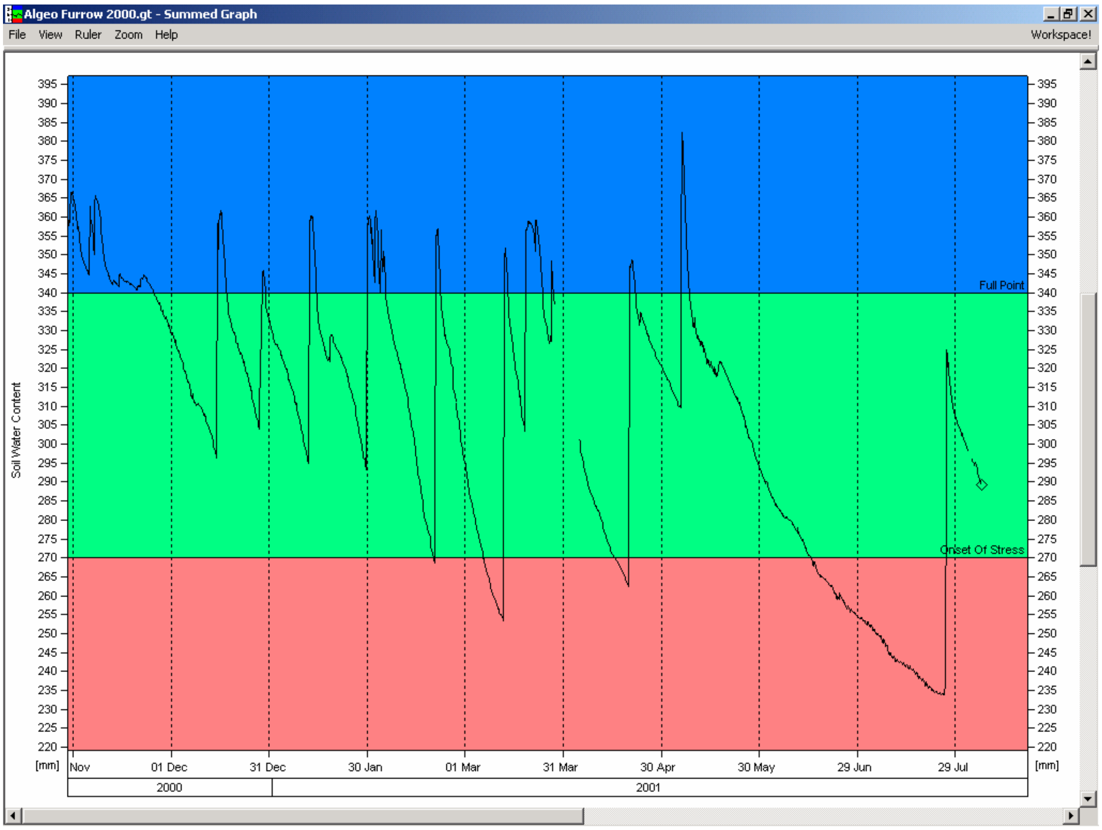


Figure E-9 Summed soil water content down to 1 m at field site 5

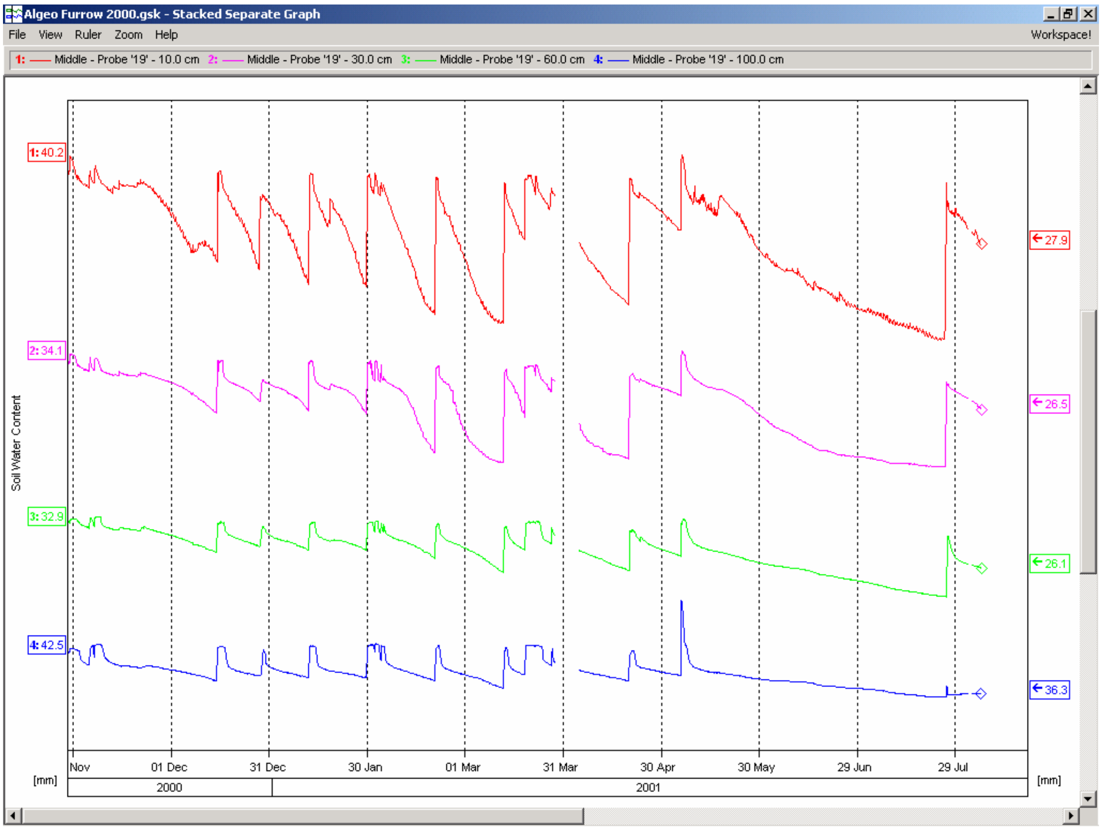


Figure E-10 Separate level soil water content at field site 5

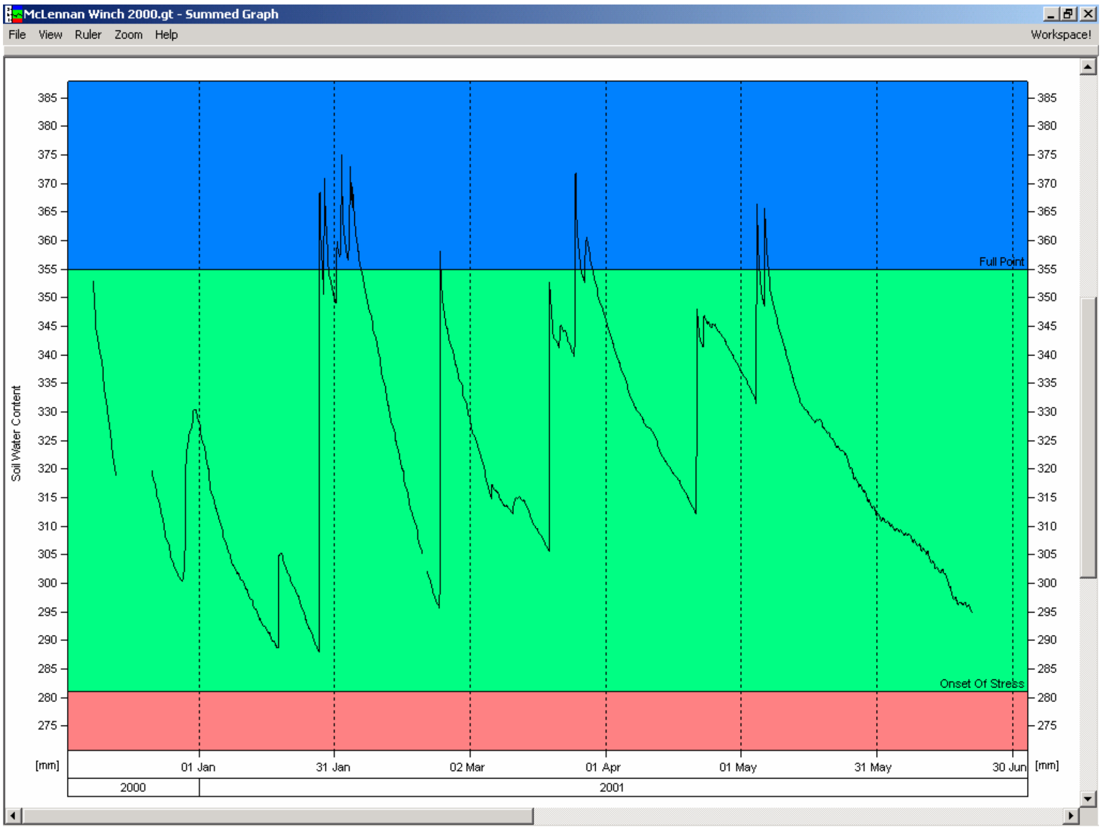


Figure E-11 Summed soil water content down to 1 m at field site 6

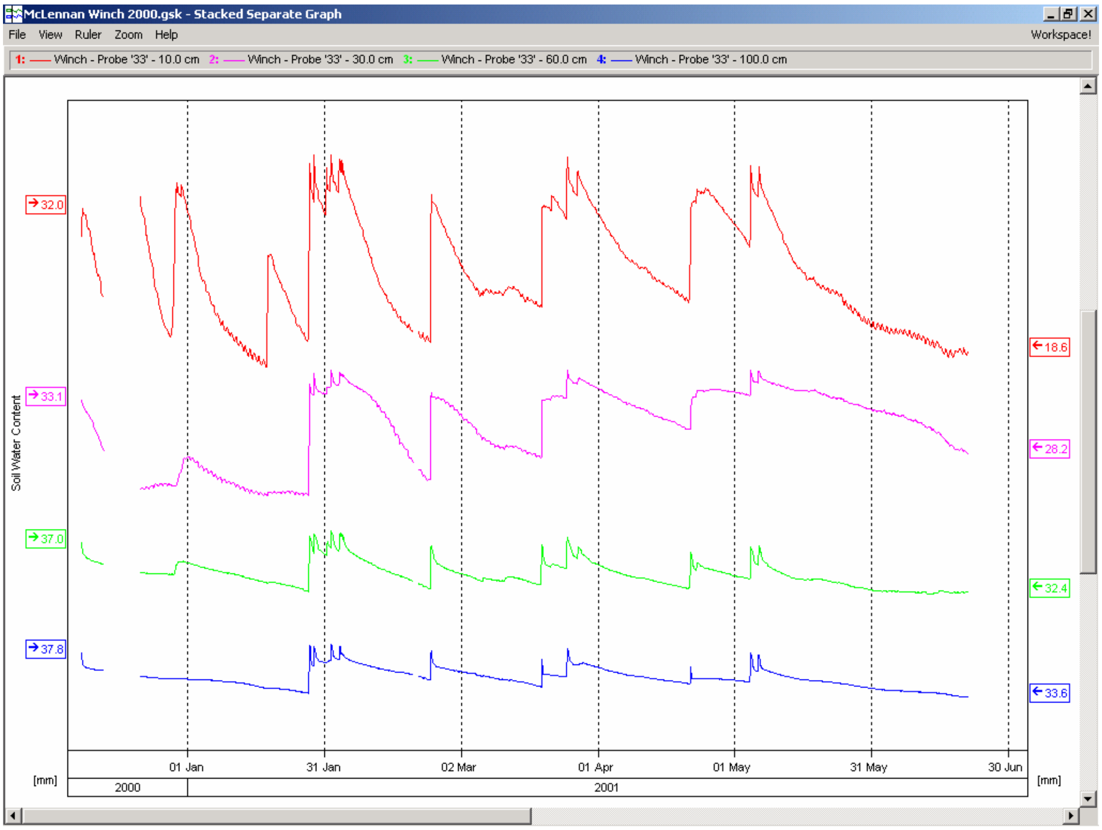


Figure E-12 Separate level soil water content at field site 6

Appendix F A Comparison of Soil Moisture and Stem Elongation

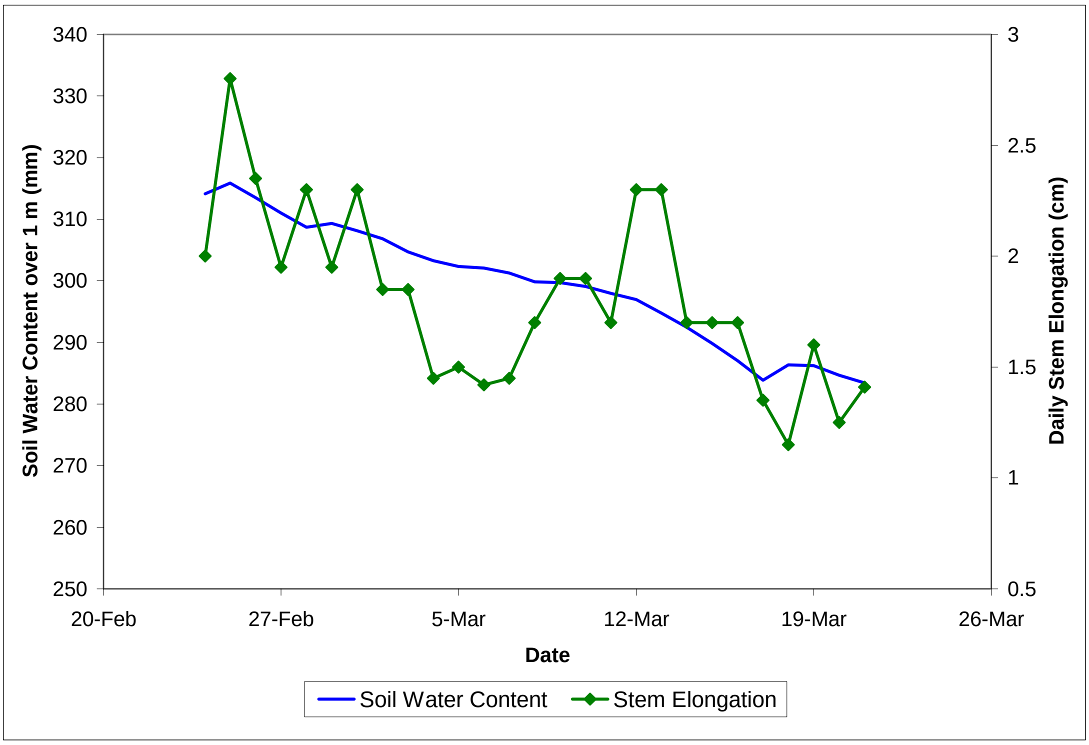


Figure F-1 Total soil water content and stem elongation at field site 1

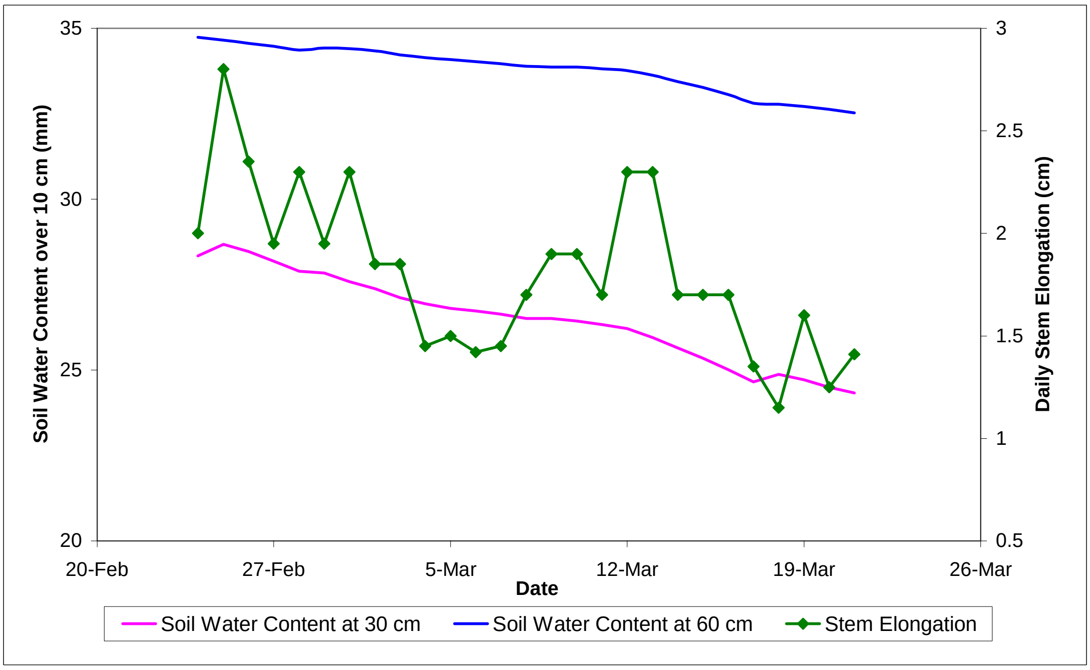


Figure F-2 Separate level soil water content and stem elongation at field site 1

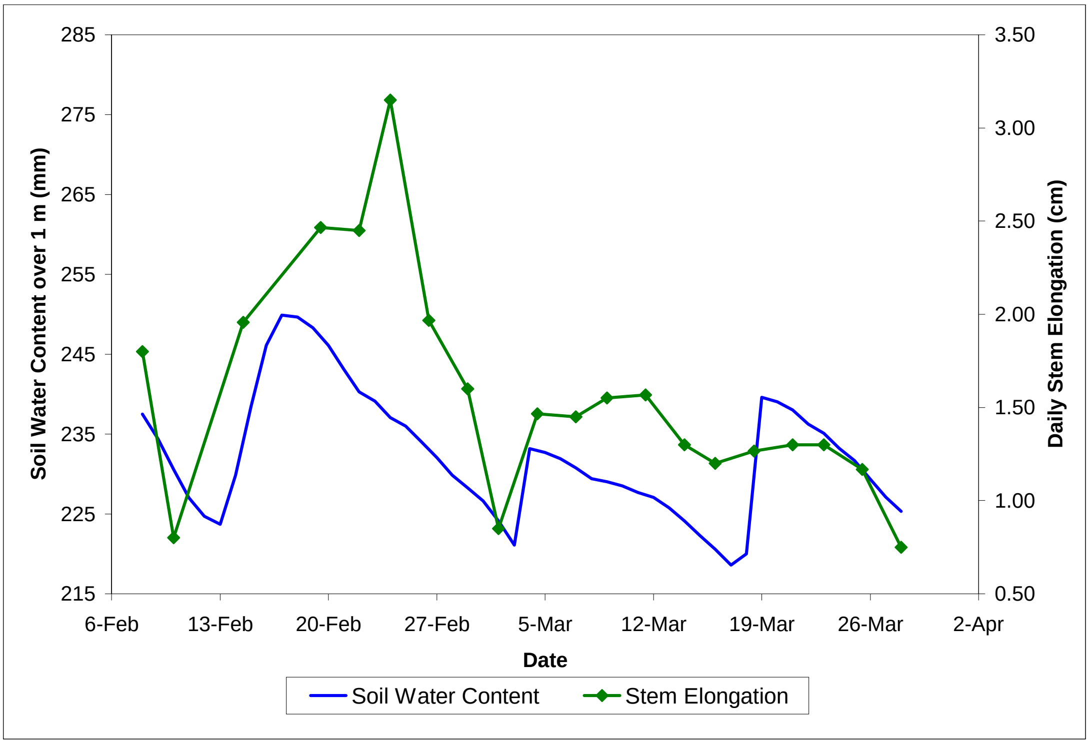


Figure F-3 Total soil water content and stem elongation at field site 4

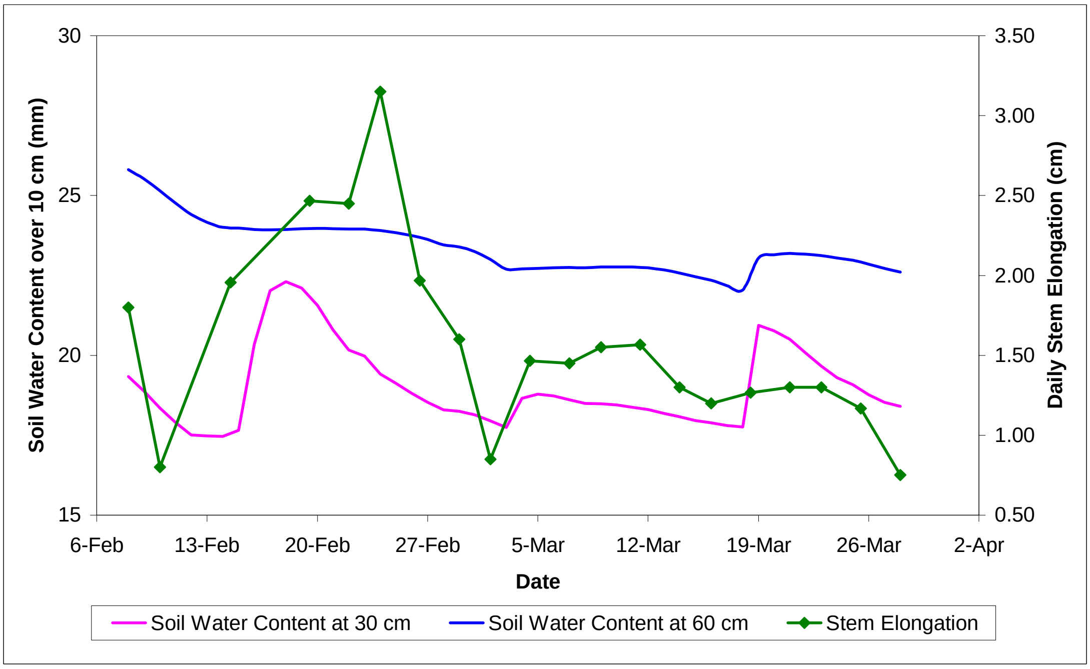


Figure F-4 Separate level soil water content and stem elongation at field site 4

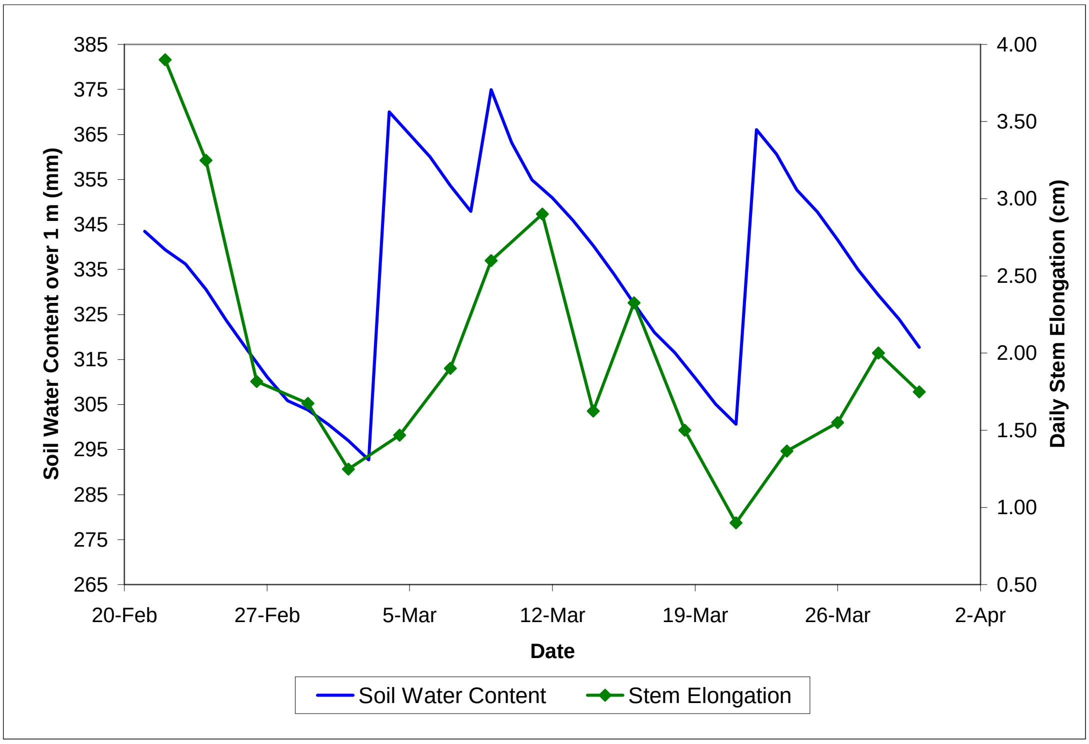


Figure F-5 Total soil water content and stem elongation at field site 5

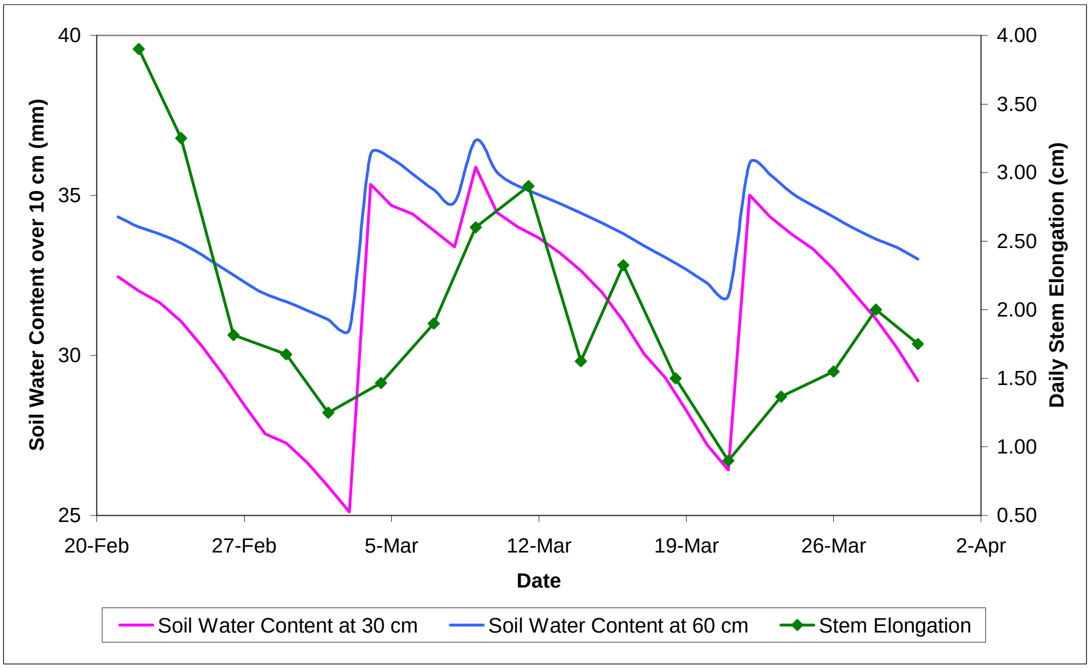


Figure F-6 Separate level soil water content and stem elongation at field site 5

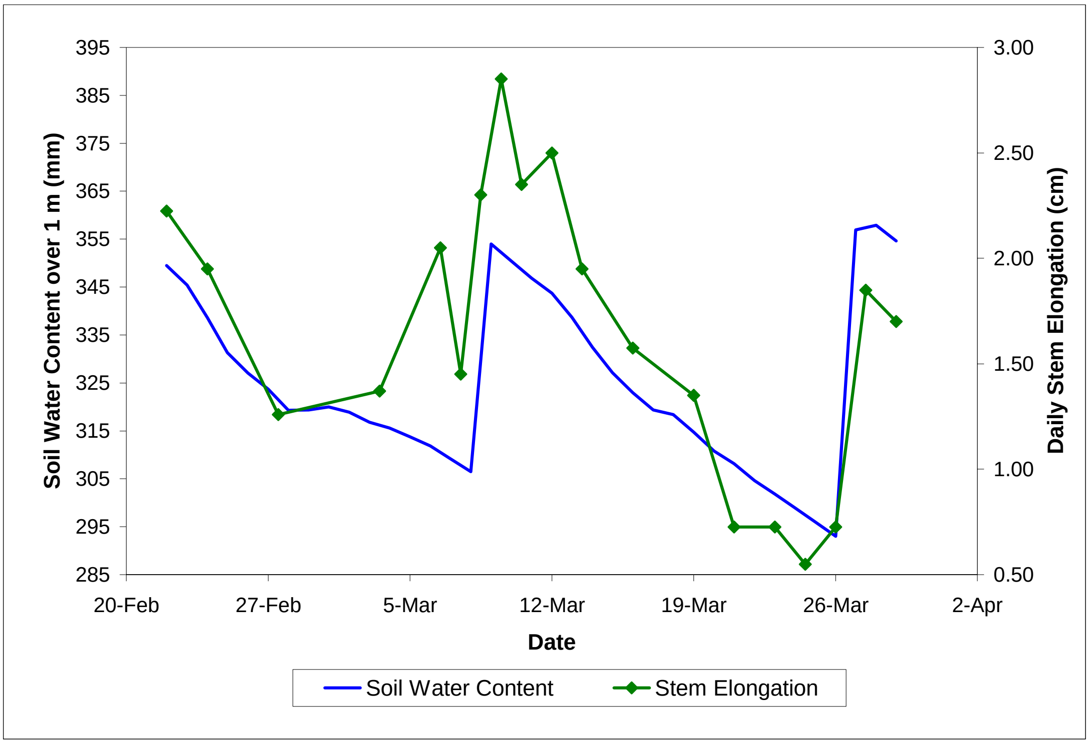


Figure F-7 Total soil water content and stem elongation at field site 6

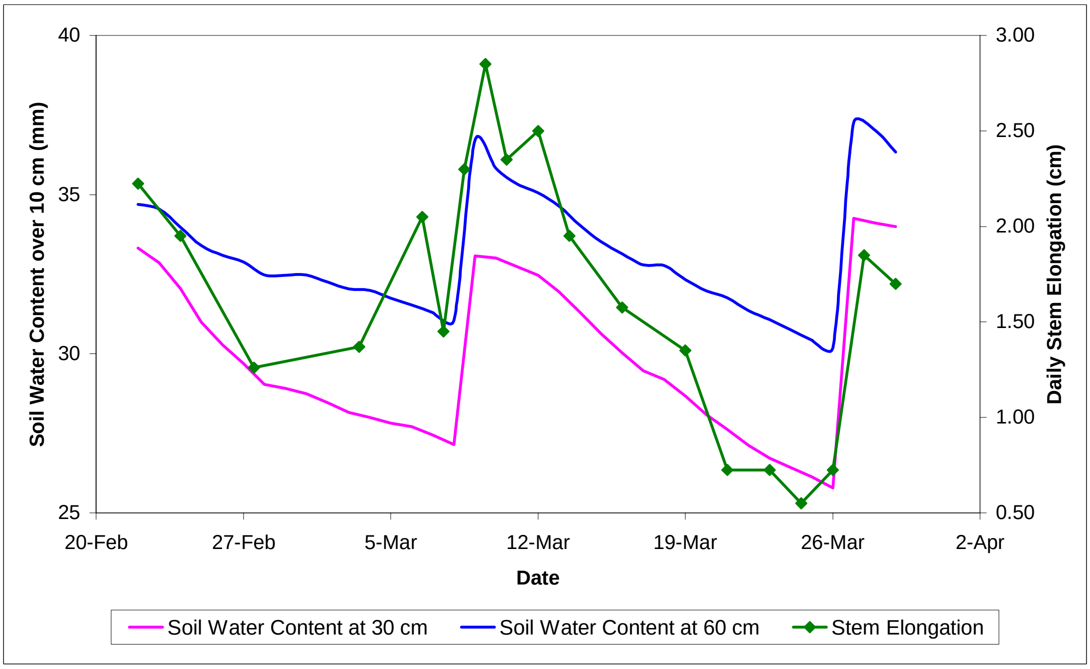


Figure F-8 Separate level soil water content and stem elongation at field site 6

Appendix G Simulation of Earlier Irrigation Start up at Field Sites

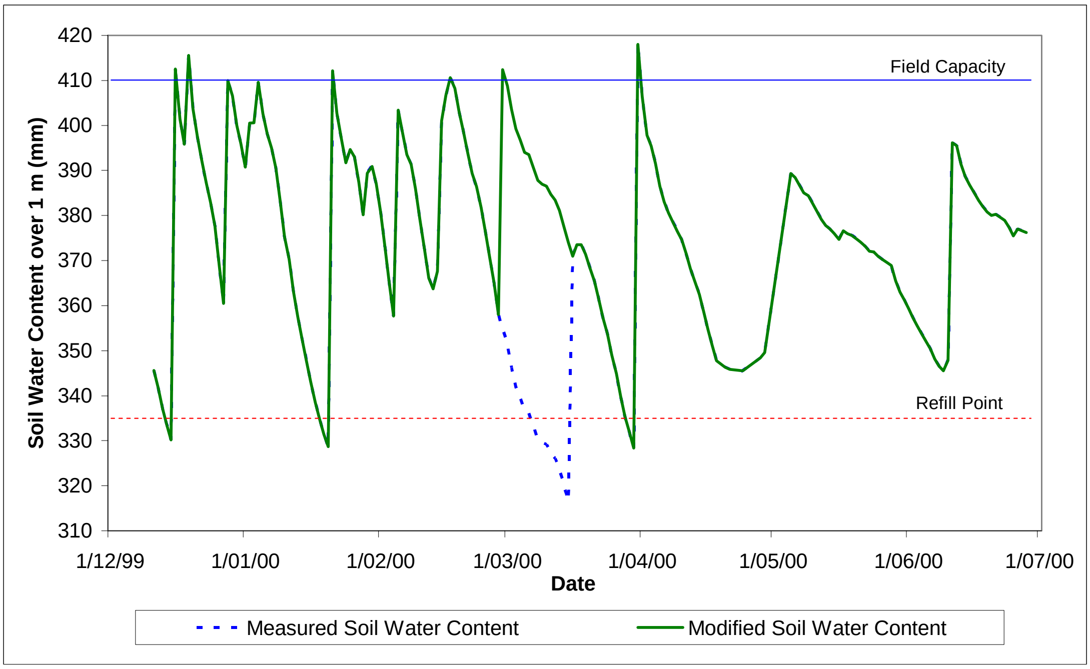


Figure G-1 Simulated early irrigation start up site 2 (1999 - 2000)

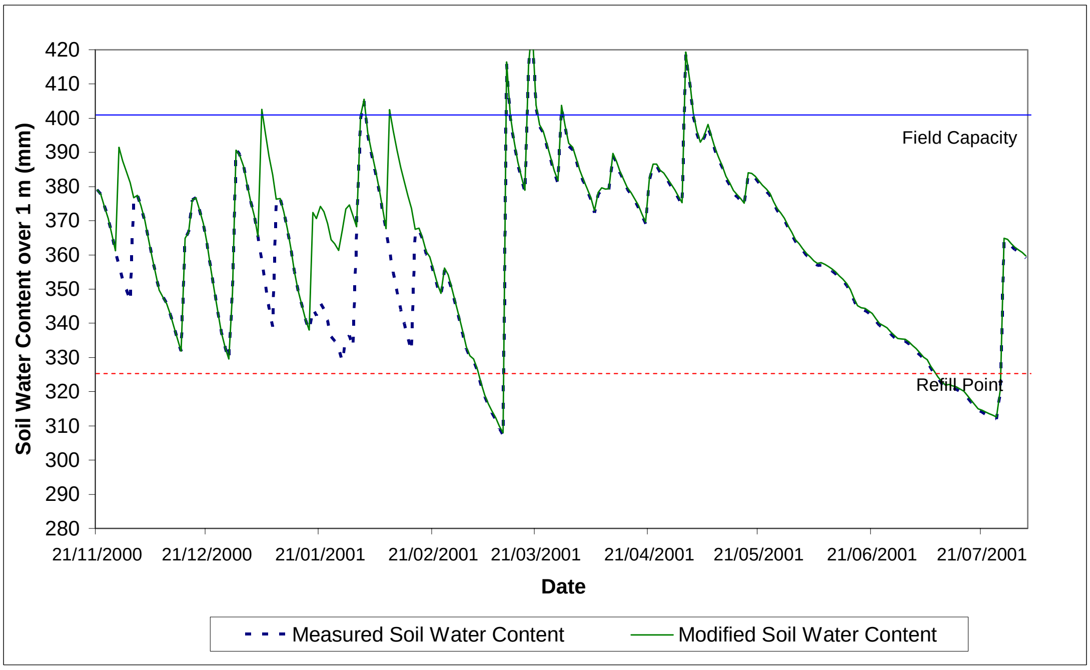


Figure G-2 Simulated early irrigation start up site 2 (2000 - 2001)

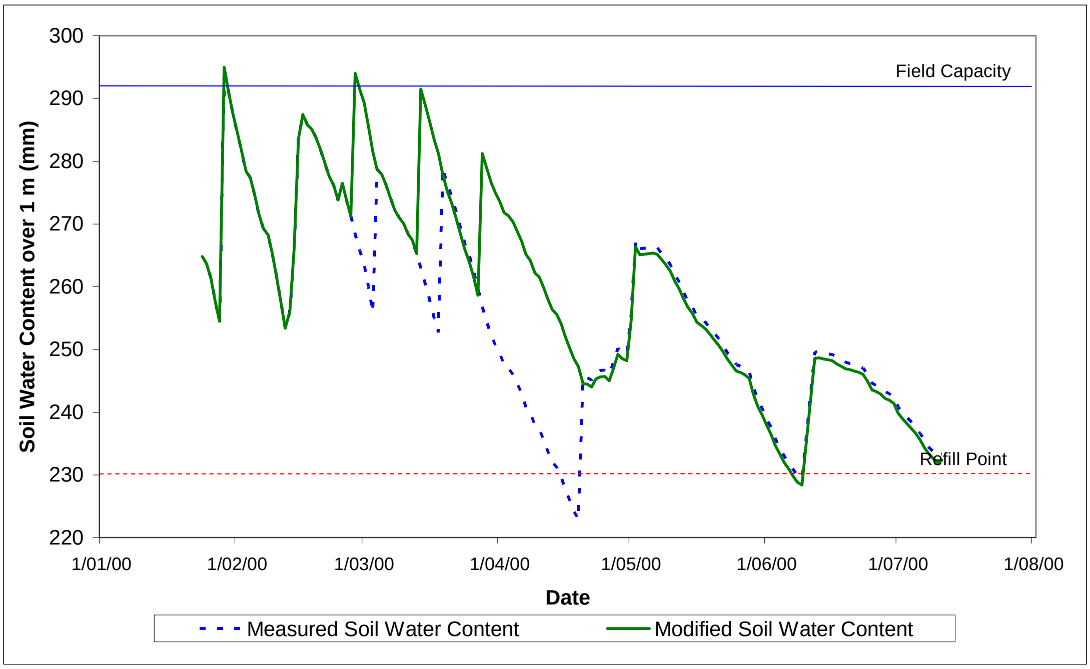


Figure G-3 Simulated early irrigation start up site 4 (1999 - 2000)

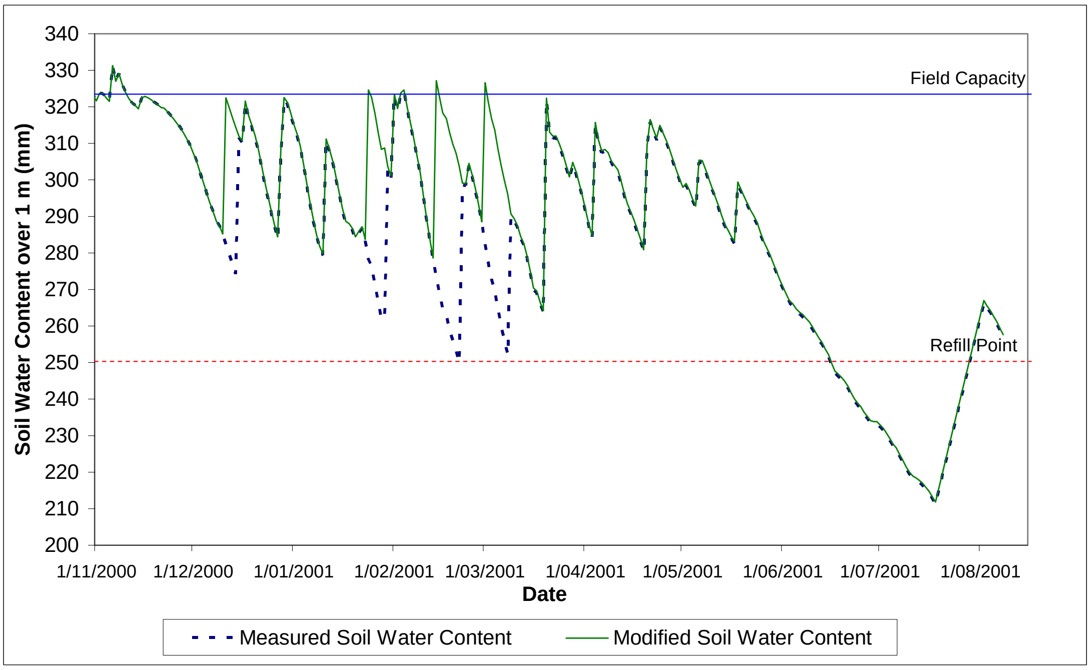


Figure G-4 Simulated early irrigation start up site 4 (2000 - 2001)

`

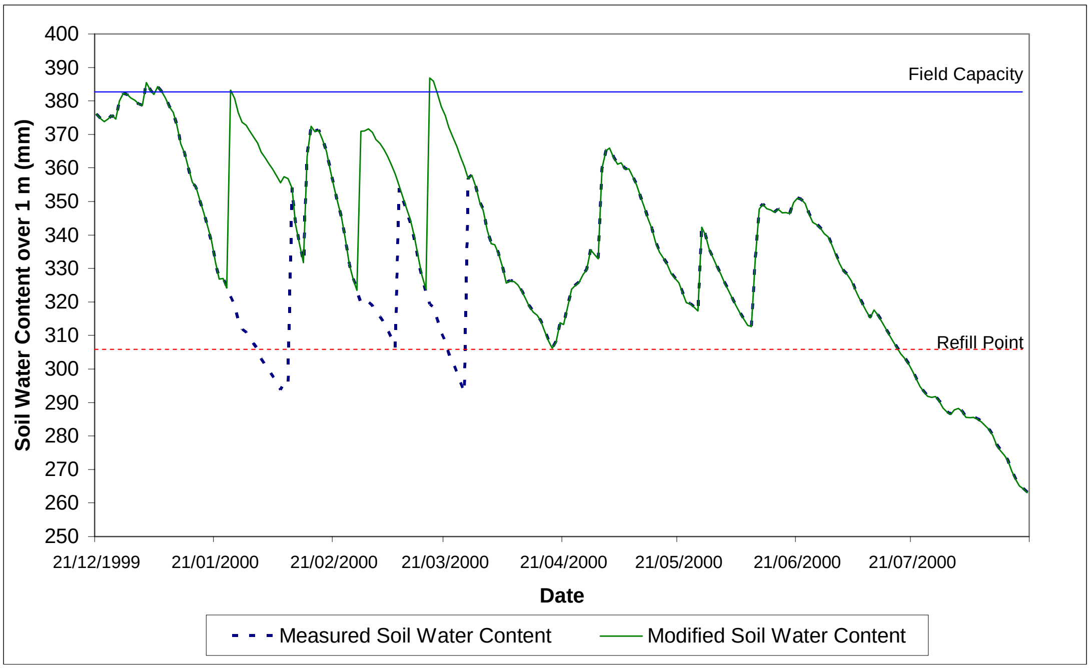


Figure G-5 Simulated early irrigation start up site 6 (1999 - 2000)

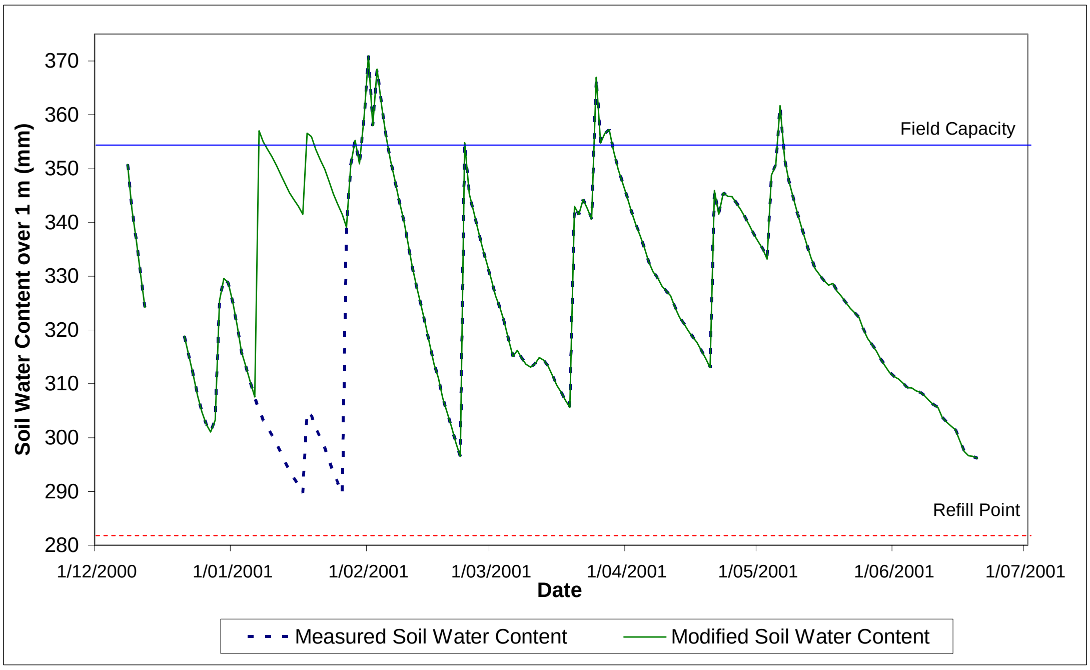


Figure G-6 Simulated early irrigation start up site 6 (2000 - 2001)

Appendix H Irrigation Start Dates For Modelled Treatments

Yellow Chromosol; 2ML/Ha & 3ML /Ha @ 75% irrigation efficiency; Irrigate at deficit of 0.25 fasw

	Treatments	Days After Sowing (DAS)					
Season		1st Irrig	2nd Irrig	3rd Irrig	4th Irrig	5th Irrig	6th Irrig
92-93	-14	165	188	202	216	230	244
	-7	172	195	209	223	237	251
	0	179	202	216	230	244	258
	7	195	209	223	237	251	277
	14	202	216	230	244	258	284
93-94	-14	196	211	246	277	291	316
	-7	203	218	253	284	298	323
	0	210	225	260	291	305	330
	7	218	253	284	298	323	337
	14	225	260	291	305	330	344
94-95	-14	77	178	192	206	220	234
	-7	84	185	199	213	227	241
	0	91	192	206	220	234	248
	7	185	199	213	227	241	293
	14	192	206	220	234	248	300
95-96	-14	145	159	175	189	203	217
	-7	152	166	182	196	210	224
	0	159	173	189	203	217	231
	7	166	182	196	210	224	273
	14	173	189	203	217	231	280
96-97	-14	141	188	215	237	284	299
	-7	148	195	222	244	291	306
	0	155	202	229	251	298	313
	7	195	222	244	291	306	324
	14	202	229	251	298	313	331
97-98	-14	129	161	177	191	206	275
	-7	136	168	184	198	213	282
	0	143	175	191	205	220	289
	7	168	184	198	213	282	296
	14	175	191	205	220	289	303
98-99	-14	193	207	221	266	281	325
	-7	200	214	228	273	288	332
	0	207	221	235	280	295	339
	7	214	228	273	288	332	345
	14	221	235	280	295	339	352
99-2000	-14	145	171	185	199	213	263
	-7	152	178	192	206	220	270
	0	159	185	199	213	227	277
	7	178	192	206	220	270	290
	14	185	199	213	227	277	297
2000-2001	-14	173	215	233	252	266	280
	-7	180	222	240	259	273	287
	0	187	229	247	266	280	294
	7	222	240	259	273	287	301
	14	229	247	266	280	294	308

Red Kandosol; 2ML/Ha & 3ML /Ha @ 75% irrigation efficiency; Irrigate at deficit of 0.25 fasw

	Treatments	Days After Sowing (DAS)					
Season		1st Irrig	2nd Irrig	3rd Irrig	4th Irrig	5th Irrig	6th Irrig
92-93	-14	101	138	159	173	188	202
	-7	108	145	166	180	195	209
	0	115	152	173	187	202	216
	7	145	166	180	195	209	223
	14	152	173	187	202	216	230
93-94	-14	165	207	226	254	286	314
	-7	172	214	233	261	293	321
	0	179	221	240	268	300	328
	7	214	233	261	293	321	335
	14	221	240	268	300	328	342
94-95	-14	101	138	191	208	222	241
	-7	108	145	198	215	229	248
	0	115	152	205	222	236	255
	7	145	198	215	229	248	293
	14	152	205	222	236	255	300
95-96	-14	141	155	169	183	197	211
	-7	148	162	176	190	204	218
	0	155	169	183	197	211	225
	7	162	176	190	204	218	293
	14	169	183	197	211	225	300
96-97	-14	185	212	228	285	300	318
	-7	192	219	235	292	307	325
	0	199	226	242	299	314	332
	7	219	235	292	307	325	339
	14	226	242	299	314	332	346
97-98	-14	101	121	135	159	173	187
	-7	108	128	142	166	180	194
	0	115	135	149	173	187	201
	7	128	142	166	180	194	209
	14	135	149	173	187	201	216
98-99	-14	192	206	220	234	276	309
	-7	199	213	227	241	283	316
	0	206	220	234	248	290	323
	7	213	227	241	283	316	340
	14	220	234	248	290	323	347
99-2000	-14	147	171	185	199	213	263
	-7	154	178	192	206	220	270
	0	161	185	199	213	227	277
	7	178	192	206	220	270	292
	14	185	199	213	227	277	299
2000-2001	-14	169	183	216	233	250	264
	-7	176	190	223	240	257	271
	0	183	197	230	247	264	278
	7	190	223	240	257	271	285
	14	197	230	247	264	278	292