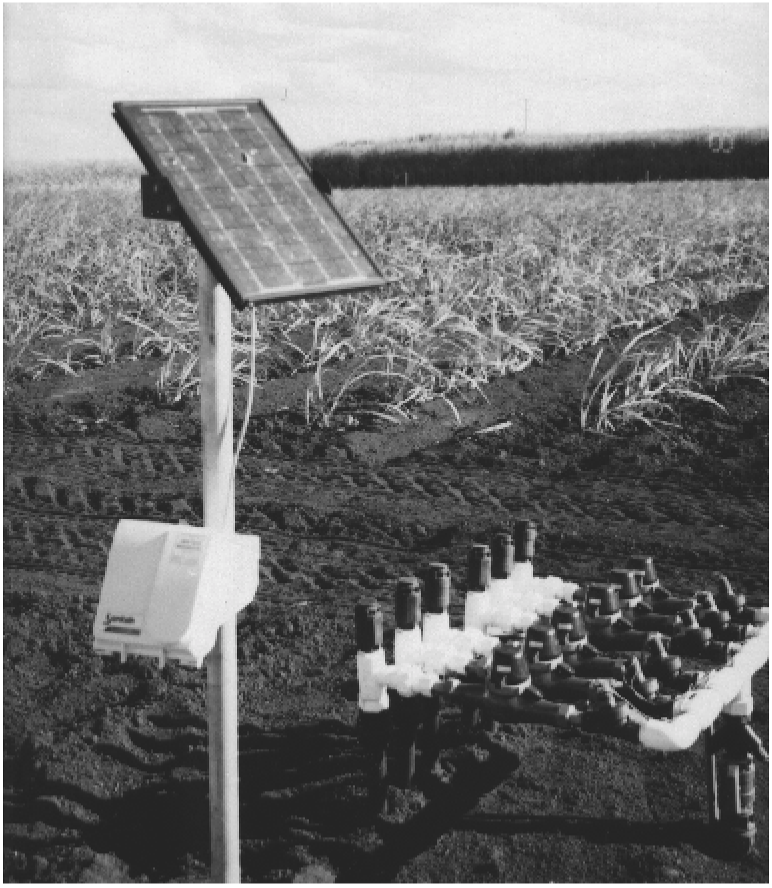
ASSESSMENT OF IRRIGATION STRATEGIES FOR BEST USE OF LIMITED WATER



A REVIEW OF RELEVANT RESEARCH TO DATE

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ASSESSMENT OF IRRIGATION STRATEGIES FOR BEST USE OF LIMITED WATER- A REVIEW OF RELEVANT RESEARCH TO DATE.

by
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1 ABSTRACT

This project has researched available information on critical stress levels for sugarcane irrigation at different stages of crop growth, and utilised these in the APSIM modelling framework, to develop irrigation scheduling recommendations for current irrigation districts.

It was found that adequate irrigation should be provided for establishment of the crop, and that moderately severe soil moisture stress could be tolerated in cooler months immediately following crop establishment, when slower crop growth could be expected. In the main growing period in summer cane growth was found to be restricted at moderate stress levels, compared to low stress levels prior to irrigation, but water use efficiency and cane sugar levels were improved. The optimum stage for irrigation during this period was considered to be at stalk growth rates of 30% of maximum values, or at a soil moisture deficit of around 70% of plant available water (PAWC). In most districts moderate stress levels prior to irrigation therefore appeared optimum, if normal water allocations were available. With restricted water allocations moderate to severe water stress prior to irrigation (deficits of 70-80% of PAWC) gave optimum yields, and the highest irrigation water use efficiency (IWUE). For sandy soils, irrigation at lower water stress levels of around 50% of PAWC was recommended, if full water allocations were available. This is equivalent to stalk growth rates of around 50% of the maximum rate following irrigation.

The exception to the discussion above was in fully irrigated districts such as the Burdekin and Mareeba where soil moisture deficits equivalent to 50% stalk growth rate were considered to give optimum cane and sugar yields on all soil types.

Detailed irrigation scheduling recommendations were developed for each of the main supplementary irrigation districts using the crop growth model, APSIM, to compare different irrigation strategies.

Economic evaluation of irrigation responses suggests that limited irrigation should be spread over most of each farm, but that irrigation with limited water was generally uneconomic as along term proposition. The economics of irrigation improved markedly in districts such as Bundaberg with increase in available water allocation. Irrigation systems with higher water application efficiency generally gave higher economic returns, despite the higher capital cost. This was most significant on sandy soils with low PAWC.

2 EXECUTIVE SUMMARY

2.1 Introduction

Irrigation is essential to stable production in many sectors of the Australian sugar industry. It has been estimated that 60% of sugarcane production depends on some form of irrigation. The increased reliance of the industry on irrigation has placed pressure on finite water resources, and increased the emphasis on efficient use of these resources.

The challenge for irrigators is make best use of both irrigation and rainwater to optimise cane productivity. Strategies will obviously be different for situations with limited and adequate irrigation water resources. With limited resources maximising irrigation water use efficiency (IWUE) will be the main goal, while with adequate water irrigators will aim to maximise profitability from irrigation, and this may not correspond to maximum IWUE. For both these situations guidelines are required for scheduling of irrigation to optimise crop growth response.

The most commonly used technique has been to irrigate when cane stalk growth falls to 50% of its' maximum value. This has been defined in terms of the soil moisture stress level at which growth falls to 50% of the maximum rate in freshly irrigated soil; or the amount of water that can be used by the crop before growth falls to 50%. This amount of water is commonly termed readily available water (RAW). Obviously, where irrigation water is restricted it may not be possible to water at the 50% growth rate, and a higher level of stress must be allowed before irrigating. The level of stress that may be tolerated may differ for crop establishment, early growth, and the main growth period during summer. Also, the level of water stress at these times is likely to vary from year to year in each district, and from district to district, and a modelling approach is most appropriate for determining how this affects average yield response to irrigation.

This review draws on available trial data to establish these critical stress levels in a form that can be used in long term modelling studies. The aim is to use long-term weather data to assess how stress at these times will affect predicted yield with different irrigation strategies. The crop production model APSIM has been developed to facilitate such studies, and validation using trial data in several districts is required to ensure acceptance of results. Both timing of water use throughout the season, and the most appropriate soil moisture stress level or water deficit for irrigation, will be evaluated for situations of adequate or limited water availability. Recommendations will be drawn up for each district, based on the strategies that give the best combination of high irrigation water use efficiency (IWUE) and economic response to irrigation.

2.2 Findings

2.2.1 Critical soil moisture stress for irrigation

The first stage of the project was to evaluate the effect of soil moisture stress on crop growth at different stages of the growing season. The main research on crop growth versus soil moisture stress was carried out in the Bundaberg region in the 1970's. This indicates that cane stalk growth rate is highest in the peak growing period during summer, and that growth rates fall rapidly as soil moisture stress increases, reaching 50% of maximum, at a stress level in the main root-zone of approximately 98 kPa. Growth rate falls to 30% at a stress level around 160 kPa. The latter stress level is equivalent to approximately 76% depletion of plant available water (PAWC) in the soil type used for trial work. The main water use was in the top 0.6m of soil under low stress conditions, with limited water use to a depth of 0.9m at the 30% growth rate.

It was found that cane yield was reduced slightly in dry years if irrigation was carried out at the 76% depletion level, but sugar yields were optimised compared to irrigation at 51% depletion of soil moisture. There was also a significant water saving by watering at the 76% depletion level, resulting in higher IWUE. This suggests that sugar yields, and IWUE, will be optimised by irrigating at either 30% of maximum stalk growth rates in the peak growth periods, or alternatively, at around 75% depletion of soil moisture reserves in the red volcanic soil used for this trial work. Where higher stress levels occurred in unirrigated cane, it took some time after rain for crop growth to return to normal, and this resulted in significant yield loss. Irrigation should therefore not be delayed beyond 75% water depletion if water is available.

Stalk growth rate of cane was closely linked to average daily temperature, with a rapid increase in growth rates above 24°C. This defines the main growing periods for Ayr, Mackay, and Bundaberg as September-April, October- April and November to March. Outside this peak growth period in the Bundaberg region, it has been demonstrated that increased moisture stress levels can be tolerated before crop growth rates are significantly reduced. In the period from October to December 50% and 30% growth rate occurred at higher soil moisture stress levels of 160 and 300 kPa, respectively. This should allow delay of irrigations in this period without significant loss in yield potential. For coastal districts from Mackay north, this effect is likely to be less pronounced.

There is little trial evidence on critical soil moisture stress levels at the time of crop establishment, but there is strong practical experience indicating that irrigation is required for optimum crop establishment in dry conditions, in all districts. This is particularly true in loose sandy soils where poor stalk anchorage may have caused significant damage to ratoon stubble at harvest.

The readily available moisture (RAW) levels corresponding to 50% stalk growth rate has been determined for a number of sugar industry soils, and in some cases the total plant available water(PAWC) is also known for these soils. For the Bundaberg red volcanic soil, the RAW is 63% of PAWC. Over a number of sugar industry soil types the ratio RAW:PAWC ranges from 0.65 to 0.75. If a growth rate of 30% of maximum is used as the signal for irrigation, a deficit of around 70-80% of PAWC would appear realistic for most soil types. There is sound economic evidence to support this from recent research in the South African sugar industry.

This deficit does not appear suitable for full irrigation conditions in the Burdekin, as reduced sugar yields have been recorded if irrigation is scheduled at higher deficits than the RAW.

There are several practical tools available for indicating when the correct moisture deficit for irrigation has been reached, involving indirect measures such as pan evaporation, and direct measurements in the soil. Based on the above discussion, and experience overseas Class A pan factors of 0.85 and 0.64 appear most appropriate for scheduling irrigation during the peak growth period in full and supplementary irrigation areas, respectively.

2.2.2 Assessment of irrigation efficiency

The success of irrigation strategies is usually assessed by determining the cane water index (CWI) or tonnes cane per Ml of irrigation plus effective rainfall. A CWI of around 12.2 has been achieved in irrigation trials, and a practical CWI for commercial conditions is considered to be around 8.5 t cane/Ml. This has been achieved in the Bundaberg area where the district CWI is now approximately 9.0 t cane/Ml. Irrigation water use efficiency (IWUE) is a much more variable index, due the strong influence of rainfall on irrigation responses. Effective rainfall has been demonstrated to be extremely variable in the sugar industry, particularly in the Mackay-Proserpine area. In the assessment of irrigation strategies CWI, IWUE and predicted average yield were compared. If close to maximum yields were predicted, with the highest IWUE and CWI, the strategy was considered to be the most suitable.

2.2.3 Model validation

Prior to evaluation of APSIM as a tool for assessing different irrigation strategies, a review of trial validation data for APSIM predictions was carried out. This includes data from northern New South Wales, Bundaberg, Mackay, Proserpine, the Burdekin and Ingham areas. In general APSIM has proved very successful in predicting overall trial yields and marginal responses to irrigation. It is recognised that there are still difficulties in predicting the influence of factors such as waterlogging, crop lodging and the contribution of shallow watertables to crop water uptake, on crop yields. Since APSIM is a paddock based model there is some difficulty in predicting district cane yields due to the range of factors influencing these average yields. However, it is considered the most adequate tool currently available for assessing on farm irrigation management.

2.2.4 Developing recommended irrigation strategies

A range of ‘best bet’ irrigation strategies were evaluated for the main irrigation districts within the sugar industry using APSIM, bearing in mind research results on the most suitable soil moisture deficits prior to irrigation at different times of the year.

In all districts a range of typical soil types were used for testing irrigation strategies. Irrigation increments of 20-30 mm were scheduled at low deficits in the top 0.6m of soil for crop establishment, usually in the first month of crop growth. In most cases the crop rootzone was considered to extend to a depth of 0.9m for scheduling purposes in the remainder of the season. A ‘spending’ or runout strategy involving irrigation at moderate soil moisture deficits until all available water had been used, was compared with various ‘saving’ strategies considered appropriate for each district. Appropriate drying off periods prior to harvest were allowed for each strategy to minimise the depression of CCS by late irrigation. Irrigations during the main growing season were appropriately sized to replace part or all of the set deficit at irrigation for each soil type. The comparisons were carried out for the main supplementary irrigation districts.

2.2.5 Recommended irrigation strategies

In the Bundaberg-Maryborough area water allocations approximating nominal full allocation and half allocation were compared, recognizing that allocations have been restricted for Bundaberg-Childers over the last 7 years. With full water allocation a moderate saving schedule, with irrigation at a deficit of 70% of PAWC was found to most suitable for soils with moderate to high PAWC, and a spending strategy with lower soil deficits of 50% of PAWC most suitable for sandy soil with low PAWC. With half allocation a saving strategy with deficits of 70-80% of PAWC was most suitable for a range of soil types. An alternative strategy of extending the period for crop establishment to 2 months, delaying the main irrigation season to mid-January, and irrigating at a deficit of 50% of PAWC to maintain high crop growth rates, was considered satisfactory for both full and half allocations. A longer drying off period was scheduled with this philosophy to minimise CCS depression with full water allocation.

In the Mackay area there was no apparent difference between a runout strategy with irrigation at a deficit of 65% of PAWC in the 0-0.6m layer and saving strategies, for a limited water allocation of 1.5 Ml/ha. This is in accordance with high trial responses to 1 or two irrigations scheduled early in crop growth. With a more liberal allocation of 3 Ml/ha a relatively severe saving strategy (deficit 80% of PAWC) gave optimum yields, and the highest IWUE. This allowed spreading of water into responsive dry periods between January and March.

The Proserpine district has a higher irrigation demand than Mackay, and this is up to 6 Ml/ha/year in the drier sections of the district. As for Mackay there was no advantage from saving strategies with limited water allocation (2 Ml/ha), and a simple runout strategy with irrigation at a deficit of 65% of the PAWC in the top 0.6m of soil was recommended. This strategy also appears suitable for a higher allocation of 4 Ml/ha. The use of the top 0.6m of soil for determining soil deficits for irrigation is based on observations of water use patterns in Proserpine soils.

In the Burdekin district irrigation at a deficits corresponding to 50% stalk growth rate appears most appropriate for optimising cane and sugar yields and IWUE. Effective rooting depths and RAW as a percentage of PAWC vary widely between soil types, and on farm calibration of stalk growth rate against minipan estimates of soil moisture deficit appears the most successful irrigation scheduling technique. Drying off periods from 1-3 months are recommended for increasing CCS levels, depending on soil texture, and time of harvest. The main gains expected in water use efficiency in the Burdekin are from improvements in water application efficiency.

In the Ingham area a saving strategy based on irrigation at a deficit of 80% of PAWC was found to be marginally more effective than irrigating at a 50% deficit. With the saving strategy, rewarding cane yield responses of >10 t cane/ha to 2 Ml/ha of irrigation, were predicted in 93% of years.

At Atherton a saving strategy of a deficit of 80% of PAWC prior to irrigation gave optimum cane yields, and the highest IWUE. An allocation of 3 Ml/ha was fully utilised in 78 and 54% of years in red earth and krasnozem soils. The predicted IWUE decreased with increasing water allocation. In this study it was assumed that the crop could extract water from an extremely deep soil profile, and further investigation of the depth of water use under irrigation may be required.

The Mareeba area has a high irrigation allocation of 8 Ml/ha and is similar to the Burdekin in water requirements. In this region a runout strategy with irrigation at moderate water deficits of 65% of PAWC to a depth of 0.6m, after the initial crop establishment period, gave the highest IWUE.

2.2.6 Economic implications

In the Bundaberg area economic studies indicate that limited water allocations should be spread over a majority of the farm to maximise returns. The gross margin from irrigation increases with increasing irrigation allocation, and returns are marginal with 50% of the current nominal water allocation. There is some economic benefit from using irrigation systems with high water application efficiency such as drip irrigation, despite their high capital cost, and benefits are maximised in soils with a medium to low RAW value. This highlights the current dilemma in the Bundaberg district, where investment in more efficient irrigation systems, such as drip, is being limited by low effective water allocations.

Findings are similar for the Mackay district, where predicted economic returns from irrigation are highest on sandy soils. Low water allocations of 1 Ml/ha were assessed as uneconomic, and with 3 Ml/ha allocations, only more efficient irrigation systems such as drip and centre pivot irrigation were considered economic.

Similarly for the Atherton area with water winch irrigation, only higher water allocations around 4 Ml/ha were considered economic on red earth soils.

2.3 Farmer adoption

This review draws together material available for use by irrigation extension officers in encouraging improved irrigation scheduling by farmers, and should encourage improved efficiency in using both restricted and full water allocations. Recommendations are framed in a form that can be readily used for guiding irrigation in the crop establishment phase and in the main irrigation period.

2.4 Further research

While there is a large body of irrigation research results available to the sugar industry there are still some gaps in data on soil moisture characteristics and limits to the flexibility of the APSIM crop growth model.

There is a limited suite of soils for which the relationship between RAW and PAWC has been defined for guiding crop modelling studies, and further work is required to define a representative range of soils in all districts. Some unpublished data was not accessible for this study. The ratio of RAW:PAWC appears to be a fairly robust indicator of the most suitable stress levels for model studies to optimise irrigation scheduling.

There is also a need to further develop APSIM to take account of yield limiting factors such as lodging and waterlogging, so that district yields can be represented more closely in long term simulations.

3 BACKGROUND

Irrigation is essential to stable production in many sectors of the Australian sugar industry. It has been estimated that 60% of sugarcane production depends on some form of irrigation (Holden *et al*., 1998). Currently within the sugar industry full or supplementary irrigation is required in the Ord River, Tablelands, Burdekin, Proserpine, Mackay, Bundaberg and Maryborough areas. Limited supplementary irrigation is used in the Cairns, Herbert and Rocky Point regions (Table 1).

TABLE 1
Irrigation requirements in each sugar producing district

District	Annual crop water use mm	Effective rainfall mm	Irrigation requirement mm
Ord	1960	550	1410
Cairns	1630	1360	270
Mareeba/ Dimbulah	1550	405	1145
Atherton	1170	760	410
Tully/Babinda	1310	1500	nil
Herbert	1350	1100	250
Burdekin	1520	450	1070
Mackay/Proserpine	1490	630	860
Bundaberg/Maryborough	1360	580	780
Moreton	1100	1180	nil
Rocky Point	1150	990	160
Northern NSW	1200	1000	200

(From Holden *et al*., 1998)

The increased reliance of the industry on irrigation has placed pressure on finite water resources, and increased the emphasis on efficient use of these resources. Improved efficiency involves better irrigation application efficiency, better timing of irrigation to obtain optimum cane yield response, and close matching of applications to soil water holding capacity to minimise runoff and deep drainage losses. These issues have been addressed in recent research (Shannon *et al*., 1996; Holden *et al*., 1998; Hardie *et al*., 2000. The current review will draw together the above research, with particular emphasis on strategies for the most efficient use of limited water resources to optimise crop productivity.

In the partially rainfed situations within the sugar industry, crop water use efficiency has been assessed in terms of overall crop water use efficiency (WUE), expressed as tonnes cane Ml^{-1} of effective rainfall plus irrigation (Kingston, 1994; Robertson *et al*., 1997). Similarly, irrigation water use efficiency (IWUE), expressed as tonnes cane Ml^{-1} of irrigation has been used as an index of crop efficiency in utilising irrigation water (Bamber *et al.*, 1999; Ridge and Hillyard, 2000). The challenge for irrigators is make best use of both irrigation and rainwater to optimise cane productivity. Strategies will obviously be different for situations with limited and adequate irrigation water resources. With limited resources maximising IWUE will be the main goal, while with adequate water irrigators will aim to maximise profitability from irrigation, and this may not correspond to maximum IWUE.

For both these situations guidelines are required for scheduling of irrigation to optimise crop growth response. The most commonly used technique has been to irrigate when cane stalk growth falls to 50% of its' maximum value (Leverington and Ridge, 1975; Shannon *et al*, 1996). In the Proserpine area, Hardie *et al*, 2000 used a stalk growth index of 30% of the maximum value to schedule irrigation. In trial work at Bundaberg, Kingston and Ham (1975) found that a 50% stalk growth rate during the peak growth period corresponded to a mean soil water potential in the rootzone of approximately -80 kPa. Shannon *et al.*, (1996) established a critical soil water deficit for different soil types, corresponding to a 50% reduction in stalk growth rate. This was termed the readily available soil water (RAW).

This review will draw on trial data and crop yield modelling studies to develop guidelines for irrigation strategies with different levels of available irrigation water. Both timing of the use of water throughout the season, and the most appropriate soil moisture stress level or water deficit for irrigation will be evaluated.

4 PROJECT OBJECTIVES

- To review published and unpublished research on sugarcane response to soil moisture stress at different stages of crop growth
- To supplement actual trial data with simulations using APSIM where necessary to predict yield response to different stress regimes
- To develop recommendations for critical stress levels prior to irrigation at different times of the year, based on the level of available water
- To report the results of the review in a suitable form for use by irrigation extension officers

5 METHODOLOGY

The first step in the project was to review published and unpublished data on sugarcane irrigation, with particular emphasis on research aimed at improving irrigation efficiency through optimising the level of stress prior to irrigation. Since irrigation in the Australian sugar industry includes both supplementary and full irrigation over a range of environments, an attempt was made to include the typical range of irrigation scenarios. A range of indices of water stress, including measured soil water stress in the root zone, percent deficit in readily available soil water (RASW), and different pan evaporation crop factors were evaluated.

The crop production simulation model APSIM (McCown *et al*., 1996; Keating *et al*., 1997) was used to evaluate various irrigation scenarios to supplement published modelling studies. In particular, an attempt was made to optimise irrigation strategies for limited or typical full allocation water availability in different districts in terms of 'spending' or 'saving' irrigation water, and the use of different levels of water deficit as a trigger for irrigation. Where possible, recommended strategies were related to trial data for the particular district. Typically model simulations were carried out with long-term weather data for each district, usually for a period of around 40 years.

Recommended irrigation strategies were developed for several districts based on trial data and model simulations.

6 RESULTS AND DISCUSSION

6.1 Water application efficiency

The application efficiency of typical irrigation systems in use in the sugar industry has been found to vary enormously. Raine and Bakker (1996) found the application efficiency for flood irrigation systems in the Burdekin varied from 14% to 90%. Shannon *et al*., (1996) reported water application efficiencies for travelling irrigators (water winches) in the range 70-85% and for drip irrigation in the range 10-90%. For travelling irrigators, lower efficiency was caused by non-uniformity of application in most cases, and for drip irrigation low efficiency resulted from water applications in excess of the soil water holding capacity. It is obviously critical to optimise application efficiency in order to be able to fine tune irrigation scheduling strategies with limited water, and to obtain optimum economic returns from irrigation.

There have been significant improvements in flood irrigation efficiency in the Burdekin and other districts through adjustment of cut off times, furrow flow rates and furrow shape, and through modified practices such as alternate furrow irrigation and tailwater recycling (Raine and Bakker, 1996; Hardie *et al*., 2000). The adaptation of the SIRMOD model for Australian conditions has allowed optimisation of furrow flow rates, furrow lengths, furrow shapes and irrigation cut off times with limited field measurements of furrow advance times (Raine *et al*., 1997). This has led to significant improvements in irrigation application efficiency on highly permeable soils, low permeability soils and in trash blanket situations (Raine *et al*., 1997; Hardie *et al*., 2000; Linedale *et al*., 2001).

Similarly, drip irrigation efficiency has been significantly improved in the Bundaberg district by better matching of individual applications to the soil water holding capacity (Holden *et al*., 1997). This is particularly critical on sandy soils and strongly structured red soils where lateral movement of water from drip emitters is limited to approximately 200mm (Holden *et al*., 1997; Thorburn *et al*., 2000).

The implications of different application efficiencies for travelling irrigators, furrow irrigation and drip irrigation for cane yield and profitability under commercial conditions in the Bundaberg area were evaluated by Willcox et *al*. (1997) using a combined water balance, production and economic model. They assumed efficiencies of 60%, 75%, 80%, and 85% for furrow irrigation, travelling irrigators, furrow with tailwater return, and drip irrigation, respectively. In general it was found that both cane yield and profitability followed irrigation efficiency, despite higher capital costs for drip irrigation. Similar studies were carried out by Inman-Bamber *et al* (1999) for Mackay, comparing drip irrigation, travelling irrigators and centre pivot irrigators, assuming application efficiencies of 90,85 and 75% and capital costs of $3335, $1678 and $2365 per hectare, respectively. Again, the travelling irrigator was the least economic system.

Under experimental conditions where similar efficiencies are obtained with different systems, there is no clear evidence of differences in cane yield and IWUE between systems. Similar yields and water use efficiency were obtained for drip and furrow irrigation in trials on Krasnozem and gley podzolic soils at Bundaberg (Ridge and Hillyard, 2000; Ridge and Hewson, 1995). Kingston (pers.comm.) obtained similar yields for drip and spray irrigation on a krasnozem soil at Bundaberg. In the Burdekin Ham (1979) obtained no gain in either yield or water use efficiency from drip irrigation in comparison to spray or furrow irrigation.

However, there is some evidence that commercial cane yields are in accordance with relative water application efficiencies and model predictions. Commercial production figures in the Millaquin mill area at Bundaberg show CWI gains with drip irrigation of approximately 12% on soils with high or medium water holding capacity, and approximately 25% on soils with low water holding capacity (Haines, 1999, pers.comm.). This corresponds to a period where average irrigation water use for all systems was 3.7 Ml/ha.

6.2 Indices for scheduling irrigation

6.2.1 Soil moisture stress in relation to cane growth

The determination of critical soil moisture stress levels for scheduling irrigation is an essential pre-requisite for maximising yield potential with either limited or adequate water resources. With limited water supplies the irrigator is interested in the maximum stress levels that can be tolerated between irrigations, without reducing overall yield response to rainfall and irrigation. Where water supplies are adequate the aim is to maximise yields, provided marginal responses to additional water are economic. The effects of soil water stress on the cane ripening process must also be taken into account.

Pioneering work on the effect of soil moisture stress on cane growth was carried out by Leverington *et al*., (1970), and Kingston (1972). They reported on an irrigation trial at Bundaberg on a krasnozem soil, in which unirrigated cane was compared with cane watered at soil water potentials of -98 kPa and -390 kPa, measured at a depth of 229mm. At the time of irrigation, the estimated average soil water deficit in the 0-900mm zone for the two irrigation treatments was 51% and 76% of plant available water capacity (PAWC), respectively (Kingston and Chapman, 1975). The above depletions corresponded to average soil water potential in a 1.2m profile of –40 and –160 kPa, respectively. The equivalent average soil water stress prior to irrigation at a depth of 458 mm was 86 and 176 kPa, respectively. This suggests that there is limited use of water below a depth of around 600mm for these irrigation regimes.

It was found that stalk elongation decreased significantly when soil water potential at 229mm was less than -98 kPa, and ceased at approximately -980 kPa. It was also found that cane stressed to greater than -390 kPa at a depth of 229mm in unirrigated plots took some time to return to normal stalk elongation rates following rainfall. On this basis, it was considered that cane should not be stressed beyond -390 kPa on this soil type during the peak growth period, as there was a risk of serious reduction in cane yield.

A similar trial at Bundaberg (Kingston and Ham,1975) showed that a 50% reduction in stalk elongation rate, during the peak growth period in summer, corresponded to a mean soil water potential to a depth of 1.2 m of –0.80 kPa (Figure 1). The 50% growth rate corresponds approximately to the watering point for the –98 kPa treatment of Kingston (1972).
In sub-surface drip irrigated cane on the same soil type, Ridge and Hillyard (2000) found that 50% growth rate corresponded to a soil water potential at 300mm depth of –60 to –80 kPa, depending on cane variety. Hardie et al (2000) reported similar soil water potentials for soils in the Proserpine area, corresponding to 30% growth rate.

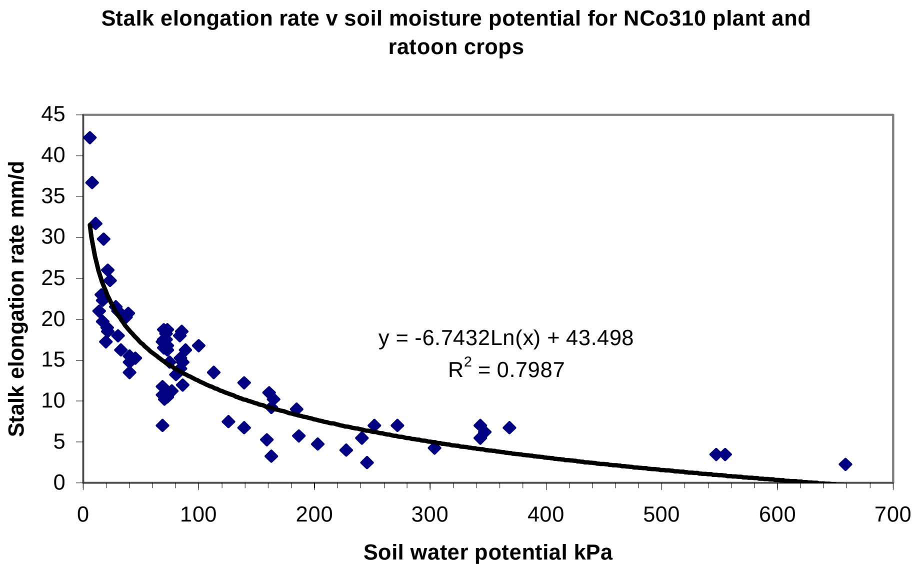


Fig.1- Effect of soil moisture potential on stalk growth rate of NC310 for peak growth months in plant and ratoon cane.

(Kingston, 1975)

Cane growth rate is also closely linked to daily average temperature, and the effect of prevailing temperatures on stalk growth rates is well documented (Anon, 1967; Bieske, 1967; Kingston, 1975). The effect of temperature on stalk growth is illustrated in Figure 2.

Using a mean daily temperature of 24°C or more as an index, Kingston and Chapman (1975) defined the peak growth growth period for Ayr, Mackay and Bundaberg as September to April, October to April, and November to March for the respective districts.

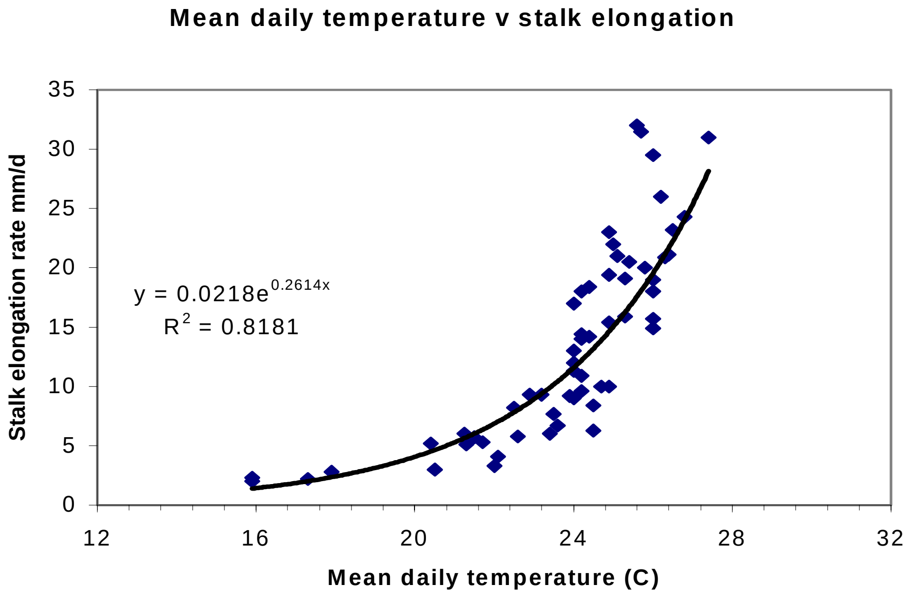


Fig. 2- Stalk elongation rates at Bundaberg in relation to mean daily temperature. *(after Kingston, 1975)*

Bearing this in mind early season irrigation (Spring period) in Bundaberg or further south would be expected to contribute more to maintenance of the crop, than to growth. In addition it might be expected that soil moisture stress during this period would be less critical than in Mackay or Ayr. Data collected by Kingston (pers.comm.) in a plant cane irrigation scheduling trial conducted in 1973/74 supports this view (Figure 3). Comparison with Figure 1 shows that 50% stalk elongation occurs at a significantly lower soil water potential of around -180 kPa, compared to –80 kPa in the peak growth period.

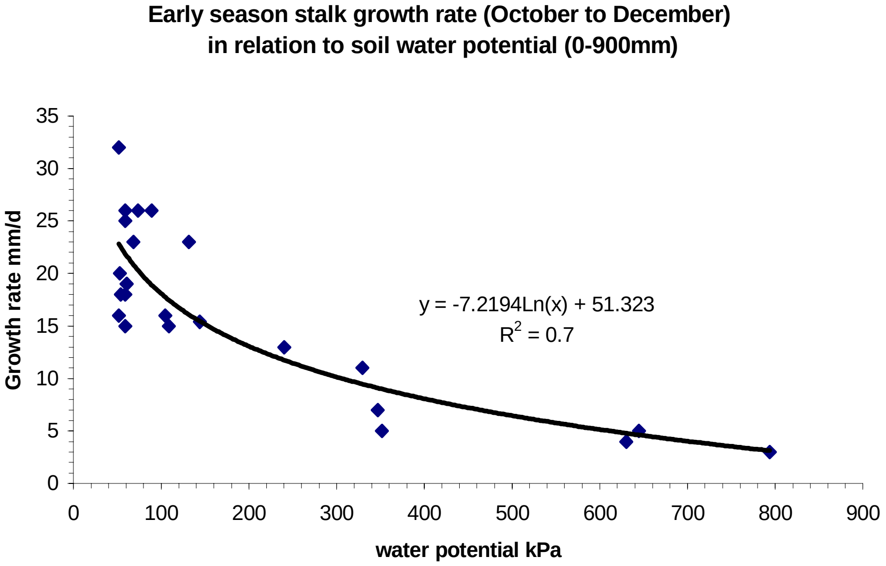


Fig. 3- Effect of soil water potential on early season (October to December) stalk elongation rates of March plant cane at Bundaberg. *(Kingston, pers.comm.)*

6.2.2 Scheduling based on soil water deficit or pan factors

Irrigating at a prescribed soil moisture deficit is commonly used alternative to measurement of soil water potential. The deficit may be measured directly using equipment such as the neutron probe, EnviroSCAN or Diviner, or estimated indirectly using devices such as a class A pan or minipan. Irrigation is applied to replace all or part of the estimated soil moisture deficit.

Various techniques have been used to determine suitable soil moisture deficits for irrigation. The most common approach recently in the sugar industry has been to measure the soil moisture deficit corresponding to a 50% reduction in stalk elongation rates, usually during the summer peak growth period (Shannon *et al.*, 1996; Holden *et al.*,1997). The soil moisture deficits corresponding to 50% stalk growth rate, termed readily available water (RAW), have been measured for a number of major soil types in the sugar industry, taking into account the effective rooting depth of each soil under irrigated conditions. A range of typical values for the Bundaberg and Proserpine areas are given in Table 2 (Holden *et al.*, 1997; Hardie *et al.*, 2000). The Proserpine data is for a soil moisture deficit corresponding to a 70% reduction in stalk elongation.

TABLE 2
Readily available soil water (RAW) for a range of soils in the Bundaberg and Proserpine districts

Soil Type	RAW in the root zone (mm)
Bundaberg	
Alluvial- clay loam	90
Red volcanic	90
Humic gley	70
Red earth	60
Red podzolic	60
Yellow podzolic- fine sandy loam	60-70
sandy loam	40-50
Gleyed podzolic- fine sandy loam	60-70
sandy loam	40-50
Black earth	50-60
Alluvial- sand	40
Proserpine	
Sodic Duplex	60-64
Sand	66
Cracking clay	80-82
Alluvial – silts and clays	80

There is some evidence that cane should be watered at a soil moisture deficit greater than that corresponding to 50% stalk elongation in the Bundaberg district to optimise sugar yield. The data of Zund and McDougall (1997) as quoted by Inman-Bamber *et al.*, (2000) shows that 50% stalk elongation corresponds to a soil moisture deficit of approximately 63% of PAWC in the Red Dermosol soil type utilised for the trial work described by Kingston and Ham (1975). In this trial work optimum sugar yields and significantly reduced water inputs were obtained where irrigation was carried out at a soil moisture deficit of 76% of PAWC rather than 51%.

In a drying-off experiment in the Burdekin region Inman-Bamber (pers.comm.) found that cane biomass and sugar accumulation continued significantly beyond the soil moisture deficit corresponding to a 50% reduction in stalk elongation rates. He found that fresh biomass accumulation was seriously reduced at around 25% stalk elongation rate. However caution is required in applying this approach in the peak growing period in the Burdekin. Holden *et al*., (1997) compared irrigation at a minipan deficit of 120mm, corresponding to 50% stalk growth rate, with irrigation at a deficit of 150mm. The results are summarised in Table 3, and show a significant reduction in cane and sugar yield with the higher deficit. Similarly, Ham (1985) reported that cane yield was significantly reduced on a loamy sand soil when stalk elongation rates fell below 50% during the peak growth period. Estimated soil moisture potential (from neutron probe readings, and soil moisture release characteristics) was approximately -490 kPa in periods of stress with stalk elongation below 50% of maximum rates. Robertson *et al*., (1999) reported that soil moisture stress early in crop growth in the Burdekin had an immediate impact on crop biomass, and the resultant yield reduction increased as the crop progressed.

TABLE 3
Effect of minipan deficit on cane and sugar yields
in a cracking clay soil in the Burdekin

Minipan deficit mm	Cane Yield t/ha	Sugar yield t/ha
120	132.9	20.73
150	104.2	16.26

The use of class A pan evaporation for scheduling irrigation is a more indirect approach, involving the use of crop canopy factors to adjust the pan estimates of crop water use, to account for the gradual development of a full crop canopy. Kingston and Ham (1975) reported measured crop canopy factors for the Bundaberg and Burdekin districts. There is little Australian data on the optimum pan factor for cane after full canopy development. Robinson *et al*., (1963) in Hawaii, found that a management ratio of 0.85 for full canopied cane gave optimum sugar yields. Similarly, Gosnell (1970) showed that sucrose yields in Rhodesia were maximised at management ratios of 0.84 and 1.0 in trashed and burnt cane. However, water use efficiency per unit of sugar production was maximised at management ratios of 0.68 and 0.84.

Ridge and Hillyard (2000) utilised pan factors of 0.64 and 0.8 to schedule irrigations in full allocation and unlimited water drip irrigation treatments in a trial at Bundaberg, conducted with 6 current varieties. For a March yield sampling in the plant crop, when available water had been fully used in the full allocation irrigation treatment, there was a yield response of 20 t/ha to an additional 1.7 Ml/ha of irrigation in the 0.8 pan treatment. While sugar content of cane was not measured at this stage, final CCS levels at harvest in these treatments were only marginally different. This suggests that the 0.8 pan factor can be justified in a dry year at Bundaberg. However, Kingston (Per. comm.) with older cane varieties and wetter seasonal conditions found no significant difference in cane yield between 0.85 and 0.5 pan factors over a plant crop and two ratoons.

In a similar trial at Mackay, Chapman and Chardon (1979) reported average yield responses to irrigation over 10 harvests of 7 and 9.5 t cane/ha in 0.5 and 0.9 pan treatments with a CCS depression of 0.08 unit in the 0.9 pan treatment. Again these trials were conducted in relatively wet years with older cane varieties having relatively low yield potential, and there was no significant yield difference between the two pan factors.

6.3 Measured water use efficiency versus irrigation amount

As discussed earlier, the two common measures of water use efficiency in the sugar industry are WUE and IWUE. WUE refers to tonnes of cane per Ml of irrigation plus effective rainfall (allowing for runoff and deep drainage). WUE is sometimes termed the Cane Water Index (CWI) to take into account the fact that no allowance is made for irrigation application efficiency. The term CWI will be used in following discussion. Irrigation water use efficiency (IWUE) refers to tonnes cane per Ml of irrigation water (again with no allowance for application efficiency). Both indices vary significantly with seasonal conditions, level of irrigation, soil type and between districts with different irrigation demand (as detailed in Table 1).
Kingston (1994) analysed a range of data from Australia and overseas to produce the relationship below between cane yield and crop evapo-transpiration under trial conditions:

$$\text{Cane Yield T/ha} = 12.21^{*} (\text{ET}/100) - 17.99 \text{ ------ Equation 1.}$$

When this equation is applied to the Bundaberg area the maximum expected cane yield for 1450mm evapo-transpiration over 12 months (0.85 pan) is 159 t/ha ± 21 t/ha. The maximum sugar yield of 17-21 T sugar/ha was predicted at 1270mm evapo-transpiration.

For commercial conditions this model was refined using a discounting factor of 0.7 to the form below:

$$\text{Cane Yield T/ha} = 8.55^{*} (\text{Effective rainfall} + \text{applied irrigation}) – 12.59 \text{ --- Equation 2.}$$

Trial and commercial yield data from different districts are analysed below, to illustrate some of the factors affecting the WUE (or CWI) indices discussed by Kingston, and the IWUE.

6.3.1 Bundaberg

The data of Kingston (1972) from an irrigation trial with the variety Nco310 on a krasnozem soil type is summarised in Table 4.

TABLE 4
Variation of WUE and IWUE with soil water potential at irrigation, and effective rainfall

Year	Crop class	Effective rain mm	IWUE t cane/Ml		CWI t cane/Ml		
			Irrig -98 kPa	Irrig -392 kPa	Dryland	Irrig -98 kPa	Irrig -392 kPa
1968	P	1179	0	0	10.9	8.4	10.1
1969	1R	504	10.8	15.7	7.4	10.6	12.7
1970	2R	832	7.0	10.5	11.6	10.9	12.5
1971	3R	1002	0	0	9.8	8.7	10.0
Mean		**879**	**4.4**	**6.6**	**9.9**	**9.6**	**11.3**

This data indicates that IWUE varies considerably from year to year, and tends to fall at high irrigation levels (-98 kPa). In dry years limited irrigation produces very high IWUE values. In contrast CWI is less variable under irrigated conditions, but again moderate irrigation gives a higher CWI than ‘unlimited irrigation’ as exemplified by the -98 kPa irrigation treatment. Similarly, CCS generally declined in the -98 kPa treatment.

Similar CWI efficiency figures were obtained by Ridge and Hewson (1995) for drip irrigation at moderate stress levels on a sandy gley podzolic soil. For plant and first ratoon cane, CWI was 12.5 and 13.5 t cane/Ml with effective rainfall of 650 and 500 mm, respectively.

Holden *et al.*, (1997) reported a relatively high IWUE at Bundaberg of 11.9 t/Ml from a single irrigation of 100mm applied in Autumn 1995, following dry conditions in late Summer. This response was achieved in small cane in a year with low effective rainfall.

Ridge and Hillyard (2000) showed the effect of varying water allocations on CWI and IWUE in 17 month old plant cane, with a relatively low effective rainfall of 880mm (Figure 4)

The IWUE declined from a very high level of 22.8 t cane/Ml at the nominal half allocation (2.4 Ml) for the Bundaberg district to 13.9 t cane/Ml with unlimited irrigation (8 Ml). The CWI increased with increasing irrigation up to the full nominal allocation of 4.8 Ml/ha for the Bundaberg district, and declined with unlimited irrigation. The average CWI of around 12.2 t cane/Ml for all irrigation treatments is similar to the figure quoted by Kingston (1994). In the following ratoon crop grown with an effective rainfall of 1050mm the response to irrigation was small, and IWUE declined from 3.6 to 1.1 t cane/Ml with increasing irrigation. Similarly, the CWI declined from 10.7 t cane/Ml for unirrigated cane to 8.4 t cane/Ml with full irrigation. In this case the CWI was dominated by the rainfall contribution to final yields.

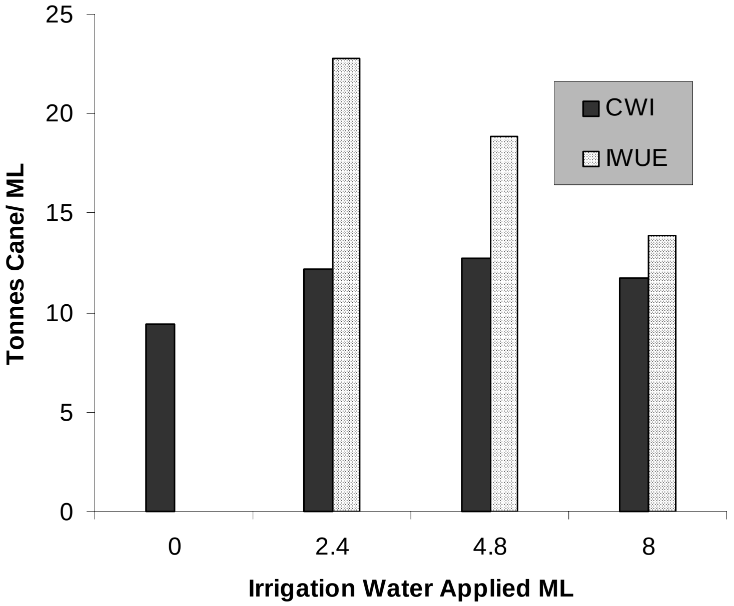


Fig. 4- Change in CWI and IWUE with irrigation application in plant cane (averaged for six cane varieties and drip and furrow irrigation).

This trial also illustrated that some varieties (eg. Q124 and Q170) continue to respond well to irrigation above the nominal full allocation for Bundaberg (Figure 5). This difference between varieties can become significant when comparing the response to irrigation between current and older varieties. Similarly, two varieties (Q138 and Q170) increased in CCS with increasing irrigation up to 8 Ml/ha, whereas most varieties peaked in CCS in the full allocation treatment (4.8 Ml/ha).

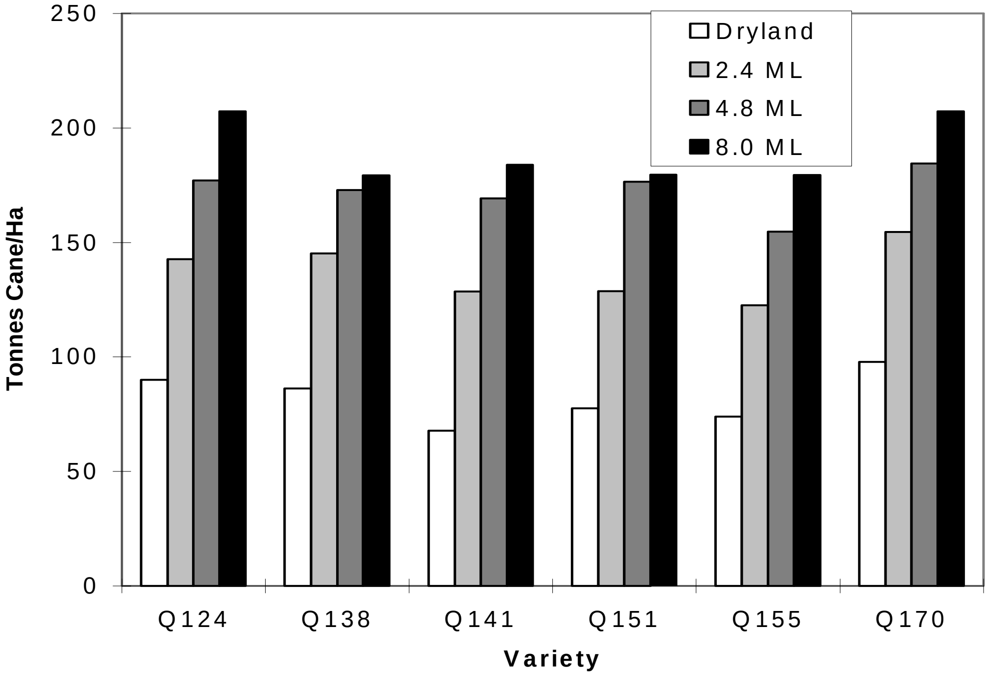
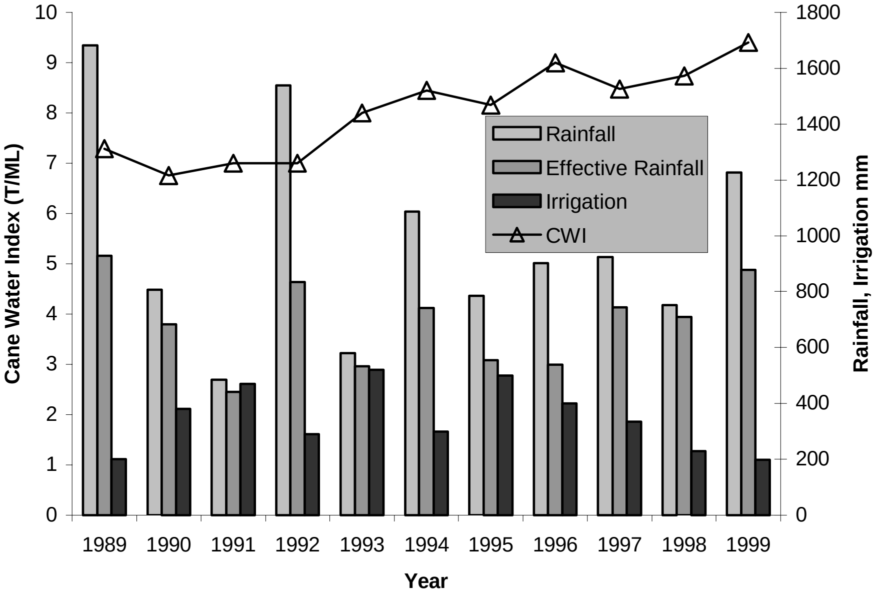


Fig 5- Varietal cane yield versus irrigation water application in the plant crop of an irrigation trial at Bundaberg.

Kingston (1994) showed that the relationship in Equation 2 above could be used to accurately predict both dryland and irrigated yields in the Maryborough district from effective rainfall and irrigation data. It was also used to provide relatively accurate estimates of irrigation usage in the Millaquin mill area at Bundaberg, from cane yield and effective rainfall data. This suggests that the relationship is relatively robust for the southern region of the industry.

The Bundaberg district CWI since 1989 has been estimated from recorded cane yield and irrigation use, and APSIM calculations of effective rainfall. This data is summarised in figure 6 taken from Ridge (2000). It shows that the CWI is relatively consistent on a district wide basis, and that it reflects the gradual improvement in the CWI with improved irrigation efficiency in the Bundaberg area.

Fig. 6- CWI, rainfall, effective rainfall and irrigation for the Bundaberg district from 1989 to 1999



6.3.2 Mackay

In the Mackay area, there are14 years of irrigation trial data comparing dryland production with irrigation, scheduled using Class A pan evaporation. This covers a relatively wet period from 1972 to 1978 (Chapman and Chardon, 1979), and a drier period from 1989 to 1995 (Chapman, 1997). Trial data has been used to calculate the CWI and IWUE over the 14 years (Table 5)

The Mackay trial results differ from Bundaberg, in that the CWI generally falls with irrigation, and high IWUE values do not necessarily correspond to years with low effective rainfall. In Mackay, the highest IWUE values appear to be due to opportunistic responses to small amounts of irrigation in years with relatively high effective rainfall. This is most evident for the most recent trial series as illustrated in Figure 7. Earlier trials at Mackay, reported by Kingston and Chapman (1975), showed average IWUE values for one irrigation in September (66.8 mm), and two irrigations in September and November (totalling 133.8 mm) of 24.1 and 19.3 t cane/Ml, respectively. The high IWUE values were attributed to better establishment of the ratoon crop prior to the wet season. In both of the latter trial series there was no significant effect of irrigation on CCS at harvest.

TABLE 5
CWI and IWUE in irrigation trials conducted over a 14 year period in the Mackay area

Year	ER dryland mm	ER irrig. mm	Irrigation mm	IWUE T cane/Ml	CWI t cane/Ml	
					dryland	irrigated
Q96, NCo310						
1972	877	839	170	0	8.3	7.3
1973	698	643	468	7.4	11.2	10
1974	1014	957	85	0	9.5	9.4
1975	997	930	85	0	6.6	6.7
1976	1017	979	85	3	7.9	8
1977	965	855	276	1.8	10.1	8.8
1978	924	898	383	3.9	9.1	7.6
Mean	***927***	***872***	***222***	***2.3***	***9.0***	***8.3***
Q124, Q138						
1989	1171	1106	114	13.6	10	10.9
1990	723	542	687	4.4	11.8	9.4
1991	706	655	529	2.4	10.7	7.4
1992	732	565	590	7.5	13.6	12.5
1993	792	620	438	6.4	13.5	12.7
1994	962	827	207	8.1	13.1	13.8
1995	859	780	369	7.9	10	10
Mean	***849***	***728***	***419***	***7.2***	***11.8***	***11.0***

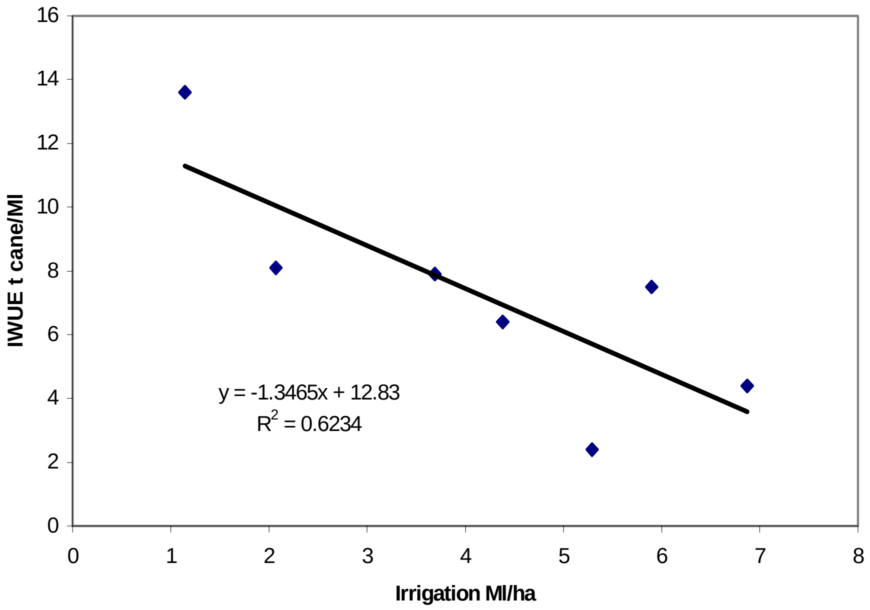
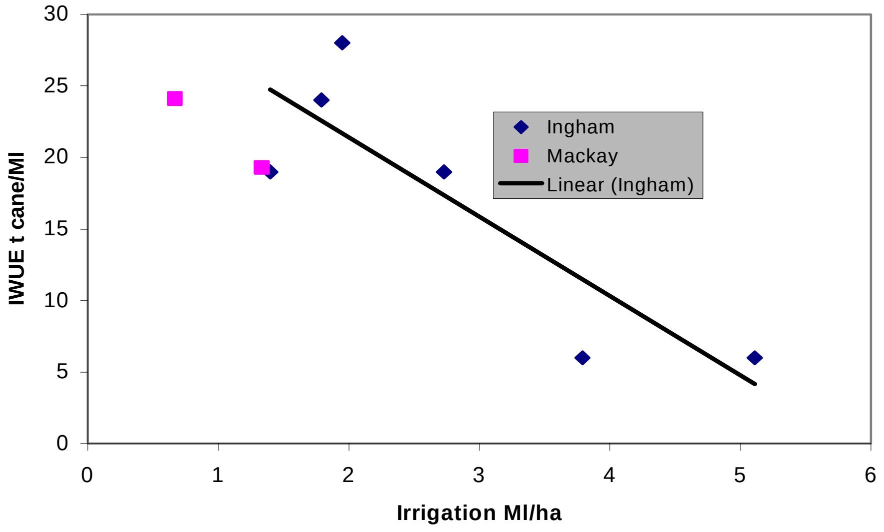


Fig. 7- Relationship between IWUE and the amount of irrigation for the 1989-1995 trial series at Mackay.

6.3.3 Ingham

Trial results from the Ingham area show a similar pattern to those for the Mackay area. Bamber *et al* (1999) reported average IWUE values for irrigated treatments of 6 and 24 t cane/Ml for plant and ratoon crops, respectively. In the plant crop an IWUE of 19 t cane/Ml was evident at 7 months of age with limited irrigation, but this declined at harvest, with further irrigation and the presence of a shallow watertable. In both plant and ratoon cane CCS was depressed in irrigated treatments at harvest in August. The similarity of the responses to limited irrigation at Mackay and Ingham is illustrated in Figure 8.



6.3.4 Proserpine

There is limited irrigation trial data available for the Proserpine district and this was summarised by Hardie *et al*., (2000). In trials harvested in the 1998 and 1999 seasons the IWUE ranged from 2.2 to 7.7 t cane/Ml, with the higher IWUE values corresponding to higher water applications in the dry 1998 season. CCS was depressed in irrigated treatments.

6.4 Use of crop growth models for developing irrigation strategies

The value of irrigation trial data in assessing irrigation strategies is limited by the difficulty in accounting for long term variability in climatic conditions, the effect of soil type on yield responses, and practical limitations to the number of strategies that can be tested. The use of crop production models allows assessment of a range of irrigation strategies and soil types using long-term weather records for each district.

6.4.1 Model validation

The success of crop production models depends on their ability to accurately predict cane yields for the range of climatic conditions, soil types and irrigation strategies appropriate for each district. Trial results in each district provide a valuable means of validating model performance. However, as Kingston (1994) indicated, trial results may have to be discounted when simulating district yield trends.

6.4.1.1 APSIM

The crop production model APSIM has been widely used in the sugar industry for predicting long term responses to irrigation, with representative irrigation scheduling strategies.

Much of the validation work for APSIM in sugarcane is summarised by Keating *et al.*, (1999). The data reported shows relatively good agreement between actual and simulated yields for a range of environments and soil types, and for both irrigated and dryland conditions.

Bamber *et al.*, (1999) also presented comparative trial measurements and APSIM predictions of IWUE for trials located at Ingham and Mackay. In both cases there was relatively close agreement between measured and predicted IWUE values. As indicated in the discussion of their paper there are several estimated variables used in simulations that may cause small deviations from field results. These include vapor pressure deficit, leaf area index, fraction of biomass apportioned to stalks and dry matter content of stalks. Yield accumulation may also be curtailed when crop lodging occurs (Muchow *et al.*, (1995).

Further validation was carried out for the data of Ridge and Hillyard (2000), showing good prediction of both plant and ratoon yields with a range of irrigation regimes. In these simulations allowance for loss of effective leaf area following lodging improved the accuracy of results (Lisson, pers.comm.).

Hardie *et al.*, (2000) showed relatively good agreement between predicted and actual cane yields for two harvests of an irrigation trial at Proserpine.

In comparisons of district average cane yields at Bundaberg over an 11year period with yield predicted using APSIM (Ridge, 2000), an R^2 value of only 0.36 was obtained. These simulations were carried out using an average district soil type, average district irrigation applications and effective rainfall derived from representative rainfall records. The main reasons for the relatively poor correlation appeared to be over prediction of yields in relatively wet years, and underestimation of cane yields in very dry years.

In this case the regression model below was used to predict commercial yields:

Cane yield = 0.1 * (Eff. rainfall + irrig.) + 0.0249 * solar radiation – 87.2 - - Eq. 3
Where effective rainfall and irrigation in mm was from July1 to June 30
Solar radiation was from December 1 to April 30

The regression model gave an R^2 value of 0.69. Comparative predicted yields with varying levels of irrigation over the period 1958 to 1999 are shown in Table 6.

TABLE 6
Predicted cane yield, CWI and IWUE for the Bundaberg district using APSIM and a regression model over the period 1958 to 1999

Gross irrigation Ml/ha	Average cane yield t/ha	CWI t cane/Ml	IWUE t cane/Ml
Regression			
2	82.9	8.9	7.6
4	94.0	9.0	6.6
6	105.5	9.1	6.3
7	108.5	9.2	5.8
APSIM			
2	78.9	8.5	8.5
4	99.6	9.6	9.6
6	118.2	10.2	10.2
7	123.0	10.4	10.4

6.4.1.2 Other models

The simplified model proposed by Kingston (1994), relating cane yield to effective rainfall plus irrigation, was shown to adequate for predicting historical district average yields. It was also used successfully by Willcox *et al*., (1997), in combination with a water balance model, to predict dryland yield, and the response to varying levels of irrigation in the Bundaberg district. It was also used to evaluate responses to different irrigation systems on contrasting soil types. The main problem with this model, and the simple model of Ridge (2000), discussed above, is that the response to irrigation plus effective rainfall is assumed to be linear under all conditions. There is no adjustment allowed for varying stress levels prior to irrigation, or higher incremental yield responses to irrigation under favourable climatic conditions as noted by Chapman and Nicholson (1972), Bamber *et al*., (1999), and Ridge and Hillyard (2000). The APSIM model has therefore been used in assessment of strategies for irrigation, as discussed below.

6.4.2 Use of the APSIM model for assessing irrigation strategies in different districts

There have been a number of studies of irrigation requirements in different districts, and of strategies for irrigation to optimise the yield return from available irrigation water, using APSIM. In more recent studies emphasis has been placed on predicted yield responses to ‘spending’ and ‘saving’ strategies. ‘Spending’ refers to irrigating at moderate stress levels on demand, until available water has been exhausted. In this case limited water resources are generally used up early in crop growth. ‘Saving’ refers to limited irrigation early to establish the crop, and subsequent irrigation at relatively high stress levels until water reserves are fully used. With this strategy limited resources will be used later in the growing season, and moderate resources may not be fully utilised. Appropriate stress levels prior to irrigation are selected, bearing in mind the earlier discussion of the effects of stress on cane growth. The use of APSIM is discussed below on a district by district basis, to account for the fact that different strategies may be required in each district. In most of the following studies irrigation application efficiency is assumed to be 100%. It is also assumed that irrigation should be applied where necessary to assure crop establishment. This is strongly supported by difficulties in ratoon establishment following harvesting in dry conditions, particularly on loose sandy soil types that may accentuate damage to ratoon stubble at harvest.

6.4.2.1 Bundaberg

Long term yields for a range of soils under dryland and irrigated conditions were predicted by Inman-Bamber *et al*., (2000), using a 'saving' strategy involving replacement of only part of the water deficit with each irrigation. Allocations of 2 and 4 Ml/ha were applied in 25mm amounts when the equivalent of 50% of PAWC had been depleted, provided 10 days had elapsed since the last irrigation. Irrigation continued until the allowed allocation had been depleted. Details of the soils, and predicted water use efficiencies are given in Table 7. In these simulations the depth of soil used to determine PAWC refers to maximum rooting depth, rather than the effective rooting depth determined by Zund and McDougall (2000).

TABLE 7
Mean effective rainfall per crop, rainfall efficiency, CWI and IWUE for a range of Bundaberg soils

Soil order	Depth m	PAWC mm	Rainfall		CWI t cane/Ml	IWUE t cane/Ml	
			Effect mm	Effic. %		2 Ml	4 Ml
Aeric Podosol	1.9	83	829	68	8.4	12.7	14.2
Yellow Chromosol	1.9	88	849	70	8.4	13.4	14.7
Black Vertisol	0.7	110	902	74	8.1	14.9	16.2
Yellow Dermosol	1.15	113	914	75	8.9	15.4	16.2
Red Ferrosol	1.0	142	949	77	8.9	15.9	16.5
Red Kandosol	1.6	150	952	77	9.3	14.6	15.6
Red Dermosol	1.6	153	942	76	9.1	14.4	15.5

Effective rainfall and CWI were found to increase with increasing PAWC of the soil type, whereas IWUE was highest in soils with a moderate PAWC. The predicted IWUE increased with increasing water allocation. There was considerable variation in year to year IWUE values within the one soil type. The relatively high IWUE suggests that this saving strategy should be effective for the Bundaberg district. However, the IWUE values are much higher than those expected from irrigation trials discussed earlier. This may in part be due to the high PAWC values used in this study.

A further evaluation of different irrigation strategies for the Bundaberg district was carried out as part of this project. Two contrasting soil types were used, the Aeric Podosol and a Red Dermosol, with the effective profile depth assumed to be 0.9m during the main irrigation season, and 0.6 m in the first month after harvest.

Simulations were carried out for 40 years from 1960 to 1999. Three different irrigation strategies were evaluated for 2.5 and 5 Ml of available irrigation water in continuous ratoon cane. Each ratoon crop extended from Sept 1 to August 31.

For the Red Dermosol, the first strategy was a spending strategy, where 25 mm of irrigation was applied when 50% of PAWC had been used from the 0-0.6m zone in the first month of ratoon growth; and 50 mm was then applied at a deficit of 50% in the 0- 0.9m zone, until all available water had been used. A drying off period of 2 months was allowed prior to harvest. The second strategy was a conservative saving strategy with watering in the first month at a deficit of 60% of PAWC, and thereafter at a deficit of 70%. A third strategy included more stringent saving during the main irrigation period, with watering at an 80% deficit. The minimum time between irrigations was 10 days.

Similar strategies were used for the Aeric Podosol, but irrigation applications were adjusted to match predicted deficits prior to irrigation. For the spending strategy 20 mm of irrigation were applied each time for the first month after harvest, and 35mm for the remainder of the season. In the saving strategies 20mm per irrigation was used initially, 30mm until the end of December, then 35mm for the remainder of the season. The minimum time between irrigations was 8 days. The results of simulations are summarised in Table 8. The strategies considered to be most appropriate for each soil type and water allocation are highlighted in the table.

TABLE 8
Mean effective rainfall, CWI, IWUE, Cane yield, and irrigation amount for selected spending and saving irrigation schedules in Red Dermosol and Aeric Podosol soil types.

Schedule	Rainfall		CWI	IWUE	Yield	Irrigation
	Eff mm	Effic %			t cane/ha	Ml
Red Dermosol						
Spend 2.5 Ml	798	73	9.4	11.0	99.4	2.5
5.0 Ml	764	70	10.7	12.8	133.6	4.8
Save 1 2.5 Ml	813	74	9.6	12.5	102.5	2.5
5.0 Ml	799	73	**10.6**	**13.7**	**127.7**	**4.0**
Save 2 2.5 Ml	814	74	**9.6**	**12.6**	**102.4**	**2.4**
5.0 Ml	808	74	10.4	13.8	119.4	3.4
Dryland yield (t cane/ha) 71.9						
Aeric Podosol						
Spend 2.5 Ml	691	63	8.5	8.5	81.2	2.5
5.0 Ml	634	58	**10.0**	**10.8**	**113.1**	**4.9**
Save 1 2.5 Ml	716	66	8.9	10.8	86.5	2.5
5.0 Ml	699	64	9.7	11.9	104.2	3.7
Save 2 2.5 Ml	721	66	**8.9**	**11.2**	**86.4**	**2.4**
5.0 Ml	711	65	9.4	11.7	95.1	3.7
Dryland yield (t cane/ha) 59.9						

It is evident from Table 8 that the predicted performance of the two soil types is distinctly different. The Aeric Podosol, with a PAWC in the 0-0.9m zone of approximately 42 mm, has performed poorly in terms of water use efficiency in relation to the Red Dermosol, with a PAWC of 90mm.

For the Red Dermosol the most appropriate irrigation with adequate water supplies (5 Ml) appears to be a moderate saving schedule, with a deficit of 70% of PAWC at irrigation during the main growing period. This is similar to the figure derived from the work of Kingston (1972). This strategy gives a significant saving in irrigation water, and a high IWUE, without a significant yield sacrifice in relation to the spending strategy, where irrigation was scheduled at a deficit of 50% of PAWC. The work of Kingston (1972) and Ridge and Hillyard (2000) indicates that the moderate saving strategy is likely to optimise cane sugar levels for most varieties.

With limited irrigation (2.5 Ml), both moderate and severe saving (80% use of PAWC prior to irrigation) strategies gave similar predicted responses, and the severe saving strategy would be favoured for the common restricted availability of water in the Bundaberg district of 2-2.5 Ml.

In the Aeric Podosol the spending strategy appears most appropriate if adequate water is available, as the yield loss in the two saving strategies is more substantial. Despite the higher predicted water use in the spending strategy, and the lower IWUE, the overall CWI is higher, and the marginal return in cane yield should justify additional irrigation costs. As for the Red Dermosol, the two saving strategies appear superior with limited water, and the severe saving strategy would be recommended with limited water. It is critical on this soil type that irrigations be sized appropriately to replace the expected water deficit without any wastage as deep drainage.

It is considered that schedules based on the above selected strategies would be satisfactory for soils with moderate to high RAW (Red Dermosol), and low RAW (Aeric Podosol). In all cases cane should be irrigated early with appropriate individual applications (20-25mm) to ensure crop establishment.

Hardie *et al*., (2000) carried out similar simulations for three representative soil types in the Bundaberg area, a Yellow Dermosol, an Aeric Podosol, and a generic silt soil used in estimating commercial CWI values for the Bundaberg district (Ridge, 2000). In these studies a minimum irrigation cycle time of 15 days was assumed. Saving strategies included a severe strategy similar to that discussed above, and a modified version of the moderate saving strategy discussed above. This included initial irrigation to establish the crop, watering at a deficit of 80% to mid-December, and then at a deficit of 50% of PAWC, as in the spending strategy discussed above. These are commonly suggested strategies for the Bundaberg region. The saving strategies were compared with a runout strategy, with watering when 65% of PAWC to a depth of 600mm had been used.

The results of Hardie *et al*., (2000) are similar to those discussed above. With a nominal full allocation of 3.5 Ml/ha the runout strategy gave the highest yields and IWUE values. For a restricted allocation of 1.75 Ml/ha, the severe saving strategy gave the highest cane yields and IWUE values.

6.4.2.2 Childers

Hardie *et al*., (2000) repeated these simulations for the Childers area, again for three representative soil types, an Isis Red Dermosol, a Yellow Dermosol and a Red Ferrosol and a 14 day irrigation cycle. Similar irrigation strategies were evaluated with the exception of the 'moderate' stress treatment. This included irrigation at a deficit of 35% of PAWC in the 0-0.6m zone in a crop establishment period extending to mid-October, no irrigation until the main irrigation season commenced in mid-January, then irrigation at a 50% deficit in the 0-0.9m zone. With the expected full allocation of 4Ml/ha, similar yields were obtained in the runout and moderate saving strategies, but the latter produced significantly higher water use efficiency.

With a limited allocation of 2 Ml, the moderate stress treatment gave marginally higher cane yields, and significantly higher water use efficiency.

These results suggest that irrigation at relatively low stress levels to establish the crop, then saving water to the peak growing period in mid-January, and irrigating to maintain crop growth rates, is a suitable strategy for either restricted or full allocations in the Childers area. In this case a drying off period of 100 days was used, and this would be expected to minimise depression of CCS by low water stress levels late in the main irrigation period.

6.4.2.3 Mackay

The Mackay area has an extremely variable rainfall, with annual rainfall varying from 604 mm to 3359mm in recorded weather data. As a consequence, irrigation responses are extremely variable, as described in trial results discussed earlier. Predicted average dryland yield is 84 t/ha (Hardie *et al*., 2000).

Several APSIM simulation studies have been carried out for the Mackay area. Robertson *et al*., (1997) compared a saving strategy (50mm applied when the soil moisture deficit reached 130mm), with a spending strategy (50mm applied at a depletion of 80mm). In both cases irrigation was applied at ratooning if the deficit in the 0-0.2m zone was greater than 50%. The water conserving strategy was found to give marginally higher yields with 2 and 4 Ml allocations, and significant water savings with the 4 Ml allocation. Effective rainfall was in the range 52-58%, and this presents one of the problems in assessing irrigation responses in the Mackay area, as there is potential for severe waterlogging during the main growing season.

Hardie *et al*., (2000) carried out further simulations for the Mackay area, with an attempt being made to simulate actual district practice. The major soil types, a silt, clay, and heavy clay, with PAWC values of 84 to 126 mm to a depth of 0.9m, were used for the simulations. The minimum cycle between irrigations was set at 20 days to correspond to system capacity on most farms, and the drying off period was set at 110 days to commence in early May. Again a runout strategy was compared with two saving strategies similar to those used for the Bundaberg study. Initial irrigations for crop establishment were 30mm, followed by 60mm irrigations for the remainder of crop growth.

For Mackay, an allocation of 3 Ml /ha appeared sufficient for the long cycle times achieved with limited investment in irrigation equipment. With a limited water allocation of 1.5 Ml, the three irrigation strategies gave similar cane yields and IWUE. The IWUE was significantly lower with an allocation of 3 Ml, and the severe saving strategy gave the highest cane yield and IWUE.

The study also indicated that additional allocation could be utilised if irrigation system capacity was expanded to shorten the cycle time, but this would need to be justified by improved economic returns (see later). With limited water availability, the current practice of irrigating to ensure crop establishment, followed by moderate irrigations at a relatively high water deficit of 80%, appears the most practical. This is supported by trial results for the Mackay area.

6.4.2.4 Proserpine

For the Proserpine area Hardie *et al*., (2000) carried out an initial assessment of predicted responses to irrigation, using a deficit of 35% of PAWC to a depth of 0.6m to schedule irrigations. Irrigation cycle time was a minimum of 10 days, and the drying off period was 50 days. Four soil types, ranging from sand with a PAWC of 63mm to clay with a PAWC of 126mm, were included in the simulations. The sand was found to have the lowest predicted effective rainfall and CWI values for allocations ranging from 2 to 8 Ml. The CWI values were found to be higher for periods of El Nino weather patterns than for average or La Nina weather patterns. The marginal response to irrigation was found to decrease with increasing water allocations. The current allocation for Proserpine is around 4 Ml.

A further study of selected irrigation strategies similar to those discussed for other districts was carried out with three representative soil types, varying in PAWC from 90 to 126 mm to a depth of 0.9m. An irrigation cycle time of 14 days, and a drying off period of 60 days were used for all strategies. The standard runout treatment with irrigation at a deficit of 65% in the top 0.6m was compared with two saving strategies similar to those used previously. Both were moderate saving strategies with firstly application of 30mm of irrigation at a deficit of 65% of PAWC to a depth of 300mm for crop establishment, then 80 mm irrigations with varying strategies for the remainder of crop growth. The first saving strategy was irrigated at a deficit of 65% in the 0-0.9m zone for the remainder of the season, and the second at a deficit of 85% to late December, then 65% for the remainder of the season.

With a 2 Ml allocation there was no apparent difference between the runout strategy and the second saving strategy in cane yield or IWUE. For a full allocation of 4 Ml these strategies were again similar, and superior to the first saving strategy. The predicted IWUE increased with increasing water allocation and it was considered that the drier areas of Proserpine would obtain economic irrigation responses from allocations as high as 6 Ml.

6.4.2.5 Burdekin

The Burdekin area is considered to be a full irrigation area (Table 1), due to low effective rainfall (450mm) and high crop water demand (1520mm). Robertson *et al*., (1997) showed a relatively high average vapour pressure deficit for the Burdekin region, and predicted a moderate CWI of 12.7 relative to other districts with a lower vapor pressure deficit. From earlier discussion it appears that irrigations scheduled when stalk elongation rates are 50% of maximum values are most appropriate for this district. The data available for effective rooting depths and RAW as a percentage of PAWC (Table 9) indicates that there is extreme variability between and within soil types in the Burdekin. This means that the current recommended practice of using minipans calibrated against stalk growth for irrigation scheduling on individual farms, is likely to be most effective. The main gains in irrigation efficiency in the Burdekin area are likely to be through improved water application efficiency (Holden *et al*., 1997).

TABLE 9
Typical range in effective rooting depth, RAW and PAWC for several Burdekin soils

Soil group	RAW:PAWC	Rootzone m	RAW mm
Cracking clays	0.42-0.6	0.8-1.0	60-96
Non-sodic duplex	0.38-0.56	1.0-1.2	48-72
Sodic duplex	0.37-0.54	0.45-0.6	34-55

6.4.2.6 Ingham

Responses to limited irrigation in the Ingham area were evaluated by Bamber *et al*., (1999) using simulated drip irrigation and taking into account the influence of shallow watertables on irrigation response. Sub-surface drip irrigation was simulated by removing the evaporation component associated with a wet soil surface. The watertable effect was simulated by assuming soil saturation following heavy rainfall events, and supplying crop water demand from the watertable for the next 6 weeks, corresponding to the period of high watertable levels. Irrigations of 50mm were scheduled at deficits of 50 and 80% of PAWC to simulate spending and saving strategies. The simulation results are summarised in Table 10.

A simulated watertable was shown to have a minor effect on irrigation responses, and relatively high IWUE values were predicted in a significant percentage of years, particularly with the highest allocation of 2 Ml. For the conditions prevailing at the Ingham trial site for which the simulations were carried out, a saving strategy with at least 2 ML of irrigation would provide rewarding yield responses (>10 t/ha) in 93 % of years. The saving strategy gave superior predicted cane yields to the spending strategy, and it is likely that it would be superior for using limited water in the Ingham area.

TABLE 10
Simulated probabilities (%) of achieving different levels of IWUE with different irrigation strategies and water allocations, with or without simulated watertable (WT)

IWUE class		0 to 10 t/Ml		10 to 20 t/Ml		>20 t/Ml	
Strategy	Alloc Ml	No WT	WT	No WT	WT	No WT	WT
Saving	0.5	51	46	27	27	22	27
	1	29	22	44	51	27	27
	2	7	7	54	51	39	41
Spending	0.5	54	51	27	24	20	24
	1	32	29	41	44	27	27
	2	12	20	61	46	27	34

6.4.2.7 Atherton

Simulation of cane yield response to irrigation in the Atherton area over a 100 year period was carried out by Bamber e*t al*., (1999) for deep red earth and krasnozem soil types with PAWC values of 162 and 290 mm, respectively. Irrigation was scheduled at deficits of 30%, 50% and 80% of PAWC, with allocations of 0,1,2,3 and 4 ML/ha. The minimum irrigation interval was 10 days. With the saving strategy an allocation of 3 Ml was fully utilised in only 78 and 54% of years, respectively, in the red earth and krasnozem soils. Predicted yield responses to irrigation are summarised in Table 11.

TABLE 11
Predicted cane yield response from irrigation (t/ha) by irrigation strategy, soil type and allocation

Soil	Strategy	Allocation Ml/ha			
		1	2	3	4
Red earth	Liberal	17	29	41	53
	Spend	18	32	46	58
	Save	19	35	48	58
Krasnozem	Liberal	10	21	31	39
	Spend	12	24	34	42
	Save	14	25	33	38

The predicted yield response is similar for spending and saving strategies, but IWUE values are generally higher for the saving strategy due to lower predicted irrigation usage. IWUE declines with increasing allocation in both soil types. The predicted irrigation responses are higher for the red earth than the krasnozem, reflecting the difference in PAWC between the two soils.

6.4.2.8 Mareeba

The Mareeba area has an available allocation of 8 Ml, an effective rainfall of 573mm, and an estimated dryland yield of 29 t/ha (Hardie *et al*., (2000). It is therefore closer to the Burdekin in irrigation demand than to other districts.

Further simulations of yield responses to irrigation were carried out by Hardie *et al.*, (2000) for the Mareeba area. Again a range of irrigation strategies were compared for two standard soil types, a silt and clay, with PAWC values of 90 and 126 mm, respectively, to a depth of 0.9m. The minimum irrigation interval was 10 days and the drying off period 56 days. The standard runout strategy was compared with two alternative strategies. In the first strategy, 30mm of irrigation was applied at a deficit of 65% in the surface 0.6m of soil after planting in May, and irrigation in 50mm increments was recommenced at a deficit of 50% of PAWC in the surface 0.6m after Nov 1. In the second strategy the first irrigation was 40mm, but irrigation was continued from May 22 to December 15, with 50mm applied at a deficit of 90% in the 0-0.9m layer, before changing to a deficit of 65% in the surface 0.6m.

The runout strategy performed best in this situation in terms of predicted yields and IWUE, and it is recommended that growers irrigate at a moderate deficit of 65% until water is fully used.

6.5 Economics of irrigation

While assessment of the economics of different strategies for scheduling irrigation was not included in the objectives of this project, economic returns from irrigation determine the level of investment possible in establishing infrastructure for irrigation, and this may limit the options for irrigation management.

Ferguson and Hampson (1975) stated that a number of factors should be considered in deciding irrigation strategies, including CCS and yield response to irrigation, facilitation of on farm operations such as fertilising and weed control and establishment of plant and ratoon crops. They concluded that a more economic response is likely to be obtained by spreading irrigation over the farm, rather than concentrating on part of the farm.

Brennan *et al.*, (1999) carried out a detailed economic evaluation of a range of strategies for utilising available irrigation resources. In the Bundaberg district, with water application costs of $100/Ml, the gross margin predicted with 8Ml/ha of water was estimated to be twice that with 2 Ml/ha. The highest gross margin with 2 Ml/ha was obtained by applying this water across all ratoons in a simulated whole farm situation. Smith *et al.*, (2000) used the data from the trial conducted by Ridge and Hillyard (2000) to assess the economics of yield responses to different levels of available irrigation in a dry year. They found that the gross margin from irrigation increased with increasing irrigation up to 8 Ml/ha, despite the declining marginal yield response.

Again for the Bundaberg district, Willcox *et al.*, (1997) compared economic returns from different levels of irrigation for a range of irrigation systems. They found that increasing the quantity of irrigation water from 50% (2.7 Ml) to 100% (5.4 Ml) of allocation increased benefit:cost (B:C) ratios markedly, with returns being positive but marginal at 50% allocation. For greenfield development, furrow irrigation with tailwater return was superior to other irrigation methods on soils with high water holding capacity, while drip was superior on soils with low to medium water holding capacity, despite the higher capital cost for drip irrigation. These findings are in accordance with field experience of yield responses to drip irrigation (Haines, 1999). The B:C ratio increased with increasing soil water holding capacity due to higher predicted cane yields for a given level of water allocation.

The above results highlight the difficulty in obtaining economic returns from supplementary irrigation. In the Bundaberg district economic returns can obviously be achieved if the full nominal allocation is available for irrigation.

In higher rainfall districts such as Mackay investment in irrigation infrastructure has been limited by the marginal returns from irrigation (Hardie *et al*., 2000). The economics of irrigation in the Mackay district was first assessed by Chapman and Chardon (1979), using trial results obtained during a relatively wet period. They concluded that irrigation could not be justified from trial responses. Re-assessment of the viability of irrigation was carried out by Inman-Bamber *et al*., (1999), using APSIM to give long-term yield projections. These yield projections were higher than those used by Chapman and Chardon (1979), and were in approximate agreement with more recent trial results. Comparisons were carried out between water winch, centre pivot and drip irrigation using assumed water application efficiencies of 75, 85 and 90%, respectively. Responses to irrigation were assessed using discounted cash flow (DCF) analyses over a twenty year period, taking into account capital costs for the respective irrigation systems. The DCF analyses indicated that profitability varied with irrigation application efficiency, soil type and available irrigation water due to the effect of these factors on predicted yield responses. In general irrigation was considered uneconomic with a water allocation of 1 Ml, and with 3 Ml allocation was only economic for centre pivot and drip irrigation.

A similar study of economic returns from water winch irrigation in the Atherton area on a red earth soil showed that the optimum saving strategy for irrigation (irrigation at a deficit of 80% of PAWC) was marginal with 1.3 Ml of available water, but profitable with a 4 Ml allocation. Irrigation was not economic on a krasnozem soil with a very high PAWC.

Singels *et al*., (1999) used a combined yield simulation and economic model to assess the net economic income from different irrigation strategies, for two soil types in two irrigation districts in South Africa. The strategies included applying 25mm of irrigation at deficits of 30, 50 and 70% of PAWC, with long term or daily evaporation figures used for irrigation scheduling. An additional treatment used weather forecasts to delay irrigation where more than 10mm of rainfall was expected. It was found that watering at a deficit of 50% of PAWC gave the highest economic returns with no benefit from using daily evapotranspiration data or weather forecasts. The schedule with a 70% deficit in PAWC gave the highest IWUE, but lower economic returns. This is in contrast to predictions for most irrigated districts in Queensland where the 70% deficit would be expected to give optimum returns. This may be explained by the data cited by Inman-Bamber *et al*., (1998) which indicates an average ratio of RAW:PAWC of 0.54 for South African soils, compared to 0.65-0.75 measured by Zund and McDougall (1997) for a range of Queensland soils.

7 CONCLUSIONS

The main objectives of the project have been addressed through a comprehensive review of relevant literature on sugarcane response to soil moisture stress at different stages of growth, and the use of supplementary APSIM simulations to address gaps in the literature. Recommendations have been developed for irrigation strategies in most districts to utilise expected irrigation resources. The recommendations have been expressed in a form suitable for use by irrigation extension officers, on a district by district basis.

8 APPLICATION OF RESULTS TO INDUSTRY

The results of the project have potential value to the sugar industry in relation to the following issues:

- Water use efficiency- the final recommendations for each district indicate that saving strategies with relatively high overall water use efficiency and irrigation water use efficiency are generally most appropriate for optimum sugar yields.
- Whole farm systems/ economics- an analysis of economic returns from irrigation in several districts supports the general philosophy of using water saving strategies in irrigation scheduling, and the need for adequate irrigation allocations to cover the cost of irrigation infrastructure.
- Sustainability- the project supports the concept of sustainability of irrigation resources through conservative water use, but also the need for economic sustainability through provision of appropriate irrigation allocations for each district.
- Model development and use- the crop growth model APSIM has been used extensively in this project, and its’ flexibility in assessing cane yield responses to different irrigation strategies has been demonstrated. The results of modelling various ‘best bet’ strategies for efficient water use in each district have been related to existing knowledge of water stress effects on crop growth in several districts.
- Links to adoption programs- the project has potential links to adoption programs through providing guidelines for irrigation scheduling at different stages of crop growth, and with different water allocations. These could be readily used in conjunction with different irrigation scheduling tools.
- Training programs- the project recommendations should be suitable for training programs regarding timing of irrigation, and adjusting irrigation strategies where appropriate for different levels of available water.

9 INTELLECTUAL PROPERTY

There is considered to be no intellectual property arising from this project.

10 RECOMMENDATIONS FOR FURTHER RESEARCH

There is a limited suite of soils for which the relationship between RAW and PAWC has been defined for guiding crop modelling studies, and further work is required to define a representative range of soils in all districts. Some unpublished data was not accessible for this study. The ratio of RAW:PAWC appears to be a fairly robust indicator of the most suitable stress levels for model studies to optimise irrigation scheduling.

There is also a need to further develop APSIM to take account of yield limiting factors such as lodging and waterlogging, so that district yields can be represented more closely in long term simulations.

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