Best Practice Irrigation in Sugarcane Production Short Course

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Course Manual

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FOREWORD

Agriculture is under challenge. The globalisation of markets requires ever-greater efficiencies to maintain profitability in the face of intensifying competition. At the same time, there are increasing demands for practices that maintain the productive capacity of the natural resource base and cause minimal harm to the wider environment. The pressures are particularly acute with irrigated agriculture. Competition among users for water has increased, as have concerns about the downstream effects on water quality and on the amounts of water available for environmental flows.

These challenges are increasingly apparent in irrigated sugar production. On the one hand, the sugar industry sells into highly competitive export markets to dispose of about 85% of its production. Moreover, in recent times, the industry has become more reliant on irrigation to improve and importantly to stabilise production in several regions. On the other hand, water is becoming increasingly expensive, as governments use market and regulatory approaches to ration an increasingly scarce resource among competing needs. In addition, with sugar production often located adjacent to environmentally sensitive coastal wetlands, reef and rainforests, there is also pressure to minimise off-farm run-off of nutrients, sediments and agricultural chemicals.

Whether irrigation water is drawn from surface or underground sources, and whether the water is used only to supplement rainfall, or to provide most of the crop’s water needs, the broad direction is the same. Water users are being required to use less water, to make optimum use of the water that they do use, and to minimise any adverse effects of their enterprise on downstream water quality. The purpose of this course is to help water users in the sugar industry to manage these challenges as effectively as they can, based on up-to-date scientific knowledge. It is part of CRC Sugar’s education program to better equip the sugar industry with the technical knowledge needed to underpin profitable and environmentally acceptable practices.

The course provides an overview of current understanding of water management practices. It focusses on the key principles underlying the design and management of irrigation systems to maximise water use efficiency and optimise profitable use of water, depending on variables like the amount available, crop demand, soil type etc. It also addresses strategies for minimising run-off of nutrients and pesticides, water re-cycling and re-use of effluents.

The primary targets of the course are the technical people who provide advice to those actively involved in the irrigation industry. These include BSES and other sugar industry extension staff, agricultural consultants, agribusiness advisors, and local government and community advisors. In designing the course, the presenters have assumed that participants have a basic technical understanding of crop agronomy, soils and the environmental sciences.

The course is a synthesis of knowledge from many sources – not just work conducted within CRC Sugar – and provides a synopsis of current scientific understanding of the principles and processes that need to be considered when developing better practices. In addition to CRC Sugar staff, the course draws on the understanding of leading specialists from the BSES, CSIRO, Qld Department of Natural Resources and Mines, and the Rural Water Use Efficiency Initiative.

The design and development of an advanced level short course is not a trivial task, and takes time and commitment. On behalf of CRC Sugar, I thank all of those involved in providing source information, the course advisory panel, the authors of the individual sections, the course presenters and in particular, the coordinators, Drs Robin Bruce and Keith Bristow. I trust you enjoy the course and find it stimulating and helpful.

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1. IRRIGATION IN THE WIDER CONTEXT
IRRIGATION WITHIN AN INTEGRATED WATER MANAGEMENT FRAMEWORK

KL Bristow

1. INTRODUCTION

Sugar production in Australia takes place on coastal plains and river valleys along 2100 km of the eastern seaboard from Grafton in northern New South Wales to Mossman in far north Queensland, and in the Ord River Irrigation area of north Western Australia. There are some 7000 farms ranging in size from 30-2000 ha, with the average farm size around 70 ha. The total land area assigned for sugarcane production exceeds 545,000 ha. Over 40% of the Queensland sugarcane crop is irrigated, which accounts for some 60% of total crop production (Holden et al. 1998). The Australian sugar industry produces roughly 4.4% of world production and is one of the world’s largest exporters with more than 80% of the sugar produced being exported. This equates to roughly 12% of world exports (ABARE 1998). Sugar is by any measure an important component of the Australian economy.

Like all other sectors of the Australian economy, the sugar industry is critically dependent on reliable supplies of good quality water. Rainfall, the ultimate source of water, is highly variable in both space and time across the industry, with amounts ranging from roughly 1000 mm yr⁻¹ in some districts (e.g. Bundaberg) to more than 4000 mm yr⁻¹ in others (e.g. Tully). This highlights the need for a range of management strategies across districts, with drainage of excess water being most important in some districts and implementation of effective irrigation management strategies being critical in other districts. Like climate, soils and social pressures also vary widely across the industry, further emphasising the need for different approaches and farm management practices in different regions. A major challenge for Government and the sugar industry is therefore to develop and implement policies and management practices that deliver both profitable and environmentally sound outcomes at the paddock, farm, region, and catchment scale.

2. WATER NEEDS AND SUPPLY

As indicated above, the sugar industry relies on access to good quality water, which in future will become scarcer as more water is made available for environmental flows and demands for water continue to increase from all other sectors of the economy. These demands will lead to increasing competition for water with other urban and industrial users willing to pay more and more for access to water. Current availability of water varies across the industry with the Wet Tropics and Northern New South Wales depending largely on rainfall, the Mackay and Bundaberg regions requiring supplementary irrigation, and the Burdekin, parts of the Atherton Tableland and Ord River districts being dependent on irrigation.

Sources of water for the sugarcane plant include water stored in the soil, that fraction of rainfall captured by the soil and subsequently available for plant uptake (effective rainfall), water provided by upward flow from shallow water tables and irrigation. Roughly 100 mm of water (equivalent to 1 megalitre per hectare) is needed to produce 5–15 t/ha sugarcane. Just how much irrigation water is needed varies from region to region as indicated in the reports by Holden et al. (1998), Kingston et al. (2000), Inman-Bamber et al. (2002) and no doubt others. The actual methods used to determine irrigation requirement and the numbers obtained vary somewhat between these authors, but the basic message remains the same, different regions need different amounts of irrigation (see for example Table 1).

Irrigation involves application of water to that part of the soil profile that serves as the rootzone, for the immediate and subsequent use by plants (Hillel 2000). Methods used to deliver irrigation water include furrow, overhead (e.g. water winches, centre pivot, lateral move) and trickle irrigation. The methods used vary from region to region with more than 99% of irrigators using furrow irrigation in the Burdekin, 75% using furrow on the Atherton Tablelands and some 30% using furrow in the Mackay/Proserpine/Sarina districts. Overhead (70-75%) and trickle (5%) are the preferred methods in
the Bundaberg/Isis districts (Tilley and Chapman 1999). In-field irrigation performance is usually assessed in terms of irrigation uniformity and application efficiency. The aim is to apply irrigation water with a high degree of uniformity while keeping wastage (losses) to a minimum. Uniformity is predominantly a function of the system design characteristics while losses are usually due to evaporation, deep drainage or surface runoff, and are predominantly a function of management. Typical application efficiencies are 35-75% for furrow, 60-90% for overhead, and 70-90% for trickle irrigated systems (Raine and Bakker 1996, Solomon 1993). While higher efficiencies are usually expected through use of overhead and trickle systems, these systems require higher quality management to achieve the higher efficiencies. Inappropriate management of even the most expensive high-tech system can still lead to highly inefficient performance.

Table 1. Variation in mean annual rainfall, effective rainfall and irrigation water requirements (mean annual rainfall was obtained from the SILO database (NR&M 2000) and the remaining data from Holden et al. 1998)

<table>
<thead>
<tr>
<th>District</th>
<th>Rainfall data details</th>
<th>Rainfall (mm)</th>
<th>“Effective rainfall” (mm)</th>
<th>Irrigation requirement (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ord</td>
<td>Silo: Kununurra 2038</td>
<td>814</td>
<td>550</td>
<td>1410</td>
</tr>
<tr>
<td></td>
<td>[1957 - 2001]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mareeba/Dimbulah</td>
<td>Silo: Mareeba 31066</td>
<td>919</td>
<td>405</td>
<td>1145</td>
</tr>
<tr>
<td></td>
<td>[1952 - 2001]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Herbert</td>
<td>Silo: Macknade 32032</td>
<td>2127</td>
<td>1100</td>
<td>250</td>
</tr>
<tr>
<td></td>
<td>[1892 - 2000]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Burdekin</td>
<td>Silo: Kalamia 33035</td>
<td>1058</td>
<td>450</td>
<td>1070</td>
</tr>
<tr>
<td></td>
<td>[1913 - 2000]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mackay/Proserpine/Sarina</td>
<td>Silo: Mackay 33045</td>
<td>1726</td>
<td>630</td>
<td>860</td>
</tr>
<tr>
<td></td>
<td>[1913 - 2000]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bundaberg/Maryborough</td>
<td>Silo: Fairymead 39037</td>
<td>1084</td>
<td>580</td>
<td>780</td>
</tr>
<tr>
<td></td>
<td>[1910 – 2000]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Northern NSW</td>
<td>Silo: Harwood 58027</td>
<td>1309</td>
<td>1000</td>
<td>200</td>
</tr>
<tr>
<td></td>
<td>[1915 - 2001]</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Although the paddock (or field) and farm are often considered the main management units and water the main ingredient in irrigation, recognition is now being given to the fact that irrigated systems are not that simple. The paddocks and farms, and the regions and catchments within which they are located, are connected in many different and complex ways and this improved understanding is requiring new ways of thinking about irrigated systems. There is also realisation that if we are to make significant progress in the way we manage irrigated systems we need to take a more integrated approach and address an increasing number of issues at a range of scales, all simultaneously.

3. THE FATE OF WATER AND SOLUTES IN IRRIGATED SYSTEMS – THE CHALLENGE OF SCALE

When addressing irrigation it is not sufficient to talk only of water. There are a range of solutes (salts, nutrients, agro-chemicals) are associated with irrigation and it is the fate of the excess water and solutes that is of critical importance in establishing efficient and robust irrigation practices. In some situations particular emphasis needs to be given to water management since, if water is appropriately managed within the root zone, the solutes will be as well. In other situations however, one could argue that investing greater effort in improving solute management rather than just water management could help avoid unwanted impacts of solutes moving beyond their zone of need. The key issue is that water and solutes are inextricably linked, so programs aimed at improving irrigation management must proactively target the fate of water and solutes simultaneously if we are to see real improvements in performance of irrigation systems.

We also need to acknowledge that irrigated systems are complex and cut across a range of scales and that the fate of water and solutes will in many ways depend on the scale at which one focuses attention.
It is important to understand the interactions and complexities of irrigated systems and take them into account when developing changed management practices. Reliance on ‘simple rule of thumb strategies’ is seldom adequate and can lead to unexpected longer-term problems if they do not account for the scale and complexity of the irrigated system and the catchment within which it is located. Lack of understanding may also mean that opportunities for improving the performance of parts of and/or the whole system may be missed.

Improving knowledge of the storage, transport and fate of solutes is one area in need of particular focus. There is much attention being given to ‘catchment management’, but many of the most important management decisions are made at the paddock and farm scale (the management units). Progress at the paddock scale will require greater attention to biophysical issues, involving improved understanding of the coupling of the physical, chemical and biological processes at the aggregate, soil profile, and paddock scale. It will involve specialisation and development of more mechanistic and quantitative models (Figure 1) and require improved understanding of and better integration of the local climate (e.g. rainfall and evaporative demand for water), physiology and functioning of the sugarcane plant (e.g. capture of sunlight, carbon dioxide, nutrients, water and conversion into useful and profitable product), soil biology (e.g. soil organisms and soil health), soil physics (e.g. soil water storage and movement processes), soil chemistry (e.g. solute storage, exchange and transport processes) and especially of the links between the sugarcane paddock and the surrounding surface and groundwater systems.

Progress at the larger region and catchment scale will require greater attention be given to issues in addition to the biophysical aspects of catchments. This will include socio-economic aspects of changed water and solute management practices, which will require development of more functional and qualitative (empirical) models (Figure 1).

![Figure 1. Schematic of the range of scales over which water and solutes must be understood and managed.](image)

While it may be easier and quicker to implement change in management practices at the paddock scale than at the catchment scale, efforts need to be made to continually look for improvements at both the smaller and larger scales simultaneously. This demands both specialisation and integration at the same time (Dent 2000), which will require changes to the way research teams are assembled and science is carried out. It will require greater ability to deal with complex systems and more rapid implementation of adaptive management practices that are continually reviewed and updated. As we make progress in these areas we also need to accept that experimentation alone will never be sufficient to meet all needs.
Experiments can only provide exposure to a subset of the wide range of possibilities of climatic, soil and management conditions, so are inherently limited in their predictive capability. While field and/or laboratory experiments will be essential to help address knowledge gaps on specific issues, modeling and scenario analysis will provide the predictive capability that is necessary to address the complexities associated with water and solute management and the overall performance of irrigated systems. We therefore need much better integration of the experimental work within appropriate modeling frameworks to ensure that critical new findings are captured by models which enable more generic quantification of our current best understanding of how a system and its parts work (Inman-Bamber et al. 2001). Having access to an appropriate modelling ‘toolkit’ will be essential for dealing with the many complex interactions, competing demands, spatial and temporal variability, scenario analysis, and the need for extrapolation of findings in both space and time. We also need more people using models to challenge our current thinking, to guide our experimental efforts, and to ‘look ahead’ in an attempt to explore likely consequences of the impact of current decisions and changed management practices. Application of these methodologies involving better integration of the experimental and modeling work will help in the development of more robust water and solute management strategies and hence more sustainable irrigation systems.

The urgent need for progress in these areas is obvious when one considers that a large part of the Queensland sugar industry lies adjacent to World Heritage listed areas, the Wet Tropics, Rainforests, and the Great Barrier Reef. This has in recent years focussed attention on the industry in terms of the types of practices used and their impacts, or likely impacts, on the surrounding environments. Governments and environmental groups in particular have increased their level of scrutiny of the industry, challenging the need for further expansion and demanding implementation of better natural resource policy and planning processes to minimise impacts of current and future practices.

In Queensland there is particular concern about the potential impact of excess nutrients and agro-chemicals that enter the river and groundwater systems and near shore marine environments. A recent GBRMPA working group has defined 10-year water quality targets (2011) for the entire Great Barrier Reef catchment, which include a 38% reduction in sediment, 39% reduction in nitrogen, 47% reduction in phosphorus, a 30-60% reduction in chlorophyll, and a reduction in detectable levels of heavy metals and pesticides (GBRMPA 2001). There is currently vigorous debate about the actual values but based on what is happening internationally, it seems that within catchment and end of catchment water quality targets for all receiving waters are inevitable. It is important therefore that the irrigation and all other industries operating within a particular catchment play a lead role in helping the community to both develop meaningful targets and implement appropriate monitoring systems to ensure compliance with agreed targets. This will require ongoing assessment and improvement of all irrigation practices, which must be optimised to meet both profitable production and environmental goals.

4. MAKING THE “WHOLE” SYSTEM WORK

The impacts of management decisions made at the paddock scale are often expressed at the paddock, and/or farm, and/or region, and/or catchment scale. It is these impacts that will reflect very strongly on the progress or lack of progress made in improving on-farm irrigation management practices. The interconnectedness of the systems we are dealing with indicates that it is not sufficient to think only about what is happening on an individual property (Figure 2, Figure 3). It is possible that a particular irrigator could be doing the ‘right’ thing and still go out of business if someone else ‘upstream’ is using inappropriate practices that cause unwanted ‘downstream’ effects. It is imperative therefore that every irrigator understands the systems affected by decisions he or she makes, at both the farm scale and regional scale, and that the impact of current decisions often have considerable time lags associated with them.

Similarly, water providers and managers of irrigation schemes need to understand the implications of policies and decisions they implement, again at the full range of scales from the paddock to farm to region to catchment. Water pricing structures, if not thought through and carefully implemented, can result in unexpected and/or unwanted consequences. Also, if water cannot be made available to individual paddocks as and when it is needed, it is difficult, and in most cases impossible, for an irrigator to practice meaningful irrigation scheduling. This can in turn lead to inefficient practices with unwanted environmental impacts such as increasing groundwater levels and water logging.
Development and implementation of effective drainage management at the farm and scheme level is also essential for the long-term well being of any irrigation scheme. This includes recycling and disposal of surface and deep drainage in an environmentally acceptable manner. Although seldom practiced, planning for and implementing drainage management plans is most effective when carried out prior to implementing an irrigation scheme. This aspect of irrigation management is unfortunately often omitted, and can be hugely costly to implement later in the life of an irrigation scheme and after problems have started to appear. Avoiding unwanted outcomes associated with irrigation will require that every effort goes into improving relationships and understandings between all players involved in irrigation to help ensure implementation of effective water and irrigation management practices that deliver the required economic and environmental goals.

Salinity is another key issue associated with sustainability of irrigation schemes that requires an integrated approach to its management. It is important to recognise that salinity is a symptom of inappropriate management of local and/or regional water balances and, depending on the particular cause, requires different approaches to its solution and/or management. Dryland salinity in the upper catchment can impact on water moving downstream and ultimately the quality of water available for irrigation lower down the catchment. Addressing this form of salinity requires management of that part of the catchment upstream of the irrigation area.

Irrigation is by default a ‘concentrating’ process and demands that considerable effort go into understanding and managing the water and salt balance associated with the different soils and water qualities available for individual paddocks. In these cases care is needed to avoid rising water tables and subsequent water logging and salinisation.

A third form of salinity that may need attention is that associated with saltwater intrusion. This is particularly important in the Burdekin, Mackay, Bundaberg and other districts that occupy coastal floodplains and use groundwater supplies for irrigation. Great care is needed in these districts to ensure that the ground water levels are not drawn down excessively, especially in places where the change in elevation with distance from the ocean is small. This can make it difficult to maintain or re-establish adequate groundwater levels to ensure the salt-water wedge is subjected to a sufficient pressure head to

Figure 2. Schematic showing the farm enterprise within a broader catchment setting (ofws = on-farm water storage).
prevent it moving inland. Threat of seawater intrusion could be one of the more important issues faced by these irrigated coastal districts. In these cases there is a requirement to develop and management practices that meet farm and regional needs while at the same time ensuring the saltwater wedge is managed in a way to prevent its inland migration.

Clearly, all three forms of salinity can have negative impacts on irrigated sugar districts and its avoidance requires effective management of local and regional water and solute balances. This will become all the more important as rural sectors link more closely with urban and industrial sectors and there is greater reuse and recycling of waters of various quality between the different sectors, which will result in additional salts and other chemicals being brought into irrigated systems (Figure 2).

When contemplating making changes to the way water and/or irrigation is managed, it is essential that we take a systems approach to water resources and water management and be fully aware of and understand the interconnectedness of the various water and solute balance components (flows and storages). Figure 3 developed for the lower Burdekin, demonstrates the wide range of issues and challenges involved (Bristow et al. 2001). Depending on which area within the lower Burdekin one is dealing with, these issues include water quality, rising ground waters, salinity, nutrient leaching, groundwater pollution, falling water tables (groundwater depletion) and salt-water intrusion, amongst others.

Improved water use efficiency (WUE) and sustainability are clearly key drivers, but here too, progress is needed in terms of just what this means. Do we mean improved WUE on a particular paddock or for the scheme as a whole? Are they one and the same things? If something works in one region will it work in a nearby region with different soils and/or crops? If we talk about sustainability, what is the time period we are interested in? These are just some of the questions that need careful thought and analysis in the search for meaningful farm and region specific irrigation management practices.

We can use data in Table 2 to highlight some of the challenges involved. If we focus attention on the water use efficiency data for the Burdekin (70% for the BRIA and 41% for the Delta), it suggests that the BRIA irrigators are more efficient than those in the Delta, but what does this really mean? There is mounting concern in the BRIA about rising water tables, water logging and salinity, which suggests that focusing on individual irrigators’ water use efficiencies is not sufficient to ensure sustainable
management of the wider region. In the case of the BRIA, the introduction of surface water in the late 1980s suggests that attention shifted from the groundwater systems and that despite attention given to improving ‘water use efficiency’, if that is the sole focus and done in isolation from other aspects of the system, parts of the region or the region as a whole can still run into trouble and suffer degradation.

Table 2. Water use efficiency of key sugar producing districts in Queensland. Here BRIA stands for the Burdekin River Irrigation Area (after Tilley and Chapman 1999)

<table>
<thead>
<tr>
<th>District</th>
<th>Water Use Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atherton Tablelands</td>
<td>75</td>
</tr>
<tr>
<td>Burdekin – BRIA</td>
<td>70</td>
</tr>
<tr>
<td>Burdekin – Delta</td>
<td>41</td>
</tr>
<tr>
<td>Proserpine</td>
<td>73</td>
</tr>
<tr>
<td>Mackay</td>
<td>70</td>
</tr>
<tr>
<td>Plane Creek</td>
<td>70</td>
</tr>
<tr>
<td>Bundaberg</td>
<td>75</td>
</tr>
<tr>
<td>Childers</td>
<td>80</td>
</tr>
<tr>
<td>Maryborough</td>
<td>75</td>
</tr>
</tbody>
</table>

All the above demonstrate the interconnectedness of irrigated systems and the need to understand potential long-term impacts of maintaining the status quo or of implementing changes at the farm and/or scheme level. When making changes we need to avoid shifting problems from one area to another or generating different and maybe worse problems because we have not fully explored the impact and flow-on effects of changes we think need to be made. As indicated earlier, development and application of appropriate modeling tools and scenario analysis will be important in tackling these issues and clearly need greater attention than they are currently receiving. This includes development of and, where possible, coupling of biophysical, economic (e.g. Lisson et al. 2000, Qureshi et al. 2002) and, ultimately, social models. The future quality, productivity and community acceptance of irrigation within the sugar industry will be determined largely by how successful we are in developing and implementing improved farm and area-wide policies and practical management practices that deliver economically viable and environmentally resilient irrigated systems.

5. REFERENCES


WATER REFORM IN QUEENSLAND

S Parker

1. INTRODUCTION

The laws in Queensland provide that all water is “vested” in the State, and licences have been issued to people to take and use that water. Only the State, through its departments, had the expertise and capital needed to build and operate dams that supplied the water. The licences gave people access to a volume of water, or a right to irrigate a certain area of land. However, the licensing regime and legislation under which it operated was one characterised by administrative discretions. Operating rules for dams were not specified, nor were the terms and conditions of supply to irrigators. The prices charged for water rarely covered the operation and maintenance costs of the infrastructure that supplied it.

Because the State owned all the water, operated all the infrastructure, and was not too concerned about the prices charged, there was little need to specify the entitlements. However, as governments began to move to cost reflective pricing and entities other than governments became involved in operating dams, there was a need to define more accurately what people were paying for. What was the “product” being purchased? What were the entitlements of the dam owner? Under what circumstances could these entitlements be varied by the State? Pricing reforms cannot be viewed in isolation from reforms to the way in which entitlements are defined and dam operators are regulated. This paper seeks to outline various aspects of institutional reform, pricing reform, entitlement reform and their inter-relationships.

2. BACKGROUND

Historically, the construction of dams and the supply of water in Queensland has been provided by the State, and to a lesser extent, local governments. Many of the dams built by the State have been for the provision of water for irrigated agriculture, with irrigators being granted licences by the State to take water supplied from the dams. Water supplied from dams owned by local governments was treated by the local government and then supplied to households for domestic supply. Prices charged for the water for irrigation rarely covered costs and reflected a policy of government subsidies to encourage regional development through irrigated agriculture.

Because the dams were owned by the State, there was no need to define with any certainty what the total amount of water was or who owned it. The original dam designs may have included estimates of yields, but volumes or entitlements were never formalised in a regulatory instrument. Similarly, the way in which the dams were operated and water supplied was not clearly specified. Regional officers and local engineers who operated the schemes did so with wide discretionary powers.

All the matters that we now regard as necessary to provide commercial certainty for the supply of a service were simply administrative arrangements.

Pricing issues were also dealt with less rigorously when compared to current approaches. Some dams were built in places for reasons of political expediency rather than commerciality, and few were constructed with a view to generating a positive rate of return on the value of the assets. The general approach was that pricing for irrigation water would be subsidised by the State (i.e. there would be no return on the capital, merely attempts to recover some operation and maintenance costs). Water supplied by local governments for domestic use was not charged for volumetrically, but as a component of general land rates - thereby making it difficult to determine if revenues being generated were covering the costs of supply.
3. RECENT TRENDS AND REASONS FOR CHANGE

A number of developments in recent years has led to fundamental reconsideration of the way in which entitlements to water are specified and prices for water determined. Some of the drivers of change are listed below:

- Because of the separation within State agencies of the regulation from the service provision components of existing water supply operations, the local administrative arrangements and discretions were not sustainable. There was a need to specify total volume of water available for sale and rules for operation of dams. These operating rules need to be documented because they determine the product being sold to end users by specifying things such as reliability of supply.
- The supply of water under licences granted to irrigators did not recognise the commercial relationship between the dam operator and those who held the licences. Instead of the terms of supply and other matters being dealt with as administrative matters, there was a need to put the relationship between dam owners and customers on a more commercial footing through supply contracts. Terms of supply cover matters such as price, how often meters are read, when bills are sent, remedies for non-payment of charges etc.
- There has been a move to catchment-based planning so as to more properly assess how much water is available for consumptive use and what is needed maintain the health of rivers and dependant eco-systems. The previous approach of “incremental licensing” whereby licences were dealt with on a case by case basis rather than assessing the cumulative effects became unsustainable as demands increased. While the State could continue to issue licences, in some places this had the effect of undermining the reliability of those licences previously granted. Catchment based planning is necessary to define the total resource available and whether that which has been allocated is sustainable. This helps to define whether that which has been allocated by the State in the past is in fact available – and if not, what needs to be done to entitlements over a period of time to provide necessary certainty.
- In areas where there was no capacity for any future water resource development, the only way in which increasing demands could be met was to allow trading of the water already allocated.
- The subsidies being paid by the State for the continuing operation of its water assets was resulting in significant budgetary pressures. There was a need to move to cost reflective pricing to ensure the long term viability of the infrastructure.
- For local government storages, the reforms to their pricing arrangements for domestic supply have also led to similar pressures to clearly specify total volumes available in an effort to calculate cost recovery.
- There are now a corporations law company (i.e. a private sector entity) involved in the industry in Queensland and two proposals for the private sector to build dams in central Queensland and on the Burnett River in Bundaberg. While it was less of an issue for governments when dams were originally built, these companies and their lenders need certainty as to what they have to sell. To be able to make the proposed dam project “bankable”, there has been a need to determine with certainty the total volume and reliability of water supply that may be available for sale when the dam is constructed.

3. REGULATORY ARRANGEMENTS

In dealing with all of these changes and pressures, a new regulatory framework for the water industry has been developed in Queensland. The new regulatory arrangements have four key elements:

1. Defining entitlements: A new planning and allocation framework. There was a need for a fundamental change in assessing how much water was available for consumptive needs and how entitlements to water were specified.
2. Asset Regulation: Maintenance of Infrastructure and Dam Safety. Increasing private sector involvement in the industry and commercial pressures on newly created government owned businesses bring some risk of operators running down assets. There was a need to ensure that assets were properly maintained - in part motivated by political concerns that, irrespective of ownership, when significant utilities or water supply systems fall into disrepair, the State will be perceived publicly as being responsible for fixing it.
3. Pricing Regulation: Because dam owners are monopoly suppliers there was a need to establish a framework to ensure that the prices charged for the water were not excessive.
4. Separation of regulatory activities from service provisions: Commercialisation of Government Businesses. Historically, the water resources agencies undertook the (conflicting) roles of:

- resource planning and allocation;
- infrastructure development; and
- service provision.

That part of the department that operated all the State owned dams and irrigation areas was set up as a separate government owned business in October 2000 and named SunWater. The water planning and allocation activities remained with the Department of Natural Resources and Mines. The planning framework provides that if “spare” water is defined in a catchment for future development, this will be done in a competitive way to allow private sector involvement. This is done through a number of mechanisms, including access to statutory powers for compulsory acquisition of land if the project is regarded by the State as being of significance.

5. DEFINING ENTITLEMENTS: WHO OWNS THE WATER?

Since the early 1900s, all water in Queensland has vested in the State. This includes all freshwater in rivers, lakes and underground. Since September 2000, “overland flow” – that is, water crossing floodplains or erupting from watercourses – also vests in the State. The term vesting means that the State exercises rights over the “flow use and control”. In a legal sense, this has meant that the Acts regulating water since the 1900s required the State to issue licences for the taking of water. These licences covered both water supplied from dams, and water from watercourses where there was no infrastructure.

The licences granted under these Acts have never given rights to water in perpetuity. Rather, the licences were granted for set periods, usually for between two and ten years (mostly for around seven years) with no right to renewal. They could be cancelled, amended or changed at any time by the chief executive with no rights to compensation. While water was available however, they were routinely renewed.

Essentially these arrangements allowed for continuing State control over the water. Nevertheless, irrigators had made significant investments on the basis of these licences. The new entitlement and allocation framework needed to be able to balance what are clearly two competing objectives for water resource managers:

- providing commercial certainty to the dam operators and the water users so that they know that any entitlement granted to them is sufficiently certain for them to be able to secure finance and to be able to sell the water, while
- retaining State control over all water and allowing adaptive management of a public resource.

The new framework, legislated for in the Water Act 2000, provides for a two-stage planning process to achieve this balance.

Firstly, there is a catchment wide Water Resource Plan that seeks to determine, at a strategic level, the consumptive/non-consumptive balance for the catchment. The Plans are developed using hydrologic models based on streamflow data for periods of up to 100 years. Where streamflow data is not available, it is modelled using rainfall records. There is input from scientific panels, comprising experts in freshwater ecology and geomorphology, and consultation with interest groups through community reference panels. The Plans determine environmental flow objectives and reliability objectives for water users. The Plans are monitored during their ten-year life to determine whether the objectives are being met.

Water Resource Plans, once approved by the government, are given effect through subcatchment or more localised Resource Operations Plans. As an outcome of these implementation plans, existing licences are converted to a new form of entitlement known as a “water allocation” that is separate from land and tradeable according to rules developed in the Resource Operations Plan. If there is spare water in the dam, water allocations are also granted to the dam owners. The water allocations are registered by the State in way similar to land title and may be used as security.
Dam operators are issued Resource Operations Licences for their storages that set out things such as release rules for the environment and water sharing rules for their customers (e.g. the announced allocation policy).

The framework represents a fundamental shift from licences and administrative discretions, to defined volumes and contractual relationships with dam operators for supply. Licences will gradually be converted into a water allocation (for the volume) and a supply contract (for the terms and conditions of delivery) – underpinned by rules in the Resource Operations Licence about the reliability of the supply of the water.

Another key element of the reforms is that certain rights are now given to dam operators over the allocations they deliver. These arrangements provide that:

- if an irrigator wants to sell their water allocation to another person, a new supply contract must be entered into between the purchaser of the allocation and the Resource Operations Licence holder.
- in the event that an allocation holder does not pay money owed to the Resource Operations Licence holder, the holder may exercise a power of sale over the allocation and return the water to the market. Under the old licensing regime, such breaches usually resulted in the licence being cancelled. Under the new arrangements, however, such action would mean less revenue for the dam operator in terms of storage and delivery charges unless the water allocated can still be used.

5.1 TRANSITIONAL ARRANGEMENTS FOR SUNWATER

The Water Resource Plans referred to above will take some years to complete and implement through Resource Operations Plans.

To allow SunWater and its customers to begin moving toward the new system, the Water Act 2000 provides for transitional arrangements pending the completion of the Water Resource Plans. This has been achieved through all existing licences for the supply of water from dams now owned by SunWater being “unbundled” (Figure 1) into:

- an interim water allocation for the volume of water available under the licence; and
- a supply contract for delivery of that allocation.

Standard supply contracts for delivery are now in place in the 34 supply schemes operated by SunWater throughout the State. For some storages, there is some spare water i.e. water which has not been committed or allocated through licences. This water has been allocated to SunWater to do with it as they wish. Options include leasing the water (i.e. making available on contracts for a set term for those in need) or selling an entitlement.

In addition, Interim Resource Operations Licences have been issued to SunWater to specify operating rules for infrastructure.

As Water Resource Plans are finalised throughout the State, these interim arrangements will be replaced with Resource Operations Licences and Water Allocations. Figure 2 shows how water licences are “unbundled” as part of the interim arrangements and also following the completion of a Water Resource Plan. The main difference between the two is that water allocations established following a Water Resource Plan are separate from land and tradeable.
6. IRRIGATION WATER PRICING ISSUES

In an effort to move to more cost reflective pricing for water in these schemes, SunWater has been given a 5 year price path determined by the Government for all irrigation licences. The price path seeks to ensure that as many schemes as possible over the five-year period move to a position where they are at least recovering the operation, maintenance and refurbishment costs of the dam and supply systems. These price paths were determined over a period of some 18 months of negotiations with local users and have led to changes in tariffs. They were developed through the steps summarised below.

6.1 ANALYSIS OF COSTS

Independent consultants undertook a detailed analysis of scheme delivery costs in two stages. Firstly, there was an independent review of actual costs and revenue information. A determination of what costs were to be passed on to irrigators was made. Secondly, efficient costs of service delivery were determined through an independent benchmarking process. The business was dissected into component parts with an efficiency analysis for these parts being benchmarked by independent experts.

6.2 ANALYSIS OF REVENUES AND TARIFF STRUCTURES

For the modelling of the price paths, revenues were based on two measures: the price of the water and the quantity of water used.

A full review of the water demand and use in each of the schemes owned by SunWater was undertaken. Water use forecasts were generally based on historical average water use. Other considerations included the impacts of water trading, sales of “spare water” granted to the dam owner and changes in cropping patterns. The potential changes of water use with increases in prices were also examined and it was clear that for many of the irrigators, there was a low elasticity of demand with respect to water price.

The existing two part tariff was maintained, with a fixed charge per ML (megalitre) of nominal allocation (Part A) and other charges which applied to each ML of water actually used (Part B). Generally, tariffs were restructured so that the Part A charge would recoup the ongoing fixed costs, providing revenue stability for the dam owner. The Part B charge was set so as to recoup variable costs. For most schemes, the new price path tariff were designed to deliver 70% of required revenues from the fixed charge, with 30% being delivered from the water use charge in the “average” water use year for the scheme.
6.3 ECONOMIC STUDIES

Price increases were staged over a 5, 6 or 7 year period depending on each scheme. The variation in timeframes was generally based on an assessment of the irrigator’s capacity to pay. This was determined on the basis of examination of industry economic conditions and the potential impacts on irrigators of pricing changes. A general conclusion of these economic studies was that the water costs only represented a small percentage of total farm costs. Therefore, the duration of the price path was principally determined on the basis of the dominant crop e.g. schemes with a large proportion of sales to dairy farms were given an extra year due to some industry deregulation occurring at the same time.

7. SUMMARY

Changes to the water industry in Queensland over the last two years have sought to integrate, as much as possible, the issues of regulatory reform (allocations and asset maintenance issues), institutional reform (creation of SunWater and reform of other statutory authorities) and pricing. All three areas are interrelated and, importantly, allow water users to put the various elements within a context. It also means that, for the first time since the State issued licences in the 1890s, water users know what it is they are paying for.
Figure 2. Diagrammatic representation of “unbundling” of entitlements under the *Water Act 2000*. 
2. PRINCIPLES UNDERLYING IRRIGATION MANAGEMENT
OVERVIEW

NG Inman-Bamber and PB Charlesworth

The following papers on soil and water suitability for irrigation, plant water relations, water use efficiency (WUE) and irrigation scheduling have been compiled from a number of conference papers and journal articles. While these papers capture a large proportion of what has been published on these subjects, there is a large amount of local knowledge that may not have been adequately captured. In the presentation of this Irrigation Short Course we hope that a lot of this local knowledge will be shared, compared and contrasted to what has been through the scientific peer review process. In places the notes are very detailed and will be of most interest to those who want to burrow a bit deeper to find out how the more practical conclusions were derived.

Of the 11 papers that make up this section, eight deal with various aspects of the soil-plant-atmosphere continuum in regards to water flow and its effects on plant growth. While these papers are not exhaustive reviews they do capture some major scientific aspects needed to make best use of irrigation and rainfall in sugarcane production systems. The remaining three papers on irrigation scheduling bring together the main points out of the preceding eight papers in order to discuss options for scheduling irrigation in schemes where water is normally adequate for crop demand and also in schemes when this is seldom the case. Practical means of scheduling have often been developed and applied long before the science is completed and, in reality, the science will probably always lag behind the advances made in the practical use of water.

In all sessions, delegates are invited to share their experiences and to enrich the prepared notes.

The papers that make up these notes fit the framework provided below (Figure 1). Three papers are about water supply to the crop from the soil. Paper 1 talks about the physical constraints that sodicity presents to water supply, paper 2 addresses water holding capacity of the soil in relation to rooting depth, and paper 3 is concerned about water originating from a water table that may be available to the roots. Paper 4 deals with issues in measuring how much soil water is available to the crop.

In addition to knowing how much water is available, we also need to know what the atmospheric demand is. This is the subject of paper 5 on Evapotranspiration. When the demand exceeds the soils ability to supply sufficient water to meet the plants water requirements, the plant becomes stressed (paper 6). This has implications for water use efficiency and rainfall effectiveness (paper 7) which in turn has implications for soil water supply. Some degree of water stress is desirable for increasing CCS, so knowledge of the crop’s response to water stress helps to set drying-off targets (paper 8). Knowledge of crop water stress, soil water and evapotranspiration is necessary for irrigation scheduling (papers 9, 10 and 11).

It has not been possible to rewrite the papers in a common style and in a way that reinforces the above framework so when working on these papers it will be helpful to keep this framework in mind and to recognise the important linkages between the various papers.
Figure 1. Diagramatic framework showing the linkages between the 11 papers in the section entitled ‘Principles underlying irrigation management’.
1. WHY ARE SODIC AND SALINE SOILS AN ISSUE?

1.1 EFFECTS OF SODICITY AND SALINITY ON SUGARCANE GROWTH

Typical effects of sodicity on crop production include reduced plant populations and poorer growth of those populations. Growth restrictions are due to waterlogging, poor infiltration and availability of water, and limited rooting depth. Sodic soils have low structural stability when wet, which results in undesirable conditions for crop growth. Such instability causes large pore collapse, clogging of small pores and reduced permeability to both water and air. This leads to waterlogging and anaerobic conditions in flat fields or increased runoff where gradients are greater. It has been conservatively estimated that soil sodicity reduces annual production in the industry by 500,000 t (Ham et al. 1995).

Spalding (1983) investigated the relationship between yield and CCS and soil sodicity and salinity in a rain-fed block in the Mackay district. Growth was variable across the block and 15 plots were chosen to cover the range of yields. Yield was correlated best with the exchangeable sodium percentage (ESP) of the 0.25-0.5 m depth layer. The relationship was linear, decreasing from a yield of 100 t ha⁻¹ at ESP 0 to 0 t ha⁻¹ at ESP 66 (a decrease of 1.5 t ha⁻¹ for each 1% ESP, Figure 1). Nelson and Ham (2000) carried out a similar study at 16 irrigated sites in the Burdekin district. The combined effects of soil sodicity and salinity accounted for 79.5% of the variation in yield across all sites. Although there were differences between sites, there was no consistent effect of variety or crop class. Over all sites, yield decreased by 2.1 t ha⁻¹ for each 1% increase in ESP in the 0.25-0.5 m depth layer (Figure 1). The more pronounced effect of sodicity in the Burdekin was attributed to higher potential yield at low levels of sodicity in the Burdekin. Kazman et al. (1983) showed infiltration rates decreasing with increasing sodicity (Figure 2).

Sodicity and ameliorative treatments have small and variable effects on CCS. In general, the effects on yield far outweigh any effects on CCS. Different varieties may vary in their tolerance of sodicity, and ratoon crops usually suffer more than plant cane, but in general, yield is reduced by sodicity.

![Figure 1. Sugarcane yield is directly related to soil sodicity. The graph shows data from 16 sites in the Burdekin (Nelson and Ham 2000) and one site at Mackay (Spalding 1983).](image-url)
1.2 EFFECT OF SODICITY ON NUTRITION AND DISEASE

- Main problems for nutrition are caused through waterlogging, low organic matter and low microbial activity, which result in a low capacity to supply N.
- Sodic soils with low CEC may exhibit calcium deficiency, particularly if they are also acidic. Calcium deficiency is corrected where lime or gypsum is added as an ameliorant.
- Roots that are stressed have been shown to be more susceptible to disease.

1.3 EFFECT OF SODICITY ON CULTIVATION AND TRAFFICABILITY

- Due to the water content range for optimum cultivation being very narrow in sodic soils, the time period for effective cultivation is shorter than for non-sodic soils.
- If soil is too wet, cultivation causes smearing; if too dry, the soil breaks up into large clods or pulverises (Figure 3).
- Sodic soils are particularly prone to compaction due to their low structural stability.

Figure 2. Sodicity and infiltration rate (from Kazman et al. 1983).

Figure 3. Large clods of a sodic soil
1.4 ENVIRONMENTAL IMPACTS OF SODICITY

- Dispersive clay from sodic soils is highly prone to erosion and runoff.
- Clay remains suspended and reduces light penetration and the productivity of submerged aquatic plants in creeks and wetlands.
- May lead to increased amounts of nutrients and pesticides moving off paddock due to their being largely bound to clay.
- Low yields on sodic soil mean larger areas need to be cleared and infrastructure costs are higher.

2. WHY DO SODIC SOILS BEHAVE AS THEY DO?

2.1 WHAT ARE SODICITY AND SALINITY?

Definitions of ‘salinity’, ‘sodicity’ and ‘sodic soil’ are:

- Salinity is the concentration of soluble salts in the soil. In Australian saline soils, the most common type of salt is sodium chloride.
- Sodicity is defined as the proportion of the cation exchange capacity of the soil that is occupied by sodium. The proportion is expressed as a percentage and called the exchangeable sodium percentage (ESP). Soils with ESP > 6 within their A or B horizons are defined as sodic soils and those with ESP > 15 are classed as highly sodic soils.

2.2 HOW SODICITY AFFECTS SOIL PHYSICAL PROPERTIES

In sodic soils, the physical problems of crusting, poor penetration of water and roots, difficulties in effective cultivation and erosion are all related to clay dispersion. The influence of sodium on clay particles is illustrated in Figure 4 a-c.

If clay disperses upon wetting, soil structure is very unstable and larger aggregates collapse. In highly sodic soils, the wetting action alone is enough to cause structural collapse. In less sodic soils, structure is more stable, but will still collapse if disturbed by raindrop impact, cultivation or compaction. Therefore, stable soil structure is not possible in soils containing dispersive clay.

2.3 LABORATORY AND FIELD ANALYSIS

- Decisions on how to manage sodic soils depend on accurate diagnosis of the problems. Other factors such as salinity, compaction, nutrition and disease may also be involved.
- Sodicity and related problems are best diagnosed by the measurement of ESP, CEC, EC, pH and texture in the laboratory. However, these analyses can be expensive and have slow turn-around times in laboratories.
- A Field Kit has been produced for in-field diagnosis of sodicity and related problems in the Australian sugar industry (Nelson 2000).

3. WHERE DO SODIC AND SALINE SOILS OCCUR?

The occurrence of saline and sodic soils in sugar cane growing areas is summarised below.

- **Mareeba-Dimbulah Irrigation Area** – Sodic soils make up 40% of 7500 ha under sugarcane. Occurrence of sodic soils is highly variable.
- **Herbert** – Sodic soils confined to drier parts at western and southern extremes. Also occur in higher rainfall, Seymour and Abergowrie areas.
- **Burdekin River Irrigation Area** – Soils with a sodic B-horizon comprise 72% of the 50,000 ha area surveyed. These soils fall in 3 orders, Vertosols, Chromosols, and Sodosols.
- **Proserpine/Mackay** - Of the 152,000 ha mapped in the Proserpine area, 77,900 ha were identified as sodic soils, representing approximately 32% of the total cane growing area. This figure is likely to be similar for the Mackay cane growing area.
- **Bundaberg/Childers** - In the Bundaberg-Childers area, strongly sodic soils (ESP>15 in major part of the B horizon) occupy 58% of the total area mapped. Strongly sodic soils predominantly occur in lower slope positions on hillslopes and older parts of the alluvial plains.
(a) The dotted line separates the exchangeable cations, which balance the charge on the clay particles, and the soluble cations, whose charge is balanced by anions in solution. When the dominant exchangeable cation is calcium, the layer of exchangeable cations (“double layer” or “diffuse double layer”) is thin, because the calcium ions are bound close to the surface of the particles. The two clay particles normally repel each other, because each is surrounded by a positively charged layer of cations. However, in a non-sodic soil, because the diffuse double layers are thin, the particles can come quite close together. If they come within 0.002 µm of each other, short range attractive forces, similar to gravity, take over, and the particles stick together or flocculate.

(b) In a sodic soil, there are more exchangeable cations in the diffuse double layer than in a soil dominated by calcium or magnesium, because the sodium ions have only one charge per ion. Also, because the sodium ions are less highly charged, they are not bound closely to the clay particles. Therefore, the diffuse double layer is thicker than in non-sodic soils, and clay particles cannot approach close enough for attractive forces to dominate. The clay is dispersed.

(c) In saline-sodic soils, the high concentration of ions forces the sodium ions close to the surface, so the diffuse double layer is compressed, the clay particles can come close together, and flocculation occurs. While the soil remains saline, the clay remains flocculated. However, as soon as the salt is leached out, the clay particles revert back to the situation in b), and dispersion occurs.

Figure 4. The effects of sodicity at the scale of two clay particles, which are flat and shown in cross section. Each particle is only about 0.01-2 µm in diameter.
4. HOW SHOULD SODIC AND SALINE SOILS BE MANAGED?

Management strategies for sodic soils fall into three main categories:

1) Avoiding cropping sodic soils
2) Reducing sodicity and preventing it from getting worse
3) Managing the soil despite it being sodic

In reality, most management options involve a combination of two or three of these principles. An essential part of management is to get all the other factors, principally irrigation, nutrition and pest/disease management, right. However, it is important to note that factors such as nutrition or varieties cannot compensate for sodicity-related restrictions to growth.

4.1 FARM PLANNING, BLOCK DESIGN AND LEVELING

• The most effective practice for managing sodic soils is to avoid bringing them into production. Sodic soils are expensive to develop and provide lower returns than non-sodic soils. Soil maps are a valuable resource for farm planning as they indicate the occurrence of sodic soils.

• Sodic layers should be buried as deep as possible. A non-sodic layer of at least 300 mm depth is preferable. It is possible to apply gypsum to the subsoil following levelling and before the topsoil is replaced. Where possible, non-sodic soil should be used for top-dressing paddocks and sodic soil should be placed in non-cropped areas such as headlands and roads.

• Sodic soils have poor structural stability. Management should aim at limiting structural damage and encouraging improvements in structural stability. Structural damage caused by disturbance or compaction can be limited by minimising cultivation and traffic. Structural stability can be improved by maximising inputs of organic matter.

• In areas where groundwater is close to the surface, adequate provision must be made for drains so as to maintain the water table at more than 1 m below the soil surface.

• An adequate source of good quality irrigation is necessary for amelioration of sodic soils. In furrow-irrigated blocks, arranging the block so that sodic soils are near the top allows them to be irrigated more frequently

• Water intake is reduced in blocks that have too great a slope. Where water penetration is poor, the slope should not exceed 0.125 per cent or 1:800. Table 1 shows that reducing slope from 0.49% to 0.07% increased cane yield by 24% over a crop cycle in a block with no trash blanket (Ham et al. 1997).

Table 1. Cane yield (t/ha) of Q117 on a sodic soil at Gaynor (Burdekin), levelled to different slopes

<table>
<thead>
<tr>
<th>Crop class</th>
<th>0.07% slope</th>
<th>0.49% slope</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plant</td>
<td>106</td>
<td>93</td>
</tr>
<tr>
<td>1st ratoon</td>
<td>64</td>
<td>50</td>
</tr>
<tr>
<td>2nd ratoon</td>
<td>65</td>
<td>52</td>
</tr>
<tr>
<td>3rd ratoon</td>
<td>34</td>
<td>21</td>
</tr>
</tbody>
</table>

4.2 IRRIGATION

4.2.1 Irrigation technique

• General objective is to overcome the low permeability of sodic soils.
• Irrigation methods that apply water frequently in small amounts allow water to penetrate sodic soils and allow the crop to obtain sufficient water from the less sodic topsoil.
• Under furrow irrigation, water penetration can be greatly improved by forming small hills and making a broad flat interspace. Lower flow rates and slopes will improve soakage and restrict runoff.
• Tail-water retention has several benefits for managing sodic soils. Overall water use efficiency is greater, salt concentrations tend to increase, leading to better penetration, and the movement of turbid water off-site is reduced.

4.2.2 Irrigation water quality
The importance of irrigation water quality cannot be over-emphasised. There are three main hazards that irrigation water can pose to soil behaviour (Figure 5):

• Salinity hazard (measured by electrical conductivity [EC]) – risk of accumulating salt in the soil profile.
• Sodicity hazard (measured by sodium adsorption ratio [SAR] and residual alkali [RA]) – risk that irrigation water will increase soil sodicity. In the longer term the ESP of the soil will become equivalent to the SAR of the irrigation water.
• Dispersion hazard (combination of EC, SAR and RA) – Risk is greatest with low salinity water.

Irrigation waters are classed into one of seven classes based on the dominant hazard or combination of hazards. These are shown in Table 2 along with treatment measures.

![Figure 5 Dispersion hazard of irrigation water.](image-url)
Table 2. Summary of water quality types

<table>
<thead>
<tr>
<th>Type</th>
<th>Quality</th>
<th>Corrective measures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type 1</td>
<td>Poor on light soils</td>
<td>May be mixed with gypsum, or alternatively, treat soil with gypsum or lime</td>
</tr>
<tr>
<td>EC = 0 – 0.6 dS/m</td>
<td>RA = 0 – 0.2 mmol/L</td>
<td></td>
</tr>
<tr>
<td>Type 2</td>
<td>Poor on light soils</td>
<td>As above</td>
</tr>
<tr>
<td>EC = 0 – 0.6 dS/m</td>
<td>RA = 0.2 – 2.4 mmol /L</td>
<td></td>
</tr>
<tr>
<td>Type 3</td>
<td>Good</td>
<td>Nil</td>
</tr>
<tr>
<td>EC = 0.6 – 1.5 dS/m</td>
<td>RA = 0 – 0.6 mmol /L</td>
<td></td>
</tr>
<tr>
<td>Type 4</td>
<td>Good-fair</td>
<td>Light soils may need gypsum or lime</td>
</tr>
<tr>
<td>EC = 0.6 – 1.5 dS/m</td>
<td>RA = 0.6 – 2.4 mmol /L</td>
<td></td>
</tr>
<tr>
<td>Type 5</td>
<td>Fair-poor</td>
<td>Ensure irrigation is heavy enough to prevent salt accumulation in the soil. Deep rip.</td>
</tr>
<tr>
<td>EC = 1.5 – 2.2 dS/m</td>
<td>RA = 0 – 2.4 mmol /L</td>
<td></td>
</tr>
<tr>
<td>Type 6</td>
<td>Very poor</td>
<td>Use on sandy soils only. Wet soil to a depth of at least one metre.</td>
</tr>
<tr>
<td>EC = 2.2 – 3.2 dS/m</td>
<td>RA = 0 – 2.4 mmol /L</td>
<td></td>
</tr>
<tr>
<td>Type 7</td>
<td>Unsuitable</td>
<td>DO NOT USE</td>
</tr>
<tr>
<td>EC &gt; 3.2 dS/m, or</td>
<td>RA &gt; 2.4 mmol /L</td>
<td></td>
</tr>
</tbody>
</table>

4.3 AMELIORANTS

Soils can be made non-sodic by adding a soluble source of calcium, such as gypsum, and leaching it through (Figure 6). The calcium replaces the sodium, and the leaching water moves the sodium down below the root zone. Sodium that has leached below the root-zone may also move back up again as water is drawn up by evaporation and crop uptake or if the groundwater rises.

Figure 6. Management of sodic soils usually aims at replacing exchangeable sodium with calcium and leaching the sodium below the root zone.
4.3.1 Lime or Gypsum?
The main difference is solubility. When dissolved in water, gypsum attains a maximum EC of ~2 dS/m, whereas lime attains a maximum EC of approximately 0.01 - 0.40 dS/m. The solubility of gypsum is not influenced by soil pH, whereas that of lime is. Lime is insoluble at pH > 8.5. Therefore, lime is unlikely to have any benefit on sodic soils with pH greater than 7.

4.3.2 Gypsum
What gypsum is and how it works:
- Gypsum raises the EC and supplies calcium, which replaces exchangeable sodium. Hence, it reduces clay dispersion.
- Gypsum can be applied to the surface of the soil, dissolved in irrigation water, or placed at depth in ripper lines.
- Gypsum itself has no significant effect on soil pH. However, in combination with leaching, it can reduce the pH of alkaline sodic soils.
- Gypsum is the preferred ameliorant for most sodic soils because of its price and solubility.
- Gypsum is not soluble enough to cause salinity problems, except where it is added to soils that already contain a significant amount of salt.
- Unfortunately, complete desodification is normally not economic and sodic soils need to be managed carefully, even if gypsum has been applied.

Gypsum rates and responses
Several trials have shown the effects of gypsum on sugarcane yield on sodic soils (Ham et al. 1997). A subsequent replicated trial on a sodic duplex soil (Dowie series) and cracking clay (Barratta series) showed significant responses to gypsum in the ratoons (Ham et al. 1997). A trial in the Mareeba-Dimbulah Irrigation Area (MDIA) showed considerably better results with dissolvenator rather than surface-applied gypsum (Table 3). The yield response was sufficient to recover the capital cost of the dissolvenator in two crops over the 50 ha block. The soil had an ESP of 18.4 at 0-25 cm depth and an exchangeable magnesium percentage of 92.4% at 25-50 cm depth. Surface application of gypsum provided no additional benefit to the dissolvenator treatment. Soil pH was 6.3-6.6 in the top 50 cm, but lime did not improve yield over the control.

Table 3. Sugarcane yield (t/ha) in dissolvenator trial at Arriga Park, Atherton Tableland (D. Burgess, pers. comm.)

<table>
<thead>
<tr>
<th>Treatment</th>
<th>3rd ratoon 1997</th>
<th>4th ratoon 1998</th>
<th>5th ratoon 1999</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dissolvenator</td>
<td>119</td>
<td>102 a</td>
<td>105</td>
<td>107.5 a</td>
</tr>
<tr>
<td>Dissolvenator + gypsum (5 t/ha)</td>
<td>100</td>
<td>96 a,b</td>
<td>100</td>
<td>97.9 b</td>
</tr>
<tr>
<td>Gypsum (5 t/ha) + lime (2.5 t/ha)</td>
<td>95</td>
<td>85 b,c</td>
<td>89</td>
<td>89.8 c</td>
</tr>
<tr>
<td>Gypsum (10 t/ha)</td>
<td>91</td>
<td>87 b,c</td>
<td>91</td>
<td>89.7 c</td>
</tr>
<tr>
<td>Lime (5 t/ha)</td>
<td>85</td>
<td>83 c</td>
<td>83</td>
<td>83.6 d</td>
</tr>
<tr>
<td>Control</td>
<td>86</td>
<td>83 c</td>
<td>89</td>
<td>86.1 c,d</td>
</tr>
<tr>
<td>l.s.d. (P=0.05)</td>
<td>n.s.</td>
<td>12</td>
<td>n.s.</td>
<td>4.7</td>
</tr>
</tbody>
</table>

Gypsum application rates of 5-10 t/ha are normally recommended for sodic soils. The computer program “Gypsy” (Nelson et al. 2000) can be used to estimate the most economic rates of gypsum to apply. When rates greater than approximately 10 t/ha are indicated, it is suggested that annual rates of 5-10 t/ha be considered, until the predicted rate is reached. On saline-sodic soils, lower rates, such as 2-4 t/ha, should be added and salinity monitored. Additional gypsum can be added later.

When sealing of surface soil is apparent, placement of gypsum on the surface is a sound strategy. More commonly, it is better to incorporate surface-applied gypsum well into the soil, especially if high rates are involved.
4.3.3 Lime

- The main purpose for applying lime is to increase pH and supply Ca in acid soils.
- It can also be effective in improving the structure of poorly structured soils, particularly for improving water penetration in soils with low EC.
- Lime may be more effective than gypsum in saline sodic soils because a) its solubility is increased by the presence of sodium salts, and b) it is not soluble enough to add significantly to the salt load of the soil as gypsum does.
- Too much lime may increase pH by more than desirable, leading to nutrient deficiencies.

4.4 MANAGING SALINITY

This manual concentrates on sodicity rather than salinity, but the two are closely related. The QDNR ‘Salinity Management Handbook’ (Anon. 1997) deals with salinity management. In order to manage soil salinity, the landscape must be understood and the origin of the salt must be known. Salt may originate in the soil itself, from saline irrigation water, or from a shallow groundwater table. Even if the groundwater is not particularly saline, movement of water upwards by plant uptake and evaporation can concentrate salt in the root zone. Management should aim at a net movement of salt out of the root zone (Figure 7).

Irrigation must be carefully managed to prevent soil salinisation. Groundwater must be kept deep enough that water does not move up into the root zone. Management of irrigation and drainage are discussed in the BSES booklet ‘Irrigation of Sugarcane’ (Holden 1998) and the QDNR ‘Salinity Management Handbook’ (Anon. 1997). Several computer models (eg. HYDRUS, SALF, SWIM and SWAGMAN) are available for determining the movement of salts in soil.

5. ACKNOWLEDGEMENTS AND FURTHER READING

This paper has been condensed from the publication:

Nelson PN (Ed) (2001) Diagnosis and Management of Sodic Soils under Sugar Cane. (CRC Sustainable Sugar Production, Townsville, Queensland)

Contributors to that publication were: Paul Nelson, Gary Ham, Graham Kingston, Drew Burgess, Andrew Wood, Nev Christianos, Scott Hardy, Peter Wilson, Adam Lawer.

6. REFERENCES

Anon. (1997) ‘Salinity Management Handbook’ (Department of Natural Resources, Brisbane)
In all cases, rainfall moves salt downwards, and evaporation moves salt upwards. A net concentration of salt in the root zone must be avoided.

Figure 7. Salt movement with respect to irrigation system.
CONTRIBUTION OF SHALLOW WATER TABLES TO CROP WATER REQUIREMENT

C Sweeney, P Thorburn, K Bristow, and D Lockington

1. INTRODUCTION

Fresh, shallow water tables can supply a large proportion of a crop’s water requirements without affecting yields, provided they are deep enough not to cause waterlogging. Investigation of upflow from water tables as deep as 2 m has shown considerable contributions towards evapotranspiration from sugarcane, wheat, soybean, cotton, and maize crops (Hunsigi and Srivastava 1977, Torres and Hanks 1989, Myer et al. 1989, Ayars and Hutmacher 1994, King et al. 1995). When shallow water tables influence the water balance in the root zone, modifications to irrigation scheduling to reflect upflow rates can lead to improved irrigation water use efficiencies (Ayars and Hutmacher 1994). Modifications to irrigation scheduling are particularly important in areas where irrigation is scheduled using pan based estimates of evapotranspiration. Pan losses will not reflect upflow from the water table, and hence become an inappropriate indicator of soil moisture deficits. Alternative scheduling methods, such as the use of tensiometers or measures of plant water stress are more likely to incorporate the effect of upflow. If upflow is ignored, irrigation applications will be larger than that required, resulting in losses to deep drainage, and a recharging of the shallow water table.

Increasing irrigation water use efficiency (IWUE; as defined by Inman-Bamber et al. 1999) has major implications for the Australian sugar industry. In some irrigated areas, production is limited by water restrictions, yet in other areas, over-irrigation has resulted in rising water tables and associated problems (Tilley and Chapman 1999). Thus, incorporation of upflow into irrigation scheduling has the potential to increase yields where water is a limiting factor, and to reverse some of the unwanted environmental impacts of over-irrigation by reducing recharge to the shallow water tables. Growers in the sugar industry are most likely to be using pan based estimates of irrigation requirements, implying the potential for increases in IWUE is high.

Despite the evidence that shallow water tables can supply crops with water, there is still a large degree of uncertainty as to how irrigation should be adjusted to account for upflow. As upflow rates are dependent on the soil type, depth of water table, evaporative demand, and plant characteristics (Thorburn et al. 1995), modifications to irrigation will need to be site specific. One example where reduced pan coefficients were developed and tested for a cotton crop resulted in 100 mm less of irrigation water applied (Ayars and Hutmacher 1994). Development of these modified coefficients involved the use of lysimeters, where upflow rates were measured over two years for static water table depths of 1.2 and 2 m. Information for possible reductions to crop or pan coefficients can be obtained indirectly from irrigation experiments where yields from a range of pan or crop factors have been compared above shallow water tables. Often these studies involve a limited range of pan or crop factors, or have been carried out with a specified water table depth that is likely to change in field conditions. It would be useful if more generic approaches to improving irrigation management in the presence of shallow water tables could be developed.

The aims of this paper are to review information on the water resource potential of shallow water tables for sugarcane, a major irrigated crop grown in northern Australia, and to demonstrate, using modelling and scenario analysis, the possible increases in IWUE that may result from their presence. Three soil types were modelled in order to answer the following questions: a) the depth at which water tables can meet the crops water requirements b) the depth at which water table contributions become negligible, and c) possible changes to irrigation management that would result in improved irrigation water use efficiency/crop response to irrigation when water tables lie within these extremes.

2. REVIEW OF WATER TABLE IMPACTS ON SUGARCANE PRODUCTION

The majority of published literature considers shallow water tables in a waterlogging context. However, many of these studies compare yields of sugarcane for static water table depths ranging from
0.3 m to 1.2 m. Sugarcane yields from static water tables at depths of 0.5 m and below show no significant difference (Juang and Uehera 1971, Gosnell 1971, Escolar et al. 1971), although some varieties exhibit waterlogging effects from water tables shallower than 0.5 m. This suggests that water tables at 0.5 m and below are beneficial in terms of sugarcane production. In other studies, sugarcane crops have been shown to receive all or large proportions of evapotranspiration from shallow water tables. Cenicana (1984, as cited in Torres and Hanks 1989) reported that sugarcane yields were not depressed when irrigation was withheld for a water table fluctuating between 1.2 to 1.5 m. In India, lysimeter studies determined 86 and 55 % of sugarcane evapotranspiration was supplied by water tables at 0.4 and 0.6 m depths respectively (Gupta and Yadav 1993). The ability of sugarcane to exploit shallow groundwater resources is also supported by irrigation experiments where sugarcane yields have not increased with irrigation (Inman-Bamber et al. 1999, Patel and Joshi 1985, Hunsigi and Srivistava 1977).

Very little is known about measured daily rates of upflow from water tables in sugarcane systems. Knowledge gaps also exist on the effect of shallow water tables on sugarcane root distributions and activity, although observations have been made about the cessation of root growth within 0.1 m of static water tables (Juang and Uehara, 1971, Pitts et al. 1990, Gosnell 1971). As rooting depth is an important factor in determining the contribution of upflow to a crop (Thorburn 1997) further work is required to quantify not only upflow rates from various water table depths, but also upflow rates at various distances between active roots and the water table. The effects of fluctuating water tables on nutrient dynamics in sugarcane crops is largely unknown, although soil column studies have shown water table depths impact on a range of solutes. In particular, deeper water table depths can increase nitrate losses via denitrification (Brown et al. 1998).

The studies cited above show that potential increases in IWUE are high for the Australian sugar industry, given that shallow water tables are widespread throughout irrigated areas. Yet most irrigators do not monitor for water tables in any greater sense than installing drains where waterlogging is a serious problem (Sweeney et al. 2001). It is also apparent that while irrigation reduction is possible, a wider systems approach for developing modified crop or pan factors is required to recognise and attempt to address knowledge gaps on the interactions between soil type, irrigation frequency, depth to water table, and root characteristics. Field experiments, while necessary, are impractical for completely exploring the range of complexities that occur in shallow water table systems. Modelling and scenario analysis are able to complement field work by exploring a much wider range of system factors, provided these processes can be adequately predicted with a cropping systems model. This combined modelling-measurement approach has been the basis for the development of other irrigation best management practices (Robertson et al. 1999). Results from some exploratory modelling are presented in the following section.

3. SIMULATION OF SHALLOW WATER TABLES IN SUGARCANE SYSTEMS

A numerical model based on Richards’ equation (SWIMv2.1) was used to demonstrate the usefulness of modelling and scenario analysis to address some important and currently unanswered questions for irrigation management in shallow water table systems. These include questions such as:

- When does upflow meet all plant water requirements so that no irrigation is required?
- When is upflow negligible, such that the presence of a shallow water table has no effect on irrigation scheduling? and
- How can irrigation applications be reduced without having negative impacts on yield?

Three soil types previously characterised for the Bundaberg irrigation area, representing a range of saturated hydraulic conductivities found in agricultural soils, were assessed in terms of irrigation requirements for three different water table depths (1, 1.5, and 2 m). The effects of root length densities and rooting depths on irrigation requirements were also investigated through scenario analysis. Conditions in the simulations were chosen to represent a closed canopy sugarcane crop during conditions of high potential crop water use.
3.1 THE SWIMv2.1 MODEL

SWIMv2.1 has been successfully applied to both water and solute transport simulations (Verburg et al., 1996). Required inputs to SWIMv2.1 include soil hydraulic properties throughout the soil profile, water inputs and evapotranspiration, root distribution, and vegetative growth. The smoothed Brooks-Corey form of both the moisture characteristic (after Hutson and Cass 1987) and hydraulic conductivity (Brooks and Corey 1964, 1966) functions were used in this study to describe the soil hydraulic properties. SWIM approximates plant growth by changing the fractional interception of potential evapotranspiration (PET) over time. It requires this to be input as parameters for describing the shape of a sigmoidal curve representing the fraction of intercepted PET with time, or by inputting the fractional interception of PET at specific times. In the later case, SWIM uses linear interpolation to determine fractional interception between the times specified.

Root distributions are described as functions of depth and time relative to a maximum root length density. Rooting characteristics with depth can be input as an exponential function or as pairs of data specifying the fraction of maximum root length density at specified depths. For both of these cases, the changes with roots over time are assumed to follow the same sigmoidal distribution as the fractional interception of potential PET. The other option for describing the spatial and temporal rooting characteristics is to input a matrix of relative root length density with depth and time. Water uptake by the roots is equated to transpiration. Potential transpiration is constrained by soil water availability. The actual rate of water uptake from each soil layer is a function of root length density and soil-plant water potential gradients. Root radius and root conductance affect the supply rate of the soil.

3.2 SIMULATIONS AND PARAMETER VALUES

Scenarios were set such that upflow was the only source of water available for crop growth (no irrigation or rainfall was applied). Extreme climatic conditions were approximated by setting the potential evapotranspiration rates at 10 mm day$^{-1}$, with a maximum of 8.5 mm day$^{-1}$ transpiring through the crop (PET). Simulations were run over a period of 100 days to overcome the effect of initial conditions, and to approximate the length of time sugarcane has a closed canopy during conditions at high PET. Initial soil matric potentials were set to approximate field capacity (-10 kPa).

Constant water tables at depths of 1, 1.5, and 2 m were simulated via a constant potential ($\psi = 0$ kPa) bottom boundary condition. Three soil types were chosen from a range of soils previously described by Verburg et al. 2001). Uniform soil profiles were simulated based on data taken from an AP horizon of a Fairymead soil, an AP horizon from an Alloway soil, and a B22 horizon from an Oakwood soil (Table 1). The saturated hydraulic conductivities of the Oakwood and Alloway soils are at the extremes of soil types typically used for agricultural purposes (Marshall et al. 1996), while the Fairymead soil has a saturated hydraulic conductivity well above this range.

In order to represent the closed canopy conditions of mature sugarcane, fractional interception of PET was set at a constant value of 1. That is, PET was always at the maximum value of 8.5 mm day$^{-1}$. The root distribution was set as per the generic root description described by Danielson (1967), in which 40, 30, 20, and 10% of roots are found in successive quarters of the root zone. In the SWIM environment, this distribution was input by setting the fractions of maximum root length density as 1, 0.75, 0.5, and 0.25 for successive quarters of the root zone. Measured root length densities for sugarcane have ranged from 1 to 1.5 cm cm$^{-3}$ in Australia (M.Robertson, pers comm. 2001) and up to 2.75 cm cm$^{-3}$ overseas (Ball-Coelho et al. 1992). It was decided therefore to investigate irrigation requirements using three different values for maximum root length density (1, 1.5, and 2.5 cm cm$^{-3}$). Root radius was set at 0.024 cm, the average found by Ball-Coelho et al. (1992), and root conductance at 1.4 d-7 cm$^2$ h$^{-1}$ cm$^{-1}$ root (Bristow et al. 1984).
Table 1. Soil hydraulic property data for the soils used in the simulations: \( \theta_s \) is the saturated volumetric water content; \( \theta_r \) the volumetric residual water content; \( \psi_e \) the air entry potential; \( b \) the slope in the smoothed Brooks Corey water retention function; \( K_{sat} \) the saturated hydraulic conductivity; and \( \theta (\psi = -10kPa) \) is the volumetric water content as per initial conditions (Source: Verburg et al. 2001)

<table>
<thead>
<tr>
<th>Soil Properties</th>
<th>Fairymead</th>
<th>Alloway</th>
<th>Oakwood</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field texture</td>
<td>medium clay</td>
<td>sandy loam</td>
<td>light medium clay</td>
</tr>
<tr>
<td>( \theta_s (\text{cm}^3/\text{cm}^3) )</td>
<td>0.456</td>
<td>0.475</td>
<td>0.38</td>
</tr>
<tr>
<td>( \theta_r (\text{cm}^3/\text{cm}^3) )</td>
<td>0</td>
<td>0.040</td>
<td>0.097</td>
</tr>
<tr>
<td>( \psi_e \ (\text{cm}) )</td>
<td>4.17</td>
<td>11.63</td>
<td>8.09</td>
</tr>
<tr>
<td>( b )</td>
<td>12.75</td>
<td>2.30</td>
<td>7.64</td>
</tr>
<tr>
<td>( K_{sat} (\text{cm/hr}) )</td>
<td>161.72</td>
<td>39.47</td>
<td>4.71</td>
</tr>
<tr>
<td>( \theta (\psi = -10kPa) )</td>
<td>0.356</td>
<td>0.201</td>
<td>0.298</td>
</tr>
</tbody>
</table>

Initial rooting depths of 0.8 m were simulated, using the lowest maximum root length density (1 cm cm\(^{-3}\)). If transpiration rates were below potential, rooting depth was increased by 0.1 m to within 0.2 m of the water table. That is to 1.3 and 1.8 m for the 1.5 and 2 m water table scenarios respectively. Where the rooting depth was extended below 0.8 m, the fraction of maximum root length density from the bottom quarter of the 0.8 m simulation (0.25) was applied to the rootzone below 0.8 m. At each rooting depth, the irrigation requirements were assessed for the 1, 1.5, and 2.5 cm cm\(^{-3}\) maximum root length densities. Irrigation requirements were assessed from simulated transpiration rates once these transpiration rates approached steady state, which usually occurred around 30 days into the simulation.

4. SIMULATION RESULTS

4.1 FAIRYMEAD SOIL

The Fairymead soil is highly permeable, and this was reflected in the soil’s ability to maintain maximum transpiration rates over the 100 days even at water table depths of 2 m with rooting depths as shallow as 0.8 m and maximum root length densities of 1 cm cm\(^{-3}\). Resulting soil water contents throughout the profile for the 1m water table are above field capacity through most of the rootzone (Figure 1). While soil water contents are slightly drier for the 1.5 and 2m water table simulations, the water contents are above –100 kPa, within the range of water that should be easily extracted by plants. Provided the assumption that roots at 0.8 m are actively extracting water is valid, mature sugarcane would not require irrigation when water tables are within 2 m of the surface.

4.2 ALLOWAY SOIL

In the Alloway soil simulations with a rooting depth of 0.8 m and maximum root length density of 1 cm cm\(^{-3}\), maximum transpiration rates were achieved over the 100 days for the 1 and 1.5 m water table depths. Water contents at the end of 100 days for the 1 m water table were above field capacity, and were within the range easily extracted by plants for the 1.5 m water table (Figure 1). With a water table at 2 m, the resulting soil water profile at the end of 100 days was quite dry (Figure 1). Simulated transpiration rates from a water table at 2 m with a 0.8 m rooting depth and maximum root length density of 1 cm cm\(^{-3}\) reduced to 4.6 mm day\(^{-1}\) after 32 days and remained constant for the remainder of the 100 days. Increasing the maximum root length density to 2.5 cm cm\(^{-3}\) increased the constant transpiration rate in the later part of the simulation to 5.6 mm day\(^{-1}\). By increasing the rooting depth above the 2 m water table such that the distance between the active root zone and the water table was reduced, transpiration rates were increased (Figure 2). As the distance between the root zone and the water table decreased, simulated transpiration rates showed greater sensitivity to maximum root length densities until the distance between the root zone and water table was less than 0.7 m, at which stage, potential transpiration rates of 8.5 mm day\(^{-1}\) were achieved for all root length densities (Figure 2).

These simulations suggest that irrigation would not be required for mature sugarcane with roots actively extracting water at depths of 0.8 m, when water tables are within 1.5 m of the surface. For
deeper water tables, a combination of surface irrigation and sub-irrigation may be required to meet potential transpiration rates. The amount of surface irrigation required would depend greatly on the rooting characteristics, but should take into account that upflow is able to contribute at least 4.6 mm day\(^{-1}\).

4.3 OAKWOOD SOIL

The Oakwood soil is a slowly permeable soil, and this is reflected in the water contents at the end of 100 days of simulation. Water contents at the end of 100 days with a rooting depth of 0.8 m and a maximum root length density of 1 cm cm\(^{-3}\) are above –100 kPa when the water table is at 1 m, but the water content profile is much drier than that of the other two soils, which for similar simulations have water contents above field capacity (Figure 1). For a water table at 1.5 m, transpiration rates reduced to 6.9 mm day\(^{-1}\) after 25 days and remained constant for the remainder of the 100 days in the simulation with a rooting depth of 0.8 m and maximum root length density of 1 cm cm\(^{-3}\). If roots were extended to 1 m (within 0.5 m of the water table), potential transpiration rates were met by all maximum root length densities (Figure 2).

Simulations with the 2 m water table resulted in transpiration rates reducing to 2.9 mm day\(^{-1}\) after 26 days before remaining steady, for a rooting depth of 0.8 m and a maximum root length density of 1 cm cm\(^{-3}\). At this rooting depth, transpiration rates were only slightly increased when the maximum root length density was increased to 2.5 cm cm\(^{-3}\). At deeper rooting depths, the effect of increasing root length density was more pronounced (Figure 2). Once the roots were within 0.4 m of the water table, potential transpiration rates were met, regardless of maximum root length densities (Figure 2).

These results indicate that for water tables at 1 m and above, no irrigation would be required for mature sugarcane. For deeper water tables, the irrigation requirements would need to consider the likely rooting depth and root length density. However, contributions towards sugarcane evapotranspiration from water tables at 1.5 and 2 m would supply at least 6.9 mm day\(^{-1}\) and 2.9 mm day\(^{-1}\) respectively.

![Figure 1](image-url)  
**Figure 1.** Water content profiles at the end of 100 days from simulations with a maximum root length density of 1 cm cm\(^{-3}\) and rooting depth of 0.8 m for a) Fairymead soil b) Alloway soil and c) Oakwood soil. Water content profiles are given for the 1, 1.5, and 2 m water table depths. Water contents corresponding to field capacity (-10 kPa) and the lower limit of readily available water (-100 kPa, Inman-Bamber et al. 1998) are shown for reference.
5. DISCUSSION

The results of the simulations, showing all or large proportions of sugarcane’s water requirements can be met by upflow from water tables as deep as 1.5 m, are consistent with literature findings (Cenicana 1984, as cited in Torres and Hanks 1989, Hunsigi and Srivistava 1977). The magnitude of upflow simulated in the Fairymead soil from the 2 m water table must be considered with caution, as there are no experimental studies quantifying upflow from water tables below 1.5 m. The simulations suggest that a general rule of thumb of not applying irrigation to mature sugarcane when water tables are within 1 m of the surface may be applicable to a wide range of soil types. Further work is required to investigate whether this holds true for layered soils.

Guidelines for irrigating above water tables deeper than 1 m will need to be based on soil type, and take into account the active rooting depth and root length densities. It is not uncommon for sugarcane to extract water at depths of 2 m and below (Inman-Bamber et al. 1998), although in the extremely wet soil profiles above shallow water tables, water extraction by roots is difficult to identify from soil water measures. While rooting parameters are rarely measured, local knowledge, such as barriers to root proliferation could be used to develop sensible irrigation guidelines. A summary of irrigation guidelines based on the results of these simulations is presented in Table 2.

Table 2. Summary of irrigation requirements based on the simulations for three different soil types at three different water table depths

<table>
<thead>
<tr>
<th>Water table depth</th>
<th>Permeability of uniform agricultural soils</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low</td>
</tr>
<tr>
<td>1 m</td>
<td>&gt;RAW*</td>
</tr>
<tr>
<td>1.5 m</td>
<td>Needs irrigation</td>
</tr>
<tr>
<td>2 m</td>
<td>Needs irrigation</td>
</tr>
</tbody>
</table>

* >1 bar matric potential

The influence of soil type on irrigation requirements becomes more evident as the distance between the water table and the root zone increases. At larger distances, increasing root length densities had little effect on transpiration rates, indicating that upflow rates were being limited by soil properties. However, as the gap between the root zone and the water table decreased, root length densities showed a much greater effect on the long term transpiration rates. These results are in agreement with previous modelling studies (Thorburn and Meyer 1997) and also with theoretical predictions that increased root depths can increase capillary rise fluxes (Thorburn 1997).
Saturated hydraulic conductivities appear to be a better indicator of potential upflow rates as opposed to soil texture. The general rule of thumb that upflow is higher in loam soils than it is in sandy and clayey soils is not supported by the above modelling. The heaviest textured soil (Fairymead) had the highest saturated hydraulic conductivity and was able to transmit upflow at higher rates than the sandy loam (Alloway) and light medium clay (Oakwood) soils for deeper water table depths.

The results of these simulations should be applicable to a wide range of crops with similar root length densities such as maize (King et al. 1995) and lucerne (Smith et al. 1996). As the simulations were carried out using high values of evaporative demand, transpiration rates may be met from deeper water tables under conditions of lower evaporative demand.

The Australian sugar industry has a current target of increasing water use efficiency by 6% (Anon. 1999). The scenarios modelled in this study suggest that in areas with fresh, shallow water tables currently scheduling by pan based methods, this target could be reached easily. There are other potential benefits for the Australian sugar industry beyond a more efficient use of water resources. In irrigated areas where irrigation allocations depend on the reliability of irrigation supplies, allocations can range between 24 and 74% of the required irrigation (Tilley and Chapman 1999, Holden 1998). Improved ability to draw on shallow water tables as a source of crop water in these areas will enable more efficient use of restricted water, and potentially increase yields. Use of naturally occurring water tables as a method of subirrigation should also decrease the costs associated with pumping and purchasing of surface irrigation water. Economic benefits to farmers will largely depend upon the availability of water, and economic benefits will be higher where available water is well below that required for potential crop growth. Other savings may include the pumping and labour costs of irrigating surface water. Economic benefits will also arise where the quantity of water supplied by the water table results in a surplus of irrigation water that could be used elsewhere.

6. CONCLUSIONS

The potential for increasing irrigation water use efficiency in areas of irrigated sugarcane where shallow water tables occur is high, particularly as irrigation scheduling via pan based methods is common. Previous experimental studies, along with the results from simulations presented in this paper, suggest that mature sugarcane will not require irrigation for a range of agricultural soils when fresh water tables are within 1 m of the soil surface. This rule would be applicable to other crops with maximum root length densities greater than 1 cm cm\(^{-3}\) and rooting depths of at least 0.8 m. Our data also suggest that for uniform soil types: a) If near-saturated hydraulic conductivities are high, then deeper water tables (> 1 m) may also be capable of meeting the water requirements of mature sugarcane. b) Water tables as deep as 2 m are still likely to have a positive impact on the sugarcane water balance and c) Where irrigation is required, the amount will be dependent on local rooting characteristics such as rooting depth and density.

Further refinement of these findings will require additional work to address issues such as soil layering, and how sensitive predictions of required irrigation are to hysteresis and preferential flow. Investigation of plant responses to water tables of varying water quality is also required.

7. ACKNOWLEDGEMENTS

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SOIL MOISTURE MONITORING ISSUES, TECHNIQUES AND EQUIPMENT.

P Charlesworth

1. INTRODUCTION

Irrigation farmers are under increasing pressure to manage water more prudently and more efficiently. This is driven by product quality requirements, economic factors, demands on labour and the desire to minimise the resource degradation and yield loss that can result from inefficient irrigation (waterlogging, salinisation, degraded surface water quality). In response to this situation there has been an explosion in the range of equipment available for measuring soil water status as an aid to decision making for irrigation management (when to irrigate, how much water to apply, when to stop irrigating).

The key to efficient on-farm irrigation water management is good knowledge of the amount of water in the soil profile that is available to the crop and the crop water use requirement. Measuring and monitoring soil water status are essential parts of an integrated management package which helps to avoid 1) economic losses due to the effects of either under-irrigation or over-irrigation on crop yields and quality, and 2) the environmentally costly effects of overirrigation: wasted water and energy, leaching of nutrients or agricultural chemicals into groundwater supplies and degradation of surface waters with contaminated irrigation water runoff.

The following sections focus on the issues surrounding soil moisture monitoring, explanation of the major instruments used and where future development will focus. A more comprehensive guide to available products can be found in Charlesworth (2000).

2. MEASURES OF SOIL WATER STATUS

There are three common ways to describe the wetness of soil. These are gravimetric soil water content (SWC), volumetric SWC, and soil water potential. Which description is used depends partly on how the information will be used. All methods may be used for the same purpose e.g. to identify the need to irrigate.

2.1 GRAVIMETRIC SWC

Gravimetric SWC refers to how much water is in the soil on a weight basis e.g. 0.3 g water per 1 g of dry soil. This is the easiest way to measure SWC. All it requires is to take a small soil sample, weigh it, dry in an oven for a day, and then weigh again. The weight difference is the water lost from the sample.

2.2 VOLUMETRIC SWC

One problem with gravimetric measurement is that the densities of different soils vary and therefore a unit weight of soil may occupy a different volume. Hence, to allow comparison of the water content of different soils and to calculate how much water to add to a soil to satisfy a plant’s requirement a volumetric measurement is made.

Volumetric SWC is the most popular method of reporting the moisture status of soil. It is calculated by multiplying the gravimetric SWC by the soil bulk density and has the units of cubic centimetres (or millilitres) of water per cubic centimetre of soil. Bulk density is the mass of soil solids per unit volume. Bulk density is also used to calculate how much water a soil can hold.

2.3 SOIL WATER POTENTIAL

Volumetric measurements are convenient for measuring how full the soil is but give no indication of how difficult the water is to remove. As soil becomes drier, water is held more tightly and requires more energy to be extracted. The soil water potential is a measure of this tension and is expressed in...
kilo Pascals (kPa). Potential is also referred to as soil water suction. This is the term that will be used throughout this paper. Thresholds have been identified and irrigation can be managed to maintain soil water suction within this range to ensure a crop is not stressed through a suction that is too high or too low. However, as mentioned, trial and error are required to determine the volume of water to be added.

As a basic introduction to these measurements, average values for a range of soil textures are presented in Table 1.

**Table 1. Representative gravimetric (g/g) and volumetric SWC (cm³/cm³) and soil water suction values (kPa) for three soil textures**

<table>
<thead>
<tr>
<th></th>
<th>Sand (BD = 1.65 g/cm³)</th>
<th>Loam (BD = 1.55 g/cm³)</th>
<th>Clay (BD = 1.3 g/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>G V S</td>
<td>G V S</td>
<td>G V S</td>
<td>G V S</td>
</tr>
<tr>
<td>Saturation</td>
<td>0.23 0.38 0</td>
<td>0.27 0.42 0</td>
<td>0.38 0.5 0</td>
</tr>
<tr>
<td>Field capacity</td>
<td>0.10 0.17 33</td>
<td>0.24 0.37 33</td>
<td>0.33 0.43 33</td>
</tr>
<tr>
<td>Wilting point</td>
<td>0.07 0.12 1500</td>
<td>0.15 0.23 1500</td>
<td>0.25 0.33 1500</td>
</tr>
</tbody>
</table>

(G)ravimetric, (V)olumetric, (S)uction.

### 2.4 VARIABILITY

Agriculturalists are very aware of the variability that exists in their systems. In fact much effort is expended in attempting to even out this variability e.g. to ensure a uniform product. Subtle and sharp changes in soil type are evident both across the paddock and down the profile. Variation in crop growth may identify soil changes, past paddock use, disease, or irrigation application problems e.g. blocked drippers. Even within the soil very close to a plant there will be variation in where it extracts water. Time brings in another level with differences throughout the day and season in where and how much water is being extracted from the soil as roots and canopies develop.

All currently available soil water measuring instruments will tell us the soil water status at a particular point in a paddock. If we have a number of sensors then an array may be placed throughout the profile to give more information. But still, due to other practical limitations such as the time taken to read them or wiring, these will generally be within close proximity. Depending on the soil water monitoring system there may be only a single reading every few hectares. This reading is averaging out all the variability present in the whole area. That is, we are assuming the instrument is placed in the average soil type, next to the average plant, at the depth of average water uptake and in the zone of average water application. An irrigation schedule is then designed to satisfy the plant and soil in this position. Even if there are enough sensors present to show the variation in the field, how do we react to these? Do we water to satisfy the driest part of the field, ensuring no plant is under-watered? Or do we water to the wettest instruments, thus using water very efficiently but at the risk of decreased yield in those drier areas? All these issues must be taken into account when designing a soil water monitoring system. The following example demonstrates the spatial variability issue. Tensiometers were placed every 6 rows in a 42 row research plot of melons. The irrigation system was buried drip and the tensiometers were placed in identical positions in relation to an emitter. Readings were taken every morning.

To present this data, three soil suction brackets were selected relative to their implication for plant stress:

1. **WET**: $< 10$ kPa = no irrigation needed.
2. **GOOD**: $10$ kPa to $- 39$ kPa = irrigate tomorrow.
3. **DRY**: $> 40$ kPa = irrigation required yesterday.

The following graph [Figure 1](#) shows the number of tensiometers in each bracket for a given day. For instance, the trial commenced with six WET tensiometers. These progressively dried until the 23/1/98 when all were DRY. An irrigation then occurred which brought four tensiometers up to WET with two remaining DRY.
Figure 1. Rock melon trial - number of tensiometers in each tension bracket.

Figure 1 demonstrates the problem a producer faces with spatial variability when scheduling a whole field. While the aim was to maintain all tensiometers in the ‘GOOD’ range one can see that out of 77 days the aim was met on two days (20-21 Feb). Variation in soil, installation, blocked drippers, and plant condition can all contribute to the range of values measured and makes the problem of dealing with spatial non-homogeneity very hard to deal with. The most common solution would be to irrigate to keep the driest tensiometer in the right range, thus causing over-irrigation in other parts of the field but not risking yield decline.

3. TECHNOLOGIES FOR MEASURING THE SOIL WATER STATUS

Equipment representing both soil water status measurements (suction and volumetric water content) is used in the agricultural industry. By far the greatest number of products fit into the latter group. As technology has developed we have seen a move from manual data recording equipment with high labour requirements to in situ logging instruments with lower labour requirements but higher capital investment.

3.1 POROUS MEDIA

Porous media instruments are constructed from materials that are porous to water (water can move through and be stored in the pores). Water is drawn out of the porous medium in a dry soil, and from the soil into the medium in a wet soil.

Porous media instruments measure soil water potential and take three forms. These are tensiometers, resistance blocks, and volumetric SWC/porous material composite devices.

3.1.1 Tensiometers

A tensiometer is an instrument which directly measures soil moisture potential. It consists of a porous ceramic tip, a sealed water filled plastic tube and a vacuum gauge. The porous cup is buried in the soil and allows water to move freely between the water filled tensiometer and soil. As the soil around the cup dries the potential increases and water moves out of the tensiometer until the potential within the tensiometer is the same as that of the soil water. Since the tensiometer is an airtight device, as water moves out from the porous cup a negative pressure (a vacuum or suction) is created in the tensiometer equivalent to the soil potential. If the soil around the tensiometer becomes wetter (e.g. due to rain or...
irrigation) the soil potential decreases and soil water flows through the porous walls of the cup into the
tensiometer and the suction decreases. The soil suction reading relates directly to the amount of energy
that a plant must expend to remove water from the soil. Hence it is a more meaningful measure of plant
stress than soil water content. The suction is measured using a vacuum gauge or pressure transducer.
The transducer can be either a hand held device used to manually read many tensiometers or
permanently installed in the tensiometer and connected to a logger. The portable device has a hollow
needle which is inserted through a rubber bung or septum to measure the vacuum.

Tensiometers cannot be used to measure soil water suction greater than 75 kPa. Suctions above this
cause the vacuum in the tensiometer to break down through air entering the ceramic tip. Whereas this is
fine for most annual vegetable crops, orchards, nuts and pasture it is not sufficient during the controlled
stressing of plants such as grapevines where suctions as high as 200 kPa are recommended to produce
good wine quality.

3.1.2 Resistance blocks
Resistance blocks consist of two electrodes embedded in a block of porous material which is buried in
the soil. As with tensiometers, water is drawn into the block from a wet soil and out of the block from a
dry soil. The electrical resistance of the block is proportional to its water content which is related to the
soil water potential of the surrounding soil. Examples of these products are gypsum blocks and granular
matrix sensors.

![Figure 2. Measurement range of several soil water tension monitoring instruments.](image)

Key points:
- Tensiometers suited to well watered crops.
- Gypsum blocks and granular matrix sensors are suited to crops which benefit from periodic or
  prolonged soil drying.
- Thermal heat sensor and equitensiometer cover the whole range – best suited for research work.

3.2 NEUTRON MODERATION METHOD

The neutron moisture meter (NMM) was first used for measuring SWC in the 1950s. In Australia, it
gained popularity in the 1970s and 1980s and was the instrument of choice for irrigation scheduling
consultants. Most irrigation areas still have neutron probe services but the development of newer
electronic equipment with less emphasis on human input and the nuclear stigma have meant their use is
decreasing.

The neutron moderation technique is based on the measurement of fast moving neutrons that are
slowed (thermalised) by an elastic collision with existing hydrogen particles in the soil. Hydrogen is
present in the soil as a constituent of soil organic matter, soil clay minerals, and water. Water is the only form of hydrogen that will change from measurement to measurement. Therefore any change in the counts recorded by the NMM is due to a change in the water with an increase in counts relating to an increase in soil water content. The biggest advantage of NMM is its large measurement sphere of radius up to 20cm. The main downside is the nuclear issue and the increased licensing requirements.

### 3.3 SOIL DIELECTRIC

The dielectric constant is a measure of the capacity of a nonconducting material to transmit electromagnetic waves or pulses. The dielectric of dry soil is much lower than water and small changes in the quantity of free water in the soil have large effects on the electromagnetic properties of the soil water media.

Two approaches have been developed for measuring the dielectric constant of the soil water media and, through calibration, the SWC.

The speed of an electro-magnetic signal passing through a material varies with the dielectric of the material. Time domain reflectometry (TDR) instruments (eg. TRASE/Tektronix) send a signal down steel probes (called wave guides) buried in the soil. The signal reaches the end of the probes and is reflected back to the TDR control unit. The time taken for the signal to return varies with the soil dielectric, which is related to the water content of the soil surrounding the probe.

TDR instruments give the most robust SWC data with little need for recalibration between different soil types. Their downside is that they are extremely expensive and may require additional electronic equipment to be operated.

Frequency domain reflectometry (FDR) measures the soil dielectric by placing the soil (in effect) between two electrical plates to form a capacitor. Hence “capacitance” is the more commonly used term for these instruments. When a voltage is applied to the electric plates a frequency can be measured which varies with the soil dielectric.

The major expansion in soil water monitoring equipment lies in the FDR product group.

All dielectric sensing products share a relatively small measurement sphere of ~10 cm radius with 95% of the sphere of influence within 5 cm. This makes them sensitive to inconsistencies introduced through installation such as air gaps beside access tubes. The Aquaflex, developed in New Zealand, seeks to integrate such problems over a large soil volume by making the single sensor very long (~1 m).

Within the product group a variety of installation methods are represented including access tube, portable sensors, and buried sensors. The DIVINER and GOPHER products are operated similarly to a neutron probe where one sensor is lowered down an access tube to the required depth. It can then be moved to another location. EnviroSCAN®/C-Probe® also use an access tube, however they consist of an array of identical sensors placed permanently at set depths offering the advantage of both time and depth series logging.

A compromise is required between labour requirement and capital investment. Manual instruments offer lower cost per site but higher labour costs whereas logging, multisensor systems have a higher initial cost but lower labour costs. Cost is not the only consideration. Manual readings require not only greater labour but also higher commitment, motivation, and discipline. It is quite common for manual equipment to be used regularly in the initial period but discontinued as other activities take priority.

### 3.4 WETTING FRONT DETECTION

#### 3.4.1 Wetting front detectors as tools for irrigators

*(Dr. Paul Hutchinson – CSIRO Land and Water, Griffith, NSW)*

Wetting front detectors are soil moisture switches that are buried at the locations of interest. When soil moisture increases above a set point, the detector switches on. When the soil dries to below the set point the detector switches off. Wetting front detectors are inexpensive because they do not need to have continuous outputs that are calibrated to soil water content.
Wetting front detectors provide useful information to irrigators in three main ways;

i). **Warning signals**
A wetting front detector can act as a warning signal that over-irrigation is occurring if the detector is placed near the bottom of the root-zone. Irrigation beyond this depth is wasted because the crop cannot access this water. Irrigators can use a wetting front detector to reduce over-irrigation, fertiliser loss and water-logging and, as a consequence, to increase crop yield.

ii) **Regulation of irrigation amount**
Wetting front detectors can be used to regulate the amount of irrigation to the crop-water demand by placing the detector within the root-zone and turning off the irrigation when the wetting front is detected. This regulation occurs because wetting front speed depends on how dry the soil is before irrigation. If the soil is relatively dry the wetting front moves slowly into the soil. This occurs because the soil absorbs much of the water and hence slows the progress of the wetting front. Conversely, if the soil is already wet the wetting front moves fast because the irrigation water finds little available space to occupy.

iii). **Collection of soil-water samples**
Wetting front detectors can be designed to collect a sample of soil-water from the wetting front. This sample contains solutes such as salt and nitrate. When analysed, this sample can provide useful information to the irrigator for the management of fertilisers and the leaching of salt from the root-zone (Stirzaker and Hutchinson 1999).

### 3.5 FUTURE DEVELOPMENTS

Although we have seen rapid development in soil moisture monitoring equipment there are still some challenges to be faced which will steer future direction.

#### 3.5.1 Installation disturbance
The age-old problem of disturbing a system to measure it is very apt. Any water status measurement we make involves placing an instrument inside the soil, thus causing a disruption. Many of the instruments available have extremely small measurement spheres, which means the very material being measured is also the most disturbed part of the system.

#### 3.5.2 Variability
Our current techniques are based on point source measurements. Thus our ability to capture the variability of our systems is limited by the number of instruments that can be practically deployed and analysed.

#### 3.5.3 Soil and water quality
Stricter product quality, economics, environmental constraints, and overall pressure to optimise the inputs in our systems will increase our need to monitor not just water but solutes, particularly salts and nutrients. Combination devices will allow measurement of a number of parameters. The W.E.T sensor from Delta-T is the first such sensor to offer measurement of water content, electrical conductivity, and soil temperature.

A major move will be made to develop instruments that are able to measure without disturbance. Techniques adapted from other fields, for example earth science, include electromagnetic induction, resistivity measurement, and remote sensing.

### 4. REFERENCES

EVAPOTRANSPIRATION IN SUGARCANE

N.G. Inman-Bamber and M.G. McGlinchey

1. INTRODUCTION

Accurate estimates of crop water use are required to determine irrigation allocations and to improve management of both surface and underground water storages. For example, the delta region of the Burdekin Irrigation scheme and the Ord Irrigation scheme (Australia) are both vulnerable to impacts of irrigation on the water table and it is important to have reliable estimates of water use in order to better calculate runoff and drainage losses from sugarcane fields. It is also important to improve estimates of crop water use in order to improve irrigation system design and scheduling and ensure that water supply and crop water requirement are well matched on a daily or weekly basis. Matching water supply and demand is essential for productivity and sustainability in any irrigation scheme (Meyer 1997).

Kingston (1994) inferred a long term annual water use of 1786 mm for sugarcane in the Burdekin from lysimeter work that he and co-workers conducted in the 1970s. Roberston et al. (1997) used the APSIM-Sugarcane model (Keating et al. 1999) to calculate an annual water use of 1502 mm for 12-month crops planted and ratooned in spring in the Burdekin. The mean irrigation requirement for these crops was 1054 mm. Irrigation is also essential for the production of a viable sugarcane crop in Swaziland. The climate is semi-arid with hot wet summers and cool dry winters. Rainfall varies little through the region and averages 784 mm per annum. McGlinchey (1988) used the CANEGRO crop model (O’Leary 2000) to determine effective rainfall (386 and 510 mm), irrigation requirement (944 to 1173 mm) and annual water use (1454 to 1559 mm).

Micrometeorological methods for measuring evapotranspiration (ET) have not been applied widely to sugarcane. Grantz and Meinzer (1991) used Bowen ratio energy balance (BREB) to determine stomatal responses in sugarcane to humidity. Crop evapotranspiration (ETC) determined from BREB was used in canopy conductance equations to derive stomatal conductance over a limited number of days. Denmead et al. (1997) used BREB to assess the effect of trash mulch on evaporative losses from sugarcane crops in the early stages of development. The longest experiment was 18 days and the results were not compared with more accessible methods for estimating crop water use. Inman-Bamber and Spillman (2000) demonstrated near closure of the water balance in trickle irrigated field of sugarcane over a period of six weeks. Cumulative rain plus irrigation was close to cumulative ETC, determined with BREB, at times when the change in soil water near zero. Drainage was shown to be minimal and rainfall and consequent runoff were low.

Combined energy balance and aerodynamic approaches have been used to estimate potential ETC from sugarcane in southern Africa. Thompson (1986) developed coefficients for the Penman-Monteith (PM) equation in order to calculate ETC of cane in weighing lysimeters. McGlinchey and Inman-Bamber (1996) developed a reference ET for sugarcane (ETcane) which allowed for the influence of increasing cane height on aerodynamic resistance and hence on ETC. This modification to the PM equation led to accurate predictions of ETC of cane crops growing in lysimeters. However there were no independent ETC measurements to confirm ETC obtained from the modified PM procedure. This procedure is now being used to schedule irrigation in Swaziland.

The Penman-Monteith equation is now endorsed by the United Nations Food and Agriculture Organisation (FAO) as the preferred method for determining reference evaporation worldwide (Smith et al. 1996). FAO have recently produced clear guidelines (FAO 56) on determination of water requirements for a number of crops including sugarcane (Allen et al. 1998). The guidelines make use of reference evaporation (ET0) determined with the Penman-Monteith equation and crop coefficients that are used to convert ET0 to ETC for a particular crop at a particular stage of development. It is necessary for the sugar industry to consider new developments in micro-meteorology not only for possible use in scheduling but also to meet demands by the community at large for increased efficiency of water-use.
The aim of this research was to confirm or otherwise refine FAO 56 crop coefficients for sugarcane based on simultaneous BREB measurements in Australia and Swaziland. A second aim was to verify or refine ETc simulation in the APSIM-Sugarcane model (Keating et al. 1999).

2. METHODS

2.1 BOWEN RATIO ENERGY BALANCE (BREB) - KALAMIA, AYR, AUSTRALIA

BREB installation was initiated on 28 September 2000, in a 10.26 ha commercial block of sugarcane (cv. Q127, first ratoon) at Kalamia estate (19.57°S, 147.4°E), near Ayr in the Burdekin. At this stage the crop was 35 days old, 300 mm tall and had about 5% leaf cover. Location of the system was based on wind direction measurements over the previous 12-month period. Wind from an arc of 200° to 300° occurred only 10.9% of the daytime (0600 to 1800 h). BREB data were rejected when the wind came from this westerly direction even though the entire region was under irrigated sugarcane at full canopy for most of the duration of the experiment. The minimum fetch at 200° and 300° was about 75 m and the maximum fetch was nearly 350 m in a NE direction (Figure 1).

Crop evaporation (ETc) was obtained from latent heat flux (Le) as \( ETc = \frac{Le}{\lambda} \), where \( \lambda \) is latent heat of vaporisation of water = 2500.9 - 2.373T1 (J kg\(^{-1}\)) and T1 is air temperature at height (z1) of the lower arm. Le was obtained by solving the surface energy balance equation; \( Rn - G - H - Le = 0 \) where Rn is net radiation above the crop, G is the soil heat flux density and H is total sensible heat flux density (units are W m\(^{-2}\)). Bowen ratio (\( \beta \)) is the ratio of sensible heat flux to latent heat flux (H/Le) and was determined as \( \beta = \frac{\lambda (T1 - T2)}{e1 - e2} \) where e is vapour pressure (kPa) obtained from the Dew 10 and the psychrometric constant (\( \lambda \)) = \( \frac{\rho C_p}{\epsilon} \) where \( \rho \) = air pressure (101.23 kPa), \( C_p \) = specific heat of air at constant pressure (4190 J kg\(^{-1}\) K\(^{-1}\)) and \( \epsilon \) = the ratio of molecular weights of water vapour and air (0.622). Subscripts 1 and 2 refer to lower and upper arms respectively. Soil heat flux (G) was the sum of soil heat flux density at a depth of 80 mm and the heat stored in the 0 to 80 mm soil layer.

2.2 TUBE SOLARIMETERS - KALAMIA

On 22 October 2000, four recently calibrated tube solarimeters (1 m long) were placed on the soil surface in two places near the BREB installation, to span the dual crop row configuration exactly. Two more tube solarimeters were mounted above the canopy so that fraction of intercepted radiation could be determined. The solarimeters were multiplexed and logged at 20-minute intervals.
2.3 BOWEN RATIO ENERGY BALANCE (BREB) - SWAZILAND EXPERIMENT

The BREB system (CSI) in Swaziland was similar in many ways to the system installed at Kalamia. The BREB system was erected over a mature, erect, fully canopied sugarcane crop, variety NCo376, near Simunye, Swaziland (26°12'S and 31°54'E) for period of 70 days. Two nine metre masts were erected in the middle of an 80 ha commercial field to maximise fetch in any direction. Distance to the nearest field edge was 400 metres and there was no need to discard data on the basis of wind direction as was the case at Kalamia.

2.4 AUTOMATIC WEATHER STATIONS AND ET CALCULATIONS

On 17 September 1998, a purpose built (CSI) automatic weather station (AWS) was installed in an open grassed area about 1000 m from the BREB system at Kalamia. The AWS consisted of a tipping bucket rain gauge (T.B.3; Hydrological Services, Warwick Farm, Australia) an anemometer (RM Young Co. Traverse City, Mi USA), a pyranometer; (Li 200x, Licor Inc, Lincoln, NE, USA) and a combined temperature and humidity sensor (HMP45ac, Vaisala, Helsinki, Finland). The 50 x 50 m area around the AWS was mown and irrigated frequently. In Swaziland a similar model AWS was positioned 800 m from the BREB site over a well watered grass sward 50 x 35 m in size. The instruments were identical to those installed at the Kalamia site with the exception of the tipping bucket rain gauge, which was manufactured by Texas Weather Instruments (Dallas, Texas). All instruments were logged hourly.

AWS data were used to determine daily reference evaporation (ET₀) from equation 1 (Allen et al. 1998, FAO 56), where

\[ R_n = \text{net radiation at the crop surface (MJ m}^{-2}\text{ day}^{-1}) \]
\[ G = \text{soil heat flux density (MJ m}^{-2}\text{ day}^{-1}) \]
\[ T = \text{air temperature (°C) at 2 m height} \]
\[ u_1 = \text{wind speed at 2 m height (m s}^{-1}) \]
\[ VPD = \text{vapour pressure deficit (kPa)} \]
\[ \Delta = \text{slope vapour pressure curve (kPa °C}^{-1}) \]
\[ \gamma = \text{psychrometric constant (kPa °C}^{-1}) \]

\[ \text{An estimate of } ET_{\text{cane}} \text{ was also obtained from the AWS, using a modified two step approach, which was fully described by McGlinchey and Inman-Bamber (1996).} \]

2.5 NET RADIATION

The BREB system used at Kalamia was previously installed at a site at Millaroo about 60 km inland from Kalamia (Inman-Bamber and Spillman 2000). Readings from this net radiometer at Millaroo and later at Kalamia and the net radiometer in Swaziland were compared to assess the method for estimating net radiation in FAO 56.

2.6 IRRIGATION

At the Kalamia site, furrow irrigation was scheduled by an experienced grower using the mini-pan method of Shannon and Holden (1996). Inflow and outflow measurements made by Charlesworth (pers. comm.) provided information on infiltration for each irrigation. In the Swaziland experiment irrigation was applied on the soil surface using drip irrigation tape laid between each crop row. Irrigation was scheduled on a daily basis using a soil water balance approach in line with current estate practice in Swaziland.

2.7 APSIM SIMULATION OF KALAMIA EXPERIMENT

Daily radiation, temperature and rainfall from the AWS at Kalamia provided climatic data for simulation of the crop in the BREB experiment at Kalamia using the APSIM-sugarcane model (Keating et al. 1999). The soil (clay to 1m over sand) was similar to that described by Inman-Bamber and Spillman (2000) except that the clay layer was 100 cm rather than 40 cm. Soil hydraulic properties for input to the model were adjusted accordingly. Irrigation and rainfall was such that very little stress was
simulated thus reducing the impact of errors in soil hydraulic values. Genetic coefficients for cultivar Q96 were used because those for cultivar Q172 in the experiment have not been documented yet.

2.8 APSIM SIMULATION OF LYSIMETER EXPERIMENTS BY THOMPSON (1986)

Thompson (1986) reported lysimeter experiments with sugarcane (cv. NCo376) in sufficient detail to allow simulation of his experiments with APSIM-Sugarcane. The experiment involved a plant and a first ratoon crop growing in three weighing lysimeters, 1.22 m deep and 2.44 x 1.22 m at the surface. Irrigation was applied to minimise water deficits and $ET_C$ was measured daily. Soil input data for the simulation was modified from Robertson et al. (1999) to cater for the limited depth of the lysimeters. Genetic coefficients for the cultivar NCo376 were supplied with the APSIM software.

![Figure 2](image)

Figure 2. Daily climate and irrigation at Kalamia (1) and Swaziland (2). Maximum and minimum temperature (a1, a2), radiation (b1, b2), FAO reference evaporation, $ET_C$ (c1, c2), rainfall (solid bars) and irrigation (broken bars) (d1, d2). Note different scales in d1 and d2.

3. RESULTS

3.1 WEATHER AND IRRIGATION

Maximum temperatures at Kalamia were less variable than those in Swaziland for the same period of the year (Figure 2a). This was due to some low maximum temperatures in Swaziland during the summer months rather than differences in higher values, which were about 33 °C in both localities.
Minimum temperatures were lower in Swaziland than at Kalamia for the comparable period. During autumn and winter at Kalamia, minimum temperatures decreased more than maximum temperatures and there were several nights when minimum temperatures dropped below 10 °C. The range in radiation was similar in the two locations but the range in ET₀ was lower in Swaziland (Figure 2b, 2c). This was due to greater wind speed at Kalamia (187 km d⁻¹) than in Swaziland (129 km d⁻¹) as well as lower minimum relative humidity at Kalamia (43%) than in Swaziland (59%) over the comparable period (31 January to 21 March). Daily rainfall was considerably greater at Kalamia than in Swaziland, however rainfall at Kalamia after mid January was infrequent and irrigation had to be applied regularly (Figure 2d). Irrigation was required in Swaziland only towards the end of the experiment.

3.2 NET RADIATION

Net radiation (Rn) is the most important variable in both FAO reference ET₀ and in sugarcane reference ETᵅ. At Kalamia and Millaroo, the Rn estimate in FAO 56 was biased in a similar way but the random (unsystematic) error at Millaroo was small compared to that at Kalamia (Figure 3). Rn used to calculate ETᵅ in Swaziland was estimated using an equation developed by Wright (1982). Empirical constants in the equation were adjusted during initial model development (McGlinchey and Inman-Bamber 1986). Rn estimated with this method was similar to Rn estimated using the FAO 56 approach, however both underestimated measured Rn at Simunye. The bias was similar to that obtained at the Kalamia and Millaroo sites.

The reliability of the Rn estimate at a particular site will affect ET₀ to a varying extent depending on the relative sizes of the energy and aerodynamic components of the PM. It should be emphasised that ET₀
is a reference for comparison with crop ET (ETc) and errors in estimating Rn will affect the comparison between ETc and ET0 but not ETc which is the main reason for calculating ETc in the first place (Allen et al. 1998). The similarity in the bias in Rn estimate at all sites provides common ground for comparisons between measured ETc and ET0 in Australia and Swaziland.

3.3 CANOPY RADIATION INTERCEPTION

Canopy development at Kalamia was reflected in measurements of the fraction of intercepted radiation (FIR). Simulated FIR was lower than measured FIR when this was less than 0.7. Simulated FIR was greater than measured FIR when this was between 0.7 and 0.9 and then measured FIR rose to 1.0 while simulated FIR remained at about 0.9 (Figure 4). The crossover between measured and simulated FIR occurred when solar radiation (Figure 2b1) changed from the lowest to highest levels recorded during the experiment. APSIM-Sugarcane does not account for the effect of diffuse light on radiation interception, which would have been greater than simulated interception during cloudy weather in November (Figure 2b1). There was a rapid increase in measured FIR when the crop started to lodge after a storm on 19 January but this was reflected in the simulation.

The Swaziland experiment was designed to measure evaporation during the fully canopied period only.

Figure 4. Time course at Kalamia of measured fraction intercepted radiation (FIR, symbols) and simulated FIR (line).

3.4 CROP COEFFICIENT (Kc)

Determination of Kc described in FAO 56 is in relation to crop development and is essentially obtained from measured ETc divided by ET0. Kc measured in the Kalamia experiment increased from 0.4 to 1.0 while the fraction of intercepted radiation (FIR) increased from about 0.05 to 0.25. Then Kc rose sharply to 1.4 after rain on 30 October 2000 and remained at about this value for 8 of the following 12 days while FIR was <0.5 (Figure 4). Kc varied between 0.5 and 1.5 while FIR increased from 0.5 to 0.8 and then Kc became more stable at about 1.3 declining slowly to about 1.1 prior to irrigation on 19 April which may have relieved a period of mild water stress (Figure 2d1). Winds up to 15 m s⁻¹ caused some lodging on 19 January but this did not have a major impact on Kc. Mean ETc for the period when FIR>0.8, was 5.48 ± 0.13 mm and mean ET0 was 4.44 ± 0.07 mm (n=112). Weighted mean Kc was thus 1.23.

Over the 70 days duration of the Swaziland experiment, a total of 30 days were considered useable in the light of rejection criteria discussed previously. Mean ETc for this period was 5.19 ± 0.26 mm and mean ET0 was 3.98 ± 0.16 mm and weighted mean Kcmid for this period was thus 1.30. Kcmid varied between a low of 0.91 and a high of 1.54 (Figure 5). These lower values occurred during the first half of the measurement period when evaporation was low due to overcast conditions on some days (Figure 2b2, 2c2).
Weighted mean Kc for the two experiments was 1.24. Kc for a closed sugarcane canopy during the grand period of growth (Kc_{mid}) in FAO 56 is 1.25 and is therefore authenticated by these results. It is suggested that canopy closure is essentially complete when FIR>0.8 and that Kc = 1.25 for sugarcane crops in this condition. In FAO 56, Kc for the initial stages of crop development Kc_{initial} (0.4) was equal to the lowest Kc in the Kalamia experiment. This initial value is therefore also authenticated by these results. Kc for the final stages of crop development Kc_{fin} (0.7) differed considerably with the Kalamia results (Figure 5). It is possible that data for FAO Kc_{fin} were based on experiments where drying off was more severe than in the Kalamia experiment. There is no reference to supporting data in FAO 56. We suggest that Kc should apply to a crop with adequate water supply throughout its development. An additional coefficient could be invoked to force the crop to use water deeper in the soil profile and to impose some stress, which may be necessary to enhance sucrose concentration (Robertson et al. 1999). This would ensure consistency in FAO 56, which defines Kc in terms of adequate water, nutrients, disease and pest control (Allen et al. 1998).

The relationship between daily ET\(_0\) and daily ET\(_c\) measured when canopy was closed (FIR>0.8 at Kalamia) was similar to the relationship between daily ET\(_0\) and daily ET\(_c\) measured in Swaziland (Figure 6). Differences between intercept and slope coefficients were not statistically significant. This constitutes a good agreement between two sets of data for determining Kc across different countries. The similarity between Kc_{mid} determined in Australia and Swaziland indicates that crop coefficients derived from these experiments are sufficiently robust to be used across contrasting environments and cultivars.

### 3.5 ET\(_O\) APSIM AND TRANSPIRATION USE EFFICIENCY (TUE)

APSIM-Sugarcane partitions ET\(_c\) between E and T on the basis of FIR, thus inaccuracies in FIR simulation will lead to inaccuracies in this partitioning. ET\(_0\) was of course much reduced during periods of low radiation (Figure 2c) and errors in partitioning E and T would have reduced impact on cumulative E and T during these periods.
In APSIM-Sugarcane, T is proportional to the increment in above ground biomass (w) when soil water is not limiting (eqn 2).

\[ \Delta T = \frac{\Delta w \cdot VPD}{TUE} \]  

where TUE is transpiration use efficiency and VPD is the vapour pressure deficit calculated from minimum temperature. The model simulated \( \Delta w \) accurately between samplings 1 and 4 and between samplings 5 and 6 (Figure 7). Low \( \Delta w \) between samplings 4 and 5 corresponded with the period of reduced \( K_c \) (Figure 5). The default value of TUE in APSIM is 8.0 g kPa kg\(^{-1}\) obtained by calibration to datasets exhibiting water deficits (Keating et al. 1999). The satisfactory simulation of \( \Delta w \) and FIR between samplings 1 and 4 provided an opportunity to determine TUE directly provided the estimated partitioning between E and T during this period was accurate. While it is not possible to prove the accuracy of this estimate it is reasonable to assume that the error would be similar to the error in predicting FIR which was 10% at most (Figure 4). Thus T could be derived from the product of measured \( E_T \) and simulated partitioning fraction (T/ET). Regression of cumulative T over the period of samplings 1 to 4 yielded a slope coefficient of 4.88 ± 0.023 mm d\(^{-1}\) (or kg m\(^{-2}\) d\(^{-1}\)). Regression of measured biomass (w) on time yielded a slope coefficient of 34.1 ± 2.15 g m\(^{-2}\) d\(^{-1}\). Mean VPD for this period, calculated by APSIM as 3/4 the difference in saturation vapour pressure between maximum and minimum temperature, was 1.24 ± 0.028 kPa. From eqn 2, TUE then becomes 8.7 g kPa kg\(^{-1}\). Difficulties in predicting and averaging VPD obviously affected calculation of TUE. For the period between samplings 1 and 4, mean VPD derived from APSIM was similar to mean VPD measured by the BREB system between 600 and 1900 h (1.22 ± 0.032 kPa). These difficulties are fully discussed by Tanner and Sinclair (1983).

As far as is known this is the first time that TUE has been derived independently from simultaneous measurements of \( E_T \) and \( \Delta w \). The fact that the measured value is not far from the original approximation lends credence to the work of Keating et al. (1999) who found good agreement between

Figure 6. Daily \( E_T \) measured with Bowen ratio at Kalamia (○) and in Swaziland (●) versus FAO daily reference ET(ET0). Kalamia \( E_T \) was with FIR>0.8.
simulated biomass, LAI and sucrose yield for a large number of experimental crops across several countries.

Figure 7. Time course at Kalamia of above ground total biomass measured (- - - -) and simulated with transpiration use efficiency (TUE) = 8.0 g kPa kg$^{-1}$ (---). Bars are standard errors of the mean.

3.6 APSIM ET$_C$ AND LYSIMETER EVAPORATION

With the new TUE coefficient, APSIM simulated cumulative ET$_C$ of lysimeter 2 almost exactly during the plant crop (Figure 8). Cumulative ET$_C$ of the other two lysimeters was slightly above and below that of lysimeter 2 for the plant crop. In the ratoon crop the agreement between lysimeters was good. Simulated cumulative ET$_C$ was similar to measured cumulative ET$_C$ until the summer of 1968/69 when the simulated values were increasingly greater than measured. Simulated and measured mean cumulative ET$_C$ differed by 108 mm at most mid 1969. At the end of the first ratoon crop the difference between simulated and measured cumulative ET$_C$ was negligible (Figure 8).

The acceptable simulation of the lysimeter experiment provided independent proof of the validity of TUE = 8.7 g kPa kg$^{-1}$ and indirectly of Kc=1.25 for mid and late phases of crop development.

Figure 8. Cumulative evapotranspiration (ET) from three weighing lysimeters (Thompson, 1986) and simulated ET using the APSIM-Sugarcane model with revised transpiration use efficiency (TUE = 8.7 g kPa kg$^{-1}$)
4. DISCUSSION

BREB measurements in two countries have provided a sound basis for determining the crop coefficient for sugarcane during the middle period of development (Kc_{mid}) as presented in FAO 56 (Allen et al. 1998). Sugarcane in these two countries and many others has a relatively short period in the ‘initial’ and ‘development’ phases hence the emphasis on the mid and final stages in this research. ET_C measurements at Kalamia started during the ‘development’ phase when as little as 5% of incident solar radiation was intercepted by canopy. There was good agreement between measured Kc and Kc determined from FAO 56 while FAO 56 Kc was less than 0.8. This was done following the rules in FAO 56 with Kc_{init} = 0.4 and Kc_{mid} = 1.25. Thus Kc_{init} = 0.4 is appropriate. Measured Kc varied substantially when FAO Kc>0.8 until the canopy was essentially complete and intercepting >80% of radiation. This variation was consistent with the variation in Kc_{ini} in FAO 56 in relation to varying soil wetness and reference evaporation (Allen et al. 1998).

The support for Kc_{mid} of about 1.25 is substantial. We have pointed out difficulties in estimating net radiation for ET_0 calculations that will affect Kc_{mid}. Wind and humidity can also alter Kc_{mid} even though they are taken into account in the ET_0 calculation (eqn 1). Allen et al. (1998) provided equations to account for humidity and wind and when this was done for the Kalamia experiment Kc_{mid} was reduced to 1.1 at times when humidity was high and wind speed low (data not presented).

It is suggested that for irrigation of sugarcane in the east coast of Australia and in Swaziland, Kc_{mid} = 1.25 will result in adequate water supply to the crop with little wastage and there is little need to consider fine adjustments to Kc to account for the foregoing concerns. It is arguable that lower values could be tried at least in some soils where large soil water deficits may not result in yield reductions. Deficits up to 120 mm had no impact on cane yield or sucrose content in irrigation experiments in the Ord irrigation scheme in Western Australia (Muchow et al. 2001).

An important finding in this research is that there is no justification for reducing Kc during the final stages of crop development even if lodging occurs as was the case in the Kalamia experiment. It is possible that Kc would change if flowering occurred however. Growers need to reduce or cease irrigation during this phase in order to improve sucrose content (Robertson et al. 1999) but there is no evidence that the demand for water is in fact reduced.

The research discussed thus far is of value to irrigation schemes with access to FAO 56 technology supported by a good weather station network. Cropping system models for sugarcane are now available (O’Leary 2000) and these account for leaf area development and soil wetness during the complex partial canopy period. In many situations it would be better to use these models which not only deal with complex surface conditions but with rainfall and the water balance in general. The approach to ET estimation in the APSIM model is taken from one of the simpler approaches involving a transpiration use efficiency concept proposed by Tanner and Sinclair (1983). The Kalamia experiment provided data to determine transpiration use efficiency (TUE) of sugarcane for the first time. TUE = 8.0 g kPa kg^{-1}, originally assumed for sugarcane in APSIM (Keating et al. 1999) was not greatly different from TUE = 8.7 g kPa kg^{-1} found in the Kalamia experiment. The range in TUE for maize was 8.2 to 12.0 g kPa kg^{-1} with mean = 9.5 g kPa kg^{-1} (Tanner and Sinclair 1983), thus sugarcane may be inherently less efficient than maize in the use of water. The new value for TUE gave close agreement between simulated cumulative ET_C and measured cumulative ET_C in lysimeter experiments in South Africa (Thompson 1986). There is therefore a sound basis for using APSIM with the new TUE to estimate crop water use on a seasonal basis. The ET algorithms in APSIM model are probably too simplistic for a reliable daily estimate of ET_C. The RMSE (deviations from observed values) of the APSIM estimate of daily ET_C measured in the Kalamia experiment, was 1.3 mm or 34% of mean ET_C which is unacceptable. RMSE of weekly mean ET_C was 0.64 mm which is probably acceptable for weekly irrigation schedules. It is evident from equations 1 and 2 that APSIM’s ET_C estimate could be excessive in more arid conditions where VPD may be several times greater than VPDs measured at Kalamia. We recommend that FAO ET_0 and APSIM ET_C be compared when using the ASPSIM model in arid climates. Care should also be taken to check that APSIM’s estimate of VPD is accurate, as was the case in the Kalamia experiment.
5. ACKNOWLEDGEMENTS

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6. REFERENCES


CROP RESPONSE TO WATER STRESS

NG Inman-Bamber

1. INTRODUCTION

Reduced elongation of stalks and leaves in plants is one of the first symptoms of water stress and sucrose accumulation one of the last (Hsiao 1973). This distinction has wide implications for the management of irrigation in sugarcane. Varieties differ in response to water stress and these differences can also be exploited to make best use of climatic and soil conditions in a particular area. Quite a lot is known about stress physiology in cane and this paper will summarise some of this knowledge. There is not a great deal of data on varietal differences in response to water stress. Most of the data come from research on South African varieties. This will be summarised to give some idea of the scope of differences to be expected in Australian cultivars.

2. WHAT IS CROP STRESS?

Leaf extension rate (leaf plus stalk) was used to identify four stages of stress after a sugarcane crop received 50 mm rain on 29 March 1993 (Inman-Bamber 1995).

2.1 MILD STRESS

Leaf extension rate (LER) remained above 2 mm h\(^{-1}\) for 3 days after rain (Figure 1a). A short period of rapid growth occurred at about 1800 h each day and LER decreased at night in concert with air temperature. Plant extension was reduced sharply around midday on the 4th day after rain and the periods of suppressed midday growth were more pronounced on the 5th and 6th day. The diurnal pattern of growth during the first 3 days after rain could typify the growth of plants under minimal stress and the pattern observed during the subsequent 3-day period could identify plants under slight stress.

2.2 MODERATE STRESS

Another diurnal pattern became evident eight days later (Figure 1b). Evening and nightly growth was reminiscent of the pattern seen previously (Figure 1a) but was slightly reduced in relation to temperature. Day-time growth was minimal. This could be termed moderate stress. This type of diurnal pattern has been noted previously in sugarcane (Van Dillewijn 1952). Night-time growth (1730-0700 h) exceeded day-time growth (0700 to 1730 h) for a period of 200 days in both irrigated and rainfed treatments of a sugarcane experiment (Batchelor et al. 1992). The period of rapid growth at about 1800 h is thought to result from the accumulation of solutes in the cell during the day from photosynthesis.
These solutes reduce the osmotic potential in the vacuole and this combined with reduced transpiration and increased xylem water potential results in water uptake and increased turgor pressure and consequent cell expansion.

2.3 SEVERE STRESS

During severe stress LER was zero or negative during the day and was substantially reduced at night. The peak in growth in the evening and the decline at night, which were evident when soil water status was more favourable, were absent (Figure 2a).

2.4 VERY SEVERE STRESS

During the extremely dry period of June to August, plants extended slightly at night and shrank during the day (Figure 2b). Several stalks died at this time of very severe stress. Kozlowski (1972) documented several species in which shrinkage occurred under conditions of severe stress.

![Figure 2](image-url)

Figure 2. Mean hourly leaf or plant extension rates (LER or PER) and screen temperatures during a period of severe stress (a) and during a period of very severe stress (b). Bars indicate night (1800 to 0600 h) (after Inman-Bamber 1995).

2.5 RECOVERY FROM SEVERE STRESS

The diurnal pattern in LER described above for very severe stress changed immediately after rain. Two days after this rain, the diurnal growth pattern was similar to that of moderately stressed plants. This pattern lasted for 3 days and then more rain resulted in a recovery to a minimum or a slight stress (Figure 3).

![Figure 3](image-url)

Figure 3. Mean hourly leaf or plant extension rates (LER or PER) and screen temperatures before and after 28 mm rain overnight on 17 and 18 September (after Inman-Bamber 1995).
3. LEAF EXTENSION AND YIELD LOSS

Diurnal patterns of LER were determined in an irrigation experiment at Childers (Inman-Bamber and Spillman 2002). In a rainfed treatment, mild water stress was observed shortly after rain in early February 2001. Four to five weeks later, after no further rain had fallen, the diurnal pattern indicated that the crop was under moderate stress as defined above. At this point it rained again and stress was relieved. The best irrigated crop yielded 123 t cane/ha while the rainfed crop yielded 108 t/ha. It could therefore be concluded that moderate stress would lead to some yield loss. Mild stress is not considered to be a limitation to cane yield. A certain amount of stress particularly during the heat of the day is inevitable because the plant has to meet evaporative demand for water through transpiration. Water flows through the plant ‘down’ an energy gradient, which means that cells in the leaf are under some negative pressure. This reduces cell turgor and hence leaf and stalk elongation. Peak growth rates in the evening (Figure 1) could be considered as compensation for reduced elongation during the day.

4. PLANT STRESS AND LEAF WATER POTENTIAL

The negative water pressure (suction) experienced in plants is termed ‘water potential’ which is analogous to electrical potential. Water, like electrical current, flows from an area of high to low potential. If a transpiring leaf is cut and then pressure is applied to the leaf to squeeze the water out, the pressure required to get the water back up to the cut surface is equal to the water potential of the leaf. Most studies on crop response to water stress have used water potential to compare sensitivity of different crops and different growth processes to water stress. This is useful because we can also look at soil water availability in terms or water potential. For example in the paper "Plant available water and rooting depth" we saw that sugarcane experienced stress when the soil water potential reached –100 kPa. Instruments like tensiometers measure soil water potential directly. Leaf water potential (LWP) is usually much lower (more negative) during the day than soil water potential but when transpiration stops at night the potential gradient through the plant is reduced and LWP can equal soil water potential after several hours of equilibration.

Threshold LWP for various growth process in three South African varieties (NCo376, N12 and N14) are shown in Table 1.

<table>
<thead>
<tr>
<th>LWP (kPa)</th>
<th>Attribute</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-200 Plant extension rate falls below potential</td>
</tr>
<tr>
<td>2</td>
<td>-300 Stomatal resistance starts to rise gradually</td>
</tr>
<tr>
<td>3</td>
<td>-400 to –900 Plant extension ceases</td>
</tr>
<tr>
<td>4</td>
<td>-800 Youngest unfurled leaves start to roll</td>
</tr>
<tr>
<td>5</td>
<td>-1000 to –1700 Green leaf area is reduced</td>
</tr>
<tr>
<td>6</td>
<td>-1200 to –1700 Stomatal resistance rises rapidly</td>
</tr>
<tr>
<td>7</td>
<td>-1400 to –2300 Stomata finally close</td>
</tr>
<tr>
<td>8</td>
<td>-2000 Youngest unfurled leaf rolls fully</td>
</tr>
<tr>
<td>9</td>
<td>-2600 Apical meristem is permanently damaged</td>
</tr>
</tbody>
</table>

Previous stress history and varietal differences were responsible for the range in threshold values for attributes 3, 5, 6 and 7 above. Plants can sometimes become hardened by stress. Solutes can accumulate in the vacuole during a period of stress and this preconditions the plants for subsequent stress. This is known as osmotic adjustment or osmoregulation. The threshold LWP for plant extension decreased during successive stress cycles in a pot experiment and this was due to a general decrease in leaf osmotic potential (Inman-Bamber and de Jager 1986a). The threshold for the rapid increase in stomatal resistance differed between varieties, stress cycles and rates of stress imposition. The drought resistance of N12 was explained at least partially by the relatively high sensitivity of its stomata to decreasing LWP and the converse was true of N14, a variety known for lack of drought resistance. This
type of resistance in sugarcane distinguishes the species as one that avoids rather than endures drought (Kriedermann and Barrs 1983).

Sugarcane is not capable of large osmotic adjustments observed in other crops (Ludlow 1980). Drought endurance is not highly evolved in sugarcane. Drought avoidance mechanisms such as leaf shedding, leaf rolling and rapid stomatal closure have been observed in some varieties (Inman-Bamber and de Jager 1986a, b). In dry conditions, varieties endowed with these mechanisms yielded better than those without them but the reverse was true in conditions of full irrigation (Inman-Bamber 1982). It is important therefore to know the drought tolerance of different varieties in order to match varieties to soil types and climatic/irrigation conditions.

5. ONSET OF STRESS, YIELD AND CCS

The data in Table 1 are not very useful for management decisions since LWP is not a common practical measure of crop water status. In the Australian sugar industry, stalk elongation rate is probably the most common measure of water stress in the crop. Some measure of soil water deficit using electronic sensors, like EnviroSCAN, or neutron moisture meters is sometimes available. It would be useful to know how the various attributes in Table 1 are related to more common measures of crop water status. Stomatal resistance in Table 1 refers to resistance to gaseous diffusion through the leaf epidermis. This diffusion, which is controlled by stomatal aperture, is a major component of the photosynthetic and transpiration processes. Several dry-down experiments have been conducted in Australia and South Africa to determine what happens as crops run out of water. Instead of measuring stomatal resistance, total crop biomass was measured since this is the result of crop photosynthesis. Consideration of one experiment conducted in the Burdekin will serve to identify which processes are affected and in which order in relation to soil water deficit and leaf or stalk elongation.

5.1 BURDEKIN DRY-DOWN EXPERIMENT – EFFECT OF WATER DEFICITS ON GROWTH ATTRIBUTES

This dry-down experiment was conducted on young cane (5 to 7 months) during spring and summer of 1999. The crop was ratooned in late April 1999, well ahead of the milling season, to ensure that we had a reasonably large leaf canopy during spring and summer. Irrigation was applied to all plots up to 21 September 1999 and then to only half the plots. Leaf extension rate of dry plots relative to those of irrigated plots was reduced about 10 days after withholding irrigation and relative stalk elongation rate was reduced after about 15 days without irrigation (Figure 4). Total fresh biomass was reduced 35 days after the last irrigation and cane yield was severely reduced 49 days after irrigation. Stalks had not developed sufficiently to determine cane yield in earlier samplings. Dry cane yield was reduced by the stress treatment to a lesser extent than fresh cane yield 49 days after the last irrigation (Figure 4). At this stage about 50 mm rain occurred. This resulted in an immediate start to recovery of leaf and stalk elongation rate and total recovery after about 10 days. Growth in fresh and dry cane yield over the 14-d period following rainfall, was similar in ‘dry’ and ‘wet’ treatments but cane yield accumulation in the dry treatment stopped after 216 days of growth, 64 days after the last irrigation. At this point there was no difference in sucrose yield between wet and dry treatments because of a marked increase (>100%) in sucrose content due to water stress (Figure 4). Sucrose content continued to increase in wet and dry treatments alike despite the lack of cane growth in the dry treatment. The increase in sucrose content due to water stress was not sufficient to offset the substantial reduction in cane yield when the last sampling was carried out 235 days after ratooning and sucrose yield was significantly reduced by water stress at this point (Figure 4).
Figure 4. Time course for daily rainfall, leaf and stalk extension rates of stressed cane relative to well-irrigated cane (a), for total dry biomass (b), for total fresh biomass and cane yield (c), for dry stalk yield and sucrose yield (d) and for sucrose content (e). Broken lines in b,c,d and e show the well irrigated treatment and solid lines the dry treatment.
The order in which growth processes were first affected by water stress in relation to soil water deficit is shown in Figure 5. Leaf elongation was the first process to suffer from water stress, then stalk elongation, then total fresh biomass accumulation, then fresh and dry cane yield accumulation and finally sucrose accumulation. Critical points in the onset of stress in the elongation processes are also shown in Figure 4. The current recommendation in the industry is that irrigation is applied when stalk elongation rate reaches 50% of elongation rate of non-stressed plants. This point was reached when 72 mm water had been extracted and this amount constitutes the readily available water content of this soil as defined by Shannon et al. (1996). The research supported use of the 50% stalk elongation criterion as a safe method of scheduling irrigation but it also indicated that a lower threshold (25%) would also be ‘safe’ in terms of preventing a drop in photosynthesis due to water stress. Growers with limited water may well be able to adopt this lower threshold in order increase effectiveness of rainfall and water use efficiency.

Figure 5. Time course for total soil water content to a depth 2.25 m, showing when various stress thresholds were reached.

6. EFFECT OF STRESS AT DIFFERENT GROWTH STAGES

Two field experiments were conducted in the Burdekin by Robertson et al. (1999) to assess the impact of withholding irrigation from the crop at various stages of development. Deficits imposed during the tillering phase, while having large impacts on leaf area, tillering and biomass accumulation, had little impact on final yield (Table 2). On the other hand, water deficits imposed when the canopy was well established (leaf area index >2) had a more deleterious impact on final yield of total biomass, stalk biomass, and stalk sucrose.
Table 2. Components of yield at final harvest from two water stress experiments in the Burdekin, variety Q96. (Values followed by a common letter are not significantly different at P<0.05)

<table>
<thead>
<tr>
<th>Variate</th>
<th>Experiment 1, planted 12 April 1995</th>
<th>Experiment 2, ratooned 17 July 1996</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Well watered</td>
<td>Early season deficit</td>
</tr>
<tr>
<td></td>
<td>14/4/95 until 62 mm rain on 2-8/8/95</td>
<td>26/11/96 to 21/1/97</td>
</tr>
<tr>
<td>Total dry biomass t ha⁻¹</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td></td>
<td>56.8 a</td>
<td>47.6 a</td>
</tr>
<tr>
<td>Cane yield t ha⁻¹</td>
<td>149 a</td>
<td>120 a</td>
</tr>
<tr>
<td>Sucrose yield t ha⁻¹</td>
<td>24.2 a</td>
<td>19.6 a</td>
</tr>
<tr>
<td>Seasonal fraction of radiation intercepted</td>
<td>0.75 a</td>
<td>0.73 ab</td>
</tr>
<tr>
<td>Seasonal radiation use efficiency g MJ⁻¹</td>
<td>1.16 a</td>
<td>1.23 a</td>
</tr>
</tbody>
</table>

These results were explained very well by the APSIM model (Inman-Bamber et al. 2001). The lack of response to irrigation during early stages of development was due to low water use by the crop rather than greater resistance to stress at that stage. Conversely, the large response to irrigation mid-season was because of rapid water use and rapid onset of stress when irrigation was withheld. The model was then used to assess the risk of yield loss to lack of irrigation at various growth stages defined in terms of leaf numbers per stalk (Table 3). Table 4 shows when these leaf stages normally occur during the calendar year. This information can be used to assist with water savings during the early stages of crop development and also to point out to growers the risk of yield loss by delaying irrigation during mid stages of development.

Table 3. Median yield loss, irrigation saved and irrigation water use efficiency (IWUE) resulting from withholding irrigation during various growth stages. Data were derived from simulations of crops ratooning on two dates on two Burdekin soils for the period 1961 to 1997

<table>
<thead>
<tr>
<th>Soil</th>
<th>Ratoon date</th>
<th>Leaf phase</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0 to 5</td>
<td>5 to 10</td>
</tr>
<tr>
<td><strong>Median Yield loss (t ha⁻¹)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shallow October</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Shallow June</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Moderate October</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Moderate June</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td><strong>Median irrigation saved (mm)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shallow October</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Shallow June</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Moderate October</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Moderate June</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td><strong>Median response to irrigation (t ML⁻¹)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shallow October</td>
<td>.</td>
<td>7.0</td>
</tr>
<tr>
<td>Shallow June</td>
<td>.</td>
<td>9.6</td>
</tr>
<tr>
<td>Moderate October</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>Moderate June</td>
<td>.</td>
<td>.</td>
</tr>
</tbody>
</table>
Table 4. Median, earliest and latest date for the appearance of leaves on primary stalks (leaf stage) of crop ratooning in October or June in the Burdekin derived from simulations using APSIM- Sugarcane

<table>
<thead>
<tr>
<th>Leaf phase</th>
<th>Appearance date</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>October crops</td>
</tr>
<tr>
<td></td>
<td>Median</td>
</tr>
<tr>
<td>0 to 5</td>
<td>31-Oct</td>
</tr>
<tr>
<td>5 to 10</td>
<td>26-Nov</td>
</tr>
<tr>
<td>10 to 15</td>
<td>24-Dec</td>
</tr>
<tr>
<td>15 to 20</td>
<td>20-Jan</td>
</tr>
<tr>
<td>20 to 25</td>
<td>20-Feb</td>
</tr>
<tr>
<td>25 to 30</td>
<td>27-Mar</td>
</tr>
</tbody>
</table>

7. REFERENCES


WATER USE EFFICIENCY AND EFFECTIVE RAINFALL

N.G. Inman-Bamber

1. INTRODUCTION

In recent years there has been an increase in public awareness of water as a production factor and more importantly as a national resource and a major component of a fragile environment. The National Agenda for Water Reform has moved in the direction of full recovery of water supply cost, separate water and property rights, specific water allocation to the environment, and increased water use efficiency in agriculture. A new initiative on water use efficiency has been launched by DNR&M who have asked the sugar industry to make 60 000 ML available for irrigation from existing water resources. Definition and benchmarking of water use efficiency (WUE) has been a major concern of CRC Sugar.

There are many expressions of WUE, all with some measure of crop production in relation to water used. Definitions of water used include total rainfall, effective rainfall, total irrigation and net irrigation. Definitions of cane crop production include cane yield, sucrose yield and $ value of product. Kingston (1994) reviewed a number of experiments where water use by sugarcane was compared with cane yield. The average cane yield per 100 mm water used via evaporation and transpiration in the Australian experiments was 12 t/ha while the average for the South African experiments was about 10 t/ha per 100 mm water used. A more convenient term for WUE is t/ML, which is numerically the same as t/ha per 100mm. Thus the sugar industry has generally settled on a WUE definition based on tonnes of cane per ML water used via evaporation and transpiration. Irrigation experiments showed that responses of up to 27 t/ML irrigation could be achieved (Inman-Bamber et al. 1999) and this made it necessary to distinguish between crop response to irrigation and yield of cane in relation to water used over the season. The acronyms CRI (crop response to irrigation) and CWI (cane water index) are now in vogue to make this distinction.

2. CANE WATER INDEX (CWI)

The Bundaberg industry has been benchmarking WUE in the form of CWI for many years. CWI is defined as cane yield divided by effective rainfall plus irrigation. In the early 1990’s, a fixed 70% of the total July to June seasonal rainfall was selected as a measure of effective rainfall. This gave an average CWI in the range 7 to 8 tonnes cane per ML (t/ML). In the first two years, this measure proved to be a very useful extension tool focusing growers’ attention on water use efficiency by comparing their farm results with their respective mill area average.

Robertson and Muchow (1997) showed that the effective proportion of the total seasonal rainfall could vary from 56 to 81% rather than a constant 70%. Different methods were used to determine effective rainfall. A situation arose in 1998 where the CWI reached almost 12 t/ML for the entire district. As this value was equal to the maximum level proposed by Kingston (1994), critical evaluation of the method used to calculate effective rainfall and CWI was considered necessary. This criticism and the current political climate relating to rural water use efficiency also generated a need to re-examine the CWI benchmark. Standard settings of the APSIM-Sugarcane model have now been established in order to allow comparisons between years without confounding effects soil type, irrigation allocation, and cropping sequences. One reason for the high CWI in 1998 was the lack of realistic PAWC data for use in model runs. Of the four typical soil profiles available, the silt option was regarded as most representative of the Bundaberg industry. Using this soil and standard model settings, trends in CWI over the period 1989 – 1998 were determined.

CWI values calculated in this way were considerably lower than the maximum of 12 t/ML reported previously but the trends are similar with the CWI increasing from about 7.2 t/ML in 1989 - 92 to 8.8 t/ML over the period 1996 -98.
3. CROP RESPONSE TO IRRIGATION (CRI)

CRI is defined as the cane yield response to irrigation divided by the amount of net irrigation. This can also be termed ‘irrigation water use efficiency’ or IWUE. In full irrigation schemes CRI and CWI will be similar because a large proportion of the water used by the crop is derived from irrigation not rainfall. With supplementary irrigation, the reverse is true. Irrigation as low as 1/10 of rainfall is applied at irregular intervals, sometimes before and sometimes after canopy closure. Applications after canopy closure result in low evaporation losses from the soil. Applications before canopy closure may hasten canopy development resulting better in use of subsequent rainfall. Robertson et al. (1997) used a simple theoretical framework out of the APSIM-Sugarcane model to show that responses to limited irrigation could be as high as 22 t/ML at Mackay. Since APSIM was being used to develop best-bet irrigation strategies for limited water, it was important to see if the theory matched observed experimental results.

An experiment was conducted in 1996/97 on a Molonga series soil on the farm of Roy and Barbara Pace, Bambaroo in the Herbert. In one treatment irrigation was applied only before the wet season. Growth of experimental crops were simulated with APSIM which helped to fill in some of the detail which could not be measured (Table 1).

<table>
<thead>
<tr>
<th>Irrigation Treatment</th>
<th>Irrigation (ML/ha)</th>
<th>Irrigation plus rain (mm)</th>
<th>Evapotranspiration (mm)</th>
<th>Transpiration (mm)</th>
<th>Total dry biomass (t/ha)</th>
<th>Cane yield (t/ha)</th>
<th>CRI (t/ML)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Meas/Sim</td>
<td>Meas</td>
<td>Meas</td>
<td>Sim</td>
<td>Sim</td>
<td>Sim</td>
<td>Meas</td>
<td>Meas</td>
</tr>
<tr>
<td>Rainfed</td>
<td>30</td>
<td>1658</td>
<td>1075</td>
<td>673</td>
<td>36.4</td>
<td>42.7</td>
<td>102</td>
</tr>
<tr>
<td>Irrigation</td>
<td>179</td>
<td>1807</td>
<td>1288</td>
<td>912</td>
<td>46.5</td>
<td>55.3</td>
<td>143</td>
</tr>
<tr>
<td>Response</td>
<td>9.0%</td>
<td>19.8%</td>
<td>35.6%</td>
<td>27.7%</td>
<td>29.6%</td>
<td>40.1%</td>
<td></td>
</tr>
</tbody>
</table>

While irrigation only was 9% of rainfall, it increased evapotranspiration by nearly 20% because irrigation was applied only when necessary, whereas the crop could not use a lot of the rain. Irrigation increased transpiration by 36% because canopy development was more rapid in the irrigated than the
rainfed crops. Increased transpiration translated into a 28% or 30% increase in simulated or measured total dry biomass. The theoretical response in biomass was similar to the measured response even though the absolute biomass yields were not correctly simulated. Cane yield response was greater than biomass response because of an increase in the fraction of cane in total biomass due to irrigation (0.777 to 0.813) as well as a decrease in dry matter content of cane (32.3 to 31.4). With a combination of conventional field experimentation and theoretical modelling, large responses to limited irrigation, as predicted by Robertson et al. (1997), were shown to be possible and reasonable.

High CRI was also demonstrated in an allocation x irrigation system x cultivar irrigation scheduling trial in Bundaberg (Ridge and Hillyard 2000). Furrow irrigation was more efficient than usual because of short furrow lengths. The results in Table 2 confirmed the benchmark CWI of 12 t cane/ML proposed by Kingston (1994) and they showed that CRI can be much greater than CWI when allocations are low. However, as allocation increased and irrigation became a major source of water used by the crop, so CRI tended towards CWI.

Table 2. Mean water use efficiency (t cane/ML) for different allocations averaged over drip and furrow systems and over cultivars in an experiment at Bundaberg (Ridge and Hillyard 2000)

<table>
<thead>
<tr>
<th>WUE index</th>
<th>Allocation (ML/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td>CWI</td>
<td>9.4</td>
</tr>
<tr>
<td>CRI</td>
<td>-</td>
</tr>
</tbody>
</table>

4. IMPACT OF SOIL TYPE ON EFFECTIVE RAINFALL, CWI AND CRI

Soil input parameters for APSIM-Sugarcane were established for 11 Bundaberg soils from the data of Zund and McDougall (1997) and Donnollan et al. (1999) using the new maximum rooting depths and PAWC estimates (see the paper Plant available water and rooting depth). The range of soils simulated was augmented by four well-characterised profiles. These were a Clansthal sand of the rainshelter experiment in South Africa (Inman-Bamber 1986), a Molonga series cracking clay from Bambaroo (Inman-Bamber et al. 1999), an artificial duplex (300 mm clay loam overlying coarse sand) from Ayr (Robertson et al. 1999) and a Red Dermosol from Mr Schulte’s farm in Bundaberg (P Thorburn, pers. comm.).

The model was configured to simulate a typical cropping sequence for Bundaberg of a crop planted in March and harvested in June followed by four 13-month ratoon crops. Allocations per crop of two or four ML/ha were applied, 25 mm per irrigation, when the equivalent of 50% PAWC had been depleted, provided 10 days had elapsed since the last irrigation and it was not raining. Irrigation ceased after the allocations had been fully used. Rainfed conditions were also simulated.

Average effective rainfall per crop was greatest (981 mm) in the Red Ferrosol (2) and least (829 mm) in the Aeric Podosol (Table 3). Effective rainfall and rainfall efficiency were related to PAWC only when PAWC was less than 130 mm. Effective rainfall was greater than 940 mm and rainfall efficiency was greater than 75% in soils with PAWC more than 130 mm (Table 3). Year to year or crop to crop variation in rainfall efficiency was greater than the variation across soil types, as could be expected from the large year to year variation in rainfall (Figure 2a and 2b). However the difference in rainfall efficiency between soils was greater in some years than others. Soils tended to be more alike in years of high rainfall efficiency than in years of intermediate or low rainfall efficiency (Figure 2b).
Table 3. Mean effective rainfall per crop, rainfall efficiency, cane water index (CWI) and crop response to irrigation (CRI) for various soil types

<table>
<thead>
<tr>
<th>Soil Order/Profile Class (Site)</th>
<th>Dep. (m)</th>
<th>PAWC (mm)</th>
<th>Effect. Rainfall (mm)</th>
<th>Effic. (%)</th>
<th>Mean (t/ML)</th>
<th>CWI Min (t/ML)</th>
<th>Max (t/ML)</th>
<th>2ML (t/ML)</th>
<th>4ML (t/ML)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aer. Pod./Colvin</td>
<td>1.90</td>
<td>83</td>
<td>829</td>
<td>68</td>
<td>8.4</td>
<td>5.0</td>
<td>11.3</td>
<td>12.7</td>
<td>14.2</td>
</tr>
<tr>
<td>Yell. Chrom./Isis</td>
<td>1.90</td>
<td>88</td>
<td>849</td>
<td>70</td>
<td>8.4</td>
<td>5.4</td>
<td>11.4</td>
<td>13.4</td>
<td>14.7</td>
</tr>
<tr>
<td>Clay-sand duplex (Ayr)</td>
<td>0.70</td>
<td>110</td>
<td>902</td>
<td>74</td>
<td>8.1</td>
<td>4.2</td>
<td>11.3</td>
<td>14.9</td>
<td>16.2</td>
</tr>
<tr>
<td>Black Vert./Maroondan</td>
<td>1.15</td>
<td>131</td>
<td>814</td>
<td>72</td>
<td>8.5</td>
<td>4.8</td>
<td>11.8</td>
<td>15.4</td>
<td>16.2</td>
</tr>
<tr>
<td>Molonga (Bamharoo)</td>
<td>1.80</td>
<td>130</td>
<td>842</td>
<td>71</td>
<td>8.2</td>
<td>4.4</td>
<td>11.7</td>
<td>14.1</td>
<td>16.8</td>
</tr>
<tr>
<td>Yell. Derm.1/Kepnock</td>
<td>1.90</td>
<td>132</td>
<td>843</td>
<td>73</td>
<td>9.2</td>
<td>5.0</td>
<td>12.0</td>
<td>14.1</td>
<td>15.8</td>
</tr>
<tr>
<td>Red Ferr.3/Childers</td>
<td>1.00</td>
<td>142</td>
<td>949</td>
<td>77</td>
<td>8.9</td>
<td>4.7</td>
<td>11.8</td>
<td>15.9</td>
<td>16.5</td>
</tr>
<tr>
<td>Red Kand.1/Oakwood</td>
<td>1.60</td>
<td>150</td>
<td>952</td>
<td>77</td>
<td>9.2</td>
<td>5.1</td>
<td>12.0</td>
<td>14.6</td>
<td>15.6</td>
</tr>
<tr>
<td>Red Kand.2/Oakwood</td>
<td>1.60</td>
<td>150</td>
<td>944</td>
<td>77</td>
<td>9.2</td>
<td>5.1</td>
<td>12.0</td>
<td>14.5</td>
<td>15.6</td>
</tr>
<tr>
<td>Red Derm./Watalgan</td>
<td>1.60</td>
<td>153</td>
<td>942</td>
<td>76</td>
<td>9.1</td>
<td>5.1</td>
<td>12.0</td>
<td>14.4</td>
<td>15.5</td>
</tr>
<tr>
<td>Red Ferr.1/Childers</td>
<td>1.30</td>
<td>176</td>
<td>975</td>
<td>79</td>
<td>9.5</td>
<td>5.2</td>
<td>12.3</td>
<td>15.7</td>
<td>15.6</td>
</tr>
<tr>
<td>Red Ferr.2/Woongarra</td>
<td>1.30</td>
<td>184</td>
<td>981</td>
<td>79</td>
<td>9.6</td>
<td>5.2</td>
<td>12.3</td>
<td>15.8</td>
<td>15.4</td>
</tr>
<tr>
<td>Red Derm.2/Otoo (Schulte)</td>
<td>1.50</td>
<td>210</td>
<td>942</td>
<td>76</td>
<td>10.7</td>
<td>7.3</td>
<td>13.1</td>
<td>13.7</td>
<td>12.6</td>
</tr>
<tr>
<td>Clanthal (S Afr.)</td>
<td>3.00</td>
<td>216</td>
<td>967</td>
<td>79</td>
<td>11.6</td>
<td>9.1</td>
<td>13.7</td>
<td>11.2</td>
<td>11.7</td>
</tr>
</tbody>
</table>

CWI varied considerably over successive crops and years (Figure 2c). The interaction between climatic conditions and soil type detracts from the usefulness of a long-term mean CWI for each soil type. Variation between soils in maximum CWI for the 37-year period was not excessive but mean and minimum values varied considerably (Table 3). CWI tended to be greater in high PAWC soils than in low PAWC soils.

CRI also varied considerably from year to year (Figure 2d). CRI ranged from less than 5 to more than 25 t cane/ML. Although the simulation rules always ensured that all irrigation was applied when the soil could store it in the root zone, subsequent rainfall sometimes reduced the response to irrigation. The interaction between climate (years) and soils was such that CRI was greatest in low PAWC soils in some years and least in these soils in other years (Figure 2d). Mean CRI for allocations of 2 and 4 ML tended to be greatest in soils with intermediate PAWC rather than in soils with high or low PAWC (Table 3).

If rainfall efficiency, CWI and CRI are to be benchmarked at the paddock scale or on a year by year or crop by crop basis, long-term means of these efficiencies may be misleading. It is likely that planting and ratooning dates and other management factors also interact with soil and climate. Since APSIM can deal with a large number of management, soil and climatic factors, it is argued that rainfall and water use efficiencies be determined for specific conditions using APSIM when the information is required. Soils used in this analysis are common throughout the Gin Gin, Bundaberg, Childers, Hervey Bay, Maryborough and Tiaro regions and have been mapped to a scale of 1:50 000 (Donnollan et al. 1999). It is thus conceivable that yield and water use efficiency benchmarks could be mapped along with these soils. It may also be possible in future to assess various management strategies for each soil type in each region in order to optimise water use on a regional basis. These possibilities highlight the need to improve knowledge of both soil and plant attributes that most affect cane production and water use.
Figure 2. Rainfall (a), simulated rainfall efficiency (b), simulated cane water index (c) and simulated crop response to 2ML/ha irrigation (d) for successive cropping cycles (1 to 6) of a plant, four ratoons and 5-month fallow for three Bundaberg soils.
REFERENCES


DRYING-OFF IN SUGAR CANE

N.G. Inman-Bamber, S Attard and N Stoeckl

Drying-off is the practice of withholding irrigation for a period before harvesting to enhance sucrose (CCS) accumulation as well as to ensure that the soil is dry enough to support heavy harvesting machinery. Normally the period required to enhance CCS is longer than that required to dry the soil out for harvesting traffic. We will not be concerned about soil mechanical properties in this paper on drying-off.

1. CANE YIELD AND CCS RESPONSES TO DRYING-OFF

Studies on drying-off are rare in Australia. This is in contrast to southern Africa (South Africa, Swaziland and Zimbabwe) where there have been over 30 drying-off experiments conducted from 1966 to 1995 (Robertson and Donaldson 1998). In Australia, responses to drying-off were determined in two experiments at Ayr (Robertson et al. 1999a) and the responses differed in the two seasons concerned. In 1994/95, 8 and 13-week treatments produced higher CCS and sugar yield than the minimal drying-off treatment (Table 1). Cane yield was unaffected. The lack of a reduction in cane yield in 1994/95 was possibly due to lodging occurring 6 weeks before harvest in the minimal drying-off treatment. In 1995/96, the 9/4 (13 weeks dry-off interrupted with one irrigation 4 weeks before harvest) and 13 week treatments produced higher CCS, but in contrast to 1994/95, cane and sugar yields were reduced compared to the minimal drying-off treatment.

Table 1. Cane yields, CCS, and sugar yields in two seasons of drying-off experiments at Ayr. Within a season, values followed by the same number were not significantly different at P< 0.05 (Robertson et al. 1999a)

<table>
<thead>
<tr>
<th>Drying-off treatment (weeks before harvest)</th>
<th>Season</th>
<th>Cane yield (t/ha)</th>
<th>CCS</th>
<th>Sugar yield (t/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>1994/95</td>
<td>149 a</td>
<td>15.4 a</td>
<td>23.0 a</td>
</tr>
<tr>
<td>8</td>
<td></td>
<td>159 a</td>
<td>16.7 b</td>
<td>26.7 b</td>
</tr>
<tr>
<td>13</td>
<td></td>
<td>155 a</td>
<td>16.2 b</td>
<td>25.2 b</td>
</tr>
<tr>
<td>4</td>
<td>1995/96</td>
<td>125 a</td>
<td>15.3 a</td>
<td>19.1 a</td>
</tr>
<tr>
<td>9/4</td>
<td></td>
<td>111 b</td>
<td>16.0 b</td>
<td>17.8 b</td>
</tr>
<tr>
<td>13</td>
<td></td>
<td>103 c</td>
<td>17.0 c</td>
<td>17.5 b</td>
</tr>
</tbody>
</table>

The Australian results were compared with southern African results in Table 2. Out of the 137 drying-off regimes studied in the southern African trials, a total of 83 (61%) resulted in a statistically significant change in CCS, cane yield or sugar yield. This illustrates the inherent riskiness of drying-off, where interruption by rain or insufficient time between withholding irrigation and harvest can prevent the development of crop water stress. Robertson and Donaldson (1998) found that generally, drying-off is more often associated with an increase in sucrose concentration than with an increase in sucrose yield. This was also the case with the Ayr results where CCS increased in all treatments, but sugar yield was reduced in 1995/96 (Table 1). Interestingly, the southern African results also showed that in drying-off treatments that reduced cane yield, the average response in CCS was no different from treatments where cane yield was not reduced. This was also the case at Ayr with CCS increase on average being no better in the 1995/96 season when sugar yield was reduced. In 1994/95, the increase in CCS was similar to the average for the African studies, while in 1995/96, the Ayr result was closer to the maximum ever recorded in southern African experiments.
Table 2. Summary of responses to drying-off in terms of CCS and sucrose yield from a survey of experiments conducted in southern Africa from 1966-1995 (Robertson and Donaldson 1998) and from 2 seasons of experiments conducted at Ayr. A response to drying-off was defined as when there was a statistically significant change over that of the control, which was not dried-off

<table>
<thead>
<tr>
<th>Response to drying-off</th>
<th>Summary of 84 southern Africa studies</th>
<th>Ayr 1994/95</th>
<th>Ayr 1995/96</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Proportion of drying-off treatments</td>
<td>Average</td>
<td>Maximum</td>
</tr>
<tr>
<td>Change in CCS (% units)</td>
<td>64%</td>
<td>+1.03</td>
<td>+2.1</td>
</tr>
<tr>
<td>Change in sucrose yield (t ha⁻¹)</td>
<td>23%</td>
<td>+1.3</td>
<td>+2.5</td>
</tr>
</tbody>
</table>

2. DEVELOPING TARGETS FOR DRYING-OFF

The severity of drying-off required to produce maximum return to the grower depends on the income received for the crop, minus costs that vary with the severity of the drying-off period, such as irrigation and costs of harvesting. The income received for the crop will depend upon the response of the crop to water deficit, and the method of cane payment. Sugar industries differ in the basis for cane payment. In Australia a premium is paid for cane of high sucrose concentration. In order to define the optimal severity of drying-off required to produce maximum return to the grower, one needs to account for the differential response of cane yield, sucrose yield and cane sucrose concentration to water deficit as well as the costs incurred.

2.1 RESPONSE OF CANE YIELD, SUCROSE CONCENTRATION AND SUCROSE YIELD TO DRYING-OFF

Robertson et al. (1999c) analysed the response of sugarcane to drying-off using the large dataset pooled from experiments conducted in southern Africa. They related changes in cane yield, sucrose yield, and sucrose concentration to severity of drying-off, defined as cane biomass expressed relative to a crop that had not been dried-off. Cane biomass is cane yield minus its water component. Cane yield was highly sensitive to drying-off indicating that some dehydration of the stalk occurs under drying-off (Figure 1a).

Sucrose yield was less sensitive than cane yield to drying-off. Robertson and Donaldson (1998) showed that under mild levels of stress, where cane biomass had been reduced by up to 4%, sucrose yield either increased or did not change. This is quantified here by the regression line fitted through the southern African and Australian data (Robertson et al. 1999c) \( Y = 1.048 \times X - 0.011 \), which crosses the \( Y = 1 \) line at value of relative cane biomass of 0.96 (Figure 1b).

Sucrose content was less sensitive to drying-off than sucrose yield, but more variable. Figure 1c shows the plot of relative sucrose concentration against relative cane biomass, from Robertson and Donaldson (1998) and Robertson et al. (1999c). It shows that sucrose concentration is increased by drying-off, by up to 18%, for relative cane biomass yields down to 0.5, and can decrease under severe stress levels. As response of sucrose concentration is variable at any level of relative cane yield, one can define upper, median and lower envelopes of the scatter-relationship between relative sucrose concentration and cane biomass, and these are plotted in Figure 1c.

2.2 GROSS RETURN

Cane payment is based on yield of fresh cane and its sucrose concentration so the trade-offs between the relationships in Figures 1a, 1b and 1c need to be accounted for. The envelope curves in Figure 1c can be converted, using the Australian cane payment formula, to give the response of relative gross return per unit of cane against relative cane biomass (Figure 1d). For the median curve, the return per
unit of cane does not become less that that of the well-watered crop until relative cane biomass falls to about 0.55. When this is combined with the response of cane biomass to drying-off, then the response depicted in Figure 1e is arrived at. Values of relative cane biomass of 0.82, 0.92 and 1.02, corresponding to the three curves in Figure 1c, represent the cut-offs below which drying-off reduces gross return per hectare compared to a crop that is not dried-off.

2.3 NET RETURN

As drying-off may reduce cane yield, the associated harvesting costs should be accounted for in any economic analysis of drying-off. In Australia, harvesting costs are 15-20% of the gross value of the crop. Harvesting costs are based on the weight of fresh cane harvested, hence the regression relationship in Figure 1a must be used to calculate the relative cane yield for a given relative cane biomass. The resulting relationship in Figure 1f shows that net return per hectare will be reduced once relative cane biomass reaches 0.75, 0.90 and 0.98 for the three envelope curves. These three cut-offs can be thought of as corresponding to situations where the response of sucrose concentration to drying-off is good, fair or poor.

2.4 OPTIMUM DRYING-OFF

The degree of drying off for which the median relative net returns are maximum is about 4% (Figure 1f) and the degree of drying-off beyond which the median net relative returns are less than 1.0 is 8%. Given the uncertainty in the experimental data (as in all data of this nature) it is suggested that 4% cane biomass reduction be regarded as the minimum (low risk) drying-off target and that 8% be regarded as the maximum (moderate risk) target.

Figure 1. Relative cane yield (a), relative sucrose yield (b), relative sucrose content (c), relative return per unit cane (d), relative gross return (e) and relative net return (f) in relation to relative cane biomass (drying-off). ‘Relative’ means in relation to treatments that were not dried off. In (c) curves represent the upper, median, and lower bounds of the relationship and these have been used in (d), (e) and (f) to show range of possible responses. In (d), (e), and (f) the vertical broken line is the cut-off of relative cane biomass where relative return falls below 1.0 using the median curve. In (e) and (f) the vertical dotted line is the degree of drying-off for which the median gross and net returns were greatest. (adapted from Robertson et al. 1999c).
3. OPTIMAL LENGTH OF DRYING-OFF FOR A 6% LOSS IN CANE BIOMASS

The ability of the APSIM-Sugarcane model to simulate reduction in cane biomass under drying-off has been tested using results of drying-off experiments conducted in Australia and southern Africa (Robertson et al. 1999c). Simulation output from APSIM-Sugarcane was used to determine the duration of drying-off required to reduce cane biomass by either 4% or 8% at Ayr for harvest dates on the 15th of each month from May to November inclusive. Details of the simulation set-up and analysis of output data have been described by Robertson et al. (1999b). Three soil types were simulated, having high (210 mm), medium (162 mm) and low (114 mm) amounts of total plant available water (PAWC) in a 150 cm root zone. These PAWC values correspond to readily available water (RAW) amounts (Shannon et al. 1996) of approximately 80, 60 and 30 mm respectively. A fully irrigated production system was assumed. For each harvest date, irrigation was then withheld for 0, 30, 60, 90 and 120 days before harvest. Simulations were conducted for 12 month crops for the years 1961-1985 for the historical climatic record described by Muchow et al. (1997). At Ayr, the months of the traditional harvesting season (July to November) have the lowest monthly rainfall amounts and variability. Rainfall amount and variability are greatest leading up to the May harvest date, and least leading up to the August harvest date.

The cane biomass simulated at harvest for each drying-off regime was divided by that simulated for the corresponding crop that had not been dried-off to calculate the reduction in cane biomass. The days of drying-off required to reduce cane biomass in 50% of seasons by at least 4% or 8%, varied with harvest date and soil type (Table 3). A value of 50% of seasons strikes a balance between the opposing risks of drying-off for not long enough or for too long (see below). With 15 May harvest, optimal drying-off (a 4% reduction in cane biomass) ranged from 49 to >150 days for low to high PAWC soil types, whereas a 15 October harvest date required only 29-43 days, depending on soil type. The variation in dry-off period is mainly due to variability in rainfall after drying has started and this is more prevalent in May than in other months in the Burdekin.

<table>
<thead>
<tr>
<th>Table 3. Drying off period (days) required to reduced biomass yields by target levels of 4 and 8% which correspond to maximum and breakeven $ returns due to increased CCS. Different soils and harvest dates are considered</th>
</tr>
</thead>
<tbody>
<tr>
<td>Harvest date</td>
</tr>
<tr>
<td>Yield reduction</td>
</tr>
<tr>
<td>Low PAWC</td>
</tr>
<tr>
<td>Medium PAWC</td>
</tr>
<tr>
<td>High PAWC</td>
</tr>
<tr>
<td>Harvest date</td>
</tr>
<tr>
<td>Yield reduction</td>
</tr>
<tr>
<td>Low PAWC</td>
</tr>
<tr>
<td>Medium PAWC</td>
</tr>
<tr>
<td>High PAWC</td>
</tr>
</tbody>
</table>

4. RULE-OF-THUMB FOR DRYING-OFF

A practical rule-of-thumb to guide the length of the drying-off period must be able to take account of variation in soil type (i.e. PAWC) and the crop water demand and rainfall occurring prior to particular harvest dates across the industry. The severity of soil drying during drying-off will be related to the balance of evapotranspiration and effective rainfall (total rainfall minus runoff and deep drainage). This balance can be represented roughly as the net crop water demand, defined here as evapotranspiration minus effective rainfall occurring during the designated drying-off period. Net crop water demand can be normalised across soil types by dividing it by PAWC. This is the basis of the South African rule-of-thumb, which states that sugarcane should be dried-off for a period sufficient for
total potential evapotranspiration to be approximately twice the PAWC of the soil. Effective rainfall is ignored in their calculation.

The net crop water demand during drying-off required to produce an average 4% reduction in cane biomass is presented in Table 4. While net crop water demand varied widely with soil type and harvest date, when expressed as a multiple of PAWC of the soil type it varied less, from 1.6 to 1.0, suggesting a relatively stable rule-of-thumb, particularly within a soil type across harvest dates. PAWC is approximately twice the amount of readily available water (RAW).

Table 4. Net crop water demand (evapotranspiration minus effective rainfall) during drying-off periods required to reduce cane biomass yield by 4% in the Burdekin, expressed as a multiple of low, medium and high PAWC values (114, 162 and 210 mm respectively)

<table>
<thead>
<tr>
<th>PAWC (mm)</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
</tr>
</thead>
<tbody>
<tr>
<td>114</td>
<td>1.6</td>
<td>1.6</td>
<td>1.8</td>
<td>1.6</td>
<td>1.7</td>
<td>1.7</td>
<td>1.6</td>
</tr>
<tr>
<td>162</td>
<td>1.3</td>
<td>1.2</td>
<td>1.3</td>
<td>1.3</td>
<td>1.3</td>
<td>1.3</td>
<td>1.3</td>
</tr>
<tr>
<td>210</td>
<td>1.1</td>
<td>1.2</td>
<td>1.2</td>
<td>1.1</td>
<td>1.2</td>
<td>1.0</td>
<td>1.0</td>
</tr>
</tbody>
</table>

5. RECENT MODIFICATIONS

Recent modifications to the foregoing have been made following interaction with growers in the Burdekin. Growers would prefer to know the minimum dry-off period required to enhance CCS without risking loss in CCS yield. This is different from the approach of Robertson et al. (1999b) in that it ignores rainfall. The concept is that growers can make their own judgements about the likelihood of rain and start drying off ahead of the minimum dry-off period but if expected rain does not occur they can then irrigate. Growers would also prefer current recommendations based on current weather conditions rather than the generic recommendations produced by Robertson et al. (1999b). For example, dry-off periods were recalculated in April 2002 ignoring rainfall for the 2002 harvest season (Table 5).

Table 5. Minimum (no rain) drying-off periods (days) required to reduced biomass yields by 6% for different soils and harvest dates at two sites in the Burdekin. Calculations were done in April 2002 for the 2002 harvest season

<table>
<thead>
<tr>
<th>Soil</th>
<th>Site</th>
<th>Minimum drying-off periods (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Jun 15</td>
<td>Jul 15</td>
</tr>
<tr>
<td>Sand</td>
<td>Kalamia</td>
<td>42</td>
</tr>
<tr>
<td>Silt</td>
<td>Kalamia</td>
<td>57</td>
</tr>
<tr>
<td>Clay</td>
<td>Kalamia</td>
<td>68</td>
</tr>
<tr>
<td>Heavy Clay</td>
<td>Kalamia</td>
<td>75</td>
</tr>
<tr>
<td>Sand</td>
<td>Millaroo</td>
<td>36</td>
</tr>
<tr>
<td>Silt</td>
<td>Millaroo</td>
<td>49</td>
</tr>
<tr>
<td>Clay</td>
<td>Millaroo</td>
<td>61</td>
</tr>
<tr>
<td>Heavy Clay</td>
<td>Millaroo</td>
<td>66</td>
</tr>
</tbody>
</table>

The target dry-off periods were generally shorter than those that took rainfall into account, as would be expected. However the impact of rainfall on the target dry-off period was small during August to October when the chance of getting rain is low. Target dry-off periods for 2002 were generally shorter at Millaroo than at Kalamia because of the higher daily temperature and lower humidity at Millaroo compared to Kalamia which is much nearer the coast. Target dry-off periods have generally been rounded to the nearest 5 days. It is not possible to be more accurate than this, given uncertainties about soil types and the general nature of the variability of experimental results.
6. REFERENCES


IRRIGATION SCHEDULING BY SOIL WATER STATUS

PB Charlesworth and RJ Stirzaker

1. INTRODUCTION

There are three methods for matching irrigation with crop water requirements. The first is to measure how much water the soil contains. The second is to monitor some attribute of the plant that is related to water deficits. The third is to calculate how much water the atmosphere can extract from a well-watered crop. This chapter is about the first method, irrigation management by soil water status. Successful irrigation by this method requires more than just the ability to measure soil water status. We need to know how to relate measurements of soil water status to the amount and timing of irrigation, and how this ultimately affects crop yield.

2. DEFINITIONS OF SOIL WATER STATUS

Soil consists of a range of different sized particles from fine clays (< 2µm diameter) through silts and sands to gravels (>2mm). Water adheres to the surface of these particles, so soils with a finer texture (more clay) can store more water than soils with a sandier texture. The soil particles are also arranged so as to produce aggregates and pores or voids, giving the soil the property termed structure. Pores with a diameter in the range of 0.5-50 µm are important for storing water. Pores larger than these are normally air-filled and water in pores smaller than this is usually not available to plants.

For the purposes of irrigation, the water status of the soil is usually expressed as the volume of water in a given volume of soil. Thus, if a cubic metre of soil contained 300 litres of water the volumetric water content would be 0.3 cubic metre of water per cubic metre of soil (0.3m³ m⁻³) or 30%. Since rain and irrigation are measured in depths (mm) it is often easier to express 0.3 m³ m⁻³ as a depth equivalent i.e. 300 mm of water in 1m depth of soil.

Plants can easily extract water from wet soil because the water is held in large pores. As soil becomes drier, water is held more strongly in smaller pores or closer to the soil particles themselves. To obtain water, roots must be in contact with the water films around soil particles and, in effect, the roots must be “drier” or exert more “pull” on the water than the soil. The size of this “pull” can be expressed in energy terms and is called soil water or matric potential. It is usually measured in kilopascals (kPa) and this gives a measure of the force needed to extract water from the soil matrix. When the soil is wet, little force is needed, as it dries, more force or pull is needed.

A soil water retention curve (SWRC) is used to convert the amount of water in a soil (volumetric water content) to its availability (energy status as given by the matric potential). As the clay content of a soil increases, the SWRC curve is displaced towards higher water contents (Figure 1).

3. MEASURING SOIL WATER STATUS

Field monitoring of soil water potential began in the 1930’s with the development of the tensiometer (Richards and Neal 1936). Routine, non-destructive measurements of soil water content were made possible by the development of the neutron scattering technique (Gardner and Kirkham 1952). The last 20 years have seen the rapid development of new tools for measuring soil water content, particularly measurements based on time domain reflectometry, capacitance and heat dissipation (White and Zegelin 1995). A description of 25 commercially available products for measuring matric potential and soil water content and their mode of operation is given by Charlesworth (2000).
4. USING SOIL WATER MEASUREMENTS

During irrigation, the soil water potential rises close to 0 kPa. If the application rate exceeds the infiltration rate of the soil then the soil water potential rises to 0 kPa and water ponds on the soil surface. Immediately after irrigation large pores drain rapidly, so the wetted depth of soil increases and the average water content of the topsoil falls. The rapid drainage phase is usually completed within two days and the soil water content at this stage is termed the Drained Upper Limit (DUL). In reality, drainage continues indefinitely, although at slower and slower rates, so the DUL is not an intrinsic property of the soil. However, the drainage rate at the DUL is generally very much lower than the other source of water loss from soil, evaporation, so for practical irrigation purposes DUL is a convenient measure of the full point.

A plant will extract water from the full profile until the soil is so dry that the plant wilts, even if the relative humidity around the leaves is near 100%. The soil water content at this stage is called the Lower Limit (LL). The amount of water between the DUL and LL is called Plant Available Water (PAW), a term first used by Veihmeyer and Hendrickson (1949). Ritchie (1981) discusses the main assumptions, errors and remedies in deriving these terms.

In practice, water becomes increasingly less available to plants between the DUL and LL. Some studies have shown that growth can be sustained until 70-80% of the PAW has been consumed (e.g. Meyer and Green 1980). For practical purposes a more conservative value of 0.5*PAW is often recommended as the depletion amount below DUL at which the profile should be refilled. This amount is referred to as Readily Available Water (RAW). The idea of having this conservative refill point is to avoid the possibility of growth and yield reductions from the drying conditions in commercial crops.

The amount of water readily available to a crop is calculated as the RAW multiplied by the rooting depth. Table 1 gives examples of average values for water contents at DUL and LL and the RAW over 1m depth for a range of soil textures.
Figure 2. The change in water content during an irrigation event followed by 10 days of drying. The soil water content falls rapidly immediately after irrigation when drainage dominates, and slows after the readily available water has been transpired (assumes constant evapotranspiration).

When considering the water availability, a soil water potential of 0 kPa indicates the soil would be saturated or waterlogged. Most soils have sufficient air for root function once the soil water potential drops to –5kPa. Once the soil dries to –50kPa, many plants will experience some water stress. By –1500 kPa only small amounts of water can be extracted from the soil and most plants will wilt.

Table 1. Representative volumetric water contents (m$^3$m$^{-3}$) and the Readily Available Water in 1 m of soil for soils of three textures (Marshall et al. 1996)

<table>
<thead>
<tr>
<th></th>
<th>Sand</th>
<th>Loam</th>
<th>Clay</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saturation</td>
<td>0.4</td>
<td>0.5</td>
<td>0.6</td>
</tr>
<tr>
<td>Drained Upper Limit</td>
<td>0.06</td>
<td>0.29</td>
<td>0.41</td>
</tr>
<tr>
<td>Lower Limit (LL)</td>
<td>0.02</td>
<td>0.05</td>
<td>0.2</td>
</tr>
<tr>
<td>RAW for 1m root zone</td>
<td>20 mm</td>
<td>120 mm</td>
<td>105 mm</td>
</tr>
</tbody>
</table>

5. WATER DEFICIT AND PLANT GROWTH

The calculation of RAW above is a useful approximation but belies much of the complexity of soil plant water relations. In reality the rate of water uptake needed to sustain rapid growth is determined by the atmospheric conditions, the leaf area, rooting distribution of the crop and the soil type and water status (Slater 1967, Gardiner 1960, Philip 1966). More recently, evidence is accumulating that chemical signals produced by roots growing in drying soil affects plant growth. Stomata may close and growth rates fall before there is any detectable change in leaf water potential (Passioura 1994). These signals could also lead to the root distribution changing to exploit wetter regions of the soil. Such adaptation may be limited by both soil strength and crop growth phase. The majority of crops are most sensitive to water deficits at the time of flowering and fruit set and more tolerant during the vegetative and maturation stages (Rudich et al. 1977).
6. OLD VERSUS NEW CONCEPTS IN IRRIGATION

The calculation of readily available water represents the maximum extraction of water before the crop yield may decline. Such a concept has its roots in flood irrigation and sprinkler irrigation systems where pipes had to be moved from field to field. Flood irrigation is best suited to applying large volumes of water at infrequent intervals, and the method specified how long that interval could be. In the case of sprinkler irrigation, a long interval cuts down the cost associated with moving pipes.

The advent of drip and micro irrigation and centre pivot or lateral move sprinkler systems has changed the focus away from refill points. Since these systems allow irrigation to be performed at virtually anytime, there is no need to approach the refill point and the associated dangers of drying the soil out too much. The aim is to keep the soil near the full point by applying water daily, or at most, weekly.

Drip and micro irrigation only wet part of the root zone, so the wetted volume of soil is much smaller than for flood or sprinkler. This means irrigation management must be more precise, as the reduced amount of stored water increases the risk to crop health of, for example, equipment failure. In many cases these systems have been shown to produce higher yields. Micro irrigation also entails special problems related to the placement of soil water sensors with respect to the emitters (Or and Coelho 1996).

Interpretation of soil water content measurement is also more difficult for frequent irrigation, where plant uptake, redistribution and drainage of water can be occurring simultaneously. Few irrigators understand that water can be moving into a layer of soil at the same rate as it is moving out, and make the mistake of interpreting a fairly flat water content versus time trace as evidence of no drainage.

There is also a much greater understanding of the way in which plants respond to water stress at different growth stages. For example, the practice of Regulated Deficit Irrigation (RDI) can save up to 60% of the seasonal water requirement with little effect on fruit yield or quality (Goodwin et al. 1998). The deficit is allowed to develop after flowering and fruit set at the time vegetative growth is at its maximum, and removed when the fruit size starts to increase. A variant of RDI is Partial Rootzone Drying, where half the root zone of a perennial crop is irrigated and the other half allowed to dry (Stoll et al. 2000). Irrigation is alternated such that the previously dry half is re-irrigated and the previously wet half allowed to dry. In this way half the roots are well watered and half experience drying soil. Roots in the drying soil produce hormonal signals that reduce vegetative growth and provide a more favourable balance between vegetative and fruit production. Again yields are unaffected by the stress or even increased. Of even greater importance is the impact of these controlled stresses on fruit quality, particularly in the wine industry.

7. ADOPTION BY IRRIGATORS

Irrigation management by soil water status is a method that has been promoted for over 50 years. However, despite decades of extension work, the uptake by irrigators remains disappointingly low. There are several reasons for this. In most situations water is not a major percentage of the variable costs and many irrigators baulk at the time and expense of collecting, interpreting and implementing the information soil water sensors provide. In practical terms the cost to the individual farmer of over-irrigation is less than the penalty of under irrigating, and there is no doubt large quantities of irrigation water are wasted as a result (Stirzaker 1999). Water treatment, algal bloom control and salinity are all examples of off-site impacts of over-irrigation which are generally not included in the cost-benefit analysis.

Point to point variability in soil water content within a field is also a major disincentive for soil water monitoring. This variability is due to changes in soil properties, plant growth and non-uniformity of water application. To properly account for such variation requires the installation of far more equipment than is practicable (Schmitz and Sourell 2000). The problem of variability makes the atmosphere-based methods of irrigation scheduling more attractive. However errors in this method, particularly related to the estimation of leaf area and root distribution, mean that some combination of atmospheric and soil based measurement will provide the most robust feedback system. Irrigation scheduling by soil water status should show further improvements through the development of new soil
water measuring technology, especially the associated software that simplifies interpretation of data for the irrigator.

8. REFERENCES


IRRIGATION SCHEDULING WITH EVAPORATION MINIPANS AND WEATHER DATA

S Attard

1. EVAPORATION MINIPANS

Scheduling furrow irrigation using the evaporation minipan relies on calibration of the soil type with daily stalk growth rates. Calibration should occur after the crop has developed approximately 1m of stalk growth and the canopy is closed. Representative stalks are tagged, and at the same time each day their height (to the top visible dewlap) is measured from a fixed point.

After an irrigation is completed, the minipan is refilled. Daily minipan evaporation can be recorded at the same time as the stalk heights are measured.

When the growth rates fall to 50% of the maximum-recorded growth rate, note the draw down on the minipan. This draw down becomes the minipan deficit that will be used to indicate when irrigations should occur for that soil type. Minipan deficit figures are not a measurement of actual soil moisture deficits because evaporation from the minipan could be quite different (usually higher) from crop evaporation.

1.1 USEFUL HINTS WHEN USING THE EVAPORATION MINIPAN

- Works best when cane has at least one metre of stalk and the canopy is closed. Difficulties arise when attempting to schedule the crop between germination and canopy closure.
- Locate the minipan in an open area, off the ground, and ensure that animals will not drink the water.
- Repeat the process during the growing cycle. Daily readings are recommended for greater accuracy.
- This process relies on the soil profile being completely filled after the irrigation. Therefore, if the irrigation does not completely fill the profile it is difficult to determine how much water to put into the pan after the irrigation.
- Rainfall events, particularly frequent, small events that do not refill the soil profile, may require the adjustment of the schedule.

BSES monitored a number of grower-based trials in the Burdekin between 1993 and 1996. These trials showed that growers using the minipan to schedule irrigations consistently increased yields (Holden et al. 1998).

2. IRRIGATION SCHEDULING WITH WEATHER DATA

Daily weather dictates how much water is lost from the soil profile through:

- the crop’s demand for water or transpiration, and
- surface evaporation.

Data such as solar radiation, temperature, humidity, rainfall and wind run are collected from weather stations. Strategic positioning of weather stations can capture climate variability across a region.

Allen et al. (1998) outline the procedures for determining reference evapotranspiration (ET\text{\textsubscript{o}}) according to the FAO Penman-Monteith method as well as updated procedures for estimating the evapotranspiration of different crops for different growth stages. Reference evapotranspiration (ET\text{\textsubscript{o}}) is converted to sugarcane evapotranspiration (ET) using crop factors that reflect canopy development.

Calibration of the soil to stalk growth rates (using the same principles as for the minipan) is necessary in order to find out what soil water deficit to allow before irrigating. However, daily weather data is used to determine ET\text{\textsubscript{o}}, and then a crop factor is used to convert this to sugarcane ET. Cumulative soil
water loss is calculated. When the stalk growth rate reaches the desired level, e.g., 50% of maximum stalk elongation, the cumulative soil water loss is noted and becomes the trigger point (or refill point) for subsequent irrigations.

Once the irrigation point has been determined, a spreadsheet water balance is maintained. The water balance requires daily $ET_0$ (or ET) to be determined along with the quantities of effective rainfall and irrigation. An example of a spreadsheet water balance is shown in Table 1.

<table>
<thead>
<tr>
<th>Date</th>
<th>$ET_0$ (mm)</th>
<th>Sugarcane ET (mm)</th>
<th>Effective rainfall (mm)</th>
<th>Effective irrigation (mm)</th>
<th>Water balance (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15/02/02</td>
<td>1.0</td>
<td>1.3</td>
<td>0.0</td>
<td>55.0</td>
<td>0.0</td>
</tr>
<tr>
<td>16/02/02</td>
<td>3.4</td>
<td>4.3</td>
<td>3.2</td>
<td>0.0</td>
<td>-1.1</td>
</tr>
<tr>
<td>17/02/02</td>
<td>3.8</td>
<td>4.1</td>
<td>1.2</td>
<td>0.0</td>
<td>-4.7</td>
</tr>
<tr>
<td>18/02/02</td>
<td>4.2</td>
<td>5.2</td>
<td>0.0</td>
<td>0.0</td>
<td>-9.9</td>
</tr>
<tr>
<td>19/02/02</td>
<td>4.1</td>
<td>5.2</td>
<td>0.0</td>
<td>0.0</td>
<td>-15.1</td>
</tr>
<tr>
<td>20/02/02</td>
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<td>6.3</td>
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<td>-1.3</td>
</tr>
<tr>
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<td>0.0</td>
<td>-7.4</td>
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<tr>
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<td>6.7</td>
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<td>55.0</td>
<td>0.0</td>
</tr>
<tr>
<td>25/02/02</td>
<td>5.3</td>
<td>6.7</td>
<td>0.0</td>
<td>0.0</td>
<td>-6.7</td>
</tr>
</tbody>
</table>

An irrigation or rainfall event that completely fills the profile will reset the water balance to zero.

This water balance technique can be used to monitor irrigation applied by various application methods, e.g., furrow, overhead, low pressure and trickle. Irrigations that partially fill the profile and rainfall events can be easily incorporated. Also, the entire crop cycle can be scheduled with the use of crop factors.

3. ACKNOWLEDGEMENT

The notes on scheduling with minipans are based on ‘Irrigation of Sugarcane’ (Holden 1998).

4. REFERENCES


SCHEDULING OF LIMITED WATER IN SUGARCANE

NG Inman-Bamber, C Baillie and J Willcox

1. INTRODUCTION

Irrigation water allocations in many sugarcane production regions are insufficient to make up the difference between crop water requirement and effective rainfall (Holden 1998). Irrigation requirement varies from year to year because of the high variability in rainfall for the sugar industry. Low allocations and high rainfall variability are prevalent in the Bundaberg - Childers region where there is limited water storage capacity and allocations can be as low as 1 or 2 ML/ha. Growers need to judge when to use these low allocations, which could amount to only 2 to 4 irrigations.

A number of growers have access to soil water measurements either through their own instrumentation or through an instrument network installed by the Rural Water Use Efficiency Initiative and these data are being used to guide growers when to use their limited allocations. There is little published information on what soil water extraction patterns mean in terms of crop water stress and yield loss. Water stress in sugarcane can be detected early by regular automatic measurement of leaf extension making use of the diurnal extension pattern to minimise confounding effects of temperature on leaf extension (Inman-Bamber 1995). A stress index based on daytime and morning extension rate was highly sensitive to changes in soil water content determined by capacitance sensors (Starr and Paltineanu 1998) similar to those available to growers in the Bundaberg-Childers region. Soil water content 400 mm below the stool provided the best correlation with the stress index. The stress index reached a critical value of 0.5 when 75 to 80% of available water at this depth had been extracted. Total crop fresh biomass (hence cane yield) was reduced after 5 days of stress beyond the critical level and dry biomass was reduced after 10 days (Inman-Bamber and Spillman 2002).

While it is useful to know what degree of stress or yield loss is being incurred when soil water extraction slows down at a particular depth and position relative to the crop row, this information needs to be complemented with some kind of forecast to guide growers how to spread their limited irrigation through the season. In low rainfall years, the allocation should be used when soil water content is low and potential evapotranspiration is high, in order to reduce yield loss to a minimum. Conversely in wetter years, irrigation can be applied at relatively low soil water deficits to maintain higher yields.

The APSIM-Sugarcane model has been tested under a wide range of conditions in several countries (Keating et al. 1999, Cheeroo-Nayamuth et al. 2000). Soil water content, leaf area index and sucrose yield of an irrigation experiment were simulated accurately when sound soil physical properties were provided (Inman-Bamber et al. 2000). Root mean square error for simulated sucrose yield was 1.9 t/ha in the range 0 to 23 t/ha.

This paper explores the use of a computer simulation procedure using APSIM to predict the best general timing of limited irrigation and soil water monitoring technology to help growers with more immediate decisions about whether or not to irrigate.

2. METHODS

Two replicated experiments were established in October 2000 on ratoon crops in the Bundaberg and Childers region of southeast Queensland. Both trials were on Red Kandosols (Isbell 1996). The Bundaberg trial was superimposed on a second ratoon crop of Q151 ratooned in July 2000 and the Childers trial on a third ratoon of Q170 ratooned in August 2000. The trials were designed in conjunction with the Bundaberg and Childers management committees of the Rural Water Use Efficiency Initiative (RWUEI). These committees selected the same four treatments for each trial. A ‘Rainfed’ treatment was not irrigated. Another treatment was given a ‘Capped’ allocation of 2 ML/ha to be scheduled by computer. Two other treatments were designed to mimic a typical allocation scenario. This entailed a starting allocation of 2 ML/ha plus additional water that may be announced by the water authorities. One of these treatments was scheduled by computer and the other was scheduled by the grower. The treatments were called ‘Plus’ and ‘Grower’ respectively. For scheduling by
computer, essential elements of the two experiments were captured in a configuration of the APSIM model. Soil details of a Red Kandosol were obtained from Inman-Bamber et al. (2000). Climate data pertaining to the trials were obtained from an automatic weather station (AWS) less than 1 km from the Childers site and from another AWS about 10 km from the Bundaberg site. Rainfall was measured automatically by mounting a rain gauge about 1 m above the canopy at each site. Long-term climate data were obtained from the SILO database of the Bureau of Meteorology. The Capped and Plus treatments were simulated in real time using current climate data from the AWSs. Simulations continued up to the expected harvest date in July 2001 using 100 years of climate records. Each treatment thus ended in 100 different ways depending on which year in the climate record was used to complete the simulation. Up to 10 irrigation strategies were used for each year in the simulation and the strategy with the highest yield was then used to identify a date for the next irrigation.

Plots were 15 m long and 12 rows wide. Irrigation was applied through trickle tape on the surface but applications were more like those from a winch system (30 to 40 mm), which is the most prevalent irrigation method in these regions. In the Childers trial, five auxanometers as described by Inman-Bamber and Spillman (2002) were installed in one replication of each treatment (20 total). These instruments were designed to measure leaf plus stalk extension continuously on an hourly basis. An EnviroSCAN (ES) system (Sentek Pty Ltd, Australia) was installed by inserting two tubes near each set of auxanometers. One tube was in the crop row and the other midway between rows, which were 1.5 m apart. Capacitance sensors were set at depths of 100, 200, 400, 600, 800 and 1000 mm. A similar system with sensors set at depths of 100, 300, 600 and 1000 mm, was installed at Bundaberg but not in time to contribute to this study apart from the calibration procedure. An approximate calibration of the ES systems at Childers and Bundaberg was conducted on 19 October 2001. One gravimetric soil sample was taken to match each of the 80 sensors in both systems in terms of depth and position in the crop row or interrow. Samples were taken about 2 m from the ES tubes to avoid interfering with the ES readings. A precise calibration would require removal of soil adjacent to each sensor.

The trials at Bundaberg and Childers were sampled to determine yield, CCS and a number of other crop attributes on 21 to 24 May and again on 23 to 26 July 2001 using the method of Muchow et al. (1993).

3. RESULTS AND DISCUSSION

3.1 SCHEDULING IN FIELD TRIALS

An example of a computerised schedule for the Plus treatment at Childers is shown in Figure 1. These calculations were done after the 7th irrigation in order to set a date for the 8th irrigation. In about 45 % of the years the best bet date for 8th irrigation was 3 April. The median date was 4 April. In 75% of years the 8th irrigation would be required before 14 April and in the remaining 25 % of years the best use of the 8th irrigation would be between 14 April and 17 July. The median date was used so that the chances of irrigating too early or too late were equal. A possible date for the 9th irrigation was also produced but the procedure was repeated about a week after the 8th irrigation in order to take up-to-date climate information into account.
Most irrigation scheduled by the two growers or by the computer was timed well between rainfall events. Rain occurred shortly after the first irrigation at both sites in mid December and 60 mm rain fell only three days after irrigating the Grower, Capped and Plus treatments at Childers on 16 March (Figure 2). At Bundaberg the grower used his third irrigation on 5 January 2001, long before the computer required the third irrigation to be applied to the other treatments. A large amount of rain occurred in the mean time. The third irrigation was applied to the Plus treatment on 13 February and to the Capped treatment on 23 February. Apart from one other occasion the Capped treatment was irrigated at the same time as the other treatments until the full 2 ML/ha had been used (Figure 2a). Thus the Plus treatment was the last to be irrigated in the Bundaberg trial.

In the Childers trial small amounts of water were applied while sorting out some infiltration problems. Apart from this, irrigation in the Grower and Capped treatments started about 9 weeks after applying the first irrigation to the Plus treatment. Treatments were irrigated at the same time thereafter until allocations for the Capped and Plus treatments ran out. The grower then had one more irrigation to complete his allocation. When this was done the system was left on for too long and the intended allocation was exceeded by 25 mm (Figure 2b).

**3.2 RESPONSE TO IRRIGATION TREATMENTS**

In the Bundaberg trial, the total irrigation applied to the four treatments was 0, 2.02, 3.22 and 3.27 ML/ha for the Rainfed, Capped, Plus and Grower treatments respectively (Table 1). Irrigation had no effect on stalk population. Stalk numbers declined between May and July, particularly in the Rainfed treatment. In May there was no significant treatment effect on green leaves per stalk but in July green leaves were significantly reduced in Rainfed plots. Irrigation affected LAI significantly in May and July and LAI was lowest in Rainfed plots on both occasions (Table 1). LAI declined considerably in all treatments between May and July. A leaf area as low as 1.5 m²/m² indicates a high degree of water stress. Cane yield increased significantly with irrigation. The response was as high as 17.8 t/ha in May and 24.4 t/ha in July. The increased response in July was due to a reduction in cane yield of the Rainfed treatment between May and July, possibly due to accelerated stalk death. Differences in cane yield between irrigation treatments were not significant. Sucrose content was greater in the Rainfed than irrigated treatments in July so that the response to irrigation in terms of sucrose yield was similar in May and July. Sucrose yield for the Grower treatment was greater than for the Rainfed treatment in May and it was greater than all other treatments in July. Remote scheduling by computer resulted in a loss of sucrose yield of 1.1 t/ha, which could be regarded as disappointing. However the growers selected for this study were highly experienced and it was perhaps over ambitious to expect a computerised scheduling system to do better than these growers first time. The impact of the trial work at Bundaberg was to provide an appreciation of what could be done with APSIM-based predictions for best timing in the use of limited allocations. This led to generalised forecasting for the 2001-2002 water year to be discussed later.
Table 1. Yield components in the Bundaberg trial measured by sampling on 24/05/01 (1) and on 25/07/01 (2). Values with no letters in common are significantly different (p=0.05)

<table>
<thead>
<tr>
<th>Yield component</th>
<th>Sample</th>
<th>Treatments</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Rainfed</td>
<td>Capped</td>
</tr>
<tr>
<td>Irrigation (ML/ha)</td>
<td>2</td>
<td>0</td>
<td>2.02</td>
</tr>
<tr>
<td>Stalks per m²</td>
<td>1</td>
<td>9.7</td>
<td>9.8</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>7.8</td>
<td>7.8</td>
</tr>
<tr>
<td>Mature green leaves per stalk</td>
<td>1</td>
<td>6.5</td>
<td>6.5</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>3.1a</td>
<td>4.2b</td>
</tr>
<tr>
<td>Leaf area index (m²/m²)</td>
<td>1</td>
<td>2.7a</td>
<td>3.6b</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1.5a</td>
<td>1.8ab</td>
</tr>
<tr>
<td>Cane yield (t/ha)</td>
<td>1</td>
<td>66.4a</td>
<td>76.8ab</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>58.1a</td>
<td>73.6b</td>
</tr>
<tr>
<td>Sucrose content (%)</td>
<td>1</td>
<td>13.4</td>
<td>14.2</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>15.5a</td>
<td>15.2a</td>
</tr>
<tr>
<td>Sucrose yield (t/ha)</td>
<td>1</td>
<td>9.0a</td>
<td>10.9ab</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>9.0a</td>
<td>11.2b</td>
</tr>
<tr>
<td>Yield response above rainfed (t/ha)</td>
<td>1</td>
<td>0</td>
<td>10.4</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0</td>
<td>15.5</td>
</tr>
</tbody>
</table>

The Childers trial site received two irrigations before the experiment was laid out. Otherwise the treatments were similar to those applied in the Bundaberg trial (Table 2). Stalk population was not affected by irrigation treatment and was not reduced to the same extent as the Bundaberg trial between May and July. Green leaves per stalk were not affected by irrigation in May but were as low as 3.3 in the Rainfed treatment and as high as 5.5 per stalk in the Grower treatment in July. This resulted in significant LAI differences between treatments in July (Table 2). Relatively high green leaf numbers and LAI in the Grower treatment were probably because this was the last treatment to be irrigated before sampling. This would also explain the low sucrose content in the Grower treatment in May (Table 2). There were no significant treatment differences for cane yield, sucrose content or sucrose yield either in May or July but mean yields of cane and sucrose were always lower in the Rainfed treatment than other treatments. July yields were considerably greater at Childers than at Bundaberg probably because of the two irrigations applied before settling up the trial at Childers. While lack of significant yield response to irrigation in the Childers trial did not provide a good test of the computerised scheduling procedure the trial provided data for interpretation of soil water monitoring in terms of possible yield loss. This will be shown later.

Table 2. Yield components in the Childers trial measured by sampling on 21/05/01 (1) and on 23/07/01 (2). Values with no letters in common are significantly different (p=0.05)

<table>
<thead>
<tr>
<th>Yield component</th>
<th>Sample</th>
<th>Treatments</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Rainfed</td>
<td>Capped</td>
</tr>
<tr>
<td>Irrigation applied as treatments (ML/ha)</td>
<td>1</td>
<td>9.6</td>
<td>9.9</td>
</tr>
<tr>
<td>Stalks per m²</td>
<td>2</td>
<td>9.1</td>
<td>8.9</td>
</tr>
<tr>
<td>Mature green leaves per stalk</td>
<td>1</td>
<td>6.0</td>
<td>6.7</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>3.3a</td>
<td>4.3b</td>
</tr>
<tr>
<td>Leaf area index (m²/m²)</td>
<td>1</td>
<td>3.4</td>
<td>3.5</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>2.2a</td>
<td>2.6b</td>
</tr>
<tr>
<td>Cane yield (t/ha)</td>
<td>1</td>
<td>98.2</td>
<td>105.0</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>107.7</td>
<td>118.8</td>
</tr>
<tr>
<td>Sucrose content (%)</td>
<td>1</td>
<td>8.5</td>
<td>8.3</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>12.9</td>
<td>12.3</td>
</tr>
<tr>
<td>Sucrose yield (t/ha)</td>
<td>1</td>
<td>8.5</td>
<td>9.1</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>13.9</td>
<td>14.8</td>
</tr>
</tbody>
</table>
3.3 REGIONAL FORECASTS FOR TIMING OF LIMITED ALLOCATIONS

In September 2001, forecasts for best timing of limited irrigation were made using the same procedure for best-bet timing of irrigation in the replicated trials. With knowledge of climatic conditions up to the end of August, best use of an allocation of 2 ML/ha on early ratoons (July) would be to concentrate irrigation in November to January with most irrigation being required in December (Figure 3) based on long term climate records from September to June. With a 4 ML/ha allocation, about half the allocation would be used in November and December. There would be a greater chance that some of the allocation should be used during February to April than was the case with the 2 ML/ha allocation. For October ratoons and a 2 ML/ha allocation there was justification for using some of the allocation in October to help with ratoon regeneration but the main benefit would come from irrigation in January and February. A 4 ML/ha allocation on October ratoons would be used largely from January to April after using some of the allocation to get the crop away in October if rainfall was insufficient. Irrigations in April and May could also be useful as with the 2 ML/ha (Figure 3). When this forecast was repeated in January, climate records up to the end of December and actual allocation usage could be taken into account. The two possible allocation scenarios were also more realistic. Over half of the low allocation of 1.4 ML/ha had already been used on early ratoons (July) possibly because of earlier promotion of the need to use low allocations in November and December. A large proportion of the remaining allocation would best be used in January which would also be the best time to use a large proportion of the higher allocation of 2.5 ML/ha having already used about 30% of this allocation during November and December. An allocation of 1.4 ML/ha on October ratoons was used partly to get the crop away in November. About 20% of this low allocation would best be used in January and lower proportions would be useful in subsequent months based on long-term climate records from January to September. The remainder of a 2.5 ML allocation on October ratoons would best be used from January to March with reduced proportions being useful as late as September (Figure 3).

The data in Figure 3 are simply a guide as to when allocations are likely to be most beneficial based on long term climate trends. These forecasts are influenced to some extent by El Nino phenomena (Inman-Bamber et al. 2001) but no such phenomenon was on the horizon at the time of the forecasts.

![Figure 3](image)

Figure 3. Predicted best use of allocations in the 2001-2002 water year in Bundaberg. Predictions were made in September 2001 (a) and January 2002 (b).

3.4 SOIL WATER DEFICIT, ELONGATION STRESS AND SCHEDULING (CHILDERS EXPERIMENT ONLY)

Each sensor of the EnviroSCAN system is normalized in the factory and precise calibration under field conditions is not often done. The results of the approximate field calibration procedure were subjected to regression analysis with gravimetric soil water content, multiplied by an assumed bulk density of 1.4 t/m³, as the independent variable. ES soil water content (Y) accounted for 53% of the variation in measured soil water content (X). The regression equation was \( Y = 4.8 + 0.972X \pm 3.5\% \) by volume. Thus changes in ES and measured soil water content were similar even though the absolute values differed by 4.8% units.
A large amount of rain during the afternoon and evening of 13 March 2001 provided an opportunity to determine the drained upper limit (DUL) for the soil surrounding each pair of ES tubes (Figure 4). Drainage occurred rapidly after rain ceased and then slowed considerably during the early morning on 14 March. Soil water content (SWC) at 600 h was regarded as DUL and the difference between DUL and SWC was regarded as the soil water deficit (SWD). SWD did not exceed 50 mm for long at any stage in the Grower and Plus treatments (Figure 5). Deficits exceeding 70 mm occurred in the Capped and Rainfed treatments but these were short-lived in the Capped treatment during summer months. The soil dried out considerably during June and July prior to harvesting and deficits were greatest in the Rainfed and Capped treatments at this time, as would be expected (Figure 5).

The elongation stress index reflected changes in SWD as reported by Inman-Bamber and Spillman (2002). Stress was relieved within a few days after rainfall or irrigation but stress developed again as SWD increased (Figure 6). The greatest level of stress encountered in the Childers experiment was in the Rainfed treatment during February and March when SWD exceeded 50 mm for about three weeks. It is likely that the observed differences in yield components between Rainfed and irrigated treatments (Table 2) developed during this period. Previous research showed that cane yield would be reduced if the stress index remained below 0.5 for more than 5 days (Inman-Bamber and Spillman 2002). In the Rainfed treatment of the Childers experiment, the stress index was below 0.5 for about two weeks in February and March 2001. While the cane yield difference of 16 t/ha between Rainfed and Plus treatments did not reach significance (Table 2), there is evidence from the stress index that this difference was not merely due to experimental error. From this it can be deduced that a deficit of more than 50 mm for more than a week during high evaporative conditions would lead to yield loss in this type of soil. A simple rule of thumb of this nature would help growers to assess the risk of withholding irrigation when the soil water deficit falls below 50 mm in the main growing months.
Figure 6. Elongation stress index based on daytime and early morning leaf extension rates (Inman-Bamber and Spillman, 2002) for the Rainfed and Plus treatments of the Childers experiment. 0 = severe stress, 1.5 = minimal stress.

3.5 SOIL WATER DEFICIT AND SOIL WATER EXTRACTION

Daily increment in SWD when SWC<DUL was probably due mostly to evapotranspiration (ET) particularly when SWD was high. The effect of SWD on ET could be assessed by comparing ET of the Rainfed treatment with maximum ET of the Grower and Plus treatments (Figure 7). Maximum ET of these two treatments would be closest to potential ET. When this comparison was made for the period up to mid May, Rainfed and maximum ET were similar provided SWD of the Rainfed plots was less than 50 mm (Figure 7a). At relatively high maximum ET (>4 mm/d), Rainfed ET was lower than maximum ET when SWD for the Rainfed plot exceeded 50 mm. It is not certain to what extent roots were able to extract water below 1000 mm however the level of elongation stress in the Rainfed treatment with SWD>50 mm indicated that water below 1000 mm was not readily available. Reduced ET under conditions of high evaporative demand and high water deficits normally results in yield loss (Denmead and Shaw 1962). A different situation was apparent after mid May when maximum ET was mostly less than 4 mm/d. In this case there was little difference in ET between Rainfed and maximum ET even though SWD was considerably greater in the Rainfed than in the Plus and Grower treatments at this stage (Figure 7b). Thus a deficit of 50 mm would have been appropriate as a signal for irrigation during periods of high evaporative demand but not when the demand is low.

Figure 7. Evapotranspiration (ET) derived from daily increment in soil water deficit when drainage was low (SWC<DUL) of the Rainfed treatment versus the maximum ET of Plus and Grower treatments for the period preceding 15 May 2001 (a) and after 15 May (b). Symbols show SWD range of the Rainfed treatment.
4. CONCLUSIONS

The optimising procedure based on the APSIM model was able to schedule irrigation nearly as well as experienced growers cooperating in replicated experiments at Bundaberg and Childers. This was the first time this type of scheduling had been attempted as far as is known and improvements could be expected in time. The results of these experiments provided sufficient confidence in the procedure leading to generalised predictions about when best to use limited irrigation in the 2001/2002 water year in Bundaberg. For early ratoons (July) most of a 2 ML/ha allocation would best be used in November, December and January and for late ratoons most of this allocation would best be used in January and February. There were significant shifts in timing of irrigation when the allocation was increased from 2 to 4 ML/ha and there were significant shifts when the information was updated four months later to account for more realistic allocations as well as antecedent rainfall and irrigation.

The yield results of the Childers trial confirmed that daytime leaf elongation could be reduced by water stress for a considerable period without affecting cane yield to any great extent. While leaf and stalk elongation are reduced at relatively low water deficits, irrigation at a deficit of 50 mm in the deep red soil of the Childers experiment would prevent yield loss. Yield loss would probably occur if soil water deficit were allowed to decline below 50 mm for more than a week in conditions of high evaporative demand such as those occurring during summer in Childers or Bundaberg. During periods of low evaporative demand deficits of 70 mm or greater can be tolerated.

General forecasts can be made at various stages during the water year about when limited allocations can best be used. Automatic soil water monitoring can then be used to make more tactical decisions about when to irrigate.

5. ACKNOWLEDGEMENTS

Ms Sandra Dennis, Mrs Chris Willcox and Mr Michael Spillman were responsible for the establishment and operation of experiments at Bundaberg and Childers. Dr Natalie Stoeckl assisted with data analysis. Mr Pat Menkens of Sentek Pty Ltd installed the EnviroSCAN system at Childers. Mr David Lawson of Bundaberg and Mr Graham Webb of Childers provided land and labour for the experiments on their farms. The Bundaberg and Childers RWUEI management committees led by Mr Barrie McLellan and Mr Joe Russo were active in the research. The willing contribution of all these people is gratefully acknowledged. The cost of the 48-sensor EnviroSCAN system was met equally by the Childers RWUEI adoption project and by Sentek Pty Ltd. Funding by SRDC and by the Rural Water Use Efficiency Initiative (QDNR) is acknowledged.

6. REFERENCES


3. DESIGN AND MANAGEMENT OF IRRIGATION SYSTEMS
FURROW IRRIGATION

P Sutherland

1. INTRODUCTION

“No single type of well managed irrigation system is inherently more or less efficient than another”. To qualify this statement, well managed furrow, overhead and trickle systems can achieve application efficiencies in excess of 90%. Management is the key to efficient and profitable irrigation.

This paper discusses the strengths and weaknesses of the furrow irrigation system and explores the critical factors affecting the management and operation of an efficient furrow irrigation system. In addition, the advanced management strategies and concepts associated with surge irrigation and the furrow irrigation of trash blanketed cane will be discussed.

2. SURFACE IRRIGATION

To the uninitiated, surface irrigation would appear to be the simplest form of irrigation. Water is lifted onto the field at the high end of the field where the forces of gravity distribute the water by overland flow. Surface irrigation is certainly the oldest form of irrigation, many thousands of years old, and is still the most common form of irrigation practised on the planet.

Surface irrigation can be one of the simplest, cheapest forms of irrigation to establish if a simple distribution system is utilised to transport water under gravity from the river or other water supply to the field. Low lying soils adjacent to rivers and streams are generally high in clay with a gentle to moderate slope away from or parallel to the water source. Water is applied at the top until such time as it exits the bottom of the field. At this point the water is turned off and applied to the next section. Irrigation in this form is still practiced in this country, and many others, in roughly the same way with little or no regard for the impact of the various losses on the surrounding environment.

The weaknesses of a surface irrigation system are often perceived as being:

- Inefficient, with large tail water losses
- Losses to deep drainage, carrying nutrients and pesticide
- Poor water distribution uniformity
- Built to a price not criteria
- Generally lack any formal design

There is always a little truth behind the myth so I have added some weaknesses that relate to the manageability of the system:

- Considerable skill required to manage furrow irrigation efficiently
- High labour component for poor farm design
- Limited ability to apply small volumes of water
- Limited control of distribution uniformity- soil type dependant

To an extent these weaknesses exist in some surface systems but in fairness, all of the other types of system can have similar weaknesses.

The strengths of surface irrigated systems are perceived as few but the following could be considered:

- Low pumping costs as result of low pumping pressures
- Low labour costs on well designed systems
- Generally low tech
- Low initial set-up costs??
- Field generally receives adequate water
3. FACTORS AFFECTING SURFACE IRRIGATION EFFICIENCY AND ECONOMICS

The infiltration rate of the soil, the accumulated infiltration relative to inflow and, to a lesser degree, field slope and surface roughness are the main considerations for surface irrigation efficiency.

Infiltration is the most significant issue to be managed in surface irrigation. The Kostikov equation reflects this with infiltration dominating the equation and furrow slope and shape playing roles. There are a number of points that need to be made in relation to infiltration. Soil type and clay content largely determine the infiltration rate. Consideration of uniform soil types or groupings of soil types based on their infiltration rate is essential at the planning stage to reduce operating costs associated with managing a variety of soils in the one field. Soils with relatively high infiltration can be managed with compaction and furrow shape. Soils with low infiltration rates can be improved by the use of ameliorants such as gypsum or lime depending on the soil chemistry. Care needs to be taken to apply only the required amounts of ameliorants or periods of excessive infiltration will occur. The negative impact of poor quality water cannot be emphasised enough, as the application of poor quality water will result in poor quality soil. Careful management is required to avoid this situation arising.

Laser levelling or precision grading is essential to maximise uniformity of application, water advance and therefore runoff volumes. The greater the variation in slopes and soil types the more difficult it is to control and manage the irrigation event. Water will infiltrate into different soils at differing rates on the different grades and the arrival time of the wetting front will be staggered, making management of runoff very difficult if not impossible. The variation in the advance time of furrows in a precision levelled field has been recorded at 3 to 5% of advance time, while later ratoons or wet harvested fields can have a variation of 25 to 30% in advance time.

While laser levelling or brushing between crop cycles is recommended, laser levelling is a very expensive operation if large cuts and fills are required. A great deal of planning is required to reduce the costs of the operation. Sub surface laser levelling is hugely expensive and consideration for an alternative system, for example low-pressure overhead, needs to be given as the costs of sub surface levelling can exceed the costs of system change. The other practice of lining the sub surface with a compacted layer of clay to reduce infiltration rates is generally uneconomical.

By virtue of the fact that water is applied at the top and allowed to run to the bottom indicates the top of the block will be wetter than the bottom because the water has been on the surface for a greater time at the top than at the bottom. Given a uniform soil type with the same infiltration characteristics this will always be the case - the opportunity time will be greater at top than at the bottom of the field. This can be used to good advantage if the higher sections of the field have low permeability and the bottom of the field has a more permeable clay or clay loam. This is certainly the case in large areas of the Burdekin. Where uniform soil types do exist, the use of compound slopes can improve the distribution uniformity. A steeper grade is placed on the top 1/3 of the field to increase advance rate and reduce recession time with the mid-field having an intermediate grade with a little less slope than the top. The bottom is flatter again to reduce the speed of the advance and slow down the recession on the lower section. This provides a greater opportunity time for the water to infiltrate. This is best demonstrated with the use of the SIRMOD program.

4. IMPROVING APPLICATION EFFICIENCY

The accumulated volume infiltrated into the soil is a function of time, infiltration rate and the inflow rate. The inflow rate should exceed the infiltration rate, both steady state and crack fill, so water can advance down the field. When the water recedes during the day or water fails to emerge at the bottom of the field, the inflow rate is insufficient to exceed the infiltration rate. A word of caution, in fields with single grades, the greater the inflow the greater the runoff potential. The use of recycle pits will reduce the runoff losses and improve the efficiency of the system.

As mentioned above most surface irrigation systems have a limited capacity to vary the application volume. The ability to vary inflow rates and application volumes is required as the season progresses. Cultivated, deep ripped soils in plant cane need high inflow rates and later in the season, small frequent
applications are required to maximise growth and effective rainfall. Systems with head ditches and
siphons are the least flexible as the inflow rate can vary by 30% if the discharge end of the siphon is not
placed at a uniform height relative to the head of water in the head ditch. Field trials show that if the
end of the siphon varies by 100mm in height, inflow can vary by as much as 1 L/s for each siphon.
Furrow inflow rates can be varied by placing one or more siphons into each furrow. However, the
uniformity of inflow rates is the big issue in controlling advance time and later runoff losses.

Surface systems using flexible layflat fluming can be managed to provide greater inflow uniformity and
to some extent, varied application volumes. However, the labour component required to change flow
controllers or cups can limit the practicality and economics of this operation.

Laser levelling the headland is required to reduce the variation in head in the fluming and provide the
basis for uniform inflow rates. The second point is the use of controllers or cups with a moulded
orifice in preference to the blank cups that are cut off by the irrigator on the back of the ute using the
knife. Differences in the size of the holes can vary inflow to the same degree as the siphons. The
variation of furrow inflow is a contributing factor in the uniform arrival of water at the bottom of the
field and thus directly affects the runoff volume.

Surface roughness relates to the effect that surface features in the furrow have on slowing the water
advance. A cloddy cultivated surface will run slower than a furrow that has been irrigated several
times. Grass, cane trash, billets and fallen cane leaves are good examples of surface roughness
features.

5. ECONOMICS

The economics of a particular irrigation system usually consider capital outlay, labour, pumping cost
and maintenance. Another factor to be considered is the ability of the system to meet the needs of the
crop. It could be argued that a trickle or low-pressure overhead system is more economical because it
uses less water than a furrow system. There may be less impact on the environment, reasonable
pumping costs and better distribution uniformity. The reality is that focusing economics on the inherent
efficiencies of these systems can have a major impact on the final economics of a particular system if
management is not considered. For example, the economic reality of saving 2 ML/ha by using an
overhead system versus a furrow system in the BRIA will mean a saving of $90/ha for water, pumping
and labour. Therefore, on a 100ha system this will be $9 000 or 300t at $30/t fresh mill weight. The
capital outlay for a 100ha centre pivot is $250 000. At this rate the system would take in excess of 25
years to recover costs if no increase in yield is taken into consideration. The life of low-pressure
overhead systems is said to be 15 to 20 years. Cane growth measurements taken on irrigation trials in
the Burdekin have shown that being one day late for an irrigation during the rapid growth phase,
October to January, will result in a loss of 10mm of cane which equates to 0.5t/ha/day or $1 500 for
100ha. This means irrigation scheduling is more critical for an overhead system than for a furrow
system.

A lack of understanding of the need for irrigation scheduling can be demonstrated by the number of
furrow irrigated crops that significantly out-yield overhead irrigated crops in the Mareeba area.
Management is the issue rather than the system itself.

6. ADVANCED IRRIGATION PRACTICES

6.1 HIGH FLOW

High flow is a strategy where a relatively high inflow rate is used to reduce the opportunity time thus
reducing the accumulated infiltration. As mentioned earlier, the main disadvantage with increasing
inflow rate is the potential increase in runoff. The use of recycling systems reduces the impact of this
strategy. However, in the long term, it is better to have an efficient irrigation rather than have to re-lift
the water from the storage recycling system. The use of a cutback strategy was ruled out in the past
because a suitable technology for cutting back the pump flow was not available. With the advent of
variable flow controls on pumps the cutback strategy can be used. At a predetermined point in the
advance phase, say 75% of the advance time, the pump flow is cutback reducing the inflow and
potential for a major runoff event under the high flow conditions. The same effect can be achieved using surge irrigation.

6.2 SURGE IRRIGATION

Surge irrigation was first trialed in America in the late 1970’s. Pulses of water are sent down the furrow using a switching system now commonly known as a surge valve. The major benefit comes from the consolidation of the surface of the furrow where fine sediments are held in place on the surface using negative pressure generated by the infiltration of water through the profile. The important management factors in surge irrigation are the correct inflow for the field conditions and setting the timer on the advance phase. Runoff and irrigation uniformity can be adjusted using a number of quick pulses at the end of the irrigation called the soak cycle. Applications need to be monitored carefully as the soil profile may not be filled. Applications of 30 to 40 mm have been achieved using surge irrigation on 650m rows in the Burdekin. Irrigation scheduling is essential when using surge irrigation.

A combination of high flow rates, minimum tillage, strategic compaction and alternate furrow surge irrigation has been used on the Ahern farm to apply 45mm applications for a number of years. Pumping costs are reduced along with infiltration and runoff losses. Fertiliser applications have been reduced as soil moisture monitoring showed that water had only penetrated to 80cm in depth.

7. CONCLUSION

Management is the key to efficient irrigation. The future of surface irrigation is bright with the adoption of surge irrigation and high inflow strategies indicating a reduced impact on the environment. The main advantages of a furrow system are that it is low tech and has relatively low operating costs if the farm is designed properly. The main disadvantage is the combination of different soil types, slope, surface conditions, furrow lengths and water quality add complexity to the system and a high level of knowledge and understanding is required to manage surface irrigation efficiently so as to reduce off site impacts.
OVERHEAD IRRIGATION

RC Bruce

1. INTRODUCTION

An indication of the adoption of various irrigation systems in sugar districts of Queensland is given by the data in Table 1 collected by Tilley and Chapman (1999). Of the overhead irrigation systems, winch (travelling gun) irrigation is the favoured method in the Herbert, Proserpine, Mackay, Sarina, Bundaberg, Childers and Maryborough areas while low-pressure overhead irrigation systems, which include centre pivot and lateral move, are gaining in popularity in the Tableland, Proserpine, Mackay and Childers areas. Furrow is generally the most favoured method of irrigation where full irrigation is required in the Burdekin and Tableland areas. Drip irrigation has developed steadily in Bundaberg-Childers and has been introduced in the Atherton Tableland.

Table 1. Adoption of various irrigation systems across Queensland sugar districts (Tilley and Chapman 1999)

<table>
<thead>
<tr>
<th>District</th>
<th>Furrow</th>
<th>Drip</th>
<th>Water winches</th>
<th>Centre pivot</th>
<th>Lateral move</th>
<th>Hand-shift sprinkler</th>
<th>Growers with irrigation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tablelands</td>
<td>73</td>
<td>4</td>
<td>2</td>
<td>15</td>
<td>6</td>
<td>-</td>
<td>95</td>
</tr>
<tr>
<td>Herbert</td>
<td>2</td>
<td>-</td>
<td>96</td>
<td>-</td>
<td>-</td>
<td>2</td>
<td>9</td>
</tr>
<tr>
<td>Burdekin</td>
<td>99.5</td>
<td>0.4</td>
<td>-</td>
<td>0.1</td>
<td>-</td>
<td>-</td>
<td>100</td>
</tr>
<tr>
<td>Proserpine</td>
<td>25</td>
<td>1</td>
<td>63</td>
<td>1</td>
<td>11</td>
<td>-</td>
<td>85</td>
</tr>
<tr>
<td>Mackay</td>
<td>32</td>
<td>0.3</td>
<td>54</td>
<td>4</td>
<td>1</td>
<td>9</td>
<td>70</td>
</tr>
<tr>
<td>Sarina</td>
<td>34</td>
<td>0.1</td>
<td>62</td>
<td>-</td>
<td>2</td>
<td>2</td>
<td>58</td>
</tr>
<tr>
<td>Bundaberg</td>
<td>25</td>
<td>5</td>
<td>70</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>96</td>
</tr>
<tr>
<td>Childers</td>
<td>20</td>
<td>5</td>
<td>70</td>
<td>-</td>
<td>5</td>
<td>-</td>
<td>97</td>
</tr>
<tr>
<td>Maryborough</td>
<td>-</td>
<td>2</td>
<td>96</td>
<td>2</td>
<td>0.5</td>
<td>-</td>
<td>50</td>
</tr>
</tbody>
</table>

2. OVERHEAD SYSTEMS

Overhead irrigation systems can be characterised into two groups depending on whether they operate on low or high water pressure (Tilley and Chapman 1999).

2.1 HIGH PRESSURE IMPACT SYSTEMS

Known as water winches (also water cannons or travelling guns) in the sugar industry, these units were an innovative move from the labour-intensive system of hand-shift spraylines but have inherent disadvantages of high maintenance costs, high operating costs and uneven application under windy conditions. Dependent on their forward speed, nozzle size and operating pressure, the instantaneous application rate may be greater than the soil infiltration rate, resulting in surface runoff. This is despite the overall application rate being matched to the soil infiltration rate. A traffic lane must be left every 80 to 90 m across the field. Water is fed via a flexible hose attached to a hydrant and the trolley-mounted high rise nozzle is pulled through the field by an anchored steel cable. The cable is wound onto a hydraulically driven drum located on the trolley.

Due to the effect of wind on the uniformity of application, water winches are often operated only at night. A recent innovation has been the development of the ‘hard hose’ water cannon that recovers the delivery hose on a giant reel rather than have it drag along the ground surface. The hose acts as the towing mechanism allowing the nozzle trolley to be a much smaller unit than the ‘soft hose’ version.
2.2 LOW PRESSURE OVERHEAD SYSTEMS (LPO)

LPO systems are attracting increasing interest, particularly in greenfield development or where irrigation water supplies have become limited. These units have low operating costs due to the low pressure required and a low labour requirement. Other advantages are the ability to automate, an easily varied application rate, a uniform distribution pattern under relatively windy conditions and large areas covered in one operation. Being low pressure, these units can use class 6 pipe instead of class 9 for the mainline, a saving of approximately 30% in capital costs. A disadvantage is the relatively high initial capital cost. There are a number of LPO systems available that are briefly discussed below.

Lateral move irrigators consist of a number of spans fitted with irrigation droppers. Spans vary from 30 m to 60 m in length and by adding additional spans total widths of up to 1.5 km are achieved. Each span is mounted on a pair of electronically driven wheels. Water is fed to the unit either from a flexible hose or open channel. Altering the advance rate of the unit varies application rate. This is a distinct advantage on low permeability soils.

Centre pivot units are similar to lateral move except that they operate in a circle with one end of the boom stationary. They can be used to irrigate large areas with some units 800 m in length, covering 200 hectares. They can be operated on undulating country by shortening the length of the spans that range from 40 m to 60 m in length. Sensors are located in each tower and assist in keeping the unit in a straight line.

Boom irrigators consist of a wheeled cart supporting a large boom with water supplied from a flexible hose up to 300 m long. A disadvantage with this system is that regularly spaced traffic lanes are required every 60 to 80 m across the field.

A comparison of some characteristics of irrigation systems is given in Table 2.

Table 2. A comparison of some characteristics of irrigation systems used in the Queensland sugar industry (Holden 1998)

<table>
<thead>
<tr>
<th></th>
<th>Furrow</th>
<th>Water winch</th>
<th>Lateral move</th>
<th>Centre pivot</th>
<th>Drip</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital costs</td>
<td>Low-</td>
<td>Medium</td>
<td>High</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Labour</td>
<td>High</td>
<td>Medium</td>
<td>Low</td>
<td>low</td>
<td>Medium</td>
</tr>
<tr>
<td>Management needs of system</td>
<td>Low</td>
<td>Medium</td>
<td>Medium</td>
<td>Medium</td>
<td>High</td>
</tr>
<tr>
<td>Special requirements</td>
<td>Land levelling</td>
<td>Traffic lanes</td>
<td>Traffic lanes</td>
<td>Suitable slopes</td>
<td>Maintenance filtration</td>
</tr>
<tr>
<td>Potential irrigation efficiency</td>
<td>Medium</td>
<td>Medium</td>
<td>Medium</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Limitations</td>
<td>Wind</td>
<td>Speed of operation</td>
<td>Speed of operation</td>
<td>Water quality</td>
<td></td>
</tr>
<tr>
<td>Relative costs to apply water</td>
<td>Low</td>
<td>High</td>
<td>Medium</td>
<td>Medium</td>
<td>Low</td>
</tr>
<tr>
<td>Opportunity to apply low rates</td>
<td>Low</td>
<td>Low</td>
<td>High</td>
<td>High</td>
<td>High</td>
</tr>
</tbody>
</table>

3. PERFORMANCE

The performance evaluation of in-field application systems can be divided into the two major components of water losses and uniformity of application (Raine and Foley 1999). Although both
components are influenced by system design and management practices, the losses are predominantly a
function of management while the uniformity is predominantly a function of the system design
characteristics.

3.1 WATER LOSSES

The major losses of water by in-field application systems are due to evaporation (from either the
atmosphere, free water surface or soil surface), deep drainage or surface run-off. The dominant loss
mechanism is closely related to the method of application but may be substantially reduced by the
adoption of appropriate management practices.

The efficiency of spray irrigation systems will be maximised by the adoption of strategies which:

- minimise spray drift losses
- reduce evaporation losses
- match application rates to the infiltration characteristic to reduce minimise run-off
- match application volumes to root zone storage volumes
- increase uniformities to reduce deep drainage and surface run-off losses.

Spray drift losses may be minimised by not irrigating during high wind periods and by the use of
droplet sizes appropriate to the wind conditions.

Evaporative losses are heavily influenced by the droplet size distribution, wind velocities and
temperatures. For example, Calder (2000) found evaporative losses from sprinkler systems as high as
40-50% of the discharge volume when the pan evaporation was greater than 13 mm/day and daily wind
runs were approximately 300 km. Hence, one strategy to reduce evaporative losses is to irrigate during
the night when temperature and wind conditions are usually lower. Another potential benefit of night
irrigation may include reduced pumping costs due to the use of off-peak electric rates. Increasing the
operating pressure of spray systems increases the distance the stream is thrown but increases the
number of fine droplets produced and increases evaporation and wind drift losses.

Surface run-off and evaporative losses associated with surface ponding of water may represent
significant loss mechanisms in poorly designed or managed sprinkler irrigation systems. A key
component of spray irrigation design involves matching the application rates to the soil infiltration
rates. However, while average application rates may not exceed the average infiltration characteristic of
the soil, non-uniform application may occur and lead to excessive rates in some sections resulting in
unwanted runoff.

Deep drainage losses may be substantial where irrigations are conducted too frequently or too soon
after rainfall events.

3.2 UNIFORMITY OF APPLICATION

Uniformity of application refers to how evenly irrigation water is applied across the field (Foley and
Raine 2001). In fields not watered uniformly, some parts will be irrigated to the desired depth, while
other parts will be either under or over irrigated. These non-uniformities lead to yield variation across
the irrigated area resulting in differences in economic return for different portions of the field. The
uniformity of water distribution in sprinkler systems is usually measured using Christiansen’s (1942)
Uniformity Coefficient (C_u). The positioning of sprinklers and the droplet sizes produced have a
dominant effect on uniformity as they influence the degree of overlap and the potential for drift.

Factors that contribute to non-uniformity include:

- emitter spacing, nozzle operating pressure, and emitter configuration
- nozzle size and selection with location along the machine
- nozzle height, angle and wear
- machine movement including step size and its consistency
- flow rate variations due to discontinuous end-gun operation, and variations in pump performance
- runoff from high application rates.
4. IMPROVING WATER USE EFFICIENCY

Substantial increases in water use efficiency should be achievable (Raine 1999) by:

- matching applied volumes to soil-water deficits
- matching application rates to the infiltration characteristics of the soils
- reducing spray evaporation losses through more appropriate matching of droplet size (eg. nozzle size and type and operating pressure) to environmental conditions (eg. wind speed and direction)
- modification of sprinkler spacings and field layouts to improve distribution uniformities.

Research into some of these is discussed in the next paper of this Manual.

5. ACKNOWLEDGEMENTS

This paper has drawn on, sometimes directly, the following references, which would be suitable for further reading:


6. REFERENCES


Christiansen JE (1941) Hydraulics of sprinkling systems for irrigation. Transactions of the American Society of Civil Engineers 107, 221-237.


PERFORMANCE OF TRAVELLING GUN IRRIGATION MACHINES

R Smith, C Baillie and G Gordon
(Reprinted, with permission, from Proceedings of the Australian Society of Sugar Cane Technologists, 2002)

1. INTRODUCTION

Travelling gun (or winch) irrigators are high pressure (up to 650 kPa), high capacity, high application rate, continuous move, sprinkler systems (Figure 1). A large proportion of the Australian sugar crop is irrigated by travelling gun irrigation machines, including approximately 60% of the crop in the Bundaberg district. However, little is known of their performance in the field. They are characterised by a single high-pressure water jet that is rotated by a knocker arm. The throw distance of the water jet in still air can be up to 70 m.

Figure 1. Features of a typical travelling gun irrigation machine.

Travelling irrigators operate along regularly spaced, parallel towpaths. The lane spacing is generally a specified (by the manufacturer) fraction of the wetted diameter and the length of travel is typically about 400 metres. Water is supplied to the irrigator either through a flexible hose, which is pulled behind the machine, or through a hard hose, which is wound onto a reel at the end of the towpath.

They are self-powered and employ either turbine or piston drive mechanisms. Typically, water diverted from the main flow is used to drive the turbine or piston, which in turn drives a winch and cable mechanism. The water so used is then applied to the crop via one or more “walker” jets. These are smaller diameter lower pressure sprinkler nozzles. In newer style machines, the entire flow passes through the drive turbine and thence to the main nozzle, doing away with the “walker” jets.
The nozzle type and size, pressure and the travel speed of the machine determine the application rate. Application rates can range from 10 to 110 mm, but for irrigation of sugarcane in the Bundaberg region, typically 50 mm is applied. To alter the application rate the travel speed is altered, by varying the flow of water passed through the turbine or piston.

Travelling gun machines have long been known to apply water to the field non-uniformly, particularly when lane spacing is excessive and under windy conditions. Australasian studies indicating this poor performance are those of John et al. (1985), Bell (1991) and Wigginton and Raine (2001), although the range of machines and nozzles tested was quite limited.

Travelling gun irrigators are employed on most soil types and topography, and tend to be operated in most wind conditions. Because current irrigation systems often have insufficient capacity for the area they are required to service, it becomes necessary to irrigate in adverse conditions and accept the less than optimum uniformity and efficiency rather than wait until conditions improve. There are several settings on the machines that can alter their performance. Typically an irrigator is configured for low wind conditions and the settings are left unaltered. Very little is known about how these settings alter the irrigation performance across the range of wind conditions.

2. METHODOLOGY

2.1 MACHINES

All trials were performed on Bundaberg Sugar properties. The first six trials were undertaken on the Avondale plantation and the remaining sixteen at Fairymead. The soils at Avondale were light sands and at Fairymead were heavy alluvial clays. Both farms are in close proximity to the coast and experience unobstructed sea breezes.

The irrigators tested were all Trailco Traveller, T450-2. The machines were typical of those used throughout the Bundaberg region; they were fitted with Nelson P200 guns all with a 21° trajectory angle. The machines were set up and operated for a range of conditions typical of those for normal grower operation. The drive mechanism was set to give a travel speed of 20 m/h and the rotation angle of the gun was set at 330°.

The trial sites were selected on the basis of crop height. A suitably low crop was needed so that there was no interference between the crop and the water caught in the catch cans.

2.2 TRIALS

Variables considered in the trials were nozzle type and diameter, operating pressure, and wind speed and direction.

2.2.1 Nozzle type and size
There are two types of P200 nozzle available, ring and taper nozzles. Taper nozzles offer the greatest stream integrity and maximum distance of throw with minimum distortion by wind. Ring nozzles provide better stream break-up at lower operating pressures for delicate crops. Ring nozzles are available in seven sizes ranging from 32.8 to 49.0 mm diameter and taper nozzles from 26.7 to 48.3 mm. The nozzles tested were the commonly used 1.2T and 1.3T taper nozzles and the equivalent sized ring nozzles, the 1.46R and 1.56R.

2.2.2 Pressure
The nozzle pressures used in the trials were 515, 550 and 585 kPa (75, 80 and 85 psi). The lowest of these, 515 kPa, is indicative of the minimum pressure recommended by the manufacturers so the machine doesn’t encounter walking problems, while 585 kPa is toward the top of the recommended range.

2.2.3 Wind speed and direction
Given the variety of wind conditions experienced in the Bundaberg region during the irrigation season, the trials were grouped according to wind speed and direction. Two groupings were used for wind speed, high and low, being greater or less than 5 m/s, respectively.
Wind direction was categorised relative to the travel path of the irrigator, as parallel (0 to 45°) and crosswind (45° to 90°). For the low wind category wind direction was not considered important and was omitted. The wind speed and direction was recorded every six minutes throughout each trial. The measurement system consisted of a Monitor Sensors anemometer and wind direction sensor.

2.3 MEASUREMENT

2.3.1 Nozzle discharge and pressure
Discharge was measured by an in-line flow meter located in the supply pipeline at the hydrant. The meter is accurate to +/-3%. Pressure was measured by a pressure gauge installed immediately upstream of the nozzle.

2.3.2 Depth of irrigation applied
Applied depths either side of the tow path were measured along transects perpendicular to the travel of the machine, known as a single leg test. Catch cans were located at 5 m spacings along the transects. The catch cans were constructed from 90mm uPVC pipe, fixed to timber stakes. The volume in the catch cans was measured and then converted to depths.

The catch cans were installed at a height of 900 mm to raise them above the young crop to minimise interference by the crop. To retain the usual height difference between nozzle and ground surface, the nozzle was raised 900 mm by installing an extended riser on the irrigator. A few trials were conducted with the catch cans located 3 m above the ground surface to assess the change in the wetted pattern caused by the interception of the spray by a mature cane crop.

3. RESULTS AND DISCUSSION

3.1 SUMMARY
The 17 trials are summarised in Table 1. In each case the uniformity is calculated assuming adjacent passes of the machine at 75m lane spacing. The lane spacings that would give the highest uniformity for the given conditions are also presented.

The uniformity is expressed in terms of the Christiansen uniformity coefficient (CU), as proposed by Christiansen (1941):

\[
CU = 100 \left( 1 - \frac{m}{X} \right)
\]  

(1)

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

\[
m = \frac{\sum |x_i - X|}{n}
\]  

(2)

\( X \) is the mean applied depth, and \( n \) is the number of depth measurements. The Christiansen coefficient was originally developed for sprinkler irrigation and remains the most widely used uniformity measure for that purpose.
Table 1. Summary of trials

<table>
<thead>
<tr>
<th>Trial #</th>
<th>Nozzle</th>
<th>Pressure (kPa)</th>
<th>Can height</th>
<th>Wind speed &amp; direction</th>
<th>Mean applied depth (mm)</th>
<th>CU (%) (75 m lane spacing)</th>
<th>Optimum lane spacing (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.2T</td>
<td>550</td>
<td>high</td>
<td>high – parallel</td>
<td>47.3</td>
<td>84.2</td>
<td>65</td>
</tr>
<tr>
<td>2</td>
<td>1.2T</td>
<td>550</td>
<td>low</td>
<td>high – cross</td>
<td>41.8</td>
<td>79.6</td>
<td>75</td>
</tr>
<tr>
<td>3</td>
<td>1.2T</td>
<td>515</td>
<td>low</td>
<td>low – cross</td>
<td>35.1</td>
<td>77.8</td>
<td>85</td>
</tr>
<tr>
<td>4</td>
<td>1.2T</td>
<td>585</td>
<td>low</td>
<td>high – parallel</td>
<td>40.7</td>
<td>73.1</td>
<td>65</td>
</tr>
<tr>
<td>5</td>
<td>1.46R</td>
<td>550</td>
<td>low</td>
<td>high – parallel</td>
<td>38.1</td>
<td>48.3</td>
<td>55</td>
</tr>
<tr>
<td>6</td>
<td>1.46R</td>
<td>550</td>
<td>high</td>
<td>high – parallel</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>1.46R</td>
<td>515</td>
<td>low</td>
<td>high – parallel</td>
<td>42.6</td>
<td>56.5</td>
<td>55</td>
</tr>
<tr>
<td>8</td>
<td>1.46R</td>
<td>585</td>
<td>low</td>
<td>high – parallel</td>
<td>54.2</td>
<td>69.6</td>
<td>65</td>
</tr>
<tr>
<td>9</td>
<td>1.3T</td>
<td>515</td>
<td>low</td>
<td>low – cross</td>
<td>59.5</td>
<td>80.5</td>
<td>55</td>
</tr>
<tr>
<td>10</td>
<td>1.3T</td>
<td>550</td>
<td>low</td>
<td>high – cross</td>
<td>47.7</td>
<td>84.5</td>
<td>75</td>
</tr>
<tr>
<td>11</td>
<td>1.3T</td>
<td>585</td>
<td>low</td>
<td>high – cross</td>
<td>50.4</td>
<td>77.2</td>
<td>65</td>
</tr>
<tr>
<td>12</td>
<td>1.3T</td>
<td>550</td>
<td>low</td>
<td>high – cross</td>
<td>52.9</td>
<td>78.6</td>
<td>55</td>
</tr>
<tr>
<td>13</td>
<td>1.3T</td>
<td>515</td>
<td>low</td>
<td>high – parallel</td>
<td>58.6</td>
<td>83.5</td>
<td>65</td>
</tr>
<tr>
<td>14</td>
<td>1.2T</td>
<td>550</td>
<td>low</td>
<td>high – parallel</td>
<td>52.7</td>
<td>79.1</td>
<td>65</td>
</tr>
<tr>
<td>15</td>
<td>1.2T</td>
<td>550</td>
<td>high</td>
<td>high – parallel</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>1.46R</td>
<td>550</td>
<td>low</td>
<td>high – parallel</td>
<td>44.5</td>
<td>60.9</td>
<td>65</td>
</tr>
<tr>
<td>17</td>
<td>1.2T</td>
<td>585</td>
<td>low</td>
<td>high – parallel</td>
<td>40.0</td>
<td>48.8</td>
<td>55</td>
</tr>
<tr>
<td>18</td>
<td>1.2T</td>
<td>515</td>
<td>low</td>
<td>high – cross</td>
<td>32.4</td>
<td>67.1</td>
<td>55</td>
</tr>
<tr>
<td>19</td>
<td>1.46R</td>
<td>515</td>
<td>low</td>
<td>high – cross</td>
<td>37.3</td>
<td>66.8</td>
<td>55</td>
</tr>
<tr>
<td>20</td>
<td>1.46R</td>
<td>550</td>
<td>low</td>
<td>high – cross</td>
<td>49.0</td>
<td>80.0</td>
<td>85</td>
</tr>
<tr>
<td>21</td>
<td>1.46R</td>
<td>585</td>
<td>low</td>
<td>high – cross</td>
<td>46.5</td>
<td>70.8</td>
<td>65</td>
</tr>
<tr>
<td>22</td>
<td>1.2T</td>
<td>515</td>
<td>low</td>
<td>high – parallel</td>
<td>54.0</td>
<td>72.3</td>
<td>65</td>
</tr>
</tbody>
</table>

3.2 APPLICATION PATTERNS

The pattern of applied depths of irrigation from one pass of a travelling irrigator is shown in Figure 2. The data in this case are from trial # 3, which is a 1.2T nozzle operating at 515 kPa. The salient features of this pattern are:
(i) a wetted radius of 50 m;
(ii) the peaks, each side of and close to the winch track, caused by the operation of the walker jets; and
(iii) peaks at about 30 m from the winch track, most probably resulting from the 330° angle of rotation of the nozzle.
Figure 2. Typical distribution pattern from single pass of a machine (Trial # 3).

Of greater importance is the pattern of applied depths between two winch tracks, resulting from adjacent passes of the machine. In this case the pattern is the result of the overlapping of two individual patterns spaced apart a distance equal to the winch track spacing. This is illustrated in Figure 3 using the pattern from Figure 1 at the spacing of 75m. Here the lane spacing is about 75% of the wetted diameter of the sprinkler and the result is clearly an unacceptably non-uniform irrigation. The mean applied depth is 35.1 mm but depths range from 50 mm mid-way between the winch tracks down to nearly 20 mm at the 60 m mark, and return a Christiansen Uniformity coefficient (CU) of applied depths of 77.8%. A CU of about 84-86% is traditionally seen as an acceptable performance for sprinkler systems. Only three of the machines tested satisfied this requirement but then only marginally.

Figure 3. Typical overlap distribution pattern (Trial # 3).

An alternative way of looking at these data is in the form of a cumulative distribution of the applied depths (Figure 4). This type of plot shows the proportion of the area receiving an irrigation depth of at least \( d \) mm, and for any specified target depth of irrigation allows assessment of the areas that are under- or over-irrigated and by how much. For example, if it was deemed that at least 90% of the field should receive an application of 35 mm, then the average application needs to be increased to about 45

115
mm. Note that neither of these figures includes any allowance for spray evaporation, drift or interception losses.

![Cumulative distribution of applied depths (Trial # 3).](image)

By varying the lane spacing and hence the degree of overlap, it is possible to determine the lane spacing for which the uniformity (CU) is a maximum. For the case illustrated in Figures 2 to 4, the variation in CU with lane spacing is illustrated in Figure 5. The maximum is a CU of 86% at a lane spacing of 85 m. For this machine it is clear that none of the lane spacings considered here will result in more than a marginally acceptable uniformity (although high uniformity may be achievable with very low lane spacings, for example, spacings equal to or less than the wetted radius of the machine). The optimum lane spacings presented in Table 1 were calculated by this process.

![Example of the variation of CU with lane spacing (Trial # 3).](image)
3.3 NOZZLE TYPE AND SIZE, OPERATING PRESSURE AND THE EFFECT OF WIND

From the summary of results presented in Table 1 there is a clear indication that the performance of the ring nozzles was inferior to the taper nozzles across the range of nozzle sizes, operating pressures, and wind conditions.

The role of the other variables was less clear, with any trends in performance due to nozzle size and pressure masked by the modifying influence of the wind. Isolating the individual role of these variables would require many more trials under more controlled conditions.

Similarly it is difficult to draw anything but the most general conclusions concerning the effect of wind on machine performance. Importantly, the data presented in Table 1 do not contradict the generally known effects of wind. As expected, the high parallel winds caused the most pronounced reduction in the uniformity of applications. This is because of the considerable reduction in the throw of the sprinkler in the direction perpendicular to the wind.

3.4 LANE SPACING

Apart from a couple of trials, the performance of the machines would be greatly improved, for most nozzles and pressures and for most wind speeds and directions, by reducing the lane spacing. This can be seen in Table 1 where the optimum lane spacings are most commonly between 55 and 65 m. Wetted diameters were generally in the range 90 to 110 m (reducing to about 80 m for the trials involving high parallel winds). The lane spacings of 75 to 80 m, commonly used in the Bundaberg region, equate to between about 90 to 70% of that wetted diameter.

Lane spacings recommended by the different machine manufacturers (who employ the P200 nozzle) range from 65 to 80% of wetted diameter and would give lane spacings less than 75 m. These recommendations and the lane spacings used in the Bundaberg region compare poorly to the more general recommendations provide by irrigation texts which suggest lane spacings of 65% of the diameter, reducing to 40% in high wind conditions (Jensen, 1983; Solomon, 1990). The optimum lane spacings determined in Table 1 are more consistent with these latter recommendations.

4. STRATEGIES FOR IMPROVING UNIFORMITY OF APPLICATIONS

To maximise the uniformity of their irrigations, Bundaberg growers would need to reduce their lane spacings substantially: to between 60 and 65 m if they intend to irrigate only in low wind conditions, and to around 50 to 55 m if they intend to irrigate in all wind conditions.

For many established growers, reducing lane spacings will be impractical. Lane spacings have been fixed by limitations imposed by the farm layout and water supply infrastructure. In these instances other strategies need to be adopted to give improved uniformity such as changing to tapered nozzles and/or altering the angle of rotation of the gun.

Tapered nozzles have been shown to increase the wetted radius in all wind conditions and hence increase the overlap of adjacent passes of the machine. Uniformity is increased as a consequence.

The commonly used 330° angle of rotation of the nozzle appears to have a pronounced effect on the uniformity of applications. Improvements in performance for the present lane spacings and for high wind conditions may result from a reduction in the angle of rotation. This is the subject of current research being undertaken by the NCEA.

5. REFERENCES

Christiansen JE (1941) Hydraulics of sprinkling systems for irrigation. Transactions of the American Society of Civil Engineers 107, 221-237.


TRICKLE IRRIGATION FOR SUSTAINABLE SUGARCANE PRODUCTION

PJ Thorburn, CA Sweeney, KL Bristow, FJ Cook and KA Collins

1. INTRODUCTION

Irrigation is vital to sugarcane production in Australia (Meyer 1997). However, in an environment of increasing pressure on resources and a greater need to reduce off-site impacts of agriculture, the efficiency of water use must be maximised and leaching of pollutants (including nitrogen fertiliser) from the root zone minimised. Drip irrigation enables water to be delivered at precise locations in small quantities at much higher frequencies than other irrigation methods (Hillel 1980a). Potential advantages for drip irrigation include a more controlled irrigation system which allows farmers to match the rate and frequency of irrigation to factors such as the crop’s evapotranspiration and nutrient requirements, the soil’s hydraulic conductivity, and salinity conditions of the soil and irrigation water. The general aim of such a system is to meet the crop’s water and nutrient requirements without saturating the soil profile or allowing excess leaching of water or chemicals, whilst avoiding salinity build-up (Dasberg and Bresler 1985, Institute of Hydrology 1988). Unfortunately there is often a difference between the possible and actual productivity gains achieved with trickle irrigation (Phene 1995a).

Drip irrigation is often quoted as having the potential for improving water and nutrient efficiency, reducing off-site impacts and increasing crop growth and/or yield (Kruse et al. 1990). For this to happen, a trickle system must be tailored to soil type and crop water demand (which depends on growth stage and climate). Adequate water and nutrients are needed for the crop, but too much may give leaching and ground water pollution in light soils. In clay soils, low soil permeability may lead to water logging or insufficient water supply. These problems may arise because both the volume and shape of soil wet during application from a trickle emitter differ greatly, depending on soil type and water content, so the interaction between the trickle system and the crop and environment is variable. Research quantifying the extent of ground water pollution from fertigated crops is still very much in its infancy. Indeed, whilst a fair amount of research has taken place on the affect of nitrogen application rates on crop growth, few authors have considered the leaching fraction.

While drip irrigation is not always successful, a large proportion of such findings can usually be attributed to a lack of understanding of how the system works, or a lack of adequate maintenance. Perhaps the greatest obstacle to drip irrigation research is that summed up by Phene (1995a), who states that “unless the problem of supplying water accurately in time and space is first solved (one of the greatest potential advantages of microirrigation), results from applying many other treatments (such as fertility, row spacing, plant density, irrigation frequency, etc.) will give contradictory, insignificant and/or invalid results.”

Throughout this document, particular emphasis will be placed on the sugarcane growing, coastal regions of Queensland and northern New South Wales, which are most likely to be under trickle irrigation systems. This region is characterised by summer dominated rains, with humid tropical conditions in the north and a temperate climate in the south (Hubble and Isbell 1983). Some of the more fertile agricultural soils within the region include black earths, red-brown earths, grey clays, krasnozems, and prairie soils (Hubble and Isbell 1983).

Our interest in this area stems from the need to establish agronomic practices that maximise resource efficiency whilst minimising off-site impacts and ground water deterioration. Increasing salinity in some Queensland coastal areas due to seawater intrusion, and the proximity of ecologically sensitive areas, such as the Great Barrier Reef, have prioritised the necessity for practical farming guidelines which achieve such goals.
This report provides a summary of key literature covering the many components of drip irrigation. These include factors influencing drip irrigation, agronomy, fertigation, environmental issues, management and scheduling, and design.

2. DEFINITIONS

Drip or trickle irrigation generally refers to low pressure irrigation systems consisting of lengths of plastic tubing along which emitters are placed, or orifices occur, typically discharging a few litres per hour. There is some inconsistency in the literature with regards to the definition of drip irrigation. Gibson (1978) classifies drip irrigation as those systems that are destroyed with harvesting operations, and subsurface as those which endure harvesting. Keller and Bliesner (1990) define trickle irrigation as a category of irrigation systems containing drip, spray, bubbler and subsurface irrigation designs. Their definition of drip irrigation encompasses systems that deliver water to the soil surface via emitter openings. They suggest that the discrepancy surrounding the definition of trickle irrigation may be a result of translation problems.

The ASAE (1988) chooses the broader category ‘microirrigation’ to include drip/trickle, subsurface, bubbler and spray irrigation. Drip/trickle irrigation is referred to as surface or near surface systems delivering less than 12 L hr⁻¹. Subsurface irrigation refers to the same system beneath the ground. Bubblers refer to systems in which the rate of discharge is between 12 L hr⁻¹ and 225 L hr⁻¹ via small streams, while spray refers to applications greater than 100 L hr⁻¹.

Yet another definition is given by Dasberg and Bresler (1985) in which drip and trickle are synonymous and described as surface or subsurface systems which deliver less than 10 L hr⁻¹ of water per emitter at operating pressures between 20-200kPa. This definition then excludes microjets and minisprinklers. The general consensus in the literature is more aligned towards the definition given by Dasberg and Bresler (1985); hence, their definition of drip irrigation will be used throughout this report.

3. AGRONOMIC PRODUCTION

We begin this section by describing generally accepted advantages/disadvantages of drip irrigation, then follow with a more in depth examination of relative successes and failures experienced in its application to the sugarcane industry. As sugarcane is the main focus of this report, the drip irrigation systems used in other crops are generally not considered, as the systems must be designed according to each crop’s specific physiology, and environment. The complex nature of designing such systems is summed up by the Institute of Hydrology (1988) who state that, “drip system design involves selection of dripline type, dripline placement with respect to row crops, spacing between emitters along the dripline, and emitter or orifice discharge rates. The optimal combination of these will depend on crop type, soil type, climate, agricultural practices and economics.”

3.1 ADVANTAGES OF DRIP IRRIGATION

The following list of advantages is widely cited for drip irrigation:

- Uniform discharge can be achieved throughout a field regardless of its slope or soil type (Hillel 1980a, Dasberg and Bresler 1985). Keller and Bliesner (1990), however, report that uniform discharge is not achieved on steep slopes. They imply that up to 50% difference in volume intended can occur for some emitters on steep slopes although no source/citation is given for this figure. The authors also caution that the lines will drain through emitters in lower elevations once irrigation ceases, which may cause over watering.

- Further research indicates that this uniformity of water delivery largely depends upon the type of drip line used. Bui (1988) showed that emitter discharge uniformity depended on age of drip lines, due to an increase in the number of emitters plugging over time, as well as on brand of drip line used. Emitter flow coefficients of variation were between 50% and 150% at the time of harvest, compared with initial coefficients of variation of less than 10%. This may be due to improper management. Bui (1988) also found that a larger number of emitters became clogged towards the
tail end of the tubing as a result of lower flow velocities. One concern raised by Bui was the implications for this non-uniform water distribution and the application of fertilisers.

- The claim that drip irrigation produces highly uniform discharge has been refuted by Hanson et al. (1995). Table 1 contains an excerpt from findings from over 959 irrigation systems throughout California. These results indicate that furrow and border irrigation systems have the highest distribution uniformities. Distribution uniformity refers to the average depth of infiltration of the lowest quarter of measurements divided by the average depth of infiltration. The authors do suggest that properly designed and managed microirrigation systems can achieve distribution uniformities greater than 80%, as was the case with 38% of the drip systems.

Table 1. Average distribution uniformities (DU) for the listed irrigation methods (Hanson et al. 1995). Numbers in parenthesis are standard deviations. Values with the same letter are not statistically different at a level of confidence = 95%

<table>
<thead>
<tr>
<th>Irrigation method</th>
<th>Sample Size</th>
<th>DU (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hand-move/solid-set sprinklers</td>
<td>164</td>
<td>62 (15) c</td>
</tr>
<tr>
<td>Continuous-move sprinklers</td>
<td>57</td>
<td>75 (10) a</td>
</tr>
<tr>
<td>Under tree sprinklers</td>
<td>28</td>
<td>79 (16) ab</td>
</tr>
<tr>
<td>Microirrigation (permanent crops)</td>
<td>458</td>
<td>73 (15) a</td>
</tr>
<tr>
<td>Microirrigation (row crops)</td>
<td>23</td>
<td>63 (16) c</td>
</tr>
<tr>
<td>Furrow</td>
<td>157</td>
<td>81 (14) b</td>
</tr>
<tr>
<td>Border</td>
<td>72</td>
<td>84 (14) b</td>
</tr>
</tbody>
</table>

- Recent claims by industry show that much has been done to address dripper uniformity, with the majority of systems recording emission uniformities of 85% or above. The study by Hanson et al. (1995) showed that 12 out of 17 tapes/tubing tested had manufacturing coefficients of variation less than or equal to 0.05.

- Water-use efficiency is improved due to increased control over the rate at which water is applied, reducing loss to drainage. There is also less surface evaporation of water, particularly with subsurface drip irrigation (Keller and Bliesner 1990, Bucks 1995, Phene 1995b). Dart et al. (1996) point out that an increase in water use efficiency does not necessarily correspond to a decrease in water consumption, particularly when heavy textured soils with high water holding capacity are involved.

- Drip irrigation is suitable for soil types that have traditionally been problematic for other irrigation methods, such as coarse sands and clays (Hillel 1980a, Dasberg and Bresler 1985). Selker et al. (1995) state that drip irrigation is not well suited to cracking clays or soils with fissures or cracks, in which a high volume of water drains through macropores. This type of problem, however, is not specific to drip irrigation. In Australia, subsurface drip irrigation is being used in cracking clay soils.

- Soil moisture can be maintained at a high level without saturation occurring. This allows for soil aeration as well as easier root penetration (Hillel 1980a).

- Incidences of leaf scorch and fungal diseases are less likely (Dasberg and Bresler 1985, Bucks 1995). The spread of pathogens is also reduced due to decreased surface run-off (Or 1995).

- As the inter-rows are kept dry, weed growth is minimised (Dart et al. 1996, Bucks 1995).

- The low pressure requirements can translate into energy savings where pumping is required (Hodnett et al. 1991). Churchward and Curd (1995) reported pump savings of A$45/ML under drip irrigation versus water winching. The type of pump used was not mentioned.

- Labour is reduced when compared to overhead irrigation systems (Institute of Hydrology 1988). Smajstrla et al. (1995) indicate that this is not the case for fruit crops, as the amount of
maintenance and frequency of scheduling required make drip irrigation more labour intensive than previous systems.

- Evidence of increases in some crop yields (providing the system is properly managed) particularly when the irrigation water is of poor quality (Bucks 1995). The literature is abundant with examples of varying degrees of success/failure of drip irrigation. It is noted that:

1. The system must be managed correctly for drip irrigation to produce benefits to crop yields.
2. Care must be taken with confounding effects. For example, Moore and Fitschen (1991) report increased yields for sugarcane under drip irrigation as compared to furrow irrigation. Water of different quality was used for both methods, with the furrow irrigation receiving water of high silt and sediment load. Thus the increase in yield cannot be attributed to the irrigation method used as the response may or may not be due to the water type used.
3. Extraneous factors may be the cause of discrepancies between studies. For example, two studies of similar environmental and experimental conditions may be carried out, one recording no differences in yield whereas the other shows substantial yield increases. Upon closer examination, the substantial increases were exhibited in times of extreme drought whereas the other study was conducted during a higher than average rainfall period. In this case, the extraneous factor would be rainfall amount.

- There is potential for more efficient use of fertilisers, herbicides and pesticides because of increased control over application rates. Applications can be tailored to different stages of plant growth (Bucks 1995).

- Saline waters unsuitable with conventional methods can be used successfully under drip irrigation, due to efficient leaching of the wetted zone around the emitter (Keller and Bliesner 1990, Dasberg and Bresler 1985). Or (1995) states that high frequency drip irrigation using saline waters of EC 7 dSm⁻¹ can achieve crop yields similar to those irrigated with ‘normal’ water.

- Less compaction and soil structure damage occur due to dry interrows, particularly when machinery or picking is required (Dasberg and Bresler 1985).

- Environmental impacts from water pollution on aquatic ecosystems are more manageable (Bucks 1995).

### 3.2 DISADVANTAGES OF DRIP IRRIGATION

The following list of disadvantages for drip irrigation are mentioned in the literature:-

- There are difficulties in designing the system to adjust to local conditions, emitter spacings and crop type and stage of growth. While this is true for all irrigation systems, for drip systems a failure to match the system to existing conditions is more likely to cause crop damage over a shorter time period. The emitter discharge rate must be adjusted according to the soil infiltrability, the timing and length of irrigation applied, seasonal changes, and the stage of crop development (Hillel 1980a).

- A build up of salts may occur at the soil surface and at the edges of the wetted zone, which may be problematic in arid areas or for subsequent crops (Keller and Bliesner 1990). Dasberg and Bresler (1985) suggest these salts may be leached out via sprinkler or flood irrigation in between crops or that emitters be retained in the same spot for subsequent crops. Keller and Bliesner (1990) warn of the danger of the surface salt being leached into the root zone when rainfall events are less than 50mm. They suggest that the irrigation should continue after such rainfall events to ensure the salt is leached below the root zone.

- Crops are more prone to damage from mismanagement or scheduling changes. This is due to the root growth proliferating in the wetted zone around the drip emitter. Crops then become very sensitive to water supply to this zone and therefore upon the irrigation schedule. Drying of the soil due to an interruption in irrigation may also lead to water moving from the perimeter of the wetted
zone towards the emitter. If there is a considerable salt build up at the edges of the wetted zone, this may cause crop damage (Keller and Bliesner 1990).

- There is a possibility of high drainage/leaching directly beneath emitters, particularly in highly permeable soils (Selker et al. 1995).

- Clogging of emitters can occur due to suspended particles (requires filtration), algae (requires algicide to be passed through system), salt precipitation (requires regular acidification of lines), or root intrusion (requires use of specially designed orifices or herbicides) (Hanson 1995).

- Drip lines may be susceptible to damage by rodents or insects searching for a water source. As an alternative to poison, Dasberg and Bresler (1985) suggest placing alternative sources of water about the field for these animals to access.

- Yields may be affected if fertilisers are not applied, due to the roots usually being confined around the emitter to a smaller than normal volume of soil from which the nutrients are removed quickly (Dasberg and Bresler 1985).

- Fertilisers, toxic to humans or animals, applied via drip irrigation may back flow into the main water supply if adequate safeguards are not installed (Zoldoske and Jorgensen 1990).

3.3 SUGARCANE RESEARCH

The sugarcane industry was one of the earliest adopters of trickle irrigation in Australia, it being practised for over 20 years (Meyer 1997). In the early 1990s there was renewed interest in trickle irrigation, particularly in the Bundaberg area (Churchward and Curd 1995, Ridge and Hewson 1995, Dart et al. 1996, Dart and Baillie 1997). However, there has also been strong interest in the use of trickle irrigation for growing sugarcane in other countries, notably Hawaii (Pyle and Moore 1985) and Mauritius (Institute of Hydrology 1988).

Research into sugarcane responses to drip irrigation has been fairly extensive but geographically limited, with the bulk of research emanating from Hawaii and Mauritius. Useful information has also been reported from Australia, India and Swaziland. The studies are generally of two types viz. the comparison of yields either under different irrigation application methods or under trickle irrigation scheduled in different ways. Some studies also present information on water use efficiency in the different treatments. However, the lack of consideration to the possibility of water being lost to drainage and the inclusion of complete soil water balances means the efficiency of the systems studied remains largely unknown. Additionally, the value of comparisons between studies over time may be limited due to the technological advances in drip irrigation systems, such as a more efficient combination of dripline placements, emitter spacings, and irrigation regimes. Furthermore, the results of these studies cannot be extrapolated due to their empirical nature. Table 2 lists some of the results found in the literature.

3.3.1 Sugarcane yield under trickle irrigation

There are a number of papers summarising on-farm comparisons of yields under different irrigation application methods. Churchward and Curd (1995) found that sugarcane yields were almost 40 % (25-30 t/ha) higher when water was applied by trickle irrigation than water winch. Pyle and Moore (1985) and Moore and Fitschen (1991) summarise the experience on farms of the Hawaiian Commercial and Sugar Company, where trickle irrigation increased sugar yields by more than 20 % compared with furrow irrigation (Table 2).
Table 2. Recorded yields in response to various treatments. Yields are in t ha⁻¹ unless otherwise specified (e.g. tonnes of sugar per acre per month (tsam))

<table>
<thead>
<tr>
<th>Author</th>
<th>Soil type and location</th>
<th>Treatment</th>
<th>Treatment yield</th>
<th>Comments</th>
</tr>
</thead>
</table>
                            2. Trickle placed 30cm below surface | Increased yield under trickle of 25-30t ha⁻¹ | Experimental design not given; figures based on commercial experience. |
| Magar and Bhapkar (1988) | Vertisols, India       | 1. Drip on surface for every cane row  
                            2. Furrow (without earthing up)  
                            3. Furrow (with earthing up) | 1. 146.41  
                            2. 122.09  
                            3. 127.25 | Age of crop not given, but presumed is plant crop |
| Magar and Bhapkar (1988) | Vertisols, India       | 1. Ridge and furrow  
                            2. Graded furrow  
                            3. Drip daily  
                            4. Drip second daily  
                            5. Normal furrow  
                            6. Paired row furrow  
                            7. Alternate furrow | Plant cane:  
                            1. 158.28  
                            2. 148.62  
                            3. 166.67  
                            4. 167.27  
                            First ratoon  
                            5. 96.4  
                            6. 95.95  
                            7. 88.88  
                            3. 107.33  
                            4. 110.92 | Surface pair row planting |
                            1. Drip buried 7cm deep in interrow  
                            2. Sprinkler  
                            3. Furrow | 1. 0.56 tsam  
                            2. 0.4 tsam  
                            3. 0.46 tsam | These were yields taken at 9 months of age, prior to harvesting, due to cyclone damage. 1.62 m line spacing |
| Soopramanien et al. (1988) | Silty clay, Mauritius  | 1. 20cm below ground, 1.2 L hr⁻¹, 1.0 ETc  
                            2. 20cm below ground, 2.4 L hr⁻¹, 1.0 ETc  
                            3. 20cm below ground, 1.2 L hr⁻¹, 0.5 ETc  
                            4. 20cm below ground 2.4 L hr⁻¹, 0.5 ETc  
                            5. Surface of alternate interrows, 1.2 L hr⁻¹, 1.0 ETc  
                            6. Surface of alternate interrows, 2.4 L hr⁻¹, 1.0 ETc  
                            7. Surface of alternate interrows, 1.2 L hr⁻¹, 0.5 ETc  
                            8. Surface of alternate interrows, 2.4 L hr⁻¹, 0.5 ETc  
                            9. Unirrigated | Plant cane:  
                            1. 112.9  
                            2. 110.3  
                            3. 94.5  
                            4. 94.4  
                            5. 85.0  
                            6. 101.8  
                            7. 86.3  
                            8. 69.3  
                            9. 10.7 | These were yields taken at 9 months of age, prior to harvesting, due to cyclone damage. 1.62 m line spacing |
                            2. Spray  
                            3. Drip  
                            4. Furrow | Plant cane:  
                            1. 181  
                            2. 181  
                            3. 183  
                            4. 179  
                            First ratoon  
                            1. 140  
                            2. 147  
                            3. 142  
                            4. 136 | No significant yield differences between treatments in plant cane, first ratoon or second ratoon (p<0.05)  
Yield decline under drip was attributed to plugged orifices. |
<table>
<thead>
<tr>
<th>Study</th>
<th>Location</th>
<th>Treatment</th>
<th>Yield 1</th>
<th>Yield 2</th>
<th>Yield 3</th>
<th>Yield 4</th>
<th>LSD</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chapman (1978) as cited in Chapman (1980)</td>
<td>Mackay</td>
<td>1. No irrigation 2. Drip, 0.4 Pan 3. Drip, 0.6 Pan 4. Drip, 0.8 Pan</td>
<td>112</td>
<td>109</td>
<td>89</td>
<td>105</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Plant cane</td>
<td>107</td>
<td>115</td>
<td>113</td>
<td>129</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>First Ratoon</td>
<td>88</td>
<td>118</td>
<td>112</td>
<td>132</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Second Ratoon</td>
<td>108</td>
<td>104</td>
<td>105</td>
<td>101</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Batchelor and Soopramanien (1995)</td>
<td>Silty clay, Mauritius</td>
<td>1. 1.0 ETc with TAM=20mm G, 20mm T, 20mm E. 2. 1.0 ETc with TAM=20mm G, 30mm T, 20mm E. 3. 1.0 ETc with TAM=20mm G, 30mm T, 50mm E. 4. Target potential of -8kPa with tensiometer placed 0.15m from dripline 5. Target potential of -8kPa with tensiometer placed 0.3m from dripline 6. Rainfed</td>
<td>170</td>
<td>169</td>
<td>158</td>
<td>163</td>
<td>160</td>
<td>73</td>
</tr>
<tr>
<td>Dodsworth et al. (1990)</td>
<td>Shallow sandy topsoil, overlaying saline/ sodic clay, Swaziland</td>
<td>1. Drip, daily according to class A pan evaporation 2. Flood irrigation</td>
<td>175.7</td>
<td>163.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Plant cane</td>
<td>129.3</td>
<td>131.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>First Ratoon</td>
<td>129.5</td>
<td>128.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The yield advantages of trickle irrigation are not as pronounced, however, in controlled studies comparing different irrigation application methods (Table 2). In most studies, yields were 5-15% higher in the trickle irrigated treatments. It seems unimportant whether sugarcane or sugar yields are compared, as there are few reports of CCS being systematically affected by irrigation method.

Where there has been no yield advantage with trickle irrigation there appear to have been problems with the trickle irrigation system. Ham (1979) found no significant difference in yield under different irrigation methods (Table 2) although yields in the trickle irrigation treatment were very low in the second ratoon due to clogged emitters. Dodsworth et al. (1990) also found little advantage of trickle irrigation over flood irrigation.
irrigation in Swaziland. However, they attributed the poor results with trickle irrigation in the ratoon crop to practical problems with the trickle system (e.g. power cuts affecting scheduling, cultivation damaging roots, clogged emitters).

3.3.2 Sugarcane water use efficiency under trickle irrigation
Estimates or measurements of water applied have been given in some studies, allowing irrigation use efficiency (i.e. sugarcane yield relative to the applied irrigation water) to be assessed. Pyle and Moore (1985), Magar and Bhapkar (1988) and Churchward and Curd (1995) report 50-80% higher irrigation use efficiency. Dodsworth et al. (1990) found advantages in irrigation use efficiency in trickle irrigation, increasing from 5% in the plant crop to 30% in the second ratoon, despite there being no yield increase. It is difficult to judge the impact of trickle irrigation, with either surface or buried tape, on runoff and hence effective rainfall (Robertson et al. 1997), as there have been no studies comparing water balances under different irrigation application methods. Effective rainfall may well be higher with trickle irrigation, as the soil surface is more likely to be dry, promoting infiltration and reducing runoff of rainfall. Thus, if the contribution of rainfall to water used by the crop was considered in these studies the total water (irrigation and rainfall) use efficiency advantages of trickle irrigation would be decreased compared to other irrigation application methods.

4. FERTIGATION/CHEMIGATION
Fertigation is a general term referring to the application of fertilisers via irrigation water (Dart et al. 1996). Bisconer (1985) defines chemigation as “the application of fertilisers, nematicides, herbicides, insecticides and fungicides through irrigation systems”. Potential advantages of chemigation are equipment, labour and fuel costs are decreased; applications can be made at any stage of plant growth; health and safety is improved by lower exposure times to toxic chemicals; and nitrogen losses to volatilisation are reduced (Bisconer 1985, Dart et al. 1996).

Nematicides have been successfully used with drip irrigation. Less chemical is required than with other methods and it is usually applied only at the time of root flush (Bisconer 1985). Herbicides are not commonly applied via drip systems as the goal is to cover areas close to the soil surface rather than apply to the root zone. Insecticides usually require direct contact with their target species and therefore are not generally applied via drip irrigation (Bisconer 1985).

The following guidelines are recommended when chemigating via drip lines: ensure the system is being properly maintained; avoid emitter clogging by choosing soluble chemicals, and if mixing chemicals, check for precipitate formation by pre-mixing in a jar and letting this stand for 24 hours; use correct scheduling to keep water/chemicals within the plant root zone; flush lines completely after applications, preferably with an indicator dye; and adhere to government regulations (Bisconer 1985, Haynes 1985).

The most common fertilisers applied via drip irrigation include nitrogen, phosphorous and potassium. Both phosphorous and potassium appear more mobile within the root zone under drip irrigation than other irrigation methods. This is thought to be due to the saturation of fixing sites close to the emitter, allowing the excess chemical to move with the water. The extent of movement of relatively immobile ions will depend on the cation exchange capacity of the soil (Haynes 1985).

Fertigation of these chemicals under drip irrigation has definite advantages. Research regarding nitrogen applications under drip irrigation indicates that the efficiency is much higher than other irrigation methods (Bisconer 1985, Ng Kee Kwong and Deville 1994, Neibling and Brooks 1995, Dart et al. 1996). The increase in efficiency may or may not be accompanied by increases in yields.

Uneven distribution of nutrients under drip irrigation is a consideration when fertigating in the early stages of plant growth, particularly in conjunction with drip line placement. Batchelor et al. (1985) looked at sugarcane root responses to the different water distributions achieved via subsurface inter row and beneath row drip placement. Prior to 24 weeks, root densities in the proximity of inter-row emitters were sparse, whereas beneath-row placement of the drip line produced a high density of roots surrounding the emitter. Thus, accessibility of the nutrient to the root zone and the amount leached will depend on the type of chemical applied and dripline placement, particularly in early growth stages.
4.1 NITROGEN APPLICATION

Large savings in fertiliser application have been associated with application via trickle irrigation under optimum conditions (Haynes 1985) but unfortunately, little specific information is available on optimum nitrogen fertiliser management for trickle irrigated sugarcane.

Haynes (1985) reports that the distribution of nitrogen is very much dependent upon the source of nitrogen applied. Ammonium tends to be adsorbed close to the emitter, which may pose a problem for denitrification if this area is continually saturated (due to lack of oxygen). Urea is relatively mobile and is reported to have a fairly uniform distribution throughout the wetted area. Nitrate, which is highly mobile, is pushed to the periphery of the wetting zone. Haynes (1985) indicates that plants will adapt their rooting patterns to areas of high nutrient concentrations by either increasing their absorption rate or by proliferating new roots.

In Mauritius, efficiency of nitrogen uptake increased by up to 80% over two crops (first and second ratoon) when urea was applied (at 120 kg N/ha) to sugarcane via trickle irrigation as compared with the same rate side dressed (Ng Kee Kwong and Deville 1994). However, the increased uptake efficiency was not accompanied by significantly increased yields. This result indicates that nitrogen application rates for sugarcane could be reduced if nitrogen is applied through trickle irrigation (Ng Kee Kwong and Deville 1994).

Ridge and Hewson (1995) studied nitrogen application rates in furrow and trickle irrigated sugarcane growing on a sandy loam soil at Bundaberg. Treatments included nitrogen application rates in a first ratoon crop of 90, 135 and 180 kg/ha via trickle irrigation (in four equal applications), with the highest rate also applied “conventionally” to trickle irrigated sugarcane, and 180 kg/ha applied “conventionally” to furrow irrigated sugarcane. The only significant result was a yield reduction of approximately 15% in the first ratoon crop where the lowest rate of nitrogen was applied by trickle irrigation. Leaf nitrogen contents, taken after the final application of nitrogen in the trickle irrigated treatments, were similar in all treatments.

Loss of nitrogen from green tops in sugarcane crops was higher for fertigated treatments than for a buried nitrogen treatment (Ng Kee Kwong and Deville 1994). The authors suggest this was due to the increased efficiency of plant uptake, in which the amount of nitrogen taken up by the plant exceeds the nitrogen storage capacity of the plant. The treatments involved in the study included 120 kg ha⁻¹ applied by: burial 10cm to one side of the cane row; daily application through drip system over 5 weeks; daily application through drip system over 10 weeks; daily application through drip system over 20 weeks; daily application through drip system of 1/3 in the first ten weeks, 2/3 in the following ten weeks. A further finding of the study indicated that the nitrogen efficiency taken at harvest time may not give a true reflection of nitrogen efficiency, as the fertiliser nitrogen measured in the above ground sugarcane was highest just after fertigation cessation, after which it declined until harvesting time.

Dart et al. (2000) and Thorburn et al. (2002a) considered the response of cane and sugar production to different rates (0-240 kg ha⁻¹ yr⁻¹) of fertigated N, spanning that recommended for conventional irrigation systems (160 kg ha⁻¹ yr⁻¹). Yields of cane and sugar responded to application of N fertiliser in the three ratoon crops, but were not significantly increased by applying more than 80 kg ha⁻¹ of N, which is half the conventional rate. There were no N responses in the plant crop as there was > 200 kg ha⁻¹ of soil mineral N (SMN) to 2 m depth at the site prior to planting and SMN concentrations were relatively high (~ 20 mg kg⁻¹) in the surface soil. Depletion of the SMN occurred most slowly during the plant crop with higher rates of N application, particularly in soil between the crop rows. However, there was no difference in SMN between treatments or row position (row v. inter-row) at harvest of the ratoon crops.

From these studies it is hard to judge what the optimum nitrogen application rates in trickle irrigated and fertigated sugarcane will be as compared with more common irrigation and fertiliser management systems in Australia. However, it is likely that nitrogen application rates can be reduced at least 25%.

The difficulty in judging optimum nitrogen application rates for fertigated sugarcane systems arises, in part, from the lack of long-term data comparing different nitrogen application methods over a wide
range of application rates. In an attempt to overcome this, Thorburn et al. (2002b) conducted simulations of nitrogen responses where N and irrigation water were applied either through trickle irrigation or conventionally. The simulations were conducted over two contrasting soil types (a grey clay and a red loam) and five climatic regions (northern NSW, Bundaberg, Mackay, Burdekin and Ingham) spanning irrigation areas in the Australian sugar industry using historical climate data. In all scenarios simulated, maximum yields in both systems occurred at similar N application rates (generally 150 kg/ha applied to ratoon crops) but the yield was higher where N and irrigation water were applied through trickle irrigation (Figure 1). The difference in yields between the conventional and trickle irrigation systems were greatest at N application rates (90 to 120 kg/ha applied to ratoon crops) lower than those giving maximum yields. In fact, improvements in yield given by trickle irrigation were lost at lower and higher N application rates. As expected, environmental losses of N became increasingly significant as N application rates increased above those providing maximum yields in all scenarios. Losses were always higher from the convention system than the trickle irrigated system at all rates of applied N, but this difference also became more pronounced as N application rates increased above those providing maximum yields.

![Figure 1. Sugar cane yield response to the application of different N fertiliser rates and irrigation water through trickle irrigation (■) and conventional surface application (●).](image)

Given the above information, fertigation under drip irrigation appears to require less nitrogen, due to increases in efficiency, for the same yields. If this is the case, then a modified set of fertiliser guidelines is required for growers using drip irrigation.
5. ENVIRONMENTAL IMPACTS

In this age of sustainable agriculture and environmental protection, drip irrigation is seen as having the potential to reduce ground water pollution, conserve water resources and enable a long term outlook for farming practices. These philosophies have come about as a result of increased demand for water resources, by both agriculturalists and those wishing to maintain water quality and quantity within existing aquatic and riparian ecosystems for purposes of environmental protection (Bucks 1995). The trend towards water conservation and minimising pollution could be accelerated within farming communities if economic benefits, either through increased yields or savings in fertilisers/pesticides, could be demonstrated. Both of these are widely reported benefits of drip irrigation.

5.1 NITROGEN

Common research topics in this area include the impact of nitrogen leaching through drip irrigation systems and the reduction in water consumed. Swietlik (1995) undertook studies of the recovery of nitrogen fertiliser in the form of nitrates, to depths of 300cm after the first four years of growth of grapefruit trees under different scheduling and nitrogen application rates (Table 3). For pan scheduled flood irrigation, the concentrations of NO$_3$ were highest and increasing from depths of 120cm to 300cm. Under tensiometer scheduled trickle, the NO$_3$ concentrations increased over the top 210 cm of soil and decreased afterwards. The higher losses of nitrogen under pan scheduled trickle and flood irrigation may be due to higher water application, or increased denitrification due to poor soil aeration as a result of over irrigation.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Nitrogen applied (g m$^{-2}$)</th>
<th>Total soil NO$_3$ - N (g m$^{-2}$ 3m$^{-1}$)</th>
<th>N recovery (%)</th>
<th>Total area water applied over four years (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flood irrigation of 15cm upon 50% depletion of soil water in top 30 cm (first 3 years) and 30-60 cm (fourth year): via Neutron probe</td>
<td>0</td>
<td>8.3</td>
<td>--</td>
<td>244.1</td>
</tr>
<tr>
<td>Trickle using 0.7 ET (first 3 years) and 0.5 ET (fourth year): based on Class A pan evaporation.</td>
<td>112</td>
<td>24.2</td>
<td>14.3</td>
<td>244.1</td>
</tr>
<tr>
<td>Trickle using average tensiometer readings of 0.02MPa at 30 cm depths</td>
<td>112</td>
<td>61.4</td>
<td>44.8</td>
<td>8.5</td>
</tr>
</tbody>
</table>

Table 3. Measurements of nitrogen taken four years after different irrigation and nitrogen treatments were initiated (Swietlik 1995)

If nitrogen application rates can be reduced by at least 25 % compared with conventional systems, as implied by the results of many studies, maintenance of “conventional” rates could increase nitrogen losses through leaching below the root zone. This conclusion is supported by the observations of Stanley et al. (1990) who measured two dimensional soil nitrate distributions to 0.9 m depth beneath trickle irrigated sugarcane with the nitrogen applied at three different rates (6, 9 and 18 kg N/ha/wk). At 11 weeks after planting, nitrate had accumulated (> 70 mg/L) to approximately 0.3 m depth in the soil between the rows in all treatments, but was low (< 10 mg/L) in the deeper soil only under the lowest application rate. By 22 weeks nitrate concentrations were low (< 3 mg/L) at all soil locations under the lowest application rate. However, areas of high nitrate still existed in the soil under the higher application rates and nitrate appeared to have been leached below the root zone (approximately 0.6 m depth).
Also, Thorburn et al. (2002a) determined N balances in four trickle irrigated sugarcane crops under different rates (0-240 kg ha\(^{-1}\) yr\(^{-1}\)) of fertigated N, spanning that recommended for conventional irrigation systems (160 kg ha\(^{-1}\) yr\(^{-1}\)). During the four crops, net removal of N from the treatment with no applied N totalled 207 kg ha\(^{-1}\). When 80 or 120 kg ha\(^{-1}\) yr\(^{-1}\) of N was applied to ratoon crops, outputs of N from the harvested crop approximately balanced inputs from fertiliser and depletion of SMN during the experiment. Inputs clearly exceeded output at higher N application rates. Assuming that the net removal of N from the treatment with no applied N was the same as the net mineralisation of N from soil organic matter in all treatments in the experiment, from 204 to 639 kg ha\(^{-1}\) of N was unaccounted for in the treatments with applied N over the whole of the experiment. While some of this N (e.g. 45 kg ha\(^{-1}\)) may have resulted in small (and undetectable) increases in total soil N, much would have been lost to the environment. The authors suggest that the high soil water contents maintained with daily application of irrigation water through the trickle system promotes mineralisation of soil organic matter and that if not accounted for through adjustments to fertiliser applied N, could result in considerable quantities of N being lost to the environment. Thus, particular care is required to avoid over-application of N in fertigated sugarcane.

Unfortunately, there have been no quantitative studies published on nitrogen leaching from trickle irrigated sugarcane. However, studies in other crops show that nitrogen leaching can be considerable if water and nitrogen applications are not optimised. Castel et al. (1995) estimated nitrogen leaching, from chloride and water balance methods, under citrus at two crop factors (0.5 and 1.4) and two nitrogen application rates (120 and 210 kg N/ha/yr). The proportion of applied nitrogen that was leached below the root zone ranged from less than 50 % in the low water-low nitrogen treatment, to 99 % in the highest water-highest nitrogen treatment. While these leaching rates appear excessive relative to estimates of leaching for sugarcane crops in Australia (Keating et al. 1997), they illustrate the need for relevant guidelines for water and nitrogen management of trickle irrigated sugarcane crops.

5.2 WATER

Reduced water consumption is often reported under drip irrigation compared to previously used methods. A few examples of decreased water consumption include: Magar (1995) showed 60% savings compared with ridge and furrow irrigation for a sugarcane crop; Sivanappan (1995) recorded savings of 40-80% over a range of crops in India.

Further reductions in water wastage through drainage may be achieved with new technological advances referred to as minute drip irrigation. These drippers use pulses of 2 seconds/70 seconds with discharge rates of 100mL hr\(^{-1}\). The advantages of such low flow emitters include lower drainage rates in sandy soils, higher aeration of low permeability soils, and possible 24-hour irrigation (Or 1995).

Recent research has been looking at the suitability of drip irrigation for wastewaters. The benefits of recycling wastewaters include solutions to water scarcity and an environmentally sound way of disposing of sewage effluent (Kenig et al. 1995). In Israel, the use of secondary treated effluent for non-edible crops is increasing due to new designs of drip systems. Or (1995) cautions that for water close to wells, sandy soils and shallow soil above crusty rock, tertiary treatment is required. The technique described by Or is somewhat confusing. Firstly, the drip line is planted at a depth of 30 to 50cm, which is said to be below the rootzone, and it is implied that the roots receive water via upwards movement. The statement is then made that this procedure prevents contamination of the water table. This is confusing, in that logic would state that a system relying on upwards movement of water to the root zone would be loosing more water due to gravitational forces. The use of waste water for drip irrigation still requires full investigations for impacts on ground water pollution, salt build up, and chemical toxicity in crops grown for human consumption.

6. MANAGEMENT AND SCHEDULING

The section on the disadvantages of drip irrigation outlined the need for correct scheduling i.e. the amount of water applied should equal the crop’s requirements. This section summarises the scheduling methods available to drip irrigation, using examples from sugarcane research. Not only are the rate and volume of water applied important, but also the correct maintenance of drip lines is necessary in order to achieve optimal crop yields.
Consequences of under irrigation, crop water stress and suboptimal growth, are fairly obvious but over irrigation with drip irrigation can also have negative impacts on crop production. Increases in the wet zone and drainage raise the water table and increase salinity and the leaching of essential nutrients, such as nitrogen, which contributes to ground water pollution (Hodnett et al. 1991, Institute of Hydrology 1988). Over irrigation can also have effects on plant growth and activity. Roberts et al. (1990) found that under an irrigation regime in which water was applied at a rate of 1.5 ETc, the leaf water potential, net photosynthesis and stomatal conductance of sugarcane were sometimes lower than those of 1.0 ETc. They suggested this was a result of waterlogging under the higher irrigation rate.

Major differences to scheduling under drip as compared to traditional irrigation methods include the reduced volume from which water is extracted and the increased frequency of irrigation. Under conventional methods, the whole field is irrigated to a certain soil moisture (usually field capacity) and allowed to dry to a certain level or refill point before applying further irrigation. Under drip irrigation a much smaller volume of the soil is wetted, from which plant abstraction takes place. Instead of the more traditional approach of field capacity, scheduling under drip systems can achieve a more constant soil water content within the root zone through more frequent applications.

Hodnett et al. (1991) identified three scheduling procedures, each using different aspects of the hydrological cycle as a basis for water application. The first is based on replacing the estimated water lost, the second on measurements of water content or water potential, and the last on plant measurements such as leaf water potential. The focus of scheduling research appears to be on maximum production, and rarely looks at the actual water distribution occurring beneath emitters. The danger associated with this way of thinking is that excess irrigation on highly permeable soils may show no signs of crop damage, even while a large amount of water is being lost to drainage.

Moore and Fitschen (1991) suggest scheduling be based on soil type, crop age, estimated evapotranspiration rate and the amount of rainfall received. Roberts et al. (1990) argue that the most beneficial type of scheduling is based on direct crop measurements, as the plant itself integrates all aspects of climate and soil water conditions. Within the literature, the most commonly used schedules are those using measurements of soil water content or soil water potential.

One point of interest put forth by Roberts et al. (1990) was that it may be beneficial to subject sugarcane crops to short stress/recovery cycles to produce higher yields. This is based on findings by Inman-Bamber and de Jager (1986) who found plants subjected to a short period of stress recovered to leaf extension rates greater than those found in the unstressed plants within 3 to 4 days of resumed irrigation. Although this was not tested statistically, Magar and Bhapkar (1988) recorded marginally higher yields for surface drip irrigated sugarcane when irrigated on a second daily basis rather than on a daily basis (166.67 t ha⁻¹ for daily vs. 167.27 t ha⁻¹ for second daily for plant cane, and 107.23 t ha⁻¹ for daily vs. 110.92 t ha⁻¹ for second daily for ratoon crop).

Abbott and Ah-Koon (1992) found that for trials carried out in Mauritius, soil matric potential distributions varied considerably in sugarcane irrigated during night time hours versus day time irrigation. The matric potentials under both regimes cycled diurnally with higher potentials during the night (when root abstraction ceased) and lower potentials during the day. The amplitude exhibited by night time irrigation was much greater as root abstraction was occurring during the time when irrigation had ceased, causing more drying out than was evidenced in the day time irrigated plot. Day time irrigation gave a larger volume of soil containing available water over the 24 hour period. Abbott and Ah-Koon (1992) discuss two possible implications of their research: either the crop benefits from night time irrigation due to increased aeration in afternoon periods or the crop benefits from day time irrigation due to increased available moisture during plant abstraction.

Correct management procedures, such as filtration, applications of algicide and acidic flushing, are imperative to successful drip irrigation systems. Inadequate maintenance results in higher emitter clogging and water consumption. Dalvi et al. (1995) conducted studies on the performance of 42 randomly selected irrigation systems in Maharashtra State. They found that not only did farmers with properly managed and regularly maintained systems achieve higher water savings (some above 45% savings), but also they generally exhibited higher yields. Low emission uniformities and water savings were found to be common where farmers were unfamiliar with the operations of their systems. In these
cases, clogging of emitters, unchecked leakages, inadequate filtration and neglect of system cleaning were found to be responsible.

6.1 CROP FACTORS FOR TRICKLE IRRIGATED SUGARCANE

Most data on crop factors for trickle irrigated sugarcane come from an intensive study of trickle irrigation management conducted by the Institute of Hydrology (1988) in Mauritius (Table 4), although some experiments were conducted earlier by Chapman (1978, 1980). The Institute of Hydrology (1988) work had crop factors in factorial experiments with other factors (tape placement, emitter rates and row spacing). Crop factors of 0.5 and 1.0 were used in most studies but they went up to 1.5 in one (Batchelor et al. 1990). Two of the studies in Mauritius (Hodnett et al. 1990, Batchelor and Soopramanien 1995) also examined the application of water to maintain the root zone at a “target” soil water potential.

The research in Mauritius provides inconclusive results. Although neither Soopramanien et al. (1988) nor Batchelor et al. (1990) presented a statistical analysis of the main treatment effects in their experiments, there was no consistent advantage of a crop factor of either 0.5 or 1.0 (Table 4). With lower emitter rates, yields were highest with a crop factor of 1.0, but the reverse was true with the higher emitter rates (Soopramanien et al. 1988). For the single row spacing treatment, similar to that common in Australia, there was little difference in yields at the two crop factors regardless of whether the tape was placed in each row or second row (Batchelor et al. 1990). In that study, however, there was a clear trend for yields to be lower with a crop factor of 1.5 (Table 4). In the study of Hodnett et al. (1990) higher yields were obtained with crop factors of 0.5 than 1.0. Water logging may have been impacting on yields in the higher irrigation rates in both these experiments (Roberts et al. 1990).

In Australia, Chapman (1978,1980) found consistent trends to highest yields with a crop factor of 0.8 in plant and first ratoon crops (Table 4).

It is difficult to judge a “universal” crop factor for trickle irrigated sugarcane from the literature as no study has covered a comprehensive range of values incrementing in small steps (e.g. 0.3, 0.6, 0.9, 1.2, 1.5). Additionally, comparison of crop factors between studies is difficult because of the different climates under which the experiments were conducted and the different estimates of potential evaporation (e.g. class A pans or the Penman equation) used. From the data given in Table 4, however, appropriate crop factors for sugarcane are likely to be between 0.5 and 1.0. The application of cropping systems models (e.g. Robertson et al. 1997, Thorburn et al. 2002b) may be of value in determining optimum crop factor values for different climates and soil types.

6.2 MEASUREMENTS OF SOIL WATER CONTENT/POTENTIAL AS A BASIS FOR SCHEDULING.

Scheduling of irrigation based on soil moisture conditions (especially soil water potential) is appealing as it overcomes the need for empirical crop factors and uncertainties associated with estimating potential evaporation. There have been too few studies in sugarcane to properly assess the utility of scheduling irrigation to a target soil water potential. However, provided the results of the two studies comparing this method of scheduling with crop factor based methods (Table 4) are applicable to other soil types, they suggest that yields would be comparable between the two scheduling methods. Water use efficiency may also be improved with soil water based scheduling (Hodnett et al. 1990). The variation in the choice of tensiometer placement and target potential will result in yield variations similar to those associated with choice of crop factors (Table 4). However, tensiometer placement guidelines may be derived using soil physical models (e.g. Coelho and Or 1996) more efficiently than the empirical determination of crop factors.

Table 4. Summary of sugarcane yields under trickle irrigation scheduled using different crop factors (CF) in combination with different tape placements, emitter rates (ER) and row spacings (RS). Reference evaporation was given by a “class A” pan in Chapman’s study and Penman potential evaporation in the remaining studies
<table>
<thead>
<tr>
<th>Irrigation treatment</th>
<th>Yield (t/ha)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Chapman (1978, 1980), Mackay</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rainfed</td>
<td>P / 1R / 2R</td>
<td>l.s.d (P = 0.05) 15 in P and 1R.</td>
</tr>
<tr>
<td>CF - 0.4</td>
<td>107 / 88 / 108</td>
<td></td>
</tr>
<tr>
<td>CF - 0.6</td>
<td>115 / 118 / 104</td>
<td>No significant differences in 2R.</td>
</tr>
<tr>
<td>CF – 0.8</td>
<td>113 / 112 / 105</td>
<td></td>
</tr>
<tr>
<td></td>
<td>129 / 132 / 101</td>
<td></td>
</tr>
<tr>
<td><strong>Soopramanien et al (1988), Mauritius, silty clay</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tape - each row, ER - 1.2 L hr⁻¹, CF - 1.0</td>
<td>146</td>
<td>Tape depth 20 cm.</td>
</tr>
<tr>
<td>Tape - each row, ER - 2.4 L hr⁻¹, CF - 1.0</td>
<td>141</td>
<td></td>
</tr>
<tr>
<td>Tape - each row, ER - 1.2 L hr⁻¹, CF - 0.5</td>
<td>139</td>
<td>ER = emitter rates.</td>
</tr>
<tr>
<td>Tape - each row, ER - 2.4 L hr⁻¹, CF - 0.5</td>
<td>156</td>
<td></td>
</tr>
<tr>
<td>Tape - 2nd inter-row, ER - 1.2 L hr⁻¹, CF - 1.0</td>
<td>155</td>
<td>Results are for plant cane, mean of</td>
</tr>
<tr>
<td>Tape - 2nd inter-row, ER - 2.4 L hr⁻¹, CF - 1.0</td>
<td>141</td>
<td>three varieties, and were affected by</td>
</tr>
<tr>
<td>Tape - 2nd inter-row, ER - 1.2 L hr⁻¹, CF - 0.5</td>
<td>127</td>
<td>cyclone damage 8 months after</td>
</tr>
<tr>
<td>Tape - 2nd inter-row, ER - 2.4 L hr⁻¹, CF - 0.5</td>
<td>143</td>
<td>planting.</td>
</tr>
<tr>
<td>Rainfed</td>
<td>68</td>
<td></td>
</tr>
<tr>
<td><strong>Batchelor et al. (1990), Mauritius, silty clay</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tape - each row, RS - a, CF - 1.5</td>
<td>P / 1R / 2R</td>
<td>RS = row spacing: a = single row</td>
</tr>
<tr>
<td>Tape - each row, RS - a, CF - 1.0</td>
<td>166 / 135 / 112</td>
<td>1.62 m wide; b = dual row (0.97 m</td>
</tr>
<tr>
<td>Tape - each row, RS - a, CF - 0.5</td>
<td>168 / 147 / 122</td>
<td>apart) separated by 2.26 m.</td>
</tr>
<tr>
<td>Tape - each row, RS - a, CF - 1.5</td>
<td>157 / 148 / 123</td>
<td></td>
</tr>
<tr>
<td>Tape - 2nd inter-row, RS - a, CF - 1.0</td>
<td>144 / 139 / 116</td>
<td>Tape depth 20 cm.</td>
</tr>
<tr>
<td>Tape - 2nd inter-row, RS - a, CF - 0.5</td>
<td>142 / 131 / 122</td>
<td></td>
</tr>
<tr>
<td>Tape - 2nd inter-row, RS - a, CF - 1.5</td>
<td>147 / 149 / 130</td>
<td>l.s.d (P = 0.05) 24 in P and 15 1R and</td>
</tr>
<tr>
<td>Tape - each row, RS - b, CF - 1.5</td>
<td>160 / 134 / 113</td>
<td>2R.</td>
</tr>
<tr>
<td>Tape - each row, RS - b, CF - 1.0</td>
<td>145 / 155 / 132</td>
<td></td>
</tr>
<tr>
<td>Tape - each row, RS - b, CF - 0.5</td>
<td>136 / 150 / 124</td>
<td></td>
</tr>
<tr>
<td>Tape - 2nd inter-row, RS - b, CF - 1.5</td>
<td>156 / 140 / 118</td>
<td></td>
</tr>
<tr>
<td>Tape - 2nd inter-row, RS - b, CF - 1.0</td>
<td>148 / 143 / 107</td>
<td></td>
</tr>
<tr>
<td>Tape - 2nd inter-row, RS - b, CF - 0.5</td>
<td>142 / 141 / 122</td>
<td></td>
</tr>
<tr>
<td>Rainfed, RS - a</td>
<td>69 / 111 / 104</td>
<td></td>
</tr>
<tr>
<td>Rainfed, RS - b</td>
<td>60 / 100 / 94</td>
<td></td>
</tr>
<tr>
<td><strong>Hodnett et al. (1990), Mauritius, silty clay</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tape - each row, CF - 1.0</td>
<td>118</td>
<td>Row spacing: dual row (0.97 m apart)</td>
</tr>
<tr>
<td>Tape - each row, CF - 0.5</td>
<td>121</td>
<td>separated by 2.26 m.</td>
</tr>
<tr>
<td>Tape - narrow inter-row, CF - 1.0</td>
<td>111</td>
<td>2nd ratoon crop.</td>
</tr>
<tr>
<td>Tape - narrow inter-row, CF - 0.5</td>
<td>123</td>
<td></td>
</tr>
<tr>
<td>Tape - each row, potential of -8 kPa</td>
<td>131</td>
<td>Tape depth 20 cm.</td>
</tr>
<tr>
<td>Tape - each row, potential of -20 kPa</td>
<td>123</td>
<td>Tensiometers located 65 cm below</td>
</tr>
<tr>
<td>Tape - narrow inter-row, potential of -8 kPa</td>
<td>115</td>
<td>ground, 30 cm away from row.</td>
</tr>
<tr>
<td>Tape - narrow inter-row, potential of -20 kPa</td>
<td>128</td>
<td></td>
</tr>
<tr>
<td><strong>Batchelor and Soopramanien (1995), Mauritius, silty clay</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CF - 1, TAM = 20mm G, 20mm T, 20 mm E.</td>
<td>P / 1R</td>
<td>TAM = total available moisture, G =</td>
</tr>
<tr>
<td>CF - 1, TAM = 20mm G, 30mm T, 35 mm E</td>
<td>170 / 134</td>
<td>germination phase, T = tillering</td>
</tr>
<tr>
<td>CF - 1, TAM = 20mm G, 30mm T, 50 mm E</td>
<td>169 / 128</td>
<td>phase, E = elongation phase.</td>
</tr>
<tr>
<td>Potential of -8 kPa, tensiometer 15 cm from tape</td>
<td>158 / 124</td>
<td></td>
</tr>
<tr>
<td>Potential of -8 kPa, tensiometer 30 cm from tape</td>
<td>163 / 128</td>
<td>Tape placement: 15 cm below dual</td>
</tr>
<tr>
<td>Rainfed</td>
<td>73 / 106</td>
<td>row (as for RS - b above).</td>
</tr>
<tr>
<td></td>
<td>170 / 134</td>
<td>Tensiometers located 50 cm below</td>
</tr>
<tr>
<td></td>
<td>169 / 128</td>
<td>ground.</td>
</tr>
<tr>
<td></td>
<td>158 / 124</td>
<td></td>
</tr>
<tr>
<td></td>
<td>160 / 129</td>
<td></td>
</tr>
<tr>
<td></td>
<td>73 / 106</td>
<td></td>
</tr>
<tr>
<td></td>
<td>170 / 134</td>
<td></td>
</tr>
<tr>
<td></td>
<td>169 / 128</td>
<td></td>
</tr>
<tr>
<td></td>
<td>158 / 124</td>
<td></td>
</tr>
<tr>
<td></td>
<td>160 / 129</td>
<td></td>
</tr>
<tr>
<td></td>
<td>73 / 106</td>
<td></td>
</tr>
</tbody>
</table>

Scheduling based on measures of soil water content or potential aim to maintain the root zone at a predetermined value. The biggest difficulty associated with using soil water measurements to regulate scheduling is where to place the sensors for optimal management. Soils of different hydraulic properties can produce very different subsurface wetting patterns. For example, one soil may have more lateral or more vertical movement than another and therefore the time the wetting front takes to reach a sensor some lateral distance from the emitter will vary considerably. In a soil with high vertical
There may be a considerable amount of drainage occurring before the wetting front moves laterally.

The idea then is to find the position required for the specific soil type which best describes the containment of water within the root zone.

A study conducted by Rolston et al. (1991) on drip irrigated almonds investigated the spatial variability of soil water distributions in five different irrigation treatments (0.5, 0.75, 1, 1.25 and 1.75 times ET) over a three year period. Two areas were chosen within each treatment where 23 neutron access probes were inserted at various locations surrounding emitters. They found spatial patterns to be fairly consistent over time, but less so for treatments in which water was applied at rates greater than 1.0 times ET, where surface ponding was extensive.

The authors suggest this type of study be carried out at the beginning of an irrigation system in order to identify a single access tube which best estimates the mean soil water storage (determined from the 23 access tubes) over the wetted area. Once this location has been found, it can be used for the rest of the season. The use of the same location for the subsequent year was found to produce small errors (<6%) and thereafter, larger errors.

With regards to the timing of soil water measurements, Hodnett et al. (1991) found it best to measure soil water potential in the period between dawn and the start of irrigation, as this was the time when the rate at which soil conditions were changing was the lowest. This would be the case regardless of the type of instrument being used.

As mentioned, these methods require the use of instrumentation for the measurement of either soil water content (neutron moisture meter, Enviroscan, and time-domain reflectometry, TDR) or soil water potential (tensiometers, heat dissipation and gypsum blocks). Table 5 lists some of the advantages and disadvantages for each of these sensors. The neutron moisture meter operates by using a radioactive source and recording the number of thermalised neutrons - a measure of the hydrogen atoms within the soil. A calibration curve is then used to convert this count to gravimetric water content. The Enviroscan works on the capacitance principle and also uses a calibration curve to determine soil water content. Tensiometers use a porous ceramic cup that measures the changes in pressure due to water moving into and out of the cup within the soil profile (Hodnett et al. 1991). TDR is based on the propagation velocity of electromagnetic pulses through porous media (Grantz et al. 1990).
### Table 5. Commonly used instrumentation in measuring soil water and their respective advantages and disadvantages

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutron moisture</td>
<td><em>In situ</em> measurement results in less soil damage</td>
<td>Radioactivity</td>
</tr>
<tr>
<td></td>
<td>Quick and easy</td>
<td>Requires a calibration curve</td>
</tr>
<tr>
<td></td>
<td>Repetitive</td>
<td>Readings may be affected by high amounts of organic matter</td>
</tr>
<tr>
<td></td>
<td>Single vertical profile</td>
<td>Readings may be affected near the surface due to neutron escape to the atmosphere (Hillel 1980b)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>High cost</td>
</tr>
<tr>
<td>Enviroscan</td>
<td>Real time</td>
<td>Readings may be affected by air gaps resulting from poor soil/tube contact</td>
</tr>
<tr>
<td></td>
<td><em>In situ</em></td>
<td>Problems may occur with soils exhibiting swelling/shrinkage (Christen 1997)</td>
</tr>
<tr>
<td></td>
<td>Suitable for data logging</td>
<td>Salinity can cause errors (Mead 1997)</td>
</tr>
<tr>
<td></td>
<td>Gives continuous record</td>
<td>High cost</td>
</tr>
<tr>
<td></td>
<td>Single vertical profile</td>
<td></td>
</tr>
<tr>
<td>Tensiometers</td>
<td>Fairly inexpensive</td>
<td>Tensiometers are reported to be accurate to 0.2kPa in the range of 0 to -20kPa, after which, the accuracy decreases; tensiometers can measure up to -80kPa (Hodnett et al. 1991).</td>
</tr>
<tr>
<td></td>
<td>Quick to read</td>
<td>Requires continuous maintenance (Hodnett et al. 1991)</td>
</tr>
<tr>
<td>(Hodnett et al. 1991)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time domain</td>
<td>Rapid and repeatable measurements</td>
<td>High cost</td>
</tr>
<tr>
<td>reflectometry</td>
<td>Safe</td>
<td>May be unreliable in saline soils</td>
</tr>
<tr>
<td></td>
<td>Suited to automated data collection</td>
<td>Requires calibration (Topp et al. 1980)</td>
</tr>
<tr>
<td>(Grantz et al. 1990)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

An example of a scheduling method outlined by Hodnett et al. (1991) using tensiometers is given in Table 6. Daily measurements were taken using *in situ* tensiometers. The scheduling was adjusted daily according to whether the soil was drying or wetting. They found this method to be inexpensive, quick (10 readings/minute), but requiring some maintenance.

### Table 6. Scheduling method based on tensiometer readings (Hodnett et al. 1991)

- **Daily**
  - Record 6 tensiometers
  - Calculate mean index reading
  - Look up amount of water to apply (Total time=5 minutes/field)

- **Weekly**
  - Purge/maintain index tensiometers (10 minutes/field)

This procedure requires *a priori* knowledge of the wetted zone (for correct placement of tensiometer), a target potential for the wet zone, and guidelines for water application. In the study conducted by Hodnett et al. (1991), the index tensiometers were placed at the edge of the wet zone (0.3m for subrow placements, and 0.5 for interrow driplines) at depths of 0.5m to 0.65m. Fluctuations in potential were found to be too high near the surface for accurate readings. Hodnett et al. (1991) found a target of -8kPa produced higher yields and fewer fluctuations than a target of -20kPa. Guidelines were then determined using six possible irrigation rates, with the maximum being ET<sub>p</sub> (Penmann potential evaporation). The daily scheduling was then determined depending on the mean index reading for that day (from the six index tensiometers), the mean index for the previous day (whether or not soil is...
wetting or drying), and the amount of irrigation given on previous day. The scheme is basically self-correcting, so the initial amount of irrigation applied is of little importance. The guidelines given by Hodnett et al. (1991) for a target potential of -8kPa is given in Table 7.

Table 7. Guidelines used to determine the amount of irrigation to apply for the target potential of -8kPa (Hodnett et al. 1991)

<table>
<thead>
<tr>
<th>Mean index potential (kPa)</th>
<th>Irrigation to be applied if mean index potential has:</th>
<th>If irrigation on previous day</th>
<th>If no irrigation on previous day</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Decreased (wet zone becoming smaller)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt; -7.0</td>
<td>NONE</td>
<td>NONE</td>
<td>NONE</td>
</tr>
<tr>
<td>-7.0 to -8.0</td>
<td>1.0mm</td>
<td>1.0mm</td>
<td>1.0mm</td>
</tr>
<tr>
<td>-8.1 to -12.3</td>
<td>+1</td>
<td>4.5mm</td>
<td>-1</td>
</tr>
<tr>
<td>&lt; -12.4</td>
<td>+2</td>
<td>6.0mm</td>
<td>0</td>
</tr>
</tbody>
</table>

Standard irrigation amounts were: 1.0, 2.0, 3.0, 4.5, 6.0, and 7.5mm

Note: +1 means apply next HIGHER amount of irrigation
      -1 means apply next LOWER amount of irrigation
      0 means apply same amount as previous day

Or (1995) gave an example of how tensiometers could be used as a basis for when to start irrigation. Once a determined matrix potential is reached, irrigation begins for a constant amount of time, as opposed to the amount and timing of irrigation changing on a daily basis. The author stated that this method contributed to higher crop production because of increased soil aeration, although no results were given for the basis of these claims.

7. SYSTEM DESIGN

It is beyond the scope of this report to detail the specific aspects of agricultural engineering which are required for the design of drip irrigation systems to ensure correct water pressure is maintained. Instead, it concentrates on factors involved in the delivery of improved water and nutrient use efficiency, namely emitter spacing, depth, and flow rate, and the importance of matching these with the soil’s wetting characteristics and the amount and timing of water supply to the crop.

7.1 SOIL WETTING

Broad soil texture ranges (e.g. sand, loam, clay) are usually the only information related to soil wetting used in trickle system designs. In the study by Thorburn et al. (2002c), dimensions of wetted soil were calculated from hydraulic properties of 29 soils covering a wide range of textures and soil hydraulic properties to assess the impact of soil texture and/or type on soil wetting patterns. The soils came from two groups that differed in the extent to which hydraulic properties depended on soil texture. Vertical and radial distances to the wetting front from both surface and buried emitters were calculated for conditions commonly associated with daily irrigation applications in a widely spaced row crop (sugarcane) and horticultural crops. In the first group of soils, which had least expression of field structure, the wetted volume became more spherical (i.e. the wetted radius increased relative to the depth of wetting below the emitter) with increasing clay content, as is commonly accepted. However, in the second group of soils in which field structure was preserved, there was no such relationship between wetted dimensions and texture. For example, five soils with the same texture had as great a variation in wetting pattern, as did all 11 soils in the first group, indicating the considerable impact of field structure on wetting patterns. The implications of the results for system design and management were illustrated by comparing current recommendations for trickle irrigation systems in coastal north-eastern Australia with the calculated wetted dimensions. The results suggest that (1) emitter spacings recommended for sugarcane are generally too large to allow complete wetting between emitters, and (2) the depth of
wetting may be greater than the active root-zone for both sugarcane and small crops in many soils, resulting in losses of water and chemicals below the root-zone. It was concluded that texture is an unreliable predictor of wetting and there is no basis for adopting different dripper spacings for soils of different textures in the absence of site-specific information on soil wetting. Such information, which can be obtained by the methods of Battam et al. (2002), is crucial for the design of efficient trickle irrigation systems, yet rarely is obtained prior to designing trickle irrigation systems.

Given these results, the question was asked, “What needs to be done to convince irrigators and/or trickle irrigation system designers to invest resources into obtaining the required soils information?” Thorburn et al. (2002d) and Cook et al. (2002) proposed that the solution was the development of a user-friendly software tool, or “calculator”. This calculator could be used to illustrate the variability in wetting between individual soils and thus help people to appreciate the need to build soil-specific information into the design of trickle irrigation systems. The software tool, WetUp, uses analytical models to calculate the approximate radial and vertical wetting distances from an emitter in homogeneous soils and then uses an elliptical plotting function to approximate the expected wetted perimeter. It has the capacity to simultaneously display different sets of parameters and the resulting wetted perimeters. This allows rapid comparison of the consequences of different soil properties and management decisions (such as emitter placement as shown in Figure 2).

In contrast to the wetted perimeter predicted explicitly by the model of Philip (1984), the wetting pattern described by the ellipsoidal approximation in WetUp is accurate for slowly permeable soils. However, it tends to underestimate the radial wetting in highly permeable soils, particularly as the volume of applied water increases. The error is small in most cases and of minimal concern when applying WetUp to illustrate the important role soil hydraulic properties play in determining wetting patterns.
7.2 SOLUTE MOVEMENT

As well as inadequate description of soil hydraulic properties during design of trickle irrigation systems, soil solute transport properties and soil profile characteristics are also not adequately incorporated in the design and management of trickle systems. Cote et al. (2002) undertook a simulation study designed to highlight the impacts of soil properties on solute transport from buried trickle emitters. The analysis addressed the influence of soil texture, soil hydraulic properties, soil layering, trickle discharge rate, irrigation frequency, and timing of nutrient application on solute distribution. It was found that the fertigation strategy had a large impact on the transport and final distribution of solutes in coarse-textured soils but little effect in slowly permeable and duplex soils. By changing the strategy for coarse-textured soils from applying nutrients at the end of an irrigation cycle (Figure 3-a) to applying them at the beginning of an irrigation cycle (Figure 3-b) it was found that larger amounts of nutrients (more than double) were maintained near to and above the emitter. Specifically, 16% of the solutes remained above the emitter and 84% below when applied at the beginning, compared to 7% and 93%, respectively when solutes were applied at the end of an irrigation cycle. Further analysis showed that solutes concentrated in different areas within the soil profile. A large amount of solutes, 22 kg/ha, concentrated at depths between 0.6-0.9 m directly below the emitter when solutes were placed at the end of an irrigation cycle (Figure 3-a). While 6.4 kg/ha was held in a pocket that formed 0.1 m above the emitter when solutes were placed at the beginning (Figure 3-b). It was suggested that nutrients above the emitter line would be more readily available for plant uptake as they stay in the root zone nearer the soil surface for longer, thereby making them less susceptible to leaching losses.

The results demonstrate (1) the need to account for differences in soil properties and solute transport when designing irrigation and fertigation management strategies, and (2) that understanding the system can result in simple, yet effective management strategies to improve the management of trickle irrigation/fertigation systems.

(a) Solutes applied at the end of irrigation

(b) Solutes applied at the beginning of irrigation

Figure 3. Simulated solute concentration at 10 hrs in sand irrigated using two fertigation strategies – solutes applied at the end (a) and beginning (b) of the irrigation cycle.

8. REFERENCES

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4. ECONOMICS OF IRRIGATION SYSTEMS
ECONOMIC CONSIDERATIONS IN IRRIGATION
MANAGEMENT: THEORY AND PRACTICE

M E Qureshi, T Wilcox and K Bristow

1. INTRODUCTION

Economics provides a method of analysis that helps choose among alternatives. It deals with allocation of scarce resources among competing alternatives. Economic analysis is designed to provide a rational basis for decisions about optimal allocation of resources to business enterprises. The sugar industry has a long history of managing production resources based on yield. The increasing terms of trade for agricultural commodities and need to consider profit among ‘triple bottom line’ of sustainability (i.e. economic, social and environmental sustainability) indicate sugar producers and technical advisors should place more emphasis on economic criteria when making decisions about crop production and allocation of resources as well as managing risks associated with crop nutrition and/or irrigation requirements. Similarly, resource managers, policy makers and decision makers should also give more emphasis to economic issues when managing agricultural resources (such as water) and implementing appropriate policies.

2. ECONOMICALLY OPTIMAL IRRIGATION MANAGEMENT – THEORETICAL BACKGROUND

Economic efficiency refers to the combination of inputs that achieves individual or social objectives to the greatest possible extent in relation to individual firms and society, respectively. In the case of a single variable input, the economic efficiency relies on the location of the production function on which the farm is operating. The most profitable point of operation is obtained either by determining the most profitable amount of input or the most profitable level of output. Either method results ultimately in the same optimal level of the variable input because the production function relates input to output in a unique manner. The maximum profit does not occur where physical output is at a maximum because producing at the point of maximum yield is not compatible with the goal of maximum profit as long as there is a price attached to the input (water). This is because a stage of diminishing marginal product to a single variable input will arise and, beyond the point of maximum profit, the added units of irrigation water cost more than they are able to earn. Thus the quest for maximum yields is not an environmentally responsible goal and also is not consistent with profit maximisation unless all inputs into the production process are free (Doll and Orazem 1984), both privately as well as socially. Therefore, a farmer is considered efficient when production inputs are allocated optimally according to their relative prices. However, if the expenditure on an input (such as irrigation water) is low compared to other costs of production, then the optimal quantity will approximate that leading to maximum crop yield. The condition of optimum use of an input is that the value of marginal product (VMP) equals the price of the input (P). If VMP is lower than P, the resource is over-utilised and lowering the quantity used at the current price will increase the VMP towards optimality. On the other hand, if VMP is greater than P, the resource is over-utilised and using more of it will not bring additional gains to the grower.

1 The classical production function with stages of increasing then decreasing returns to the variable factor divides the input-output relationship into three stages. In the first stage, marginal (incremental) physical product (MPP) is greater than average physical product (APP) which is increasing throughout the stage. In the second stage, APP exceeds MPP which is decreasing but greater than zero. In the third stage, MPP is negative. If the product has a value, input use, once begun, should continue until the second stage is reached. That is because the physical efficiency of the variable resource, measured by APP, increases through stage one. Therefore, it is not reasonable to cease using an input (such as irrigation water) when its efficiency is increasing. In accordance with economic principles, irrigation water will not be applied in stage three even it was free because maximum output (cane yield) occurs on the upper boundary of the second stage and further irrigation increments decrease output (yield).

2 The marginal value product of applied water is a product of output price, marginal product of effective water, and irrigation efficiency (Boggess et al. 1993).
In situations where there are a number of crops, efficiency dictates that the marginal net benefit (marginal revenue of product less marginal cost of input) be equalised for all crops. If marginal net benefits are not equal, it is always possible to increase aggregate benefits by transferring water from those crops with low marginal net benefits to those with higher marginal net benefits, provided there is enough flexibility to allow water reallocation. The benefits given up by those crops losing water are less than those gained by crops receiving additional water. This procedure results in allocative efficiency (Samuelson and Nordhaus 1987). At this stage, water is efficiently allocated and no other outcome can improve the welfare of the water user.

If a farm or region has various soil types, then a similar economic principle applies in the allocation of water to each soil type. Maximisation of farm profit is achieved only if there is an optimal level of irrigation on each soil type and marginal productivity of water use is the same for all soil types. Efficiency dictates that the marginal net benefit be equalised for all soil types for each crop. When a single crop is dominant in a region (due to either economic or agronomic conditions), the optimal level of water application is still achieved when the cost of one additional unit of water is equal to the additional revenue it generates.

There are several factors to be considered in irrigation management to improve productivity and reduce costs. One of the key decisions is how much water should be allocated to a particular crop. This decision need to be based on the quality and availability of water resources, reliability of water supply, the physiological requirements of the crop, and the expected value of output. An important strategy for the application of water to crops is to apply irrigation water at a level that gives maximum net income. Achievement of that strategy rests with more efficient use of irrigation by involving water saving technology (or modern technology) as opposed to traditional irrigation systems that were designed to favour maximum crop growth. Modern irrigation technology is also called a land-quality-augmenting technology where capital equipment assists the land in its water holding function, thus increasing irrigation efficiency (Caswell and Zilberman 1983). The sugar industry (for example) is assumed to be competitive and farmers are profit maximisers. The optimal water use level is determined by maximising the operational profit per unit area. The profits under both technologies can be compared and more profitable technology selected (Zilberman 1984). The modern irrigation technologies are often more expensive and require heavy initial investment. In addition to other factors, the long-term viability of farm businesses will depend on the returns obtained from the adoption of new technology.

3. BASIC ECONOMIC CONCEPTS IN IRRIGATION MANAGEMENT

In the sample examples outlined in this section, basic economic concepts concerned with deriving optimum irrigation level are introduced. While only irrigation responses are used to illustrate biophysical and economic dimensions of irrigation, similar principles apply for the other inputs (such as fertiliser or pesticides).

3.1 FIXED AND VARIABLE INPUTS AND IRRIGATION RESPONSE CURVE

In cane production, inputs can be thought of as either variable or fixed. An input is fixed if the quantity used is not varied during the production period (e.g. land). Variable inputs are those which can be easily manipulated by the grower during the production period (e.g. irrigation). Figure 1 illustrates the sugarcane yield response curve for a single variable input (water). All other inputs in the cane production process are held constant.

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3 The example of irrigation water application levels and their impact on yield in this paper represents cane yield from a highly permeable soil type in the Burdekin delta in north Queensland, where high water use and high yields are common, due to local climatic conditions and soil types.
Figure 1. Response of sugarcane yield to irrigation application for a highly permeable soil type in the Burdekin delta in north Queensland.

The production response curve may vary for different sugarcane growing regions. For example, the irrigation response curve for the Bundaberg region may look like Figure 2, where maximum yield is obtained when only 8 ML/ha is applied. However, it is important to recognise that diminishing returns prevail with respect to irrigation, so that the additional cane yield from increasing units of water becomes less and less. Beyond some peak yield, additional units of irrigation may have an increasingly deleterious effect on yield (e.g. as a result of water logging or salinity).

Figure 2. Response of sugarcane yield to irrigation application for a farm in Bundaberg.

Several quantities of interest, which can be derived from the response function, include:

- average physical product (APP) of irrigation, or yield efficiency (defined as the ratio of cane yield to total irrigation applied). APP measures the physical or technical efficiency of the variable input, which is distinct from economic efficiency,
- marginal physical product (MPP) of irrigation (Figure 3), which is the increase in yield per unit of additional water. MPP of cane is computed by dividing the change in yield by the increment (or change) in irrigation. Marginal product is more relevant to economic analysis than the average product, and
- maximum yield that can be attained.
3.2 COSTS OF PRODUCTION

Costs are expenses incurred in the cane production process, and, as for inputs, can be thought of as variable and fixed. Fixed costs are independent of the level of output produced and therefore do not change with cane or sugar yield. They are incurred even when no cane is produced. The costs of variable inputs are known as variable costs and change with the level of production. Total costs of cane production are the sum of fixed costs and variable costs. The behaviour of fixed costs, variable costs and total costs to change in the irrigation level/rate is shown in Figure 4. In the short run, total costs include fixed and variable costs. In the long run, all costs are considered variable costs because all inputs are variable.

3.3 DETERMINING THE OPTIMUM AMOUNT OF IRRIGATION

Another important measure is the total value of, or revenue from, the cane produced. For any given volume of irrigation water applied, the total value of cane is the product of the quantity of cane produced and the price ($/t) received for it. Maximising profit implies maximising the difference the total value of the sugarcane produced and the cost/s of input/s used. Maximum profit can also be depicted on a profit curve, which is derived by subtracting the total cost from the total value of cane for each input level of irrigation, as demonstrated in Figure 5.
Maximum profit is derived when the slope of the profit curve equals zero. The irrigation level corresponding to this point on the profit curve is economically optimum rate. Operation at any other irrigation level would result in smaller profit. In other words, to achieve maximum profit, incremental or marginal cost (MC) must be equal to incremental revenue or marginal return. The marginal return is the MPP of irrigation (Figure 3) multiplied by the price of cane ($/t). Because of diminishing returns, prior units of irrigation water will have more than paid for themselves, but further units of irrigation water will not cover their cost.

### 3.4 Maximum Yield and Maximum Profit

When diminishing returns exist, profits do not occur where cane yield is a maximum. Maximum profit occurs at an irrigation level below that which produces maximum output, as indicated in Figure 6.

Thus the quest for maximum yields is not an economically responsible goal as it is not consistent with profit maximisation. Profit maximisation level in economics is called optimum level. The optimum level is obtained when MC is equal to the value of marginal product (VMP). This optimum level of irrigation occurs at 30 ML in Figure 7. Beyond this point marginal cost is higher than the VMP.
It is to be noted that any change in the price of cane, irrigation water, or the physical response function will change the optimum level of irrigation. For example, when gross value of cane to the farmer declines from $30 to $15/t, the optimal level of irrigation also declines. Additional irrigation application beyond this point will increase yield but will result in less profit.

4. COMPLEX ISSUES IN IRRIGATION MANAGEMENT

4.1 MULTIPLE VARIABLE INPUTS

In reality, there is more than one variable input (e.g. fertilisers and pesticides). A cane production function is modified by adding physical and economic relationships that affect a producer’s decision-making processes to maximise profit levels of these inputs. The objective is to maximise whole-farm profit, which is the value of the cane produced, minus the costs of all inputs. Therefore, to maximise whole-farm profit, the cost of the last increment of each input used should just be equal to the value of the extra output obtained by using that increment, for all inputs simultaneously. Simple calculations are easily performed using a budget-based spreadsheet. However, determination of optimum levels of inputs requires complex calculations. Economists use computer-based algebraic or mathematical programming techniques to examine profit-maximising levels (i.e. optimal levels) of all inputs in the production process.

4.2 TEMPORAL EFFECTS IN DECISION-MAKING

Other important elements are temporal effects, which are inevitable in farm decision making processes related to irrigation management. Time affects the physical crop response curve (or production) in many ways. Differences in weather conditions between years, the manipulation of the length of the growing period and carry-over effects from irrigation as well as capital cost of irrigation systems and their future impacts, are examples of how time, as a variable input, affects the response curve. This in turn, impacts on economic returns. Time also influences profits through market factors (input and crop prices vary over time) and profit opportunities. Time implies an opportunity cost – the use of inputs over time in a particular production process means that these inputs are tied up and not available for use in some other process. An opportunity cost is incurred because alternative uses of the input are forgone. The input opportunity cost is the profit forgone from not using physical inputs over time in their most profitable alternative use. The principles involved in maximising profits when time is involved are the same for the timeless example described above, i.e. equating marginal returns with marginal cost. The difference is that marginal cost over time must allow for the time opportunity cost and time preference effects as well as the direct marginal costs of inputs.

The canegrower is often required to purchase inputs that will be used for several production periods and over a period of years. Also, some investments may earn return for several years. As a result, the grower must compare costs incurred in one or more years to revenues that might accrue in one or more, but possibly different, years. Costs incurred at one point in time cannot be compared with validity to revenues forthcoming at a later date. Compounding and discounting are the primary tools for comparing the value of money received at different points in time. The basic premise of these tools is that a dollar received now does not necessarily have the same value to a person as a dollar to be received a year from now. An individual’s choice of a particular allocation of money over time is called his or her time preference.

Popular methods for summarising present and future costs and benefits are net present value, internal rate of return and benefit cost ratio.

- **Net present value (NPV)** is simply the summation of the discounted benefits over a time stream less the summation of the discounted costs. A discount rate is used to reflect time preference or opportunity cost of capital relating to the benefits and costs occurring through time.
- **Internal rate of return (IRR)** is defined as the discount rate for which the NPV of a series of cash flows is zero. In other words, the present value of incremental benefits and the present value of incremental expenditures are equal.
- **Benefit cost ratio (B/C)** is determined by dividing the discounted sum of benefits by the discounted sum of costs, i.e. it is the ratio of discounted benefits to discounted costs.
These processes also require complex calculations. Computer-based algebraic or mathematical programming models/techniques are used to examine profit-maximising levels of all inputs as well as alternative relative profitability of alternative irrigation systems (for example) in the cane production process.

4.3 RISK AND UNCERTAINTY IN IRRIGATION MANAGEMENT

For an irrigation scientist and/or farm manager, defining an irrigation response surface and calculating the economic optimum of irrigation is not an easy task due to the involvement of time dimension, multiple inputs and negative externalities. In addition, risk and uncertainty complicate the analysis of response surfaces, which are not unique and vary from site to site and season to season. Likewise, economic factors, such as input costs and product prices also vary over time. Externalities associated with production of cane are not captured in an irrigation response surface. For example, when irrigation rate increases, the likelihood of leaching and soil erosion increases, which can result in groundwater and surface contamination. Risk of soil salinity as a result of water logging also increases.

Risk can have significant impact on the behaviour of a typical system. In many agricultural situations, more interest is shown in downside risk, i.e. situations where any significant deviations from the “norm” lead to worse outcomes. In the case of irrigation, the downside risk will be that adverse soil and weather circumstances might convert what is normally an optimal level of irrigation to one of sub-optimality leading to significant yield reductions that reduce profit. Generally, growers like to be on the safe side of irrigation, i.e. over irrigation to reduce the risk of yield reduction due to water stress. In economics, this behaviour is called risk aversion. The degree of risk aversion displayed varies across individuals, time and issues. The technical definition of risk aversion is when someone is willing to forgo some expected return (e.g. profit) for a reduction in risk. Therefore, the practice generating the best long-term average returns may not be followed by a risk averse individual if another option exists which has lower long term returns but also has lower risk. An example is the common practice of over irrigation by risk averse growers where long term profitability is forgone in favour of the certainty that sufficient irrigation water has been applied to avoid reduction of yield. Generally, farmers balance their expected private costs of production, for example costs of water and fertiliser, against the returns from crops produced. However, farmers’ production decisions may have unintended long-term effects especially when a large group of them choose a production strategy that exceeds the environmental system’s capacity to deal with pollutants.

4.4 INCORPORATING RISK INTO ECONOMIC ANALYSIS

Risk effects are difficult to analyse and not only require mathematical models but also involve personal preferences or subjective judgements about the chances associated with different possible outcomes from a range of options. In economics, risky outcomes are described by probability distributions. Risky choice implies judgements about and choices between alternative probability distributions of outcomes. Because these are subjective judgements, irrigation application rate for one grower may not be appropriate for another.

A number of approaches have been advocated by economists, however it is generally agreed that the preferred option for risky choice is the decision theory approach based on expected utility. Computer packages simplify calculation of expected utility for decision making in risky environments, where the decision criterion is maximisation of utility theory rather than maximisation of profits. When there is uncertainty in yield response to a given rate of water application, growers have to effectively determine the optimum input level from a concept of numerous response functions for all the yield possibilities associated with each megalitre of water. The decision will correspond to some form of probability

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4 The negative externalities are the costs which are inflicted on others and not considered in the producer’s decision-making framework.
5 Uncertainty is often defined as the lack of certainty and a grower is unable to associate probabilities with the outcomes of production process. Risk implies uncertainty of consequences, particularly exposure to unfavourable consequences (e.g. risk of losing yield, risk of contaminating ground or surface waters, price or market risk of an input cost or output, financial risk, institutional risk of a future regulation or human or personal risk which may effect on farm business). In this situation, a grower is aware of all possible outcomes that could result from the process and could attach a probability to each outcome.
distribution which gives the grower greatest utility, and this is strongly linked to the grower’s risk preference. The theory of expected utility analysis has been widely regarded for many decades as the most satisfactory method available for choosing among risky decisions but the difficulty of using the theory in a practical sense has impaired its use.

Another approach that is commonly practised in economic analysis is sensitivity analysis. Sensitivity analysis illustrates what would happen if a small number of key variables changed and how these changes would affect the overall cost or benefit of the project. It is to be noted that, while economic principles provide strong guidance and help in the formulation of appropriate recommendations, these principles cannot provide precise recommendations of irrigation level. This is due to the lack of data, cost of analysis and the complications of real world.

5. ENVIRONMENTAL CONSIDERATIONS IN EFFICIENT WATER-USE

Irrigation has allowed the expansion of agriculture into semi-arid and even arid environments, thus helping to stabilise the revenue from farming. With the exception of crops with low added value, irrigation can bring substantial economic gains (Bonnis and Steenblik 1998). In sugarcane, irrigation plays an important role in increasing efficiency of farm management, enabling timely preparation of land, rapid establishment of plant and ratoon crops, improving efficacy of herbicides, reducing pest and disease related stresses and avoiding ammonia volatilisation from surface applied fertilisers such as urea. Potential impacts from poor irrigation management include increased salinity and sodicity, rising water tables, waterlogging, nutrient and pesticide pollution of waterways, and alterations to the biological populations in streams (Kingston et al. 2000).

Excessive use of groundwater aquifers can lead to higher concentrations of pollutants. Excessive extraction can lower water-tables leading, in some cases, to ground subsidence and, in some coastal areas, to salt-water intrusion. For example, there is concern that the lowering of watertables has led to salt-water intrusion in coastal areas of Central Queensland (Murphy and Sorensen 2001). Moreover, because irrigation water almost always contains much higher concentrations of dissolved salts than rainwater, its discharge often raises the concentration of salts in the bodies of water into which it flows (Bonnis and Steenblik 1998). Lower watertables increase pumping costs and the depletion of aquifers by irrigation raises questions about the sustainability of farming systems. In some parts of southern Australia, fertile irrigation lands have had to be abandoned due to salinisation (Bonnis and Steenblik 1998).

Current assessment of water use efficiency (WUE) in Queensland indicates that about 60% of irrigation water is used by crop or pasture production and the remainder is lost due to run off, drainage and evaporation (Barraclough and Co. 2000). This inefficient use raises several issues of social as well as private costs. If growers are more efficient and use less water for irrigation then more water will be available in the aquifer for future irrigation use. There will also be potential to use the saved water for other agricultural crops and other activities. Efficient irrigation practice will save the growers’ pumping costs and there will be less potential for the leaching of nutrients and pesticides to the aquifer.

The need for a strategic approach to manage water (including efficient water use for irrigation) has been recognised both at the national and state level. In 1994, the Council of Australian Governments (COAG) adopted a National Water Reform Agenda. This represents the first nationally coordinated strategic approach involving Federal and State governments in implementing agreed reforms based on a common strategic vision. The reforms in the rural sector seek to ensure an economically viable and ecologically sustainable water industry. It is argued that business as usual in the rural water industry will not be a viable option for irrigators or the environment on either a medium or long-term basis. The agenda integrates elements of ecologically sustainable development and the National Competition Policy (Prime Minister’s Science and Engineering Council 1996).

Changes to institutional structures are likely to offset the effects of price increases that might occur as a result of reform. Reforms will also help to identify the real value of water and make clear any subsidy or community service obligation so that the decisions can be made about how best to use and protect valuable resources. It is expected that industry performance will also be improved through the transference of responsibility to irrigators to allow them to influence levels of service and to ensure that water delivery matches production needs (AFFA 2000).
Recently, the Queensland Department of Natural Resources and Mines developed a $41 million Rural Water Use Efficiency Initiative. The initiative is a partnership agreement between rural industries (including the sugar industry) and the government to improve the water use efficiency and management of available irrigation water thereby improving the competitiveness, profitability and environmental sustainability of Queensland’s rural industries (Barraclough and Co. 2000). The major aim of the RWU Initiative is to place more emphasis on water use efficiency and wastewater use.

Effective irrigation management is vital for irrigated crop production. It is essential for sustainable utilisation of the resource and management of potential ecological impacts. Effective management of irrigation can minimise ecological impacts of irrigation, conserve water supplies and improve net returns of producers. Best irrigation management practice requires growers to be more efficient in irrigation. Various management practices and irrigation technologies are available to enhance efficiency of applied water in irrigation agriculture. Adoption and long term use of one of these irrigation systems or technologies depends on a number of factors including climate, site characteristics (such as soil permeability, slope), overall irrigation efficiency, impact on yield, installation and operating costs, water charges and concern for the local environment (such as impact on aquifer and ground and surface water quality). It also depends on initial capital available to a grower in the form of savings, rate of interest for borrowing and off farm investment as well as on government regulations and financial support programs. Therefore, an integrated approach is required to assess impacts of alternative irrigation systems.

6. APPLICATION OF ECONOMIC PRINCIPLES IN IRRIGATION MANAGEMENT

In this section, two analytical frameworks are presented to briefly demonstrate the economic principles discussed in the above sections. The frameworks were developed to:
(a) to determine optimal levels of irrigation water across soil types and to estimate farm profitability of growing cane on various soil types and
(b) to estimate the relative profitability of changing from current furrow irrigation to an alternative irrigation system by estimating the net profitability of these systems on a multi-period (long-term) investment basis in the Burdekin delta in north Queensland.

A brief description of the case study area is as follows.

The Burdekin delta is one of the few areas in Queensland where cane is grown under full irrigation and conjunctive use of groundwater and surface water is common practice 6. The North and South Burdekin Water Boards (NBWB and SBWB) were established in 1965 and 1966 respectively, to replenish and manage the underground aquifers. Artificial recharge is still practised in the delta, although the Water Boards (particularly the NBWB) are promoting a practice of more efficient water use requiring less artificial recharge. There are differences in the structure of groundwater charges between the two boards and in the threshold per-hectare volume of surface water for low-rate charges. Also, the proportions of groundwater and surface water used are different, due to differences in quality of groundwater and need to recharge the aquifer. In NBWB, the proportions of groundwater and surface water are 40% and 60%, while in case of SBWB, these proportions are 70% and 30% respectively. The average cane farm in the area serviced by NBWB uses less groundwater and more surface water than an average cane farm in SBWB area. Based on recent estimates (Arunakumaren 1998), the proportions of three soil types on a 60 ha farm in the study area are assumed to be: low permeability 33%, medium permeability 56%, and high permeability 11%.

6.1 APPLICATION A: OPTIMAL LEVELS OF IRRIGATION WATER ACROSS SOIL TYPES AND FARM PROFITABILITY

The analytical approach applied in this analysis for a representative cane farm in the study area includes using a biophysical simulation model to predict crop yields of sugarcane, linked to a linear programming model to determine the levels of irrigation which maximise farm profitability for various soil types. A brief description of the analytical framework and its components is presented in this section. A more detailed description of the model is given by Qureshi et al. 2002.

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* Conjunctive use means using a combination of stored surface water and groundwater for irrigation
Biophysical information such as crop yield is necessary for a comprehensive economic analysis. The APSIM cropping systems model (McCown et al. 1996) was used to obtain these data by linking a sugar crop module, a soil water module, a soil nitrogen module and a surface residue module, as described by Probert et al. (1997). The model ‘APSIM-Sugarcane’ was configured to simulate continuous cropping over a 20-year period from 1975 to 1995 with a cycle consisting of one plant crop followed by three ratoon crops. A series of crop simulations were performed to estimate response to applied irrigation water for a range of soil types, water allocation levels and application efficiencies, under the widely used furrow irrigation system. The water inputs and yields obtained from the 20-year simulation runs were averaged. Simulated yields were about 20% higher than the average sugar yield in the region. This was because the model did not account for losses associated with pests, diseases, weed competition, waterlogging or unusual climatic events, and yields were based on uniform soil characteristics. Therefore, yields for the various irrigation levels were reduced by 20% for each of the three soil types. Average water inputs and yields simulated over the 20 years were used in the economic analysis.

A linear programming model was developed using GAMS (General Algebraic Modelling System) software (Brooke et al. 1998) to analyse responses to changes in water prices and other management options in both the North and South Burdekin Water Board areas. The aim of the analysis for which the model was developed was to determine optimal levels of irrigation for major soil types in the delta. The model estimated after-tax annual net revenue of cane per hectare for each soil type under the current water-pricing scheme as well as under alternative pricing policies. It was assumed that the farmers are risk neutral and their objective is maximisation of long-term profit from their activities. For the analysis (to maximise farm profit), the optimal levels of irrigation were determined for each soil type, amount of land resources allocated to crop type (plant cane and ratoons only), water source and irrigation level (which can vary from 0-35 ML/ha). The proportions of the three soil types in the study area were taken as low permeability 33%, medium permeability 56%, and high permeability 11%. This model has been used to evaluate and compare case study farms in the North and South Burdekin Water Board Areas. Average yields obtained by using the APSIM biophysical simulation model type for a furrow irrigation system on each soil were used in the linear programming model.

Total revenue from each soil type and irrigation water level, represented income from selling cane to the local mill and was calculated using the standard Australian sugar industry price formula. In the model, costs were divided into three components: irrigation-related costs; other production costs such as fertiliser, harvesting, maintenance and other variable production costs; and fixed costs. Irrigation-related costs were obtained by adding irrigation system operating costs, cost of electricity for pumping ground and surface water, cost of groundwater and cost of surface water. Aggregate net revenue was calculated by deducting total costs from total revenue while after-tax net revenue was estimated by deducting tax payable from aggregate net revenue.

A simulation experiment was performed using water charges for both the NBWB and SBWB areas along with a volumetric water charging policy option. The optimal water application levels for three soil types of representative farms as well as the volumetric water charging option are presented in Table 1. The optimal water application levels for a farm with three soil types in the SBWB area are higher than those for the NBWB area. The higher optimal levels are due to the relatively greater use of less expensive groundwater on the SBWB farms compared to the NBWB farms. The optimal water levels for both farms under the volumetric water charging option are lower due to higher water costs.

<table>
<thead>
<tr>
<th>Soil type</th>
<th>NBWB</th>
<th>SBWB</th>
<th>Volumetric water charge option</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low permeability</td>
<td>23</td>
<td>27</td>
<td>22</td>
</tr>
<tr>
<td>Medium permeability</td>
<td>28</td>
<td>31</td>
<td>26</td>
</tr>
<tr>
<td>High permeability</td>
<td>35</td>
<td>35</td>
<td>35</td>
</tr>
</tbody>
</table>

Estimated net revenues (before-tax) per hectare for cane production on three soil types for the representative farms are reported in Table 2. These figures indicate that profitability of cane on low permeability soil is higher than on medium and high permeability soils. The profitability of each soil type is also higher for the SBWB farm than the NBWB farm, and much lower for the volumetric water charge option.
Table 2: Net revenue ($/ha) of cane growing from three soil types for the NBWB and SBWB areas and the volumetric water charge option

<table>
<thead>
<tr>
<th>Soil type</th>
<th>NBWB</th>
<th>SBWB</th>
<th>Volumetric water charge option</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low permeability</td>
<td>1816</td>
<td>1918</td>
<td>1235</td>
</tr>
<tr>
<td>Medium permeability</td>
<td>1612</td>
<td>1765</td>
<td>903</td>
</tr>
<tr>
<td>High permeability</td>
<td>1237</td>
<td>1425</td>
<td>356</td>
</tr>
</tbody>
</table>

Optimal after-tax revenues are presented in Table 3. The SBWB area farm has higher gross profit before and after tax than the NBWB area farm because of the higher proportion of less expensive groundwater used. The volumetric water charge option results in lower after-tax revenue due to relatively high water charges based on volume rather than charges based on area of production.

Table 3. Net revenue ($/farm) before and after tax for the NBWB and SBWB areas and the volumetric water charge option

<table>
<thead>
<tr>
<th>Net revenue ($/farm)</th>
<th>NBWB</th>
<th>SBWB</th>
<th>Volumetric water charge option</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before tax</td>
<td>78 630</td>
<td>85 336</td>
<td>45 714</td>
</tr>
<tr>
<td>After tax</td>
<td>54 294</td>
<td>57 848</td>
<td>36 848</td>
</tr>
</tbody>
</table>

The model has also been run to determine the optimal level of irrigation under a pricing schedule that involved increasing water charges. Here, only surface water costs have been increased to examine the impact on the optimal level of irrigation for three soil types (in the SBWB area only) because the groundwater charges are based on area of production and have no relation to the optimal level of irrigation. The optimal level of irrigation and after-tax income was determined for each soil type when water charges were increased in $10 increments. The optimal level of irrigation for low permeability soils reduces from 27 to 23 ML/ha when there is only a $10 increase, then this level remains constant until the water charges are $45.40 and $53.67, respectively. This level of irrigation remains the same even when the low and high water charges are further increased to $95.40 and $103.67. For the medium permeability soil, the optimal water quantity changes from 31 to 28 ML/ha when the low and high water charges rise to $35.40 and $43.67, respectively, after which the quantities remain constant. The optimal water level for highly permeable soil type does not change with any price increase, indicating a highly inelastic demand for irrigation water in response to price changes. It is to be noted that for the SBWB area farm, the available proportion of surface water is only 30%. Therefore, the impact of any increase in surface water charges is not great due to its low contribution to total costs, although there is a sharp drop in after-tax farm income, from $57 848 to $37 011.

6.2 APPLICATION B: RELATIVE PROFITABILITY OF CHANGING FROM CURRENT FURROW IRRIGATION TO AN ALTERNATIVE IRRIGATION SYSTEM

For biophysical information, the APSIM systems model and the procedure described above was used to estimate yield responses to applied irrigation for a range of soil types, water allocation, and application efficiencies varying from 30% to 90% for each of three irrigation methods, namely furrow, centre pivot and trickle irrigation systems. Initially, it was assumed that a grower could use as much water as required to achieve maximum yield. However, as application rate increases, profitability will ultimately be reduced. A detailed description of the model including data acquisition is provided in Qureshi et al. (2001), however, a brief description is as follows.

Because of the complex nature of calculations (such as groundwater-surface water proportion per hectare, differential surface water charges and progressive Australian taxation regime), a multi-period algebraic model (called CANEIRRI) has been developed using the GAMS (General Algebraic Modelling System) software package (Brooke et al. 1998). Annual farm cash surpluses for alternative irrigation technologies were simulated over a 20-year planning horizon, and net present value (NPV) computed by using 7% real discount rate. CANEIRRI consists of separate modules for furrow irrigation (with no new capital outlays), centre pivot (immediate capital investment during the fallow period) and trickle irrigation (capital investment spread equally over five years). Investment in trickle irrigation is timed to follow the four year crop and one year fallow cycle. Operating costs during the transition are based on proportion of area under trickle irrigation. Provision is made for deductions from income for capital investments on irrigation equipment, and for carrying forward business losses.
for taxation purposes. No allowance is made for scrap value of the irrigation equipment at the end of 20 years. This model has also been used to evaluate and compare case study farms in the North and South Burdekin Water Board Areas. Average yields from each soil type and for each irrigation system obtained by using the APSIM biophysical simulation model were used in CANEIRRI economic model.

Results from the preliminary analyses for NBWB and SBWB case study farms are presented in Table 4 along with a volumetric water charging policy option. These results indicate that NPVs of the southern area farm are higher than for the northern area farm because the relatively greater input of less expensive groundwater. The ranking by NPV of the three irrigation systems is the same in each district. The furrow system has the highest NPV followed by centre pivot then trickle irrigation system. In SBWB, a positive taxable income is achieved in Year 5 with centre pivot irrigation, but not till Year 9 with the trickle irrigation system. When volumetric water charges are used instead of area-based groundwater and differential surface water charges, the rankings of technologies changes and centre pivot has the highest NPV followed by furrow then trickle, but the NPV for trickle irrigation becomes negative ($-94 785). Under the volumetric water charging option, the overall NPVs for each irrigation system are lower than the NPVs for area-based water charges.

Table 4: Net present values ($1000s) for three irrigation technologies, NBWB and SBWB and volumetric water charge option

<table>
<thead>
<tr>
<th>Irrigation system</th>
<th>NBWB</th>
<th>SBWB</th>
<th>Volumetric water charge option</th>
</tr>
</thead>
<tbody>
<tr>
<td>Furrow</td>
<td>399</td>
<td>446</td>
<td>98</td>
</tr>
<tr>
<td>Centre Pivot</td>
<td>321</td>
<td>348</td>
<td>111</td>
</tr>
<tr>
<td>Trickle</td>
<td>161</td>
<td>194</td>
<td>-94</td>
</tr>
</tbody>
</table>

The values for key parameters – discount rate, sugar prices, capital investment costs, farm ownership arrangement, and other important variables – have been varied systematically to examine their effect on the rankings of the three systems. Discount rates used were 5%, 7% and 9%. The price of sugarcane and capital cost of centre pivot and trickle systems have been altered by ±20% from base values. Only results for the SBWB farm sensitivity analysis are reported. The rankings of these irrigation options do not change by altering values of any of these parameters. The NPV of centre pivot becomes higher than that for furrow irrigation only when there is more than 40% reduction in its capital cost. Similarly, the NPV of the trickle option only becomes higher than furrow when its capital cost is reduced by 80%. This level of reduction in these capital outlays is not likely to happen. Switching from sole owner to partnership increases after-tax income, but does not change the NPV ranking of the irrigation options. When proportion of high permeability soil is altered to 100%, there is a change in the rankings of the irrigation options. Centre Pivot becomes the best option with highest NPV ($325 665) followed by furrow ($261 508) then trickle ($111 481). These results indicate that the rankings are sensitive to the proportions of the different soil types.

7. CONCLUSION

Effective irrigation management is vital for irrigated crop production. It is essential for sustainable utilisation of the resource and management of potential ecological impacts and to improve producer net returns. Various management practices and irrigation technologies are available to enhance efficiency of applied water in irrigation agriculture. Adoption and long term use of one of these irrigation systems or technologies depends on a number of factors including impact on farm profitability of these changes. Economics provides a method of analysis that helps choose among alternatives by allocating scarce resources (such as water) among competing alternatives (crops/soil types). However, a comprehensive economic analysis relies on biophysical data such as climate, site characteristics (soil permeability, slope), overall irrigation efficiency, impact on yield. It also depends on social as well as economic information. Therefore, an integrated approach is inevitable to determine optimal level of irrigation, farm profitability and relative profitability of alternative irrigation systems. The examples presented in this study demonstrate economic principles by using algebraic and mathematical models. They also demonstrate how an integrated approach is used for a comprehensive economic analysis. The economic information so generated can be used to inform farmers about the profitability of growing cane on various soil types and the likely long-term consequences of investment decisions involving modern irrigation technology. Other applications include environmental considerations such as impact of irrigation on groundwater/surface water quantity and quality and social impacts.
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5. IMPROVING IRRIGATION THROUGH ON-FARM WATER STORAGES
IMPROVING IRRIGATION MANAGEMENT THROUGH ON-FARM WATER STORAGES

SN Lisson, LE Brennan, KL Bristow, BA Keating and DA Hughes

1. INTRODUCTION

Water storages are, in many instances, critical to ensuring reliable supplies to meet irrigation demand as and when it occurs. While large-scale storages are managed as part of an irrigation scheme, there is at present no formal coordination/management of smaller on-farm water storages (OFWSs). Furthermore there is no overall assessment of their effectiveness and impact that can serve as a benchmark against which to measure future changes. As demand for water from all sectors of the economy increases, there are likely to be increasing numbers of OFWSs as farmers look to maximise their security of water supply, increase their irrigation management flexibility by accessing out of allocation and potentially tradeable water, and optimise their management of available water resources. There is also the potential for OFWSs to play an important role in managing tailwater and water quality both on the farm and as it leaves the farm. This means that both environmental and economic issues associated with OFWSs need to be taken into account when considering investment in, and subsequent management of OFWSs.

The decision to invest in such storages requires assessment of a range of biophysical, economic and social factors, and the interactions between these factors. Within the biophysical arena, there are complex interactions between OFWS design characteristics, farm management, crop, climate, soil type and catchment related factors. Economic feasibility is sensitive to many variables including cost of installation, method of repayment, and year-to-year fluctuations in yield and sugar price. Computer simulation models can capture many of these processes and their interactions and provide a useful decision support capability for farm advisors (extension officers and/or agribusiness consultants). With this in mind, a software package has been developed within CRC Sugar, called Dam EaSy (Bristow et al. 2000), that couples biophysical and economic modelling tools in a way that enables analysis of various scenarios regarding investment in OFWS, and the likely benefits and costs of such investments (Figure 1).

In this paper we describe the various components of the Dam EaSy software package and demonstrate its capability via a case study for sugarcane in the Bundaberg region. While the current version of Dam EaSy has been customised to meet the specific needs of sugarcane farmers in Bundaberg, Dam EaSy is generic in nature and could be adapted to other regions and/or crops.

![Diagram](image)

Figure 1. Relationship between core interest groups and Dam EaSy development.
2. DAM EASY STRUCTURE

2.1 GENERAL

Dam EaSy consists of three main components: a database of pre-run biophysical model output for a range of OFWS-based production systems, a ‘real-time’ economic model, and an interface through which the operator interacts with the package (Figure 2). Production systems of interest to the operator are ‘constructed’ within Dam EaSy by selecting from a discrete number of ‘optional’ factor settings (e.g., irrigation area, OFWS capacity) contained in drop-down menus within the user interface. This construction process serves to identify farm systems held within the biophysical database that match or come close to matching the farmer’s specific needs. Other biophysical factors are ‘fixed’ to values representative for the region in question. The operator also sets a comprehensive range of income and cost related economic factors (e.g., sugar price, water charges, interest rate) which, in conjunction with biophysical data from the database, are fed into the economic model. The package offers a variety of biophysical and economic outputs and different types of graphical representation for subsequent interpretation and analysis.

![Figure 2. Structure of Dam EaSy.](image)

2.2 BIOPHYSICAL DATABASE

Each database in Dam EaSy is specific to a particular crop type and production site and is comprised of model output for a large number of representative farm systems. The database design allows rapid analysis and simultaneous appraisal of prospective scenarios. The large number of design factors available within Dam EaSy mean that there is potentially an infinite number of possible farm systems that can be configured. Consequently, the scope of the database needs to be carefully defined so that it is achievable in terms of computing resources and yet covers a sufficient number of farm systems for analysis. Typically, the database will cover current management and production systems in a particular region as well as alternative systems for the purpose of scenario or ‘what if’ analyses. The operator is required to select and interpolate between systems from the database which most closely resemble those of interest. It is recognised by the developers of Dam EaSy that the database imposes restrictions in terms of choice and a degree of ‘coarseness’ in the ensuing analysis. With this in mind, it is possible to make additions to the database if necessary.

For each farm system, model runs are conducted over a 40-year period using historical climate files so as to capture responses to season-to-season climate variability and to enable short to medium-term investment analysis. Annual ‘at harvest’ simulated results are provided for 38 separate soil, crop and irrigation related output variables.

The databases are created using the systems model APSIM (Agricultural Production Systems sMulator; McCown et al. 1996). APSIM simulates agricultural production systems by combining modules describing the specific processes within the system under investigation. In the case of Dam EaSy, the soil water module SOILWAT (Probert et al. 1997), the soil nitrogen module SOILN (Probert et al. 1997), and the surface residue module RESIDUE (Probert et al., 1997) are linked with a crop module of choice. In the case study presented in this paper, the sugar crop module APSIM-Sugarcane
(Keating et al. 1998) is used to investigate OFWS-based sugarcane production systems in the Bundaberg region, Queensland, Australia.

2.2.1 Irrigation features
The crop module of APSIM is configured to enable simulation of an irrigated production system using water from any possible combination of OFWS, out of allocation (OOA), or scheme allocation (Figure 3).

Figure 3. Framework of biophysical model.

2.2.2 Out of allocation water (OOA)
OOA refers to surplus water in the irrigation scheme river, not previously allocated for irrigation purposes. Typically, OOA becomes available during large rainfall events when the flow rate of the river exceeds a specified maximum for a specified number of days. These thresholds are incorporated into the APSIM configuration and combined with daily streamflow data for the simulation period (40 years) to identify potential OOA access periods. When OOA water is available and not being used for irrigation purposes, it is used to top up the OFWS (if available). The maximum daily pumping rate (ML/day) is user-defined. OOA transfer is conditional on there being sufficient residual storage capacity to accommodate this transferred volume. Future regulations may require the maintenance of specified environmental flows in scheme rivers. A simple adjustment to the model would enable the use of daily streamflow data to identify periods when pumping is prohibited.

2.2.3 Allocation water
The allocation is defined by an amount (ML/ha) and a period over which it is accessible to the farmer. In many irrigation schemes, the carry-over of unused allocation water from one allocation period to the next is not allowed. Hence, in order to minimise the volume of ‘carry-over’ water, farmers often transfer surplus allocation water into the OFWS for use at some future time. This is captured in Dam Ea$y through the transfer of allocated water (At) into the OFWS (if present), during a pre-defined period at the end of the allocation period. Transfer occurs at a user-defined daily rate (ML/day) and is conditional on there being sufficient residual capacity in the storage to accommodate this volume of transferred water and on the irrigation water not being required on the day in question.

2.2.4 On-farm water storage
Both the capacity of the OFWS and the catchment area from which runoff is received are model variables. The stored water volume ($V_{ofs}$) is calculated daily and takes into account the various elements of the storage water balance. Inflows include water sourced from catchment runoff ($R_{o}$), direct rainfall capture ($R_{f}$), recycled tailwater ($T$), water from other more regular sources such as springs and sewage treatment plants (X) and allocation (At) and OOA (Ot) water transferred from the scheme to the storage. Outflows are from surface evaporation ($E_{ofs}$), irrigation of caneland (I), seepage losses (S) and overflow (Ov). The mass balance can be expressed in equation form as:
Daily catchment runoff from non-sugarcane areas is estimated using the QDPI model, RUSTIC (Runoff, Storage and Irrigation Calculator) (QDPI 1994). The method adopted in RUSTIC for predicting runoff is that developed by the United States Department of Agriculture (USDA 1971). This method requires selection of a ‘KII factor’ which takes into account the prevailing soil type, land use / vegetation type and the general condition of the catchment. In Dam Ea$y, the catchment can be divided up into multiple sub-catchments each defined by an area (ha) and a ‘KII factor’. The USDA method for predicting runoff from daily rainfall totals has been used extensively in farm supply projects throughout Queensland and has reportedly performed well. While far from perfect, it is regarded as being as good as any of the relatively simple methods available (Horton and Jobling 1992). Runoff (mm) from the sugarcane production area is estimated by APSIM and then multiplied by the caneland area (ha) to give the total caneland runoff. Estimated runoff from all sugarcane and non-sugarcane sub-catchments is then summed and discharged into the OFWS.

The storage dam can be located either within or external to the catchment for which runoff is being calculated. If the irrigated caneland area is to be included within the catchment for the on-farm storage, then an adjustment can be made to the catchment area to reflect this additional source of rainfall runoff.

The ‘shape’ and volume (V, ML), depth (D, m) characteristics of the OFWS are defined by the following relationship, as defined by Watts (1986):

\[ V = a \times D^b \]

The constant ‘a’ defines the shape of the OFWS. Constant ‘b’ relates the surface area to depth and volume attributes of the OFWS.

Direct rainfall capture by the storage (R_{ofs}, ML/day) is estimated from the daily rainfall (R, mm) and the current water depth (D),

\[ R_{ofs} = \{(a \times (D + R))^b \} - \{(a \times D^b )\} \]

Evaporative loss from the storage (E_{ofs}, ML/day) is assumed to be 70% of that from a Class A pan (Pratt et al 1974). Pan evaporation (E_{pan}, mm) is taken to be equivalent to that from a bare, saturated soil, calculated using algorithms from the CERES-Maize model (Jones and Kiniry 1986) and based on minimum (T_{min}, °C) and maximum (T_{max}, °C) temperatures, incident radiation (R_n, MJ/m^2) and the soil albedo (\( \alpha \)):

\[ E_{ofs} = \{(a \times D^b )\} - \{(a \times (D – (0.7 \times E_{pan} / 1000))^b )\}, \text{ where} \]
\[ E_{pan} = R_n \times 23.8846 \times (0.000204 - (0.000183 \times \alpha )) \times (29 + (0.6 \times T_{max} + 0.4 \times T_{min})) \]

Seepage losses (S, ML/day) depend on the depth of water in the storage (D, metres) and the permeability (k, m/day) of the soil underlying the storage. Two storage lining types have been incorporated in the model: (i) a deep, homogeneous, uniformly permeable underlying soil or (ii) a thin layer of low permeability material (thickness t, metres) sealing the storage and overlying a deeper material of higher or contrasting permeability. The equations for seepage loss come from Horton and Jobling (1992). In the case of design (i):

\[ S = \{(a \times D^b )\} - \{(a \times (D – k \times D^b )\} \]

In the case of design (ii):

\[ S = \{(a \times D_1^b )\} - \{(a \times (D_1 – (k \times (D_1/t))^b )\} \]
Overflow occurs when the capacity of the storage is exceeded. The model reports the seasonal overflow volume (ML), the number of overflow events of one or more days in duration, and the total number of days that the storage was overflowing. Similarly, the ‘efficiency’ of the storage is reported as the number of events of one or more days in duration in which the stored water volume exceeds a specified fraction of the storage capacity. The total number of days during the season when the storage is full is also reported.

2.2.5 Dual storage designs
In addition to simulating single storages, Dam Ea$y can also be used to simulate dual storage designs such as sump and ‘ring tank’ (above ground storage) combinations, popular in some irrigated production areas of Australia. With these designs, the sump collects all of the catchment runoff, which is subsequently pumped into the ring tank at a user-defined rate (ML/day). Water stored in the ring tank is then used for irrigation purposes. The remaining elements of the water balance for the sump and ring tank are calculated in the same way as for the single storage option. The transfer of runoff into the ring tank means that the sump has more residual capacity in the event of a subsequent runoff event, thus minimising overflow and improving storage efficiency. Furthermore, the ring tank can be constructed from the ‘fill’ removed when digging the sump, thus saving on construction costs.

2.2.6 Irrigation rules
The model is configured so that on any given day and depending on availability, out of allocation water is the irrigation source of first choice, followed by stored water and then allocated water. OOA water is used first because it is only accessible for limited periods, and hence the farmer will want to make the most of this resource while it is available. Stored water is used in preference to allocated water so as to pass evaporation losses onto the scheme provider.

In order for an irrigation event to take place, a number of conditions must be satisfied.

a) The daily plant extractable soil water over the maximum rooting depth, expressed as a fraction of the maximum possible plant extractable soil water (SW_{max}), must be less than (or equal to) a specified critical minimum (F_{crit}). The magnitude of the associated soil water deficit is a function of the soil type and rooting depth.

b) A farmer will normally take several days to irrigate the entire farm over what is referred to as an irrigation ‘cycle’. Given that APSIM is a single paddock model, all irrigation is assumed to be applied on the first day of the cycle with no subsequent irrigation until the defined cycle length has been completed.

c) In many locations, irrigation water (typically allocated scheme water) is withheld for a certain period of the year in order to conserve limited irrigation supplies for high demand or water sensitive growth stages, and/or as a strategy for increasing rainfall efficiency. This is captured in the biophysical model, through the specification of irrigation-free periods, as defined by a start and end date, and an F_{crit} value.

d) Furthermore, in irrigated sugarcane production, water is usually withheld prior to harvest to make the field trafficable for harvesting operations, and to raise both the sucrose content of the cane and sucrose yield. The duration of this ‘drying-off’ period can be specified by the model user.

e) There must be sufficient water available to meet the minimum volume requirements for irrigation from one of the three possible sources (see below).

2.2.7 Irrigation amount
The ‘effective’ irrigation (I_{effect}) is that which enters the profile and is potentially available for crop uptake. The amount of ‘applied’ irrigation water (I_{app}) is larger than I_{effect} to account for irrigation losses associated with application inefficiencies (E). This inefficiency is expressed as a fraction of applied irrigation.

\[ I_{app} = \frac{I_{effect}}{E} \]

In order to maintain water balances for each of the irrigation sources, this applied irrigation is converted to ML (I_{ML}) of applied irrigation using the irrigation area (A_{irr}).

\[ I_{ML} = \frac{(I_{app} * A_{irr})}{100} \]
In the event that the remaining allocation volume is less than \( I_{\text{app}} \), a smaller volume is applied that reduces the allocation volume to zero, whereupon it remains until the next allocation is issued.

In order to represent the fact that a farmer will not normally pump all of the water from an OFWS, a minimum OFWS volume \( V_{\text{min}} \) is specified in the model at which irrigation ceases. As the stored volume declines, the amount available for irrigation from the OFWS (above \( V_{\text{min}} \)) may fall below \( I_{\text{app}} \). An amount of irrigation \( I_{\text{red}} \) less than \( I_{\text{app}} \) will be applied from the storage provided that it exceeds a specified minimum \( I_{\text{min}} \).

\[
I_{\text{red}} = \min(I_{\text{min}}, \left\{ \frac{(V_{\text{ofs}} - V_{\text{min}}) \times 100}{A_{\text{irr}}} \right\})
\]

This justifies the commitment of irrigation equipment and labour resources and prevents numerous small irrigation events from the OFWS. If allocation water remains then the outstanding irrigation requirement (or part thereof) will be met from this source.

In order to reduce the runoff losses associated with inefficient irrigation practices, runoff (or tailwater) is often collected in the storage and then reused as irrigation water. In the model, it is assumed that the tailwater is returned directly to the OFWS (if it exists), even though in reality it may be held in a separate tailwater storage. The amount recycled is expressed as a percentage of the total applied irrigation water.

**2.2.8 Other features**

By establishing this model within the larger framework of APSIM, the simulation capability is extended to encompass the broader crop production system. Within this framework, it is possible to configure detailed management events relating to the cropping cycle (ie species, planting dates, harvesting dates), tillage practices (ie implement used, depth and timing), crop residue management (ie timing, depth and fraction of residues incorporated) and fertiliser management (ie amount, type, timing, depth) (Lisson et al. 2000). The climatic conditions for a particular site are captured through the use of site specific, historical, daily climate data. Soil characteristics relating to nitrogen, organic matter and water holding capacity are captured in fully parameterised soil files.

**2.3 ECONOMIC MODEL**

The economic model in Dam Ea$y provides the operator with an ability to evaluate OFWS and irrigation investment options, based on the following key criteria: net present value (NPV) of the investment, internal rate of return (IRR) on capital invested and annual net cash flow over the life of the investment. The economic model has been developed from the spreadsheet model of Schuurs and Wegener (1999) which incorporates OFWS and reticulation capital and operating costs. Economic calculations performed in Dam Ea$y are based on the simulated crop and water storage yields from the biophysical database. The biophysical database supplies crop yield and irrigation totals for the three irrigation sources associated with selected system designs. Additional physical and financial parameters characterising the farm must also be specified by the operator of Dam Ea$y. These include the farm size, cane area lost to the OFWS structure, commodity price, scheme allocation, scheme allocation water charge, OOA water charge, total OFWS set-up costs, reticulation system and associated operating costs, tax regime, financing arrangements for the OFWS (ie using existing or borrowed funds), duration of investment period, discount rate, and other fixed and variable cane production costs. Default data sets are supplied for many of these parameters. OFWS investments can be assessed in Dam Ea$y with or without inflationary effects (ie in nominal or real terms).

**2.3.1 Budgeting approaches for investment analysis**

When analysing an OFWS investment, the key question for a farmer is ‘with what do I compare the performance of a proposed OFWS investment?’ Dam Ea$y performs calculations of NPV, IRR and annual cash flows using only additional costs and income above the ‘do nothing’ option (ie a benchmark design), which represents the existing situation on the farm (this could be either irrigated or non-irrigated production). This is referred to as a partial cash flow budget. The user nominates a proposed OFWS investment scenario and the benchmark scenario. The additional income from the OFWS investment is generated from the extra yield produced in response to increased water supply. The additional costs attributable to the OFWS investment include capital costs (ie OFWS construction and irrigation equipment), irrigating equipment operating costs and water charges, and any additional
overhead costs. Annual net cash flows are also presented as separate, actual annual net cash flow budgets, for both the benchmark and proposed OFWS design.

### 2.3.2 Net present value

Both the NPV and IRR are based on a partial discounted cash flow budget. A grower/advisor can use net present value (NPV) to assess the total net benefit of an OFWS over the entire investment period. The NPV calculation sums the discounted, additional costs and benefits involved in the OFWS investment compared to the ‘do nothing’ design for each year of the investment period. For a farmer, investment in an OFWS is acceptable when, subject to budget constraints and other relevant conditions, the NPV is positive. The NPV of an OFWS investment over \( n \) years can be calculated from the following equation, where \( B_t \) and \( C_t \) are the additional benefits and costs in year \( t \), and \( r \) is the discount rate:

\[
\text{NPV} = \sum_{t=0}^{n} \frac{(B_t - C_t)}{(1+r)^t}
\]

Discounting is a calculation that converts future cash flows into present-day values to enable a sum of money received today to be compared with a sum of money received in the future. This process captures an investor’s time-preference for money, i.e. a dollar received today is worth more than a dollar received at some time in the future. Put another way, discounting means deducting from an investment’s expected earnings the amount that the investment funds could earn in the most profitable alternative use (also known as the opportunity cost). An appropriate discount rate could be the current market interest rate available for a low volatility investment for a similar amount of funds and for a similar period (Makeham and Malcolm 1993). If the NPV of the investment after discounting is positive then this investment is better than the alternative earnings.

Because the discounting process ‘erodes’ the value of benefits received in the future, the timing of the OFWS investment will impact on the NPV. For example, an OFWS investment coinciding with a sequence of ‘good’ years followed by ‘bad’ years will have a higher NPV than if the sequence of good and bad years was reversed. Dam Ea$y allows for the assessment of risk associated with the timing of the investment. The biophysical database contains simulated crop and storage yields over 40 years, enabling a distribution of possible NPVs to be generated by calculating NPVs of OFWS investments with different starting years.

### 2.3.3 Internal rate of return

A related measure of profitability is the internal rate of return (IRR) on the capital invested in the OFWS. The IRR in Dam Ea$y is the interest rate which just balances the present values of additional income and additional costs. IRR is the discount rate that makes the net present value equal to zero and for this reason, is also known as the break-even discount rate. The IRR can be interpreted as the maximum interest rate that a farmer could afford to pay for the funds to carry out the investment and not lose any money. A decision rule is to accept investments in which the IRR is greater than or equal to the discount rate used to calculate the NPV of the investment. The IRR can also be thought of as being like the average annual return on capital invested in the project. The IRR return refers to the return over the whole life of the investment. As for NPV, a distribution of IRRs can be generated by calculating IRRs of OFWS investments with different starting years. The internal rate of return is the discount rate \( r \) such that:

\[
\sum_{t=0}^{n} \frac{(B_t - C_t)}{(1+r)^t} = 0
\]

While IRR is a straightforward measure and a practical statistic, which gives some idea as to whether an investment is worth undertaking, it does come in for some serious criticism at a rigorously theoretical level. It should therefore be used only as supplementary to the NPV (Makeham and Malcolm 1993, p.317; Department of Finance 1991, pp.117-118).

### 2.3.4 Annual net cash flow

NPV and IRR are appropriate measures to summarise economic feasibility over the entire duration of an investment. However, they do not provide information about year-to-year income variability within the investment period. For example, an investment with a positive NPV could be rejected if cash flow
variability is considered too high. Dam EaSy allows operators to assess financial feasibility by comparing annual and cumulative net cash flows for various investment scenarios, based on actual or partial budgets. The basic annual net cash flow calculation for each OFWS design (and benchmark design) is: cash income from cane production less cash variable and cash overhead costs less other cash used (such as loan repayments, tax and personal drawings if these options are selected) for each year of the investment. An option is also available to view only additional annual net cash flows (ie additional costs attributable to the OFWS investment subtracted from the additional income generated for each year of the investment). Annual net cash flows can be examined with or without adjustments for tax deductions and payments, personal drawings, and repayments on borrowed capital. The debt repayment is calculated as an annuity (annualised cost) based on the capital cost of the investment. If the operator does not choose to examine net annual cash flows incorporating a debt repayment, it is assumed that the capital costs are incurred in the first year of the investment period.

3. CASE STUDY: SUGARCANE PRODUCTION AT BUNDABERG

3.1 BACKGROUND

Sugarcane production in the Bundaberg region, Queensland, Australia (~28.9°S 152.4°E) is often limited by the availability of sufficient irrigation water. While the deficit between sugarcane demand and effective rainfall in this region is approximately 7.8 ML/ha (at 85% irrigation application efficiency) (Willcox et al. 1997), the average allocation per grower has in recent years been less than 4 ML/assigned ha. This is one reason why farmers are particularly interested in OFWS structures in this area. In the case study presented, our benchmark case assumed a sugarcane farmer operating with access to a small scheme allocation (3 ML/ha) and OOA water only. The key biophysical characteristics for the benchmark system were a 150 ha catchment, 50 ha assigned irrigation area, an irrigation system with 75% efficiency, and a ‘clay’ soil with 126 mm plant available water within the top 90 cm of the soil profile. In addition to the benchmark we have analysed three OFWS capacities (10, 30 and 50 ML), rainfed (‘water limited’) and fully irrigated (‘water unlimited’) systems for comparison.

The analyses are based on a representative cropping cycle for the Bundaberg region, in which the cultivar Q124 is planted on September 1 to a depth of 15 cm. This plant crop is harvested on September 20 of the following year. Subsequent ratoon crops are harvested over the next four years on days 248, 232, 227 and 217, respectively. Crop residues are retained after each crop with full incorporation to a depth of 40 cm at final harvest. Nitrogen fertiliser rates were set to be non-limiting.

Water for irrigation is obtained from the Burnett River Scheme, with the allocation period set from 1 July to 30 June of the following year with no carry-over of unused allocation water allowed. OOA within this scheme is made available when the daily flow rate over the Burnett river barrage exceeds 2400 ML for a minimum period of seven days. Each system described above was simulated over a 40-year period, using Bundaberg GPO weather station data and river flow records from 1957 to 1997. The climate data was derived from a combination of recorded weather station data, in-filled with data from generated historical meteorological surfaces (Courtesy of the Bureau of Meteorology and the Data Drill, Queensland Centre for Climate Applications, 1998).

Table 1 lists the key economic parameter settings for the sugarcane farm used in the case study. It is assumed that the OFWS was constructed without loss of production area. For this specific example, OFWS construction costs (ie earthworks, underground costs and pumps) are assumed to be financed with the grower’s own funds. Borrowed funds repayments are therefore not included in the net annual cash flow calculation. The economic analysis is presented in real terms ie without the effects of inflation. For the taxation calculation, it is assumed that the farm business has two partners subject to personal income tax rates that applied for the 1999-2000 financial year. As permitted by the Australian Income Tax Assessment Act, capital expenditure on the OFWS is tax deductible. The deduction is claimed in equal installments over 3 years. Income from cane production in the Australian sugar industry is based on the cane payment formula, where CP is the cane price ($/t), CCS is the commercial cane sugar content, SP is the sugar price ($/t), and HL is the cost of harvesting and levies ($/t):

\[
CP = \{SP \times 0.009 \times (CCS - 4) + 0.608\} - HL
\]
Table 1. Key parameter settings for the economic model

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Setting</th>
</tr>
</thead>
<tbody>
<tr>
<td>OFWS construction cost</td>
<td>$2500/ML (10ML), $2000/ML (30ML), $1500/ML (50ML)</td>
</tr>
<tr>
<td>OFWS pump and underground works costs</td>
<td>$20000</td>
</tr>
<tr>
<td>Pumping cost (scheme to OFWS)</td>
<td>$25/ML</td>
</tr>
<tr>
<td>Water charges(^1)</td>
<td>$38.76/ML</td>
</tr>
<tr>
<td>Cost of installing reticulation equipment(^2)</td>
<td>Nil</td>
</tr>
<tr>
<td>Sugar price</td>
<td>$300/t (assumed constant)</td>
</tr>
<tr>
<td>CCS</td>
<td>14.3</td>
</tr>
<tr>
<td>Harvesting and levies</td>
<td>$6/t</td>
</tr>
<tr>
<td>Discount rate (opportunity cost of capital)</td>
<td>6%</td>
</tr>
<tr>
<td>Investment period</td>
<td>20 years</td>
</tr>
<tr>
<td>Operating cost for reticulation(^3)</td>
<td>$41/ML</td>
</tr>
<tr>
<td>Other variable production costs(^4)</td>
<td>$712/ha</td>
</tr>
<tr>
<td>Fixed production costs(^5)</td>
<td>$14 750</td>
</tr>
</tbody>
</table>

\(^{1}\) Current scheme water charges for allocation and OOA (Passmore 1999).
\(^{2}\) An existing winch reticulation scheme is assumed.
\(^{3}\) Includes repairs and electricity costs.
\(^{4}\) Includes other input costs such as fertiliser, cultivation costs etc.
\(^{5}\) Fixed costs are also known as ‘overheads’ and include insurance, registrations etc.

3.2 CASE STUDY RESULTS

3.2.1 Biophysics

In the absence of an OFWS, the combined irrigation from the allocation and OOA sources (195 ML averaged across the 40-year simulation) met ~50% of the irrigation demand under unlimited conditions (393 ML). The addition of OFWSs of 10 ML, 30 ML and 50 ML capacity increased this irrigation reliability to 60%, 72% and 81%, respectively. This improvement in reliability with increased storage capacity can be attributed to gains in storage efficiency, as more of the available runoff is held by the OFWS. That is, of the 402 ML (40-year average) of runoff generated by the catchment, the proportion lost as overflow decreased from 92% for the 10 ML storage, to 72% for the 50 ML storage. Storage size also influenced the efficiency of allocation usage. Given the preference for irrigating with OFWS water before allocated water, we would expect a decline in allocation irrigation with increasing OFWS size. Indeed, allocation irrigation declined from 150 ML in the absence of an OFWS, to 143 ML with a 50 ML OFWS. The modest nature of this decline reflects the fact that the irrigation supply from OFWS and out of allocation sources, for each of the OFWS-based systems, was substantially less than the irrigation requirement under unlimited conditions. Hence, most of the nominal allocation was required in each system.

Figure 4 depicts 40-year cumulative distribution frequency (CDF) plots of cane fresh weight for each of the six systems. This presentation format allows risk to be considered in a quantifiable sense. For example, a grower assessing the 10ML storage can identify that 25% of the yields achieved in the 40-year simulation period fell below 100 t/ha. As expected, cane fresh weight increased with greater availability to irrigation. Under rainfed production, seasonal yields ranged from 23 t/ha to 137 t/ha with a median yield of 81 t/ha (corresponding to a cumulative probability of 0.5). Under fully irrigated conditions, yield ranged from 126 t/ha to 183 t/ha with a median yield of 160 t/ha. The reduction in the yield range between these two extremes demonstrates the impact of irrigation in reducing the effects of season-to-season rainfall variability. Interestingly, the yield range (maximum minus minimum) for the OFWS-based systems was relatively insensitive to storage size. This reflects the fact that in low rainfall years, when yield tends to be small, catchment runoff will also be small and the larger storages will be under-utilised. At the other extreme, large yields will tend to occur in high rainfall years, when the efficiency of all storages is likely to be reduced and the irrigation demand will be low.
3.2.2 Environmental considerations

Tailwater recycling, deep drainage and nutrient leaching are some of the more critical environmental issues that need addressing when installing and managing any form of irrigation, including OFWS based irrigation systems. Figure 5 shows the cumulative distribution frequency for deep drainage for the Bundaberg case study. These curves show typical trends with the least amount of water draining from the water limited rainfed conditions, and increasing amounts of water draining from the wetter systems.

What is somewhat counter intuitive however, is the nitrate leaching results shown in Figure 6. These results show that the least amount of nitrate leaching occurs with the larger OFWSs and fully irrigated systems, and that most nitrate leaching occurs in the rainfed systems, where lack of water limits crop growth. The reduction in crop growth will result in less nitrate uptake by the crop as compared with the ‘wetter’ treatments, allowing accumulation of nitrate in the soil profile, and enhanced leaching during subsequent rainfall events. Similar results have been reported previously by Verburg et al. (1996) and highlight the need to adjust nitrate fertilisation rates to match irrigation management practices and crop needs. These results also highlight the value of tools such as Dam EaSy that allow assessment of both economic and environmental implications of alternative irrigation management practices, and suggest
that greater effort needs to be invested in evaluating these findings under field conditions. Reasons for this are that the simulation analyses presented here represent efficient irrigation strategies where differences in the nitrate leaching response are associated with differences in nitrate uptake by the crop. It is possible that high frequency and/or inefficient irrigation practices, implemented within the ‘wetter’ systems involving larger OFWSs could lead to increased deep drainage and increased nitrate leaching.

![Figure 6. Cumulative distribution frequency plots showing nitrate leaching over the 40 year simulation period for the rainfed, benchmark (no OFWS), three OFWS-based systems (10, 30 and 50 ML), and full irrigation systems.](image)

3.2.3 Economics

3.2.3.1 Net present value: Using forty years of data to analyse an investment period of 20 years, it was possible to calculate 20 NPVs for each of the three OFWS-based systems for this Bundaberg case study. NPV cumulative distribution frequency plots (not shown) were prepared for each sugar price/OFWS capacity combination. From these plots, NPV values corresponding to 25, 50 and 75% probabilities were estimated (Table 2).

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<td>30 ML</td>
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All storage capacities have positive NPVs and can be viewed as positive investments based on the variables specified in the analysis. NPVs for the 50 ML OFWS were always the largest of the three storage capacities, and hence this storage size appears to be the best investment option. Lower sugar prices significantly depressed the range of NPVs achievable for each system (Table 2). Such sensitivity testing of the investment is particularly pertinent in the current period of low sugar prices facing Australian sugar producers.

3.2.3.2 After-tax net annual cash flow: Annual after-tax net annual cash flow for the three OFWS-based systems and the benchmark system are displayed over the period from 1977-1996 in Figure 7. This is one of the 20 possible investment periods that could be examined. These cash flows commence in the year after the purchase of the storage. This particular investment period generated the highest NPVs of $32 091, $68 145 and $96 884 for the 10 ML, 30 ML and 50 ML OFWS-based systems, respectively.
Net annual cash flows were generally lowest under the OFWS-free system and highest for the 50 ML OFWS system, however cash flows for all OFWS systems showed volatility reflecting cane yield variability associated with these systems. The relative insensitivity to OFWS capacity in 1989 and 1992 can be attributed to high rainfall in these years (1609 mm and 1530 mm, respectively) and hence a reduced reliance on irrigation. Similar insensitivity was apparent in 1983 (1323 mm rainfall) but the net annual cash flow was much lower. This is attributed to the poor distribution of rainfall in this year, with over 50% of the seasonal total falling in just eight days, resulting in substantial OFWS inefficiency (across all capacities) due to overflow losses.

4. CONCLUSION

In deciding whether or not to invest in an OFWS, farmers and their advisors are confronted with a plethora of questions relating to the biophysical, management and economic implications of such an investment. Decisions are further complicated by year-to-year climate fluctuations, and hence the yield distribution over time. This, coupled with temporal variability in commodity prices, has a strong influence on the year-to-year return on OFWS investment. The adoption of a modelling approach such as that employed in Dam Ea$y offers a means of capturing and interpreting some of this complexity. The inclusion of a database comprised of pre-run biophysical simulation output for a large range of farm systems, linked directly to an economic model in which there is flexibility in the setting of key economic variables, provides a rapid means of analysing a large range of different scenarios. Running the biophysical simulations over a 40-year period using historical climate data captures the influence of temporal climatic variability on yield and the associated investment implications.

The case study analysis reported in this paper demonstrated a small part of the Dam Ea$y capability. It is not intended that the results of the case study be used to form recommendations for the Australian sugar industry on best options for OFWS investment in the Bundaberg district. Rather, the Dam Ea$y economic output, characterised by substantial climatic and sugar price driven income variation for even a single OFWS design, supports the conclusion that generalised recommendations are not appropriate. Furthermore, while the biophysical model captures the most important processes and events in a cropping system, there are some yield-limiting constraints such as weed competition, disease, insect damage, waterlogging and severe weather effects, which are not captured by the model. Hence, Dam Ea$y cannot provide the ‘ultimate solution’. However, it can serve as a powerful tool to assist individual operators make their own assessment of what investment option would best suit their particular farm characteristics, attitudes to risk and other personal preferences.
5. ACKNOWLEDGEMENTS

The authors would like to thank members of the Bundaberg OFWS Working Group for their valuable contribution to the development of Dam Ea$y. We would also like to thank the Agricultural Production Systems Research Unit (APSRU) for providing APSIM and APSIM-Outlook, specifically Dean Holzworth for his assistance with the development of the Dam Ea$y software and Stuart Brown for helping with database creation.

6. REFERENCES


6. MANAGING SALINITY AND DRAINAGE IN IRRIGATED SYSTEMS
SALINITY AND DRAINAGE IN IRRIGATED SYSTEMS

KL Bristow

1. INTRODUCTION

Irrigation can and has been used to great advantage to supplement low and variable rainfall in order to improve production and profitability of a range of agricultural crops, including sugarcane. In most cases, irrigation will also result in changes in the biophysical functioning of irrigated areas compared with the original natural systems, especially in terms of the local and regional water and solute (salt, nutrient and chemical) balances. If appropriate steps are not taken to manage these changes effectively they can lead to unwanted environmental impacts and, in the longer-term, degradation of soil and water resources and loss of productivity of irrigated land. Potential impacts include rising water tables, water logging, salinisation, and ground and surface water pollution. In general, it is to be expected that wherever there is irrigation there will be 1) a ‘salinity problem’ that needs to be managed, 2) increased surface drainage that may impact on surface water quality, and 3) increased deep drainage that may result in water logging and increased risk of salinisation as well as increased risk of groundwater pollution. In some districts along the Queensland coast where irrigation draws heavily on groundwater as a source of irrigation water, saltwater intrusion can also be a problem when groundwater levels are allowed to fall too far. Dryland salinity, which usually occurs in the upper catchment areas upstream of irrigated areas, can also be of concern as it can affect the quality of river water that enters and serves as the source of water for irrigated areas. All these issues highlight the need for a thorough understanding of the many interacting factors involved in irrigation and the need for a systems approach to the establishment and management of an irrigation system. A key aim in any irrigated system, whether at a farm, region or catchment scale, is to minimise unwanted on- and off-farm impacts, especially those associated with salinity, deep drainage and surface drainage.

2. SALINITY

There are two main processes of salt accumulation in the root zone of irrigated crops, one is due to accumulation of salt introduced via the irrigation water and the other is due to accumulation of salt supplied by capillary upflow from shallow saline water tables (Christen and Ayars 2001). For productive irrigation farming to take place, adequate leaching and drainage are necessary to remove the excess salt left in the root zone after soil evaporation and transpiration by the crop (Hoffman 1985).

2.1 IRRIGATION WATER QUALITY AND CROP RESPONSE

All irrigation water contains at least some dissolved mineral salts so from the outset it is important to realize that irrigation requires effort to manage the salt as well as the water. The concentration and composition of the dissolved salts vary according to the source of the water. The main dissolved salts found in irrigation water are sodium (Na⁺), calcium (Ca²⁺) and magnesium (Mg²⁺), which are positively charged ions called cations, and chloride (Cl⁻), sulfate (SO₄²⁻), and bicarbonate (HCO₃⁻), which are negatively charged ions called anions. Potassium (K⁺) may be present in some irrigation waters but its concentration is usually kept low by interactions with soil particles, especially clay minerals. Carbonate (CO₃²⁻) is generally not a major component unless the pH of water exceeds 8.0.

Plants respond to the total dissolved solids (TDS) in soil water. The response is influenced by irrigation practices and by the concentration of TDS in the irrigation water. TDS represent the total milligrams of salt that would remain if a liter of water were evaporated to dryness, and is usually expressed in mg/L or ppm, which are numerically equivalent. Determining the salinity hazard of water therefore requires estimating the TDS of the water. Because there are no easy ways to do this, the more common way is to measure the electrical conductivity (EC) of the water by means of an EC meter and relate this to the TDS through a previously determined empirical relationship. A commonly used relationship is:

\[
\text{TDS (ppm or mg/L)} = 640 \times \text{EC (dS/m), or EC (dS/m)} = 1.56 \times 10^{-3} \times \text{TDS (ppm or mg/L)}
\]

Note that 1 dS/m equals 1000 µS/cm. Salinities of various waters are given in Figure 1.
Salt added = \( \rho_w \cdot V_i \cdot C_i \)

= (1000 kg_w / m_w^3) \cdot (irrigation \times 10^4 \frac{m_w^3}{ha}) \cdot (640 \frac{mg_s}{L}) \cdot (1 \frac{kg_s}{10^6 mg_s})

= 6400 kg_s / ha

= 6.4 tonne salt / ha

Here \( \rho_w \) is the density of water, \( V_i \) is volume of irrigation water added, and \( C_i \) is concentration of salts.

The key question is, or should be, “what happens to the salt?” If the salt is allowed to accumulate in the root zone the concentration will very quickly reach a level that is too high for optimum plant growth and yield. When this occurs the soil is said to be salinised. Irrigation must therefore be managed to ensure salt levels in the root zone do not become problematic for crop production.

### 2.2 CROP SALT TOLERANCE

Salts dissolved in soil water can reduce crop growth and yield in two ways, by osmotic influences and by specific ion toxicities. As salinity in soil water increases, the difference in concentration between constituents in the soil water and those in the root decrease, making soil water less available to the plant. It is not uncommon in salt affected soils to see ‘water stressed’ plants in wet soils. Salinity can also affect crop growth through the effects of chloride, boron, sodium and other ions on plants, called ion-specific effects, which occur when these constituents accumulate in the plant. Specific ion toxicity can cause leaf burn, impede nutrient uptake and impact in other ways to reduce crop growth and yield.

The ability of a crop to tolerate salt is not given by an exact value but depends on many factors such as type of salt, climate, soil conditions, and plant age. A linear function is commonly used to describe the relationship between yield and soil salinity, such that

\[ Y = 100 - B \times (EC_e - A) \]

where \( Y \) is relative yield (%), \( A \) is the maximum root zone salinity (in dS/m) at which 100% yield occurs, \( B \) is the slope of the linear relationship (the % reduction in relative yield per increase in soil salinity, in dS/m), and \( EC_e \) is the average root zone soil salinity (in dS/m). This equation is valid for \( EC_e \) values greater than \( A \).
Published data for sugarcane, which is rated as being moderately sensitive to salinity, provide a sugarcane specific equation

\[ Y = 100 - 5.9 \ (EC_e - 1.7) \]

This means that maximum yield (100%) is achieved in soils with average root zone salinities less than 1.7 dS/m and that yield is reduced as salinity increases, falling to around 86% of maximum when average root zone salinity is 4 dS/m (Figure 2).

![Figure 2. Relative yield of sugarcane as a function of average root zone salinity (after Hanson et al. 1993).](image)

**2.3 SALINITY EFFECTS ON INFILTRATION**

The salinity and sodium adsorption ratio (SAR) of irrigation water can have significant effects on the rate at which water infiltrates soils. The SAR is a value that quantifies the concentration of sodium (Na) in irrigation water relative to the concentrations of calcium (Ca) and magnesium (Mg). At a given SAR value, infiltration rate increases towards a maximum as the salinity (or electrolytic concentration) increases. However, at a given salinity, the infiltration rate decreases as the SAR increases. The effect of SAR is greatest in low salinity conditions. This phenomenon is caused by the response of clays in soil to SAR and salinity.

The clay fraction of soil consists of clay platelets, which are negatively charged and attract positively charged ions (sodium, calcium magnesium) in soil water. This causes greater concentration of these ions near the platelets and forces water to flow into spaces between platelets causing soil swelling and a reduction in infiltration rate. If the space between platelets becomes too large, dispersion occurs and the platelets then become lodged in the larger soil pores, causing further decreases in infiltration rate. Swelling and dispersion occur more readily in sodium-dominated soils and less readily in calcium dominated soils. Also, low electrolytic water causes greater swelling and dispersion than high-electrolytic water. Because of the many interacting factors involved, field trials may be necessary to define actual water quality effects on infiltration at a particular site.

Conjunctive water use, which involves mixing water containing too little salt with water such as saltier bore water, can improve the quality of irrigation water and thereby encourage aggregation of soil particles and improve water infiltration. A concern in some areas is that long periods of use of relatively saline irrigation water can enhance the hydraulic conductivity of the entire soil profile, leading to more porous soils over time. This can then result in excess deep drainage and rising water tables and associated problems.
It is clear from the above that there are several factors that need to be addressed in determining the suitability of water for irrigation. The types of questions that need to be asked include:

- Will crop yield be affected by the salinity of the irrigation water?
- Are concentrations of specific ions present in the water toxic to or likely to affect crop growth and yield?
- Will infiltration be affected by the irrigation water?

### 2.4 SALT MOVEMENT AND DISTRIBUTION IN SOIL

Although salt movement and distribution in soils are strongly influenced by soil water movement, there are several factors including soil type, type of salts, amount of water applied and method of water application that affect the ultimate salt movement and distribution in soils. For example, water infiltrating downward into the soil will tend to carry salt near the surface to deeper depths in the soil profile. When the water stops moving downward, the salts that have been carried to deeper depths may become redistributed and when evaporation rates are high, much of that salt could move back up towards the soil surface.

Long-term salt distributions reflect a complex interaction between irrigation water salinity, the amount of leaching, and the redistribution of water and salts through evapotranspiration. Where leaching is occurring, long-term distributions show relatively low levels of soil salinity near the surface, reflecting the relative salinity of the irrigation water. In some situations soil salinity can increase with depth, with the amount of increase depending on the amount of leaching and on the salinity of the irrigation or leaching water. When the amount of irrigation is insufficient to move the salts deep down into and below the root zone, the salt distribution is usually highest near the surface and then relatively constant with depth. The higher concentration near the surface reflects the accumulation there due to evapotranspiration.

Because salt movement is strongly influenced by water movement, salt distributions under different irrigation methods tend to reflect the water flow patterns generated by the particular irrigation method used. Typical salt distributions in various irrigated situations are summarised in Figure 3.

Figure 3. Typical salt distributions in A) furrow irrigated systems, B) Overhead irrigation and rainfall dominated systems, C) subsurface trickle irrigation systems, and D) situations influenced by shallow saline water tables (after Nelson 2001).
In surface drip irrigation, salinity tends to be lowest directly beneath the plant row and emitter, gradually increasing with distance from the emitter and highest midway between emitters. Rainfall will in general work to move salts from near the soil surface deeper into the soil profile.

Salt patterns can be quite different in subsurface drip, with very high soil salinity levels near the soil surface above the emitter. Salinity levels tend to decrease with depth through the soil profile and increase with horizontal distance from the emitter. Salinity is lowest directly beneath the drip tape. Because subsurface drip does not allow leaching of salts that accumulate above the emitter, care is needed to ensure rainfall does not leach salts downward into the root zone to the detriment of shallow rooted crops.

In furrow irrigation, the water tends to move downwards below the furrow and laterally into the mound and upward by capillarity into the top of the mound. This means that when every furrow is irrigated, salts can accumulate near the centre and top of the mounds. When alternate furrows are irrigated, salts will tend to accumulate on the far side of the mound and cause fewer problems to the shallow roots of crops planted in the middle of the mound. Care is again needed to minimise accumulation of salts in the root zone and just how difficult this will be depends to some extent on the interactions between rainfall and irrigations.

In overhead irrigation, water is usually applied to the whole soil surface and infiltrates downward taking salts with it to deeper in the profile. The actual distribution of salts will depend to a large degree on the uniformity of water application.

2.5 SALT CONTRIBUTIONS FROM SHALLOW WATER TABLES

Salt distributions in the root zone can also be affected by shallow water tables, where upward flowing saline water can cause salt to accumulate in the root zone. The rate of upflow is affected by soil texture, depth to the water table, root depth, groundwater salinity, soil water depletion and climatic conditions. When water tables are shallow the rate of upward flow is controlled largely by climatic conditions, which affect crop transpiration and soil water evaporation. When water tables are deep the upward flow is controlled more by the soil properties. As an example, upflow rates are generally slower in sandy soil than in clay loam soil. Soil salinity near the soil surface will tend to reflect that of the irrigation water, while at depth it will tend to reflect the salinity status of the shallow groundwater. Just how much salt accumulates in the root zone will depend on the salinity of the shallow groundwater and on the degree of upward flow. Obviously the more groundwater contributes to evapotranspiration during a season the more salt accumulates in the root zone. Water table contributions to seasonal crop water use can be substantial if the groundwater is of good quality and are discussed further by Sweeney et al. (2002).

2.6 LEACHING FRACTION (LF)

Managing the salt status of the root zone in irrigated systems is clearly an important task and although the theory is well worked out it remains a challenge in practice. Salinity of the root zone is affected by the salinity of the irrigation water and by the leaching fraction (LF), which is the percent of infiltrated water that percolates below the root zone. It can be defined as

\[ LF = \frac{100 \ D_d}{D_a} \]

where \( D_d \) is the amount of water draining below the root zone and \( D_a \) is the amount of irrigation applied minus the surface runoff.

Both the salinity of the irrigation water and LF define the average soil salinity of the root zone and the distribution of salts in the root zone. For a given irrigation water salinity the average root zone salinity will be relatively high for a low LF. It will decrease as the LF increases, approaching the salinity of the irrigation water for very large LFs. The attainable LF is the smallest average LF required under a given set of conditions to satisfy crop needs and control salinity. The actual leaching fraction at any location in a field depends on how uniformly water is applied. The less uniformly the water is applied, the greater the differences in the amount of water received by different parts of the field and the higher the average LF needed to control salinity in those parts of the field receiving the least amount of water.
Experiments on a range of crops have shown that there is a minimum LF required for maximum yield. It has also been shown that crop yield appears to respond to average root zone salinity and that it is not greatly affected by the salt distribution in the root zone, provided there is sufficient soil water in the lower salinity part of the root zone to meet the crops needs for water. This probably would be the case for sugarcane as well.

The leaching requirement (LR) is the LF (the amount of excess water) needed to keep the root zone salinity level within that tolerated by the crop. This requirement is determined by the crop’s tolerance to salinity and by the salinity of the irrigation water. Traditional methods for estimating LF and LR assume that salt in the irrigation water is the sole contributor to root zone salinity. Where saline shallow water tables are present they can contribute substantial amounts of water to crop water use and hence substantial amounts of salt to the soil profile. Alternate methods are required for determining LF and LR in these cases (Hanson et al. 1993).

LFs are used to ensure that salts do not accumulate in the root zone but, if inappropriately applied, the LF could be one of the main causes of rising groundwater in many irrigated areas. This is because the inclusion of LFs can lead to large quantities of water draining below the root zone (Bristow et al. 2001). This water is usually not considered ‘wasted water’ and there is currently discussion as to whether this additional water applied for deliberate leaching of salts should be considered as “irrigation water beneficially applied” (Barrett Purcell and Associates 1999). Based on this, LFs are thought to be of benefit at the farm enterprise level. What has not been adequately addressed when applying LFs is the effect the ‘excess irrigation’ may have on leaching of soil-applied nutrients and chemicals and the potential on- and off-site effects such as pollution of ground and surface waters. Impacts on the broader groundwater systems and the potential for causing rising water tables have not been adequately considered and these issues warrant much greater attention than they have received to date.

Given the potential problems associated with LFs, perhaps the whole concept needs rethinking, at least in those situations with questionable soils and geohydrology. It could be better to match irrigation with crop water needs and rely on rainfall and inevitable inefficiencies in irrigation management to ensure a net downward movement of salts out of the root zone. If irrigation water quality is such that salt accumulation still occurs, then it suggests that irrigation will not be sustainable unless adequate subsurface drainage and appropriate management of the drainage waters are implemented. The choice therefore seems to be between careful scheduling to meet crop water needs with no specific LF or application of a LF and implementation of proper management of the deep drainage. Either way it is important that the irrigation be properly scheduled and, to achieve this, irrigation water must be available to each irrigation field as and when it is needed.

3. DEEP DRAINAGE

When irrigating one must always consider the quality and quantity of drainage water moving below the root zone and its ultimate fate. In deep, freely draining soils the excess irrigation water that drains below the root zone may not appear to be a problem, at least in the short term. Over time though it may also result in rising water tables and, depending on local and regional conditions, water logging and salinisation. Figure 4, which summarises data for a particular bore in the lower Burdekin, provides an example of what can happen when deep drainage is ignored. This figure shows that prior to 1987 water table levels fluctuated around the 12-14 m depth and were relatively independent of seasonal rainfall variations. Following completion of the Burdekin Falls dam in 1987 and introduction of surface water into the Burdekin River Irrigation Area, there has been a steady increase in water table height to its present depth around 4 m. Salinity levels have increased as well and if left unchecked, both the rising water table depth and salinity could seriously affect the long-term viability of these irrigation districts.
Figure 4. Water level and electrical conductivity of a representative bore in the Burdekin River Irrigation Area from 1973 to 2000. Annual rainfall is included (after Bristow et al. 2001).

Where high water tables are present for lengthy periods in sugarcane, it has been shown that yield losses of up to 0.5 tonnes per ha per day can occur for every day the water table is within 0.5 m of the soil surface (McGuire et al. 1998). In these situations with shallow water tables it will, depending on the soil properties, be necessary to lower the water table depth to 1-2 meters below the soil surface to provide a rootzone environment suitable for optimising crop production.

Suitable drainage can be achieved using a grid or herringbone system of subsurface pipes or open drains. Buried perforated plastic drainage pipe is usually preferred as it does not interfere with farm layout and farm operation. Laterals are connected to a main and extended throughout the paddock. Laterals may be spaced at even intervals, spread evenly over the area to be drained, or located as needed. The laterals and mainline convey the drainage water to a discharge point, normally a gravity outlet discharging into an open drain ditch or sump. A pump is used to remove water from the sump and discharge it into a disposal facility. The water level of the open ditch (gravity discharge) or of the sump must be kept below the elevation of the drainage pipe to take full advantage of the drain depth.

Mole drainage is also an option, particularly in soils with clay contents between 30 and 50%. Sodic soils are not suitable for mole drains because they disperse when wet and the mole drains collapse. Mole drains are installed by pulling a ‘torpedo’ (usually 50 mm diameter) attached to the end of a blade through the soil at a depth of 0.5 to 0.75 m. For best results a plug or expander is used to follow the torpedo to expand and consolidate the channel formed by the torpedo. The maximum recommended length of mole drains is 200m and in most cases, mole drains will need to be renewed each crop cycle.

The spacing of subsurface drains will depend on the deep percolation rate, soil hydraulic conductivity, drain depth, maximum water table height above the drains if there is a water table, location of relatively impermeable lenses, etc. Designing a drainage system is not an exact process and drainage systems often need some modification following experience with the system after installation. The main ways to reduce the amount of deep drainage and improve performance of the installed drainage system are to 1) prevent over irrigation, and 2) improve uniformity of irrigation.

Over irrigation can be prevented by shortening the irrigation time, but achieving this depends on irrigation water being available as and when needed. Non-uniform irrigation causes more water to infiltrate in some parts of the paddock and if the least watered areas receive an amount of irrigation equal to the soil moisture depletion, other areas will receive excess irrigation leading to increased deep drainage and/or surface drainage.
Finding an appropriate way to dispose of deep drainage water is essential but, because of changing government and community expectations, is becoming more difficult. In the past, drainage water, no matter what its quality in terms of salinity or contaminants, was discharged into surface channels (irrigation canals, rivers, etc) and allowed to flow downstream and ultimately out to sea. That practice is now no longer acceptable and careful thought and management of drainage waters are needed to meet EPA guidelines and environmental goals.

Evaporation basins are being used increasingly in several irrigated industries around Australia to dispose of drainage waters. This could be a reasonable short-term solution but may prove not to be acceptable over the long term because of the accumulation of salts and other chemicals associated with irrigation drainage waters. Use of evaporation basins will also depend on the availability of suitable sites that must ensure there is minimal leakage from the evaporation basin and that any leakage is contained within the drained area. Jolly et al. (2000) provide detailed guidelines regarding the design, siting and management of evaporation basins.

4. SURFACE DRAINAGE

Applying irrigation by surface irrigation methods can also lead to tail-water discharge, which, apart from indicating an inefficient use of water, requires thought as to how best to reuse and/or dispose of the ‘excess’ tailwater. Changing expectations in terms of minimising unwanted environmental impacts have resulted in increased use of tailwater or recycling pits, which are used to capture and store the surface drainage water for later use. Tailwater recycling pits do not however guarantee efficient operation as excessive irrigation that leads to surface runoff probably also results in appreciable in-field deep drainage.

In some districts there is also an increase in the use of on-farm water storages to maximise the benefits of any water that becomes available (Lisson et al. 2002) during the season. Some irrigators have been able to adjust their farm layout so that nearly all their tailwater drains back into the on-farm water storage and in this way further increase the use and reuse of all available water. An issue that needs careful attention when attempting to maximise benefits in this way that involves combining the supply and drainage systems associated with irrigation is to ensure that accumulation of pollutants (salts, nutrients, pesticides, herbicides and other toxic elements) does not over time lead to new and more difficult problems to deal with, as currently being experienced in the central valley in California (Christen and Ayars 2002)

Another issue associated with irrigation that has come to light in recent years is the potential for surface drainage waters to contain high levels of sugars (mostly sucrose). This is most likely to occur in the first irrigations following harvest. When drainage waters with high levels of sugars flow into waterways their high biological oxygen demand (BOD) levels can deplete the dissolved oxygen (DO), sometimes to levels that are too low to support healthy fish (Bohl et al. 2002, Rayment and Bruce 2002). This has been found to occur following harvest of both green and burnt cane. New work is now underway which aims at improving the efficiency of cane harvesters so as to reduce losses of juice during harvest and at developing management practices that minimise potential adverse impacts. Until there is clarification of these issues it is recommended that irrigators use practices with minimum or zero runoff to streams or storages, at least for the first irrigation after harvest (Rayment and Bruce 2002).

The importance of developing and implementing appropriate drainage systems for both deep drainage and surface drainage, and for developing protocols for managing the drainage waters at the farm, scheme and regional scale, cannot be emphasised enough. It is worth heeding the message of Meyer (1997) in particular, who said that ‘the single most outstanding issue is that irrigation must be accompanied by drainage. Without adequate provision for surface and subsurface drainage, without confronting the need to reuse, store or change the form of irrigation effluents, namely excess water, salt, nutrient and chemicals, irrigation will not be allowed or be economically viable in the long term’.
5. ACKNOWLEDGEMENTS

This paper has drawn heavily on material, sometimes directly, from the publications of Hanson et al. (1993) and Holden (1998). These volumes are recommended for further reading.

6. REFERENCES


DISSOLVED OXYGEN AND IRRIGATION RUNOFF FOLLOWING CANE HARVESTING

GE Rayment and RC Bruce

1. INTRODUCTION

The community expects that land use, whether urban, industrial, recreational, horticultural, pastoral, agricultural or aquacultural, will have minimal adverse impact on water resources and the plants and animals dependent on them. Because of its public visibility and location along coastal Queensland and New South Wales, the Australian sugar industry is under pressure to minimise any adverse impacts it may cause on aquatic ecosystems. The industry is located in 29 major river catchments in Queensland and NSW. These waterways and their associated wetlands and lagoons provide critical habitat in the life cycles of many fish and other important aquatic species, including approximately 70-75% of the commercial fishery of coastal Queensland.

The health of aquatic ecosystems depends on complex and interdependent chemical, physical and biological components. However, most studies of water quality have concentrated on nutrients (especially nitrogen and phosphorus). The occurrence of fish kills in waterways in cane growing areas has focussed attention more recently on the importance of oxygen dissolved in water (DO) as several of these incidents have been linked to depleted oxygen levels in streams (Veitch 1999).

Many aquatic organisms (fish, invertebrates, and microorganisms) rely on DO for efficient functioning and survival. Exposure to low oxygen may cause slower growth rates, reproductive difficulties, stress, susceptibility to disease and in cases of severe depletion, premature death. Fish tend to be the least tolerant of aquatic fauna to low DO.

2. DISSOLVED OXYGEN IN WATER

The amount of oxygen present in water represents a balance between processes of addition and removal. The DO status also fluctuates through the diurnal cycle (24 hours). A typical daily trend is shown in Figure 1, with lowest DO concentrations expected around dawn or soon after. Concentrations of DO also vary with water depth, particularly when the water is slow moving or still, such as in deep irrigation tail-water storages. Indeed, water bodies are prone to stratify into distinct layers, separated during warm weather by a shear-plane called a thermocline. “Bottom” waters typically contain less DO than surface waters (Figure 2).

Figure 1. Expected variation in dissolved oxygen in an estuary across a 24 h diurnal cycle.
Water obtains most of its oxygen from surface contact with the atmosphere but oxygen is also produced in daylight hours by the photosynthesis of aquatic plants and algae.

Losses of oxygen occur through:
- Respiration of aquatic plants and animals
- Decomposition of organic matter by microorganisms. The oxygen required for this process is called biochemical oxygen demand (BOD).
- Chemical oxidation reactions involving elements such as iron and sulphur. The oxygen required for these processes is called chemical oxygen demand (COD).

Temperature and salinity also affect the amount of oxygen that can dissolve in water. The concentration of oxygen at which saturation in water occurs decreases predictably as temperature and salinity increase.

### 3. MEASURING AND MONITORING DISSOLVED OXYGEN

Three important measured parameters are DO, BOD and COD. Laboratory procedures are used for BOD and COD. Because the method commonly used for BOD takes five days, it is typically expressed as BOD$_5$. Interestingly, there is a strong correlation (Figure 3) between BOD$_5$ and total dissolved organic carbon in surface waters from recently harvested canefields in north Queensland.

For in situ monitoring of DO, hand held O$_2$ – temperature meters based on membrane-electrode technology are readily available and relatively inexpensive. Typical ranges are 0-40 mg/L of DO and 0 – 199.9% saturation, for temperatures up to 100°C. There are also more complex / comprehensive sensors that can be mounted in the water and programmed to read such things as DO, electrical conductivity (salinity), pH and temperature at predetermined intervals (e.g. each 15 min). Monitoring
data derived from such an instrument over an extended period in a sugar-growing area of south-east Qld are shown in Figure 4. Continuous monitoring of DO provides a realistic indication of the combined effects of diurnal variations, tidal influences, climatic “events”, and the “pressure” exerted by local land and water management.

![Figure 4. Time trends in mean dissolved oxygen, pH and discharge volume for Sandy Creek in the Pimpama sub-catchment for the period September-December 1998 (data of F. Gavine and E. Gardner).](image)

Preferred levels of DO, expressed as a percentage of the total that can dissolve in water (% saturation), vary across Australia and with the type of water-body. ANZECC 2000 guidelines for ecosystem protection in cane growing regions are in Table 1.

There are guidelines for DO, BOD₅ and COD for the protection of aquaculture species in freshwater and for DO in saltwater. DO levels > 5 mg/L apply to the two systems. Recommended guidelines for BOD₅ and COD in freshwater are < 15 and < 40 mg/L, respectively. For recreational purposes, a guideline value of > 80% saturation (= 6-7 mg/L) of DO applies.

<table>
<thead>
<tr>
<th>Ecosystem type</th>
<th>DO (% saturation – daytime)³</th>
<th>Lower limit</th>
<th>Upper limit</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sth-east Aust</td>
<td>Trop. Aust</td>
<td>Sth-east Aust</td>
</tr>
<tr>
<td>Upland river</td>
<td>90</td>
<td>90</td>
<td>110</td>
</tr>
<tr>
<td>Lowland river</td>
<td>85</td>
<td>85</td>
<td>110</td>
</tr>
<tr>
<td>Freshwater lakes/ reservoirs</td>
<td>90</td>
<td>90</td>
<td>110</td>
</tr>
<tr>
<td>Wetlands</td>
<td>No data</td>
<td>90 in Qld</td>
<td>No data</td>
</tr>
<tr>
<td>Estuaries</td>
<td>80</td>
<td>80</td>
<td>110</td>
</tr>
<tr>
<td>Marine</td>
<td>90</td>
<td>90 (in- &amp; off-shore)</td>
<td>110</td>
</tr>
</tbody>
</table>

³The median DO concentration for the period should be calculated using the lowest diurnal DO concentrations. As a performance indicator, measurements should be made under low flow conditions for rivers and streams and during low flow and high temperature periods for other ecosystems.
The organic matter loading of effluent water used on forested plantations in southern Australia is recognised as a possible hazard. Effluent has been allocated a low, medium and high hazard rating at BOD levels of < 40, 40 – 1000, and > 1000 mg/L. The limits were set because of concerns that excessive organic matter in the water can be a source of offensive odours, may clog equipment, induce anaerobic growing conditions, clog soil channels, and reduce water infiltration, soil permeability and soil aeration. Mean BOD₅ and COD concentrations in secondary-treated municipal effluent are typically in the range 17 and 50 mg/L, respectively. The Qld EPA limit for BOD of municipal effluent is 20 mg/L.

4. DISSOLVED OXYGEN AND THE SUGAR INDUSTRY

BOD₅ associated with discharges of sugar mill cooling waters that contain sugar juices and vapours have reached values of 20-100 mg/L. Fortunately, the discharge of such wastewater is well regulated and in control.

Water quality monitoring of major streams of sugar areas has shown that, in recent years, the majority of sites were within ANZECC guidelines for DO most of the time. However there were some instances where DO levels were low (<5 mg/L) and where cane growing seemed to be implicated as a possible cause (Wilhelm 2001, Rayment and Bohl 2002a).

It is now apparent that sugar juice (mostly sucrose) lost during commercial cane harvesting spreads labile carbon across cane fields, irrespective of whether the cane is harvested green or burnt. Under certain conditions, runoff following rainfall or irrigation can transfer these substances to adjacent waterways where their high BOD can deplete DO, sometimes to levels that are too low to support healthy fish.

In recent research (Bohl et al. 2002), high BOD₅ concentrations (up to 400 mg/L) were found in runoff from the first irrigation after harvest of both green and burnt cane. Sugar concentrations were also high in both cases (up to 500 mg/L) and were identified as the major contributor to the high BOD₅. Runoff-water with BOD₅ values of around 300 mg/L, if allowed to reach a local waterway, could cause a potentially serious, short-term, environmental hazard. Every litre of runoff would contain sufficient labile carbon to consume all of the oxygen in 50 litres of that waterway, assuming the ambient DO of the local waterway was 6 mg/L. In practical terms, 100 000 L of runoff of water with a BOD₅ from sugars of 260 mg/L would eventually strip the oxygen from 4 ML of receiving water with an initial DO concentration of 6.5 mg/L.

In response to mounting evidence that runoff water from cane farms may have high BOD and cause low DO levels in streams, there is new agronomic/environmental research with the aim of developing management practices to minimise potential adverse impacts. Other work is directed at improving the efficiency of cane harvesters so as to reduce losses of juice during harvest. Until there is clarification of these issues, the following actions are suggested to help maintain DO in surface waters:

- Avoid harvesting cane blocks near sensitive waterways when heavy rain is expected.
- Use irrigation practices with minimum or zero runoff to streams or storages, at least for the first irrigation after harvest.
- Keep waterways and storages cool and free of exotic weeds: this helps retain DO.
- Minimise the movement of strong acid drainage from acid sulfate soils to lessen opportunities for DO removal when ferrous iron oxidises.
- Prevent free-run liquid and leachate from mill mud from reaching waterways and storages.

5. ACKNOWLEDGEMENTS AND FURTHER READING

This paper has been prepared largely from the following publications, which would be suitable for further reading:


6. REFERENCES


7. PESTICIDE MANAGEMENT IN IRRIGATED SYSTEMS
IRRIGATION AND PESTICIDE USE

BW Simpson and LJ Ruddle

1. INTRODUCTION

Pesticide usage in the sugarcane industry forms part of the total management system for all canegrowers. Whilst the dependency on irrigation will vary depending on the amount and pattern of annual rainfall, the types and quantities of pesticides used are more related to local pest pressures and trash management, rather than whether the crop is irrigated or not. Both irrigated and non-irrigated crops have the potential to produce off-site losses that may result in unacceptable contamination of water resources (surface or sub-surface). The addition of irrigation imposes a further level of risk for such losses, particularly where there may be limited understanding of the links between the persistence and mobility of the pesticides being used. Whilst there is no ability to control the amount and timing of rainfall, the decision to irrigate triggers a number of processes in addition to the increasing of soil moisture.

Effective control by some pre-emergent herbicides such as atrazine or diuron, often rely on some form of early incorporation such as cultivation or ‘watering in’ by rainfall or irrigation (O’Grady and Sluggett 2000). This process of ‘watering in’ requires some of the pesticide to be dissolved, thus mobilising the product in the water phase, taking it to below the soil surface to be available to weed seeds or roots. It is therefore not difficult to predict that if not handled correctly, this ‘watering in’ process may also contribute to off-site losses to either groundwater or to surface water via runoff. Many canegrowers are simply unaware of chemical or physical properties of the pesticides that they use and even when used exactly according to label, there may be considerable off-site losses due to lack of awareness of important drivers of off-site losses.

With an increased awareness of pesticide properties, efficient irrigation (Holden 1998) should not directly result in unacceptable off-site chemical losses. Irrigation efficiency, which is aimed at keeping the water near the root zone, should result in positive environmental outcomes in which losses of farm chemicals through leaching and runoff should be minimal. However the addition of water via irrigation establishes a higher soil moisture status and thus, for the period where this is maintained, rainfall may result in a far higher level of surface runoff or leaching than if a similar rainfall event fell when there was a water deficit (non-irrigated).
2. PESTICIDE PROPERTIES

2.1 WHAT PESTICIDES ARE USED?

Herbicides are the dominant pesticide group used in sugar production and, since the removal of the organochlorine insecticides from agricultural use, the organophosphate chlorpyrifos in controlled release form (suSCon® Blue) is the most widely used insecticide.

Estimates of the top eight pesticides used (kg of active ingredient/year) by the Queensland and New South Wales sugar industries are given in Table 1 (Hamilton and Haydon 1996, 1997).

Table 1. Estimates of annual major pesticide usage in Eastern Australian sugar production

<table>
<thead>
<tr>
<th>Pesticide</th>
<th>Queensland (460 000 ha)</th>
<th>New South Wales (32 000 ha)</th>
<th>Total (492 000 ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atrazine</td>
<td>331 000</td>
<td>34 800</td>
<td>365 800</td>
</tr>
<tr>
<td>8Diuron</td>
<td>197 000</td>
<td>6 600</td>
<td>203 600</td>
</tr>
<tr>
<td>2,4-D</td>
<td>141 000</td>
<td>11 200</td>
<td>152 200</td>
</tr>
<tr>
<td>Glyphosate</td>
<td>85 600</td>
<td>13 100</td>
<td>98 700</td>
</tr>
<tr>
<td>Ametryn</td>
<td>76 000</td>
<td>1 200</td>
<td>77 200</td>
</tr>
<tr>
<td>Chlorpyrifos</td>
<td>74 500</td>
<td>5 100</td>
<td>79 600</td>
</tr>
<tr>
<td>Paraquat</td>
<td>42 800</td>
<td>6 500</td>
<td>49 300</td>
</tr>
<tr>
<td>Trifluralin</td>
<td>21 200</td>
<td>420</td>
<td>21 620</td>
</tr>
</tbody>
</table>

2.2 PERSISTENCE

Some pesticides e.g. the herbicides atrazine, trifluralin and diuron are applied directly to the soil to control or eradicate unwanted pest species. Other pesticides may be directed at a target plant (eg. the herbicides paraquat or 2,4-D, or many insecticides when used for foliar protection) using appropriate spray technology, but invariably a proportion of the active ingredient lands on the surrounding soil or is washed off the foliage onto the soil.

Figure 1. Dissipation of pesticides in surface soil (0-2.5cm) of a redoxic hydrosol in the Bundaberg area.
Volatilisation, photolysis, chemical (e.g. hydrolysis or oxidation) and microbial breakdown all contribute to decreasing the persistence of applied pesticides in soil. Breakdown products may not be harmless. Often, these products are as toxic as the parent compound and in some cases, even more toxic, more persistent or more mobile. The term “terminal environmental residue” refers to the compound or compounds expected to be found in the environment. Where the “parent compound” is listed as the ‘terminal environmental residue’ e.g. for the herbicide diuron, it can usually be taken that there are no other significant breakdown products. For atrazine, the ‘terminal environmental residues’ include the parent compound atrazine, plus 2-hydroxyatrazine, de-ethylatrazine and de-isopropylatrazine.

Field studies (e.g. Hargreaves et al. 1999) have provided information on the persistence of pesticides under sugar production for understanding the processes and key risk periods for potential off-site losses.

Pesticide dissipation in a surface soil (0-2.5 cm) from a field site in Bundaberg is shown in Figure 1. The herbicides atrazine, ametryn, trifluralin and diuron were applied at recommended application rates and techniques. The pesticide residues were determined at set times throughout the application season. In Figure 1, residue concentrations (kg/ha active ingredient) have been plotted against time, giving dissipation curves for the different compounds. The term dissipation time of pesticide is often used for field studies because there are a number of mechanisms that cause the loss of pesticide (described earlier). The residue data demonstrate that approximately 50% of atrazine applied in September 1997 had dissipated from the surface in 30 days whereas atrazine applied in December 1998 was lost at a much faster rate.

Both irrigation and rainfall will influence the distribution of pesticide throughout the soil profile. Figure 2 shows the distribution of atrazine in the soil profile to a depth of 50 cm in a grey kandosol soil from a Bundaberg site for the 1998/99 season. The percentage of initially measured (usually day 0, the day of application) pesticide remaining is shown. A number of rainfall events (12mm, 19mm and 17mm) occurred in the first week after application and Figure 2 shows the movement from surface (0-2.5 cm). In this case, atrazine was detected in soil to a depth of 30 cm after 11 days. A further rainfall event (17mm) at 13 days showed no significant movement below 30 cm. However only 12.4 % of the applied atrazine remained in the 0-50 cm soil profile after 35 days and there was no evidence of atrazine building up or persisting in the profile.
In addition to the above processes, pesticides will also be carried from the system in surface runoff or by leaching (Spencer and Claitth 1991, Troiano et al. 1993, Kookana et al. 1995 and Simpson et al. 2001). Whilst there are some limitations on controlling the chemical or microbiological reactions with pesticides, understanding the physical behaviour, particularly the transport processes, can lead to more responsible pesticide management. Both the timing and type of irrigation or rainfall events relative to pesticide application can have a major influence of the quantities of pesticide moving off-site.

2.3 PESTICIDE MOBILITY

In understanding how pesticides may move (mobility) off-site, knowledge of some physical properties is needed. Some pesticides are highly soluble in water, but because of their ionic properties they bind tightly to the soil particles and pose minimal risk for groundwater contamination. Paraquat is an example of this type of behaviour. However, some less soluble pesticides, such as atrazine, are less tightly bound to soil particles and, as a result, can move in both sub-surface drainage and in surface runoff. Figure 3 shows the variability in water solubility and soil-binding properties of some of the common pesticides used in sugar production.

![Figure 3. Relative mobility of some key pesticides](image-url)

![Figure 4. Atrazine bound to redoxic hydrosol (Bundaberg)](image-url)
Although the above information provides a useful guide, recent studies (Simpson et al. 2002) have shown that mobility of pesticides decreases with time after application. These changes in the pesticide adsorption properties after application and their dissipation rates were measured on a number of Queensland soils.

In Figure 4 it can be seen that initially atrazine is not tightly bound (5% on sediment) but over time increases to 75% sediment bound after approximately 25 days. As the amount of pesticide available for movement (pesticide persistence) decreases over time the amount of pesticide that will move in the water (dissolved) decreases more rapidly while the amount in sediment (bound) increases. Figure 5 shows data for atrazine and diuron on the redoxic hydrosol soil as the percent of total (initial) pesticide. For atrazine the primary mechanism with respect to off-site movement in the period immediately after application will be in solution (dissolved) with a shift to sediments (soil bound) over time. For diuron both dissolved and soil bound mechanisms equally contribute to the off-site movement initially but over time there is a shift to soil bound entirely.

![Figure 5. Change in availability of pesticides in water and sediment phases after application to redoxic hydrosol](image)

3. IMPLICATIONS

The above data on pesticide properties demonstrate the complexity associated with predicting how pesticides will behave when water is applied. However it is clear that when water is applied soon after application, there is significant potential for the applied pesticide to move with the water phase. Within a week after application, the amount of pesticide available to move in the water phase is significantly reduced (faster than the dissipation rate of the pesticide). However, with the reduction in availability to move in the water phase, there is often increased potential for movement via sediment.

Allowing some time for the applied pesticide to adsorb to the soil will greatly increase the ability to manage off-site losses (sediment retention strategies) and also significantly reduce the potential for leaching losses. It should also be recognised that even though applied water may only be sufficient to wet to the base of the root zone (in soil matrix), some water (and dissolved pesticide) may move via preferential flow pathways to the groundwater. This preferential flow may be detected by a rise in the water table after irrigation (or rainfall) even when the soil does not appear wet at depth. Experimental work has demonstrated that this preferential flow process can be rapid and associated solute can be detected shortly after application.

Where shallow water tables exist, excessive irrigation (and rainfall) can increase the water table to a point where it reaches and penetrates the surface. In such cases, pesticides can be mobilised by the rising groundwater and may be detected in both surface runoff and sub-surface water, which may be moving to streams via lateral interflow.
Any on-farm activities that result in water movement from the site must be seen as having the potential to move pesticides. By carefully managing the water (particularly in relation to applied pesticides) it is possible to limit pesticide losses.

4. MANAGEMENT CONSIDERATIONS

- Do not apply pesticide immediately before irrigation or in the likelihood of heavy rain
- Irrigation scheduling should avoid high risk periods (particularly where furrow irrigation or heavy overhead irrigation is used)
- Incorporate pesticide by cultivation if applicable
- Reduce soil and sediment loss from surface runoff. Significant reduction in pesticide transport from runoff can result, particularly for pesticides such as paraquat, trifluralin and chlorpyrifos, which have high adsorption on soil particles.
- Risk of significant off-site movement from the farm can be reduced by not treating large areas at the one time. This will avoid having large areas of maximum pesticide residue concentrations available for off-site transport with irrigation or rain
- Need to understand that some herbicides such as atrazine, ametryn or hexazinone are highly mobile and can move quickly off farm (runoff or leaching), particularly if irrigation or significant rainfall occurs shortly after application.
- Excessive irrigation can carry some pesticides, eg atrazine, well below the root zone (and outside the area of effective weed control). This can lead to groundwater contamination.
- Freshly applied pesticides are often more mobile (less bound) than those which have had time to “bind” to soil or foliage.
- Irrigation tailwater can contain high pesticide residues. Recycling of tailwater and avoiding excessive irrigation after pesticide applications will reduce off-site pesticide losses.
- Additional precautions should be taken where storm or irrigation runoff discharges near streams or sensitive habitats. Good water management is strongly linked to effective pesticide management.
- In highly porous soils or in areas with shallow water tables, less mobile alternatives should be considered to minimise potential contamination of groundwaters or baseflows in streams.

5. REFERENCES


8. RE-USE OF WASTEWATERS AND EFFLUENTS
REUSE OF WASTEWATER AND EFFLUENT AS RESOURCES FOR IRRIGATION

E A Gardner and R C Bruce

1. INTRODUCTION

Wastewaters and effluents are produced by intensive rural industries such as piggeries and feedlots, by agri-industrial processors such as abattoirs and dairy factories, and by sewage treatment plants. Community attitudes now demand the responsible treatment and disposal of wastewaters so that environmental impacts on soils, surface waters and underground waters are minimised. Reuse of effluents as irrigation water has a number of benefits and is an appealing solution provided it can be done in an ecologically sustainable way. Important considerations are the volume of effluent available and its composition.

The chemical composition of a range of biologically sourced effluents after pre-treatment in lagoons is shown in Table 1. Very high nitrogen (N) concentrations in effluents from piggeries, feedlots, starch factory, tannery and distillery and the relatively low concentrations in sewage effluent are of interest. Many effluents are high in phosphorus (P) and/or salinity (measured by EC). Sewage effluent has low salinity and low concentrations of all nutrients, with N and P concentrations up to an order of magnitude lower than those of other effluents.

<table>
<thead>
<tr>
<th>Source</th>
<th>Effluent composition (kg/ML)#</th>
<th>Nitrogen</th>
<th>Phosphorus</th>
<th>Potassium</th>
<th>EC (dS/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Potable water</td>
<td></td>
<td>&lt;1</td>
<td>&lt;2</td>
<td>&lt;1</td>
<td>0.4</td>
</tr>
<tr>
<td>Pulp and paper</td>
<td></td>
<td>&lt;10</td>
<td>&lt;10</td>
<td>30</td>
<td>1.9</td>
</tr>
<tr>
<td>Sewage treatment plants</td>
<td></td>
<td>10-50</td>
<td>5-15</td>
<td>10-40</td>
<td>0.6-1.7</td>
</tr>
<tr>
<td>Abattoirs</td>
<td></td>
<td>120</td>
<td>20</td>
<td>30</td>
<td>2.1</td>
</tr>
<tr>
<td>Dairy factories</td>
<td></td>
<td>200</td>
<td>100</td>
<td>160</td>
<td>0.2-5.0</td>
</tr>
<tr>
<td>Dairy farms</td>
<td></td>
<td>210</td>
<td>25</td>
<td>300</td>
<td>2.9</td>
</tr>
<tr>
<td>Fell monger</td>
<td></td>
<td>220</td>
<td>1</td>
<td>50</td>
<td>12</td>
</tr>
<tr>
<td>Wool scour</td>
<td></td>
<td>390</td>
<td>13</td>
<td>1470</td>
<td>na</td>
</tr>
<tr>
<td>Piggeries</td>
<td></td>
<td>640</td>
<td>80</td>
<td>520</td>
<td>8.7</td>
</tr>
<tr>
<td>Feedlots</td>
<td></td>
<td>700</td>
<td>75</td>
<td>850</td>
<td>8</td>
</tr>
<tr>
<td>Starch factory</td>
<td></td>
<td>850</td>
<td>160</td>
<td>1250</td>
<td>2.5</td>
</tr>
<tr>
<td>Tannery</td>
<td></td>
<td>940</td>
<td>9</td>
<td>70</td>
<td>11.2</td>
</tr>
<tr>
<td>Distillery</td>
<td></td>
<td>1700</td>
<td>130</td>
<td>na</td>
<td>na</td>
</tr>
</tbody>
</table>

# units kg/ML are numerically equivalent to mg/L

The other aspect of effluents is the volume of each that is produced. In Queensland, 335 000 ML of sewage effluent are produced each year compared to 2 000 ML for feedlots, 5 000 ML for piggeries, 10 000 ML for abattoirs, 4 000 ML for dairy farms and 1 500 ML for fresh water aquaculture (Gardner and Barry 1996).

Sewage effluent is the most attractive effluent for reuse on land for irrigation because of the large volumes available and the relatively lower concentrations of N, P and total salts. However, the consequent large total mass of N and P (volume x concentration) it contains makes its disposal a matter of environmental concern and demands proper management practices. The remainder of this paper will deal with the use of sewage effluent in irrigation.
2. SEWAGE EFFLUENT

Estimates of the generation and reuse of effluent from sewage treatment plants of water utilities in Australia in 2000 are given in Table 1. The reuse of effluent is a small proportion of the total but is increasing in some States. Most (87%) of the 342 000 ML produced in Queensland is disposed of in rivers, estuaries and ocean outfalls. Only 38 000 ML is reused on land, mostly golf courses, playing fields, parks and gardens etc. with only a small amount used to irrigate crops. Disposal of huge volumes of effluent directly into environmental waters is an environmental risk because of a number of reasons, including the nutrient loading of the effluent and emerging issues such as endocrine disruptors. It is also a significant waste of water resources as 340 000 ML of sewage effluent, equating to about 40% of the average annual irrigation releases from surface impoundments in Queensland (1997 data).

Table 2. Generation and reuse of effluent from sewage treatment plants of water utilities in Australia in 2000 (from Dillon 2000)

<table>
<thead>
<tr>
<th>State</th>
<th>Effluent generation</th>
<th>Effluent reuse</th>
<th>Effluent reuse %</th>
<th>Rate of increase in reuse ML/yr/yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>QLD</td>
<td>342 000</td>
<td>54 000</td>
<td>16</td>
<td>8.0</td>
</tr>
<tr>
<td>NSW</td>
<td>560 000</td>
<td>65 000</td>
<td>12</td>
<td>6.3</td>
</tr>
<tr>
<td>ACT</td>
<td>30 000</td>
<td>700</td>
<td>2</td>
<td>0.2</td>
</tr>
<tr>
<td>VIC</td>
<td>370 000</td>
<td>25 000</td>
<td>7</td>
<td>8.5</td>
</tr>
<tr>
<td>TAS</td>
<td>43 000</td>
<td>1300</td>
<td>3</td>
<td>0.3</td>
</tr>
<tr>
<td>SA</td>
<td>91 000</td>
<td>15 000</td>
<td>16</td>
<td>2.8</td>
</tr>
<tr>
<td>WA</td>
<td>115 000</td>
<td>7800</td>
<td>7</td>
<td>1.2</td>
</tr>
<tr>
<td>NT</td>
<td>21 000</td>
<td>2400</td>
<td>11</td>
<td>0.7</td>
</tr>
<tr>
<td>AUSTRALIA</td>
<td>1 573 000</td>
<td>171 000</td>
<td>11</td>
<td>28</td>
</tr>
</tbody>
</table>

There is increasing pressure by the Environmental Protection Authority on local authorities to either upgrade the quality of their sewage effluent to tertiary standards (a capital intensive option) or cease discharge to rivers and estuaries. This provides an opportunity for communities in rural areas to turn this problem into a win/win situation by reusing secondary treated effluent for crop irrigation. This option is particularly attractive in sugar towns where the closely settled nature of the industry presents modest pumping distances (e.g. < 20 km) and the high water consumption of cane ensures average to high irrigation demand even in tropical North Queensland. Moreover, because sugar is a processed product involving high temperatures and crystallisation in its manufacture, the health risks from ingesting sugar from effluent irrigated sugar cane are minuscule compared with the risks from say, effluent irrigation of salad crops that are eaten raw.

Queensland sugar towns produce over 60 000 ML of secondary treated sewage effluent each year (Bryant et al. 1994) which, if used for irrigation, has the potential to produce over 700 000 tonnes of extra sugar cane each year (assuming 1 ML of irrigation produces 12 tonnes cane; Kingston 1994).

There are a number of limitations and constraints associated with the safe, environmentally sustainable reuse of sewage effluent and these include chemical composition, human health risks, hydraulic balance, economics and social attitudes and we will discuss these issues in the following text.

3. CHEMICAL COMPOSITION OF SEWAGE EFFLUENT

Results of a survey of sewage effluent from 35 sewage treatment plants in coastal Queensland are summarised in Tables 3 and 4. The range of values for total N and P is consistent with data in Table 1.

The amount of nitrogen (N) and phosphorus (P) in sewage effluent depends strongly on the treatment process. For secondary treated effluent from trickling filter plants, N and P levels are of the order of 25 mg N/L and 8 mg P/L. As mg/L is numerically equivalent to kg/ML, a 5 ML/ha/year effluent application applies approximately 125 kg N/ha and 40 kg P/ha, which is a significant proportion of the fertiliser N and P normally applied to irrigated crops. Provided fertiliser applications are adjusted for
the nutrients applied in the effluent, there should be no difficulty with leaching of excess N or runoff of P. Nutrient balance problems can occur if the crop is either not harvested (e.g. long-term trees) or harvested and not removed (e.g. grazed pasture).

Table 3. Chemical composition of treated sewage effluent from 35 sewage treatment plants in coastal Queensland (Barry and Gardner, unpublished data)

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Mean</th>
<th>Range</th>
<th>Median</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>6.9</td>
<td>5.7 – 9.1</td>
<td>6.9</td>
<td>0.6</td>
</tr>
<tr>
<td>EC (dS/m)</td>
<td>0.8</td>
<td>0.3 – 2.1</td>
<td>0.7</td>
<td>0.4</td>
</tr>
<tr>
<td>Total N (mg/L)</td>
<td>12.7</td>
<td>1.4 – 36</td>
<td>9.2</td>
<td>8.5</td>
</tr>
<tr>
<td>Nitrate-N (mg/L)</td>
<td>10.7</td>
<td>0.1 – 64</td>
<td>9.8</td>
<td>11</td>
</tr>
<tr>
<td>Ammonium-N (mg/L)</td>
<td>8.3</td>
<td>0.5 – 31</td>
<td>4.3</td>
<td>8.6</td>
</tr>
<tr>
<td>Total P (mg/L)</td>
<td>6.1</td>
<td>2.9 – 13</td>
<td>6.3</td>
<td>1.9</td>
</tr>
<tr>
<td>Orthophosphate P (mg/L)</td>
<td>5.5</td>
<td>1.6 – 13</td>
<td>5.8</td>
<td>2.1</td>
</tr>
<tr>
<td>Potassium (mg/L)</td>
<td>15.3</td>
<td>6.0 – 42</td>
<td>14</td>
<td>7.3</td>
</tr>
<tr>
<td>SAR</td>
<td>5.3</td>
<td>2.0 – 13</td>
<td>5.0</td>
<td>2.4</td>
</tr>
</tbody>
</table>

Heavy metals such as cadmium, zinc, chrome, lead, arsenic and copper are frequent components of raw sewage influent due to trade waste inputs into the sewerage system, and metal dissolution from pipes. However, the major fraction of these metals are concentrated in the sludge (or biosolids) component of the sewage treatment process. In Table 4 all heavy metal concentration are low and below ANZECC (1992) irrigation water standards. This is not surprising as trade wastes are the major source of heavy metals. These industries are concentrated in large provincial towns and cities, which in turn, have the resources to implement a trade waste policy which minimises/prohibits the discharge of potentially hazardous waste into the sewerage system.

Table 4. Concentrations of heavy metals (mg/L) in sewage effluent from 23 sewage treatment plants in coastal Queensland (Barry, unpublished data)

<table>
<thead>
<tr>
<th>Element</th>
<th>Mean</th>
<th>Range</th>
<th>ANZECC guidelines for irrigation water quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>As</td>
<td>&lt;0.05</td>
<td>0.10</td>
<td></td>
</tr>
<tr>
<td>Cd</td>
<td>&lt;0.01</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>Co</td>
<td>&lt;0.05</td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>Cr</td>
<td>&lt;0.03</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>Cu</td>
<td>0.02</td>
<td>0.01 – 0.07</td>
<td>0.2</td>
</tr>
<tr>
<td>Fe</td>
<td>0.18</td>
<td>0.01 – 1.10</td>
<td>1.0</td>
</tr>
<tr>
<td>Mn</td>
<td>0.07</td>
<td>0.02 – 0.15</td>
<td>2.0</td>
</tr>
<tr>
<td>Ni</td>
<td>&lt;0.05</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>Pb</td>
<td>&lt;0.03</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>Se</td>
<td>&lt;0.04</td>
<td>0.02</td>
<td></td>
</tr>
<tr>
<td>Zn</td>
<td>0.06</td>
<td>1.02 – 0.16</td>
<td>2.0</td>
</tr>
</tbody>
</table>

Salinity and sodicity levels in sewage effluent (measured by EC and SAR respectively in Table 3) usually fall well within groundwater irrigation values, and many of the same management methodologies can be used to successfully manage effluent irrigation.

The key to salinity control is sufficient leaching to maintain the soil salinity within a range that does not adversely affect crop growth. For highly permeable soils this is achieved by irrigation applications in excess of irrigation demand. For slowly permeable soils where the soil hydraulic properties determine deep drainage, simple prediction tools such as SALF (Shaw and Thorburn 1985) allow the steady state root zone salinity to be calculated for various inputs of irrigation (mm/year) and salinity (dS/m).

Soil sodicity may not become a problem if the SAR-EC combinations are such that the soil permeability is maintained (Shaw and Thorburn 1985). Alternatively, gypsum can be added to the effluent to reduce SAR (and increase EC). Direct gypsum injection into the irrigation line is practical,
simple and cost effective using a dissolvinator. Alternatively, soil sodicity problems can be overcome using solid gypsum applications.

Pesticides that are now used in agriculture are predominantly biodegradable. Consequently, the highly energetic oxidation system at most treatment plants is very effective at breaking many organic compounds down to their component parts. Moreover, pesticides tend to accumulate in the sludge. However, validation of this expectation of low concentrations in the effluents is relatively scarce because pesticide monitoring in treated sewage effluent is limited to cities, and a few of the larger provincial towns. It is considered unlikely that pesticide levels in effluent could occur at concentrations affecting the growth of agricultural plants, but this needs to be confirmed by regular monitoring.

4. HUMAN HEALTH

Because of the relatively low cost of travelling gun spray irrigation compared with other application methods, it is highly likely that effluent will be applied by this method, especially by first time irrigators. Spray drift is then a real possibility with the potential to cause infection/illness in farm families and their neighbours.

Microbiological results from 10 sewage treatment plants along coastal Queensland that were seasonally sampled are shown in Table 5.

Table 5. Geometric mean concentration of pathogens measured in a range of sewage treatment plants along Queensland’s sugar coast

<table>
<thead>
<tr>
<th>Plant</th>
<th>Disinfection</th>
<th>Thermotolerant coliforms per 100 mL</th>
<th>Clostridium perfringens per 100 mL</th>
<th>Phage pfu* per 100 mL</th>
<th>Cryptosporidium per L</th>
<th>Giardia per L</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Yes</td>
<td>695</td>
<td>662</td>
<td>21</td>
<td>1</td>
<td>93</td>
</tr>
<tr>
<td>B</td>
<td>Yes</td>
<td>10</td>
<td>87</td>
<td>0</td>
<td>0</td>
<td>23</td>
</tr>
<tr>
<td>C</td>
<td>No</td>
<td>787 138</td>
<td>318</td>
<td>417</td>
<td>1</td>
<td>145</td>
</tr>
<tr>
<td>E</td>
<td>Yes</td>
<td>8</td>
<td>69</td>
<td>0</td>
<td>1</td>
<td>29</td>
</tr>
<tr>
<td>I</td>
<td>Yes</td>
<td>26 306</td>
<td>857</td>
<td>15</td>
<td>0</td>
<td>984</td>
</tr>
<tr>
<td>M</td>
<td>Yes</td>
<td>22 786</td>
<td>151</td>
<td>6</td>
<td>1</td>
<td>154</td>
</tr>
<tr>
<td>R</td>
<td>Yes</td>
<td>48</td>
<td>62</td>
<td>0</td>
<td>1</td>
<td>215</td>
</tr>
<tr>
<td>T</td>
<td>Yes</td>
<td>44</td>
<td>904</td>
<td>0</td>
<td>0</td>
<td>1882</td>
</tr>
<tr>
<td>V</td>
<td>Yes</td>
<td>144</td>
<td>158</td>
<td>0</td>
<td>0</td>
<td>81</td>
</tr>
<tr>
<td>Y</td>
<td>No</td>
<td>44 482</td>
<td>17</td>
<td>1</td>
<td>1</td>
<td>11</td>
</tr>
<tr>
<td>Mean</td>
<td></td>
<td>675</td>
<td>109</td>
<td>2</td>
<td>0.6</td>
<td>110</td>
</tr>
</tbody>
</table>

* pfu = plaque forming units

The thermotolerant coliform levels varied from 8 to 800 000 cfu/100mL for all effluents tested during the survey. Plants that did not disinfect (Plants Y and C) had high levels ranging from 44 500 to 800 000 cfu/100mL, while plants that did disinfect (the remaining eight plants) had levels ranging from 8 to 26 000 cfu/100mL. For plants I and M, coliform counts were up to three orders of magnitude higher than other disinfecting plants, suggesting either overloading in the trickling filter, poor removal of suspended solids or inadequate contact time in the chlorination tank.

Existing reuse guidelines for coliforms are in Table 6. Based on these criteria, only two of the sewage treatment plants (Plant B and Plant E) are suited for salad crop irrigation. Six of the ten plants can be used for agriculture (pasture) irrigation while four plants cannot be used at all.

Giardia levels were particularly high, with a maximum plant mean of 1 882 cysts/L (Plant T) and an overall survey geometric mean of 110 cysts/L. Published data suggest levels >1 000 cysts/L in raw sewage, 15 cysts/L in secondary treated, disinfected sewage, and 1 cyst/L in raw water supplies (Sykora et al. 1991). Treatment processes are available to achieve a 1 000 fold reduction in Giardia.
levels but these are considerably more sophisticated than the secondary treatment processes used in most Queensland sewage treatment plants.

Despite major national and international interest in *Cryptosporidium* in raw water supplies and treated sewage effluent its levels were low, suggesting that both human and animal carriers are relatively rare in the catchments of the plants surveyed.

Table 6. Interim guidelines for declared wastewater

<table>
<thead>
<tr>
<th>Use</th>
<th>Standard (thermotolerant coliforms/100 mL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unrestricted public access</td>
<td>&lt;10</td>
</tr>
<tr>
<td>Urban, with controlled access</td>
<td>&lt;150</td>
</tr>
<tr>
<td>Agriculture (pasture)</td>
<td>&lt;1000</td>
</tr>
<tr>
<td>Agriculture (crops eaten raw)</td>
<td>&lt;10</td>
</tr>
</tbody>
</table>

As a first estimate, thermotolerant coliforms clearly identify the plants that fail basic microbiological hygiene standards, but this may not identify effluents with other, more specific, pathogen hazards. For example, in a more detailed analysis of the results from the sewage treatment plant survey, Thomas *et al.* (2000) identified only weak correlations between coliform and *Giardia* levels ($r = 0.24$). This lack of correlation is particularly important considering the high *Giardia* levels that were measured.

To assess the health implications of irrigation with effluent, an aerosol dispersion model was developed to estimate the atmospheric concentration of microorganisms as a function of downwind distance, atmospheric stability and pathogen concentration in the effluent. By combining ingested pathogen dose with Quantitative Microbial Risk Assessment techniques (Rose and Gerba 1991), the probability of infection in a community can be predicted.

An example is shown in Table 7 for *Giardia*. At the median concentration in Table 5, it is evident that a separation distance of over 400 m is required to reduce the health risk to acceptable levels. The risk changes markedly with the infectivity of the organism, and for virus such as Rotavirus, acceptable distances are more than doubled.

Table 7. The predicted risk of infection from *Giardia* by inhaling 300 litres of aerosol at different downwind distances from the spray irrigation source. A range of effluent pathogen concentrations was used, including the median values from the effluent survey. Stable atmospheric conditions were used and 26 exposures per year were assumed

<table>
<thead>
<tr>
<th>Downwind distance (m)</th>
<th>Cysts/L</th>
<th>Infections/year/10 000 people (26 exposures/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.1</td>
<td>0.9</td>
</tr>
<tr>
<td>0.1</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>20</td>
<td>0.1</td>
<td>0.4</td>
</tr>
<tr>
<td>40</td>
<td>0.2</td>
<td>1.7</td>
</tr>
<tr>
<td>60</td>
<td>0.2</td>
<td>1.0</td>
</tr>
<tr>
<td>100</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>200</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>400</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>600</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

(1) The apparent increase in infection is due to insufficient vertical dispersion of pathogens from the 3m high aerosol plume to a receptor of height 1.2m at near downwind distances of <40m.

Solutions to these health risks include furrow or trickle irrigation (reducing the potential pathogen dose ingested by humans) or reducing pathogen concentration. Extended ponding (>30 days) is a very
effective disinfection technique and large wet weather storages have the additional advantage of storing excess effluent in wet weather, and supplying extra irrigation in dry times of the year.

5. HYDRAULIC BALANCE

Regional hydraulic balance is essential for the long-term sustainability of any irrigation scheme if shallow water tables and surface salinisation are to be avoided. In a survey of 144 Queensland land application schemes (Bryan et al. 1994), 113 were applying effluent far in excess of conventional agricultural practice (~ 1000 mm/year), and were using runoff and deep drainage as sinks for effluent disposal rather than evapotranspiration. This practice is explainable in terms of local authorities historically wanting to minimise the land area per ML of effluent. In contrast, the objective of commercial irrigators is just the opposite, with a clear price signal that effluent wastage equates to financial loss.

The other major hydraulic characteristic of effluent irrigation is that effluent production is relatively constant in time whilst the monthly agricultural irrigation demand not. Irrigation demand, along with wet weather storage volume, are central to the success or failure of an effluent irrigation scheme of given effluent supply. Daily time step biophysical models are proving invaluable in providing good estimates of irrigation demand, taking into account the interaction between climate, crop growth and soil type.

The irrigation demand – crop yield response predictions for reuse schemes involving sugar cane in different locations have been calculated using the daily time step crop growth model APSIM – Sugarcane (Keating et al. 1999). The major advantage of APSIM Sugarcane is its ability to incorporate the effects of sugar cane agronomy (such as plant vs ratoon cane, pre-harvest drying down period, and soil nutrition etc) on canopy development and on the amount and timing of irrigation requirements, and then to translate this into a predicted irrigated sugar yield.

The interaction between effluent supply, effluent storage, crop demand and climate variability was captured by adding into APSIM Sugarcane the lagoon water balance algorithms from the effluent disposal model MEDLI (Gardner et al. 1996).

Table 8 shows the average results for a 40-year simulation run under dryland and fully irrigated conditions for a range of sugar towns along coastal Australia. Predicted irrigation demand varies from 470 mm/year to 780 mm/year, yet the variation is not always explained by rainfall. Apart from the substantial annual irrigation demand for all locations (including Cairns), the modelling has identified some non intuitive results such as the similar irrigation demand for Mackay (490 mm/yr) and Grafton (470 mm/year), which has 700 mm less rain per year, but similar potential crop water use (about 1100 mm / year). In terms of maximising water use to minimise the area of irrigated cane, Ingham is the preferred location (781 mm / yr irrigation demand) closely followed by Maryborough (707 mm / year).

Table 8. Predictions by APSIM Sugarcane of average (40 year) cane fresh weight for dryland and irrigated production, seasonal and effective rainfall, irrigation demand, and crop water use for fully irrigated production

<table>
<thead>
<tr>
<th></th>
<th>Cairns</th>
<th>Ingham</th>
<th>Mackay</th>
<th>Maryborough</th>
<th>Grafton</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dryland cane fresh weight (t/ha)</td>
<td>106</td>
<td>100</td>
<td>126</td>
<td>95</td>
<td>110</td>
</tr>
<tr>
<td>Irrigated cane fresh weight (t/ha)</td>
<td>171</td>
<td>177</td>
<td>183</td>
<td>174</td>
<td>162</td>
</tr>
<tr>
<td>Average rainfall (mm)</td>
<td>2028</td>
<td>2037</td>
<td>1734</td>
<td>1117</td>
<td>1050</td>
</tr>
<tr>
<td>Effective rainfall (mm)</td>
<td>712</td>
<td>741</td>
<td>628</td>
<td>655</td>
<td>654</td>
</tr>
<tr>
<td>Average Class A pan evap (mm)</td>
<td>2130</td>
<td>2180</td>
<td>1980</td>
<td>1640</td>
<td>1650</td>
</tr>
<tr>
<td>Average irrigation demand (mm)</td>
<td>602</td>
<td>781</td>
<td>493</td>
<td>707</td>
<td>474</td>
</tr>
<tr>
<td>Crop water use (mm)</td>
<td>1314</td>
<td>1522</td>
<td>1120</td>
<td>1362</td>
<td>1038</td>
</tr>
</tbody>
</table>
Once the potential irrigation demand for a scheme is determined it must be combined with irrigation area and wet weather storage to predict hydrological behaviour. Figure 1 shows the effect of various area-volume combinations on overtopping volumes for a 2900 ML/year effluent reuse scheme in southeast Queensland, using 20 years of climate data. As the irrigation area increases from 120 ha to 270 ha there is a sharp decline in overtopping volume for all wet weather storage volumes (100 to 900 ML). This effect is far more important than the reduction in overtopping volume with increased storage volumes, for any of the chosen irrigation areas (120 ha to 700 ha).

![Figure 1](image.png)

**Figure 1.** Average (20 year) predicted annual overflow volumes (ML) for various combinations of irrigation area (120, 270, 540, 700 ha) and storage volumes (100, 200, 500, 700 and 900 ML). Effluent supply is 2900 ML/year.

As this overtopping volume is secondary treated sewage effluent, a discharge license has to be negotiated with the EPA on the basis of volume per year (eg. 10% of effluent production) or frequency of overtopping (eg. five events per ten years). This will be a location specific negotiation depending on the assimilative capacity and environmental sensitivity of the receiving environment. Most of the coastal sewage treatment plants in Queensland discharge into tidal rivers, but most of the total effluent volume is discharged into river mouths or estuaries (Bryant *et al.* 1994).

Figure 2 shows the effect of irrigation area and wet weather storage volume on the reliability of irrigation supply, defined as the percentage of irrigation demand met for unrestricted water supply (average irrigation demand for this location is 700 mm/year). This is the hydraulic performance criterion, which is of most interest to farmers.

The irrigation reliability percentage encapsulates the effect of year to year variation in effective rainfall, where in dry years, there is insufficient effluent volume to completely supply the above average irrigation demand, despite withdrawals from the wet weather storage of effluent carried over from previous (above average) rainfall years.

The major sensitivity is to irrigation area with a substantial reduction in reliability as the area increases from 270 ha to 540 ha. The initial gain in the reliability of supply with increasing storage size for a given irrigation area can be attributed to a substantial decline in overflow (or wet weather spillage) (Figure 1). Eventually the storage gets to a size where overflow losses are minimal, and irrigation reliability is primarily restricted by the supply of effluent.

A similar calculation can be presented for cane yield response but, because of the strong connection between water use and yield in the APSIM model, the form of response is very similar to that in Figure 1.
Figure 2. Average (20 year) predicted applied irrigation expressed as a percentage of the irrigation demand under fully irrigated conditions for combinations of irrigation area (120, 270, 540 & 700 ha) and storage volume (100, 200, 500, 700 and 900 ML) for a 2900 ML/year effluent supply.

It is clear that there is a convergence between low overtopping volume and high irrigation reliability as wet weather storage volume increases, but a divergence between these two outcomes as irrigation area increases. Multiple runs using optimisation techniques in models such as MEDLI (Gardner et al. 1996) can establish an area – volume domain where both irrigation reliability (eg. 80%) and spill volume (eg. 10%) criteria are fulfilled and then identify a generic minimum cost area – volume combination, (Vieritz et al. 1998) but this facility is not available in the APSIM Sugarcane model. We do not believe that this is a severe limitation for this section as the main objective of Figure 1 and Figure 2 is to demonstrate the nature of the interaction between storage volume-irrigation area on overtopping behaviour and irrigation reliability.

However, for complete scheme designs, calculating the frequency of overtopping (eg. 1 event per 10 years or 5 events per 10 years, or the volume of precautionary discharge from storage) is often required by regulatory authorities, and this will require a more rigorous analysis than shown in Figure 1.

6. ECONOMIC ISSUES

After public health, sharing the costs and benefits between effluent producers and effluent users is the most important issue in effluent reuse. These economic aspects of effluent irrigation often generate the most debates. Both the effluent producers (local authorities) and the potential effluent consumers (e.g. cane farmers) believe they are each doing the other a major favour and the recipient of this favour should bear the major cost of the irrigation scheme! The spreadsheet model SUGARCOST has been developed to perform financial evaluation of effluent irrigation by comparing the benefits to local authorities in deferring sewage treatment plant upgrade and subsidising effluent irrigation schemes vs the benefits and cost to sugar cane growers in investing in effluent irrigation infrastructure.

The basic structure of SUGARCOST is a series of linked Microsoft Excel Spreadsheets containing data for effluent storage and distribution, STP upgrading options, on-farm costs, and financial evaluations. While SUGARCOST can be used to analyse the profitability of irrigated effluent schemes stand alone, it should be used in conjunction with APSIM and MEDLI to obtain data on the yield response to applied irrigation rates associated with various storage volume / irrigation area combinations.

SUGARCOST was used in a case study from a southern Queensland regional sugar town (Maryborough) to explore the returns (and savings) to council and cane growers by commissioning a reuse scheme, thereby deferring a sewage treatment plant upgrade. The assumptions used are shown in Table 9.
Table 9. Assumptions used in the case study of a southern Queensland sugar town commissioning an effluent reuse scheme

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Effluent volume</td>
<td>2920 ML/year</td>
</tr>
<tr>
<td>Storage volume</td>
<td>700 ML</td>
</tr>
<tr>
<td>Irrigation area</td>
<td>740 ha</td>
</tr>
<tr>
<td>Number of arms</td>
<td>14</td>
</tr>
<tr>
<td>Dryland yield</td>
<td>80 t/ha</td>
</tr>
<tr>
<td>Irrigation yield</td>
<td>120 t/ha</td>
</tr>
<tr>
<td>Irrigation applied</td>
<td>3 ML/ha/year</td>
</tr>
<tr>
<td>Pipeline length (to storage)</td>
<td>6.6 km</td>
</tr>
<tr>
<td>Pipeline length (from storage to farm)</td>
<td>6 km</td>
</tr>
<tr>
<td>State Government subsidy</td>
<td>50%</td>
</tr>
</tbody>
</table>

It was assumed that local authorities and consortium of growers participating in the scheme had negotiated a cost-sharing arrangement that involved cane growers contributing to the infrastructure capital and operating costs associated with delivering effluent from the central storage to the farms. For this case study, this comprised a contribution to the capital cost of the scheme collected through a $10/ML levy over 20 years. In addition, growers also fully paid for the operating and maintenance costs of the scheme through a $/ML payment.

The local authority was eligible to claim a State Government subsidy of 50% contribution towards the capital costs of the irrigation scheme. A 40% subsidy could also be claimed towards the cost of upgrading a treatment plant from secondary to tertiary treatment, which would allow continuing discharge of effluent to water bodies.

Table 10 shows the additional annual costs and benefits to local authorities and growers from investment in an effluent irrigation scheme.

Table 10. Additional annual costs and benefits to local authorities and growers associated with investment in an effluent irrigation scheme

<table>
<thead>
<tr>
<th></th>
<th>Benefits per year</th>
<th>Costs per year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Local Authority</td>
<td>$29 200</td>
<td>$1.485m</td>
</tr>
<tr>
<td>– grower contribution to scheme collected through $10/ML levy.</td>
<td></td>
<td>– capital cost after 50% State Govt. subsidy (once off)</td>
</tr>
<tr>
<td>Individual cane grower</td>
<td>$49 918</td>
<td>$32 975 comprising:</td>
</tr>
<tr>
<td>– revenue from additional cane production of 40 t/ha.</td>
<td></td>
<td>- $8 136 (annuity for 15 years only) capital costs irrigation equipment</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- $14 800 additional harvesting costs</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- $10 039 irrigation O&amp;M costs</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- $ 4 013 total contributions to scheme infrastructure and operating costs</td>
</tr>
</tbody>
</table>

Annual costs and benefits have been incorporated into a discounted cash flow analysis to estimate the value of the investment over a 20-year period. Net present values were calculated using a 7% discount rate (Table 11).


Table 11. Discounted net benefits over 20 years associated with two effluent management options, and effluent-irrigated sugarcane production (individual farm and all farms in scheme)

<table>
<thead>
<tr>
<th>Council option 1: Effluent reuse scheme</th>
<th>Council option 2: STP upgrade*</th>
<th>Effluent irrigated cane (per farm)</th>
<th>Effluent irrigated cane (whole scheme)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-$1 154 001</td>
<td>-$12 572 392</td>
<td>$205 003</td>
<td>$2 870 043</td>
</tr>
</tbody>
</table>

* 30 000 EP Plant.

On the basis of this case study, investment in effluent reuse for irrigation was worthwhile for a canegrower. The additional annual profit (before interest and tax) compared with dryland production was approximately $17 000 ($49 000-$32 900, Table 10). Over 20 years, the net present value (NPV) was $205 003 per farm. The combined NPV for the 14 farms in the scheme amounted to $2.87 million net benefit (Table 11).

From the local authority view, investment in an effluent irrigation scheme appeared more economically attractive than replacing the STP with a tertiary treatment BNR plant. While neither option generated a positive NPV (Table 11), if faced with having to make a choice between the two options, the local authority would be better off by $11.4 million by deferring STP upgrade and investing in an effluent irrigation scheme (Table 11).

Effluent reuse schemes can clearly benefit both local authorities and cane growers. SUGARCOST presents an opportunity for both parties to negotiate for a share of these benefits.

7. SOCIAL ATTITUDE

Irrespective of the technical and ecological merits of effluent reuse, if the consumer of the food product has concerns about health risks and associated philosophical attitudinal resistance, then the system will not succeed. Simpson and Oliver (1996) have coined the term hydrocoprophobia to describe the community’s fear of sewage effluent reuse.

Community attitude was largely responsible for the Noosa and Pine Rivers local authorities not proceeding with indirect potable reuse, despite having established the technical success of the treatment process. Similarly, the packing industry refused to accept tertiary treated disinfected effluent from Pine Rivers because of the anticipated public perception that food packages (e.g. milk cartons) could be contaminated by sewage (G. Ashworth pers. comm.). Similar types of concerns were expressed to Coffs Harbour banana growers that their proposed effluent irrigation initiative could be used as a marketing disincentive by their competitors.

Balanced against these examples, are two recent consumer surveys into direct/indirect potable reuse. Hamilton (1994), using market survey techniques, interviewed 5,000 consumers in southern Queensland and northern NSW. He found that 76% of them were prepared to accept potable reuse provided they were convinced of the need for it in their community, and if there were rigorous and transparent safety precautions to ensure no public health risk.

In a recent (1996) survey by Caloundra and Maroochy local authorities, 65% of the community were prepared to accept direct potable reuse (Ron Piper, pers. comm.) in place of the construction of more dams in the coastal hinterland. However, 46% ranked public health protection as the first priority in effluent reuse. Only 8% of ratepayers considered cost the most important criterion in selecting reuse options.

In a recent (1996) survey by Caloundra and Maroochy local authorities, 65% of the community were prepared to accept direct potable reuse (Ron Piper, pers. comm.) in place of the construction of more dams in the coastal hinterland. However, 46% ranked public health protection as the first priority in effluent reuse. Only 8% of ratepayers considered cost the most important criterion in selecting reuse options.

Finally, the public of NSW is strongly opposed to the discharge of secondary treated effluent into the sea via the 35 existing ocean outfalls. This view appears to be largely influenced by the Bondi Beach effluent return disasters of the 1980s. Consequently, up to 22 coastal shires in NSW with access to agricultural land are prepared to seriously consider the cost premium to implement irrigation reuse, with the community agreeing to sewerage rate increases of up to $150/year (Anon 1997).
In summary, the public perception towards effluent reuse is changing and that has both positive and negative implications for the irrigation industry. The positives are cost subsidies local communities and state governments are prepared to pay to implement more expensive agricultural irrigation reuse strategies. This water has an almost 100% guarantee of supply. The negatives are that other potential reuse consumers are emerging who are interested in replacing their $800/ML potable water with treated effluent, and that local communities are interested in potable reuse in lieu of more dams.

Nonetheless, the public relations battle for widespread acceptance of effluent irrigated crops is far from over, and it is probably sensible to focus reuse initially on processed products such as sugarcane, potatoes and tree crops, before salad vegetables are promoted as eco friendly food.

8. CONCLUSIONS

Very large volumes of sewage effluent are essentially wasted in Queensland each year and there is increasing community pressure for effluent reuse. Environmental concerns rather than shortages of potable water are the major drivers for reuse schemes. Irrigation of agricultural areas with effluent from large urban cities is constrained by high treatment and distribution costs. However, farm irrigation with recycled water is attractive for provincial urban communities as it saves the cost of upgrading treatment plants and allows a high percentage reuse, depending on climate, of the recycled water. Large wet weather storages are an essential part of a recycled water irrigation scheme to cope with constant supply and variable demand.

The sugar industry is well placed to use for irrigation over 60 000 ML of sewage effluent produced by Queensland sugar towns. The SUGARCOST model demonstrates that even under current cost sharing arrangements with local authorities, effluent irrigation is likely to be economically worthwhile. The model has also identified the potential for effluent irrigators to gain a share of the savings captured by urban ratepayers from deferring the upgrade of treatment plants to tertiary standards. This economic argument disappears, however, if Local Authorities are forced into tertiary treatment by regulatory or other types of community pressures without other incentives being in place.

Health risks from pathogens are the major concern from using recycled water for irrigation. Cost effective disinfection has yet to be demonstrated for low value crops but lagoons look promising. Salt, sodium and nutrients have to be managed for schemes to remain sustainable. Sodicity (sodium) is likely to be an emerging problem for recycled water. Nonetheless, we are confident that environmental issues with effluent irrigation are manageable using existing knowledge.

9. ACKNOWLEDGEMENTS

This paper has been prepared largely from the following references, which would be suitable for further reading:


10. REFERENCES

9. IMPROVING IRRIGATION THROUGH CLIMATE FORECASTING
SEASONAL CLIMATE FORECASTING FOR IMPROVING THE BEST USE OF LIMITED WATER

YL Everingham, C Baillie, NG Inman-Bamber and J Baillie

1. INTRODUCTION

The best use of limited irrigation water is a key issue for the Bundaberg region. For growers supplied by the Bundaberg Water Supply Scheme (WSS), the maximum amount of irrigation that can be applied in a season is dependent upon the quantities allocated. At the beginning of the irrigation season SunWater provide an announced allocation, but depending on future streamflows, this allocation may be further increased throughout the year. Despite the tendency for allocations to be increased as the season progresses, some farmers in the Bundaberg WSS have not fully utilised their entire allocations. If farmers were to have advance knowledge of likely increases in allocations, they could better plan the use of current supplies and more effectively utilise increases in allocation.

Since increases in allocations are dependent on future streamflows, as a preliminary step, it makes sense to assess the capability of the forecast system to predict streamflows. If the climate forecast system is able to forecast streamflows, then the next challenge is to integrate this (probabilistic) knowledge of future streamflows to forecast likely allocations at the end of key periods. Knowledge of the likely allocation can then be used to identify the optimal timing of successive irrigations to maximise productivity.

In this paper we present three examples of how seasonal climate forecasts can be targeted to the needs of the industry client. The three examples will show how climate forecasting indices relate to

- streamflows
- allocations, and
- optimal timing of irrigations.

The climate forecasting system applied in each example is the five phase Southern Oscillation Index (SOI) climate forecasting system (Stone et. al. 1996). The phases of the SOI represent the change in the average SOI from one month to the next. The SOI phases are:

- consistently negative SOI phase – the SOI stays deeply negative from one month to the next
- consistently positive SOI phase – the SOI stays strongly positive from one month to the next
- rapidly falling SOI phase – the SOI falls sharply from one month to the next
- rapidly rising SOI phase – the SOI rises sharply from one month to the next
- near zero SOI phase – the SOI wobbles around zero from one month to the next.

2. EXAMPLE 1: FORECASTING STREAMFLOWS IN OCTOBER-DECEMBER USING JULY SOI PHASES.

Daily streamflow data for the Burnett River at Walla, commencing in 1911 and finishing in 1996, were provided by the Department of Natural Resources and Mines (DNRM). Daily streamflows were added to produce monthly streamflow totals. Figure 1 demonstrates how the chance of streamflows in October-December (OND) vary with July SOI phases. The underlying information provided in Figure 1 is that the consistently positive (pos) and rapidly rising (ris) July SOI phases relate to higher chances of reaching or exceeding specified streamflow amounts than the remaining SOI phases. Conversely, consistently negative July SOI phases relate to a lower chance of reaching or exceeding specified streamflows than the remaining SOI phases.
3. EXAMPLE 2: FORECASTING ALLOCATIONS

Whilst knowledge of streamflows is useful, it would be more beneficial to farmers if announced allocations at particular times of the year could be forecasted accurately. For example if there was an increased chance of above-median streamflows, but there was no storage available to capture these extra streamflows, then such a forecast on streamflows could be misleading. Given that the SOI phase system shows quite good skill at forecasting streamflows, it was decided to assess if this could be translated to forecasting allocations.

Likely allocation increases were computed by entering historical streamflow sequences for September, October, November and December into the SunWater allocation model. The streamflows were from the DNRM database. For each sequence of streamflows an allocation was produced as output from the SunWater allocation model. This allocation was however dependent upon current climate and hydrological conditions, in particular, storage levels at the start of the water year. Thus, as well as the streamflow sequences, information about observed climate and hydrological conditions was also supplied as input to the SunWater allocation model.

Figure 2 shows how the chance of certain announced allocations at the end of December 2001, varied with August SOI phases. Using the all years line, there is a 50% chance that the allocation would exceed 60% at the end of December. If the August SOI phase was consistently negative, then the chance of exceeding 60% would be about 25% or one in four. Conversely, the chance of exceeding 60% is much higher (approx. 75%) if the SOI phase for August was consistently positive. In 2001, the August SOI phase was near zero. Since the allocation distribution based on the near zero SOI phase
(green line) closely follows the grey line one can note that the forecasted allocation does not differ substantially from the projection based on the all years data for the particular scenario considered.

In summary, the outlined approach is a new and novel way of providing farmers with more detail about likely announced allocations at the end of December for the current SOI phase with a lead-time of some four months. This information has previously not been available to farmers.

This exercise was repeated at the end of December 2001 when a forecast for announced allocations at the end of March 2002 was produced. As part of a piloting process, the forecast released to growers highlighted that there was a 75% chance of having a further 20% increase in allocation by the end of March 2002. In 2002 allocations were increased by 22% by this date.

It is important to recognise that this approach is very new. Further testing is therefore required to identify improvements and strengths and limitations of the current approach. Grower interest remains high however, and growers from the Kolan section of the Bundaberg WSS have asked to have access to similar information for their region.

Figure 2. Percent chance that allocations at the end of December will exceed a certain amount. Chances are derived from climatology (all years) and for years defined by August SOI phases.
4. EXAMPLE 3: FORECASTING OPTIMAL TIMING OF IRRIGATIONS

If increases in allocations are likely, a farmer may question the optimal time to apply irrigations. The APSIM-Sugarcane crop growth simulation model (Keating et al. 1999) was utilised to provide crop yield simulation output, which was then used to provide optimal timing scheduling for irrigation applications. As an example, APSIM was used to determine how an increased announced allocation could be used best. These water use strategies were developed as part of a CSIRO limited irrigation trial. The strategies were developed for the additional 20% allocation predicted for the end of March 2002 as outlined in Example 2 of this paper. These strategies are presented in Figures 3 and 4.

The strategies used the remaining allocation as of the end of December plus increases from forecasts. To determine the remaining allocation, the water use until the end of December was based on actual use recorded across the Bundaberg WSS.

Figures 3 and 4 identify the optimum time to use water for early cut blocks and late cut blocks. For early cut blocks, the emphasis was on watering in January. For late cut blocks, irrigation was distributed mainly over January and February and tapered off towards the end of June.

![Bar chart showing the optimal time to use water for early cut blocks (July). Y-axis shows how 200ML/ha were allocated optimally over a period of 100 years with the constraint that 2ML/ha had to be used each year. The optimising procedure using the APSIM sugarcane model is described by Inman-Bamber et al. (2002).]

5. CONCLUSION

The five phase SOI system for enhancing irrigation management for the Bundaberg region was investigated. Streamflows, allocations, and timings of successive irrigations have been shown to vary with climate patterns. Results to date highlight that seasonal climate forecasting offers a significant opportunity for industry to improve the management of limited water.

6. FURTHER READING

For other examples of how seasonal climate forecasting has been used to improve irrigation management we refer the interested reader to:


![Proportion of Total Water Allocation Used](image)

**Figure 4.** Best time to use an allocation of 2ML/ha for late cut blocks (October).

7. ACKNOWLEDGEMENTS

This research has been funded in part by the Australian government through the Sugar Research and Development Corporation (SRDC) and the Climate Variability and Agriculture (CVAP) Land and Water R&D programs and the Rural Water Use Efficiency Initiative. Thanks are also extended to the Bundaberg Rural Water Use Efficiency Committee for their fruitful discussions in identifying how seasonal climate forecasts could be used to enhance irrigation management in the Bundaberg region. We acknowledge DNRM for providing access to the streamflow data.

8. REFERENCES


10. ADOPTION OF BEST MANAGEMENT PRACTICE
IRRIGATION EXTENSION – RECENT SUGAR INDUSTRY EXPERIENCE

T Willcox, J Willcox, E Danzi and B Hussey

1. INTRODUCTION

To create change in agriculture, extension and research practitioners need to be aware of differences amongst irrigators (social, economic, personal, and situational). Berridge (1998) saw Participative Action Management (PAM) as a better vehicle for achieving change than traditional “top down” technology transfer methods. PAM groups conduct a joint analysis of the problem, develop action plans and make decisions throughout the process.

Examples of where PAM processes were used successfully in the sugar industry were at Bundaberg (Smith et al. 1994, Willcox et al. 1997), the Lower Burdekin (Holden 1998b) and statewide through the Rural Water Use Efficiency Initiative (Willcox et al. 2002).

The sugar industry has also provided information on irrigation to growers through various publications and short courses. These have provided good reference material but do not normally result in change unless linked to some action learning process.

2. BUNDABERG CANE PRODUCTIVITY COMMITTEE

Smith et al. (1994) described how the Bundaberg Cane Productivity Committee (BCPC) instigated a survey to identify factors limiting cane farm productivity. QDPI Economic and Financial Services conducted the survey. This analysis showed that irrigation factors were key drivers of productivity. Yields increased where soils held more moisture, where growers used flood irrigation, where there were fewer days between irrigations and with increasing water use.

The findings prompted the BCPC to focus extension efforts on irrigation using the theme “irrigation efficiency means profitability”. In order to maximise sugar yield per unit of irrigation water applied, the industry needed benchmark figures to gauge efficiency. Kingston (1994) examined yield and crop water use data from the Burdekin and Bundaberg regions and established yield/crop water use relationships. Kingston’s commercial model with a marginal response of 8.55 t cane/ML was used by BSES extension officers and the BCPC to index water use efficiency. BCPC published annual yield and crop water relationships, which allowed growers to compare their farm’s average yield with others using the same quantity of irrigation water.

As Bundaberg growers became more aware of the irrigation efficiency of their systems, interest grew in changing systems, particularly to drip irrigation. One of the major barriers to adoption of drip irrigation identified at workshops was cost. This prompted the BCPC to initiate the project “An Economic Evaluation of Irrigation Methods and Programs” conducted by Sinclair Knight Merz (1996). The study showed for Greenfield development that furrow with tail water return was superior to other irrigation methods on soils with high moisture holding capacity, while drip was superior on low to medium moisture holding soils (Willcox et al. 1997).

To assist in the adoption phase of drip irrigation at Bundaberg, BCPC initiated a Drip Irrigation Users Group. This group met regularly and compared results of using different installation techniques, maintenance schedules etc. The group determined what the problems were and followed the results of actions taken by individuals to overcome them. This proved successful and hastened the adoption of a complex technology.
3. THE LOWER BURDEKIN

Water use efficiencies improved as a direct outcome of the “Water Check” project in the Lower Burdekin (Holden 1998b). BSES extension officers used about 500 evaporation mini pans to help growers schedule irrigation. Much of the success of Water Check was attributed to grower involvement from the onset of the project. Cane growers monitored their own crop growth rates using simple measuring sticks over an irrigation cycle. When the daily growth rate dropped to half of the maximum recorded, the corresponding level of water in the mini pan became the refill point and was subsequently used as the trigger for successive irrigation.

The Water Check project also worked on reducing deep drainage losses by encouraging growers to change the water furrow shape from a broad based “u” to a narrow “v”. Matching soil type to irrigation inflow rate was also promoted, as was reduced tillage.

4. MACKAY CATCH CANS

An irrigation application survey was carried out at Mackay using simple catch cans. The catch cans were made from 90mm PVC drainage pipe cut into 250mm lengths with a cap on one end. These were placed in the inter-rows of rows 8, 16 and 24 on both sides of the irrigator towpath.

The results of this survey showed that the amount of water applied by growers was generally well matched to the water holding capacity of the soils, although some growers had no idea of how much water they were applying. Growers had obviously received information on how fast to run the irrigator but this was not related back to a quantity of irrigation water.

As an extension exercise, the project worked well with the irrigation project officer welcomed onto the farm to check application rate. Meeting the grower before and after the irrigation event helped involve the grower with the measurements and let them see what was happening with irrigation on their farm.

After the farm visits many of the irrigators adjusted application rates to better meet the targeted amount and requested a re-check of the application amount. The simple test of a few catch cans set up under an overhead irrigation system proved a powerful tool to change the irrigation practices of growers.

5. RURAL WATER USE EFFICIENCY INITIATIVE

The Rural Water Use Efficiency Initiative (RWUEI) is a Queensland Government initiative, administered through the Department of Natural Resources and Mines, with an investment of $41 million for 4 years across four industries – sugar, dairy and lucerne, cotton and grains and horticulture. The sugar RWUEI was largely an initiative of CANEGROWERS, the peak industry body representing cane growers in Queensland, BSES (Bureau of Sugar Experiment Stations) the industry’s research, development and extension service and Queensland Department of Natural Resources and Mines.

The initiative was broken up into five regions that represented the major irrigation areas in the cane industry: -

- Atherton Tablelands.
- Burdekin
- Central region
- Bundaberg
- Southern region – including Isis, Maryborough and Rocky Point.

Six Project Officers were appointed, based on the Tablelands, Burdekin, Proserpine, Mackay, Bundaberg and Childers regions.

Five management groups were set up throughout the state. These management groups were made up of industry (CANEGROWERS, BSES and millers), community (local government), government (NR&M, EPA) and environmental groups (Landcare, Wide Bay Conservation Council etc).
These local management groups were empowered to run the RWUEI (sugar) at a regional level. This included prioritising regional issues and signing off on work plans to address these issues within project budgetary guidelines and milestones. This approach resulted in tremendous industry and community ownership of the project.

In addition to the five local management groups, a State Management Team comprising five regional Chairmen, Project Co-ordinator and State Extension Leader, was formed. This group has been highly effective at addressing State issues and liaising with industry and government.

The cane industry has concluded that the model used in the Sugar RWUEI Program should be the model for Government / Industry / Community collaboration to effectively and efficiently address natural resource management issues in the future. It has been a successful model in facilitating and implementing change.

Identifying and prioritising issues at a local level was an on-going process through the Local Management Groups (LMG) and through feedback from discussion groups, field days, bus trips and meetings. In addition to prioritising the work plan, this process was used successfully to focus efforts from the R&D component of the RWUEI onto high priority issues identified by the local industry and community. Work currently being carried out by CSIRO Townsville on the best use of limited water is a direct result of the Bundaberg and Southern LMG identifying this as their number one R&D priority. An understanding of crop response to applied irrigation water, particularly at the low end of the scale, was seen as vital in ensuring viability of cane farms with limited irrigation water.

Most irrigation equipment on cane farms throughout the state was found to be under-designed in its ability to meet crop demand. Also, the limited quantity of irrigation water means that most growers have a limited ability to apply water. Current research is allowing the RWUEI to cost the effects of stress and delayed irrigation at various crop growth stages and evaluates system and infrastructure expenditure.

This very strong link between R&D and extension in addressing issues identified and prioritised at a regional level has added to the success of the project.

A major thrust of the Sugar RWUEI was to define and document Best Management Practice (BMP) irrigation. The aim of Sugar BMP was to condense practical and theoretical knowledge into a simple and practical checklist for growers to self assess their current practices and to use this to determine opportunities to improve their existing irrigation systems.

The BMP Checklist was based around 13 subject areas:

- Scheduling – method.
- Scheduling with limited water.
- Limited ability to apply water – scheduling with limited infrastructure.
- Furrow irrigation – minimizing deep drainage.
- Furrow irrigation – recycling and run off.
- Drip irrigation – minimizing deep drainage.
- Drip irrigation – distribution uniformity.
- Overhead irrigation – distribution uniformity and reducing run off.
- Farm planning.
- Weather and climate forecasting.
- Soil management.
- Irrigating from bores.
- Irrigating with effluent water.

Local management groups and industry have endorsed this Irrigation BMP. Also, it has been incorporated into the sugar industry’s Code of Practice for Sustainable Cane Growing and its COMPASS (COMbining Profitability And Sustainability in Sugar) Self-Assessment Workbook, which is being delivered to the industry by a series of workshops throughout the State (Azzopardi et al. 2002).
The RWUEI identified reasons to change irrigation management practices through surveys and extensive industry consultation. The primary drivers were productivity, profitability, industry and farm viability and lifestyle. The reliance on environmental outcomes to trigger change met with negativity early in the project. However, the key practices identified to increase productivity and profitability through increased WUE (minimising deep drainage and run off) are also key practices in maximising positive environmental outcomes.

The adoption program in each region has been built around approximately 10 demonstration sites. These sites were chosen to represent soil type and irrigation system and to act as the focus for a discussion group based around that site.

Moisture monitoring equipment (Enviroscans, Tensiometers, Diviner 2000s, Gophers and Minipans) has been used at these sites to identify and promote irrigation BMP via discussion groups and shed meetings.

Initially this work concentrated on simple aspects of irrigation scheduling:

- How much water does my soil hold?
- How much water does my crop use?
- How much water am I putting on?

After growers and Project Officers gained a basic understanding of these concepts, the demonstration sites were used to address more complex issues such as distribution uniformity, systems comparisons, best use of limited water, management options for limited infrastructure, modelling of stream flows and predicting allocations, weather forecasting and climate prediction.

All extension methods have been employed in the project. Those that have been very successful are: -

- Discussion Groups – These have been the most powerful tools in acquiring and retaining grower involvement. A grower-driven agenda has guaranteed continuing interest.
- Roadside Signs – These have varied in their format and presentation, but regardless of layout have been highly effective in conveying key timely messages to growers.
- Radio Reports – The high rating of ABC Radio’s Rural Report at 6.15 am weekdays has guaranteed success of weekly Irrigation Reports at this time slot. This has been a key method of communicating information on crop water use, effective rainfall, and topical irrigation information. The success of this slot has been substantiated by surveys of cane growers.
- Study Tours – Study tours by the sugar industry across industries and regions have been an important catalyst in attitude change and embracing new technology. These tours have included visits to cotton, grain, horticulture and dairy regions and have resulted in good interaction between the adoption and R&D teams.

Two key outcomes of the RWUEI are: -

1. To increase water use efficiency by at least 6% (equivalent to 0.5 tonnes of cane per Ml of irrigation water applied).
2. At the conclusion of the project, 70% of irrigators will have adopted best practice as outlined in the revised industry Code of Practice.

6. IRRIGATION PUBLICATIONS AND SHORT COURSES

Cane growers have good sources of information on irrigation available. The BSES irrigation manual “Irrigation of Sugarcane” (Holden 1998a) covers all aspects of irrigation. BSES also has special subject publications such as the “Reference Manual on Drip Irrigation of Sugarcane” (Hewson et al. 1995). Also, special Fact Sheets on irrigation have been developed as part of the State RWUEI. These fact sheets cover: Soils and irrigation management; Irrigation scheduling; Irrigation management using tensiometers; and Irrigation performance. Fact Sheets are available from RWUEI Irrigation Development Officers.

Short courses on irrigation have been an integral part of the extension package offered to cane growers. An example is “Irrigation of Sugarcane”, a short course offered to Central District growers in 1994.
The RWUEI has currently updated the irrigation short course and the new course was first offered to growers in March 2002.

7. CONCLUSIONS

Irrigation extension is about creating change in irrigation practices. This has been carried out reasonably successfully in the sugar industry within the constraints of existing funds and limited water supplies.

The RWUEI has demonstrated the gains that can be made through a targeted extension program.

Various projects have demonstrated that the best way to gain adoption of complex technology is to use participative group processes where growers identify problems, test possible solutions and then implement the most profitable alternative on their farm.

8. SUMMARY

Extension is about creating change. With increased pressure on limited water supplies, the Queensland sugar industry has devoted considerable extension effort to achieving high water use efficiencies. This has come about by changes in irrigation methods and practices to improve the efficiency of existing systems. Irrigation efficiency was the key focus of attention at Bundaberg and Mackay in the 1990s and achieved a major boost statewide through the Queensland Rural Water Use Efficiency Initiative (QRWUEI), which commenced in 1999. Extension methodology was largely group-oriented to achieve grower participation through on-farm demonstrations and to set criteria for economic modeling. Examples of participative group learning projects were those initiated by the Bundaberg Cane Productivity Committee, the Bundaberg Drip Irrigation Users Group and groups formed as part of Water Check and the QRWUEI. Use of simple on-farm tools to demonstrate scheduling (mini-pans) or uniformity (catch-cans) was used to attract grower interest and identify the need to change.

9. REFERENCES


Holden JR (1998a) ‘Irrigation of sugarcane’. (Bureau of Sugar Experiment Stations, Brisbane)


