The Science of Water Balance: Why do we need to know?

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Introduction

The theme of the conference is "*Meeting the Challenge*". Amongst the many challenges the cotton industry faces are a host that relate to water. Uppermost in most people's minds are probably the increasing restrictions on access to irrigation water resulting from the COAG reform process. However, I am not addressing the reform process itself, which is economic and political, but the technical challenges that led up to it, or follow from it. These challenges include...

- rising water tables
- depletion of ground water
- contamination of ground water
- salinity - dryland and irrigated
- erosion
- transport of pesticides
- river health
- irrigation scheduling
- water use efficiency
- denitrification
- water logging
- nutrient leaching

Each challenge involves a component of the water balance.

The Big Picture

When we address such a challenge, whether in management or research, we deal with the component of the water balance involved. As a result, research has been problem-driven and problem-oriented, with each project focussing on one or two components, instead of studying the water balance as a whole. Our view of the water balance becomes fragmented, and we lose sight of the big picture. More than 30 current or recent projects, funded from eight different sources, have been identified as relevant to the water balance in cotton. There is little evidence of coordination, and much evidence of fragmentation.

When we lose sight of the big picture, and ignore the water balance, the door is open for mismanagement of the water balance. It is arguable that many of the problems in agriculture result from such mismanagement. This is certainly true of the southern Murray-Darling Basin, and is the challenge facing us in the northern Murray-Darling Basin (NMDB), and similar catchments where cotton is grown.

Pest management provides an instructive analogy. It has taken the industry 30 years to accept IPM. IPM is not primarily conserving beneficial insects, as many think; that is an outcome. IPM starts by being aware of the big picture... that you can't manage one species without affecting the others. We ignored that truth, and as a consequence we had problems.

A similar awareness is needed in water management... you can't manage one component of the water balance without affecting the others. If you manage one component without knowing what is happening to the others, it opens the door for mismanagement of the water balance as a whole, with the consequent string of problems. It is not responsible management.

What is the water balance, and why is it important?

The Water Balance

On any bit of country, whether a field, a farm or a catchment, there are inputs and outputs of water. These inputs and outputs form the components of the water balance, illustrated diagrammatically in Figure 1.

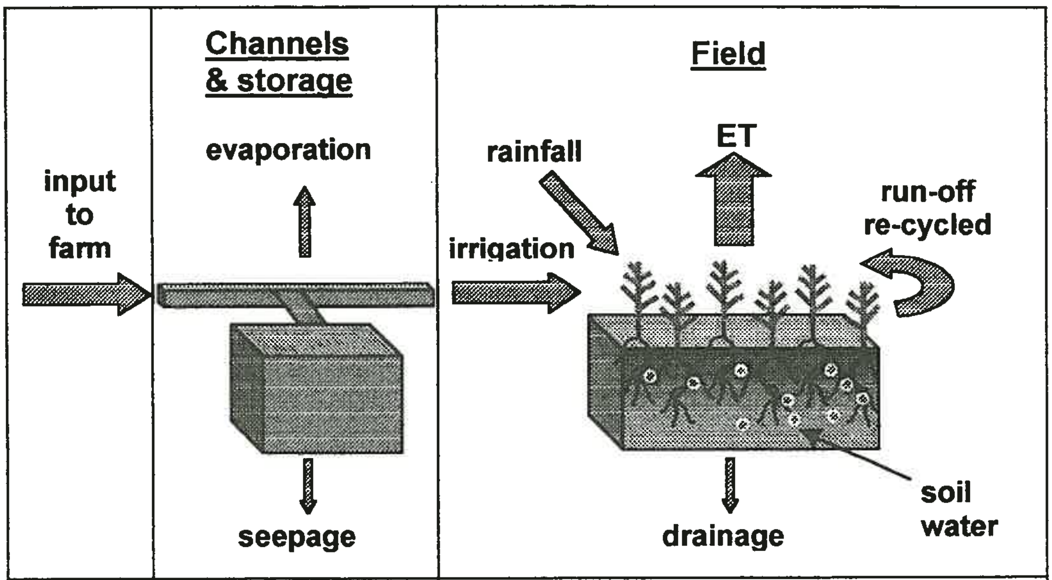

Figure 1: Field and farm water balance.

Field balance:

rainfall + irrigation = ET + drainage + run-off + soil water change

Field efficiency = ET / (rainfall + irrigation)

Farm balance:

rainfall + input = ET + drainage + run-off + seepage + drainage + soil water change

Farm efficiency = ET / (rainfall + input)

The inputs and outputs must balance; i.e. the sum of the inputs must equal the sum of the outputs. Water cannot be spontaneously created or destroyed. Thus...

Rainfall + Irrigation = ET + Deep drainage + Run-off + Soil water change

This is obvious, but what we easily overlook is the corollary - that you can't change one component without affecting the others, because inputs and outputs must balance.

As an industry, we would be well advised to become proactive in both management and research. We should become aware of the water balance now, rather than wait until the problems reach the magnitude that those relating to pests did before we adopted IPM, or those currently confronting water management in the southern Murray-Darling Basin. Without awareness of the big picture we may be putting band aids on symptoms instead of treating the underlying disease.

The Science Underpinning the Water Balance

We need to step back from the problems and focus on the water balance as a whole, and to evaluate the science being used to solve the problems. How good is the science being used? Is our knowledge of the processes involved adequate? Are our measurements accurate?

Evapotranspiration (ET)

The major output of the water balance of a crop is evapotranspiration (ET). ET is an evaporative cooling system. A crop is subjected to a heavy radiation load every day. If this energy is not dissipated, the crop will cook. ET is therefore radiation driven, and there is an energy balance just like the water balance, illustrated in Figure 2.

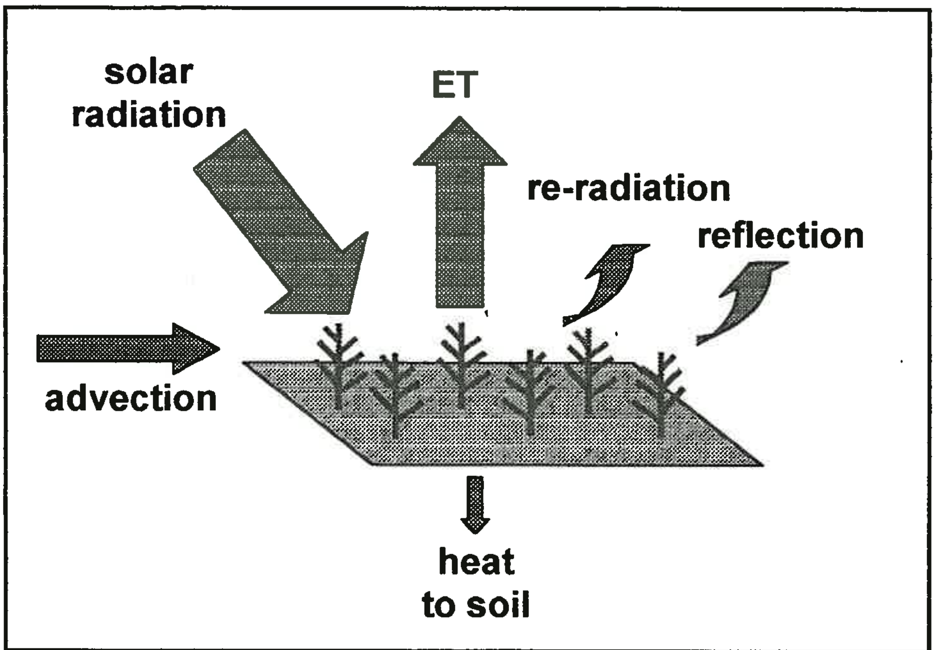

Figure 2: Energy Balance of a Crop.

Energy balance:

solar radiation + advection = ET + re-radiation + reflection

Just like the water balance, outputs must equal inputs... you cannot create or destroy energy. Just like the water balance, you can't influence one component without affecting the others. One important consequence of the energy balance and the need to dissipate the radiation load is that there is no 'magic bullet' for reducing ET to decrease crop water requirements. If ET is reduced there will be surplus energy from the radiation load on the crop that will either cook the crop or raise air temperature. In Arizona the reverse has occurred. The crop's evaporative cooling system has been enhanced as a result of breeding for yield in that very hot environment. ET has increased and WUE reduced (Radin et al 1994).

The water balance cannot be managed responsibly, if ET is not known. ET should be estimated, even if no other output is, in order to know how much of the water input is productive and generating income for the grower. All the other outputs are leaks that at best reduce the megs available for productive 'work', and at worst generate environmental hazards.

ET is estimated either from changes in soil water content, or from meteorological data. The meteorological approach uses data either from a standard weather station (using the Penman or combination equation) or from specialised in-crop instrumentation (using the Bowen ratio or micro-meteorological method).

The Penman method estimates all the components of the energy balance. It is therefore inherently conservative, as you cannot create or destroy energy. Many dismiss the Penman method as unreliable because there is no obvious connection between the crop and the data used. However the method solves the energy balance for the whole field, and not merely at a few access tubes at possibly unrepresentative sites.

The Penman combination equation has been widely used throughout the world. Although it is over 50 years since Penman published his equation, the aerodynamic term still requires local empirical calibration. A form of the Penman equation has been calibrated and validated for the southern Murray-Darling basin by Meyer (1999). It has been widely and successfully used in that region for irrigation.

There has been local calibration of the Penman equation in cotton regions, but its validity has not been tested across the whole NMDB. Versions of the equation have been incorporated in automatic weather stations but similarly have not been widely validated. There is therefore an urgent need to calibrate, validate, widely test and standardise the Penman equation across the NMDB and similar regions, as has been done in the southern MDB.

Run-Off

Run-off is the most obvious output of the water balance. It is easiest to measure. More effort has been made to manage run-off than other outputs, because it is implicated in pesticide transport and erosion. Recycling of tail water and retention of storm water is mandatory, is economically rational (given the opportunity cost of water) and is relatively easy, if costly, to engineer. However, a strong case can still be made for minimising tail water run-off at a field level, because of pumping costs, and because recycling is not 100% efficient due to conveyance and storage losses.

Deep Drainage

Deep drainage is percolation beyond the root zone, and is the most neglected output. Too often it is regrettably 'out of sight, out of mind'. There are two reasons for this neglect...

- the belief that it is negligible on the 'typical' cracking clays on which cotton is grown, to which we will return later;
- the fact that it is hard to measure, which we will address now.

The commonest method of estimating deep drainage is to measure all components of the water balance except drainage, which is then determined by difference. This method is prone to gross error because the errors or spatial variation in rainfall, runoff and ET accumulate in the drainage term. For example, a 5% error in estimating ET might amount to 40 mm annually which could be twice the expected value of the drainage term.

Other indirect methods of measuring drainage include Darcian flux calculations using tensiometers and the chloride mass balance method (used by Willis et al 1997 for example). The estimates by these methods can differ by a factor of up to four. Errors occur in estimating drainage in the cracking clays because of by-pass flow between peds along the slickenside surfaces (Ringrose-Voase et al 1998). Much work needs to be done to improve understanding of water movement in swelling soils in order to estimate drainage more accurately. A deep drainage meter is being developed, which will be an invaluable tool for water balance studies, if it successful on the cracking clays of the NMDB.

Soil Water Content

Change in soil water content can be either an input or output to the balance depending whether it increases or decreases over the period in question. It must be taken into account if the water balance method is used in order to determine drainage. Change in soil water content can also be used to estimate ET.

Measuring soil water content is prone to error on cracking clays (Ringrose-Voase et al 1998). Errors result from change in soil volume with the shrink/swell properties (causing errors of up to 80mm in soil water content). Errors also arise from inadequate calibration where the neutron probe is used. Further work needs to be done to improve methods for determining soil water, in order to make routine accurate measurements that can be used to make robust estimates of deep drainage and ET. Additional errors in laboratory estimates of upper and lower limits to plant available water content of deeper layers of cracking clays are caused by the effect of overburden.

I am not asserting that irrigation scheduling with the neutron probe is faulty. Provided the refill point has been empirically calibrated on site, good scheduling decisions can be made. However the units may be arbitrary if uncorrected for error, and the records cannot be used to estimate crop water use (ET) accurately.

Irrigation

As an input to the water balance irrigation appears to be straight forward. However in order to determine the water balance at the field level, irrigation must be measured at field boundary as well as farm gate distribution and storage losses, and to account for the input of harvested storm run-off.

Rainfall

Rainfall often varies spatially across a farm or even a field, which can be a source of error in drawing up a water balance. Some growers account for this input to the balance in terms of 'effective' rainfall. Various rules of thumb are used to discount light falls and storm water run-off. The concept of 'effective' rainfall applies only to deciding whether rainfall is adequate for stressed pastures and crops to resume growth. It is not valid for accounting for water input of a fully irrigated crop. A light fall still requires energy to evaporate the water, even if it only wets the leaves and surface soil. That energy cannot then be used again to draw water from deeper in the profile. Accurate accounting for water and balancing of inputs and outputs must take all rainfall into account.

Field and whole farm water balance

The inputs and output described constitute the water balance of a field. The water balance of a whole farm requires that the distribution and storage loses, resulting from evaporation and seepage be taken into account (Figure 1).

Water Use Efficiency (WUE)

WUE and the Water Balance

Interest in WUE has burgeoned in the last few years driven by the COAG water reform process. The result is a plethora of projects recently initiated independently by various bodies under the slogan of improving water use efficiency, with little evidence of coordination.

WUE is about how well the water balance is managed, not just how well irrigation is managed. If we are to take improving WUE seriously, we must do so in the context of the whole water balance. It is not merely a case of getting 'more bang per buck' of irrigation input.

WUE, like sustainability and IPM, means different things to different people, not least to growers, to engineers, to agronomists and to politicians and bureaucrats. Like sustainability and IPM it is in danger of becoming meaningless when used in the fuzzy way loved by politicians, making them feel good if they're advocating it. Unlike sustainability and IPM, WUE can be precisely mathematically defined as bales per meg of water. However it can be calculated in different ways, depending on how megs of water are assessed. It is crucial, not only to define it precisely, but to use the right definition for the purpose, if we are to evaluate and improve our practices. Different definitions are a source of confusion and it is not pedantic to be precise, otherwise there is risk of not comparing like with like.

'More bang per buck' of irrigation input is 'the bottom line' for growers, assessed as bales or $ per meg of irrigation input, and can be termed Farm Irrigation WUE. By calling it 'the bottom line', we make a useful analogy with financial accounting. If we want to improve the bottom line, for water as for finance, we must analyse the accounts in more detail. In order to do this we must introduce two more terms, each also called WUE by different professions.

Engineers use Irrigation Efficiency – the fraction of irrigation input delivered to and used by the crop in ET:

IE = ET as % of irrigation water

Agronomists use Crop WUE – what the crop produces with each meg of water it uses in ET:

Crop WUE = bales per meg of ET

Each of these three terms, as used respectively by growers, engineers and agronomists, is a valid indicator of WUE. They are related arithmetically thus....

Farm Irrigation WUE = Crop WUE x IE

... if there were no rainfall. Rainfall is a complication, but it can and must be accounted for.

Current Performance of the Industry

The National Perspective

Table 1 is an updated version of the comparison of irrigated crops presented at the last Conference. It tells the same story as last time, but more emphatically. Cotton uses less water per ha than any other industry, and produces more value per meg than any except horticulture. It uses only 12% of Australia's irrigation water, which is less than domestic water consumption by Australian households.

These data show a vastly different picture of the industry than the voracious consumer of water that the media love to bash. Nevertheless, they should not stop us asking if there is scope to improve WUE. There are no grounds for complacency. Could we do more with the water we use?

Table 1: Comparisons among irrigation industries in 1996-7 in Australia.

Crop	Megs per ha	Percentage of total irrigation water used in Australia	Percentage of farm gate value of irrigated production	Farm gate value $ per meg
Pasture	7.49	56.7	35.0	289
Horticulture	8.23	12.8	38.0	1388
Rice	10.79	10.6	4.3	189
Cotton	5.84	11.9	15.6	613
Sugar	7.14	8.0	7.1	418

Source: derived from Water Account for Australia. ABS, 2000.

Whole Farm Efficiency

At this Conference two years ago I suggested that a whole farm irrigation efficiency of 75% could be regarded as a provisional bench mark for the industry, as it was being achieved by the best performers. Later speakers in this session (Dalton 2000 and Tennakoon & Milroy 2000), using more rigorous methods, will confirm that best performers are achieving efficiencies of this magnitude. Although Dalton and Tennakoon used two quite different methods, their results agree remarkably well. However 75% is only the upper end of the range; both also found that the bottom of the range is 25%. This is appalling, and cause for consternation. It means that out of 4 megs that pass through the farm gate only 1 meg is used for the purpose intended, the useful work of meeting crop water requirements; the other 3 are lost en route.

We will hear about the procedure developed by Tennakoon & Milroy (2000) to account for all water on farm, using the records already being kept by competent growers. This accounting procedure calculates and analyses WUE, enabling growers to assess their performance, which is an essential part of responsible water management.

Routes for loss are run-off, deep drainage and in distribution and storage. Two years ago I asserted at the Conference, as most of us had thought for the past two decades, that most of losses were by seepage and evaporation during distribution and storage, because drainage was negligible and run-off was re-cycled. Conventional wisdom since the 1970s has been that deep drainage on cracking clay soils is negligible, as the soils are self regulating, taking no more water than needed to saturate the root zone because infiltration rates are very low when saturated.

Deep Drainage Re-visited

Later in this session Dalton will report that deep drainage can account for significant losses. This observation is the latest in a series (Willis et al 1997, Douglas 1998, Triantifilis et al 1998, Ringrose-Voase et al 1998, Young 1998, Hulugalle & Weaver 2000) showing potential for appreciable drainage on the cracking clay soils on which cotton is grown.

The industry has therefore reached the point where a mounting body of evidence is challenging the conventional wisdom on drainage. Are these observations from a few aberrant sites, or is deep drainage much more significant and prevalent than believed? Is negligible drainage a myth about to be exploded? This question has serious implications not only for loss of production from water lost in drainage, reflected in low WUE, but for risks of rising water tables and salinity, that Gordon (2000) will address later in this session.

The conventional wisdom originated in the 1970s. This decade was very wet with three major floods in the Namoi valley, each larger than any since. Tillage and traffic on wet soil resulted in widespread compaction which was not understood or even recognised. We now know that at that time much of the natural structure of the cracking clays had been destroyed, and with it channels for drainage along biopores and slickenside surfaces between the peds (for explanation of these terms, see SOILpak, McKenzie 1998). Now with controlled traffic, minimum tillage, permanent beds and ameliorative crops, structure has been restored. It is therefore plausible that drainage was negligible then, but is not now. However being plausible does not constitute proof. Furthermore this reasoning may not apply to sodic clays, on which hydraulic conductivity increases from negligible to substantial as the salt content increases despite compaction (McKenzie1991), so that drainage has never been negligible on such soils.

As an industry we must avoid putting our heads in the sand, and be aware that the jury is out on this question. If significant deep drainage is general, and not limited to a few aberrant sites, then further research and development will be required. Two obvious options are...

- optimise the management of conventional furrow irrigation;
- change the irrigation technology, for example to drip.

Management of Furrow Irrigation

Later in this session Dalton will discuss the potential for optimising the management of furrow irrigation in order to reduce deep drainage, involving siphon size, slope and timely pulling the siphons. We will be tempted to think... "this is reinventing the wheel... we've heard it all before!" No, we have not heard it all before; we've only heard part of it. Hodgson (1986) looked at the agronomic response of the crop to water logging induced by leaving the siphons running ***longer*** than normal. He did not look at pulling them ***earlier*** than normal in order to minimise deep drainage, nor look at the water balance.

There will be a triple bonus for getting it right...

- minimising yield loss from waterlogging;
- saving water lost in deep drainage, increasing WUE and allowing more cotton to be grown;
- conserving the resource base, by minimising risk of salinity thus enhancing sustainability.

Drip Irrigation

Drip irrigation has not lacked champions for over 20 years. However since research failed to show any increase in yield or decrease in ET (Hodgson *et al* 1990), and since drainage losses were believed to be negligible, there were no scientific grounds for advocating drip irrigation, apart from special cases on permeable soils or flat slopes. However the possibility of deep drainage being more generally significant, strengthens the case for considering drip irrigation.

Past research on drip was limited to the agronomic response of the crop in terms of yield and ET. Definitive research has not yet been done on drip in which the whole water balance is studied, and the water input partitioned among the outputs… ET, run-off and drainage. It is no longer adequate to measure water input for drip at the field boundary, and for conventional at the farm boundary, nor to measure both at the field boundary without doing the water balance. If drip uses less water, does it result from less ET or less drainage? If it is less ET, what about energy balance? What happens to the energy not used in ET?

Agronomy, engineering and Research

Irrigation involves both agronomy and engineering. In cotton research, until a few years ago, engineers and agronomists did not talk to each other; there was a glass barrier. The water balance was the casualty. Agronomists found out how much water the crop used in ET, and the crop's responses to supplying it in different ways. Engineers design the system to deliver the water, taking into account the various losses. All irrigation agronomy research in the 1970s and 1980s, including the waterlogging and drip experiments referred to, was good as far as it went, but we ignored engineering and the water balance. The only component of the water balance we studied was ET. Now engineers and agronomists are collaborating. The water balance has been discovered, and the overwhelming importance of measuring all its components is appreciated.

However a note of caution is needed to avoid unreasonable expectations of this collaboration. Engineers and agronomists, like farmers, are pragmatic. We do the best with what we have, including the knowledge currently available. The knowledge of some processes involved in the water balance on cracking clays in the NMDB is limited. I asked: "is our knowledge of the processes adequate?". The short answer is 'no'. We have nearly exhausted the intellectual capital built up by past generic research on this topic. Throughout this discussion of the water balance, I have identified a number of key research needs. These should be developed as an integrated and generic package of research to add to our depleted intellectual capital. Meanwhile, practices developed on the basis of existing knowledge are waiting to be applied. Growers can determine their own WUE using the tools developed.

Conclusion

My purpose has been to raise awareness of water balance in order to provide a background for the following speakers, and to change attitudes, so we think in terms of managing the water balance rather than just managing irrigation. In conclusion …

- Think water balance, not irrigation;
- Measure what you can, be aware of what you can't;
- Account for water, calculating and analysing WUE;
- 'Out of sight, out of mind' is no longer good enough.

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