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Deep drainage & crop water use for irrigated annual crops & pastures in Australia

– a review of determinations in fields & lysimeters

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National Program for Sustainable Irrigation

Coleambally Irrigation

CSIRO Land and Water, Griffith
Technical Report 14/03, April 2003

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Acknowledgements

This review was prepared as an activity under NPIRD project CLW21 *"Rigorously determined water balance benchmarks for irrigated crops and pastures"*. The project was a collaborative project between CSIRO Land and Water and Murray Irrigation Ltd, with supplementary funding from the Land and Water Australia National Program for Irrigation Research and Development (LWA-NPIRD) and Coleambally Irrigation Cooperative Ltd.

We thank Mark Wood and Lucy Finger of the Institute for Sustainable Irrigated Agriculture, Victorian Department of Primary Industries, Tatura, for making available their Microsoft Access database summarizing 129 investigations of water balance studies for irrigated pastures and associated soils.

ISSN 1446-6163

Citation details:

Humphreys, E, Edraki, M. and Bethune, M. (2003). Deep Drainage and Crop Water use for Irrigated Annual Crops and Pastures in Australia – A Review of Determinations in Fields and Lysimeters. CSIRO Land and Water Technical Report 14/03

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Summary

This report presents the findings from a review of field investigations of components of the water balance of irrigated pastures and annual broadacre crops in Australia. The objectives of the review were:

- to obtain data in the grey and published literature for field determinations of deep drainage, crop water use and paddock water use for the range of irrigated crops and pastures, management practices, soils and climatic conditions experienced in Australia
- to collate those data considered to be derived from rigorous determination
- to summarise the findings and identify weaknesses and gaps in the data

A database (“REFIRR”) of studies of the water balance and irrigation management for irrigated crops and pastures was developed in collaboration with Lucy Finger, Mark Wood and Matthew Bethune of Vic. DPI (Institute of Sustainable Irrigated Agriculture, Tatura). On 25 January 2003 the REFIRR database contained 222 records including 76 for irrigated crops, and 75 for pastures.

The most accurate and direct method for determining all components of the water balance is using lysimeters, however this must be done and interpreted very carefully to avoid artifacts due to edge effects and provide realistic rootzone conditions. Lysimeters are expensive to construct and not transportable, therefore there are only few studies from lysimeters for irrigated crops in Australia. Most reports come from the drainage and weighing lysimeters at CSIRO Griffith, where Meyer and team demonstrated that even for well-watered crops, crop water use from capillary upflow from shallow watertables (0.6-1.3 m) can be significant at up to 25% (soybeans), 29% (maize), 36% (wheat) and 55% (lucerne). The proportion of crop water use from upflow varied between soil types, decreased with increasing watertable depth and salinity, and increased where irrigation was withheld.

Meyer and colleagues used the data from a comprehensive series of weighing lysimeter experiments to evaluate methods for predicting crop water use, including US Class A pan, the Penman combination equation, the Priestly-Taylor equation, and the standardized FAO Penman-Monteith. They found that all methods were strongly correlated with measured ET, however Penman-Monteith underestimated ET by about 30%, and predictions using the Penman equation were improved by local calibration. In contrast, Bethune and coworkers found that the Penman-Monteith equation predicted annual pasture and rice crop water use accurately using the FAO recommended crop coefficients for strong wind conditions. The desirability of a national (uniform) approach for predicting crop water use has been discussed a number of times in the past, and is again under review. The NPIRD report of a national workshop conducted in July 2002 revealed that many methods are used for estimating crop water use, both within States and across Australia.

The review of deep drainage determinations reveals that the most comprehensive work has been done in ponded rice, and that this is the best understood in terms of the influence of soil properties, soil management and watertable depth on deep drainage. The work in rice perhaps best illustrates that deep drainage can be extremely variable within the one soil type and within the one field, and that irrigation with saline water and gypsum application can increase deep drainage. All of these effects have been observed with other landuses.

The review shows great variability in deep drainage determinations for similar landuse and irrigation management on the same soil types, and reinforces the conclusions of Lyle (2002) and Bethune (2001) that there is a need for a systematic and comprehensive approach to understanding deep drainage for a range of soil types, landuses and management practices – both its quantification

in relation to a defined set of measured soil and site parameters, and determination of what level of recharge is acceptable taking into account the local and regional hydrogeological conditions.

Strategic planning and policy development in the major irrigation areas is increasingly relying on the assessment of water use efficiency, deep drainage and net recharge using water balance models. The review shows that there is lack of good quantitative data for components of the water balance across the range of crops, climatic regions, site and seasonal conditions and management. Clearly it is impossible to carry out comprehensive determinations for all but a few situations, and water balance models must be used to estimate crop water use requirement and deep drainage for the range of situations. Such models need to be evaluated against quantitative data across a range of environments. However, there are few studies that have closed the water balance and which would allow rigorous testing of water balance models. Additionally, reported water balance studies often do not provide sufficient contextual information, nor changes over time, for adequate testing of models. Greater emphasis is required in experimental studies on providing adequate data and sufficient documentation and databases to allow future studies to use the collected data.

Introduction

Australian irrigators are under considerable pressure to increase irrigation efficiency and reduce deep drainage, driven by environmental and economic imperatives. Surface and groundwater supplies for irrigation are becoming less available, reliability of supply is declining and the cost of water is increasing as a result of environmental and National Competition Policy agendas (Humphreys and Robinson 2003). The productivity of irrigated agriculture in the major irrigated areas is threatened by rootzone salinisation as a result of excessive deep drainage causing rising watertables and secondary salinisation and waterlogging. Furthermore, shallow saline groundwaters seep into drainage systems and, together with surface runoff, contaminate drainage leaving irrigation areas, with adverse impacts on downstream ecosystems and other water users.

Information on components of the water balance, especially crop water requirement and deep drainage, will assist in identifying more or less efficient irrigation practices, and decision making aimed at increasing irrigation efficiency and controlling watertables. Such information is not readily available for irrigated landuse in Australia.

This report summarises the findings of field determinations of components of the water balance for irrigated pastures and annual broadacre crops in Australia. The objectives of the review were:

- to obtain data in the grey and published literature for field determinations of deep drainage, crop water use and paddock water use for the range of irrigated crops and pastures, management practices, soils and climatic conditions experienced in Australia
- to collate those data considered to be derived from rigorous determination
- to summarise the findings and identify weaknesses and gaps in the data

The review includes the results of measurements undertaken in the field at a range of scales from point measurements to lysimeters, small plots and commercial fields.

Approach

Sources of information

A range of on-line computer databases was searched using the following search strategy:

S1: FIND australia (116867 matches) S4: FIND irrigat? (90011 matches) S5: FIND water balance (12427 matches) S6: FIND deep drain? (209 matches) S7: FIND percolat? (5129 matches) S8: FIND evaporation OR evapotranspiration OR transpiration (33779 matches) S9: FIND runoff (15277 matches) S16: FIND S9 OR S8 OR S7 OR S6 OR S5 (58556 matches) S18: FIND S4 AND S1 (3391 matches) S19: FIND S18 AND S16

Databases searched included aesis (Australian Earth Sciences Information System), CAB Abstracts (Commonwealth and Biological Abstracts), CSPublist (CSIRO publications) and Current Contents.

Other information was sourced from peers from a range of locations and organisations including Bethune et al. (Institute of Sustainable Irrigated Agriculture, Vic. DPI, Tatura), Roth (Cotton Research and Development Corporation, Narrabri, NSW) and Sweeney (CSIRO Sustainable Ecosystems, Brisbane, Qld).

The REFIRR database

The **REFIRR** (pronounced "refer" – REF=reference, IRR=irrigation) database was developed using Microsoft Access for collating and summarizing the nature and findings of investigations for irrigated crops in Australia. Information from over 100 reports on irrigated annual field crops was entered. The irrigated crops database was combined with an irrigated pastures database, containing 129 entries, developed by the team at Tatura, as the fields in the two databases were reasonably well-matched. However the two databases were not identical, therefore there is currently some inconsistency and some redundancy in some of the records depending on whether they were originally entered into the pastures or the crops database. In some cases there is more than one publication (and therefore REFIRR record) referring to the same study, but dealing with different aspects.

The front screen, menu screen and a sample record are shown in Figures 1-3.

Figure 1. The front screen of the REFIRR database

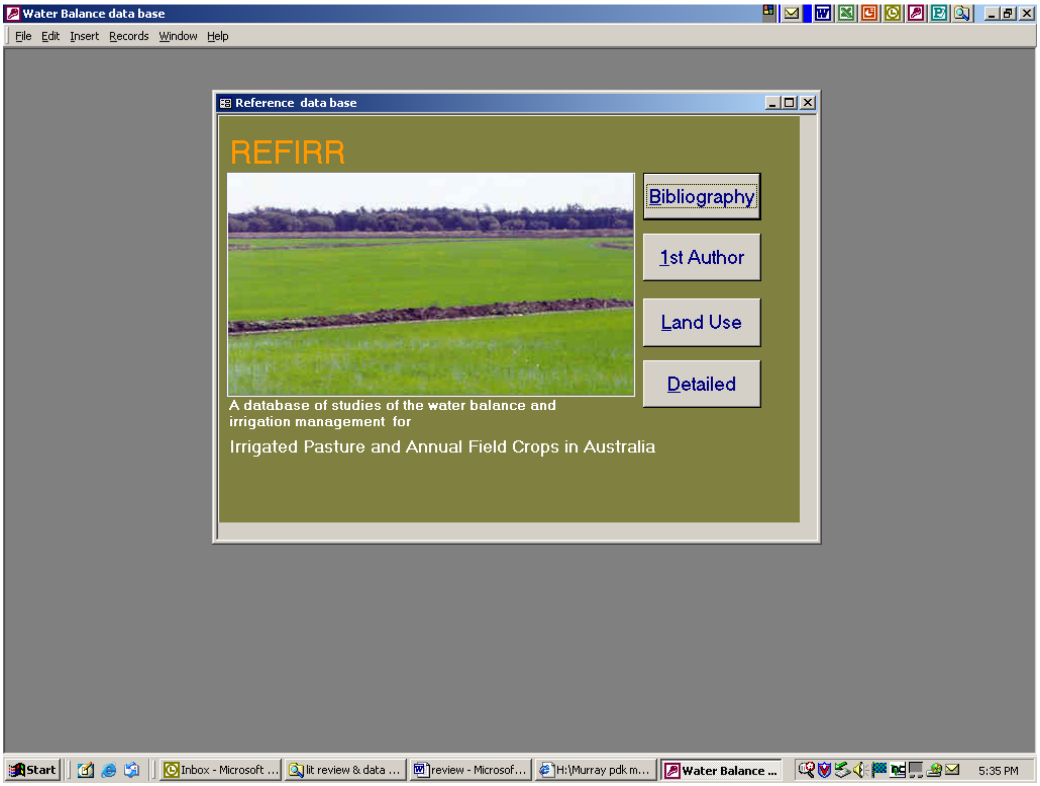


Figure 2. The menu screen of the REFIRR database

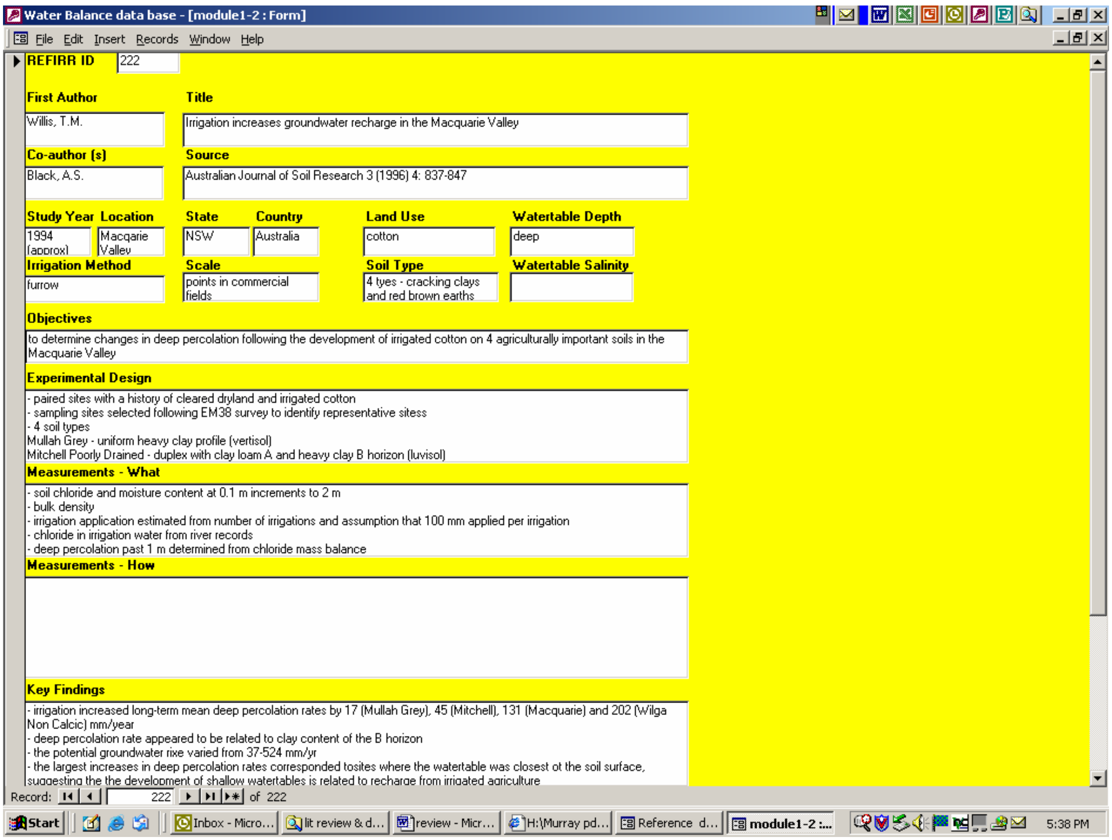


Figure 3. A sample REFIRR record (bottom fields not shown in this screen dump)

REFIRR is a very-easy-to-use data base, with capabilities of searching by landuse or by first author, and the full bibliography and details for each record are readily available. The database will be publicly available and hosted on the National Program for Sustainable Irrigation website, and its content will be expanded by including water use efficiency from the NSW Agriculture NPIRD project DAN15 “An information package on water use efficiency".

Examples of the results of searches by first author and by landuse are shown in Figures 4 and 5.

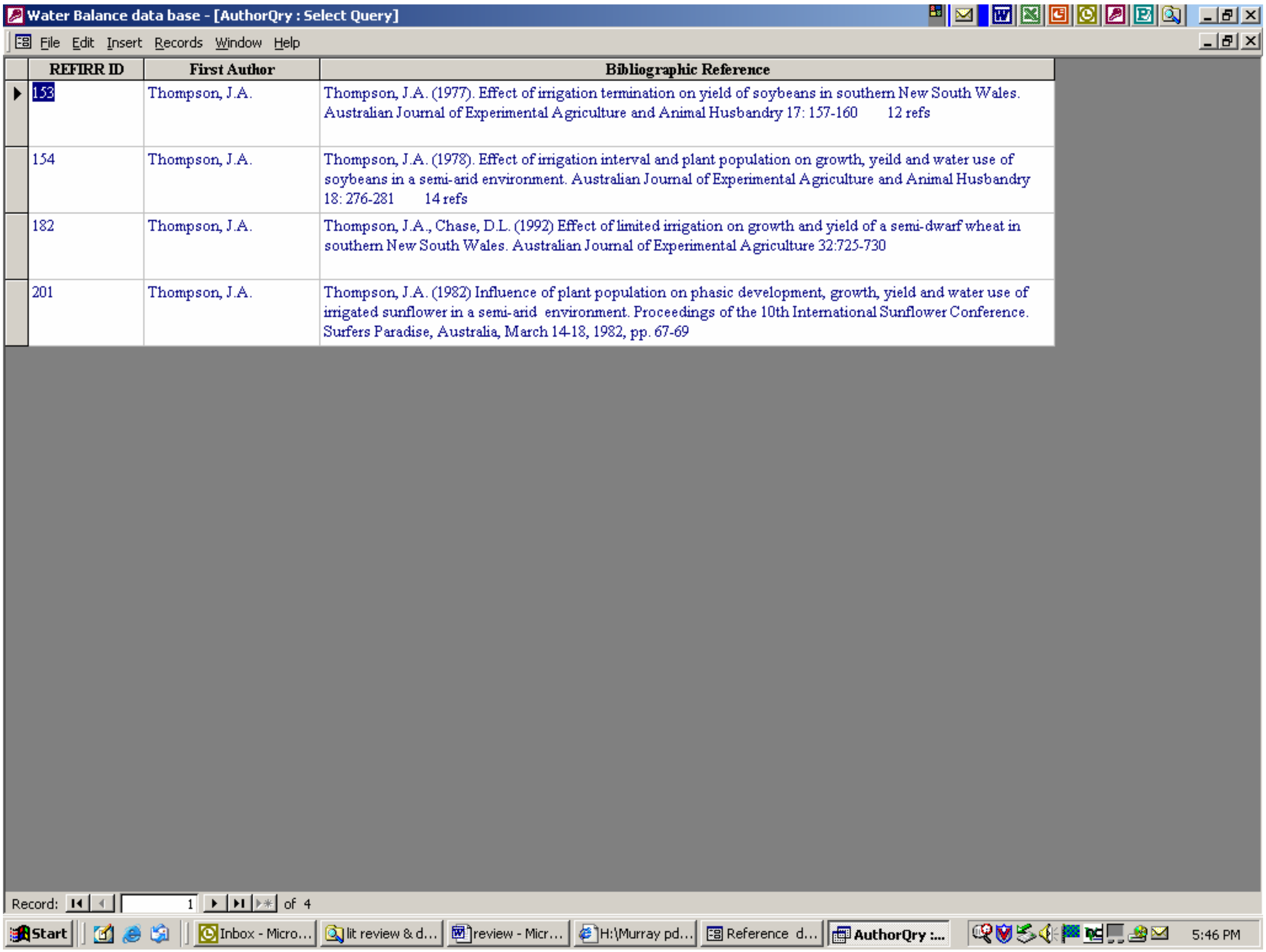
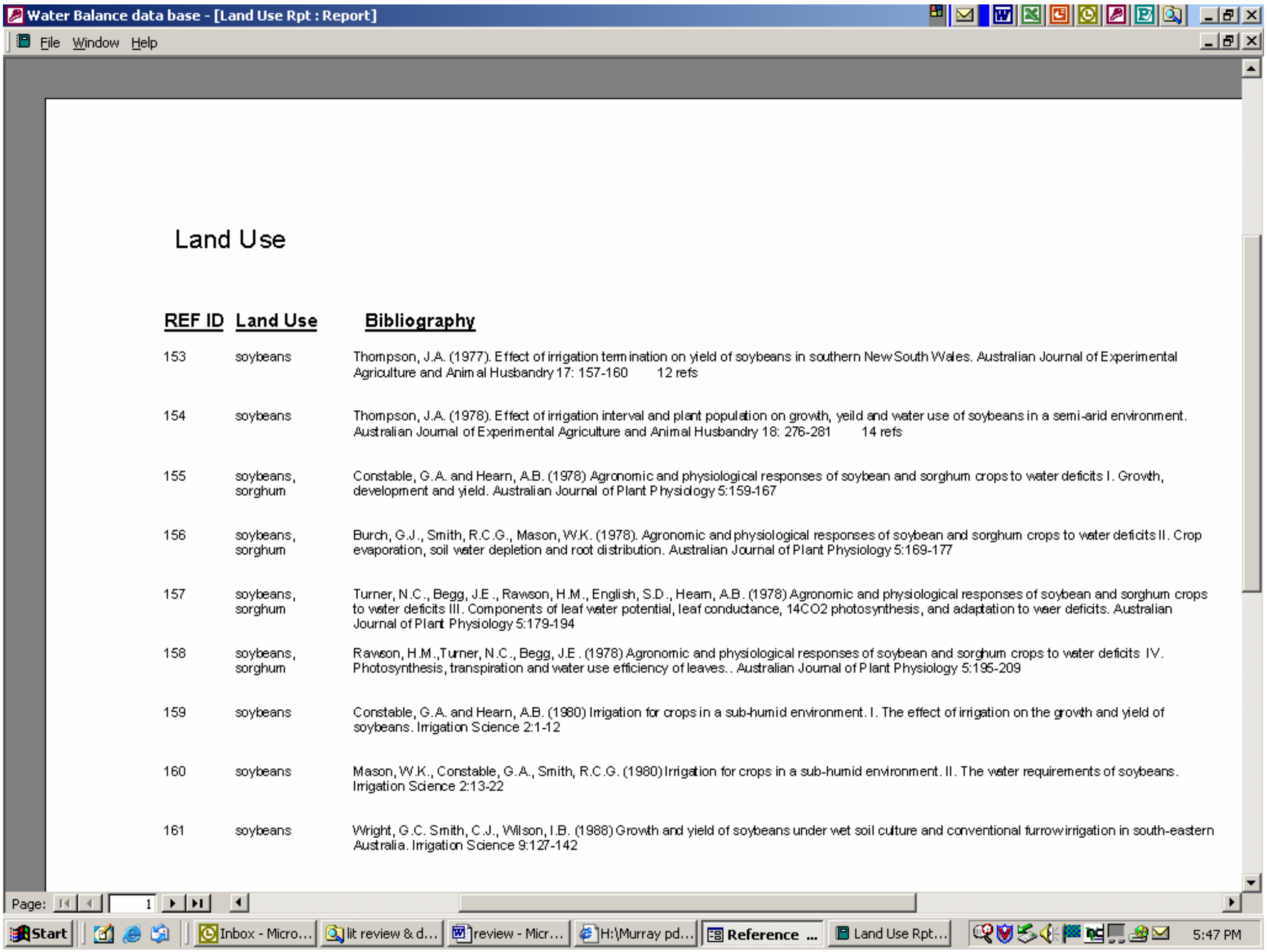


Figure 4. Results of a search by author (“Thompson, J.A.”) using REFIRR



Land Use

REF ID	Land Use	Bibliography
153	soybeans	Thompson, J.A. (1977). Effect of irrigation termination on yield of soybeans in southern New South Wales. Australian Journal of Experimental Agriculture and Animal Husbandry 17: 157-160 12 refs
154	soybeans	Thompson, J.A. (1978). Effect of irrigation interval and plant population on growth, yeild and water use of soybeans in a semi-arid environment. Australian Journal of Experimental Agriculture and Animal Husbandry 18: 276-281 14 refs
155	soybeans, sorghum	Constable, G.A. and Hearn, A.B. (1978) Agronomic and physiological responses of soybean and sorghum crops to water deficits I. Growth, development and yield. Australian Journal of Plant Physiology 5:159-167
156	soybeans, sorghum	Burch, G.J., Smith, R.C.G., Mason, W.K. (1978). Agronomic and physiological responses of soybean and sorghum crops to water deficits II. Crop evaporation, soil water depletion and root distribution. Australian Journal of Plant Physiology 5:169-177
157	soybeans, sorghum	Turner, N.C., Begg, J.E., Rawson, H.M., English, S.D., Hearn, A.B. (1978) Agronomic and physiological responses of soybean and sorghum crops to water deficits III. Components of leaf water potential, leaf conductance, 14CO2 photosynthesis, and adaptation to waer deficits. Australian Journal of Plant Physiology 5:179-194
158	soybeans, sorghum	Rawson, H.M.,Turner, N.C., Begg, J.E. (1978) Agronomic and physiological responses of soybean and sorghum crops to water deficits IV. Photosynthesis, transpiration and water use efficiency of leaves.. Australian Journal of Plant Physiology 5:195-209
159	soybeans	Constable, G.A. and Hearn, A.B. (1980) Irrigation for crops in a sub-humid environment. I. The effect of irrigation on the growth and yield of soybeans. Irrigation Science 2:1-12
160	soybeans	Mason, W.K., Constable, G.A., Smith, R.C.G. (1980) Irrigation for crops in a sub-humid environment. II. The water requirements of soybeans. Irrigation Science 2:13-22
161	soybeans	Wright, G.C. Smith, C.J., Wilson, I.B. (1988) Growth and yield of soybeans under wet soil culture and conventional furrow irrigation in south-eastern Australia. Irrigation Science 9:127-142

Figure 5. Results of a search by landuse ("soybeans") using REFIRR

Landuse entries

On 25 Jan 2003 the REFIRR database contained 222 records, with each record summarizing the nature of the investigation and major findings. The database includes investigations on 11 irrigated landuses (Table 1), however it should be noted that only the first landuse mentioned in the record is searched on, and therefore reports for landuses which are not listed first in the record are not included in the count. Studies relevant to irrigation management are included in REFIRR, such as irrigation scheduling, effects of water deficit or prolonged ponding, and comparison of irrigation technology. Other more general studies relevant to irrigation, for example on landforming, and on more generic aspects of irrigation in Australia, are also included. However, the focus of this review is on determinations of components of the water balance for irrigated crops.

Landuse	**No. of records in which landuse is the first listed**
annual pasture	5
bare soil (laboratory and field hydraulic investigations)	14
cotton	6
kenaf	2
lucerne	11
maize	9
perennial pasture	59
rice	24
sunflowers	10
sorghum	7
wheat	18

Table 1. Landuses in the REFIRR database on 25 January 2003

Components of the water balance and definitions

Components of the water balance referred to in this report are defined as:

- deep drainage – the movement of water beyond the rootzone, a specified depth which will vary with a range of factors including species and variety, stage of growth, crop vigour, soil conditions and watertable conditions
- surface drainage (runoff) as a result of irrigation or rain
- evapotranspiration – the sum of evaporation from the soil and via the plants (transpiration); also referred to as “crop water use”
- change in volumetric soil water content - final minus initial water content integrated over a specified profile depth and time
- capillary upflow – movement of water from the watertable into the unsaturated soil layers above by capillary rise and water vapour transfer
- irrigation – from surface or groundwater sources
- rain - precipitation

Methods for determining deep drainage and crop water use from field measurements

Lysimeters

Deep drainage and crop water use (evapotranspiration) are the most difficult components of the water balance to determine accurately, and the only way that they can be directly measured is in weighing and drainage lysimeters. The disadvantages of lysimeters include:

- they are expensive to construct and are not transportable, therefore their use is limited
- great care must be taken to ensure that the soil is not disturbed during excavation or extraction to avoid altering hydraulic properties, and the dimensions must be large enough to provide an unrestricted rootzone and representative entire structural units
- great care must be taken to ensure that the crop canopy in the lysimeters is contiguous with that in the surrounds to avoid edge effects (Meyer and Mateos 1990)
- it is generally not practical to install them in commercial fields, therefore scale may also be an issue in terms of factors such as duration of irrigation and its effect on deep drainage and waterlogging
- lack of connection with the surrounding soil matrix, especially at the lower boundary, and regional groundwater systems

However, when used carefully, lysimeters can provide the most accurate data on individual components of the water balance. They are also good for process studies where an exact match of the real world is not as important.

Indirect field techniques

A variety of indirect techniques have been used to estimate deep drainage (or upflow) from irrigated crops and pastures, including chloride mass balance, water balance, change in depth to the watertable, and Darcy's law using determinations of matric potential and hydraulic conductivity. Each technique has advantages and disadvantages, and the wide range of approaches for field and catchment scales has been reviewed by Gee and Hillel (1988), and more recently in the series of publications edited by Zhang and Walker (1998-2002). Gee and Hillel (1988) suggest that combining chloride and water balance is the best technique for estimating deep drainage.

The most commonly used techniques reported in irrigation studies in Australia are chloride mass balance and various forms of the water balance (the form depending on what is measured and assumed). Chloride mass balance has the advantage of being able to determine the amount of drainage (or upflow) past different depths in the soil profile. It can only be used where there is adequate chloride in the profile, and, as with all point estimates, the technique needs to be used carefully due to the very high spatial variability that can occur in soil chloride content over very small scales (Slavich and Yang 1990). The technique relies on a range of assumptions discussed by Slavich and Yang (1990), and requires data on irrigation amounts.

Water balance techniques commonly involve use of the water balance equation over a specified time period:

$$DD = I + R - SD - ET - \Delta SWC$$

Where DD = Deep Drainage beyond the rootzone (specified depth) (or upflow if negative)
I = Irrigation
R = Rain
SD = Surface Drainage

ET = Evapotranspiration
ΔSWC = Change in soil water content (final minus initial) in the rootzone

The biggest source of error in the water balance technique for determining deep drainage is the value assigned to evapotranspiration. Typically, ET is an order of magnitude greater than DD. Thus small errors in ET can lead to large uncertainty in DD estimated using a water balance approach.

ET is commonly estimated from potential evapotranspiration (calculated from weather data using a variety of theoretical equations) and crop factors. ET from rice has also been determined using Bowen ration (Bethune and Wang 2000; Inman-Bamber and Spillman 2000). In some studies evapotranspiration is estimated from the decrease in soil water content between irrigations (and rain events where they occur), and again there can be significant uncertainty in the data because of spatial variability in soil water content, errors in the calibration of instrumentation, inability to sample until the soil is dry enough to walk on (where manual determinations are made, such as with neutron probes), and drainage beyond the depth of sampling. In some situations infiltration is determined from the increase in soil water content of the profile, and is used in the water balance instead of measuring irrigation and surface drainage.

In the case of ponded rice, evapotranspiration can be readily determined from lysimeters with sealed bases in the field (e.g. Bethune et al. 2001), provided crop growth in the lysimeters is representative of the field (Humphreys et al. 1994), and there are no edge effects (due to trampling, for example). Alternatively, infiltration and change in soil water content can be used to estimate deep drainage past the nominated depth (e.g. Beecher et al. 2002). Humphreys and Barrs (1998) compared estimates of deep drainage using chloride mass balance and two methods of water balance in ponded rice, and found good agreement for a range of drainage rates, while Willis et al. (1997) found good agreement between these two techniques in furrow irrigated cotton for varying drainage rates.

The water balance equation is also commonly used to estimate ET, and frequently with the assumption that deep drainage is negligible. In this case there is uncertainty in the estimation of ET associated with errors in the determination of other components of the water balance, in addition to the assumption of negligible deep drainage.

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Table 2. Results of determinations of components of the water balance – lysimeter studies

REFIRR No.	Location	Soil		Crop	Layout	Watertable		Irrigation		Rain	Runoff	Net deep drainage (-ve = upflow)			ET (crop water use)		Source
	(nearest town)	**local name**	**type**			**depth (m)**	**salinity (dS/m)**	**method**	**amount (mm)**	**(mm)**	**(mm)**	**method**	**amount (mm)**	**depth (m)**	**method**	**amount (mm)**	
149	Macalister QLD		cracking grey clay	cotton	beds			furrow subsurface drip	*96/7 327* *97/8 343* *98/9 487* 96/7 150 97/8 142	*478* *667* *579* 478 667		Drainage collected in cavity filled with silica flour at 2m and measured in tipping bucket	182 162 152 305 95	2			Moss et al. 1999
154	Griffith NSW	Hanwood loam Mundiwa clay loam	red brown earth transitional red brown earth	maize	flat	0.6, 1.3	0.1	sprinkler - overhead	442 416	63	0	volume added to maintain WT	-212 (upflow) -57	0.6/1.3	weight change	637 530	Smith et al.1993 Prathapar and Meyer 1992
170 171	Griffith NSW	Hanwood loam Mundiwa clay loam	Red brown earth (RBE) Transitional RBE	Soybeans	flat	1 from 18 DAS	0.1	sprinkler - overhead	85/6 605 87/8 539	115 115	0 0	volume added to maintain WT	-216 (upflow) 46	1	weight change	899 710 (underest. due to edge effect?)	Meyer et al. 1990a Dugas et al. 1990 Meyer and Mateos 1990 Meyer 1988
136 132	Griffith NSW	Hanwood loam (H) Mundiwa clay loam (M)	Red brown earth (RBE) Transitional RBE	lucerne	flat	0.6 1.0 1.0	0.2 0.2 0.2 16	sprinkler - overhead	90/1 629, 707 91/2 838, 750 92/3 370, 362	69 115 381	0	volume added to maintain WT	H, M 90/1 -809, -199 91/2 -749, -587 92/3 -251, -118	0.6 1 1	weight change	H, M 1483, 905 1536, 1338 1013, 875	Meyer et al. 1996 Zhang et al. 1999
170 171	Griffith NSW	Hanwood loam Mundiwa clay loam	Red brown earth (RBE) Transitional RBE	wheat	flat	1986 1.0 1987 1.3 1986 1.0 1987 1.3	0.1 0.1 0.1 0.1	sprinkler - overhead	229 226 113 187	251 261 209 210	0 0	volume added to maintain WT	-140 (upflow) -76 -157 -42	1	weight change	501 521 433 425	Meyer 1988 Meyer et al. 1990b
134	Griffith NSW	Hanwood loam	Red brown earth	Wheat	Flat	None		sprinkler - overhead		225	0	volume collected	66	1.5	weight change	681	Meyer 1984 Meyer et al. 1987 Meyer et al. 1989
215	Echuca VIC		Clay	Rice	Flat			Ponded throughout			0	I+R-ET-ΔSWC	121 (rice on rice) 382 (1^{st} rice)	0.3	Volume added to lysimeters in field with sealed base	1276 1200	Bethune et al. 2001
	Tatura VIC	Goulburn clay loam	Shallow loam A underlain by heavy impermeable B horizon	Perennial pasture	Flat	0.6 1.2 1.8	5 5 5	Ponded for 6 hours and applied at ETo-R=50 mm ETo-R=80 mm	1999 846 2000 827	543 590	0 0	Difference between water entering and leaving the base of the lysimeters	6 5	0.6-1.8 0.6-1.8	Water balance ET=I+R-SD-DD-ΔSWC	1241 1256	Bethune and Wang (2003)

Table 3. Results of determinations of components of the water balance – field studies - COTTON

REFIRR ID	Location	Soil		Layout	Watertable		Irrigation I		Rain R	Surface drainage SD	Net deep drainage (-ve = upflow)			ET		Source
	(nearest town)	local name	type		depth (m)	salinity (dS/m)	method	amount (mm)	(mm)	(mm)	method	amount (mm)	depth (m)	method	amount (mm)	
224	Narrabri NSW		Cracking grey clay	1 m x 1000 m beds			Furrow . 1975/6 1976/7	No. 1 154 [A] 2 247 [A] 3 302 [A] 1 132 [A] 2 298 [A] 2 277 [A] 3 389 [A] 4 443 [A] infiltration	 550 550 550 502 502 502 502 502	 5 138 190 27 120 90 158 170	Hydraulic conductivity soil water relationship	Negligible upflow in all treatments		R+ΔSWC-SD	 704 659 662 607 680 689 743 775	Cull et al. 1981
147	Moree NSW		cracking grey clay (Gwydir) red loam (Gwydir) cracking grey clay (Namoi)	1 m x 1000 m beds			furrow	397 372 176	161 19 0	139 34 9	Water balance DD=I+R-ET-SD -ΔSWC (for 3-6 days during & after irrig.)	158 53 3	1	ΔSWC		Silburn and Montgomery 2001
149	Lower Macquarie Valley NSW	Mullah Wilga	cracking grey clay red brown earth	? m x 859 m beds ? m x 576 m beds	~2 m		furrow furrow	378 [A] infiltration 502 [A] infiltration	328 [B] 335 [C]		water bal Cl^- mass bal Darcy water bal Cl^- mass bal	236 214 67 145 104	2 2 1.05, 2 2 2	Kc x modified Penman	542 585	Willis et al. 1997
151	Narrabri NSW		Cracking grey clay	16 rows x 200 m 4 years			furrow surface drip subsurf. drip	89-485 [A] 122-616 149-585	215-506 [F] 193-484 [F] 187-502 [F]							Chan and Hodgson 1981
138	Griffith NSW	Wunnamurra clay Hanwood loam	cracking grey clay red brown earth	8 m x 35 m plots beds >8 m x 35 m plots beds	~1.5? 1.8		furrow furrow				ET-ΔSWC	32-42% crop water use from upflow 5-11% crop water use from upflow	1 1	Kc x modified Penman		Mason et al. 1983
222	Dubbo NSW	Mullah Grey Mitchell Poorly Drained Wilga Non Calcic Macquarie	Uniform heavy clay Duplex, heavy B Duplex light B Uniform silty loam	Point samples in paired sites with history of cleared dryland use or irrigated cotton			Furrow – farmer records of number of irrigations, and assumed 100 mm/irrigation				Chloride mass balance	17 45 131 202				Willis and Black 1996
225	Merah N. NSW		Grey self mulching clay ~67% clay and sodic	Cotton-cotton Cotton-wheat Cotton-dolochos							Cl^- mass bal	98 76 19				Weaver et al. 2002

[A] amount infiltrated based on measured change in soil water content using neutron counts
[B] rain during Oct-Dec (after first irrigation) was 272 mm, approx. double the long term average of 121 mm
[C] rain during Oct-Dec (after first irrigation) was 236 mm, approx. double the long term average of 121 mm

Table 4. Results of determinations of components of the water balance – field studies - RICE

REFIRR ID	Location	Soil		Layout	Watertable		Irrigation I		Rain R	Surface drainage SD	Net deep drainage (-ve = upflow)			ET		Source
	(nearest town)	local name	type		depth (m)	salinity (dS/m)	method	amount (mm)	(mm)	(mm)	method	amount (mm)	depth (m)	method	amount (mm)	
140 141	Coleambally NSW	1. - 2. - 3. Mixed 4. Marah 5.Tenningerie 6.Willbriggie/Yooroobla 7.Willbriggie/Yooroobla 8.Willbriggie/Birganbigil	Red brown earth Red brown earth Red brown earth Red brown earth Transitional RBE / self-mulching c Transitional RBE / self-mulching c Transition RBE /RBE	29 ha 13 ha 24 ha 24 ha 36 ha 24 ha 56 ha 25 ha	<1 <1 1-2 1-2 5 >7 >7 1-2		ponded	1300 1240 1190 1230 1840 1290 1290 1260	50 9 10 7	100						Humphreys et al. 1998 Hope 2001
205	Griffith NSW	Hanwood loam	Red-brown earth	Sprinkler 2 m strips; Ponded 10 m x 5 m	1.8		Sprinkler 3/wk 1.28 x Epan 1.12 x Epan 0.95 x E pan ponded	 1710 1560 1270 9600								Blackwell et al. 1985
206	Yanco NSW	Birganbigil clay loam	Red-brown earth	Plots 50 m x 14 m			PF= perm. flood PF at 3 leaf PF at PI One per week (2 h)	 2270 1580 900								Heenan and Thompson 1984
207	Yanco NSW	Birganbigil clay loam	Red-brown earth	Plots 50 m x 14 m			PF= perm. flood PF at 3 leaf PF at PI One per week (2 h) One per week (24 h)	 2190 1620 1210 830								Heenan and Thompson 1985
208 209 210	Whitton NSW	Mundiwa clay loam	Transitional red-brown earth	Plots 18 m x 22 m			Ponded Sprinkler 3/wk Sprinkler 2/wk Sprinkler 1/wk	1059 707 638 587	268							Muirhead et al. 1989 Humphreys et al. 1989a,b
211	Whitton	Mundiwa clay loam	Transitional red-brown earth	Plots 8 m x 20 m			Ponded 0.25 dS/m 0.5 dS/m 1.0 dS/m 1.5 dS/m 2.0 dS/m	 1832, 1802 1998, 1800 2284, 2123 2372, 2198 2456, 2466								Beecher 1991
214	Coleambally NSW	Willbriggie clay loam	Transitional red brown earth	Plots 18 m x 22 m	Deep		Aerial sown rice Aerial sown puddled Combine sown rice Direct drilled rice Direct drilled compacted	1630 1390 1570 1550 -	90		I+R-ΔSWC-ET	510 270		Lysimeter in plots (planted, 1.2 m diam)		Humphreys 1994
142	Deniliquin NSW	Noorong clay loam Neimur clay		30 ha field ? ha field	Deep Deep		ponded	1230 1330	90 130	0 80				I+R-SD-infiltration	1180 1230	Humphreys 1997
217	Various – southern NSW	Various 154 sites across 29 rice fields	Transitional RBE, RBE, self-mulching clay, non self-mulching clay	Commercial fields – point measurements	<1 1-2 >3		Ponded				Chloride mass balance; water balance where insufficient chloride	Range 40-2800 Mean 240 Median 59 75% below 180	0.9			Beecher et al. 1996, 2002
215	Echuca VIC	Light to medium clay to 0.1 m over blocky heavy clay		Two bays 1.5 and 6 ha in commercial field			ponded	N/A 1347 (I-SD)								Bethune et al. 2001

Table 4. Results of determinations of components of the water balance – field studies – RICE (continued…)

REFIRR ID	Location	Soil		Layout	Watertable		Irrigation I		Rain R	Surface drainage	Net deep drainage (-ve = upflow)			ET		Source
	(nearest town)	local name	type		depth (m)	salinity (dS/m)	method	amount (mm)	(mm)	SD (mm)	method	amount (mm)	depth (m)	method	amount (mm)	
218	Deniliquin			Small plots 20 m	6 m		Ponded				Chloride mass		1.5			Slavich et al.
219	NSW			x 6 m			Gypsum before rice				balance					1992
		Wandook clay	Heavy sodic clay (non self-				0 t/ha 6 mths					444				Slavich et al.
			mulching)				2.5 6 mths					767				1993
							5 6 mths					1022				
							10 6 mths					1020				
		Moulamein clay	Heavy sodic clay (non self-	Small plots 20 m	*> 4*		*0 18 mths*					*110*				
			mulching)	x 6 m			*2 18 mths*					*70*				
							5 18 mths					*110*				
							10 18 mths					*120*				
		Moulamein clay (saline)	Heavy sodic clay (non self-	Whole bays (4	<2		0 t/ha 6 mths					-40				
			mulching)	ha)			2.5 6 mths					110				
							5 6 mths					370				
		Birganbigil loam	Red brown earth	5 m x 5 m plots	*>4*		*0 t/ha 6 mths*					*420*				
							2.5 6 mths					*330*				
		Birganbigil loam	Red brown earth	5 m x 5 m plots			*5 6 mths*					*1010*				
					<2		0 18 mths					90				
							5 18 mths					130				
220	Deniliquin						Ponded				All- chloride					Humphreys
	NSW						Gypsum immed.				mass balance					and Barrs
							before rice at (t/ha)									(1998)
		Moulamein clay	Heavy sodic clays (non self-	Small plots 6 m x	>4		0					60				
		Billabong clay	mulching)	6 m			2.5					130				
		Moulamein clay		Small plots 6 m x	1.5-2		0					50				
				6 m			2.5					70				
				Small plots 15 m	deep		0				Also water	50				
				x 20 m			1.6				balance DD=	160				
							3				I+R-ΔSWC-ET	200				
							10				& DD= inflt-	300				
											ΔSWC					

Table 5. Results of determinations of components of the water balance – field studies - MAIZE

REFIRR ID.	Location	Soil		Layout	Watertable		Irrigation I		Rain R	Surface drainage	Net deep drainage (-ve = upflow)			ET		Source
	(nearest town)	local name	type		depth (m)	salinity (dS/m)	method	amount (mm)	(mm)	SD (mm)	method	amount (mm)	depth (m)	method	amount (mm)	
150	Homehill QLD		solodic solonised solonetz	0.75 m x 315 m beds			furrow	724 yr 1 -G 540 yr 2 -G 600 yr 2 +G			Cl^- mass bal	0-90[A] -G 70-200 [A] +G		Infiltr[B]-DD	946-918 –G 1417-1300 +G	Dowling et al. 1991
138	Griffith NSW	Wunnamurra clay Hanwood loam	cracking grey clay red brown earth	8 m x 35 m plots beds >8 m x 35 m plots beds	~1.5? 1.8		furrow furrow				ET-ΔSWC	32-42% crop water use from upflow 5-11% crop water use from upflow	1 1	Kc x modified Penman		Mason et al. 1983
140 141	Coleambally NSW	Willbriggie/Yooroobla	clay loam	34 ha 1.8 x 600 m beds	deep		furrow	900	80	100						Humphreys et al. 1998; Hope 2001
152	Finley NSW	Tuppal loam Moira loam	red brown earth	20 ha 1.5 m beds	1-3.5		furrow	802	95	?	ΔWTD and drainable porosity	46				Edraki et al. 2002
153	Griffith NSW	Marah clay loam	transitional red brown earth	flat 9 m x 10 m plots	deep		flood	636	45	0	Cl^- mass bal	10-20	1.5	I+R-ΔSWC	589	Downey 1971

[A] infiltration varied with position down the row (highest nearer supply end)
[B] infiltration calculated using the furrow irrigation model KIM and observations of advance and recession times and irrigated furrow geometry

Table 6. Results of determinations of components of the water balance – field studies - WHEAT

REFIRR ID	Location	Soil		Layout	Watertable		Irrigation I		Rain R	Surface drainage SD	Net deep drainage (-ve = upflow)			ET		Source
	(nearest town)	**local name**	**type**		**depth (m)**	**salinity (dS/m)**	**method**	**amount (mm)**	**(mm)**	**(mm)**	**method**	**amount (mm)**	**depth (m)**	**method**	**amount (mm)**	
175 176	Leeton NSW	Birganbigil clay loam	Red brown earth	Plots 15.2 m x 2.1 m			flood No irrig Ep-R=150 Ep-R=100 Ep-R=50	 - 255 290 435	 293 293 293 293	 0 0 1 10				Water balance ET=I+R-ΔSWC (assumed DD=0)	 408[A] 635[A] 707[A] 818[A]	Cooper 1980a,b
177	Griffith NSW	Hanwood loam	Red brown earth	Plots 10 m x 50 m	1.8		flood None SWD=90% SWD=70% SWD=40%	 58 [B] 349[B] 397[B] 437[B]	48		Difference between ΔSWC and estimated ET	 41 -6 19 11	1.15			Steiner et al. 1985
134	Griffith NSW	Hanwood loam	Red brown earth	Field 1981 1982 1982	1.5-2.1		Sprinkler – overhead; PAW 50% PAW 50% PAW 75%	 306 602 628 rain gauges	 200 24 24	 0 0 0	Difference between ΔSWC and estimated ET	 71 49 81	 1.5 1.7 1.7	Penman	 598 643 645	Meyer et al. 1984
178 179	Tatura VIC	Lemnos loam	Red brown earth	Plots 22 m x 3 m			Flood None Fortnightly Weekly	 - 310 380 (I-SD)	78					Water balance ET=I+R-ΔSWC (assumed DD=0)	 310 490 560	Whitfield et al. 1989 Whitfield and Smith 1989
185	Tatura VIC	Lemnos loam	Red brown earth	Plots 22 m x 3 m			Flood None 1985 Fortnightly 1985 Weekly 1985 None 1987 Fortnightly 1987 Weekly 1987	 - 190 340 - 280 440	*1985* 217 *1987* 110					Water balance ET=I+R-ΔSWC (assumed DD=0)	See Figures 1&2 in Whitfield and Smith (1992)	Whitfield and Smith 1992

[A] ET considered to be overestimated due to small plot size and edge effects

[B] Amount infiltrated based on measured change in soil water content using neutron counts

Table 7. Results of determinations of components of the water balance – field studies – GRAIN LEGUMES

REFIRR No.	Location	Soil		Crop	Layout	Watertable		Irrigation I		Rain R	Surface drainage SD	Net deep drainage (-ve = upflow)			ET		Source
	(nearest town)	local name	type			depth (m)	salinity (dS/m)	method	amount (mm)	(mm)	(mm)	method	amount (mm)	depth (m)	method	amount (mm)	
154	Leeton NSW	Birganbibil clay loam	transitional red brown earth	soybeans	6 x 15 m 0.75 m beds			Furrow I+R-SD	net 730								Thompson 1977
155	Leeton NSW	Birganbibil clay loam	transitional red brown earth	soybeans	6 x15 m 0.75 m beds			Furrow I+R-ΔSWC	net 786	66	0						Thompson 1978
161	Narrabri NSW		cracking grey clay	soybeans	10x120 m 1 m beds			furrow ET=90 ET=135	 260-451 170-290	335-551	 48-352 18-242	ΔSWC in covered bare soil	12 mm over 9 days after an irrigation	1.5	water balance with DD=0	 562-748 530-596	Mason et al. 1980
163 164	Kunnanurra WA	Cunnanurra clay	Cracking dark borwn clay	soybeans	1.5-1.8m beds, 8 rows x 30 m			furrow SSC Ep=30 Ep=60 Ep=120 Ep=240							 Epan x 1 ΔSWC ΔSWC ΔSWC ΔSWC	 688 477 638 404 593 316 469 214 345	Garside et al. 1992a, b
166	Kunnanurra WA	Ord sandy loam	fine sandy loam	Soybeans Cowpea Pigeon pea Lablab beans Green gram Black gram	30x18 m plots for irrig tmts, 30x2m variety subplots			Sprinkler – overhead; -weekly (50-60 mm) -weekly for 1st 6 weeks -weekly for 1st 2 weeks			none				Water balance ET=I+R-ΔSWC (assumed DD=0)	 559-826 412-507 239-292	Muchow 1985
140 141	Coleambally NSW – 5 fields	Cobram, Coree, WunnamurraMarah, Wilbriggee, Yooroobla	loam, clay loams, self-mulching clays, nonself-mulching clay	soybeans	13 ha – beds 27 ha beds 28 ha beds 24 ha beds 24 ha beds	<1 <1 3-6 1-2 1-2		all furrow – propellor or ultrasonic flowmeter, Dethridge wheel	2930 1750 810 1020 850	80 80 50 50 30	1950 820 110 290 200						Humphreys et al. 1998; Hope 2001

Table 8. Results of determinations of components of the water balance – field studies – OTHER CROPS (SORGHUM, KENAF, SAFFLOWER, SUNFLOWER)

REFIRR No.	Location	Soil		Crop	Layout	Watertable		Irrigation I		Rain R	Surface drainage SD	Net deep drainage (-ve = upflow)			ET		Source
	(nearest town)	local name	type			depth (m)	salinity (dS/m)	method	amount (mm)	(mm)	(mm)	method	amount (mm)	depth (m)	method	amount (mm)	
138	Griffith NSW	Wunnamurra clay	cracking grey clay	sorghum	8 m x 35 m plots beds	~1.5?		furrow				ΔSWC & modified Penman	32-42% crop water use from upflow	1			Mason et al. 1983
138	Griffith NSW	Hanwood loam	red brown earth	sorghum	>8 m x 35 m plots beds	1.8		furrow				ΔSWC & modified Penman	5-11% crop water use from upflow	1			Mason et al. 1983
193	Kununurra WA	Cununurra clay	Cracking dark brown clay	Safflower	Plots 7 m x 155 m			Flood – bordercheck Frequent to avoid water deficit		0		Soil water content, and soil hydraulic & physical properties (Rose et al. 1965)	82	1.0	Water balance ET=I+R-ΔSWC-DD	434	Stern 1965
194 195	Kununurra WA	Cununurra clay	Cracking dark brown clay	Kenaf	Plots 7 m x 155 m; 1.5 m beds			Furrow None LWP=-1.35 MPa LWP=-1.15 MPa LWP=-0.85 MPa	ΔSWC - 295 440 563	0	Measured			1.85	I-SD	Wk 6-16 ET/Ep) 267 (0.40) 473 (0.70) 686 (1.02) 785 (1.17)	Muchow 1980 Muchow and Wood 1981
196	Narrabri NSW		Cracking grey clay	Sunflowers				Furrow (0-5) irrigations early, mid, late varieties/sowings						1.65	ΔSWC	Early/early (4) 593-692 Early/late (4) 564 Mid/early (1) 534 Mid/early (2) 670 Mid/early (3) 764 Mid/early (5) 834 Late/early (1) 551 Late/early (2) 709 Late/early (3) 830 Late/early (5) 957 Late/mid (3) 555 Late/late (4) 677	Dubbelde et al. 1982
197	Leeton NSW		Red-brown earth (loam)	Sunflowers	Plots 6.8 m x 15/7.5 m 0.75 m hills			Furrow Expt 1 (Ep-R)xfrac. groundcover = 65 130 flowmeter						1.6	I+R-ΔSWC	 598 677	Browne 1977
198	Tatura VIC	Shepparton fine sandy loam	Red-brown earth	Sunflowers 2 years	Plots 13.5 m x 30 m			Flood weekly none fortnightly etc	 450, 510 , 300	121, 92				1.5	I+R-ΔSWC	 638, 620 266 , 420	Connor et al. 1985

Results

Fifty-four reports were found in which one or more components of the water balance were determined for irrigated annual crops in Australia. The results of these studies are summarised in Tables 2-8. Results of an additional 21 studies in pastures are summarised in Bethune (2001a), and his main findings are also reported below. The vast majority of the studies on irrigated crops and pastures were undertaken in the southern Murray-Darling Basin, with a few studies in northern NSW, Kununurra (WA) and Queensland. Almost one-third (17) of the 54 reports on irrigated crops were for rice, and some of these were quite comprehensive investigations over a range of soil types and locations, especially the work of Beecher et al. (1996, 2002). There were similar numbers of studies (6-8) on wheat, cotton, maize, soybeans and "other" crops.

Deep drainage and upflow determinations in lysimeters

Only eight lysimeters studies were found in which deep drainage or upflow were determined (Table 2). Direct measurement was undertaken in seven of these studies by collection and measurement of drainage, or by measurement of the amount of water required to maintain the watertable at the nominated depth in the case of upflow. Four studies involved shallow watertables, and three involved determinations of deep drainage with a deep or no watertable.

Lysimeter studies with deep watertables

Using large "suction" lysimeters in a commercial field in Queensland over three years, Moss et al. (1999) found that deep drainage from furrow irrigated cotton on a cracking clay soil ranged from 152 to 182 mm. Perhaps surprisingly, they also found significant deep drainage (95 and 305 mm) for cotton irrigated with sub-surface drip irrigation, despite irrigation application rates of about half those in the furrow irrigated field. The very high value of 305 mm in 1996/97 was due to the fact that the lysimeter was located in an area of the field where water ponded for a considerable length of time following heavy rainfall. This is a graphic illustration that deep drainage depends on more than the method of irrigation – layout and management are also important.

At Griffith, NSW, Meyer et al. (1987) determined deep drainage of 66 mm from overhead sprinkler irrigated wheat growing on a Hanwood loam, a freely draining red brown earth, in a year of slightly below average rainfall during the wheat season.

Lysimeter studies with shallow watertables

Bethune and Wang (2003) determined components of the water balance, including deep drainage, for perennial pasture in drainage lysimeters, on a Goulburn clay loam, a duplex soil with a shallow loam A horizon and a medium clay subsoil. A pond of water was maintained for six hours on the surface during irrigations, and after this time remaining surface water was removed and measured as runoff. Watertable depth (0.6, 1.2, 1.8 m) and irrigation schedule (ET-R=50, 80 mm) only had a minor impact on recharge, which averaged 2 mm/yr. There was a small amount of upflow in the peak of summer. The leaching requirement for ryegrass/clover perennial pasture is 10 mm/yr with 0.1 dS/m irrigation water, therefore salt accumulation would impact on pasture growth at some stage in the future on this soil.

In a series of studies in weighing lysimeters with shallow fresh (0.1 dS/m) watertables ranging from 0.6 to 1.3 m, Meyer and colleagues found that even for well-watered crops, crop water use from upflow from the watertable can be substantial. Water use from the watertable varied with soil type, decreased with increasing salinity of the watertable and depth to the watertable, and increased when the upper soil layers dried. In soybeans upflow from a 0.1 dS/m watertable at 1 m varied from 20 to

25% of crop water use on a Hanwood loam to 8% on a poorly structured and heavier Mundiwa clay loam (a transitional red brown earth) (Meyer et al. 1990a). Crop water use from the watertable for maize was slightly higher (29% on the Hanwood loam and 16% on the Mundiwa clay loam) for a watertable at 0.6 m from 19 to 75 days after sowing (DAS), and at 1.3 m from 78 DAS to maturity. Wheat crop water use from a 1 m watertable was similar at 28% from the Hanwood loam, and 15% from the Mundiwa clay loam with a watertable at 1 m, compared with 36% and 10% with a slightly deeper watertable (1.3 m) in the following year. Lucerne water use from a watertable at 0.6 m during the growing season was 49 to 55% of evapotranspiration (Meyer et al. 1996; Zhang et al. 1999). This increased to 90% during a drydown period when the watertable was dropped to 1 m, forcing more roots to grow in layers immediately below the upper layers as they progressively dried, and resulting in the expression of water deficit symptoms in the plant tops. The proportion of crop water use from upflow was reduced to 25% during the irrigation season when the watertable salinity was increased from 0.2 to 16 dS/m at a depth of 1 m at the end of the preceding irrigation season.

Deep drainage and upflow determinations in the field

There are few reports on field investigations of deep drainage from irrigated annual field crops, and the majority of these have been done in rice in the southern Murray-Darling Basin (MDB) (Table 3), and in cotton in the northern MDB (Table 4).

Cotton

Until recently deep drainage was generally thought to be close to zero in the cracking clay soils of the northern MDB (Hearn 2000). Willis and Black (1996) used chloride mass balance to determine the average deep drainage rates on four different soils with histories of irrigation from 5 to 23 years. They found that average deep drainage ranged from 17 to 200 mm/yr, and appeared to be related to clay content. Weaver et al. (2002a) determined deep drainage from cotton of 98, 76 and 19 mm in cotton-cotton, cotton-wheat and cotton-dichlos rotations on cracking grey clay, and found a highly significant correlation between deep drainage and change in apparent conductivity using EM38 in the horizontal mode. Further evidence of deep drainage comes from leaching of nitrate and chloride beyond the rootzone of cotton (Weaver et al. 2002a,b). Silburn and Montgomery (2001) reviewed the results for cotton and found that deep drainage varies considerably within the cracking grey clays (from negligible to 236 mm during the cropping season), and that high quantities of deep drainage were associated with saturated subsoils throughout the cropping season. These findings have led to the recommendation of a major and coordinated approach to develop better water balance and deep drainage information at field to sub-catchment scales for the northern MDB (Lyle et al. 2002).

Rice

In ponded rice fields, there have been numerous determinations of deep drainage, which has ranged from 40 to 2,800 mm (Table 4). There are trends in deep drainage across broad soil groups, but variation within soil group is too large to use soil group to predict deep drainage, and clay content is a poor predictor of deep drainage for self-mulching clays and sodic soils (Beecher et al. 2002). Spatial variability in deep drainage can be enormous within the one field (e.g. Beecher et al. 1996), and has been shown to be related to some degree to EM31 measurements of apparent electrical conductivity (ECa) and to soil sodicity. Using these relationships Beecher et al. (2002) developed an improved system of soil classification for rice for reducing deep drainage, based on EM31 measurements and sodicity of the 0-60 cm and 60-150 cm soil layers.

Deep drainage in ponded rice can be affected by the application of gypsum at various times in the crop rotation. Deep drainage was increased by up to 600 mm when gypsum was applied to sodic soils at rates up to 10 t/ha within 6 months prior to ponding for rice, however applications of up to 10 t/ha had no effect on deep drainage during the rice phase when applied 18 months prior to rice, regardless of soil type (Slavich et al. 1992, 1993; Humphreys and Barrs 1998). From lysimeter studies in the field, gypsum applied to highly sodic soils prior to ponding increased infiltration by averages of 60 mm (at 1.25 t gypsum/ha), 90 mm (2.5 t/ha) and 110 mm (5 t/ha), however the response to gypsum application was also quite variable across the nine sites (e.g. an increase in infiltration of 10 to 250 mm with 2.5 t gypsum/ha) (Humphreys and Barrs 1998).

Irrigation with saline water can increase infiltration and deep drainage and therefore field water use. Beecher (1991) found that water use by ponded rice increased by about 350 mm as irrigation water salinity was increased from 0.25 to 2 dS/m on a Mundiwa clay loam. Virtually all the increase in water use would have been due to increased deep drainage, as ET would have been similar at all salinities in a ponded crop where crop growth was unaffected by salinity, and with banks to prevent runoff. Even a small increase in irrigation water salinity from 0.25 to 0.5 dS/m in the first year increased water use by 166 mm. Similar results have been found for pastures on a Lemnos loam (Lyle et al. 1986). Thompson et al. (1997) also found that increasing irrigation water salinity from 0.1-0.5 to 1-2 dS/m almost doubled infiltration rate at two sites on red-brown earth soils, but there was no effect on a non self-mulching clay or on a self-mulching clay.

Initial soil water content and degree of cracking can also influence the amount of deep drainage from ponded rice. Bethune et al. (2001b) found much higher deep drainage (382 mm below 0.3 m, half of which occurred in the first 24 hours after ponding) in an area which had not previously grown rice, compared with a nearby area in the same field which had grown three consecutive crops of rice. They attributed the higher deep drainage to the fact that the soil was dry and cracked to depth in the new rice area. However total water application over the season at the bay scale was about 200 mm less than in the lysimeters, and it was suggested that the slower wetting of the bays (2 to 3 days to achieve ponding) may have allowed time for the soil to swell and restrict deep drainage losses. Puddling and compaction are effective in reducing infiltration and therefore deep drainage from rice (Humphreys et al. 1995, 1998).

How much of the soil water and winter rain after rice harvest is ultimately lost as deep drainage is influenced by subsequent landuse. Rice is ponded until near maturity, resulting in a saturated profile at the start of winter which is conducive to continuing deep drainage , exacerbated by low evaporative demand and winter rain. The role for crops immediately following rice to dry out the soil profile and capture and use winter rainfall and reduce net recharge has been demonstrated by Humphreys et al. (2001).

Maize

There are three reports of deep drainage from irrigated maize and one of upflow (Table 5). On a sodic soil in Queensland, Dowling et al. (1991) used chloride mass balance to determine deep drainage of 0 to 90 mm in the absence of gypsum, and 70 to 200 mm with 20 t gypsum/ha for furrow irrigated maize. Deep drainage rates decreased with distance down the 315 m long furrows due to reduced duration of ponding. Edraki et al. (2003) determined deep drainage of 46 mm from furrow irrigated maize on a red brown earth (Tuppal/Moira loam) from the rise in the watertable and the difference in volumetric water content between saturation and field capacity. This method underestimates deep drainage where there is significant downward or lateral seepage of the groundwater. Downey (1971) calculated deep drainage of 10 to 20 mm from chloride mass balance in small plots, however this would underestimate the field situation where the opportunity time for deep drainage would be much longer than in small experimental field plots with short irrigation times. Mason et al. (1983) inferred upflow from maize (and cotton and sorghum) of 5 to 40% of crop water use in the presence of watertables at around 1.5 to 1.8 m, with lower values for the lighter soil type (and possibly a deeper watertable).

Wheat

Using a water balance approach on a Hanwood loam, deep drainage over the duration of the crop from overhead sprinkler irrigated wheat varied from –6 mm (upflow) to 41 mm in the presence of a watertable at 1.5 to 2.1 m (Steiner et al. 1985). Deep drainage was greatest in plots where the wheat was not irrigated, and least when frequently irrigated (irrigated when plant available water (PAW) had been reduced to 90% of full capacity). These results demonstrate the influence of crop growth on the fate of water – poorer growth in the non-irrigated plots resulted in more deep drainage than on the irrigated plots where the crop grew better and was able to intercept more rainfall. In a different season on the same soil, with flood irrigation, Meyer et al. (1984) determined deep drainage of 49 to 81 mm when irrigating at PAWs of 50 to 75% of full capacity. Taken together, the results of these studies demonstrate that the relationship between irrigation frequency and deep drainage is complex, depending on the depth of cracking, the incidence and amount of rain, and the ability of the crop to use the water (the sink strength and its distribution within the soil profile). The findings for wheat are summarised in Table 6.

Grain legumes

Six studies of components of the water balance were found for soybeans, and one of these studies also included a range of other grain legumes (Table 7). Only one study determined deep drainage, and this was done in an adjacent bare area covered to prevent evaporation, following a single irrigation. Deep drainage (below 1.5 m) of 12 mm over 9 days after irrigation was calculated from the change in soil water content of a cracking grey clay soil at Narrabri (Mason et al. 1980). This would overestimate actual DD under the crop due to plant water uptake.

Other crops

Stern (1969) determined deep drainage of 82 mm below 1 m for well-irrigated safflower growing on a Cununurra clay in the dry season, calculated from soil water content and physical properties and theoretical relationships (Table 8). Mason et al. (1983) estimated upflow of 32 to 42% of crop water use for sorghum growing on a cracking grey clay (watertable depth uncertain, possibly within 1.5 m), and 5 to 8% for sorghum on Hanwood loam with a watertable at approximately 1.8 m.

Pastures

Bethune (2001) reviewed the findings of 21 published and unpublished studies of deep drainage under border check irrigated pasture. All these studies (but two) were carried out on perennial pasture, and the majority of them were on heavy textured soils in the southern MDB. Deep drainage was most commonly estimated from chloride mass balance, water balance or pump tests, and ranged from negligible to 600 mm/yr. Bethune (2001) concluded that the available information indicates that there is little deep drainage under flood irrigated pasture on heavy soils, with leaching fractions of 5 to 10% of the amount of water infiltrating the soil. However there are only limited data for lighter textured soils, and the available information suggests that deep drainage rates under flood irrigation on these soils could be high (>300 mm/yr).

Bethune (2001) noted that irrigation water applications are often high in the first irrigation of annual pasture (200 to 300 mm on cracking clays, 100 to 150 mm on duplex soils), and that the fate of this water is largely unknown – is it consumed in wetting up the profile or does it contribute directly to deep drainage? Bethune (2001) also noted that even if the water is restricted to wetting up the profile, then this is likely to lead to increased deep drainage over winter due to reduced storage capacity of the soil as for the situation after rice. He referred to the option of using the pasture to dry the soil profile before winter to reduce deep drainage, and calculated that a soil water deficit of 50 mm might be achievable. This would allow storage of surplus winter rain (R-ET) in an average year, however in 50% of years R-ET would exceed the available storage.

As for wheat (above), Bethune (2001) found that the relationship between irrigation frequency and deep drainage for pasture is complex and depends on the degree of cracking and the sink capacity of the pasture. Bethune (2001) also referred to several reports which showed that irrigating pasture with water of increasing salinity increased deep drainage – due to increased hydraulic conductivity, reduced pasture water use, and increased hydraulic gradients.

Crop water use (evapotranspiration) determinations in lysimeters

Bethune and Wang (2003) determined crop water use for perennial pasture on a Goulbourn clay loam over three years. Pasture water use was well approximated by reference evaporation (ETo) calculated used the standardized FAO Penman-Monteith equation. Crop water use requirement was then calculated from ETo-R for 20 years of weather data during the irrigation season, and averaged 776 mm at Tatura (northern Vic.) and 980 mm at Finley (southern NSW), assuming 100% effective rainfall, and 830 and 1,030 mm respectively for 80% effective rainfall.

Crop water use has been accurately determined in weighing lysimeters for soybeans, maize, wheat and lucerne, over a limited range of seasons, watertable conditions and management, for two soils: a Hanwood loam and a Mundiwa clay loam (Table 2). Crop water use on the Mundiwa clay loam was generally reduced due to edge effects as a result of poorer growth and a shorter canopy on this soil compared with the surrounding crop growing on Hanwood loam, causing shelter effects and reduced turbulent transfer from the crop in the lysimeter. The data on the Hanwood loam show that for the limited range of conditions experienced, water use of well-watered maize and wheat can be around 650 mm, soybeans around 900 mm, and well-watered lucerne around 1,500 mm (annually).

There have been a range of determinations of rice crop water use in lysimeters with sealed bases in commercial ponded rice fields (Evans 1971; Lang et al. 1974; Talsma and van der Lely 1976; Humphreys et al. 1994; Bethune et al. 2001b), however few of these studies involved determinations for the entire season. Lang et al. (1974) showed that evaporation from lysimeters in a 30 ha rice field surrounded by arid land was affected by proximity to the downwind edge due to advection, that a fetch of approximately 85 m was needed to avoid advective effects, and that evapotranspiration from an entire field could be estimated within 4% from determinations at the centre of the field. Rice crop water use was strongly correlated to US Class A pan, and to ETo calculated using Penman-Meyer and Penman-Monteith (Evans 1971; Talsma and van der Lely 1976; Humphreys et al. 1994; Bethune et al. 2001b). Using Penman-Meyer, the crop coefficient for calculating ET from ponded rice over the 5-month period from October to February was close to unity (Humphreys 1999). There was a trend for the crop coefficient to increase from about 0.7 early in the season to about 1.1 during the reproductive stage. Using Penman-Monteith, Bethune et al. (2001b) concluded that the crop coefficients recommended by FAO for strong wind conditions (1.1 for the first 2 months, 1.25 for the next 2 months, then 1.0 for the last month) were appropriate.

Indirect field estimates of crop water use

Cotton

Cull et al. (1981) determined cotton water use from change in soil water content and rainfall over two years of above average rain, for different irrigation frequencies. Water use was not greatly affected by irrigation management in the first year, ranging from 659 to 704 mm. In the second year, rain was not evenly distributed during the season, and crop water use increased from 607 mm to 775 mm as the number of irrigations increased from one to four (including a presowing irrigation).

Rice

Humphreys (1997) determined rice crop water use of about 1,200 mm from the water balance where irrigation and surface drainage were measured for two entire rice fields of about 30 ha in the Wakool and Denimein Irrigation Districts of southern NSW, while infiltration was measured at a range of locations with varying EM31 values across the fields. There was good agreement between ET calculated from the water balance and ETo calculated from Penman-Meyer using data from the regional weather stations at Finley and Tullakool, but the data suggested a crop factor a little lower than unity. Bethune et al. (2001) measured rice crop water use of around 1,250 mm in a rice field near Echuca and daily rice crop water use was strongly correlated with ETo calculated using Penman-Monteith, with a crop coefficient of 1.3, which was equivalent to a crop coefficient of 1.05 using Penman-Meyer. Using isotope discrimination, Simpson et al. (1992) found that over the entire rice season, about 40% of the total evaporative loss was by evaporation from the water surface. Early in the season all of the loss was by evaporation from the water surface, by late tillering two thirds of the loss was by transpiration, increasing to 90% around panicle initiation.

Maize

Very few field determinations of maize water use were found. Dowling et al. (1991) found a strong trend for crop water use to decrease with distance down the furrow on a sodic soil with and without gypsum application in Queensland. Crop water use was strongly correlated with yield, suggesting more available water nearer the top end of the furrows, where the ponding duration (and deep drainage!) were higher. Gypsum application greatly increased the water use of maize from around 930 mm to around 1,350 mm and yield from 6.2 to 7.5 t/ha. Downey (1971) used the water balance to estimate maize water use of 589 mm in small plots during a dry summer (45 mm rain) at Griffith. With current varieties and management, crop water use of irrigated maize is likely to be much higher - total biomass production of Downey’s crop was only 12.7 t/ha, compared with current levels of 25 to 30 t/ha for well grown irrigated maize in the same region.

Wheat

Wheat crop water use has been compared for different irrigation frequencies on several occasions in the southern Murray-Darling Basin, calculated using water balance and assuming zero deep drainage. All these studies were done on small plots with flood irrigation, where irrigation times would have been short and therefore the opportunity for deep drainage losses reduced. Crop water use was also considered to be overestimated in the studies of Cooper (1980a,b) due to edge effects from unplanted drains adjacent to the plots.

Crop water use ranged from 310 mm (no irrigation in a fairly dry year at Tatura, Whitford et al. 1989; Whitford and Smith 1989) to 818 mm (irrigation when Epan-R=50 mm in a year of average rain at Leeton, Cooper et al. 1980a,b). Yields increased with irrigation frequency to fortnightly irrigations on a Lemnos loam in a season of low rain (78 mm) (no further improvement with weekly irrigation, Whitford et al. 1989; Whitford and Smith 1989), and with frequency to Epan-R=100 mm on Birganbigil clay loam (no further improvement with irrigation when Epan-R=50 mm) in a year of average rain (Cooper et al. 1980a,b). There was no yield difference between irrigation at PAW=50% or 75% on a Hanwood loam in a year of almost no rain (Meyer et al. 1984).

Grain legumes

Garside et al. (1992) compared irrigation frequencies of cumulative Epan of 240, 120, 60 and 30 mm and saturated soil culture (SSC) for soybeans in the dry season on a Cununurra clay. Crop water use, determined from change in soil water content, increased from 214 (Epan=240) to 477 mm (Epan=30) in the first season, and from 345 (Epan=240) to 688 mm (SSC) in the second year. Seed yields increased linearly with irrigation frequency, and were highest for SSC.

On an Ord sandy loam, Muchow (1985) compared crop water use for a range of irrigation frequencies in a study of the effect of different periods of water deficit stress on the phenology and yield of a range of grain legumes. Under well-watered conditions (weekly), water use varied from 559 to 826 mm (determined from change in soil water content), while seed yields were similar for most varieties. ET/Epan ranged from 0.96 to 1.07, and water use efficiency ranged from 2.45 kg/ha/mm for pigeon pea (cv. Royes) to 4.61 kg/ha/mm for Lalab bean cv. Highworth.

On a cracking grey clay at Narrabri, Mason et al. (1980) compared 5 different irrigation schedules for two varieties of soybeans over three seasons. For frequently irrigated soybeans, crop water use (determined from the water balance and assuming DD=0), ranged from 562 to 748 mm. There were differences between cultivars in the rate of water use and the extent to which they could extract soil water.

Other crops

During the dry season at Kununurra on a Cununurra clay, Muchow and Wood (1981) calculated kenaf water use from the change in soil water content between irrigations (using Epan and an empirical crop coefficient to estimate ET during the 2 days between the start of irrigation and time of the next soil water content determination). The crop was irrigated when leaf water potential (LWP) reached –0.85, -1.15 or -1.35 MPa, and one treatment was not irrigated. Crop water use increased from 267 to 785 mm with irrigation frequency, and ET/Epan increased from 0.4 to 1.17 for the period week 6 to week 16. The economic yield of pulp was highest when irrigating at LWP –0.85 MPa, however it was concluded that LWP could not be recommended for irrigation scheduling because of erratic fluctuations in LWP between irrigations.

Also at Kununurra during the dry season, Stern (1965) used change in soil water content and deep drainage estimated from soil physical properties to determine the water use of well-watered safflower. The ratio of ET to free water evaporation calculated using the Penman equation rapidly rose to a peak of 1.57 at 45 days after sowing when the crop had begun to elongate, then fell to 1.25 and subsequently declined gradually to 1.0 at 100 days and to 0.21 at 140 days. Total ET was 434 mm, and ET appeared to decline from about 115 days (the onset of flowering) onwards, even before there was any depletion of soil water storage. This appeared to be in contrast with the experience with maize, where ET rates are at a peak during flowering, and was considered to be the result of the adverse effects on safflower growth of rising temperatures.

In the southern MDB, crop water use of sunflower at Tatura ranged from 598 to 677 mm for well irrigated sunflowers growing on red brown earth soils (Browne 1977; Connor et al. 1985). At Narrabri a range of varieties was compared by Dubbelde et al. (1982). Crop water use ranged from 534 to 957 mm depending on maturity type, sowing date and irrigation frequency.

Discussion

The review reveals that very few studies attempted to "close" the water balance (i.e. to directly determine all components and assess the error), and important contextual information was often missing (e.g. watertable depth and salinity, rain). All reports were for single crops during the growing season only, apart from the lysimeter study with lucerne by Meyer et al. (1996). Systems approaches are also needed which study components of the water balance over time, as they are affected by the sequence of landuses and their interactions with management and climate. Soil profile water content and physical condition at the end of one crop, and subsequent landuse, can have major impacts on surface and deep drainage from the system, and on the ability to capture and use rain and increase system water use efficiency. For example, surface and deep drainage following a landuse that leaves a soil dry and cracked to depth will be affected by soil mineralogy and the rate of wetting (influenced by rain intensity and timing and irrigation management) and tillage prior to any wetting events. Deep drainage from a wet soil profile going into winter will be affected by whether or not there is an actively growing crop or pasture.

Deep drainage

The review finds that deep drainage is highly variable across and within soils and landuse. General trends exist in deep drainage across soil types, with higher deep drainage on lighter soils (Willis and Black 1996; Bethune 2001; Beecher et al. 2002). However, extreme variability can exist within the one soil type, field and landuse (Dowling et al. 1991; Bethune 2001; Beecher et al. 2002; Weaver et al. 2002a,b). This is particularly the case for self mulching (cracking clay) soils (Silburn and Montgomery 2001). The variability in deep drainage reinforces the conclusions of Lyle (2002) and Bethune (2001) that there is a need for a systematic and comprehensive approach to understanding deep drainage for a range of soil types, landuses and management practices, and in particular its quantification in relation to a defined set of measured soil and site parameters.

The amount of deep drainage can be influenced by a range of management practices. Deep drainage is not directly related to the amount of water applied (Steiner et al. 1985), therefore measures of water use efficiency such as irrigation or total water application can be misleading in identifying more or less efficient irrigation practices or potentially greater deep drainage (except for ponded rice where the influence of crop stage and growth on ET is minor). Irrigating with saline water and application of gypsum increase deep drainage on sodic soils, the amount of deep drainage increasing with salinity (Lyle et al. 1986; Beecher 1991) or gypsum application rate (Slavich et al. 1993; Humphreys and Barrs 1997).

Wet subsoils have been associated with much higher deep drainage in irrigated cotton (Silburn and Montgomery 2001), and wet soil profiles coming into autumn/winter following ponded rice or autumn irrigation of pasture are conducive to higher net recharge. Management options have been identified to help reduce deep drainage in such situations, all of which involve using a subsequent crop or pasture to dry the profile and use winter rain. Examples include growing a winter crop immediately after rice harvest (Humphreys et al. 2001), and not irrigating annual pasture after mid to late April so that there is increased opportunity for the pasture to dry the soil profile prior to winter (e.g. Berriquin LWMP 2001; Cadell LMWP 2001). In the case of wet subsoils and cotton, the role of winter cereals in drying the profile to improve soil structure is well recognised (McKenzie 1998), but its role in helping to manage deep drainage has not been quantified.

Crop water use

While crop water use has been determined for a range of crops in a range of locations, data are generally only available for a single season, whereas weather and crop water use requirement can vary greatly between seasons due to weather variability. The exception is wheat in the southern Murray-Darling Basin, for which determinations of water use requirement were made over a range of locations and seasons. Here water use requirement of wheat managed to avoid water deficit stress ranged from 496 to 818 mm, although it was considered that the upper value may have been an overestimate because of edge effects (Cooper 1980a). In the few determinations reported in the same region, crop water use of rice and perennial pasture were similar, at around 1,200 to 1,250 mm, while water use of lucerne was generally higher (1,300 to 1,500 mm). Soybean water use was 700 to 900 mm in the season this was determined at Griffith, compared with about 500 and 650 mm for maximum yields in two dry seasons at Kununnurra, and 550 to 750 mm at Narrabri.

Meyer and colleagues have clearly shown that in shallow, fresh watertable conditions, crop water use from upflow from the watertable is a major component of the water balance even for well-irrigated crops. Crop water use from shallow watertables varied from a few per cent to 70% of total crop water use depending on species, depth to the watertable, salinity of the watertable and dryness of the upper soil layers (which can be manipulated by irrigation management). The potential to exploit water use from shallow watertables to increase water use efficiency and/or control watertables by modifying irrigation scheduling, and potential yield tradeoffs, needs further investigation. To date most work has been done in sugar cane, where a review of past studies and simulation modelling suggested that for the three soil types considered, all sugarcane water requirements could be met by watertables at 1 m, and below this irrigation scheduling guidelines would need to be developed based on potential crop water use from upflow taking into account soil type and rooting characteristics (Sweeney et al. 2002). Relying solely on shallow watertables would not be sustainable in an arid environment, where root zone salinisation would be inevitable.

Over recent years there has been increasing emphasis on matching irrigation water supply with crop water use requirement (ET) to assist watertable control and to cope with increased price and reduced availability of irrigation water. ET varies greatly depending on seasonal conditions, choice of crop and variety, and management, and is difficult to measure directly. Therefore methods for estimating ET are required, and their progressive development and evaluation have been ongoing for several decades. These methods include estimation of ET from evaporation of water from containers (e.g. US Class A pan evaporation), and from potential evaporation (ETo) from free water or a reference crop calculated using meteorological measurements (Doorenbos and Pruitt 1977; Allen et al. 1998). Several of these approaches for estimating ET have been tested in the irrigation areas of southern Australia.

Data from detailed lysimeter studies at Griffith were used to develop a locally calibrated Penman combination equation ("Penman-Meyer") for estimating crop water use (Meyer 1999; Meyer et al. 1999). Daily values of US Class A pan evaporation and two methods for calculating ETo were compared with the Penman-Meyer estimates - the standardised FAO Penman-Monteith equation (Allen et al. 1998), and a modified Priestly-Taylor equation as used in the CERES crop models. There was a close relationship between Penman-Meyer ETo and US Class A pan evaporation; pan evaporation was about 7 to 8% higher, except on days when evaporation exceeded about 10 mm/day, when the pan gave values up to 30% higher. This is consistent with the general observation that in arid and semi-arid areas, pan values tend to over-estimate reference evaporation because the water temperature in the pan is cooler than the air in summer, and some sensible energy is received through the sides of the pan, increasing the energy for evaporation. The Priestly-Taylor equations used in the CERES crop models showed good agreement with the Penman-Meyer equation for wheat, but for maize Priestly-Taylor overestimated ETo on days with lower evaporation and underestimated it on higher evaporative days in summer. Meyer et al. (1999) concluded that the Priestly-Taylor method would be adequate in situations where the available weather data were limited to a daily radiant energy value and daily maximum and minimum temperatures. Predictions of crop water use using the FAO Penman-Monteith were strongly correlated with the locally calibrated Penman equation, but ETo using Penman-Monteith was consistently about 30% lower than for the Penman-Meyer equation in the highly advective semi-arid environmental conditions typical of the irrigation areas of the southern MDB. Using Tatura weather data, Bethune et al. (2001) also found that predictions with Penman-Monteith were 24% lower than with Penman-Meyer. Meyer et al. (1999) concluded that major adjustment would need to be made to crop coefficients if the Penman-Monteith equation were used. They also presented comprehensive daily determinations of the crop coefficient (Kc= ETobserved/ETo, where ETo is calculated from Penman-Meyer) for wheat, soybeans, maize, lucerne, rice and pasture. Using Penman-Meyer, the crop coefficient for calculating ET from ponded rice over the 5-month period from October to February was close to unity (Humphreys 1999; Meyer et al. 1999). There was a trend for the crop coefficient to increase from about 0.7 early in the season to about 1.1 during the reproductive stage. Using Penman-Monteith, Bethune et al. (2001b) concluded that the crop coefficients recommended by FAO for strong wind conditions (1.1 for the first 2 months, 1.25 for the next 2 months, then 1.0 for the last month) were appropriate.

The locally calibrated Penman-Meyer combination equation was adopted for calculating reference evaporation for a range of weather stations across the southern Murray-Darling Basin including CSIROs Griffith, Finley, Hay and Tullakool stations in southern NSW, and some stations in northern Victoria and in the Riverland of South Australia. Some stations that adopted Penman-Meyer have since reverted to the FAO Penman-Monteith equation or to US Class A pan evaporation. Over the past two decades discussions have been periodically held on the desirability of a uniform approach to determining reference evaporation. In July 2002 NPIRD coordinated a national workshop to establish the need for national standards for irrigation crop water balance and crop evapotranspiration field methodologies, the steps to be taken to gain agreement, and the research needed if there was not clear agreement (Anon 2002).

Models for informing land and water management planning and policy

Strategic planning and policy development in the major irrigation areas is increasingly relying on the assessment of water use efficiency, deep drainage and net recharge using water balance models. The review shows that there is lack of good quantitative data for components of the water balance across the range of crops, climatic regions, site and seasonal conditions and management. Clearly it is impossible to carry out comprehensive determinations for all but a few situations, and water balance models must be used to estimated crop water use requirement and deep drainage for the range of situations. Such models need to be evaluated against quantitative data across a range of environments. However, there are few studies that have closed the water balance and which would allow rigorous testing of water balance models. Additionally, reported water balance studies often do not provide sufficient contextual information, nor changes over time, for adequate testing of models. Greater emphasis is required in experimental studies on providing adequate data and sufficient documentation and databases to allow future studies to use the collected data.

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