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Estimates of deep percolation beneath cotton in the Macquarie Valley

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Abstract Expansion of flood irrigation in the Lower Macquarie Valley of New South Wales, Australia, has been suggested as a major cause of increased groundwater recharge. The aim of this study was to estimate deep percolation under irrigation on two soils in the valley, in order to infer groundwater recharge. Three methods were used; water balance, Darcian flux calculations and chloride mass balance modelling. Chloride mass balance modelling and the water balance method gave comparable estimates of deep percolation for each soil. Chloride mass balance modelling was identified as the most reliable method for estimating deep percolation, but only gave an estimate for the entire growing season. These estimates were 214 and 104 mm for a cracking clay and red brown earth, respectively. While there is potentially greater error associated with estimates obtained using the water balance, this technique provided estimates of deep percolation for each individual irrigation. Results of the water balance indicated that deep percolation was greatest early in the growing season, following initial wetting of the soil, when the crop had a low leaf area index. Results calculated using Darcian flux equations were highly variable, and were therefore unreliable estimates of deep percolation. Groundwater recharge, inferred from estimates of deep percolation determined with the chloride mass balance model, was used to estimate the magnitude of potential annual groundwater rise. The potential groundwater rise during the 1992/1993 cotton growing season ranged from 465 mm beneath the cracking clay to 267 mm under the red brown earth. It is suggested that groundwater recharge and rise were highly dependent on the weather conditions prevailing during this period.

Introduction

Irrigation by the ancient civilisations of China, South America and Mesopotamia eventually resulted in soil salinisation and the halt of agricultural production (Szabolcs 1989). The historical association between soil salinisation and irrigation has led to concern about the development of waterlogging and salinity in Australian irrigation areas. Increasing concern is being expressed at the widespread soil salinity in some of the irrigated areas of the Murray-Darling system, which contains four-fifths of the currently irrigated area in Australia (Watson 1986). Flood irrigation on a regional scale, without provision of adequate drainage, has created shallow water-tables and soil salinisation across extensive areas of the Riverine Plain of New South Wales, Australia (Slavich 1992). The potential exists for this to occur further north, in the irrigated areas of the Macquarie Valley.

Rising water-tables were identified in the Macquarie Valley during the late 1980s (Anon 1987) indicating the occurrence of groundwater recharge. Regional groundwater levels have risen at an average rate of 350 mm year^{-1} and piezometric pressures indicate that the water-table is currently less than 5 m from the ground surface in an area of 17,000 ha, which represents 20% of the land developed for irrigation (G. Brereton, personal communication). There is therefore the potential for development of a shallow regional water-table, where the aquifer is unconfined, as groundwater may discharge into the overlying sediments. This has been observed in the Murray Valley irrigation areas of the Riverine Plain (Evans et al. 1990; Nolan et al. 1991).

In addition to a rising regional water-table, irrigation has been associated with the formation of shallow perched water-tables, especially on duplex soils (Loveday et al. 1978; Rab and Willatt 1987; Dowling et al. 1991). Vertical seepage from excess irrigation and horizontal seepage from channels and reservoirs have been impeded by a less permeable subsurface layer in some areas of the Macquarie Valley (Anon 1990). This has resulted in some

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waterlogging and isolated patches of salinity (Lubbers 1993).

Groundwater recharge in the Macquarie Valley occurs from several sources (Salas 1991). The infrastructure required for irrigation may contribute to groundwater recharge through leakage from weirs, reservoirs and irrigation channels. Water is suspected to flow from the river bed into a local aquifer system, while intensive irrigation is likely to contribute to groundwater recharge. Within the Lower Macquarie Valley, the principal single irrigated crop is cotton, with 34,000 ha grown out of the total 90,000 ha irrigated in the 1993/1994 season. The relative significance of each source of recharge has yet to be quantified.

The principal aim of this study was to estimate deep percolation beneath irrigated cotton in the Macquarie Valley in order to infer groundwater recharge and rise attributable to cotton irrigation. Deep percolation was estimated on two soils using a number of methods. The accuracy and reliability of estimates determined using each method were assessed.

Materials and methods

Site selection

Lubbers (1993) investigated the distribution of topsoil salinity in the Lower Macquarie Valley and concluded that salinity levels were higher on the younger red brown earths than on the heavy cracking clays. Sites were therefore selected on both a red brown earth and a cracking clay, to encompass the two extremes in soil with respect to potential salinisation. The red brown earth belonged to the Wilga soil profile class–calcic phase (McKenzie 1992), and is classified as a fine typic palleustalf (Soil Survey Staff 1975). The cracking clay was of the Mullah soil profile class–grey phase, and is classified as a fine entic chromustert (Soil Survey Staff 1975). These soils will be referred to as the Wilga (C) and Mullah (G) soils. Selected soil chemical properties were measured, while particle size distribution data of McKenzie (1992) are reported (Table 1).

The experimental sites were located on commerical fields that had been prepared for the furrow irrigation of cotton in the 1992/1993 irrigation season. Each site was 20 m wide and extended the length of the field, which was 859 m on the Mullah (G) soil and 576 m on the Wilga (C) soil. Cotton (*Gossypium hirsutum*) was established at both sites, with Sicala VI and CS76 being planted on the Mullah (G) and Wilga (C) soils, respectively. Irrigation commenced in early October with a total of nine irrigations delivered to the Wilga (C) soil and five to the Mullah (G) soil. Cultivation was performed only after the first irrigation. Crop management for both sites was the same as the standard commercial practice used in the remainder of the field.

Deep percolation

Deep percolation under irrigated cotton was estimated during the 1992/1993 irrigation season using three techniques: the water balance, Darcian flux calculations and chloride mass balance modelling.

Allison et al. (1994) state that when soil water flux is calculated at such a depth in the profile that no further extraction by roots occurs, then the flux will be equal to groundwater recharge. To estimate groundwater recharge, deep percolation must be monitored below the root zone where it would be constant (Slavich et al. 1995). The root zone of cotton was estimated to extend from 0 to 0.8 m, and deep percolation was calculated below this depth so that groundwater recharge could be estimated. Estimates of deep percolation were obtained at a depth of 2.0 m using the water balance and chloride mass balance modelling methods, since water content and chloride data were collected to this depth. Data required for the Darcian flux calculations were collected between soil depths of 0.9 and 1.2 m, and deep percolation was estimated at a depth of 1.2 m.

Water balance

Deep percolation (DP) may be described by Eq. 1, as the difference between the amounts of irrigation (I) plus rainfall (R) that have infiltrated the soil profile and evapotranspiration (ET) plus changes in stored soil water content (ΔS):

$$\mathrm{DP} = (I + 0.8\,R) - (\mathrm{ET} + \Delta S) \quad (1)$$

Table 1 Chemical and physical properties of the Wilga (C) and Mullah (G) soils

Soil	Depth (m)	pH	EC_e (dS m^{-1})	Particle size distribution as a percentage of total soil mass: Clay	Silt	Fine sand	Coarse sand
Wilga (C)	0 –0.1	6.5	1.03	32	31	5	31
	0.1–0.2	6.8	0.55				
	0.2–0.3	6.4	0.74	36	31	5	28
	0.3–0.4	6.3	1.58				
	0.4–0.5	6.5	1.75	34	33	4	29
	0.5–0.8	7.7	1.52	33	38	8	22
	0.8–1.3	8.2	0.94	47	23	11	19
	1.3–1.6			44	24	12	20
Mullah (G)	0 –0.1	7.8	0.91	49	13	8	30
	0.1–0.2	7.7	0.43				
	0.2–0.3	7.8	0.44	50	14	7	29
	0.3–0.4	7.8	0.43				
	0.4–0.5	7.8	0.37	49	15	7	29
	0.5–0.8	8.1	0.72	52	15	8	26
	0.8–1.3	8.2	0.71	52	16	7	25
	1.3–1.6			51	17	7	25

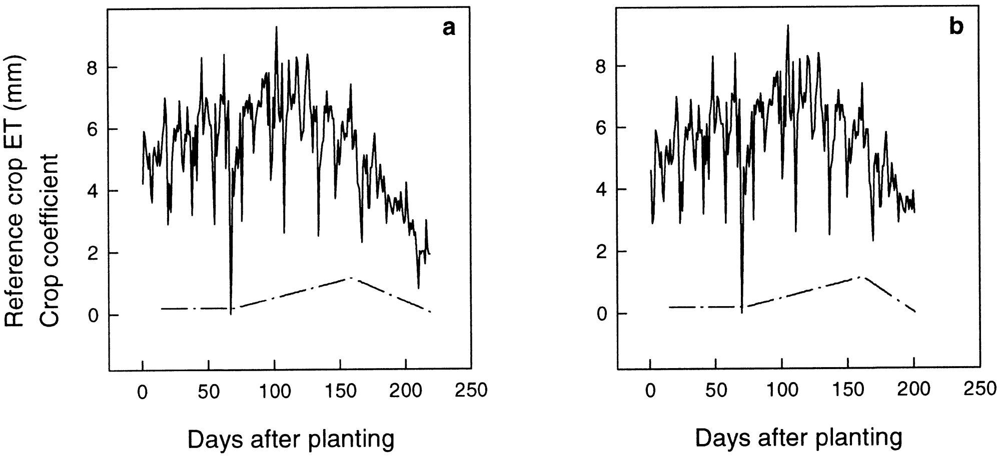

Fig. 1 a, b Reference crop evapotranspiration (—) and crop coefficients (–·–) of CS76 (**a**) and Sicala VI (**b**) cotton varieties grown on the Wilga (C) and Mullah (G) soils, respectively

Therefore, the estimation of deep percolation requires the measurement of all parameters on the right-hand side of the equation. Deep percolation was calculated for each irrigation using Eq. 1, and summed to give an estimate of deep percolation for the entire season.

Irrigation (I). Nine access tubes were installed in a grid pattern over each site, with three tubes installed at the top, middle and bottom of the field. Neutron probe readings were taken at depths of 0.2, 0.3, 0.4, 0.5, 0.6, 0.8, 1.0, 1.2, 1.4, 1.6 and 1.8 m. Standard counts were also recorded in a 200-l water drum on each day the neutron probe was used. An average standard count was calculated from 290 individual counts. Count ratios were calculated as the ratio of neutron probe readings at each soil depth and the average standard count. These were converted to volumetric soil water contents using the soil-specific calibration equations of McKenzie et al. (1990). Volumetric soil water content was converted to millimeters of water.

Volumetric soil water contents were measured at each depth increment in each access tube immediately before and after each irrigation event. These were summed to give the total water content of the profile from 0 to 2 m. The amount of irrigation water that infiltrated the profile to a depth of 2 m was calculated as the difference in volumetric soil water content immediately before ($\theta_{(0-2\text{ m})\text{ PRE IRRIGATION}}$, mm) and after ($\theta_{(0-2\text{ m})\text{ POST IRRIGATION}}$, mm) an irrigation event plus any evapotranspiration occurring between irrigation cut-off and post-irrigation soil water content measurements ($\text{ET}_{\text{CO}\rightarrow\text{READINGS}}$, mm):

$$I = \theta_{(0-2\text{ m})\text{ POST-IRRIGATION}} - \theta_{(0-2\text{ m})\text{ PRE IRRIGATION}} + \text{ET}_{\text{CO}\rightarrow\text{READINGS}} \tag{2}$$

The diurnal variation in the transpiration rate of cotton was presented by Jordan (1983). Using this information, transpiration occurring in every hour was calculated as a percentage of total daily transpiration. Total crop evapotranspiration was then determined for the day on which irrigation cut-off and post-irrigation soil water content were measured. Crop evapotranspiration during the time period between cut-off and post-irrigation measurements was calculated as the appropriate percentage of daily crop evapotranspiration. This was often quite significant, ranging from a minimum of 0.3 mm to a maximum of 6.1 mm.

The amount of irrigation water that infiltrated the soil profile was determined for each irrigation event on both soils and was the mean of measurements taken from nine access tubes. Results obtained for each irrigation event were summed to give an estimate for the irrigation season.

Rainfall (R). Rain gauges were installed to record rainfall at each site. Based on the data of Murphree and McGregor (1981) and Baumhardt et al. (1993), it was assumed that 80% of rainfall infiltrated the soil profile in a furrow-irrigated cotton field.

Change in stored soil water content (ΔS). The change in stored soil water was calculated as the difference in volumetric soil water content of the soil profile before subsequent irrigations. Estimates of stored soil water were the mean of measurements taken from nine access tubes and were converted to a depth of water in millimetres.

Crop evapotranspiration (ET). Cotton evapotranspiration was calculated by determining the reference crop evapotranspiration and modifying it with the appropriate crop coefficient. Crop coefficients accounted for both crop transpiration and soil evaporation throughout the different stages of the growing season (Doorenbos and Pruitt 1977). Reference crop ET was calculated using climatic data recorded at the Trangie Agricultural Research Centre with the NSW WATERWATCH program (Swann 1987). The NSW WATERWATCH program calculated reference crop ET by solving a modified Penman equation developed by Swann (personal communication). Daily reference crop ET was monitored until Sicala VI and CS76 cotton were defoliated 219 and 201 days after planting respectively (Fig. 1). Crop development stages were monitored to allow the construction of a crop coefficient curve for both Sicala VI and CS76 cotton varieties. Crop coefficient values were provided by Doorenbos and Pruitt (1977), except in the initial developmental stage where a value of 0.2 was considered a more reasonable estimate (R. L. Browne, personal communication). The shape of the curve was adapted from the cotton water use curve of Browne (1984). Each curve was subsequently approximated by three straight lines (Fig. 1) and daily crop coefficients were estimated.

Chloride mass balance

Six soil cores were collected before the irrigation season using a Proline auger. Samples were collected on 1 and 2 September 1992 from the Mullah (G) and Wilga (C) soils, respectively. Soil samples were collected again after cotton picking, on 11 and 12 May 1993 from the Wilga (C) soil, and on 19 and 20 May 1993 from the Mullah (G) soil. These samples were collected using a hand auger. Collection of soil samples at these times allowed changes in soil chloride to be monitored over the cotton growing season.

Samples were collected for chloride analysis at 0.1-m increments from 0 to 2.0 m. Soil samples were air dried and ground to pass through a 2-mm sieve. Soil-saturated paste extracts were prepared following the procedure of Slavich and Petterson (1993). The extracts were analysed for chloride using the coulometric-amperometric automatic titration method of Cotlove et al. (1958).

An estimate of soil bulk density was also required, to calculate soil chloride content per volume of soil. Bulk density was not actually measured at the sites as the excavation of backhoe pits was not permitted. Bulk density was determined in the Mullah (G) soil, but in a different field, using soil cores. Three cylindrical cores, 75 mm in diameter, were pushed 50 mm horizontally into a pit face at 0.2-m intervals. Soil samples were oven dried and weighed, and mean bulk density was calculated for each depth increment. McKenzie (1992) reported the median bulk density of large undisturbed clods of the Wilga (C) soil. Clods were collected from 26 profiles at depths of 0.1, 0.3, 0.7 and 1.3 m. The median bulk density was the best estimate of bulk density available for the Wilga (C) soil.

Soil chloride content (S_z) and soil solution chloride concentration (C_z) at each soil depth (z) were calculated after Slavich et al. (1995). The depth-weighted mean soil chloride content ($S_{(\mathrm{o-z})}$) was determined.

There were no significant changes in mean soil chloride content at any depth below the root zone of either soil (Fig. 2). The chloride mass balance was in a steady state and the leaching rate model (United States Salinity Laboratory, 1954) was used to calculate deep percolation (DP, mm) over the irrigation season (Eq. 3).

$$\mathrm{DP} = t(I + 0.8\,R)\,(C_{\mathrm{i}}/\bar{C}_z) \tag{3}$$

Input data required for the solution of the steady state leaching rate model included the infiltration rate of irrigation and rainfall ($I + 0.8\,R$, mm day^{-1}), time (t, days), chloride concentration of irrigation water (C_{i}, mol m^{-3}) and the mean chloride concentration of the soil solution over time ($\bar{C}_z$, mol m^{-3}) at each measurement depth (z, m). Irrigation application rate was determined from the amount of infiltrated irrigation water, as measured with the neutron probe, and it was assumed that 80% of rainfall also infiltrated. The chloride content of the irrigation water was monitored throughout the season.

Deep percolation was estimated below the cotton root zone from 1.0 to 2.0 m, at 0.1-m increments. The estimates at each depth increment should be equal, and any differences were attributed to spatial and experimental variation. Estimates at each depth were used to calculate the mean deep percolation at 2.0 m.

Darcian flux calculations

Rose and Stern (1965) described deep percolation (DP, mm) as a function of matric potential (h, mm), soil depth (z, mm) and hydraulic conductivity at the prevailing soil water content [$K(\theta)$, mm day^{-1}]:

$$\mathrm{DP} = \int_0^t K(\theta)\cdot(dh/dz+1)\,dt \tag{4}$$

Tensiometers were used to measure soil matric potential, with five groups of tensiometers installed below the cotton root zone at depths of 0.9, 1.05 and 1.2 m in the middle of the furrows adjacent to access tubes. A pressure transducer (Marthaler et al. 1983) was used to measure tensiometer potential. Daily measurements were taken for 10 days after the first irrigation in October, then progressively less often until the second irrigation in January. Measurements were taken daily from 1 January to 30 March, during which period evapotranspiration was high and irrigations more frequent. Biweekly measurements were taken throughout April and May until cotton picking. Each tensiometer potential was converted to a matric potential by adjusting for the gravitational potential (height) of the hanging water column. The date and time of each reading were also recorded.

The field saturated hydraulic conductivity (K_{fs}) of each soil was determined using a well permeameter (Elrick et al. 1989) at a soil depth of 1.05 m. The geometric mean of nine estimates was used to approximate K_{fs} between 0.9 and 1.2 m. The geometric mean estimate for the Mullah (G) soil was 0.51 mm day^{-1}, while an estimate of 0.36 mm day^{-1} was obtained for the Wilga (C) soil. The 95% confidence intervals for these estimates range from 0.35 to 0.36 mm day^{-1} and 0 to 1.03 mm day^{-1} for the Wilga (C) and Mullah (G) soils, respectively. The estimate of hydraulic conductivity is referred to as "field saturated" because under field conditions a certain volume of air is usually trapped within the soil during the infiltration process (Reynolds et al. 1985; Elrick et al. 1989). This can result in estimates of saturated hydraulic conductivity which are lower than if the soil had been completely saturated (Stephens et al. 1987; Elrick et al. 1989).

During the irrigation season, matric potential estimates were never less than field capacity (–33 kPa) and were often greater than air entry potential (–10 kPa). Field saturated hydraulic conductivity was used to approximate the range of $K(\theta)$ values occurring between field capacity and saturation. This was necessary since the soil moisture characteristic and unsaturated hydraulic conductivity functions were not available. In the Wilga (C) and Mullah (G) soil, 93% and 75%, respectively, of matric potential estimates were greater than air entry potential. The use of K_{fs} would underestimate $K(\theta)$ when the soil was saturated and may overestimate $K(\theta)$ around field capacity. This would result in over- and understimation of water flux at different times during the season.

Potential rise in groundwater levels

Total porosity was determined from bulk density and assumed particle density data for each soil. By assuming that total porosity remains constant from 2 m to the depth of the underlying aquifer, and that the lateral-flow hydraulic gradient in the aquifer is negligible, then the rate of groundwater rise may be calculated as

$$\mathrm{DP}/\mathrm{TP} \tag{5}$$

where TP is total porosity (expressed as a fraction).

Results and discussion

Deep percolation

Water balance

Total deep percolation was higher on the Mullah (G) soil than on the Wilga (C) soil during the 1992/1993 irrigation season (Table 2). Inputs and outputs of water at each site, along with the duration of each irrigation event and its timing with respect to planting provide information regarding the irrigation events throughout the season (Table 3). Changes in deep percolation in different irrigation cycles indicated variation in deep percolation over the season.

Table 2 Quantities of deep percolation and leaching fractions estimated for two soils using three techniques. The quantity of water that has infiltrated the profile (I + 0.8 R) is 758 mm and 630 mm on the Mullah (G) and Wilga (C) soils, respectively

Method	Soil	Deep percolation (mm)	Standard error (mm)	Leaching fraction (%)
Water balance	Mullah (G)	236	n/a	31
	Wilga (C)	145	n/a	23
Mass balance	Mullah (G)	214	13	28
	Wilga (C)	104	2	17
Darcian flux calculations	Mullah (G)	67	53	8

Table 3 Characteristics of each irrigation cycle of the 1992/1993 season as calculated by the water balance method (I amount of irrigation water that infiltrated the soil profile, R rainfall, ΔS change in stored soil water, ET_{CROP} crop evapotranspiration, DP deep percolation)

Soil	Irrigation number	Days from planting	Irrigation time (h)	I (mm)	R (mm)	ΔS (mm)	ET_{CROP} (mm)	DP (mm)
Wilga (C)	1	4	20.95	78.5	222.6	9.3	98.3	149.0
	2	91	24.75	77.7	3.0	10.2	49.9	20.0
	3	106	13.75	39.8	56.7	–1.5	52.9	33.7
	4	119	13.25	35.4	5.2	–2.3	40.5	1.4
	5	127	14.00	26.6	0	–14.6	45.4	–4.2
	6	135	13.60	43.2	23.0	14.4	46.2	1.0
	7	144	12.00	21.2	0	–7.2	63.5	–35.1
	8	155	12.75	29.0	17.0	18.0	60.6	–36.0
	9	164	10.00	26.6	0	–73.8	85.1	15.4
	Harvest	260						
Mullah (G)	1	4	29.30	173.4	245.2	87.0	120.3	162.2
	2	96	28.80	119.0	39.5	27.0	88.9	34.7
	3	118	17.20	90.2	4.8	25.4	63.7	4.9
	4	130	11.50	53.5	23.0	–28.4	108.9	–8.6
	5	150	12.00	65.7	22.6	–162.1	203.0	42.9
	Harvest	269						

On both soils, deep percolation was higher during the first irrigation cycle than during any other irrigation cycle in the season. This was attributed to the application of a large amount of irrigation water in the first irrigation and to the high rainfall and low evapotranspiration that prevailed from planting to late December 1992 (Table 3). Smaller quantities of deep percolation were observed after all other irrigations (Table 3). This was partly because the duration of each irrigation event was shorter, and therefore less water was applied to each site, and also because daily evapotranspiration had increased.

In some instances, no deep percolation occurred at all (Table 3). This indicated that more water had been used by the crop than had been supplied by irrigation, rainfall or the initial store of soil water. This was apparent following irrigation 4 on the Mullah (G) soil and irrigations 5, 7 and 8 on the Wilga (C) soil. However, the amount of evapotranspiration in excess of estimated plant-extractable water during irrigations 7 and 8 on the Wilga (C) soil was too large to be derived from stored soil water and suggests that an upflow of water occurred from a shallow water-table. A shallow water-table was noted at a depth of 2.15 m at the end of the 1992/1993 growing season when access tubes were removed, and again at the beginning of the 1993/1994 season.

A slight increase in deep percolation was observed during the final irrigation cycle on both soils, when compared with the previous irrigation (Table 3). This was due to lower evapotranspiration associated with a rapid decline in leaf area index attributed to plant maturation (Grimes et al. 1969). Cooler temperatures towards the end of the growing season would also have decreased evapotranspiration and allowed a greater proportion of soil water to be lost as deep percolation.

Chloride mass balance

Estimates of deep percolation, using the chloride mass balance model were obtained for the entire season but not for individual irrigation cycles throughout the season. It was expected that changes in mean stored soil chloride ($\bar{S}_{(o-z)}$) would only be accurately detected over the irrigation season, and that changes occurring at each irrigation would be too small to measure. In addition, the time required for soil sample collection, preparation and analysis for each irrigation was prohibitive.

A total of 758 and 630 mm of irrigation water and rainfall infiltrated the Mullah (G) and Wilga (C) soils, respectively. Irrigation water applied to the Mullah (G) soil had a chloride concentration of 0.96 mol m^{-3} while the chloride concentration of water applied to the Wilga soil was 1.57 mol m^{-3}. Mean total quantities of water which percolated below the depth of 2 m were higher on the Mullah (G) than the Wilga (C) soil (Table 2).

Darcian flux calculations

While deep percolation was estimated at a depth of 2 m using the other two methods, an estimate was obtained only on the Mullah (G) soil at a depth of 1.2 m using Darcian flux calculations (Table 2). An upward flux of soil water was observed in the Mullah (G) soil at 1.05 m and at both 1.05 and 1.2 m in the Wilga (C) soil (Fig. 3). The net upward flux of soil water for the irrigation season was 78.5±36.4 mm in the Mullah (G) soil, and 34.9±19.0 mm and 20.9±25.7 mm in the Wilga (C) soil at 1.05 and 1.2 m, respectively. Estimates of soil water flux are mean values. The variation in each estimate often encompasses both upward and downward flow, as indicated by the standard error. Mean values are presented

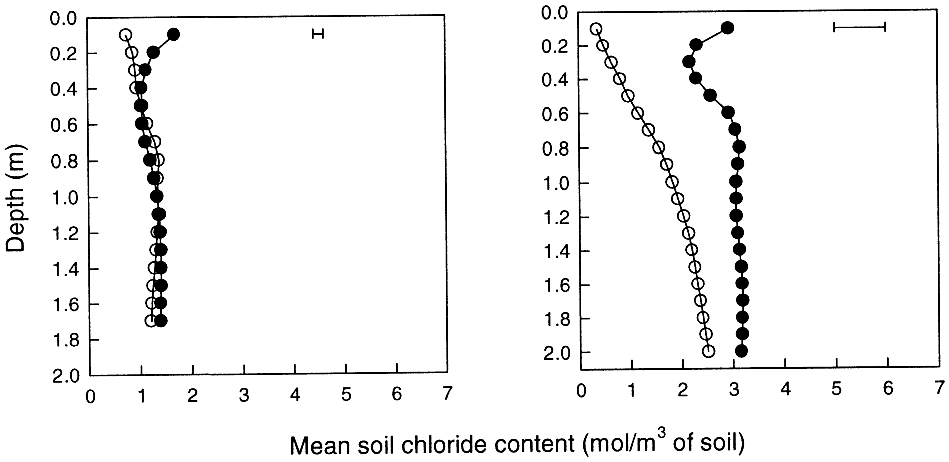

Fig. 2 Depth-weighted mean stored soil chloride content ($\bar{S}_{(0-z)}$) on the Mullah (G) (*left*) and Wilga (C) soils (*right*) before (○) and after (●) the 1992/1993 irrigation season. The *bar* represents the 95% confidence interval

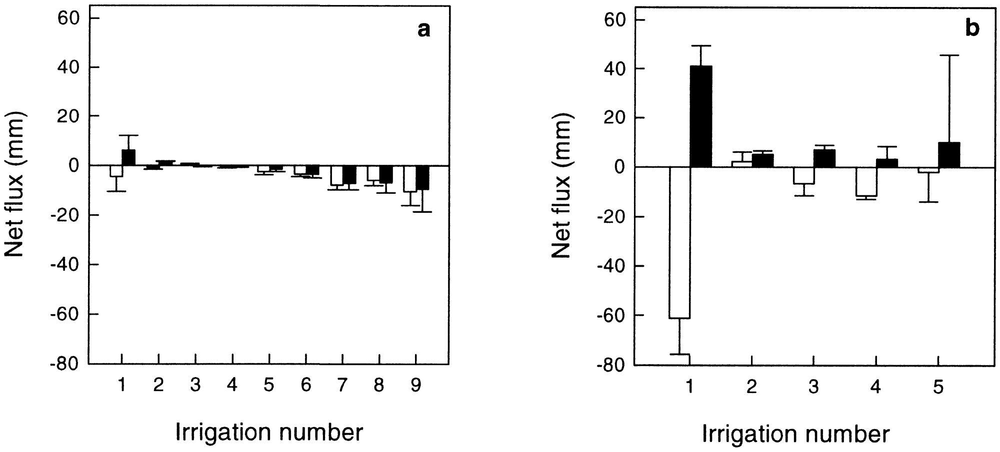

Fig. 3 a, b Soil water flux estimated during each irrigation cycle at 1.05 m (□) and 1.2 m (■), using Darcian flux calculations on the Wilga (C) (**a**) and Mullah (G) (**b**) soils

throughout the discussion but this level of variation must be kept in mind.

The largest upflow of soil water for the season occurred following the first irrigation at 1.05 m due to capillary rise from the wet subsoil and evaporation on both soils (Fig. 3). Conditions during the first irrigation cycle were conducive to soil evaporation, as vegetative cover was less than 10% and the soil surface remained relatively wet (Ritchie 1972). Deep percolation occurred at 1.2 m in the first irrigation cycle on both soils (Fig. 3). Therefore the plane of zero flux was situated between 1.05 and 1.2 m after the first irrigation of both soils.

A net upward flow of water occurred in every other irrigation cycle at both depths in the Wilga (C) soil, and at 1.05 m in Mullah (G) soil (Fig. 3). Although cotton roots did not extend below 0.8 m, plant water uptake in the root zone is likely to create a negative upward hydraulic gradient leading to the observed upward water flow. Evapotranspiration maintained a gradient for upward flow for at least some of the soil water, resulting in a net upward flow from these depths.

Comparison of soils

Deep percolation in the two soils can be compared by examining estimates obtained at 2 m using the water balance and chloride mass balance modelling methods (Table 2). Deep percolation was greater on the Mullah (G) soil than the Wilga (C) soil, may be because more water infiltrated the profile. The Mullah (G) soil received more rainfall, and more irrigation water was applied due to longer furrows. Significant deep percolation may have also occurred down cracks in the Mullah (G) soil, whereas there was no opportunity for this to occur in the non-swelling Wilga (C) soil. The leaching fractions (Table 2) show that deep percolation was higher on the Mullah (G) soil, indicating that there was a real difference in deep percolation between the two soils and that it was not solely due to differences in the amount of water that infiltrated the profile. The low hydraulic conductivity of the Wilga (C) subsoil restricted deep percolation and resulted in the formation of a shallow water-table, which further reduced the potential for deep percolation. Data of Bird et al. (1996) showed that a proportion of Wilga (C) soils had a lower saturated hydraulic conductivity than some Mullah (G) soils.

The 1992/1993 season was atypical of the long-term seasonal rainfall pattern. During the first irrigation cycle (October – December), 272 mm and 236 mm of rain were recorded on the Mullah (G) and Wilga (C) soils, respectively. The long-term average was considerably lower, with 121 mm recorded for the October – December period. Above-average rainfall would have resulted in above-average deep percolation. Deep percolation is enhanced when rain falls on soil kept relatively wet by irrigation (Chiew and McMahon 1991) since the capacity of the soil to store additional water is low and it moves rapidly through the profile to be lost as deep percolation. Therefore, deep percolation in a particular soil is highly dependent on weather conditions. Deep percolation occurring during the 1992/1993 irrigation season may be approaching an upper limit since rainfall was above average during this period.

Humphreys and Muirhead (1991) reported that 100 – 200 mm of water was lost as deep percolation from intermittently flood irrigated crops grown in the Riverina under normal commercial practices. Results of this study, obtained with the water balance and chloride mass balance techniques, indicate that deep percolation on the Wilga (C) soil is within this range, while that on the Mullah (G) soil is above it. Hence, deep percolation in the Macquarie Valley is at least comparable with that occurring in other irrigation areas where shallow water-tables and salinisation have developed. Therefore, there is cause for concern regarding the sustainability of irrigation in the Macquarie Valley.

Comparison of methods

Comparable estimates of deep percolation were obtained using the water balance and chloride mass balance methods (Table 2). Slavich and Yang (1990) also reported that results calculated using a water balance agreed closely with those calculated using a chloride mass balance model. In our study, the water balance gave higher estimates of deep percolation than the chloride mass balance, but the differences may be accounted for by error associated with each technique. Darcian flux calculations only provided an estimate of deep percolation in the Mullah (G) soil, and this estimate was lower than that obtained using the other two methods (Table 2).

The error associated with the estimate of deep percolation from the water balance method may be evaluated from the level of uncertainty in the input parameters. It is not possible, in this study, to evaluate the error associated with evapotranspiration and rainfall estimates as these measurements were not replicated. However, a source of error in the rainfall estimates arises from the assumption that only 80% of rainfall infiltrated the soil profile. Infiltration measurements were replicated, yielding an average coefficient of variation of 16% and 69% for the Mullah (G) and Wilga (C) soils, respectively. This level of uncertainty alone would contribute to considerable error in the estimate of deep percolation, regardless of the error associated with evapotranspiration and rainfall. The level of uncertainty in evapotranspiration and rainfall has been estimated at ±5% and ±10%, respectively (Gee and Hillel 1988). An error of 5% in two of the input parameters will magnify to an error of 200% in the difference between them. The similarity between estimates of deep percolation obtained from the water balance and chloride mass balance techniques suggests that such a large error was not associated with the water balance estimates. However, some error in the estimation of I, ET and R would have contributed to variation in the deep percolation estimates in the other methods.

The chloride mass balance model gave higher estimates of deep percolation than the Darcian flux calculations, and lower but comparable estimates to the water balance method. The coefficient of variation in mean deep percolation was 7% for the Wilga (C) soil and 17% for the Mullah (G) soil. The errors related to these estimates arise from spatial variation in soil chloride. Uncertainty in these estimates was also associated with the chloride concentration of irrigation water and irrigation application rate, however these are considered to be minimal. Experimental error associated with the determination of soil chloride content in the laboratory is estimated at ±2%.

Solute mass balance modelling assumes matrix flow and therefore deep percolation will be underestimated where preferential flow is significant below the root zone. However preferential flow may occur within the root zone (i. e. 0 – 0.8 m) without effecting estimates of deep percolation made below the root zone (1 m). The occurrence of "bulge"-type profiles, in the absence of a shallow water-table, is indicative of chloride transport to depth by preferential flow (Allison 1988). Bulge-type profiles were not encountered during the 1992/1993 season and therefore results obtained from this technique are not considered to be underestimated due to the occurrence of preferential flow.

The use of Darcian flux calculations to estimate soil water flux below the root zone in the Mullah (G) soil gave the lowest estimate of deep percolation. Darcian flux calculations also produced the most variable estimates. While an upward flow of soil water was observed in the Wilga (C) soil, the variation in these estimates may be considered in order to assess the reliability of this method in estimating deep percolation. The standard errors of the mean soil water flux represent an uncertainty ranging from 50 to 80% on the Mullah soil, and 55 – 125% on the Wilga calcic soil. This level of error can encompass estimates of both upward and downward flux of water in some instances. High spatial variability of soil hydraulic properties may contribute to the variability of the deep percolation estimates, with Gupta et al. (1994) reporting a coefficient of variation of 80% for hydraulic conductivity. High variability in these estimates may also result from the large variability in tensiometer potential observed as the soil dries (Hulme et al. 1991). Due to the high level of uncertainty associated with the results, and the large labour inputs required, this method was not considered to be suitable for the estimation of deep percolation in irrigated cotton.

Comparable estimates of deep percolation were obtained using the water balance and chloride mass balance methods. This suggests that both these techniques are reliable methods for the estimation of deep percolation. While there is potential for a large error associated with estimates of deep percolation from the water balance, this does not appear to be the case in this particular study. The chloride mass balance was considered the best technique, because the level of uncertainty associated with estimates of deep percolation was measurable and had the lowest labour requirements in the field.

This study demonstrates that reliable estimates of deep percolation, and thus groundwater recharge, can be obtained using either the water balance or chloride mass balance techniques. However, it is recommended that both these methods are employed for the estimation of deep percolation in the field. The level of uncertainty in deep percolation estimates can be quantified when using the chloride mass balance method. This allows the accuracy of the results obtained using the water balance to be verified. In addition, the water balance method can provide more information on the pattern of deep percolation throughout the irrigation season, since deep percolation can be assessed at each irrigation. The combined use of these two methods allows both a reliable and detailed study of deep percolation over an irrigation season.

Potential rise in water-table levels

The rate of water-table rise was estimated for the 1992/1993 season using data derived from chloride mass balance modelling. Estimated rates were 267 mm year^{-1} and 465 mm year^{-1} for the Wilga (C) and Mullah (G) soils, respectively. Over recent years, the Department of Water Resources has monitored piezometer levels in the Macquarie Valley as an indicator of groundwater rise, with increases of 100 – 500 mm year^{-1} observed. The average rate of water-table rise is 350 mm year^{-1} (Salas 1991). The coincidence of estimates from the present study with the longer-term observations in piezometer readings increases confidence in the representativeness of these numbers. It also provides circumstantial evidence that irrigation is a major contributor to groundwater additions effecting water-table levels.

Excessive groundwater recharge will increase the piezometric pressure of underlying aquifers, eventually resulting in an upward flux of groundwater to the overlying sediments. This process has occurred in the Murray Valley, New South Wales, as a direct consequence of irrigation (Evans et al. 1990). Where the aquifer is unconfined, groundwater will rise into the overlying sediments forming a shallow water-table at the site of groundwater recharge. In a confined aquifer, an increase in piezometric pressure will result in lateral groundwater flow. Flow will occur until an unconfined area is reached where the increase in pressure may be alleviated through groundwater rise. The Macquarie groundwater basin is essentially closed (G. Brereton, personal communication) and therefore groundwater recharge of the magnitude estimated in this study will certainly result in a rise in the regional water-table somewhere in the valley. The development of a shallow regional water-table of a permanent nature poses a serious threat to the long-term sustainability of irrigated agriculture in the Macquarie Valley.

Conclusions

This study clearly shows that repeatable estimates of deep percolation may be achieved using the water balance and chloride mass balance methods. It is recommended that both techniques are employed so that the water balance estimates can be compared with those obtained using the chloride mass balance, in order to assess the reliability of the estimates. Soil water fluxes after each irrigation can be monitored using the water balance, thus providing greater insight into deep percolation throughout an irrigation season. Darcian flux calculations were unsuitable for the estimation of deep percolation beneath irrigated cotton.

Deep percolation beneath irrigated cotton was higher on the Mullah (G) soil than the Wilga (C) soil. Total deep percolation was estimated as 236 and 145 mm using the water balance, and 214 and 104 mm using the chloride mass balance, on the Mullah (G) and Wilga (C) soils, respectively. Lower subsoil hydraulic conductivity and the presence of a shallow water-table restricted deep percolation in the Wilga (C) soil relative to the Mullah (G) soil.

Deep percolation beneath irrigated cotton was significant on both soils. While above-average rainfall would have resulted in above-average deep percolation during the 1992/1993 season, the magnitude observed suggests that deep percolation occurring in an average year would be substantial. There is a risk that shallow regional water-tables will develop in the Lower Macquarie Valley as a result of groundwater recharge from cotton irrigation.

To prevent the development of shallow water-tables and subsequent soil salinity and waterlogging, research aimed at developing systems to minimise deep percolation is suggested. The efficiency of current irrigation design and techniques requires assessment to identify an irrigation system that will minimise deep percolation under furrow-irrigated cotton systems. Alternatively, crop rotation systems, involving winter crops to use soil water remaining in the profile following the irrigation season and winter rainfall, may be considered as an option to reduce deep percolation. Essentially any practice which maintain the soil profile in a drier state for longer periods of time than is currently the case will reduce deep percolation.

In order to understand the process of groundwater rise, it is crucial that aquifer systems and their connections with the land surface and each other are defined. Further studies regarding the hydrogeology of the Lower Macquarie Valley are also suggested. This information is necessary for the prediction of the groundwater flow and discharge patterns that will occur in response to increasing aquifer pressures, and will enable the prediction of areas in which shallow water-tables will develop. These processes were identified in the Murray Basin aquifer systems after shallow water-tables had developed and waterlogging and salinity problems became evident. It is desirable to have an understanding of the hydrogeology of the Macquarie Valley before shallow water-tables become widespread.

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References

Allison GB (1988) A review of some of the physical, chemical and isotopic techniques available for estimating groundwater recharge. In: Simmers I (ed) Estimation of natural groundwater recharge. Proceedings of NATO Advanced Research Workshop, Turkey, March 8–15, 1987, pp 49–72

Allison GB, Gee GW, Tyler SW (1994) Vadose-zone techniques for estimating groundwater recharge in arid and semiarid regions. Soil Sci Soc Am J 58: 6–14

Anon (1987) Lower Macquarie Valley shallow groundwater project. Department of Water Resources. Technical Services Report no 1.

Anon (1990) A report on salinity and waterlogging investigations for "Byron" Agriland P/L, Narromine. Department of Water Resources. Technical Report 90/006.

Baumhardt RL, Wendt CW, Keeling JW (1993) Tillage and furrow diking effects on water balance and yields of sorghum and cotton. Soil Sci Soc Am J 57: 1077–1083

Bird TL, Willis TM, Melville GJ (1996) Subsoil hydraulic conductivity estimates for the Lower Macquarie Valley. Aust J Soil Res 34: 213–228

Browne RL (1984) Irrigation management of cotton. Agfact P 5.3.2, N.S.W. Agriculture

Chiew FHS, McMahon TA (1991) Groundwater recharge from rainfall and irrigation in the Campaspe River Basin. Aust J Soil Res 29: 651–670

Cotlove EH, Trantham V, Bowman TL (1958) An instrument and method for automatic, rapid, accurate and sensitive titration of chloride in biological samples. J Lab Clin Med 51: 461–468

Doorenbos J, Pruitt WO (1977) Guidelines for predicting crop water requirements. Food and Agriculture Organisation of the United Nations, Rome

Dowling AJ, Thorburn PJ, Ross PJ, Elliot PJ (1991) Estimation of infiltration and deep drainage in a furrow-irrigated sodic duplex soil. Aust J Soil Res 29: 363–375

Elrick DE, Reynolds WD, Tan KA (1989) Hydraulic conductivity measurements in the unsaturated zone using improved well analyses. Ground Mater Monit Rev Summer 1989: 184–193

Evans R, Brown C, Kellett J (1990) Geology and groundwater. In: Mackay N, Eastburn D (eds) The Murray. Murray Darling Basin Commission, Canberra, pp 77–93

Gee GW, Hillel D (1988) Groundwater recharge in arid regions: review and critique of estimation methods. Hydrol Process 2: 255–266

Grimes DW, Yamada H, Dickens WL (1969) Functions for cotton (*Gossypium hirsutum* L.) production from irrigation and nitrogen fertilization variables. I. Yield and evapotranspiration. Agron J 61: 769–773

Gupta RK, Rudra RP, Dickinson WT, Elrick DE (1994) Modelling spatial patterns of three infiltration parameters. Can Agric Eng 36: 9–13

Hulme PJ, McKenzie DC, Abbott TS, MacLeod DA (1991) Changes in the physical properties of a vertisol following an irrigation of cotton as influenced by the previous crop. Aust J Soil Res 29: 425–442

Humphreys E, Muirhead W (1991) Agronomic options for reducing recharge under rice. Aust J Soil Water Conserv 4: 22–29

Jordan WA (1983) Cotton. In: Teare ID, Peet MM (eds) Crop water relations. Wiley, New York, pp 213–254

Loveday J, McIntyre DS, Watson CL (1978) Aspects of hydrology of the Riverine Plain soils. In: Storrier RR, Kelly ID (eds) The hydrogeology of the Riverine Plain of south east Australia. Australian Society of Soil Science, Riverina Branch, pp 99–114

Lubbers P (1993) Spatial variation of salinity on irrigated cotton in the Lower Macquarie Valley. Thesis submitted to University of Wageningen, The Netherlands

Marthaler HP, Vogelsanger W, Richard F, Wierenga PJ (1983) A pressure transducer for field tensiometers. Soil Sci Soc Am J 47: 624–627

McKenzie DC, Hucker KW, Morthorpe LJ, Baker PJ (1990) Field calibration of a neutron-gamma probe in three agriculturally important soils of the Lower Macquarie Valley. Aust J Exp Agric 30: 115–122

McKenzie NJ (1992) Soils of the Lower Macquarie Valley, New South Wales. CSIRO Division of Soils. Divisional Report no 117.

Murphree CE, McGregor KC (1981) Runoff and sediment yield from a flatland watershed in soybeans. Trans ASAE 34: 407–411

Nolan JG, Evans RS, Sampson LD (1991) Interim results from modelling of the southern Riverine Plain, Murray Basin. In: Proceedings of the international conference on groundwater in large sedimentary basins, Perth, July 9–13, 1990, pp 355–368

Rab MA, Willatt ST (1987) Water use by irrigated potatoes on a duplex soil. Aust J Exp Agric 27: 165–172

Reynolds WD, Elrick DE, Clothier BE (1985) The constant head well permeameter: effect of unsaturated flow. Soil Sci 139: 172–180

Ritchie JT (1972) Model for predicting evaporation from a row crop with incomplete cover. Water Resour Res 8: 1204–1313

Rose CW, Stern WR (1965) The drainage component of the water balance equation. Aust J Soil Res 3: 95–100

Salas G (1991) Lower Macquarie: review information and groundwater management strategies. Department of Water Resources, discussion paper

Slavich P (1992) Irrigation using groundwater for watertable control: a model of water and salt balance limitations. Aust J Agric Res 43: 225–239

Slavich PG, Peterson GH (1993) Estimating the electrical conductivity of saturated paste extracts from 1 : 5 soil water suspension and texture. Aust J Soil Res 31: 73–81

Slavich PG, Yang J (1990) Estimation of field scale leaching rates from chloride mass balance and electromagnetic induction measurements. Irrig Sci 11: 7–14

Slavich PG, Petterson GH, Griffin D (1995) The effect of gypsum on deep drainage from clay soils used for rice. In: Naidu R, Sumner ME, Rengasamy P (eds) Australian sodic solids: distribution, properties and management. CSIRO, Melbourne, pp 205–210

Soil Survey Staff (1975) Soil taxonomy – a basic system of soil classification for making and interpreting soil surveys. USDA, Washington DC

Stephens DB, Lambert K, Watson D (1987) Regression models for hydraulic conductivity and field tests of the borehole permeameter. Water Resour Res 23: 2207 – 2214

Swann B (1987) WATERWATCH: a crop water use information service for irrigation managers. Macquarie Irrig 5: 13 – 15

Szabolcs I (1989) Salt affected soils. CRC, Boca Raton, Fla

United States Salinity Laboratory (1954) Diagnosis and improvement of saline and alkali soils. US Department of Agriculture, Agricultural Handbook no 60, Washington DC

Watson CL (1986) Irrigation. In: Russel JS, Isbell RF (eds) Australian soils: the human impact. University of Queensland Press, St Lucia, pp 334 – 356