Estimating Deep Drainage Under Pasture

R. E. White[a], B. Christy[b], A. M. Ridley[b] and L. K. Heng[c]

[a]*Institute of Land and Food Resources, The University of Melbourne, Vic. 3010 (robertew@unimelb.edu.au)*
[b]*Agriculture Victoria, Rutherglen Research Institute, Vic. 3685*
[c]*FAO/IAEA Agriculture and Biotechnology Laboratory, 2444 Siebersdorf, Austria*

Abstract: A Soil Water Balance model is described which relies on a linear relationship between actual evaporation from pastures and the soil water deficit. The model was tested against measured components of the water balance at different sites in SE Australia, and used to estimate drainage below the root zone. Using long term weather data, the model could simulate the differences between runoff and drainage under annual and perennial grass pastures.

Keywords: Drainage; Pastures; Recharge; Runoff; Soil water balance

1. INTRODUCTION

The hydrology of much of the grazing land in the high rainfall zone (HRZ) (> 600 mm/year) of southeastern (SE) Australia has been changed over the past 200 years by the clearance of native, deep-rooted, woody vegetation. Native perennial deep-rooting grasses have been replaced by shallow-rooted species, mainly subterranean clover (*Trifolium subterraneum*) and annual ryegrass (*Lolium rigidum*). With increased recharge to groundwater, watertables have risen and caused soil salinization on the western and northern slopes of the Great Dividing Range in New South Wales (NSW) and Victoria [Williamson et al., 1997]. Soil acidification has also accelerated as a result of increased nitrogen (N) inputs from the subterranean clover, followed by nitrate leaching. Together with poor management and inadequate fertilization of pastures in recent years, these processes have combined to degrade the land, leading to reduced productivity and a threat to the sustainability of agriculture.

Between the start and end of a normal year, changes in soil water storage in the pasture root zone are relatively small in the HRZ of SE Australia. The difference between rainfall and evaporation is then 'surplus water', which is a potentially valuable resource in the landscape. The surplus water is partitioned into lateral flows and deep drainage below the root zone (1-2 m deep). These lateral flows include surface runoff and any subsurface flows that occur over the top of impermeable B horizons in the duplex profiles of Sodosols, common in much of SE Australia. Knowledge of the partitioning of surplus water between surface runoff R and deep drainage D is valuable, firstly because surface runoff and shallow subsurface flows contribute directly to stream flow, which is important for the health of aquatic ecosystems and the beneficial use of water downstream, and secondly because deep drainage is potential recharge to groundwater. Slow flows from groundwater also contribute to stream baseflows. But if the balance between recharge and discharge in a groundwater system is disturbed through a substantial and consistent increase in recharge, the watertable will rise with consequent dangers of waterlogging and salinization.

Deep drainage is difficult to measure directly. Surface runoff is also difficult to measure over large areas. This paper describes a Soil Water Balance (SWB) approach to estimating both surface runoff and deep drainage for pastures, in which the soil water deficit is accurately simulated on a daily basis. The model has been tested on several pasture sites in SE Australia.

2. MATERIALS AND METHODS

Measurements of rainfall, evaporation, changes in soil water content and surface runoff for pastures were made between 1994 and 2001 at sites on Sodosols and Kurosols [Isbell, 1996] in SE Australia [White et al., 2000; Heng et al., 2001]. At Book Book near Wagga Wagga in NSW, the measurements were made in 0.135 ha paddocks of annual ryegrass and perennial grasses (*Phalaris aquatica* and cocksfoot *Dactylis glomerata*) with subterranean clover, rotationally grazed by sheep. At Maindample and Ruffy in northeast (NE)

Victoria, measurements were made in catchments of 1.8-13.7 ha on pastures ranging from native (*Microlaena*, *Danthonia* spp) and volunteer (*Vulpia*, *Hordeum* spp) grass species of low productivity, to sown phalaris-cocksfoot-subterranean clover pastures of high productivity. These pastures were set-stocked to sheep.

Rainfall P was recorded with automated tipping-bucket gauges. Reference evaporation E_o for a short green pasture, not limited for water, was calculated daily using both the Penman-Monteith [FAO, 1992] and Priestley and Taylor [1972] equations. Surface runoff and subsurface lateral flow was measured using surface barriers, interception trenches with drains, tipping-bucket flow meters, or flumes and weirs. The ratio of surface runoff to subsurface flow was highly variable from year to year, and also depended on soil type. In this analysis, the two lateral flow components were combined. Soil water content at depths up to 1.8 m was measured at several stations in each unit using a neutron probe. At Book Book, there were 4 stations per 0.135 ha and in the larger catchments at Maindample and Ruffy there was at least 1 station per ha. Measurements were made at 2-4 week intervals, depending on the rapidity of change in soil water content. Periods in winter were identified at each site when the evaporation rate was very low, and the soil profile was at or near its maximum water content. The mean water content for these periods was calculated, and the profile soil water deficit (S in mm) at all other times was calculated relative to this 'field capacity' value [Heng et al., 2001].

During winter, when the soil was wet, the actual evaporation E_a from the pasture (interception loss, transpiration and soil evaporation) was generally equal to E_o. But at other times, E_a was less than E_o. E_a had to be estimated from E_o and the soil water status, following Scotter et al. [1979]. At Book Book, this was done by calculating the measured *change* in S (ΔS) for short periods when there was no rainfall or drainage. ΔS was equated to E_a and plotted against the mean value of S for each period to give the relationship between E_a and S [Heng et al., 2001]. Evaporation was assumed to occur at the reference rate E_o for deficits up to 25 mm (absolute value). E_a was found to decrease linearly as the absolute value of S increased from 25 to >100 mm. At Maindample, direct measurements of E_a from the pasture were made, using Bowen Ratio equipment (Campbell Scientific CR23X) and both the aerodynamic and heat balance methods of calculation [Denmead, 1994]. The mean value of S for 6 stations near the Bowen Ratio equipment was measured at weekly intervals from 28 Nov 2000 to 15 Feb 2001. The daily value of E_a on each occasion was plotted against the corresponding mean S, as shown in Figure 1. These data confirmed the results from Book Book, which used the model

$$E_a = a + bS \qquad (1)$$

based on experimental measurements, to obtain daily values of E_a for each pasture type.

Subsequently at Maindample and Ruffy, a different approach was used to estimate the relationship between E_a and S. A SWB model was developed using the water balance equation in the form

$$D = P - E_a - R - \Delta S \qquad (2)$$

The start point for simulations was a day in mid-summer when there was *no drainage or runoff*, and the mean S for a catchment was known. Using a daily time step, values of the coefficients *a* and *b* in (1) were optimized by successive iterations so that the solution to the equation

$$\Delta S = P - E_a - R \qquad (3)$$

for a given day gave a value of S as close as possible to the corresponding measured value S. This was tested by regressing S (predicted) on S (measured) and forcing through the origin (for absolute values of S >25 mm). Once the coefficients in (1) had been estimated, (2) was solved on a daily basis to give values of D. If S (absolute value) was less than 25 mm on any day, E_o was used in (2); otherwise E_a from (1) was used. The value of E_a could not exceed E_o. The model was tested by optimized simulation for the full 3 years' measurements, and also for the first 2 years, with the optimized coefficients *a* and *b* being used for the remaining period.

The model was then modified to simulate both R and D by imposing a constraint on the rate of drainage at the lower boundary, based on subsoil saturated hydraulic conductivity K_s. The outputs were compared with previously measured R and predicted D values for each catchment. Having tested the model, values of R and D were simulated using 30 yr meteorological data (1 Jan 1970 to 31 Dec 2000) from the nearest Bureau of Meteorology station.

3. RESULTS

Heng et al. [2001] reported good agreement

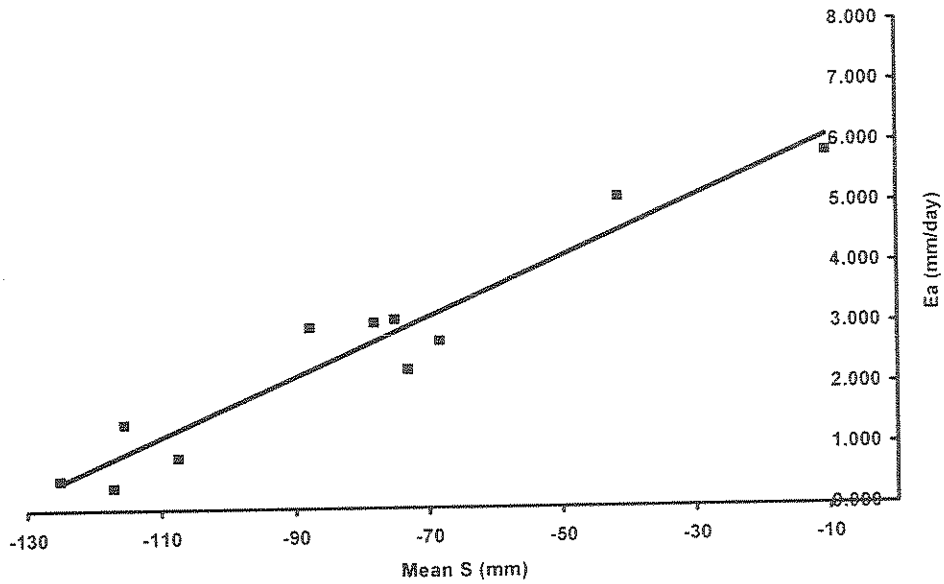

Figure 1. The relationship between E_a and mean soil water deficit S under a phalaris pasture at Maindample ($E_a = 0.0492S + 6.604$; $R^2 = 0.92$)

between simulated and measured S values under annual and perennial pastures from April 1994 to August 1997 at Book Book, NSW. The period included two 'wet' and two 'dry' winters. The estimated D values under the annual and perennial pastures averaged 33 and 12 mm, respectively. Simulations of drainage using weather data from Wagga Wagga airport (30 km away) for the previous 10 years confirmed the marked variability in annual drainage, but there was a consistent difference of 17 ± 4 mm between the annual and perennial pastures. For the period 1985-96, when the average annual rainfall was 625 mm, drainage under the phalaris pasture averaged 37 mm.

Similar results were obtained for the simulations at Maindample and Ruffy. Figure 2 shows a plot of simulated and measured values of S under a high-input phalaris pasture at Maindample from Jan 1998 to Jan 2001. Agreement between simulated and measured S values was good (regression $R^2 = 0.84$ for the 1:1 relationship). The discrepancies that occurred between the S values from late Dec 1999 to 15 Jan 2000 were due to problems with the neutron probe, so the simulated values should be close to the true values. D values for the phalaris pastures were higher at Maindample than at Book Book, mainly because of the higher annual rainfall (Table 1). D values for the cocksfoot pastures at Ruffy were much higher than in the corresponding years at Maindample. The soil at Ruffy was a Kurosol on granite, with a more gradual textural change down the profile than in the strongly duplex Sodosols at both Book Book and Maindample. Thus at Ruffy, relatively more of the surplus water drained through the profile than ran off the soil.

Differences in the relative importance of the water loss pathways were quantified using a partition ratio PR, defined as

$$PR = \frac{D}{D+R} \tag{4}$$

The mean PR value for the Sodosol at Book Book was 0.30 ± 0.04, which indicated that annually 30% of the surplus water went to drainage and the remainder to runoff. While infiltration of rain into the soil is important to replenish soil water supplies for pasture growth, it is also desirable to minimize deep drainage in areas where dryland salinization is a problem. Note that PR was in the range 0.41-0.56 at Maindample, but as high as 0.9-0.97 at Ruffy. This difference in water partitioning

Table 1. Rainfall, deep drainage and runoff under high-input phalaris pastures at Maindample and Ruffy.

Site and time	Rain-fall (mm)	Runoff (mm)	Deep drain-age (mm)	Part-ition ratio, PR
Maindample				
1998	768	117	82	0.41
1999	696	61	78	0.56
2000	769	110	112	0.53
Ruffy				
1998	624	14	130	0.90
1999	673	5	174	0.97
2000	719	15	269	0.95

was determined primarily by soil type, being unaffected by pasture type. The relationships between E_a and S established for the native, mainly annual grass pasture, and the perennial phalaris pasture at Maindample were used in a simulation of S, R and D for these pasture types, using 30 year weather data. The simulations produced a range of values for both R and D for rainfalls between 400 and 1100 mm. E_a (perennial) was consistently greater than E_a (annual), such that at 600 mm rainfall there was 63 mm more water to be disposed of in the annual than the perennial pasture. Greater runoff and deep drainage for the annual-based pasture, as shown in Figures 3 and 4, respectively, accounted for this difference in surplus water.

4. DISCUSSION AND CONCLUSIONS

The linear relationship between E_a and the soil water content for a pasture was confirmed by direct measurements of E_a, over a range of soil water deficits. The simple SWB model could accurately simulate the seasonal changes in soil water deficit that occurred under pastures in the HRZ of SE Australia. Where surface runoff and other superficial lateral water flows were measured, the model predicted deep drainage below the root zone, and could be used to upgrade estimates of leakage under annuals and perennials, such as those reported by Walker et al. [1999]. Once calibrated by measurements at such sites, the model could simulate S, R and D using only rainfall and E_0 data, provided subsoil K_s values were known.

Such information is essential for determining the most appropriate land uses and management practices to sustain productive enterprises, and to harvest adequate water for a variety of purposes. Excessive recharge to groundwater is a serious threat to productive agriculture in SE Australia, wherever there is shallow saline groundwater or ancient stores of subterranean salt. For example, in the annual rainfall range <600 to 1000 mm, Dunin et al. [1999] estimated that the surplus water available for runoff and drainage under native Eucalyptus woodland was <5-200 mm. For the same rainfall range (600-1000 mm), where woodland has been replaced by grass pastures,

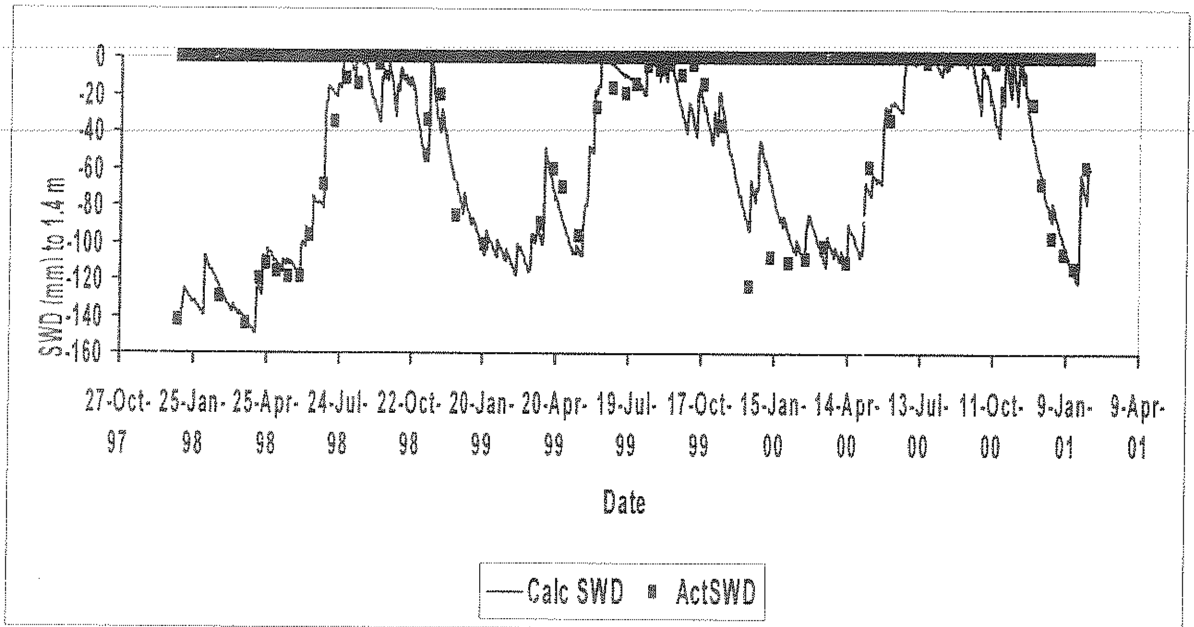

Figure 2. Simulated and measured values of S (soil water deficit SWD) for high-input phalaris pasture at Maindample

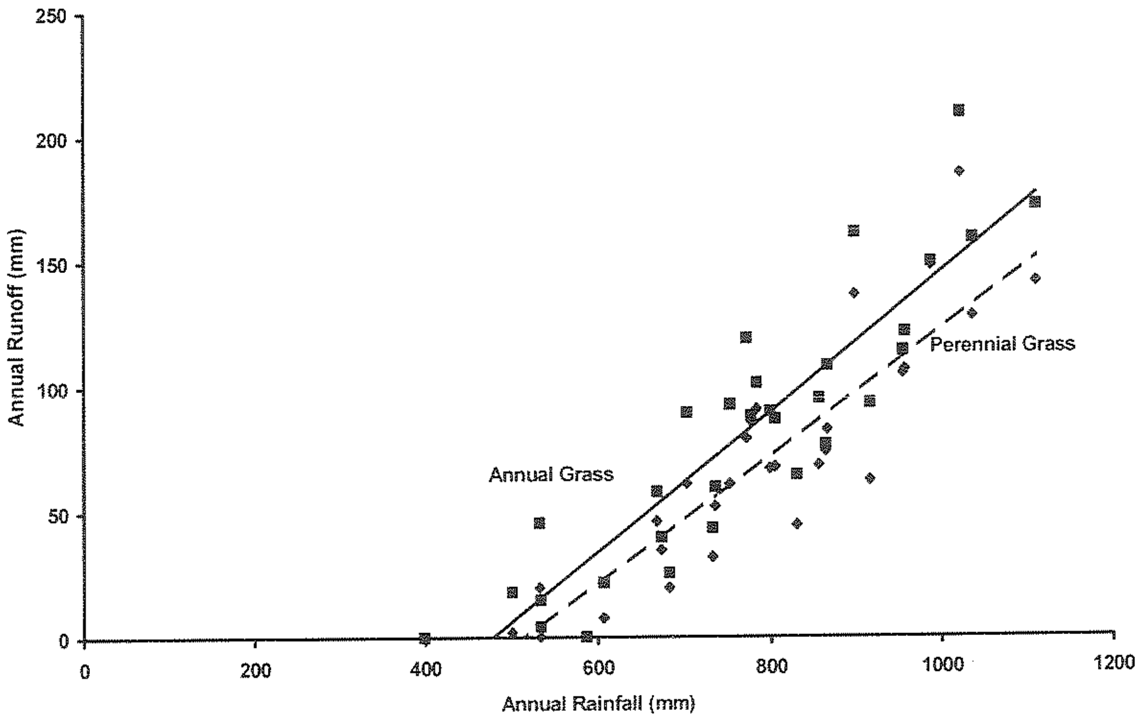

Figure 3. Simulated values of runoff R for annual grass pastures compared with perennial grass pastures on a Sodosol in NE Victoria over a 30 year period (R (annual) = 0.2796P – 133.9 (R^2 = 0.81) and R (perennial) = 0.2552P – 131.7 (R^2 = 0.82))

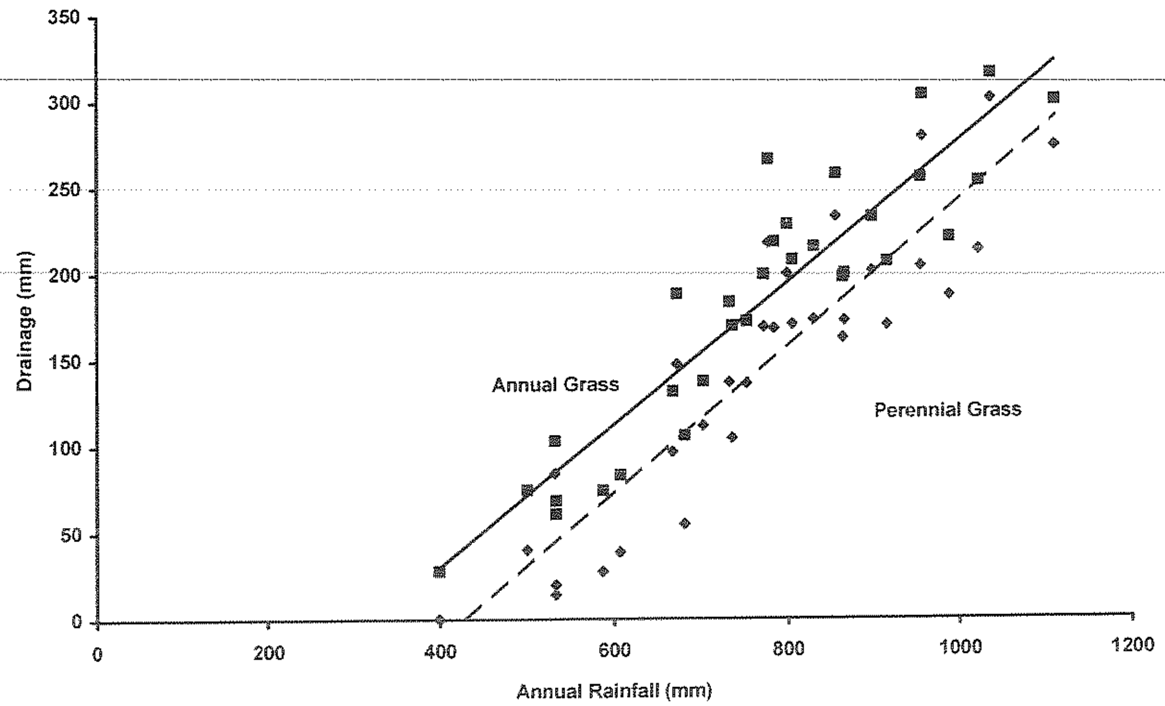

Figure 4. Simulated values of deep drainage D for annual grass pastures compared with perennial grass pastures on a Sodosol in NE Victoria over a 30 year period (D (annual) = 0.4105P – 134.0 (R^2 = 0.85) and D (perennial) = 0.4220P – 182.7 (R^2 = 0.83))

we estimate the surplus water to be 138-469 mm under annual pastures, and 75-422 mm under perennial pastures. Clearly, for many soil-geological combinations, the potential deep drainage under annual pastures is likely to be excessive over this whole rainfall range; also for perennial pastures when rainfall exceeds 700-800 mm.

However, the fate of this surplus water depends on its partitioning between runoff and drainage. The PR value depends markedly on soil type, with as little as 30% of the surplus going to drainage in Sodosols with impermeable subsoils, to >90% draining in coarse-textured Kurosols. These results have profound implications for land management because in catchments where recharge to groundwater is causing an undesirable rise in saline groundwater, no type of pasture, with the possible exception of lucerne, will be able to keep deep drainage to an acceptably low level. Alternative land uses such as plantation forestry should be considered on such soils. Currently, there is no planning provision in forestry developments to reduce deep drainage and hence recharge, whilst having minimal impact on stream flows.

The SWB model is being tested on different soil types in the HRZ of southern Australia in Meat and Livestock Australia's Sustainable Grazing Systems program. One aim of the study is to determine both the quantity of surplus water and its partitioning, as influenced by topography, soil and pasture type and grazing management. From this, the risk of excessive deep drainage from farmland can be assessed and spatially referenced. Thus, an understanding of processes affecting the unsaturated zone can be linked to knowledge of groundwater systems to develop effective solutions to the problem of encroaching dryland salinity.

5. ACKNOWLEDGEMENTS

We are grateful to Meat and Livestock Australia, the Murray-Darling Basin Commission, and Land and Water Australia for financial support. We also acknowledge the co-operation of landholders Bill Parsons, Roger Strong and Les Hudson on whose properties the Victorian work was carried out.

6. REFERENCES

Denmead, O. T., Measuring fluxes of CH_4 and N_2O between agricultural systems and the atmosphere, In *Global Emissions and Controls from Rice Fields and Other Agricultural and Industrial Sources*, (K. Minami, A. Mosier, and R. Sass eds), pp. 209-234, National Institute of Environmental Science, Tsukuba, Japan, 1994.

Dunin, F. X., J. Williams, K. Verburg, and B. A. Keating, Can agricultural management emulate natural ecosystems in recharge control in south eastern Australia, *Agroforestry Systems*, 45, 343-364, 1999.

FAO, *Expert Consultation on Revision of FAO Methodologies for Crop Water Requirements*, FAO, Rome, 1992.

Heng, L. K., R. E. White, K. R. Helyar, R. Fisher, and D. Chen, Seasonal differences in the soil water balance under perennial and annual pastures on an acid Sodosol in southeastern Australia, *European Journal of Soil Science*, 52, 227-236, 2001.

Isbell, R. F., *The Australian Soil Classification*. Australian Soil and Land Survey Handbook, CSIRO, Melbourne, 1996.

Priestley, C.H.B., and R. J. Taylor, On the assessment of surface heat flux and evaporation using large-scale parameters, *Monthly Weather Review*, 100, 81-92, 1972.

Scotter, D.R., B. E. Clothier, and M. A. Turner, The soil water balance in a fragiaqualf and its effect on pasture growth in Central New Zealand, *Australian Journal of Soil Research*, 17, 455-465, 1979.

Walker, G., M. Gilfedder, and J. Williams, *Effectiveness of Current Farming Practices in the Control of Dryland Salinity*, CSIRO Land and Water, Canberra, 1999.

White, R.E., K. R. Helyar, A. M. Ridley, D. Chen, L. K. Heng, J. Evans, R. Fisher, J.R. Hirth, P.M. Mele, G. R. Morrison, H. P. Cresswell, Z. Paydar, F. X. Dunin, H. Dove, and R. J. Simpson, Soil factors affecting the sustainability and productivity of perennial and annual pastures in the high rainfall zone of south-eastern Australia, *Australian Journal of Experimental Agriculture*, 40, 267-283, 2000.

Williamson, D. R., G. W. B. Gates, G. Robinson, G. K. Linke, M. P. Seker, and W. R. Evans, *Salt Trends*. Dryland Technical Report Number 1. Murray Darling Basin Commission, Canberra, 1997.