Estimating episodic recharge under different crop/pasture rotations in the Mallee region.
Part 1. Experiments and model calibration

L. Zhang\textsuperscript{a,*}, I.H. Hume\textsuperscript{c}, M.G. O’Connell\textsuperscript{d}, D.C. Mitchell\textsuperscript{c}, P.L. Milthorpe\textsuperscript{e}, M. Yee\textsuperscript{e}, W.R. Dawes\textsuperscript{a}, T.J. Hatton\textsuperscript{b}

\textsuperscript{a}CSIRO Land & Water, GPO Box 1666, Canberra, ACT 2601, Australia
\textsuperscript{b}CSIRO Land & Water, Private Bag PO, Wembley, WA, Australia
\textsuperscript{c}NSW Agriculture, P.O. Box 736, Deniliquin, NSW 2710, Australia
\textsuperscript{d}Agriculture Victoria, Mallee Research Station, Walpeup, VIC 3507, Australia
\textsuperscript{e}NSW Agriculture, P.O. Box 300, Condobolin, NSW 2877, Australia

Accepted 14 December 1998

Abstract

Changes in land use in the Mallee region of southeastern Australia have led to increased groundwater recharge and salinisation. This study was conducted to determine the impact of different agronomic practices on recharge control, in particular episodic recharge. During the period 1991–1995, two field experiments were carried out at Hillston (New South Wales) and Walpeup (Victoria) where soil hydraulic properties, soil-moisture content, and leaf area index were measured. Various crop and pasture rotations were considered involving fallow, field pea (\textit{Pisum sativum} \textit{L \textit{cv Dunndale}}), Indian mustard (\textit{Brassica juncea} \textit{cv F2 cross}), wheat (\textit{Triticum aestivum} \textit{cv Janz Meering}), oats (\textit{Avena sateva} \textit{L \textit{cv Coolabah}}), lucerne (\textit{Medicago sativa} \textit{L \textit{cv Arora}}) and medic pastures (\textit{Medicago truncatula} \textit{cv Parriagio, Sephi and Hykon}). Data obtained from these experiments were used to calibrate and test a biophysically based model WAVES. With minimum calibration, the simulated soil-moisture content and leaf area index are in good agreement with field observations. The parameter values are within a physically reasonable range. The success of the model in simulating soil-moisture dynamics and plant growth was due to the accurate representation of the soil and canopy processes. WAVES combined with field measurements provides a powerful tool for estimating the impacts of land-management options on water balance. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Water balance; Leaf area index; Episodic recharge; Crop rotation; Recharge control

* Corresponding author. Tel.: +61-2-62465802; fax: +61-2-62465800
E-mail address: lu.zhang@cbr.clw.csiro.au (L. Zhang)
1. Introduction

The rise of groundwater tables and associated dryland salinity have been identified as major land degradation problems in the Mallee region of southeastern Australia. This region is characterised by a semi-arid climate, and originally a low, sparse woodland of multi-stemmed individuals of the genus *Eucalyptus*. Much of the salinity problem is caused by massive clearing of native vegetation and the use of shallow-rooted annual crops and pastures (Clifton et al., 1995). These land-use changes have significantly altered the water balance of the region and led to increased recharge to the groundwater system; recharge under native Mallee vegetation is $<0.2 \text{ mm year}^{-1}$ (Allison et al., 1990), but following replacement by annual cropping increases by a factor of 100. It appears to be economically and sociably infeasible to restore the natural water balance/recharge rate/water table depth by replanting the native vegetation on a sufficient scale, but better management of agricultural practices may reduce the undesirable effects associated with dryland salinity.

The main emphasis of current salinity control strategies is to enhance plant water uptake to minimise groundwater recharge. For example, Clifton and Taylor (1995) propose that land management includes either improving the growth of existing annual crops and pastures, or replacing these with perennial vegetation. The traditional agricultural practice in the Mallee region involves winter fallows in crop rotations and this has been shown to contribute to improved crop yield (French, 1978; Fischer, 1987). However, it has also been shown that winter fallows have caused increased recharge (O’Connell et al., 1995). It is desirable to evaluate recharge rates and their long-term impact on regional water balance and salinity under different crop rotations.

A number of studies have been conducted to evaluate current rates of groundwater recharge and its relationship to environmental factors (Walker et al., 1991; Kennett-Smith et al., 1994). These have shown that a simple water-balance model can be used to analyse the general factors that affect recharge in a region. However, the need for a more detailed physically based model to evaluate the effect of different agronomic practices on recharge has also been recognised. An important step in predicting groundwater recharge is to better understand its episodic nature, how it varies across the landscape, and how it is affected by agronomic practices.

To answer these questions, we need to combine field measurements with water-balance modelling because it is difficult to use field techniques alone to determine recharge rates under different agronomic practices. Recharge is a small component of the water balance and it varies significantly with soil and vegetation. The impact of land-use changes on recharge may take many years to be noted. However, most field experiments run at a limited number of sites and for short-term periods. Results obtained from these experiments contain useful information in terms of process understanding. But they are of limited use for developing management decisions. Physically based models (e.g. Hauhs, 1990; Dawes et al., 1997) can help identify key processes and the most important factors controlling recharge, and extend results obtained from field trails and provide information that can be used to develop sustainable land-management practices.

This two-part paper is an integrated study of field experiments and modelling aimed at quantification of recharge control by agronomic practices in the Mallee region, and, in
particular, episodic recharge. In Part 1, we will describe the field experiments conducted at Hillston (New South Wales) and Walpeup (Victoria) during the period 1991–1995. We will show how the water-balance model WAVES was calibrated using data obtained from these experiments. Simultaneous fitting of observed moisture profiles and leaf area development helped us gain confidence in use of the model. In Part 2, the calibrated model is used to evaluate vegetation management strategies and their control over recharge over both, long periods as well as with large episodic events.

2. Field experiments and data

An integrated program of field experimentation was established at the Mallee Research Station, Walpeup, Victoria (35°07′ S, 141°59′ E) and on a farm property near Hillston, NSW (33°22′ S, 145°51′ E) (see Fig. 1).

The Hillston site was located on aeolian deposits of Devonian hills in the N.E. of the Murray Basin. The soil is a calcareous red earth (Stace et al., 1968) with a Northcote classification Gn 2.13 (Northcote, 1979; Isbell, 1996). The Hillston experiment was established in a field that had been cleared of trees (mallee, bulloak and western red box) in 1988. Two dryland wheat crops were grown on the site during 1989 and 1990, and it was ploughed and levelled during 1991 in preparation for the experiment and was irrigated prior to the commencement of field measurements. The site has a predominant northeasterly aspect and a uniform slope of <0.3%. The climate is semi-arid with mean annual rainfall of 371 mm (1890–1992), of which 56–68% falls in the growing season (May–November). The mean potential evaporation is \( \approx 1800 \text{ mm year}^{-1} \). The Walpeup site was located in a swale within an east–west oriented dune system (Newell, 1961; Rowan and Downes, 1963). The soil is a solonised brown soil (Stace et al., 1968) with a Northcote classification Gc 2.22 (Northcote, 1979) and has been used for agriculture since being cleared of native Mallee vegetation in 1914. The site has a westerly aspect with a uniform slope of 1%. The climate is semi-arid with a mean annual rainfall of 340 mm (1957–1994), of which 65–70% falls in the growing season (May–November) but with significant variation in quantity and distribution. The mean potential evaporation is \( \approx 1700 \text{ mm year}^{-1} \).

2.1. Experimental design

A common experimental methodology was used at both the locations, although the cropping treatments differed to reflect local cropping practice. Two perennial plantings; one traditional, and one modified rotational cropping treatments were established at each location. The rotational cropping treatments were established as a cyclic rotational experiment (Patterson, 1963). Each phase of each rotation is expressed in each year of the experiment providing an efficient means of replication in both, time and space. The spatial variability of soil properties was assessed by electromagnetic survey (Geonics EM38) and experimental treatments were allocated to account for these spatial patterns in the ‘blocking’ of the experiment. In this way, the spatial variability in soil physical properties between replicates was minimised.
2.2. Experimental layout

The Hillston site was divided into 25 plots each 40 m square. A single 4-m deep aluminium neutron moisture meter access tube was installed in the centre of each plot using the slurry method (Greacen, 1981). All agronomic and soil-water measurements were made in a $10 \times 10 \text{ m}^2$ sub-plot in the centre of the main plots to minimise any edge effects. Two treatments were allocated to these plots: a traditional rotation (fallow/oats/wheat/wheat), and a modified rotation (wheat/wheat/lucerne/lucerne) (see Table 1). The rotational treatments were established in June 1992 and grown continuously for five phases of the rotation until December 1995.

The Walpeup experimental site rotational treatments were allocated to 18 plots, each 21 m by 20 m, and separated from its neighbour by a 5–10 m buffer. Two PVC neutron
moisture meter (NMM) access tubes were installed 5.5 m deep and 10 m apart in each plot to monitor soil water. A fallow rotation treatment (fallow/wheat/field pea) and a continuous crop rotation treatment (Indian mustard/wheat/field pea) were established in June 1993 (see Table 1). Three years of biomass, soil moisture, and climate measurements were made, ending in December 1995.

2.3. Soil data

The relationships between volumetric water content, hydraulic conductivity, and soil-water potential were described with the Broadbridge and White (1988) soil model. The parameters of the soil model were estimated by inverse modelling (Hume and Mitchell, 1996). Soil water beneath each treatment was measured at intervals of two-to-four weeks. Measurements at Hillston started in November 1991 and continued until December 1995, while the period of measurements at Walpeup was from June 1993 to December 1995.

2.4. Meteorological data

At each site, meteorological data were recorded hourly by automatic weather stations. Wet and dry bulb temperature were measured using temperature sensors with a standard muslin wick at Walpeup, and relative humidity measured at Hillston. A tipping-bucket rain gauge recorded rainfall amount and intensity. Radiation sensors with a uniform spectral response from 500 to 1000 nm were used to record solar radiation. Missing rainfall data were taken from a manual rain gauge on site. Other missing meteorological data were interpolated using measurements from neighbouring weather stations.

2.5. Plant growth data

Plant biomass was sampled several times throughout each growing season, ≈3 weeks apart at Walpeup, and one harvest was conducted at Hillston. At each biomass harvest, samples of the above-ground crop, for the determination of crop biomass, were obtained from five contiguous drill-rows—each one meter long—and were dried at 80°C. The date of sowing, emergence, anthesis, and grain harvest was recorded for all traditional crops.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>crop</td>
<td>sowing date</td>
<td>crop</td>
<td>sowing date</td>
</tr>
<tr>
<td>Hillston</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>fallow</td>
<td>7 June</td>
<td>wheat</td>
<td>14 June</td>
</tr>
<tr>
<td>10</td>
<td>wheat</td>
<td>18 May</td>
<td>wheat</td>
<td>14 June</td>
</tr>
<tr>
<td>Walpeup</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>fallow</td>
<td>22 June</td>
<td>wheat</td>
<td>24 June</td>
</tr>
<tr>
<td>10</td>
<td>mustard</td>
<td>22 June</td>
<td>wheat</td>
<td>24 June</td>
</tr>
</tbody>
</table>
Ground cover of crop foliage was measured using a photographic technique similar to Siddique et al. (1989). Photographs were taken 1.5 m vertically above the soil surface at a fixed location within representative plots using a 35 mm camera to cover a ground area of $\approx 1.0 \times 0.6 \text{ m}^2$. A 99-point rectangular grid was superimposed on the image and the incidence of green and non-green foliage was recorded to estimate green area index (GAI). Biomass production of cereal crops was assessed at anthesis, by measuring the dry weight of all above-ground plant material after drying at 45°C for 24 h.

To compare simulated plant growth with the measurements, we first calculated dry weight of green material based on the total dry weight and percentage green foliage. The dry weight of green material was converted into leaf area index (LAI) using specific leaf area values from samples at each site or from the values of Armstrong and Pate (Armstrong and Pate, 1994a, b) for field pea, Sharma and Kumar (Sharma and Kumar, 1989) for Indian mustard, and Dawes et al. (Dawes et al., 1997) for oats and wheat.

3. The WAVES model

WAVES (Dawes and Hatton, 1993; Zhang et al., 1996) is a process-based model that simulates the dynamic interactions within the soil–vegetation–atmosphere system on a daily time step. The model consists of three sub-models which simulate the energy, water and carbon (plant growth) balances.

The WAVES energy balance partitions net radiation into canopy and soil available energy. WAVES calculates evaporation and transpiration with the Penman–Monteith equation (Monteith, 1981), using available energy, air temperature, and vapour pressure deficit.

The physiological control on transpiration is simulated using the stomatal conductance model of Ball et al. (1987) as modified by Leuning (1995). Plant growth stresses induced by the availability of light, water, and nutrients, are modified by air temperature and salt in the root zone, feedback to carbon assimilation and plant growth, and ultimately to stomatal conductance, and transpiration.

The soil hydrology is described by the Richards equation (Richards, 1931). This module handles rainfall infiltration, runoff, soil- and plant-water extraction, moisture redistribution, and groundwater recharge (Dawes and Short, 1993; Dawes and Hatton, 1993). The performance of the iterative solution of Richards’ equation is robust, very fast, and efficient (Short et al., 1995). A full description of WAVES can be found in Zhang et al. (1996); Dawes et al. (1997); Zhang and Dawes (1998).

4. Model implementation

The saturated and air-dry moisture contents for each soil horizon were estimated from soil-moisture measurements (Hume et al., 1997). Initial estimates of saturated hydraulic conductivity were obtained using disc permeameters (White et al., 1992). The Broadbridge–White soil parameters, $\lambda_c$ and $C$, were initially estimated from an evaluation of the soil texture profiles at each plot. Finally, the soil parameters were
adjusted using inverse modelling or calibration and kept constant throughout the period of
simulation (Hume and Mitchell, 1996) (Table 2).

Six different types of crop and pasture were selected from the two experimental sites to
evaluate the impact of agronomic practices on recharge in the Mallee region. Information
of the vegetation parameters used in WA VES is given in Table 3. Most of the parameter
values were obtained from literature (Whitfield et al., 1986; Sharma and Kumar, 1989;

Table 2
Broadbridge–White soil parameters for each soil layer used in WAVES simulations at Hillston and Walpeup

<table>
<thead>
<tr>
<th>Plot</th>
<th>Soil layer</th>
<th>Depth (cm)</th>
<th>$K_s$ a (m/d)</th>
<th>$\theta_s$ b (cm$^3$/cm$^3$)</th>
<th>$\theta_a$ c (cm$^3$/cm$^3$)</th>
<th>$\lambda_c$ d (m)</th>
<th>C e</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hillston</td>
<td>1 (sandy clay loam)</td>
<td>0–52</td>
<td>0.05</td>
<td>0.30</td>
<td>0.05</td>
<td>0.60</td>
<td>1.10</td>
</tr>
<tr>
<td></td>
<td>2 (sandy clay)</td>
<td>52–375</td>
<td>0.01</td>
<td>0.35</td>
<td>0.10</td>
<td>0.42</td>
<td>1.01</td>
</tr>
<tr>
<td></td>
<td>10 (sandy clay loam)</td>
<td>0–52</td>
<td>0.05</td>
<td>0.30</td>
<td>0.05</td>
<td>0.30</td>
<td>1.50</td>
</tr>
<tr>
<td></td>
<td>2 (sandy clay)</td>
<td>52–375</td>
<td>0.01</td>
<td>0.35</td>
<td>0.10</td>
<td>0.35</td>
<td>1.05</td>
</tr>
<tr>
<td>Walpeup</td>
<td>3 and 10 (sandy loam)</td>
<td>0–10</td>
<td>0.10</td>
<td>0.40</td>
<td>0.20</td>
<td>0.10</td>
<td>2.00</td>
</tr>
<tr>
<td></td>
<td>2 (sandy clay loam)</td>
<td>10–18</td>
<td>0.10</td>
<td>0.40</td>
<td>0.05</td>
<td>0.10</td>
<td>1.07</td>
</tr>
<tr>
<td></td>
<td>3 (sandy clay)</td>
<td>18–187</td>
<td>0.01</td>
<td>0.35</td>
<td>0.10</td>
<td>0.30</td>
<td>1.05</td>
</tr>
<tr>
<td></td>
<td>4 (light clay)</td>
<td>187–487</td>
<td>0.0001</td>
<td>0.35</td>
<td>0.10</td>
<td>0.40</td>
<td>1.10</td>
</tr>
</tbody>
</table>

a Saturated hydraulic conductivity.
b Saturated soil-moisture content.
c Air-dry soil-moisture content.
d Characteristic length.
e Shape parameter related to soil texture and structure.

Table 3
Vegetation parameters used to simulate crop and pasture growth at Hillston and Walpeup

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Oats</th>
<th>Wheat</th>
<th>Indian mustard</th>
<th>Field pea</th>
<th>Medic</th>
<th>Lucerne</th>
</tr>
</thead>
<tbody>
<tr>
<td>IRM weighting factor for water</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>IRM weighting factor for nutrients</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Specific leaf area (m$^2$ kg leaf dry weight)</td>
<td>12.0</td>
<td>12.0</td>
<td>7.5</td>
<td>10.5</td>
<td>12</td>
<td>22.0</td>
</tr>
<tr>
<td>Slope in conductance model</td>
<td>0.70</td>
<td>0.70</td>
<td>0.70</td>
<td>0.70</td>
<td>0.90</td>
<td>0.70</td>
</tr>
<tr>
<td>Maximum carbon assimilation rate (kg C m$^{-2}$ d$^{-1}$)</td>
<td>0.015</td>
<td>0.015</td>
<td>0.012</td>
<td>0.015</td>
<td>0.012</td>
<td>0.01</td>
</tr>
<tr>
<td>Light extinction coefficient</td>
<td>0.65</td>
<td>0.65</td>
<td>0.65</td>
<td>0.65</td>
<td>0.65</td>
<td>0.85</td>
</tr>
<tr>
<td>Temperature for optimum growth (°C)</td>
<td>20</td>
<td>25</td>
<td>21</td>
<td>25</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Temperature for half optimum growth (°C)</td>
<td>5.0</td>
<td>5.0</td>
<td>7.0</td>
<td>5.0</td>
<td>10.0</td>
<td>10.0</td>
</tr>
<tr>
<td>Degree daylight hours (°C h)</td>
<td>15000</td>
<td>15000</td>
<td>13000</td>
<td>13500</td>
<td>16000</td>
<td>—</td>
</tr>
<tr>
<td>Saturation light intensity (μmol m$^{-2}$ s$^{-1}$)</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
<td>1200</td>
<td>1000</td>
</tr>
<tr>
<td>Maximum rooting depth (m)</td>
<td>1.0</td>
<td>1.5</td>
<td>0.3</td>
<td>0.3</td>
<td>1.0 a</td>
<td>3.0</td>
</tr>
<tr>
<td>Leaf respiration coefficient (kg kg$^{-1}$ day$^{-1}$)</td>
<td>0.0015</td>
<td>0.0045</td>
<td>0.0065</td>
<td>0.0025</td>
<td>0.0002</td>
<td>0.0002</td>
</tr>
<tr>
<td>Root respiration coefficient (kg kg$^{-1}$ day$^{-1}$)</td>
<td>0.00012</td>
<td>0.00012</td>
<td>0.00012</td>
<td>0.00008</td>
<td>0.0001</td>
<td>0.0001</td>
</tr>
</tbody>
</table>

a The maximum rooting depth was set to 0.3 m at Walpeup.
Hodges, 1992; Hatton and Dawes, 1993; Armstrong and Pate, 1994a, b; Dawes et al., 1997) and kept constant during the simulation. Maximum rooting depth was estimated based on field measurements, while the growing season length (degree daylight hours) and the leaf and root respiration coefficients were obtained by model calibration. Once the model was calibrated, all the parameter values were kept constant and used in the model to simulate plant growth, soil moisture content, and recharge for different years of the experiments.

WA VES was run using daily values of maximum and minimum air temperatures, precipitation, vapour-pressure deficit, and solar radiation. The simulation commenced at 1 January 1992 for Hillston, at 1 January 1993 for Walpeup, and ended on 31 December 1995 for both the sites.

5. Results and discussion

5.1. Plant growth

Fig. 2 shows a comparison of simulated LAI and the measured values for six selected plant types. The model results are in good agreement with the measurements. The predicted LAI followed the measurements reasonably well for wheat, Indian mustard, and field pea. The model captured the peak LAI well in terms of timing and its magnitude. However, it slightly overestimated LAI during the first month of the growing season. For medic pasture, WA VES predicted the LAI very well. The simulated LAI for lucerne showed reasonable agreement with the observed values. There was only one measurement available for oats at Hillston; however, it is not unreasonable to assume that the LAI pattern is realistic for the site given that the simulated peak LAI was in good agreement with the measurement.

The peak LAI of Indian mustard grown at Walpeup in 1993 was only 0.5. Wheat grown after this mustard crop in the drought in 1994 reached a maximum LAI of 1.5, while wheat grown in the same year on land fallowed during 1993 reached LAI of 2.5. There was no difference in the LAI of field peas grown during 1995 suggesting that the soil moisture at sowing was similar beneath both, the fallow and non-fallow treatments. The wheat grown during the 1994 drought explored all available soil water and the effect of fallowing on crop growth was only apparent in the year immediately after the fallow. WA VES faithfully reproduced this behaviour without the need to adjust the parameters that characterise plant growth. This shows the ability of WA VES to accurately model the effect of different levels of moisture availability on growth.

WA VES is primarily concerned with the responses and feedbacks of plants on water balance under different climatic conditions. It uses a generic plant growth model incorporating the integrated rate methodology (IRM) of Wu et al. (1994). It explicitly considers the effect of light, temperature, available water, and nutrients on plant growth on a daily time step. The IRM framework provides an explicit means of combining these factors into a single response function. It also provides a means of taking into account not only the relative availability of resources, but also other possible factors such as salinity. IRM retains a mechanistic representation of relative
Fig. 2. Comparison between simulated (———) and measured (●) leaf area index (LAI) at Hillston and Walpeup.
plant growth response to resources availability in the form of its enzyme kinetics origins. The treatment of plant stomatal functioning, transpiration, carbon allocation, and respiration in WAVES is based on well-established relationships with some simplification. The canopy conductance model of WAVES is adapted from Ball et al. (1987) as modified by Leuning (1995) and it provides the key linkage between the transport of water and carbon in the system. It is well understood that the amount of transpiration by a plant is directly related to its leaf area and, therefore, it is important to be able to accurately simulate plant LAI.

WAVES uses a number of parameters to describe canopy carbon balance and plant growth (see Table 3). A necessary step in applying the model is to determine the values of these parameters or constants for the site under consideration. Parameter estimation may have at least as great an effect on the accuracy of the model results as the intrinsic accuracy of the model itself. In this study, most of the parameter values were obtained from literature as discussed previously, while the growing season length (degree daylight hours) and the leaf and root respiration coefficients (which are very difficult to measure) were obtained by the method of trial and error for the first growing season. The results shown in Fig. 2 represent the following growing seasons with the fitted parameter values. It is encouraging to note that WAVES performed well in simulating LAI for six plant types under different rotation systems, given different soils at the two sites, and that annual rainfall was quite variable during the period of experiments.

Maximum rooting depth was found to play an important role in plant growth and soil moisture distribution. At Walpeup the maximum rooting depth was set to 30 cm for wheat and medic (Table 3), which is much smaller than the values reported in the literature (Gajri and Prihar, 1985). Field measurements showed that pH was 9.6 and exchangeable sodium percentage (ESP) 18%, between 18 and 50 cm at the site. These factors indicate that the soil is highly sodic and provides highly unfavourable conditions for root growth. This restriction in rooting depth allowed more accurate modelling of both leaf area development, and soil moisture profiles. Shallow rooting depth in the Victorian Mallee has serious implications for plant growth and recharge control because rooting zone acts as a buffer in reducing recharge and shallow rooting depth means little recharge control. Incerti and O’Leary (1990) suggested that one of the options is to introduce varieties which are more tolerant to high pH.

The simulations presented here provided thorough tests for the plant growth component of WAVES. It was shown that the model performed well under a range of land use and climatic conditions and this suggests that WAVES is robust for simulating plant growth.

5.2. Soil moisture

The soil moisture of the top 50 cm layer showed rapid responses to rainfall and evapotranspiration. The simulated soil-moisture content agrees very well with the measured values at both sites throughout the study period (Figs. 3 and 4). These particular depths were chosen to represent different soil layers (see Table 2) and root zones (Table 3) at the two sites. The model was able to reproduce seasonal variations in soil moisture for different soil types under various cropping rotations. These results are
consistent with the findings of Dawes et al. (1997) and Zhang et al. (1999) for two dryland catchments at Wagga Wagga, NSW.

To further evaluate the performance of the model in simulating soil-water dynamics, we compared calculated and measured soil moisture profiles for different periods. At both sites, the model agrees very well with the measurements throughout the soil profile (Figs. 5 and 6). A drying front associated with maximum rooting density at \( \approx 1 \) m was observed throughout the study period at Hillston, below which the soil water remained relatively constant. These results also indicate that the model accurately simulated the plant water uptake patterns. This is important if the model is to be used to investigate the impact of plant on water balance, in particular recharge.

The maximum rooting depth used at Walpeup had a significant effect on modelled soil moisture. As mentioned already, soil-chemical measurements supported the use of a shallow rooting depth. Also, soil-moisture measurements indicated that any drying front penetrated to a depth of only ca. 30 cm. When we used a rooting depth of 100 cm,
WA VES was unable to reproduce the moisture profiles in the top 100 cm of soil, or the peak LAI of the plants.

It is encouraging that WA VES was able to accurately simulate soil-moisture dynamics under different soil, climatic, and vegetation conditions. The success of WA VES in simulating soil moisture dynamics can be attributed to the treatment of the canopy and soil processes. In the context of recharge control, it is important to understand the dynamic relationships and feedbacks between soil-moisture distribution and plant growth. Any model that does not incorporate such interactions will be of limited value in exploring the impact of agronomic practices on recharge.

Application of any model requires some calibration. Ideally, parameter values should be estimated directly from field measurements. In the absence of such information, a common practice is to fit model parameters based on literature values, or personal experience. However, caution must be exercised and the number of fitted parameters should be kept to a minimum. For example, WA VES requires knowledge of the soil
layering, and the parameters that describe the relationships between soil-water potential, volumetric water content, and hydraulic conductivity (Short et al., 1995). The soil layering was obtained directly from field measurements, while the values of the soil
hydraulic parameters were initially set from the WAVES User Manual (Dawes et al., 1998) and fitted by manual calibration. Hume et al. (1997) present the details of the technique, and the fitted values of these parameters are shown in Table 2.

Fig. 6. Simulated (— — —) and measured (○) soil moisture profiles at Walpeup for the selected dates (plot 10).
6. Conclusions

The WAVES model was applied to two experimental sites in the Mallee region of southeastern Australia for estimating soil moisture, and plant growth. The model was calibrated using measured LAI for the first growing season and tested for the following seasons. Most of the parameters characterising plant growth were obtained from literature values and only a few were obtained by the trial and error method. The soil parameters were obtained by inverse modelling base on limited soil-moisture measurements. These parameter values are within a physically reasonable range. The model was found sensitive to maximum rooting depth and this has important implications in terms of recharge control. The results showed that the model was able to accurately simulate soil-moisture dynamics for different soils under various crop rotations. The model also successfully simulated LAI for six plant types. The success of the model in simulating soil-moisture dynamics and plant growth was due to the reasonable representation of the soil and canopy processes.

One of the advantages of physically based models, such as WAVES, is the ability to identify key factors controlling hydrologic processes and to simulate the impact of various land-management options on water balance. Combined with field measurements, WAVES provides a powerful tool for the investigation of the hydrological and ecological effects of scenario management options. In Part 2, we will use the model to evaluate the impact of agronomic practices on recharge control, in particular episodic recharge.

Acknowledgements

This work was partially funded by the Murray–Darling Basin Commission through its Natural Resources Management Strategy Investigation and Education Program (Grant No. M4025). Technical assistance in site maintenance and data collection was provided by S.D. Blandthorn, A.J. Corbett, S. Wisneske, M.C. Brown, M.J. Ferguson, J.L. Latta, M.W. Ferguson. We are grateful to Mr. W. Milthorpe for the use of his farm at Hillston. We are grateful to G.R. Walker, V. Snow and F. Lewis, and Joe Landsberg for comments on a draft of this paper.

References


