SOIL WATER STATUS UNDER PERENNIAL AND ANNUAL PASTURES ON AN ACID DUPLEX SOIL

L.K. HENG*, R.E. WHITE, D. CHEN
Institute of Land and Food Resources, University of Melbourne, Parkville, Australia

Abstract

A comprehensive field study of soil water balance, nitrogen (N) cycling, pasture management and animal production was carried out on an acid duplex soil at Book Book near Wagga Wagga in southern New South Wales. The experiment, carried out over a 3-year period, tested the hypothesis that sown perennial grass pastures improve the sustainability of a grazing system through better use of water and N. The treatments were: annual pastures without lime (AP-), annual pastures with lime (AP+), perennial pastures without lime (PP-) and perennial pastures with lime (PP+). Soil water measurement was made using a neutron probe on one set of the treatments comprising four adjacent paddocks. Over three winter and spring periods, the results showed that perennial grass pastures, especially PP+, consistently extracted about 40 mm more soil water each year than did the annual grass pastures. As a result, surface runoff, sub-surface flow and deep drainage (percolation below 180 cm depth) were about 40 mm less from the perennial pastures. The soil water status of the four pasture treatments was simulated reasonably well using a simple soil water model. Together with the long-term simulation of deep drainage, using past meteorological records, it is shown that proper management of perennial pastures can reduce recharge to groundwater and make pastoral systems more sustainable in the high rainfall zone. However, to completely reduce recharge, more-deeply rooted plants or trees are needed.

1. INTRODUCTION

The southeastern part of Australia is important for meat production, accounting for nearly 50% of the nation’s cattle and sheep output. However, surveys show that much of the pasture base in the high rainfall zone (HRZ) (>600 mm per annum) is in a degraded condition. This is due to the replacement of native perennial summer-active species by exotic annuals that are generally winter-active and shallow-rooted. The change in land use and shift in physiological function have contributed to the degradation, notably by accelerating soil acidification and dry-land salinization, which not only reduce productivity but also threaten sustainability of agriculture in the region.

Greater storage of sub-soil moisture, as a result of incomplete use of seasonal rainfall by annual pastures under rain-fed agriculture, has augmented deep drainage and consequent recharge to groundwater. Rising water tables have been widely reported on the western and northern slopes of the Great Dividing Range (GDR) in New South Wales (NSW) and Victoria in the HRZ and drier areas. Further, with the increased N inputs and N cycling in grazed subterranean clover-based pastures, more mineral N accumulates in the soil profiles at the end of the usually dry summers. The combination of enhanced nitrification and leaching of NO$_3^-$ ions (accompanied by cations) in the wet autumns and winters has led to an increase in soil acidity, especially in the surface layers (A horizon) of the duplex soils that predominate in the region. Thus, increased nitrate leaching has added to the acid inputs associated with an increase in soil organic matter under “improved” pastures and the removal of C and N in animal and plant products.

In Australia, the total area of acid soils (defined as having a pH in 0.01 $M_CaCl_2$ <4.8) is approximately 24 Mha, with some 14 Mha in NSW and Victoria, much of which is on the western and northern slopes of the GDR in the Murray-Darling Basin. Production losses exceed $134$ million per annum, with estimates for NSW at approximately $100$ million (see [1]). These figures do not include costs of amelioration through the application of lime, which, at an average rate of 2.5 t ha$^{-1}$, can amount to as much as $40$ ha$^{-1}$ year$^{-1}$ when amortised over 5 years. Accelerated soil acidification is,
therefore, a widespread problem in the HRZ, but is not of great concern to landholders partly because it has no strikingly visible effects and partly because one of the main strategies to combat it has been to select increasingly tolerant species. However, the use of acid-tolerant species is not a long-term solution to the problem, which is expressed through decreased productivity and reduced versatility in land use.

The overall hypothesis of the Temperate Pastures Sustainability Key Program (TPSKP) was that it is practical to use grazing management and other low-cost inputs to achieve and maintain a pasture that is both more productive and more sustainable than current, degraded pastures. Sustainability studies of TPSKP were based on the premise that sown perennial grass pastures, with a longer growing season and deeper root system than common annual pastures, can improve the sustainability of the grazing system through better utilization of soil water and N, and can reduce recharge to groundwater and minimize nitrate losses from the soil. To test the “sustainability” hypotheses, a comprehensive field study on soil water, N cycling and pasture management was carried out at Book Book, near Wagga Wagga in NSW.

2. OBJECTIVES

The objectives of the project were to quantify:

- The components of the water balance,
- The major nutrient (N) pool sizes,
- Turnover rates and pathways by which nutrients (N) leak from the system,
- Soil and pasture properties that have potential as indicators of sustainability.

A summary of this work will be published elsewhere [2], only the soil water component is given here.

The experimental site is situated in the upper Kyeamba Valley, near Book Book in southeast NSW. The topography is undulating, and the soil is a red podzolic duplex, with the depth to the B horizon varying between 20 and 60 cm. The profile description of the soils is also given elsewhere [2]. The average annual rainfall of the region is approximately 650 mm.

2.1. Experimental design

Figure 1 shows the plan of the experiment site. Sixteen 0.135-ha (30x45 m) permanent pasture paddocks were chosen within the eighty paddocks of the MASTER experiment (Managing Acid Soils Through Efficient Rotations), set up by Dr K. Helyar in 1992. They represent the following four treatments: annual pastures without lime (AP-), annual pastures with lime (AP+), perennial pastures without lime (PP-) and perennial pastures with lime (PP+). Each treatment was replicated four times.

The perennial pasture contained sown species phalaris (*Phalaris aquatica*), cocksfoot (*Dactylis glomerata*), subterranean clover (*Trifolium subterraneum*) and volunteer species such as annual ryegrass (*Lolium rigidum*) and broadleaf weeds. The annual pasture contained annual ryegrass, subterranean clover, *Vulpia* spp and broadleaf weeds. Lime was applied to maintain the pH of the top 10 cm of soil at 5.5 over 5 years. The lime was disced into the top 10 cm at sowing.

The treatments were chosen to represent the worst pasture condition (annuals with poor species composition on very acid soil) and best (phalaris-subterranean clover without constraints from soil acidity) for the region. The pastures were rotationally grazed with weaner ewes or wethers. The stocking rate varied with seasons, but was kept 10 to 25% higher on the limed than the unlimed pastures.
2.2. Instrumentation and measurements

Water balance, plus soil chemical and biological properties, were measured on the sixteen paddocks from 1994 to 1997.

*FIG. 1. Experiment layout.*

Trenches (10 cm by 60 cm deep) were dug around each paddock and the wall lined with heavy-duty plastic sheets to isolate them hydrologically. A strip drain was placed at the bottom of the trench to collect sub-surface flow at the top of the clay B horizon from each plot and delivered it to
tipping-bucket flow meters. The drain was back-filled with sand and soil. The protruding plastic sheeting extended over the remainder of the excavated soil, forming into a surface barrier around each paddock. Surface runoff from each plot was also channeled to separate tipping-bucket flow meters. Four neutron access tubes were inserted to 180 cm depth in each of the four paddocks. Neutron probe readings were taken at several depths at intervals of 2 to 3 weeks. Neutron probe readings (two per paddock) were made at regular intervals also on the remaining twelve paddocks, in addition to the measurements made on the intensively monitored paddocks. However, only results from the four-instrumented paddocks are reported here.

Three sets of tensiometers were installed at three sites in each paddock, at depths of 30, 45, 60, 90 and 120 cm. Time Domain Reflectometer (TDR) probes were installed at one site in each paddock: horizontally at 20 and 40 cm in the A horizon, and vertically at 45–60 and 65–90 cm in the B horizon. Measurements of soil hydraulic properties were also made in the field and on samples in the laboratory.

An automatic weather station was installed on site, allowing meteorological data to be recorded. Rainfall was measured at hourly and 5-min intervals (using tipping-bucket rain-gauges). Global and net solar radiation, soil heat flux at 2 cm, air temperature, wet- and dry-bulb temperatures and soil temperatures at 2 and 10 cm depths, relative humidity and wind speed at 2 m height were recorded, either hourly or quarter-hourly at the site. Potential evapotranspiration ($E_p$) was calculated as described by Priestley and Taylor [3] and using Penman-Monteith equation [4], as given below.

\begin{equation}
E_{PT} = \frac{[\alpha \Delta (R_n - G)]}{\lambda}
\end{equation}

and

\begin{equation}
E_{PM} = \frac{\Delta (R_n - G) + \rho c_p (e_o - e_d)}{\Delta + \gamma (1 + \frac{r_c}{r_o})} / \lambda
\end{equation}

where

$E_{p, PT}$ is Priestley-Taylor evaporation (mm),

$E_{p, PM}$ Penman-Monteith evapotranspiration (mm),

$\alpha$ is equal to 1.26 [3],

$R_n$ is the net radiation (MJ m$^{-2}$),

$G$ is soil heat flux (MJ m$^{-2}$),

$\lambda$ is the latent heat of vaporisation (MJ kg$^{-1}$),

$\rho$ is atmospheric density (kg m$^{-3}$),

$c_p$ is the heat capacity of air (MJ m$^{-3}$°C$^{-1}$),

$(e_o - e_d)$ is the vapour pressure deficit (kPa),

$r_c$ is crop canopy resistance (s m$^{-1}$),

$r_o$ is aerodynamic resistance (s m$^{-1}$),

$\Delta$ is the slope of vapour pressure (kPa °C$^{-1}$),

and $\gamma$ is the psychrometric constant (kPa °C$^{-1}$).

2.3. Calibration of neutron probe

The neutron probe was calibrated three times in both the wet- and dry-end ranges of soil moisture, from measurement of gravimetric water contents and bulk densities. Aluminium access tubes, 43 mm in internal diameter, 2 mm wall thickness, were installed to a depth of 2 m at various locations on the MASTER experimental site. Duplicate neutron count readings were taken over 15-s intervals at each depth (15, 30, 45, 60, 75, 90, 120, 150 and 180 cm) in each hole. Four soil cores to a depth of 1.8 m were then taken within 20 cm from the access tube hole, in opposite directions. The cores were cut into 15-cm lengths for gravimetric moisture-content determination. Data from the four replicate soil samples were averaged. Bulk density was measured on these samples and volumetric
water content (θ) calculated. Calibration equations for neutron probe were then established and used to determine the water content of the soil as a function of depth for all plots, including the four instrumented plots, at regular time intervals over the whole experimental period.

2.4. Bulk density

The bulk density and its associated standard deviation, measured during neutron probe calibrations, are given in Fig. 2. Considerable scatter, with a wide range of standard deviations, was observed throughout the whole profile, reflecting the heterogeneity of the soil. A bulk density value of around 1.3 Mg m\(^{-3}\) was observed in the top 10 cm, increasing to 1.6 Mg m\(^{-3}\) at 30 cm depth, at the top of the B horizon. It then decreased slightly before becoming relatively constant around 1.65 Mg m\(^{-3}\) from 80 to 180 cm depth.

![Bulk density graph](image)

*FIG. 2. Change in soil bulk density with depth.*

2.5. Tipping bucket flow meters

The tipping bucket flow rates for surface runoff and sub-surface flow were individually calibrated during the course of the experiment. A range of flow rates similar to those observed in the field was generated during calibration. Table I gives the coefficients of the calibration equations for each individual tipping bucket.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Surface tipping bucket</th>
<th>Sub-surface tipping bucket</th>
</tr>
</thead>
<tbody>
<tr>
<td>AP-</td>
<td>(Y^a = 5.997E-5X^2 - 7.922E-4X^b + 3.308)</td>
<td>(Y = 4.432E-3X + 1.365)</td>
</tr>
<tr>
<td>AP+</td>
<td>(Y = 3.925E-5X^2 + 1.167E-3X + 3.172)</td>
<td>(Y = 4.882E-3X + 1.258)</td>
</tr>
<tr>
<td>PP-</td>
<td>(Y = 5.989E-6X^2 + 7.611E-3X + 2.960)</td>
<td>(Y = 3.493E-3X + 0.992)</td>
</tr>
<tr>
<td>PP+</td>
<td>(Y = 2.604E-5X^2 + 3.245E-3X + 2.514)</td>
<td>(Y = 4.423E-3X + 1.325)</td>
</tr>
</tbody>
</table>

\(^a\)Litres/tip, \(^b\)Tips/5 min.
3. METEOROLOGICAL DATA AND ET CALCULATION

Rainfall data from May 1994 to August 1997 are shown in Fig. 3. The winter, spring and summer periods of 1994–95 were unusually dry, as was the summer and most of the winter of 1996–97. The intervening period (autumn 1995 to spring 1996) was wetter than average. A comparison of the potential evaporation ($E_p$) calculated using the Priestley-Taylor [3] and Penman-Monteith [4] equations for 1994 to 1997 is shown in Fig. 4. High $E_p$ estimates using the Penman-Monteith equation were obtained on some days in spring and summer. During winter, the estimates from the two methods agreed well. Because of its simplicity, the Priestley-Taylor equation was chosen for the soil water balance simulation described below.

![Fig. 3. Daily rainfall for 1994-1997.](image1)

![Fig. 4. Comparison between Penman-Monteith and Priestley-Taylor methods of calculating ET, using metadata from Book-Book, NSW.](image2)

130
The total amount of surface runoff and sub-surface flow over the impermeable B horizon for the four pasture treatments over the 3 years are given in Table II. No surface runoff was recorded in 1994, the pastures, particularly the annual pastures, were in poor condition after the drought in 1994–95. When the season broke in autumn 1995, surface runoff occurred from the two annual pasture treatments almost immediately, resulting in greater amounts for the whole year in 1995 and 1996.

There was a significant difference in the absolute amounts of surface runoff for both years. Also, substantial sub-surface flow from all pastures occurred during the winters of 1995 and 1996. The amounts were greater in 1995 than 1996, mainly because of the very wet autumn and early winter of 1995. Sub-surface flow tended to be lower from the perennial than the annual pastures, and especially lower from PP+ plots. And, no surface or sub-surface flow was recorded towards the end of the monitoring period in 1997.

Overall, the amounts of surface runoff and subsurface flow were appreciable in both 1995 and 1996, and comprised a very significant component of the water balance in 1995. This means that

---

**TABLE II. SUMMARY OF RAINFALL, EVAPORATION AND SOIL WATER FLUXES MEASURED AND ESTIMATED FOR THE FOUR INTENSIVELY INSTRUMENTED PADDOCKS**

<table>
<thead>
<tr>
<th>Period</th>
<th>Treatment</th>
<th>Rain (mm)</th>
<th>Actual evaporation E_a (mm)</th>
<th>Surface runoff (mm)</th>
<th>Sub-surface flow (mm)</th>
<th>Surface + sub-surface flow (mm)</th>
<th>Deep drainage (&gt;180 cm) (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4/5–31/12 '94</td>
<td>AP-</td>
<td>205</td>
<td>229</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>AP+</td>
<td>205</td>
<td>203</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>PP-</td>
<td>205</td>
<td>253</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>PP+</td>
<td>205</td>
<td>256</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1/1–31/12 '95</td>
<td>AP-</td>
<td>697</td>
<td>467</td>
<td>77</td>
<td>69</td>
<td>145</td>
<td>45</td>
</tr>
<tr>
<td></td>
<td>AP+</td>
<td>697</td>
<td>465</td>
<td>66</td>
<td>70</td>
<td>134</td>
<td>62</td>
</tr>
<tr>
<td></td>
<td>PP-</td>
<td>697</td>
<td>477</td>
<td>55</td>
<td>62</td>
<td>115</td>
<td>44</td>
</tr>
<tr>
<td></td>
<td>PP+</td>
<td>697</td>
<td>511</td>
<td>56</td>
<td>66</td>
<td>116</td>
<td>24</td>
</tr>
<tr>
<td>1/1–31/12 '96</td>
<td>AP-</td>
<td>666</td>
<td>548</td>
<td>7</td>
<td>23</td>
<td>30</td>
<td>62</td>
</tr>
<tr>
<td></td>
<td>AP+</td>
<td>666</td>
<td>546</td>
<td>7</td>
<td>19</td>
<td>26</td>
<td>70</td>
</tr>
<tr>
<td></td>
<td>PP-</td>
<td>666</td>
<td>566</td>
<td>4</td>
<td>19</td>
<td>23</td>
<td>52</td>
</tr>
<tr>
<td></td>
<td>PP+</td>
<td>666</td>
<td>612</td>
<td>2</td>
<td>14</td>
<td>16</td>
<td>22</td>
</tr>
<tr>
<td>1/1–19/8 '97</td>
<td>AP-</td>
<td>267</td>
<td>246</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>AP+</td>
<td>267</td>
<td>243</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>PP-</td>
<td>267</td>
<td>288</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>PP+</td>
<td>267</td>
<td>240</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
rainfall that is diverted to surface and shallow subsurface flow will contribute to stream flow, rather than to deep drainage and potential recharge to groundwater.

Soil profile volumetric water contents were calculated from neutron probe measurements down to 180 cm depth for all sixteen paddocks. Fig 5 (a-d) showed the profile water content at 90, 120, 150 and 180 mm depths for the four pasture treatments. In general, soil moisture variation became less with increasing depth and that the maximum depth of water extraction under the annual grass pastures was between 90 and 120 cm, whereas the perennials extracted water down to 150 cm.

The maximum depth of water extraction was, therefore, taken to be at 180 cm, and the changes in soil water content (± AS) to 180 cm depth were expressed relative to "field capacity" of the soil, obtained from moisture values in the winter and spring of 1995 and 1996. The resulting trends in soil water deficit (SWD) or surplus, for the four pasture treatments from May 1994 to July 1997 are shown in Fig. 6. The soil did not regain "field capacity" in the winter of 1994, nor in 1997 (before measurements ceased). During the summer and autumn periods, the SWD increased to a maximum of between 142 and 182 mm under the perennial pastures, depending on the year. This maximum deficit was approximately 40 mm greater than the deficit under the annual pastures. There was little difference in the maximum SWD developed between pastures with and without lime.
3.1. Calculation of actual evaporation rate and simulated SWD

Based on the above information, the soil water balance was simulated for each of the four instrumented paddocks as follows.

$$\Delta S = I - R_s - R_{ss} - E - D$$  \hspace{1cm} (3)

where

- $\Delta S$ is the change in water storage in the soil profile (mm),
- $I$ is rainfall (mm),
- $R_s$ is surface runoff (mm),
- $R_{ss}$ is sub-surface runoff (mm),
- $E$ is evapotranspiration (mm),
- $D$ is deep drainage (mm).

Over summer, when evapotranspiration is limited by soil water availability and actual evapotranspiration ($E_a$, mm) falls behind potential evapotranspiration ($E_p$), the following approach [5] was used:

$$E_a = a + bS$$  \hspace{1cm} (4)

where

- $a, b$ are constants determined experimentally,
- $S$ is soil water storage to the depth of interest (mm).

The value of $E$ (mm) is then taken as the lesser of the two values ($E_p$ and $E_a$). As in [5], the model also accounts for the effect of rainfall on a wet surface in an otherwise dry profile, when $E$ is taken as $E_p$ regardless of $S$. A total of 25 mm of soil water was allocated for evapotranspiration at $E_p$ rates under this condition. Deep drainage $D$ (mm) is then calculated as:
\[ D = S_{n-1} + I - E - R_s - R_s \]

Otherwise,

\[ D = 0 \]

The soil water status expressed as the SWD was calculated between May 1994 and August 1997, and the daily amount of deep drainage calculated for the 4 years.

To calculate \( E_a \), it was assumed that evaporation from the pasture continued at the potential rate until the SWD reached 25 mm, when the actual evaporation rate fell below the potential rate. Periods during the summers of 1994 and 1995 were identified when no rainfall or drainage occurred, and the changes in SWD were used to calculate \( E_a \) which were then plotted against the SWD value to obtain best-fit relationships for each pasture type. Using these relationships, and initializing the SWD on 4 May 1994, when measurements started, the values of \( E_a \) and \( \Delta S \) were calculated on a daily time step and substituted into Eq. 5 to obtain \( D \). A test of the model is how well the daily values of \( \Delta S \) track the actual trends in SWD. The results of this comparison are shown in Figs. 7 and 8. The match was excellent for most of the period, particularly when the soil was near field capacity, when drainage is expected to occur.

The \( D \) values were summed to obtain the cumulative drainage during each winter period. The results, given in Table II, show that the deep drainage ranged from 24 to 62 mm under PP+ and AP+, respectively, in 1995, and from 22 to 70 mm under these pastures in 1996. There was no drainage from any of the four pastures in 1994 or 1997 (up to mid-July). This indicates that well grown perennial pasture reduced deep drainage, and potential recharge to groundwater, in normal to wet years by approximately one half to two-thirds compared with annual pasture, with or without lime. It should also be noted that deep drainage was of a similar magnitude to sub-surface flow in 1995. Because sub-surface flow carries solutes from the soil's A horizon where the nitrate concentration is high, its contribution to soil acidification may be greater than that of deep drainage which carries solutes from the lower B horizon, where nitrate concentrations are usually low.
3.2. Long-term simulation of SWD

The results from this short period of measurement suggest deep drainage is likely to be variable between years. An attempt was made to simulate SWDs and deep drainage under annual and perennial pastures (AP- and PP+) over a 10-year period (1985–94), using meteorological data from Wagga Airport.

Sunshine hours were converted to solar radiation using the following equation:

$$ R_s = (a + b \frac{n}{N}) R_a $$

where

- $R_s$ is solar radiation (MJ m$^{-2}$ d$^{-1}$),
- $R_a$ is extraterrestrial radiation (MJ m$^{-2}$ d$^{-1}$),
- $a$, $b$ are empirical constants, for average climatic conditions, taken as 0.25 and 0.5, respectively,
- $n/N$ is relative sunshine fraction.

In the long-term simulation, it was necessary to estimate the amount of surface runoff and sub-surface flow during each rainfall event. For surface runoff generation, the US Soil Conservation Service runoff curve numbers were used ([6] p.128). The approach takes into consideration the following factors: ground cover, soil type and drainage, and slope. As for sub-surface runoff prediction, a quadratic relationship was obtained from the measured sub-surface runoff and rainfall intensity during 1994–97. It was also assumed that sub-surface flow did not occur until the soil was relatively close to field capacity (SWD <30mm).

The SWD simulations, shown in Fig. 9, show consistently greater deficits (40–50 mm) under the perennial pasture by the end of summer each year. Deep drainage was estimated to average $55 \pm 40$ mm for a poor annual pasture compared with $39 \pm 36$ mm for a well grown perennial pasture. The estimated combined surface and sub-surface flow averaged 63 and 38 mm for the annual and perennial pastures, respectively. These points should be emphasized:
The simulated drainage was highly variable, ranging from 0 to 129 mm for the annual pasture, and from 0 to 103 mm for the perennial. This was due to a combination of factors such as the variable annual rainfall (range 445 to 923 mm, mean 614 mm) and its distribution, and the variable incidence of surface and sub-surface runoff. Similar yearly variability in drainage was observed previously [7] on a duplex soil at Rutherglen for the period 1990–93, when the average annual rainfall was 693 mm. After allowing for sub-surface flow, the annual drainage was estimated to be 49–56 mm under a phalaris pasture and 80–87 mm under annual ryegrass. The overall reduction under the perennial pasture was about one-third.

These deep drainage results for Wagga and Book Book (annual rainfall 614 and 650 mm, respectively) are much lower than the estimates of 228 and 314 mm for perennial and annual winter-active pastures at Bendigo, Australia (annual rainfall 605 mm) made by Clifton and Johnston [8] who predicted a reduction in deep drainage due to the perennial of approximately 25%. Their estimates were obtained from a one-dimensional simulation model (WAVES). Simulations were done for several sites of different annual rainfall and they concluded that lateral flow of water was very low at rainfalls up to 800–900 mm. These simulation results are inconsistent with our measurements and modelling of runoff (surface and sub-surface) and deep drainage at Book Book, where lateral flows (surface and sub-surface) can be comparable to, or exceed, the deep drainage flux.

Estimates of deep drainage were made under perennial and annual pastures at Rutherglen in NE Victoria over 4 years (when the average annual rainfall was 693 mm) [7]. The drainage below 1.1 m depth was 49–56 mm per year under phalaris, compared to 80–87 mm per year under annual ryegrass. These estimates included any sub-surface flow component (not measured), but were still well below the simulation results reported by Clifton and Johnston [8]. In the wetter years of 1995 and 1996, the combined lateral flows and deep drainage were 43 and 38 mm more under the annual pastures than under the perennial pastures (see Table II). These numbers are very close to the difference in the maximum SWDs (approximately 40 mm) which developed under these pastures by the end of summer in those years.

Similarly, the long-term simulation for Wagga shows that the combination of mean lateral flows and deep drainage was 118 and 77 mm for the annual and perennial pastures, respectively, again
consistent with a difference in SWD at the end of summer of about 40 mm. The data therefore show a remarkable consistency for the difference in SWD to 180 cm at the end of summer, translating into the difference in water shed from the annual and perennial pastures in winter. This water (with accompanying solutes) is shed either as lateral flows (which appear elsewhere in the landscape), or as deep drainage that can potentially recharge to groundwater. The ratio of deep drainage to the total water flux ranged from 0.23 under the perennial pasture in 1995 to 0.70 under the annual pasture in 1996. The ratio for both pasture types over the period 1985–94 was close to 0.5, a figure that could be used to make long-term predictions. Thus, on duplex soils in the temperate HRZ, if the measured or predicted difference in SWD between annual and perennial pastures at the end of summer is 40 mm, the difference in deep drainage during the following winter on average is likely to be at least 20 mm.

4. CONCLUSIONS

The main conclusions from this study of productivity and sustainability of perennial and annual pastures are that perennial grass pastures, especially PP+, consistently extracted about 40 mm more soil water each year than did the annual grass pastures. As a result, surface runoff, sub-surface flow and deep drainage (percolation below 180 cm depth) were about 40 mm less from the perennial pastures. This means that well managed perennial pastures can significantly reduce recharge to groundwater and, hence, make pastoral systems more sustainable in the high rainfall zone. Phalaris is a more desirable perennial grass species than cocksfoot because of its higher palatability to stock. But for phalaris to grow successfully and persist, the soils must be limed to at least pH 4.8 (in CaCl₂); hence, the “sustainability package” for very acid soils (pH<4.8) must include lime together with the sowing of phalaris.

REFERENCES