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Drainage to groundwater under a closed-canopy radiata pine plantation on the Canterbury Plains, South Island, New Zealand

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Abstract

The amount of soil water draining through the root zone to shallow groundwater was measured in two stands, Shellocks and Doyles, at two radiata pine (*Pinus radiata* D. Don) plantations on the Canterbury Plains, South Island, New Zealand. The soil at both sites is a free-draining, very stony silt loam, and is classified as a Pallic Firm Brown soil belonging to the Lismore Series.

Rainfall and interception were recorded and used as input to a daily water balance model. The portion of throughfall available for groundwater recharge (soil water drainage) was measured using pairs of free-draining zero-tension lysimeters. This information, together with stand transpiration (sap flow) and soil moisture storage (neutron probe) data, was used for model validation.

Rainfall for years 2001 (538 mm) and 2002 (711 mm) was below the long-term (1919–1980) mean of 801 mm. Total stand transpiration from 1 May 2001 to 31 December 2002 at Shellocks and Doyles was 480 ± 120 mm and 830 ± 180 mm respectively. Rainfall for the same period was 1139 mm and 1143 mm respectively. Throughfall recorded at Doyles from October 2001 to July 2002 was estimated to be 70% of rainfall.

During this study rainfall rarely wetted the soil to depths much in excess of 1 m. Very little water was available for deeper drainage and there were few opportunities for groundwater recharge. Under tall woody vegetation, discharge from these soils is driven by sporadic intense and/or long-duration rainfalls. In this environment, transpiration rapidly removes soil moisture and thereby reduces the potential for soil drainage. The wetting-up phases are most likely to produce soil water drainage capable of generating groundwater recharge. These phases tend to occur late autumn to early spring and occasionally during summer wet periods with high intensity and/or long duration rainfalls. For some years, when they supported a closed-canopy forest, there was no drainage at all from these soils. During the period measured, drainage was infrequent and limited to the winter months.

The daily water balance model provided an effective estimate of soil moisture conditions and timing of when drainage to groundwater was likely to occur. The soil water drainage predicted for the longer-term, higher-intensity rainfalls tended to be too high, particularly when pre-storm soil moisture conditions approached field capacity.

Keywords

Plantation water use; radiata pine; root zone soil water storage; soil water drainage; water balance model; zero-tension lysimeter.

Introduction

Extensive conversion from dry pastoral farming to dairy farming in Canterbury has rapidly increased the percentage of irrigated lands. The additional ground and surface water required for irrigation must be balanced against the traditional requirements and future expectations of other water users. Tall woody vegetation on the Canterbury Plains, in particular plantation forest, has recently been identified as a readily regulated water-consumer.

In general, the water use of tall woody vegetation is largely controlled by interception, throughfall (that portion of rainfall that reaches the ground surface), and dry canopy evaporation, i.e., transpiration. Water use by plantation radiata pine (*Pinus radiata* D. Don) in the Canterbury region has been extensively studied (e.g., Benecke, 1980; Arneth *et al.*, 1998; Miller *et al.*, 1998; Richardson *et al.*, 2002). Many of these studies are concerned with water use by trees in relation to growth and production, with water storage and competition for water within the root zone a common theme. Few investigations (Fahey *et al.*, 2001; Jackson and Rowe, 1997) have concerned themselves with the water that passes through the root zone and is available for groundwater recharge. In those studies, potential streamflow or groundwater recharge was either modelled or estimated as a residual in the water balance, whereas in this study, water passing through the plantation root zone was measured directly.

The objective of this study was to quantify the fluxes of water passing through the root zone of plantation radiata pine to shallow groundwater by monitoring soil water drainage, and comparing measured and modelled estimates of daily water balance.

Study area

The study sites, Shellocks and Doyles, were in two plantations of radiata pine on the Canterbury Plains, South Island, New Zealand. Shellocks, the younger stand, on Hunters Road, 19 km south of Darfield (43°29'S, 172°07'E), was planted in 1995 at a stand density of 1250 stems/ha. By the end of the study (June 2003) the stand had yet to reach canopy closure between rows. An understorey of *Acacia* spp. and gorse (*Ulex europaeus L.*) was present, but seasonal mowing, combined with gradual over-topping, substantially decreased understorey growth over the course of the study. Doyles, 17 km south-southwest of Darfield, is a mature closed-canopy stand of 625 stems/ha that was established along side Mitchells Road in 1978. No understorey vegetation was present at Doyles. The soil at both sites, classified as a Pallic Firm Brown soil belonging to the Lismore Series, is a free-draining, very stony silt loam (Hewitt, 1998). This soil tends to produce shallow plate-type tree root systems, in which the bulk of a plantation root mass is restricted to the upper 0.3–0.4 m of the soil profile (Watson, 2000).

Methods and instruments

This research was part of a programme to develop sustainable management practices for applying treated municipal sewage sludge to commercially forested land on the Canterbury Plains. A soil-water monitoring programme was carried out to provide information on soil-water-drainage chemistry and the potential for soil water to drain to groundwater. The latter aspect of the programme involved the measurement of soil water drainage passing through the root zone of plantation radiata pine to shallow groundwater. Rainfall, interception, and soil moisture storage (neutron probe)

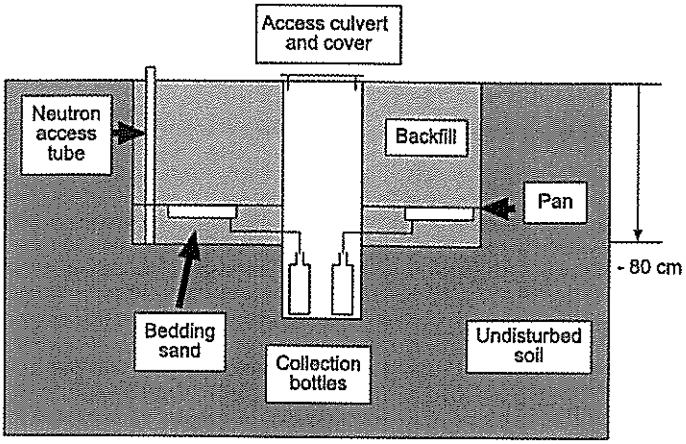

Figure 1 – Installation details of each zero-tension lysimeter pair.

data were recorded and used as input to a daily water balance model. Measurements of the portion of throughfall available for groundwater recharge (soil water drainage) were made using pairs of free-draining zero-tension lysimeters (Fig. 1). This information was used, along with stand transpiration, for model validation.

Rainfall

Tipping-bucket raingauges were installed at standard height on open ground near the Shellocks and Doyles study sites in June 2000 and May 2001 respectively. Each was supplemented with a standard 5-inch (127 mm) manual check gauge.

Throughfall

Throughfall was measured at the Doyles study site from October 2001 to July 2002. Water was collected in 5-m long troughs made from PVC household guttering. Eighteen troughs were randomly placed in fixed positions, and installed between 1.0 and 1.2 m above the forest floor. Throughfall was measured as soon as practicable after storms. Throughfall information was not collected at Shellocks, as the canopy wasn't closed.

Transpiration

Sapflow meters (model SF300, Greenspan Technology, Warwick, Australia) were used to estimate stand transpiration. The methods of sapflow measurement are described in detail in Fahey *et al.* (2001). Briefly, sapflow velocities were measured using the compensation heat-pulse technique described by Swanson and Whitfield (1981). Before installation, the size distribution of trees within each stand (based on diameter at breast height, DBH) was estimated using methods described by Goulding and Lawrence (1992). A fixed/roaming technique of sensor monitoring (Vertessy *et al.*, 1994) was employed to cover the full range of size classes within each stand. Six trees representative of the dominant size classes were selected for long-term monitoring. These were supplemented with roaming, 3–4 week monitoring of additional trees selected to represent the subdominant size classes.

Soil water

A neutron probe was used to monitor changes in soil water. One neutron-probe access tube was established with each zero-tension lysimeter pair (Fig. 1). Neutron-probe measurements at selected depths provided a profile of the water content of the soil. By comparing a number of profiles obtained over a period of time, the quantity and pattern of the soil-water storage changes can be assessed.

Lysimeters

In each stand nine randomly placed pits (5 × 1.5 m) were dug. In each pit a pair of zero-tension lysimeters was installed below the plantation-rooting zone, at depths of around 800 mm. The soil water drainage collection-bottles were accessed through a central culvert (Fig. 1). Backfilling and compaction are a problem in lysimeter studies as their effects can be difficult to quantify. During the study, attempts were made to minimise the effects of equipment installation, and although backfilled material was not processed, care was taken to reproduce the original soil and gravel profiles.

The volumes of soil water that drained from the lysimeters were carefully monitored. It was assumed that soil water draining from the lysimeters contributed directly to groundwater. However, it is widely recognised that estimates of drainage measured in this way can be highly variable because of soil heterogeneity, especially in very stony soils. The estimates may also be biased due to discontinuities in the normal flow of soil water introduced by the lysimeter pans. To minimise both of these problems relatively large collection pans, approximately 1 m^2, were used.

Daily water balance model

The model, developed by Landcare Research staff (Fahey *et al.*, 2004), is designed to examine the effects of changes in land use on water yields. A daily water balance is calculated using:

(a) daily rainfall totals,

(b) estimates of interception as a percentage of daily rainfall for the cover type under consideration, and crop transpiration,

(c) monthly evaporation based on published summaries, and

(d) available water capacity and readily available water capacity (see below).

The outputs are:

(a) daily, monthly or annual water yields, and

(b) soil water storage.

The quantity of water percolating through the soil in any time period is derived from the water balance equation (Eq. (1)), which apportions the incoming rainfall (P) into evaporative losses, i.e., precipitation intercepted by the canopy (E_i) and forest transpiration (E_t), water outflow through the soil, i.e., drainage (Q), and the change in soil water storage (ΔS).

$$P = E_i + E_t + Q + \Delta S \qquad (1)$$

Table 1 – Values of parameters and site-specific variables used to model soil water storage and drainage under forest and pasture covers.

	Forest cover	**Pasture cover**
Potential evaporation (mm/day)		
January	3.3	4.7
February	2.8	4.0
March	2.2	2.7
April	1.6	1.5
May	1.1	0.7
June	0.7	0.4
July	0.8	0.6
August	1.1	1.0
September	1.6	1.8
October	2.1	3.0
November	2.8	4.1
December	3.2	4.6
Soil		
Total available water (mm)	64	64
Readily available water (mm)	32	32
Top layer store (mm)	25	25
Vegetation		
Interception fraction	0.3	0.0
Crop coefficient	0.7	1.0

Any surplus water above the available water capacity is assumed to drain to a deeper groundwater table. It is assumed there is no overland flow.

Interception and daily rainfall were recorded on site. When the model was used for a forest canopy, the potential evaporation was based on medium-term (1981–1989) monthly evaporation rates for a closed-canopy radiata pine forest at Ashley Forest (43°14'S, 172°35'E) during periods when transpiration was not limited by soil water storage (Jackson *et al.*, 1993). When the model was used for a pasture cover, potential evaporation was based on the mean of the monthly evaporation from Lincoln (43°39'S, 172°28'E) and Christchurch Airport (43°29'S, 172°32'E) (New Zealand Meteorological Service, 1986). Table 1 shows the values of parameters and site-specific variables used to model soil water storage and drainage under forest and pasture covers.

Results and discussion

Rainfall

Monthly rainfall at Shellocks, from September 2000 and Doyles from May 2001 to December 2002 are shown in Figure 2. For the period of overlapping record (May 2001 to December 2002), rainfall totals are very similar: 1139 mm for Shellocks and 1143 mm for Doyles.

When compared to the long-term (1919–1980) Darfield mean yearly rainfall (801 mm) (New Zealand Meteorological Service, 1983), the rainfall at Doyles for years 2001 (538 mm) and 2002 (711 mm) were below average, particularly in 2001 when only two months (July and November) exceeded the long-term mean monthly rainfall (Fig. 3). The 8-month period, from December 2000 to July 2001, was exceptionally dry, in sharp contrast to January to early February 2002. It should be noted that when comparing monthly rainfall data from meteorological stations in this area of the Canterbury Plains around 60–65% of the data points commonly will track below those of the long-term mean monthly rainfall (New Zealand Meteorological Service, 1979).

Transpiration

Extrapolating the measurement of water use by individual trees to that of a stand of trees is a critical step in linking plant physiology and hydrology (Hatton and Wu, 1995). Limitations of sampling resources

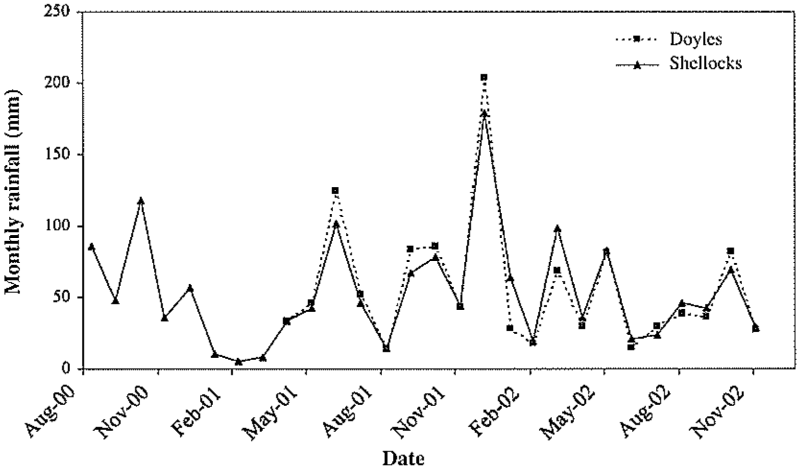

Figure 2 – Monthly rainfall at Shellocks and Doyles study sites.

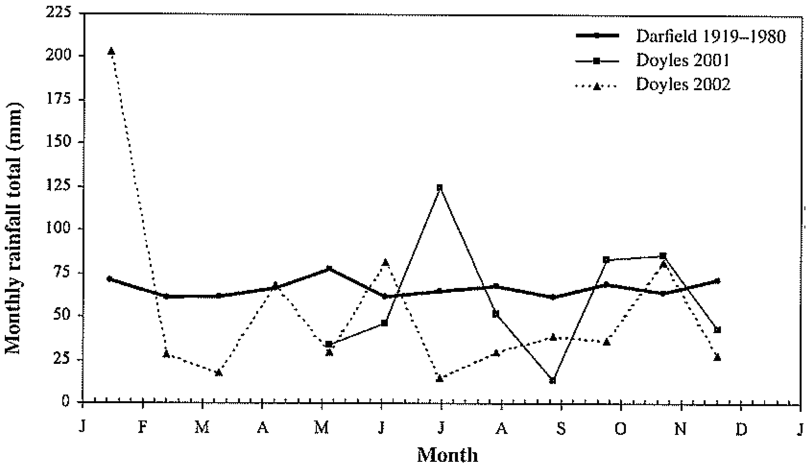

Figure 3 – Doyles monthly rainfall for 2001 and 2002 compared to the long-term (1919–1980) Darfield mean monthly rainfall.

and variation in tree size within a stand necessitate the use of some scalar relationship. Good relationships, of the form $y = ax^b$, were found between mean daily water use (y) and diameter at breast height (x) at both the Shellocks and Doyles sites ($r^2 = 0.94$, $n = 8$ and $r^2 = 0.92$, $n = 9$ respectively). Therefore diameter at breast height was selected as the scalar parameter. The use of tree diameter as a scaling parameter between individual tree water-use and stand water-use has previously been proposed by, among others, Hatton *et al.* (1995).

Radiata pine transpiration measurements from both sites are available for a 20-month period from 1 May 2001 to 31 December 2002. They are expressed as estimates of stand transpiration (mm depth of water) based on the average water use (L/day) of six monitored trees representative of the dominant size classes in each stand. During this period water loss through transpiration was estimated as 480 ± 120 mm at Shellocks and 830 ± 180 mm at Doyles. The standard error was calculated from the mean daily stand water use estimated from the sap flow measurements of the six trees selected for long-term monitoring. Shellocks and Doyles rainfall for the same period was 1139 mm and 1143 mm respectively. Stand transpiration as a percentage of rainfall for the 20-month period of the study was estimated as 40 ± 10% and 70 ± 15% for Shellocks and Doyles respectively.

Estimates of monthly stand transpiration at the two sites are shown in Figure 4. Over the period of measurement, transpiration at Shellocks, an open-canopy stand, averaged 60 ± 3% of that at Doyles, a closed-canopy stand. At the end of the study the trees at Shellocks had yet to reach canopy closure between rows, but an understorey of *Acacia* spp. and gorse effectively gave closed-canopy conditions. Unpublished results from an Upper Moutere (Nelson Region) stand of radiata of similar age with a gorse understorey indicated that the rate of transpiration of gorse was of a similar magnitude to that of the trees. This would suggest that the combined transpiration of the trees and understorey at Shellocks could be comparable to that of a closed-canopy stand, such as Doyles.

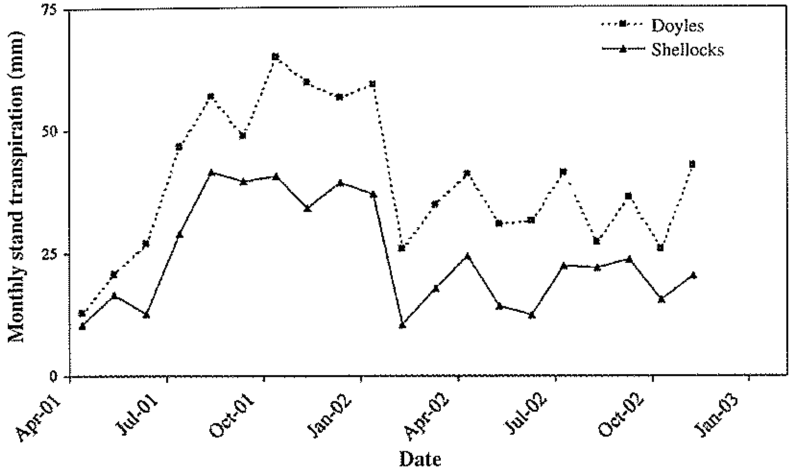

Figure 4 – Estimated monthly stand transpiration (mm) at Shellocks and Doyles study sites.

Soil water drainage

Net rainfall, the sum of throughfall and stemflow, is that portion of rainfall that, when reaching the forest floor, is available to top-up soil-moisture storage. Throughfall was recorded at the Doyles site from October 2001 to July 2002 and was estimated over that period to average 70% of total rainfall. This is comparable to the 75% of total rainfall for mature closed-canopy Canterbury radiata pine measured by Fahey *et al.* (2001). Stemflow was not recorded, but was taken to be 5% of rainfall, as measured by Fahey *et al.* (2001).

Based on Equation (1), the amount of water available for soil-water storage and drainage can be obtained by calculating the difference between rainfall and the sum of the interception and transpiration losses (Eq. (2)). This is shown in Figure 5.

$$Q + \Delta S = P - (E_i + E_t) \qquad (2)$$

where E_i = rainfall – net rainfall.

Periods when soil-water drainage availability falls below zero indicate soil-water-storage depletion.

For 12 of the 20 months (Fig. 5), soil-water-drainage availability (from Eq. (2)) was equal to or less than 0 mm. For the periods when it was available it was used either to replenish soil moisture storage or contributed to groundwater recharge, as was observed in July/August 2001, October/November 2001 and January 2002. Measured drainage did not always coincide with a positive 'available water' value, as shown for the months of May and July 2002 in Figure 5. This is due to high intensity and/or short duration rain falling within the first few days of an otherwise low rainfall month. In such situations, when the total 'available water' for that month is calculated, the resulting value may well be negative.

Available water

The study was conducted over two years that were dryer than average, but within which there occurred a broad range of rainfall durations and intensities. Given that the calculated daily water balance relies on an input of daily rainfall, it was felt that these events tested the model over a reasonable

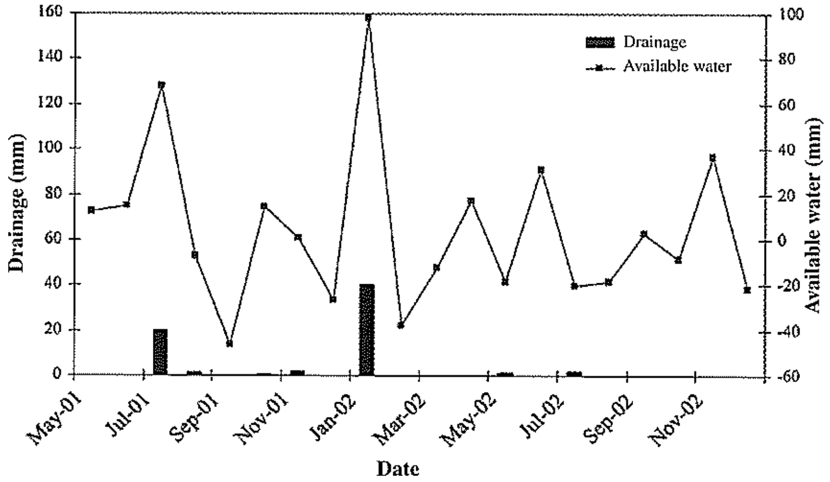

Figure 5 – Water (mm) available for soil-water storage and groundwater recharge compared to measured drainage (mm) at Doyles study site.

range of hydrological conditions. The surface-water-balance model was used to provide estimates of the amount of drainage to groundwater that could occur. It calculates the daily change in soil-water storage in the top 0.8 m depth of soil profile. This depth is the same as the collecting lysimeter pairs (Fig. 1). Available water capacity is either taken from a prior knowledge of soil properties or calculated from the difference in soil moisture at the wettest and driest extremes. In this study the latter option was available from the neutron probe measurements. Figure 6 shows the difference in average profiles for

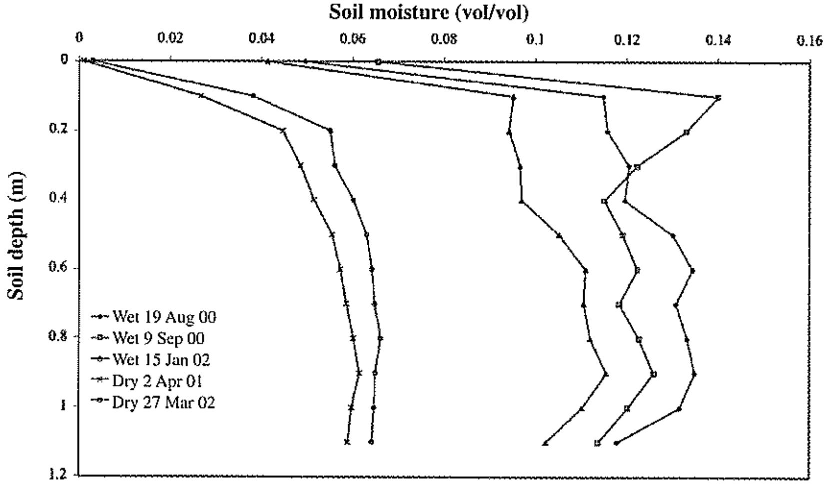

Figure 6 – Soil moisture with depth for wet and dry measurements at Doyles. The soil profiles of water content were based on a generalised calibration of the neutron probe. The surface values were derived as a field calibrated average from the top two measurements.

Doyles at wet and dry times; both the wettest (September 2000) and driest (April 2001) records are shown. It is believed that the difference in soil moisture between the wet and dry measurements, at depth, is a result of drainage within the gravels rather than extraction by roots. Anecdotal evidence from wind-blown trees at the study site suggests that the roots seldom reach beyond 0.5 m in depth. When the soil moisture measurements are converted into millimetres depth, the available water capacity was found to be 64 mm. The readily available water capacity, i.e., water available for plant growth, was assumed to be half this value, i.e., 32 mm.

The modelled versus observed soil moisture for the Doyles site is shown in Figure 7. The measured values are the average of several neutron probe 0-800 mm depth profiles taken at different times throughout the study period. Neutron probe readings were taken as part of a regular monitoring programme, but also at times during particularly wet periods. In August 2000, when the measured soil moisture were markedly above the modelled available water capacity, the measurement occurred immediately following rainfall and it is likely that the soils were still draining through to available water capacity.

The soil-water balance model effectively simulated changes in soil moisture, with the predicted pattern of root zone water content closely following the measured peaks and troughs. The model is good at estimating the soil moisture during wetting-up phases, as can be seen during August 2000 and the particularly wet period of January/February 2002. It is the wetting-up phases that are the periods most likely to produce enough soil water drainage to generate significant groundwater recharge. These tend to occur late autumn to early spring and occasionally in summer wet periods, as happened in January 2002 (Fig. 7).

The modelled versus measured monthly soil water drainage is shown in Figure 8.

During the period represented by Figure 8, the total amount of measured and predicted soil water drainage was 152 mm and 148 mm respectively. During the same period (1 August 2000 to 30 April 2003) there was

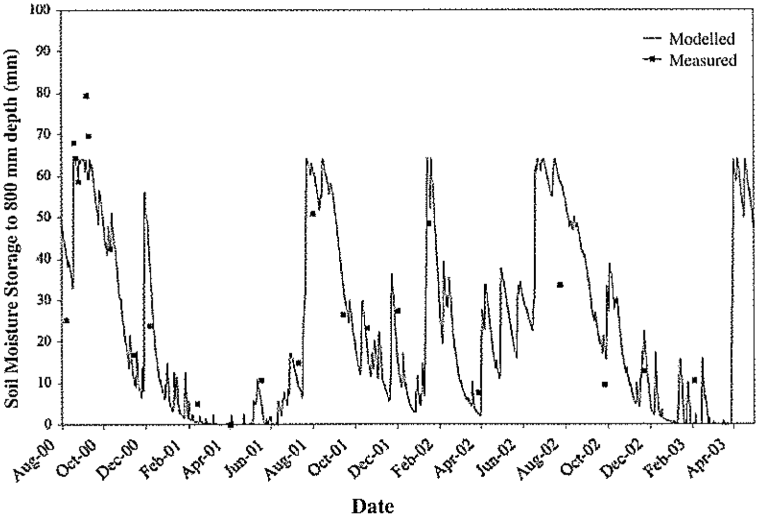

Figure 7 – Measured and modelled soil moisture storage (mm). In this simulation the available water capacity was assumed to be 80 mm.

1938 mm of rain. Hence at a soil depth of 0.8 m, about 7% of the rainfall was available to replenish soil moisture storage and/or contribute to ground water storage.

During the wet period of late winter and early spring 2000, the model predicted more drainage than was observed. This situation was repeated during the early autumn of 2003 (Fig. 8). During the mid-winter of 2001 and the wet mid-summer of 2002 the model predicted less soil water drainage than was recorded. The events of July 2001 and January 2002 followed periods of below-average rainfall (Fig. 3) and low soil moisture storage (Fig. 7). In this situation the model appears to be sluggish in its response to the initial rewetting of the soil profile. In the following month, i.e., August 2001, when the soil moisture storage had once again been replenished, the model overestimated the amount of drainage, as it had done in October 2000 and April 2003 (Figs. 7 and 8). A similar scenario occurred during the winter of 2002. Figure 8 suggests that the model is able to register drainage on those occasions when the observed drainage was in excess of 5 mm, but has some problems indicating drainage for the shorter duration events, such that occurred in January 2001, November 2001 and May 2002. Also, it would appear that the model is able to predict the timing of soil water drainage, particularly during the longer-term, higher-intensity events.

It has frequently been observed that soil-wetting fronts can have considerable spatial variation (Webb, 1989). Therefore it is feasible that the drainage detected by the lysimeter occurred in a spatially heterogeneous manner (such as through macropore flow), whereas the model is assuming drainage occurred in a more conservative homogeneous way. This may help explain the model's response to those occasions when the soil moisture prior to the event was low, resulting in low estimates of soil water drainage, such as happened in July 2001 and January 2002 (Fig. 8).

By comparing water content profiles at the start and end of a time period, the amount of the soil water lost or gained from storage over that period can be assessed. To approximate the period when transpiration measurements were available, the Doyles neutron-

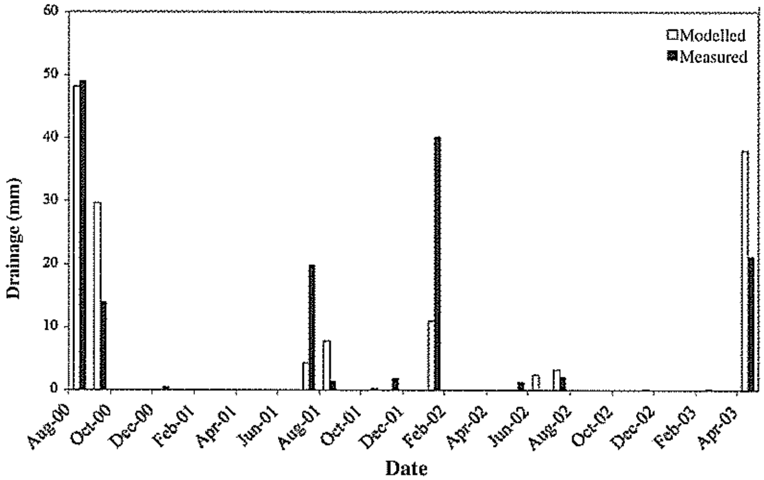

Figure 8 – Modelled drainage (mm) from the soil profile at 1 m depth compared to measured drainage (mm) recorded by the lysimeter pairs at 0.8 m depth. The data has been aggregated to monthly measurements for ease of interpretation.

probe values for the 17 May 2001 and 15 November 2002 (Fig. 7) were selected. For the same period, an estimate of the amount of water available for soil water top-up and/or groundwater recharge was obtained by adding the plus and minus values of the daily difference between rainfall and the sum of the interception and transpiration losses (as per Fig. 5).

The water available for soil water top-up and/or groundwater recharge, between 17 May 2001 and 15 November 2002 (approximately 18 months), as calculated via the daily data (see Fig. 5), was 20 mm. Over the same period there was a net gain in soil moisture of 3 mm, as estimated from the neutron probe measurements taken to 1 m depth. If there were 20 mm of water available for soil water top-up and/or groundwater recharge and a 3-mm gain in soil water storage, then 17 mm of water was lost from the system, potentially as groundwater recharge. This quantity is low. Unless the soil moisture storage is small, i.e., a shallow soil profile depth, the amount of rainfall recorded over this period (1062 mm) was not enough to wet the soil to depths much in excess of 1 m. For example, over the period in question, 67 mm (6-7% of rainfall) of soil water passed through the soil profile at 0.8 m depth as measured by the lysimeter-pairs (Fig. 8), while, based on the above calculations, only 17 mm (1-2% of rainfall) made it down to 1 m depth.

A number of simulations of the water balance model were run for this site using rainfall records from several long-term sites in the area. These simulations extended over a period of 49 years. The results indicated that for some years, there was no drainage at all from these soils when they were supporting stands of mature radiata pine. In most years, drainage was infrequent and limited to winter months.

To obtain some indication of the impact of plantation radiata pine on potential groundwater recharge, the water balance model was rerun assuming the site was in pasture (Fig. 9). The values of parameters and site-specific variables used to model soil water storage and drainage under forest and pasture covers are shown in Table 1.

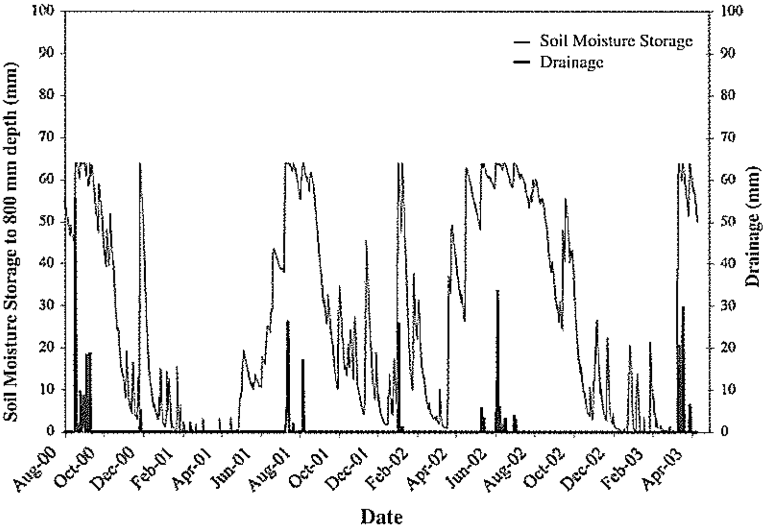

Figure 9 – Modelled soil moisture storage (mm) and drainage (mm) assuming the site was in pasture.

Under a forest canopy, the model indicated four key periods of drainage > 10 mm, August/September 2000, July/August 2001, January 2002 and April 2003 (Fig. 8). When the model was rerun for the site under pasture (Fig. 9), five significant periods of drainage were indicated: August/September 2000, July/August 2001, January 2002, June/July 2002 and April 2003. While under forest, 148 mm of soil water drainage (from 1938 mm of rainfall) was predicted to be available for groundwater recharge. When under pasture, 450 mm of groundwater recharge was predicted. As suggested earlier, both these figures are probably overestimates, as a number of storms during the analysis period tended to be associated with longer-term/high-intensity rainfall. Even if this is the case, however, the ratio of the magnitudes of the two drainages may give some idea of the difference in groundwater-recharge potential of the two types of land use.

Conclusions

During this study rainfall, and consequently throughfall, was low, particularly during 2001 (Fig. 3). For 12 of the 20 months monitored little water was available for either soil water top-up or groundwater recharge. The notable exceptions occurred in July 2001 and January 2002 (Figs. 5). In the presence of tall woody vegetation, discharge from these soils, at depths greater than 0.8 m, is driven by sporadic intense and/or long-duration rainfalls. In this environment the transpiration by mature radiata pine, approximately 70% of rainfall, rapidly removes soil moisture and thereby reduces the potential for soil drainage.

It is the wetting-up phases that are most likely to initiate the amounts of soil water drainage capable of generating groundwater recharge. These tend to occur late autumn to early spring and in wet periods, as happened in January 2002 (Fig. 7). For some years, there is no drainage at all from these soils if they are supporting mature radiata pine stands. In most years, drainage is infrequent and limited to the winter months.

Overall the daily water balance model appeared to be a good predictor of soil moisture conditions and when drainage to groundwater was likely to occur. Predicted soil water drainage for the longer-term/higher-intensity events tend to be overestimated, particularly on those occasions when pre-storm soil moisture conditions approached field capacity.

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