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An evaluation of four soil moisture models for estimating natural ground water recharge

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Abstract

From 1953 to 1978 at Winchmore Irrigation Research Station near Ashburton, New Zealand, daily recharge data were collected in six non-weighing, monolith lysimeters, 1220 mm in diameter and 900 mm deep. The soil at the Station is a Lismore stony silt loam, with stony silt loam about 350 mm thick overlying sandy gravels. The recharge data collected up to 1978 were archived but never published. Additional data were collected through the same lysimeters from September 1994 until December 1997, using tipping bucket rain gauges logging at five-minute intervals. A meteorological station on site was set up in 1950 and is a part of the national network.

Four soil moisture models have been evaluated for recharge estimation using a fifteen-year subset of the archived data, plus the recent data, from five of the lysimeters. Two of the models, *SOILMOD* and *SWIM*© produced good estimates of natural recharge under grass but underestimate recharge when the soil is bare. Both successful models proved to be very sensitive to rainfall input. Recent measurements suggested that the Station rainfall record has systematically underestimated the rain actually hitting the ground by about 10% and this was allowed for in the simulations. Neither of the successful models was very sensitive to soil moisture characteristics.

The two successful models have potential for incorporation into a system for estimating regional ground water recharge.

Introduction

Winchmore Irrigation Research Station is located some 15 km north of Ashburton in the middle of the Canterbury Plains (Fig. 1). The Station was set up in 1950 by the Department of Agriculture during a period when the New Zealand Government was building large border-strip flood irrigation schemes. Research at the Station was designed to place irrigated agriculture in Canterbury on a more scientific basis and, as part of this, lysimeter studies were carried out to examine the leaching of fertilisers under irrigation. At the time, irrigation water in Canterbury was supplied from rivers; there was little understanding of the aquifer system under the Canterbury Plains and no intention to use it for irrigation. However, in areas of the Plains outside the border-strip irrigation schemes, there has since been considerable development of irrigation using ground water, and there is now a need to understand and manage the ground water resources to ensure efficient, equitable and sustainable use.

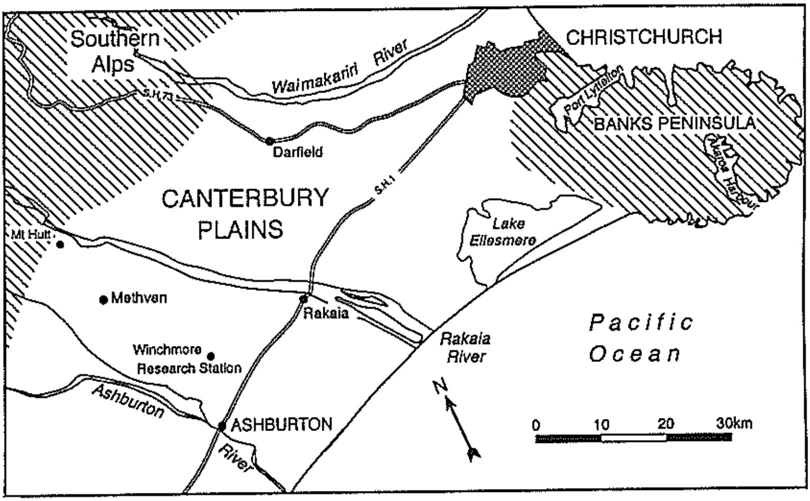

FIGURE 1 – Location of Winchmore Research Station on the Canterbury Plains, South Island, New Zealand.

For those involved with management of ground water, recharge is of fundamental interest because it sets an upper limit on the resource. This research attempts to provide a useful tool for estimating natural recharge from rainfall and evaporation data using soil moisture models.

There are numerous models describing the movement of moisture through soil (Calder *et al.* 1983; Groves, 1989; Ross, 1990; Scott and Thorpe, 1986) but far fewer which have been validated against a good set of field measurements. The unique feature of this project is the availability of many years of data, which are replicated in several identical lysimeters in close proximity under both grass and bare soil conditions.

The Winchmore lysimeters

The six lysimeters were very well constructed and contain undisturbed soil. The first two lysimeters, A and B, were commissioned in May 1953 and four more (1, 2, 3 and 4) in March 1961. The lysimeters consist of precast concrete pipes, 1220 mm in diameter and 1000 mm long, sunk 900 mm into the ground (Fig. 2). To construct the lysimeters each pipe was set on end and the surrounding soil hand excavated while the pipe was eased down around the cylindrical block of soil. The pipe interior was coated with tar to minimise leakage at the soil-concrete interface. With the pipe at the design depth of 900 mm, a perforated steel plate was jacked horizontally across the lower end and sealed to it with mastic. A shallow collecting cone was bolted on below the perforated plate and a hose conveyed drainage water to collecting tanks. All this was supported on a concrete substructure and access to the base of the lysimeters was via a trench.

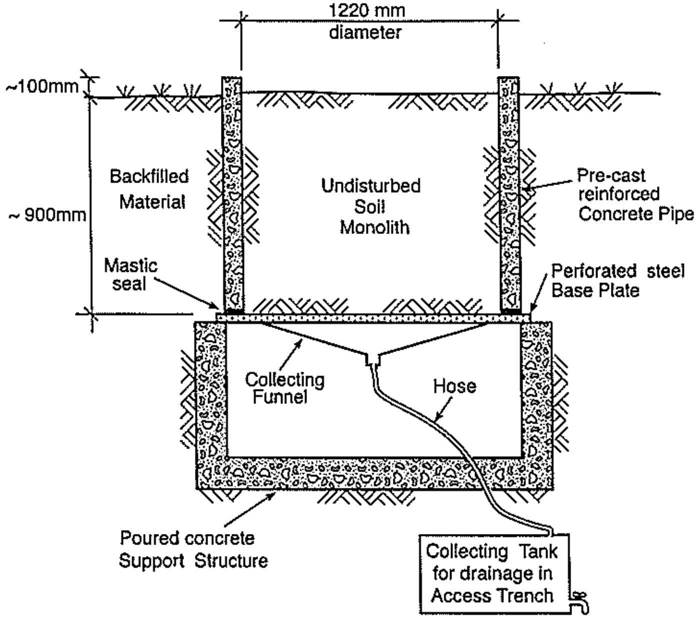

FIGURE 2 – A typical lysimeter as originally constructed.

The original lysimeter walls were 70 mm thick and projected above ground about 100 mm so that in the early research water could be ponded to depths realistic for flood irrigation. Prior to the recent data collection, the walls of all the lysimeters used were cut off at depths 50-80 mm below the ground (i.e. all except B). This was to avoid heat conduction into the soil and the development of a microclimate within the exposed concrete ring, leading to soil moisture conditions different to the general locality.

Calculating the effective lysimeter area using the diameter measured from mid-wall thickness rather than internal diameter of the concrete pipes results in apparently 12% less depth of recharge because of the increased "catchment". This applied to lysimeter A as the exposed pipe end was horizontal, so that precipitation falling on the flat end had an equal chance of falling or splashing inwards or outwards. However the pipes for lysimeters 1 to 4 were built for socket and spigot joints with the socketed end exposed. This had an internal, outward sloping ledge, forming a small annular trough, which retained most water trickling down the inside. For these lysimeters over the early data collection period, using the internal diameter to calculate effective area is reasonable. Wall thickness for the 1995-1997 data is not relevant since the walls had been cut off below ground, with a slight outward slope on the cut surface.

The lysimeters were in two groups within a paddock. For each group the lysimeters were spaced 3-5 metres apart, and the two groups were separated by about 25 metres. The paddock was in unimproved pasture and periodically grazed by sheep, although the lysimeters themselves were kept bare of vegetation from 1961 until about 1974.

Very few pasture roots extend into the gravel subsoil to 900 mm, so it can be reasonably assumed that drainage emerging from the base of the lysimeters would have become recharge.

In September 1994, after checking for leaks, tipping bucket raingauges were installed beneath three of the original lysimeters (A, 3 and 4) and another was placed across the top of the access pit to measure precipitation. These data were logged at five-minute intervals until December 1997. Recharge through lysimeters 1 and 2 was collected in the original tanks, recorded about every six weeks and used as a check on the logged data.

Physiography and soils

In the study area the Canterbury Plains are about 40 km wide and slope at a gradient of about 1 in 200 from an elevation of 500 m at the foot of Mount Hutt to the Pacific Ocean (Fig. 1). They are formed from the coalescing of several major Pleistocene alluvial fans and the area around the research site at Winchmore is typical. The fans consist of greywacke gravels, stones and boulders in a matrix of sand and silt. A thin veneer of loess blankets much of the fan surfaces and most of the soils are shallow with stones in the topsoil.

At Winchmore the soil is a Lismore Stony Silt Loam (Kear *et al.,* 1967) which is described by layer thickness as:

150mm. Very dark greyish brown silt loam with stones; friable.
250mm. Dark yellowish brown stony silt loam; friable.
350mm. Olive brown sandy gravels; compact.
On firm greywacke gravels.

The profile is effectively a two-layer system, which at Winchmore consisted of a stony silt loam layer 320 to 370 mm thick overlying a deep deposit of gravels.

The Lismore soil series covers about 450,000 ha or 25% of the Canterbury Plains. Another 35% of the Plains are covered with a variety of soils with drainage characteristics similar to the Lismore series i.e. "somewhat excessively" or "excessively" drained (Kear *et al.*, 1967).

Soil water retention, hydraulic conductivity characteristics and root density distribution were measured for this study in three pits near the lysimeters and these parameters were used in the models. Soil moisture was also measured by the neutron scattering technique at 0.15m intervals to a depth of 1.5m, at approximately 2-weekly intervals. The three soil moisture profiles measured were within three metres of the logged lysimeters.

There are considerable differences between the soil moisture-holding parameters measured on soil samples in the laboratory and those obtained with the neutron scattering technique, especially in the gravel subsoils. In this work, the values used were obtained from *in situ* soil moisture profiles measured by the neutron scattering technique. The soil moisture parameters in the simulations were those from the profile closest to the lysimeter from which the recharge data were derived. Other soil parameters were obtained from samples, undisturbed where possible, from three pits close to lysimeters A, 3 and 4, and analysed at the Physics Laboratory of Landcare Research at Hamilton. For the *SWIM*© model, parameters have been published for a variety of New Zealand soils, (Watt and Burgham, 1992) and these served as starting values for simulations.

The distribution of roots was obtained from soil sampled at various depths; the roots were separated, weighed, and root lengths determined electronically.

Precipitation at Winchmore

June 1995, during the first winter of the recent data collection period, was a record wet month and the logged lysimeters all recorded recharge which was greater than the rainfall. Obviously the logged rain was an under measure. The Winchmore meteorological site is on the research station, within 100 metres of the lysimeters, and is part of the national network, but the above observation threw into question the accuracy of the entire station rainfall record dating from 1950.

Accurate measurement of rainfall has long been a problem (Essery and

Wilcock, 1991; Rodda, 1967; Waugh, 1971) for two main reasons. Firstly, exposure to wind causes acceleration of flow over the top of the gauge and the finer raindrops are selectively blown sideways out of the gauge catch area, resulting in undercatch. Secondly, the wetting characteristics of the gauge funnel may vary, depending on either the material from which it is made or the material with which it is coated, resulting in significant evaporation losses. The cumulative effect may be more than 10% in lowland areas and much greater still in alpine sites. The best measurement of "true" rainfall is deemed to be by a gauge set in a pit with the orifice at ground level, surrounded by a mesh so that the airflow over the gauge is not disturbed (Rodda, 1967).

This does not address the matter of errors from gauge construction. Waugh (1971) reported that, over a 19-month period, two plastic gauges caught 8.51% and 9.66% more than an adjacent copper gauge. The official gauge at Winchmore was a Dynes chart recorder with a copper funnel from 1950 until March 1996, when it was replaced with a telemetered tipping-bucket gauge with a stainless steel funnel.

To clarify the matter of rainfall errors at Winchmore, a gauge matching the official one was installed a few metres away in a 900 mm diameter pit, with the orifice at ground level and surrounded with a coarse ground-level mesh. A simple plastic storage gauge was also set in a small pit among the lysimeters. Over a 13-month period the plastic storage gauge measured 21% more and the matched ground level gauge 12 % more rain than the official gauge, although the discrepancies varied markedly from storm to storm.

At the end of this period all the tipping bucket gauges were officially re-calibrated and checked. The actual tipping mechanism of the official gauge was volumetrically accurate before and after calibration (Harper, pers. comm.) but cracked and bubbled paintwork was scraped from the inside of the funnel. The matching gauge in the pit had been *under* recording by at most 3%, but after re-calibration of both gauges they now caught about the same amount! This change of relative catch must be mostly attributable to the scraping of the funnel in the official gauge, with a consequent reduction of evaporative losses of water held within the gauge funnel.

Lysimeter recharge data

The recharge and climate data used in this study were collected in two distinct periods. From 1953 to 1978, referred to as the earlier period, nominally daily data were collected as part of a long-term study of fertiliser leaching under irrigation. From 1994 to 1997, the recent period, more detailed data have been collected. As this research is to validate soil moisture models for estimation of natural ground water recharge by comparing the models with measured recharge data, it is essential to determine the quality of the data. The following sections provide details of the data collection for those two separate periods.

Recharge: 1953 to 1978

Lysimeters A and B were constructed during 1952 and trial data collection began on 11th November. Initially the lysimeters were kept bare of plants, but they were sown in grass during May 1955 and maintained as pasture until March 1960, when they were again de-grassed. During this period lysimeter B was irrigated but lysimeter A was not. Lysimeters 1 to 4 were constructed during early 1960 and data recording began on 1 March 1961. According to records from this date all lysimeters were kept carefully weeded until at least 1972, and probably until 1976 (Woods, Forsythe. pers. comm.). They were in grass again during 1978, when the earlier data collection ceased, until the present time.

Thus there are good data for lysimeter A under grass from mid 1955 until March 1960, and for A, plus another four lysimeters with bare soil, from March 1960 until around 1972. After that time, data gaps occurred for some lysimeters. For the period May 1953-June 1976 the data were nominally daily, but for the last two years to November 1978 only monthly totals are available.

Data from the paper files of AgResearch Winchmore, which now owns the site, were made available and comprised the original field books and summary sheets derived from them. These data were manually entered into a computer data base, edited and checked. Crosschecking between field books and summaries provided a valuable test of data quality. Comparisons between lysimeters and with rainfall records were also a good check for gross errors.

From 1953 to 1978, recharge was collected in large calibrated tanks and nominally daily values read from attached sight glasses. Some data were lost during extreme events when tanks overflowed, or occasionally because of leaking hoses or taps, but on the whole the standard of care in data collection was excellent for many years. It was noted in the field books that over-irrigation of a nearby grass tennis court occasionally affected lysimeter 4. Only over the last few years, during the mid to late 1970s, was deterioration apparent from the data gaps and the standard of record keeping in the field books. Information from retired station staff (Rickard, pers. comm.) indicated that there was early concern that one of the two original lysimeters leaked. Checks prior to beginning the new data collection programme showed lysimeter B to be leaking badly and subsequent analysis of the early data indicated that this lysimeter behaved differently to the other five. It was therefore not used in the model evaluations.

Recharge: 1994 to 1997

Recharge and rainfall data at the lysimeter site over the period September 1994 to December 1997 were measured in 0.5mm tipping bucket raingauges beneath lysimeters A, 3 and 4, and logged at five-minute intervals. There was almost no data loss over this period. Data at ten-minute intervals were also available from the meteorological site

General comments on data quality

It seems very likely that the official rainfall recorder at Winchmore has always substantially under-estimated the rainfall hitting the ground. This error cannot be accurately defined and has significant consequences for model evaluation. The error is thought to be about 10% and for the assessment of all the models the rain input based on the official gauge has been increased by 10%.

From September 1994 until December 1997 excellent recharge data were collected and logged from lysimeters A, 3 and 4, with some supplementary data from the original collection tanks under lysimeters 1 and 2.

Simple regression of annual recharge totals against annual rains (Table 1) gives a good indication of the consistency of data between lysimeters. It can be seen from the equations for lysimeter A and from Figure 3 that annual recharge is reduced by around 130 mm with a grass cover, compared to bare soil. The different behaviour of lysimeter B is also apparent, but the equations for all other lysimeters under bare soil are remarkably consistent. Lysimeter 4 is known from field notes to have been occasionally affected by spray irrigation drift from an adjacent grass tennis court until 1978.

TABLE 1 – Regression equations of annual recharge against annual rain for all lysimeters at Winchmore Irrigation Research Station

Lysimeter	Years	Surface	Regression Equation (mm units)	Correlation Coefficient (r^2)
A	55/56-59/60 and 1995-1997	Pasture	Recharge = .797*Rain-381	0.839
A	53/54/55 and 60/61-73/74	Bare soil	Recharge = .771*Rain-244	0.786
B	53/54/55 and 60/61-73/74	Bare soil	Recharge = .610*Rain-159	0.651
1	60/61-73/74	Bare soil	Recharge = .774*Rain-267	0.784
2	60/61-73/74	Bare soil	Recharge = .767*Rain-254	0.766
3	60/61-73/74	Bare soil	Recharge = .777*Rain-243	0.777
4	60/61-73/74	Bare soil	Recharge = .743*Rain-211	0.725

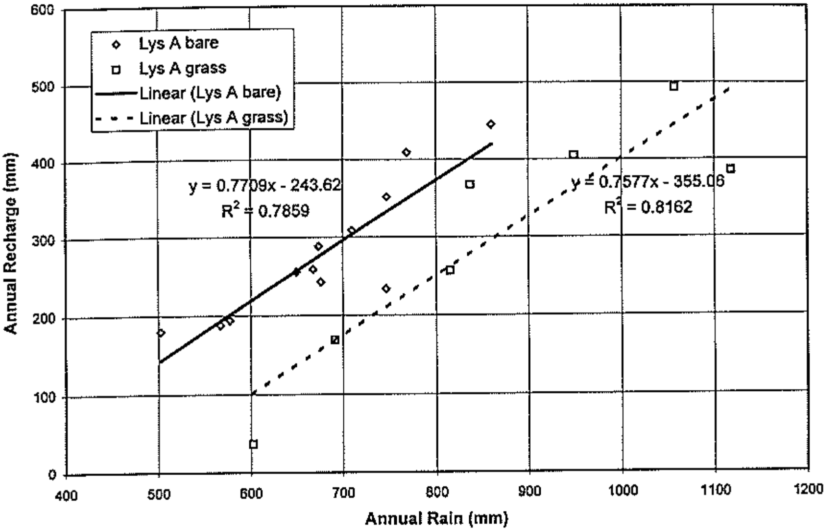

FIGURE 3 – Annual recharge from lysimeter A, under bare soil and pasture cover.

Through the 1994-1997 period, a circumferential gap several millimetres wide, caused by shrinkage, was observed during the summer months between the soil and the inner wall of the unmodified lysimeter B. Such gaps must have existed in all the lysimeters during the earlier period of data collection and might be leakage paths during heavy summer rains, but such rains would be infrequent and errors in the long-term recharge arising from them would be small. No gap was present after the soil wetted and swelled between late autumn to early spring, when most recharge occurs.

Figure 4 shows the relationship between annual rainfall and annual recharge for all lysimeters. This shows a reasonable linear relationship between rainfall and recharge and also gives a good indication of the variability of recharge between lysimeters in any one year. The outliers may be in part attributable to the seasonal variability of the recharge, as shown in Figure 5 (from Thorpe, 1992), i.e. an exceptionally wet winter would increase the recharge for a given annual total because most of the winter rain becomes recharge. Conversely an exceptionally wet summer would reduce recharge for a given rainfall because very little summer rain passes through the soil.

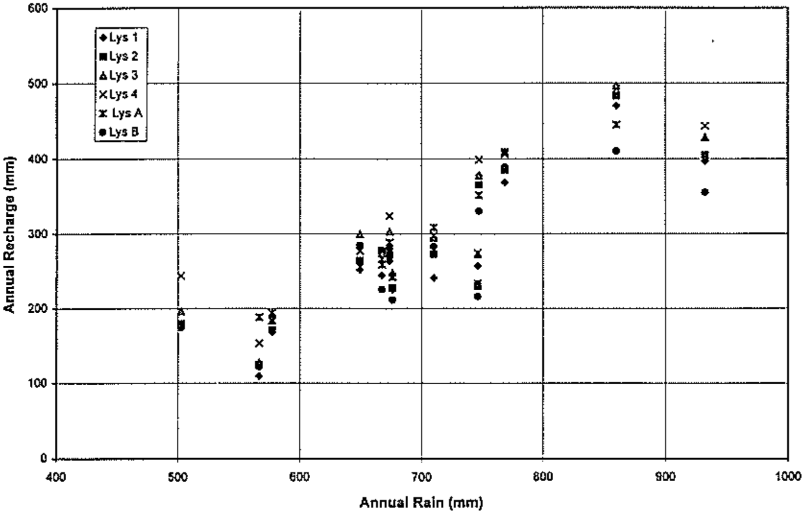

FIGURE 4 – Annual recharge vs. annual rainfall for lysimeters under bare soil.

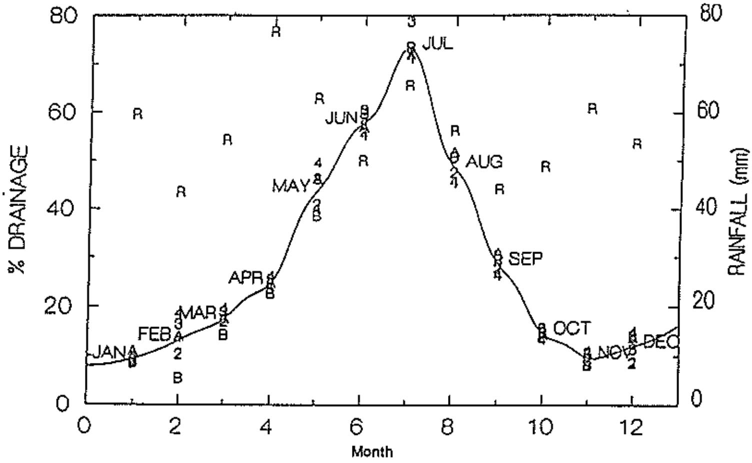

FIGURE 5 – Distribution of recharge throughout the year through bare soil at Winchmore. "R" is the long-term monthly rainfall.

Figure 6 shows time series of measured recharge from three lysimeters over the period 1961/1971, during which they all were under bare soil. The excellent consistency is apparent from a quick scan.

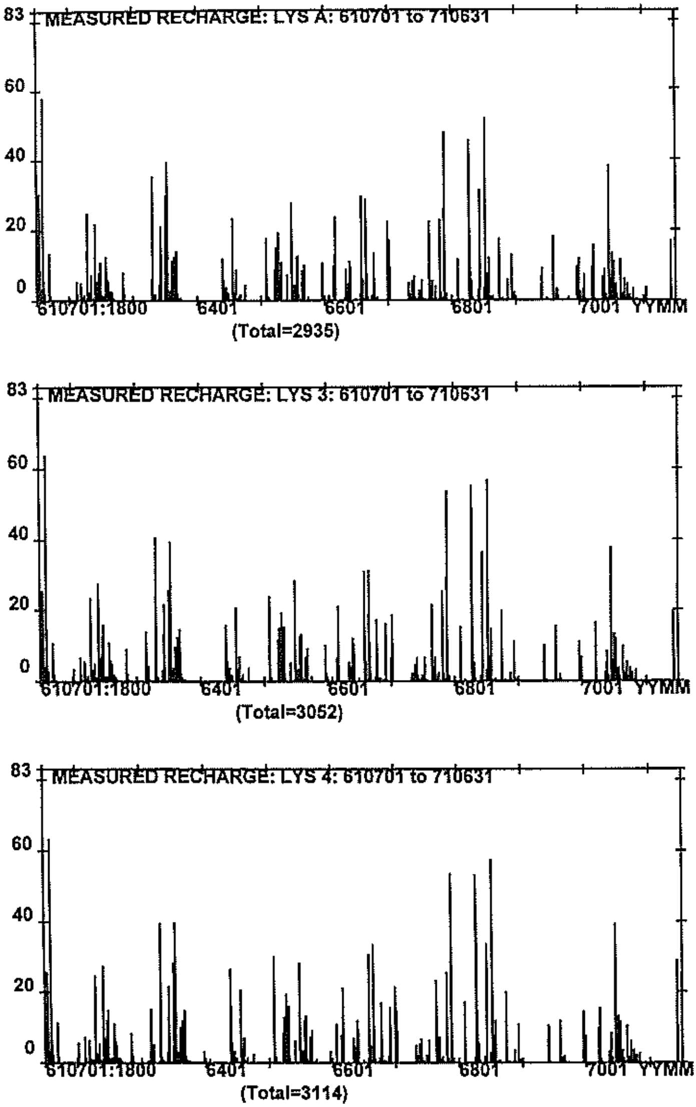

FIGURE 6 – Time series of measured daily recharge from lysimeters A. 3 and 4 for 1961 to 1971. Units are mm. Dates shown as year, month, day. [yymmdd]

For model testing, data between May 1955 and December 1971 from the earlier set was used, and from the later set, data for 1995, 1996 and 1997.

The *SOILMOD* model

SOILMOD (Scott and Thorpe, 1986) is a single-layer (lumped parameter) model based on a simple soil moisture balance, assuming no surface runoff i.e.

$$S_i = S_{i-1} + R_i + I_i - AE_i - D_i \qquad (1)$$

Where S_i = soil moisture on day i, i-1 etc.
R_i = rainfall on day i
I_i = irrigation on day i
AE_i = actual evapotranspiration on day i
D_i = drainage on day i
All terms are in mm depth.

Of the several parameters in equation (1), soil moisture and irrigation application depths can be measured with reasonable accuracy. Rainfall is subject to the uncertainties discussed above. For the earlier data set, potential evapotranspiration (PE), was estimated from pan evaporation (E_{pan}) using a New Zealand derived pan reduction factor (Finkelstein, 1973), with corrections for seasonal variation of day length and extra advective evaporation losses under the local foehn wind conditions (Smart, 1978). For the 1995-97 period the potential evapotranspiration was obtained from the Station meteorological daily data which had been calculated with the Priestley-Taylor equation, and the same day length factor was applied.

Thus, for the earlier data under non-foehn conditions.

$$PE_i = K_p.N_i.E_{pan} \text{ for } E_{pan} \leq 5\text{mm per day} \qquad (2)$$

Or for foehn conditions (Smart, 1978)

$$PE_i = K_p.N_i.1.9(E_{pan})^{0.6} \text{ for } E_{pan} > 5\text{mm per day} \qquad (3)$$

Where PE_i = potential evapotranspiration on day i ,

K_p = evaporation pan reduction factor

$\cong$ 0.86 for a sunken pan

$\cong$ 0.69 for a raised pan

and N_i = day length factor

$$N_i = 0.2[\cos \frac{N_{day}}{365} + 1] + 0.6 \qquad (4)$$

Where N_{day} = the number of day i, counting from December 21.

Thus N_i is able to vary between 0.6 and 1 and allows for the seasonal difference in daylight hours when transpiration occurs.

The calculation of actual evapotranspiration is based on the level of soil moisture and the field capacity for a specific soil. Thus for higher soil moistures in a Winchmore stony silt loam; (Fig. 7)

If $S_{i-1} > S_c$ i.e., $S_{i-1} > FC-U$, then

$$\frac{AE_i}{PE_i} = 1 \tag{5}$$

while for drier soil;

$$\frac{AE_i}{PE_i} = \frac{S_i}{S_c} = \frac{S_i}{FC - U} \tag{6}$$

where VC, a vegetation cover factor, is defined by:

$$VC = \frac{U.PE_i}{FC} \tag{7}$$

Thus

$$\frac{AE_i}{PE_i} = \frac{S_i/FC}{(1 - VC/PE_i)} \tag{8}$$

FC is soil field capacity, VC is defined by equation 7 and U is a root factor for the particular soil and plant. It is analogous to the Penman root constant (Penman, 1949).

These relationships are illustrated in Figure 7. S_c is the critical soil moisture deficit at which the actual evapotranspiration begins to fall below the potential evapotranspiration. When the potential evapotranspiration (PE) is high, the soil cannot as readily transmit water to the roots to meet the demand, and hence the ratio of actual to potential evapotranspiration is reduced to less than unity at smaller soil moisture deficits. Soil field capacity and root and vegetation cover factors (FC, U and VC) for several New Zealand soils can be found or derived from the literature (Martin, 1990; McAneny and Judd, 1983; Parfitt *et al.*, 1985a; Parfitt *et al.*, 1985b; Davoren, pers. comm.). For the Lismore stony silt loam to a depth of 900 mm, neutron soil moisture data show that soil field capacity is 200-250 mm and the vegetation cover factor (VC) can be calculated as 1.2-1.5. Therefore when potential evapotranspiration is 4 mm per day the critical soil moisture deficit, S_c, at which actual evapotranspiration begins to reduce below potential evapotranspiration is about 75 mm (from equation 7). This should not be confused with the deficit at which plant productivity begins to decline, as it is reported (Martin, 1990; McAneny and Judd, 1983; Parfitt *et al.*, 1985a,b; Scotter *et al.,* 1979) that evapotranspiration continues at the potential rate for soil moisture deficits greater than those causing reduced plant growth.

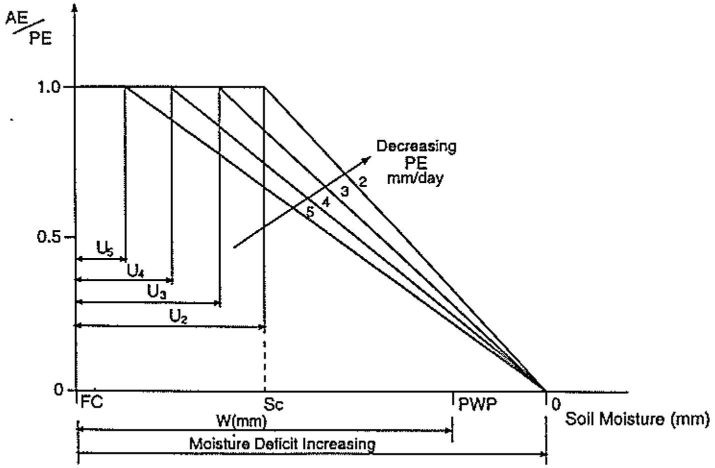

FIGURE 7 – The relationship between AE/PE ratio and the soil moisture deficit.

Drainage from the soil root zone is recharge to the ground water and this term, being the difference between all the others in equation 1, is not likely to be very accurate. With this model there is no routing of moisture through the soil. Moisture is released as recharge as soon as the holding capacity of the single soil layer is exceeded.

SOILMOD results

Sensitivity analyses indicated that *SOILMOD* is particularly sensitive to rain or irrigation input. For instance increasing the rain by an overall 10% increased the simulated recharge by 20%. This has particular significance, given the uncertainty of the rain measurements at Winchmore. Conversely the model was not very sensitive to soil moisture-holding parameters, a 33% decrease in field capacity resulting in only a 7% increase in simulated recharge. Changes in evapotranspiration cause roughly proportional changes of recharge e.g. a 10% overall reduction of input evapotranspiration results in an 8% increase of drainage. Nor was *SOILMOD* very sensitive to the root factor U for the soil; a reduction of U by 25% reduced drainage by a mere 1.6%. This implies that most recharge occurs at times of low potential evapotranspiration, i.e. winter, as observed.

It should be emphasised that, with the exception of a uniform 10% increase in rainfall to account for underestimates in the Winchmore official rainfall records, the parameters used in *SOILMOD* simulations were measured or calculated from field data. They have not been adjusted to improve model fit.

Lysimeter A has a drainage record extending from 1953 to 1978, although data quality is uneven at the beginning and end of the record. From 1953-55 it was kept as bare soil, from May 1955 to the end of 1960 it was in pasture and from then until probably 1974 it was again bare.

Figure 8 compares the measured and simulated recharge for lysimeter A under pasture over the period 1 June 1955 to 1 June 1960. The total recharge over that period can be read from the plots in millimetres. The ratio of simulated to measured recharge over the five-year period is 1.14, so simulation values are close enough to be useful to water managers.

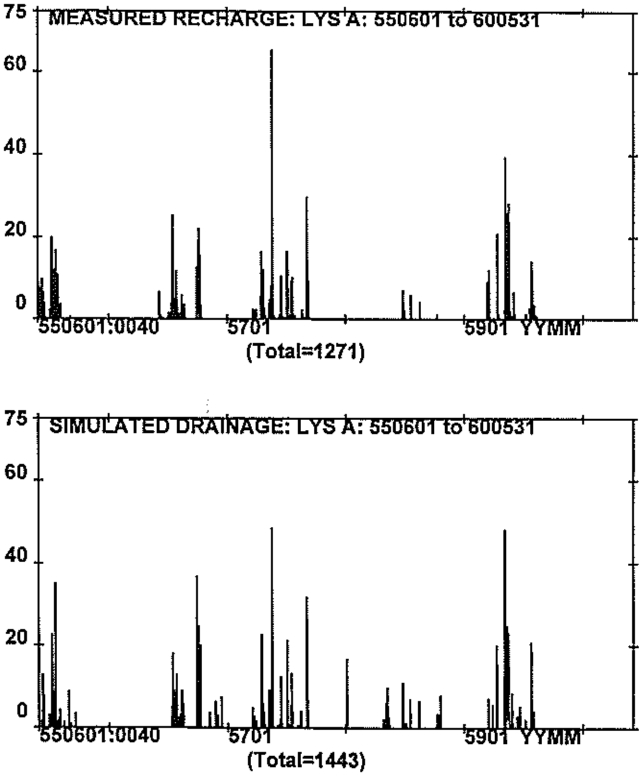

FIGURE 8 – Comparison of simulated daily drainage with measured recharge for lysimeter A under pasture cover from 1 June 1955 to 31 May 1960. Units are mm. Dates are shown as year, month, day. [yymmdd]

The data show occasional marked discrepancies in daily recharge, however recharge from the lysimeters was not always recorded daily, i.e. weekend readings were not taken, so some of the "daily" values may be accumulations over two or three days. It is apparent though that the simulation includes a number of "false positive" recharge events which were not in fact measured. *SOILMOD* overestimated recharge in every year, usually ranging up to 10%, but in the year 1 June 1957 to 31 May 1958, a year of lower than usual recharge, the overestimate was 44%.

Simulations were also done for five-year periods between 1961 and 1971 when the lysimeters had no pasture cover. With the soil parameters unchanged, but the vegetation cover factor, VC, arbitrarily reduced from 1.5 to 1.0, the simulations markedly underestimated the drainage. For instance over the period 1 June 1961 to 1 June 1966 *SOILMOD* predicted only 83%

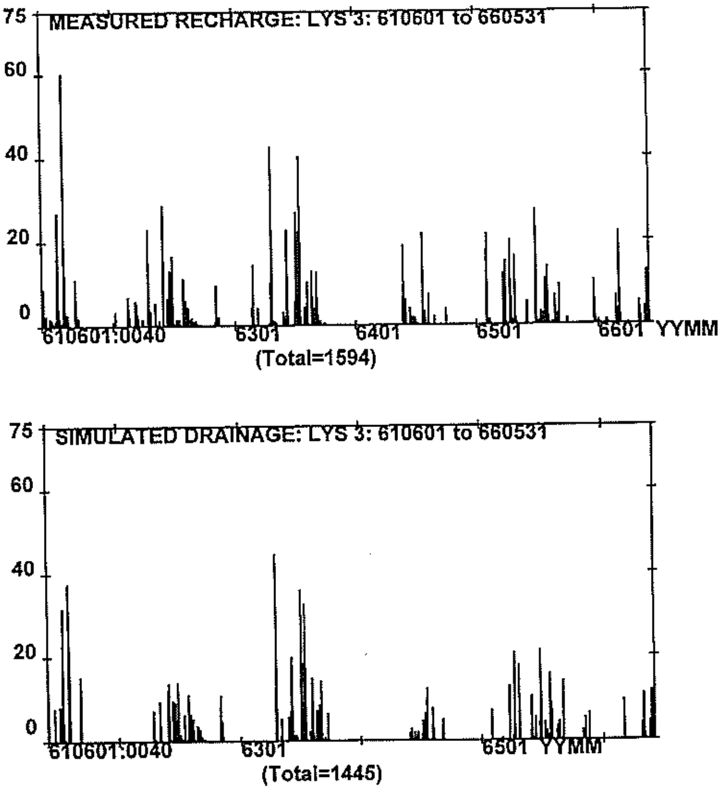

FIGURE 9 – Comparison of simulated daily drainage with measured recharge for lysimeter 3 under bare soil from 1 June 1961 to 31 May 1966. Units are mm. Dates are shown as year, month, day. [yymmdd]

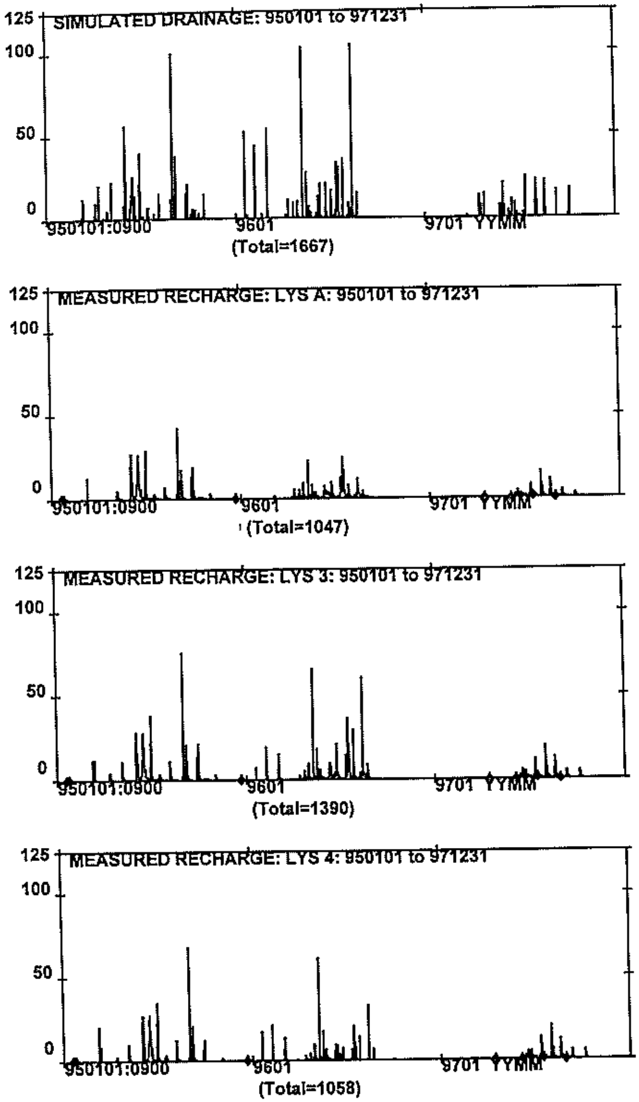

FIGURE 10 – Comparison of simulated daily drainage with measured recharge for lysimeters A, 3 and 4 under pasture from 1 January 1995 to 31 December 1997. Units are mm. Dates are shown as year, month, day. [yymmdd]

of the measured recharge from lysimeter A and for lysimeter 3 only 91% (Fig. 9). From 1 June 1966 to 1 June 1971 the equivalent predictions were 79% and 86% respectively. These simulated results for bare soil conditions were typical of all the lysimeters.

If for bare soil the parameter VC is arbitrarily further reduced from 1.0 to 0.1, the critical soil moisture deficit for potential evapotranspiration of 4 mm per day (Fig. 7) is reduced from 75 mm to around 6 mm. Under this condition the ratio of actual to potential evapotranspiration will seldom be unity, reflecting the fact that there is no vegetation, driven by atmospheric demand, extracting moisture from depth. Therefore there is less evapotranspiration and more drainage, with the result that the simulations are closer to the measured recharge totals by about 5%. While this seems a reasonable hypothesis based on the field data, there is no empirical evidence for choosing VC equal to 0.1 and there is still a significant underestimate of drainage.

Figure 10 shows the comparison of simulated and measured recharge using the more detailed data collected from January 1995 to December 1997. During this period, on five occasions, (10 March and 31 August, 1995, 19 January, 9 May and 13 August 1996), the lysimeters were spray irrigated with either 102 mm or 108 mm over a 2-3 hour period and this was allowed for in the model input. At this time the lysimeter walls had been cut down to below ground level, so that it was possible for micro topography to cause flow of intensive rain or irrigation water away from or onto the lysimeter.

The irrigation events are all apparent in Figure 10, apart from the event on 19 January 1996. On this occasion 108 mm of water was applied over three hours with zero recharge through lysimeter A and 8 mm and 18 mm through lysimeters 3 and 4 respectively. Antecedent soil moisture levels for this summer event were obviously low.

The Calder three-layer model

Calder *et al.* (1983) evaluated a number of soil moisture deficit models against an extensive database of neutron measurements. These were also based on equation (1) but with a variety of empirical relationships between actual and potential evapotranspiration. One of the variations examined by Calder *et al.* (1983) was a three-layer model, with simple rules governing the release of water from one layer to another and the relative rates of evapotranspiration from all three layers. In the present study the model layer properties were adjusted so that the moisture storages in the three layers matched those measured at Winchmore by the neutron scattering technique. The resulting rules adopted were:

Layer 1 (uppermost)	Holds 50% of plant available water. and AE = PE until layer is dry.
Layer 2	Holds 20% of plant available water. and AE = 0 when layer 1 contains water otherwise AE = 50%PE until dry
Layer 3	Holds 30% of plant available water. and AE = 0 when layers 1 or 2 contain water otherwise AE = 25% PE until dry.

The thickness of the layers is not relevant, only the water-holding capacity.

Calder model results

The above rules attempted to build some delay factors into the model to improve the short-term simulation of recharge, but model performance was not as good as *SOILMOD.* For instance, when running a 19-year simulation and comparing the results with Winchmore recharge data, simulation of totals was reasonable, but *SOILMOD* gave a root mean square error of 7.14 mm whereas the error for the three-layer model was 13.48 mm. It was not worthwhile to spend more time in evaluating the more complex model when the simpler version gave better results.

The *SWIM*© model

SWIM© is a commercially available software package, created and sold by CSIRO Division of Soils, Townsville, Australia (Ross, 1990) for simulating water infiltration and movement in soils under various types of vegetation. *SWIM*© is based on the Richards' equation (i.e. one-dimensional) and allows for water addition as precipitation, and removal by runoff, drainage, evaporation from the soil surface and, separately, as transpiration from vegetation. The drainage component from the *SWIM*© simulation is considered to be recharge, as it is computed for the sandy gravels at the lower limit of the root zone.

The model permits simulation of the water extraction characteristics of up to four vegetation types simultaneously and up to 101 soil layers. The soil surface layer is considered separately with respect to reduction of hydraulic conductivity by crusting under the impact of rain. Other soil parameters required are those commonly obtained by laboratory testing, i.e. water content at field saturation, saturated hydraulic conductivity, a moisture retention curve, soil air entry value and an initial matric potential. A wilting point is required in the form of minimum xylem potential for each vegetation type, and also parameters describing the density and distribution of roots with depth. Daily values of rain and potential evaporation have to be input as cumulative totals over the five-year simulation period.

The *SWIM*© output consists of a soil water balance at user-specified intervals, a text or graphic display of daily potential and actual evaporation, and cumulative values of precipitation, runoff, infiltration, drainage (i.e. recharge), evapotranspiration, surface storage, water in the profile and unavailable water, (i.e. held below wilting point). There is also a graphic time series, at user-specified intervals, of soil moisture profiles.

Broadly the same programme of tests as for *SOILMOD* was run, using both the archived and recently gathered lysimeter data. Again it was assumed that the recorded rainfall was underestimated and it has been increased by 10%. The *SWIM*© soil parameters published by Watt and Burgham (1992) for the Lismore stony silt loam were used at first in the simulations.

SWIM© results

Using the published soil parameters and the 1955-1960 measurements (grassed lysimeter) the model performed reasonably, in the sense that it reproduced the recharge amounts with an underestimate of about 15% and with a good simulation of recharge distribution. The simulated extreme seasonal wet and dry soil moisture profiles however were markedly different from those subsequently measured by the neutron scattering technique (Fig. 11), with the difference in moisture profiles especially large in the sandy gravel layer.

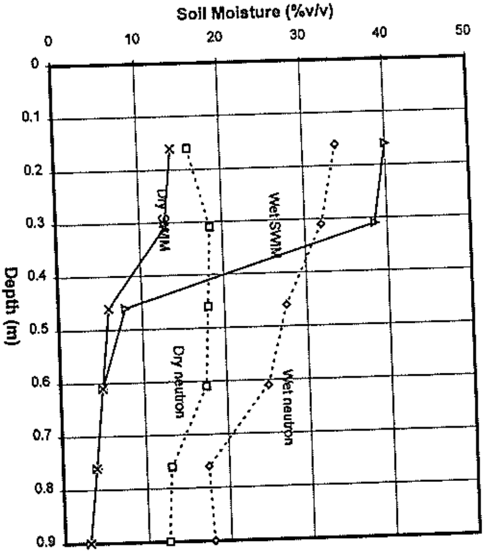

FIGURE 11 – Soil moisture profiles; measured and simulated by *SWIM*© using published soil parameters.

TABLE 2 – Published and selected parameters used in *SWIM*© simulations

Depth (cm)	Θ MVF	Θ_s *MVF*	PsiE (cm)	***PsiE (cm)***	b	***b***	K_{sat} (cm.hr^{-1})	***K_{sat} (cm.hr^{-1})***
16	.498	***.5***	-6.82	***-15***	6.46	***7***	72.3	***72***
31	.434	***.43***	-3.58	***-15***	7.77	***8***	11.4	***45***
46	.171	***.37***	-0.046?	***-15***	8.60	***10***	2.1	***2***
61	.166	***.3***	-0.198	***-15***	7.16	***10***	2.1	***2***
76	.114	***.25***	-0.158	***-15***	5.18	***10***	2.1	***2***
90	.114	***.25***	-0.158	***-15***	5.18	***10***	2.1	2

Published values shown normal and values used for simulations bolded.
Θ_s is the water content at field saturation.
PsiE is air entry value of the soil.
b is minus the slope of the log-log soil water retention curve.
K_{sat} is the hydraulic conductivity at field saturation.

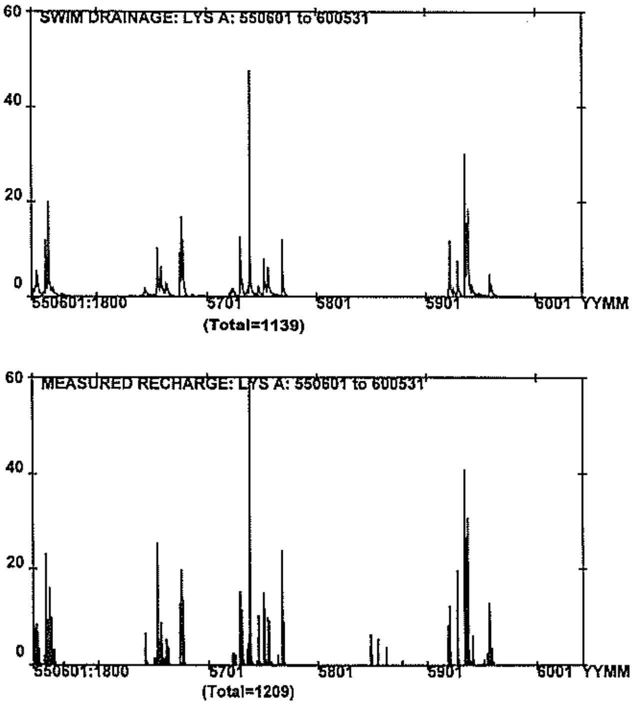

FIGURE 12 – Comparison of measured daily recharge under pasture and drainage simulated by *SWIM*© for lysimeter A from 1 June 1955 to 31 May 1960. Units are mm. Dates are shown as year, month, day. [yymmdd]

Manual adjustment of the soil parameters, within plausible limits (Table 2), allowed excellent simulation of both the extreme wet and dry soil measured moisture profiles shown in Figure 11, and with these adjustments the underestimation of recharge was only 10% over the five-year period (Fig. 12). This underestimate could perhaps be explained by macropore flow, which *SWIM*© does not allow for. The difference in the plotted peak values is of little significance, because the measurements are nominally daily values, whereas *SWIM*© computes drainage at smaller time intervals depending on a specified water increment. The greater the water flux, the shorter the time increment.

Using the 1960-1970 measurements, the same set of soil parameters as for the pasture cover, but with vegetation parameters adjusted to represent bare soil, the simulation was much less successful (Fig. 13). The underestimation of recharge for various lysimeters and various five-year periods ranged between 32% and 50%. Again the simplest hypothesis for the discrepancy is macropore flow, increased for bare soil because of the greater exposure to the weather, with consequently more shrinkage and cracking of the soil surface.

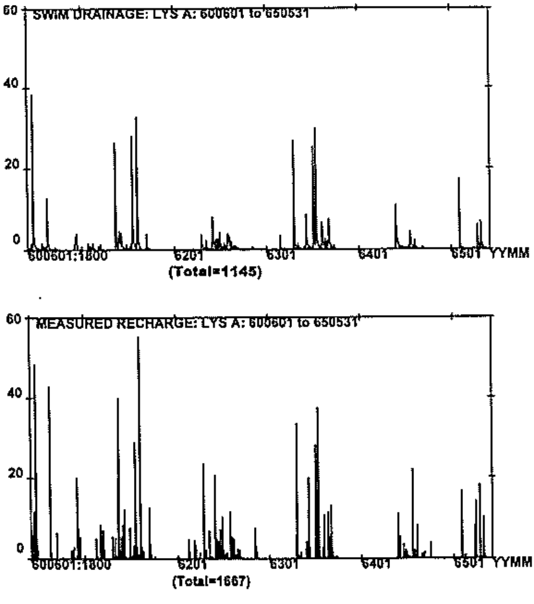

FIGURE 13 – Comparison of measured daily recharge under bare soil and drainage simulated by *SWIM*© for lysimeter A from 1 June 1960 to 31 May 1965. Units are mm. Dates are shown as year, month, day. [yymmdd]

SWIM© was evaluated further using the more detailed data collected from January 1995 to December 1997. The annual totals for 1995 and 1997 are in good agreement, but the *SWIM*© estimate for 1996 is seriously high (Table 3). Figure 14 shows the comparison of simulated and measured recharge. The irrigation recharge peaks estimated by *SWIM*© are underestimates, because the application of 102 mm or 108 mm was over a 2-3 hour period whereas the model assumed it was 24 hours and spread the drainage over a longer period, resulting in a lower peak.

TABLE 3 – Annual values of measured recharge compared with *SOILMOD* and *SWIM*© simulated drainage over the three years, 1994-97, with pasture cover.

Year	Rain (mm)	Irrigation (mm)	Total water (mm)	Lys. A meas. (mm)	Lys. 3 meas. (mm)	Lys. 4 meas. (mm)	Average meas. (mm)	*SOILMOD* (mm)	SWIM© (mm)
1995	803	210	1013	493	592	508	531	568	588
1996	806	312	1118	385	611	375	457	649	594
1997	699	0	699	169	186	1874	177	186	174
Total	2308	522	2830	1047	1389	1057	1165	1403	1356

The Groves model

Groves (1989) described a soil moisture model which, given rainfall, pan evaporation and parameters selected from a table of given soil "texture groups", estimates volumetric soil moisture in three user-defined horizons within the soil profile. Moisture is added to the soil column as infiltration and is withdrawn as both evapotranspiration and drainage from the base of the column. Analytical solutions are used to describe both the infiltration and redistribution of moisture within the soil. Actual evapotranspiration is derived from pan evaporation using a relationship similar to that shown in Figure 7, with parameters again defined by the chosen soil texture group. Weather data are input from external files and the model can accommodate multi-year data sets.

The model has a generally sound physical basis, but two assumptions are questionable. The first is that no evaporation or drainage occurs during a rainfall period, and the second is that potential evapotranspiration is equated with pan evaporation. The first assumption is observably incorrect and the second has also been shown to be wrong (Finkelstein, 1973). Another shortcoming of the model is that it allows only a single soil texture in the profile, even though there may be up to three layers within that soil. It cannot

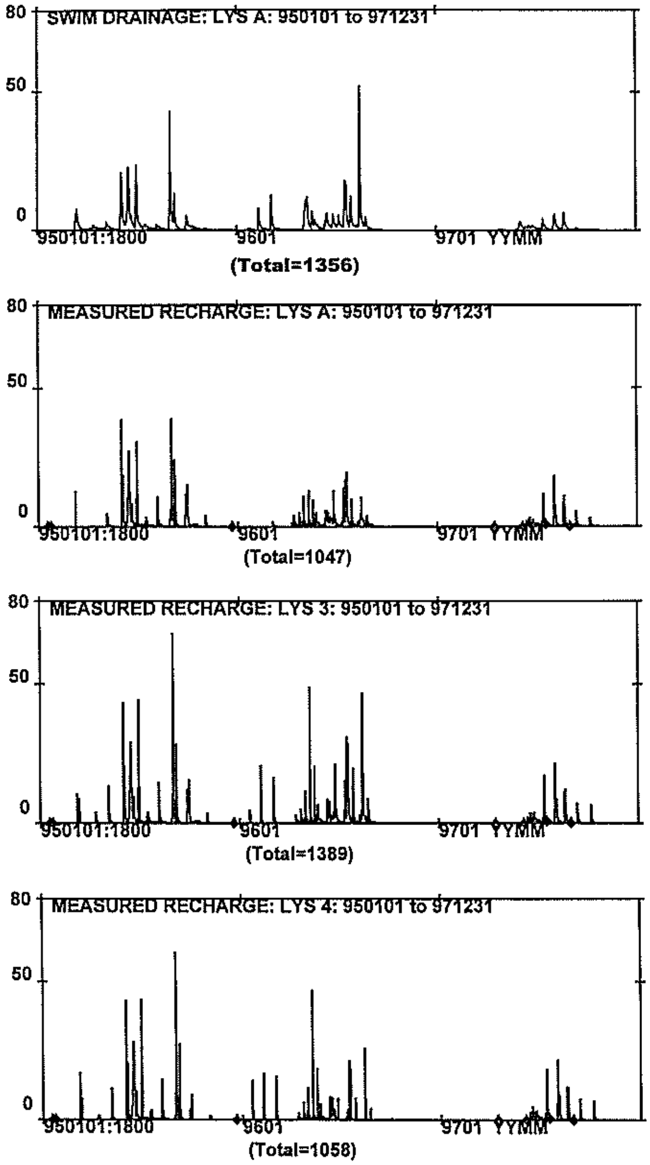

FIGURE 14 – Comparison of SWIM© simulated drainage and measured daily recharge under pasture for the years 1995 to 1997. Units are mm. Dates are shown as year, month, day. [yymmdd]

model a profile with a marked change of texture, e.g. from silty loam to sandy gravel, as for a Lismore stony silt loam. Groves claims that the model "generates reliable estimates of soil moisture profiles."

Groves' model results

Evaluation of Groves' model against the soil moisture data collected at Winchmore from 1994 to 1997 indicates that it does produce reasonable soil moisture time series, at least in the shallow silt loams, but it could not accommodate the marked change of soil texture in the column from silts to sandy gravels. More significantly, from the point of view of this research, the model did not produce good estimates of drainage. The model sets initial soil moisture at field capacity and with a five-year simulation gave reasonable drainage values for about three months, but these values then dropped to very unrealistic levels, and the overall result was a considerable underestimate.

The model seems basically sound for soil moisture prediction, and probably could be made to function as a recharge model without too much modification. However the purpose of this project was to evaluate published models rather than modify them so no further work was done.

Discussion

All the data and parameters used with the models in this work were either measured at Winchmore or derived from New Zealand values in the literature.

The published soil parameters for the *SWIM*© simulations were modified as shown in Table 2 for two reasons. Firstly, there was no way of reproducing the soil moisture measured in the gravels without some changes. Secondly, Watt and Burgham (1992) note in their publication regarding Lismore shallow silt loam that: "N.B. The subsoil horizons have been sampled using recompacted cores, these estimates should be regarded with caution."

Although the recharge data are considered to be of generally high quality, there is a doubt about the official rainfall record at the site, and it seems likely that the gauge underestimates the rain that hits the ground by about 10%. The official gauge was affected by exposure to wind and also by evaporation losses in the gauge funnel. Since the models are very sensitive to rainfall, this adds uncertainty to the simulations, even though a correction for this error in rainfall has been added. A further occasional factor would be snow, which falls and lies for a few days on average about once per winter at Winchmore and complicates both rainfall and recharge measurements and timing.

None of the models make allowance for macropore flow, nor do they allow for hysteresis in soil wetting and drying behaviour.

Several interesting features emerge from the recent data and simulations. Firstly, the irrigation recharge peaks were somewhat overestimated, especially in lysimeter A. This may be because of some runoff from the lysimeter surface during irrigation, despite efforts to prevent this. A possible cause of variability between lysimeters during this period is the effect of stock trampling which reduces soil infiltration capacity during winter. This effect was observed at the irrigation of 13 August 1996 when the maximum infiltration rate was markedly reduced compared to previous occasions, especially at lysimeter 4. A reduction in the recharge total of lysimeter 4 is very noticeable for the later part of winter 1996 (Fig. 10), with the measured values being much smaller, from about the beginning of July onwards (176 mm total), than those of lysimeter 3 (412 mm), a few metres away. Prior to this, in 1996, the two lysimeters produced very similar recharge, 223 mm and 238 mm respectively (Table 3), and over the 1997 winter they were again behaving virtually identically, with recharges of 185 mm and 198 mm respectively.

It was confirmed by farm staff that sheep were in the paddock when the soil was very soft, from early July to mid August. Presumably worm and pasture activity, plus soil shrinkage over the summer, opened up the soil again and restored the infiltration capacity for the 1997 winter recharge season. Stocking of the same intensity did not occur during either 1995 or 1997.

The hypothesis that redistribution of surface water by micro topography created discrepancies is supported by the very close agreement between the three lysimeters during 1997, which was a year of lower rainfall and recharge, with no irrigation.

During the bare soil simulation with *SWIM*©, the simulated soil moisture levels were generally higher than for the pasture cover simulation and also higher than those measured by the neutron probe set in pasture. If perfect porous medium flow were occurring, the simulated wetter soil would result in increased recharge. In fact the opposite happened. The deficit of simulated recharge under bare soil was larger than for pasture cover. This may be another indication of increased macropore flow through bare soil in the field.

Table 3 indicates that, although the input of total water in 1996 was greater than in 1995, lysimeters A and 4 both produced less recharge, while lysimeter 3 produced more. This could have been due to differing degrees of soil surface compaction by heavy stocking during the winter of 1996. Soil compaction by stock may also have occurred in earlier years, as there are some anomalous periods in the archived data when one or another of the lysimeters diverged for a period from the group behaviour.

The *SWIM*© ratio of drainage to average measured recharge for pasture cover over the years 1995 to 1997 was 1.16, compared to 0.94 for pasture cover over the period 1955-1960. Much of this difference in ratio is accounted for by the anomalous year of 1996.

Comparison of simulations with the measured recharge data for lysimeter A under grass from 1955–1960 with the data from 1995-1997 shows good consistency between the two periods. Irrigation of lysimeter A during 1995 and 1996 probably introduced some error, because the models did not accurately reproduce the extreme recharge values. Some runoff from the lysimeter surface was observed during irrigation. Natural recharge through lysimeter A over 1995-1997 may have been slightly lower than during the 1955-1975 period because of the growth of a shelter belt nearby, which protected it from north-west rain. However this is a minor component of rainfall at Winchmore and the effect is not large, except in 1996, when the heavy soil trampling by stock may also have contributed to the difference. Trampling appeared to particularly affect lysimeter 4. Lysimeter 3 is thought to most accurately represent recharge at Winchmore in 1996.

Both *SOILMOD* and *SWIM*© simulations were generally realistic in the time distribution and amounts of recharge over periods of weeks to years but not at shorter time scales. The short-term discrepancies between models and measurements is partly because the earlier measurements were only nominally daily, and partly because the models did not allow for macropore flow, hence larger daily recharge values were not well simulated.

The lack of sensitivity of the recharge models to soil parameters is thought to relate to the markedly seasonal pattern of recharge. In summer the soils are dry, recharge rarely occurs, and therefore the soil water-holding capacity is largely irrelevant. Conversely, in winter, when most of the recharge occurs, the 300-400 mm of silt loam soils are near saturation all the time; once this condition has been reached for any soil the water-holding capacity is again not important. Only in the spring and autumn, during the seasonal wetting and drying phases, do water-holding characteristics have a large effect on the amount of recharge, hence the effect would be small on an annual basis. If the soil has a small water-holding capacity, as at Winchmore, the wetting and drying phases would be shorter and hence the sensitivity to soil parameters would be less than for heavier soils.

Model sensitivity to rainfall may also relate to the shortness of the recharge season. If an extra 10% of rain is uniformly applied, the soil would attain field capacity earlier in autumn and retain it longer in spring. Rainfall at Winchmore is fairly evenly distributed throughout the year (Fig. 5) but the recharge is not, so the uniform increment of rain may extend the normal recharge season from, say, 5 months to 6 months, a 20% increase.

On the other hand the models are not especially sensitive to potential evapotranspiration. Potential evapotranspiration, of course, is greatest in summer when there is little recharge. If it is increased by, for example, a uniform 10% throughout the year, most of this increase, in absolute terms, will be in summer when the soil is already dry and the AE/PE ratio is likely to be less than one. (Fig. 7). Thus for the same daily potential evapotranspiration value, soil will dry more slowly in summer than would be expected in winter, and the model sensitivity to uniform changes in potential evapotranspiration would likely be less than the sensitivity to uniform changes in rainfall.

SOILMOD somewhat overestimated the recharge under grass and the *SWIM*© model slightly underestimated it. Since neither of the models account for macropore flow, the *SWIM*© estimate is probably more reliable in this case.

Both models significantly underestimated recharge when the lysimeters were in bare soil, with *SWIM*© again providing lower recharge totals. This under-estimation is not surprising for either model, since there were no plants to transpire water and the exposure of the soil directly to the atmosphere would probably have led to more severe desiccation of the surface layer and hence more cracking and macropore flow. It is assumed that the increase of macropore flow more than offset increased evaporation from the bare soil surface.

In autumn, for pasture, *SOILMOD* simulates recharge events that are not measured (Figs. 8 and 10), whereas for bare soil (Fig. 9) this model tends to miss events occurring early in the recharge season. Conversely, *SWIM*© represents these early recharge events very well for grass (Figs. 12 and 14) but misses them markedly under bare soil conditions (Fig. 13).

The underestimation of recharge through bare soil by both models over five years depicted in Figures 9 and 15 can be compared with the increase of measured annual recharge for lysimeter A under bare soil, compared with pasture, shown in Figure 3.

SOILMOD is computationally more efficient than *SWIM*© by an order of magnitude, a factor to be considered if they are to be incorporated in regional models of natural recharge.

Conclusions

The lengthy Winchmore rainfall and recharge data sets provided a unique opportunity to rigorously evaluate soil moisture models as means of estimating natural ground water recharge. Both *SOILMOD* and *SWIM*© performed well, although they are conceptually quite different. The additional complexity of the three-layer Calder model failed to provide the expected improvement over the simpler *SOILMOD*. The Groves model, though providing reasonable estimates of soil moisture conditions, did not produce good drainage estimates.

It should be kept in mind though that these evaluations have been carried out for only one soil type and at a site with 730mm average annual rainfall and 765mm average annual potential evapotranspiration.

The main limitation in using these models is the difficulty of measuring the rainfall hitting the ground, as both successful models are very sensitive to rainfall input. If the available rainfall record can be assumed to be an index of the amount hitting the ground then either model can be modified quite simply to allow for this.

Neither *SOILMOD* nor *SWIM*© are very sensitive to soil moisture characteristics. Both seriously underestimated recharge when the lysimeters were under bare soil. This may be due to shrinkage and cracking of the exposed soil resulting in greater macropore flow, but there is a need for better understanding of evaporation from bare soil surfaces and moisture movement beneath them. With this knowledge the modelling of recharge through bare soils could be advanced. A new algorithm to describe evaporation from bare soil may be needed and would be fairly easy to write into *SOILMOD*.

Lysimeters similar to those at Winchmore can be constructed quite cheaply with modern equipment and materials, and data collection and processing is now far cheaper and better. Such facilities should be regarded in the same light as a stream-gauging site i.e. as a basic means of collecting hydrological data. Initially at least a network of recharge measurement sites should be seriously considered. Ultimately, as confidence develops in recharge modelling, networks could be reduced to a minimum necessary for calibration checks on any model.

Ideally, the area of a lysimeter should be large compared to the scale of the surface micro-topography or there should be duplicate lysimeters.

Based on the above research there is now a practical prospect of developing regional models of recharge from precipitation that will be of practical use to water resource managers.

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