1-11-1998

Modelling direct episodic recharge in the Western Australian wheatbelt

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Cooperative Research Centre for Catchment Hydrology (Australia)

ISSN 0729-3135
November 1998

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Resource Management Technical Report No. 168

Disclaimer

The contents of this report were based on the best available information at the time of publication. It is based in part on various assumptions and predictions. Conditions may change over time and conclusions should be interpreted in the light of the latest information available.

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Acknowledgments

Dr Glen Walker suggested the study described in this report, and commented on the manuscript. Dr Ian Foster supplied evaporation data and reviewed the report. Ashleigh Kennett-Smith supplied the program code. The author was funded by both Agriculture Western Australia and the Cooperative Research Centre for Catchment Hydrology.

Abstract

In agricultural regions of Western Australia, salinity is spreading. This is because the area taken up by groundwater discharge is increasing as a result of increased groundwater recharge following the replacement of native vegetation systems by annual crops and pasture species. Attempts to reduce groundwater recharge are now being made as it is hoped that this will decrease the rate of land salinisation. At several sites, average recharge rates have been estimated to be from 2 % to 13 % of the average annual rainfall. Such estimates of average rates imply that recharge occurs in relatively small amounts and lead to suggestions that recharge can be reduced significantly by increasing the amount of water used by the annual crops and pastures. However, groundwater hydrographs from the agricultural regions indicate that at some sites recharge does not occur as small amounts every year in a regular manner, but as infrequent, unpredictable, relatively large 'episodic' events. At such sites, relatively small increases in the water use of annual crops and pastures are unlikely to have a significant effect on the magnitude of large episodic pulses of recharge.

Little is currently known about the conditions which control whether recharge at a site is regular or episodic, but it is expected that the rainfall regime is important. As part of a study into episodic recharge in the wheatbelt of Western Australia, a simple water balance model was used to assess whether some of the rainfall regimes in the wheatbelt were more likely to result in episodic direct recharge than others, and how different soil types and rooting depths influenced the recharge regime. The occurrence of episodic recharge during the 33 years from 1960 to 1992 was compared at four locations in the Western Australian wheatbelt for a range of root depths (from 50 cm to 300 cm) for both annual winter and perennial plants. The effects of different soil types were also compared at one of the sites.

The results showed that episodic direct recharge could be generated under certain circumstances at each of the four sites modelled. The form of the impact of episodic recharge varied with rainfall and evaporation. Episodic recharge made up a larger proportion of the total recharge at the site with the lowest mean annual rainfall and greatest rainfall variability. In contrast, episodic recharge contributed the largest amounts of recharge at the site with the greatest average annual rainfall. And, under some circumstances (for example, for roots from 100 cm to 200 cm deep in loamy sand) the number of times episodic recharge occurred increased with increasing average annual rainfall.

Thus, it would be wise to assess the significance of episodic recharge at any wheatbelt site where treatment to reduce recharge is being considered. Aiming to reduce recharge by only the "average" annual amount each year may have little or no effect on the spread of salinity.

1. Introduction

1.1 Groundwater Recharge Regimes and Salinity

Groundwater recharge has increased in the south-west of Western Australia since land was cleared of native vegetation in order to establish agriculture (based on annual crops and pastures). The increase in recharge has caused groundwater levels to rise and the area of land affected by groundwater discharge to increase. Most areas, which have become sites for groundwater discharge have developed salinity problems and cannot now be used for traditional agriculture. Attempts to reduce recharge are now being made as it is hoped that this will decrease the rate of land salinisation.

Average recharge rates have been estimated for a few sites in the Western Australian wheatbelt and these were summarised by Nulsen (1993). He found the estimates were from 2 % to 13 % of the average annual rainfall which ranged from 330 mm to 460 mm. Using average annual values for recharge has given the impression that during most years relatively small amounts of recharge occur in a regular manner.

If recharge does occur in relatively small regular amounts then it is thought possible that recharge can be reduced significantly by increasing the amount of water used by the annual crops and pastures. However, groundwater hydrographs from the agricultural regions indicate that at some sites recharge is not regular but episodic, that is, it occurs as infrequent, unpredictable, relatively large events. At such sites, relatively small increases in the water use of annual crops and pastures are unlikely to have a significant effect on the magnitude of large episodic pulses of recharge.

1.2 What Conditions Control Recharge Regimes?

Little is currently known about the conditions which control whether recharge at a site is regular or episodic, but it is expected that the rainfall regime is important. It is not known whether the gradual changes in rainfall regime across the wheatbelt are sufficient to generate differences in the significance of episodic recharge from one region to another. As part of a study into episodic recharge in the wheatbelt of Western Australia, a simple water balance model (WATBAL) was used to assess whether some of the rainfall regimes in the wheatbelt were more likely to result in episodic direct recharge than others, and how different soil types and rooting depths influenced the recharge regime. (Direct recharge is that which results from vertical percolation of in situ rainfall as opposed to indirect recharge which results from lateral movement of surface or shallow subsurface water before percolation to the groundwater system.)

The original WATBAL code (Keig and McAlpine 1969) used weekly precipitation and evapotranspiration figures to calculate changes in soil water storage in the active soil zone and the excess water generated when that zone was full. Cook and Walker (1990) adapted the model to use daily rain and evaporation data. The only other data the model requires are the maximum soil water storage in the active zone and a soil parameter. The model calculates the difference between a day's rainfall and evapotranspiration and if there is a rain excess, it is added to the soil water storage. If the soil water storage becomes full, then the excess is considered to become recharge.

If the evapotranspiration requirement cannot be satisfied by the day's rain, then it is taken from the soil water store.

Although the model is a very simple one and does not take into account many hydrological processes such as interception, run offer run on, ponding, preferred pathway flow, or soil hydraulic conductivity, it has been found to be useful, for example, for identifying soil moisture and pasture growth patterns, (Keig and McAlpine 1974) and the effects of soil type, rainfall and rooting depth on groundwater recharge (Cook and Walker 1990; Kennett-Smith et al. 1994). Both Cook and Walker (1990) and Kennett-Smith et al. (1994) found good general agreement between point measurements of recharge made in the field and the results of the model. They also used the model to investigate the temporal variability of recharge at a site.

In this study the model was used to compare the occurrence of episodic recharge during the 33 years from 1960 to 1992 at four locations in the Western Australian wheatbelt (Figure 1). A range of root depths (from 50 cm to 300 cm) for both annual winter and perennial plants were modelled at each site, and at the centrally located one, Corrigin, the effects of different soil types were also compared. As stated above, the aim was to determine whether the different rainfall regimes at the four sites could all lead to episodic recharge regimes, and the influence of root depth and soil type on the recharge regime.

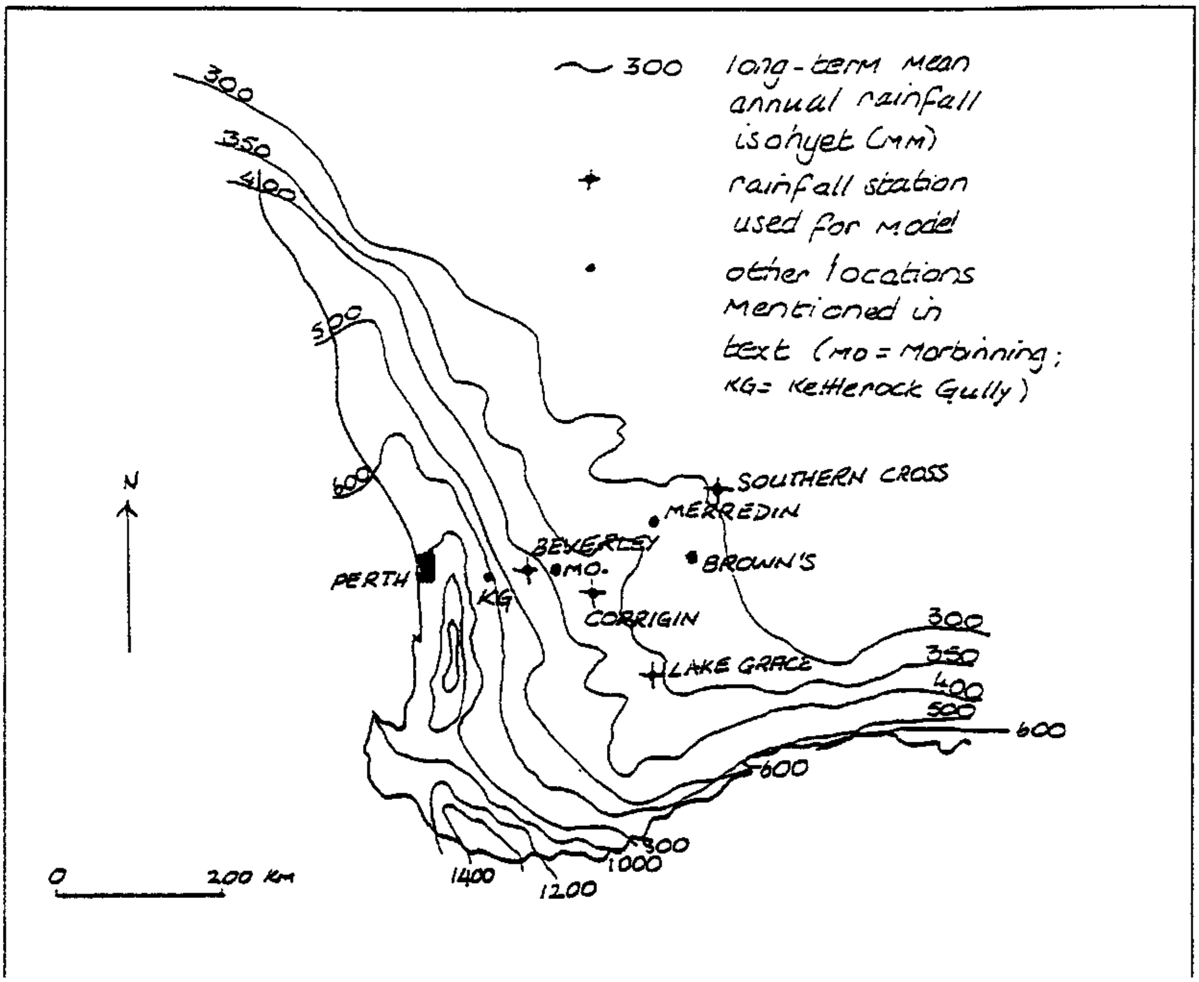


Figure 1: Locations of places mentioned in text and rainfall isohyets for south-western Western Australia

2. Model Inputs

2.1 Rainfall

Bureau of Meteorology rainfall records provided with the TACT computer program (Robinson and Abrecht 1993) were used. Runs of WATBAL were carried out with rain data from 1960 to 1992 for recording stations at Beverley, Corrigin, Lake Grace and Southern Cross (Figure 1). These stations were chosen because their rainfall records were complete and they provided good geographical coverage of the central wheatbelt. Mean annual rainfall for the 33-year period ranged from 407 mm at Beverley to 318 mm at Southern Cross.

2.2 Evaporation

Daily mean evaporation figures for the four locations were obtained from the ESOCLIM computer program (Centre for Resource and Environmental Studies, Australian National University, Canberra) which calculates mean smoothed daily pan evaporation for sites given their latitude, longitude and elevation. Therefore the evaporation figures used in the WATBAL model did not vary from year to year. Annual evaporation was 1936 mm at Beverley, 2027 mm at Corrigin, 1854 mm at Lake Grace and 2428 mm at Southern Cross.

2.3 Actual Evapotranspiration

WATBAL uses an estimate of actual evapotranspiration (AET) to determine the amount of water to be deducted from the daily balance. The AET is a proportion of the potential evapotranspiration (PET), and this proportion is called "the actual evapotranspiration coefficient" (AETCF). The PET was assumed to be 80 % of the mean daily pan evaporation. The AETCF depends on the amount of water stored in the soil and a soil parameter (Cook and Walker 1990; Kennett-Smith et al. 1994) and ranges from the value of 1 at field capacity to 0 at wilting point. The soil parameter (SP) determines how the AETCF changes with changing amount of stored water in between these end points:

$$AETCF = \frac{1-e^{(-SP \times FMS)}}{1-e^{(-SP)}}$$

where FMS is the amount of water in storage as a fraction of the maximum able to be stored (see Section 2.4 below). Cook and Walker (1990) compared the effects of three different soil parameters (3.5, 5.0, 7.4) and found that the WATBAL estimate of recharge was relatively insensitive to AETCF function because the recharge usually occurred when soil storage was full and thus evapotranspiration was at the PET rate (AETCF =1.0 under all three functions). At the start of this study, model runs were made using the same three parameters and they confirmed that the results were relatively insensitive to the soil parameter value. So all of the results presented are from modelling runs which used a value of 5.0 for the soil parameter.

2.4 Soil Water Storage

The model requires the maximum soil water storage (MAXST) available in the active zone. The active zone is the depth over which water abstraction by evapotranspiration takes place.

MAXST varies with soil type as it is the difference between the water contents at field capacity and wilting point.

For this study the WATBAL code was adapted to model a "two bucket" system. The original code represented one '"bucket" which was filled by rain and emptied by evapotranspiration and any overflow of water was considered to be recharge. In the two bucket model, evapotranspiration was only allowed to occur from the first bucket. The "depth" of this bucket reflected the active depth for bare soil evaporation during summer, then increased during the annual plants' growing season, and decreased again following senescence (Figure 2). (Details of growth stages are described in a following paragraph.) Any overflow from the first bucket was stored in the second bucket and became available for evapotranspiration once the active zone deepened. Any overflow from the second bucket was considered to be recharge. The sum of the maximum total storage available in the two buckets remained constant throughout the year and depended on the soil type and the maximum active depth being modelled.

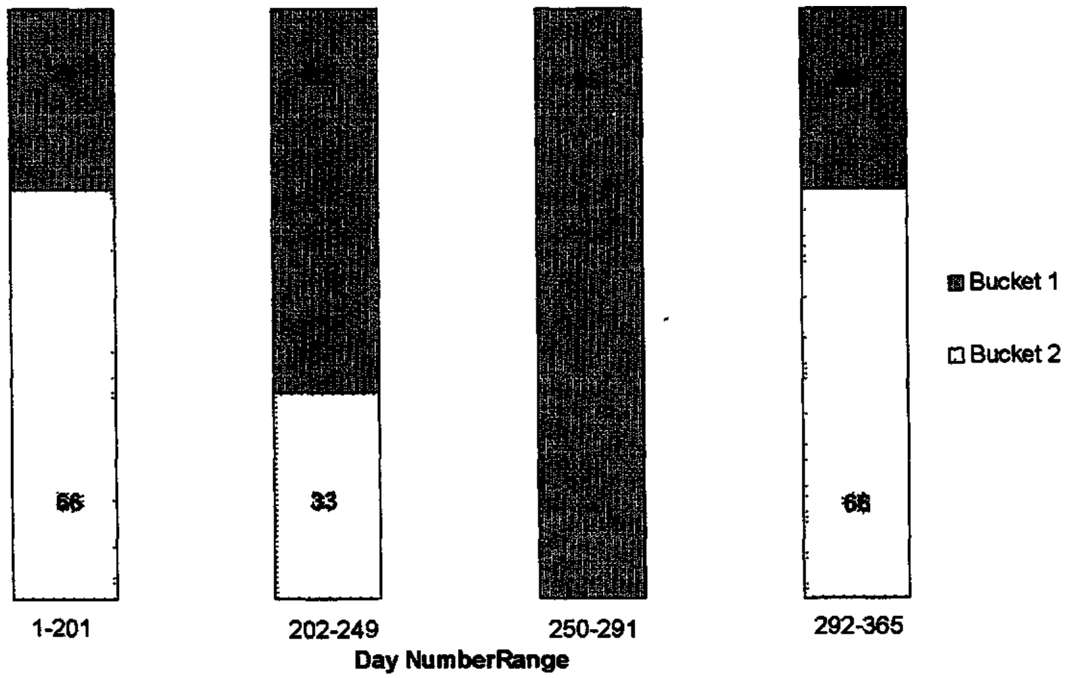


Figure 2: Changes in maximum available soil water storage (in mm) during a year for Buckets 1 and 2 for Soil-Root Model 1 with maximum root depth of 150 cm

The four sites were modelled using soil water storages relevant for loamy sand soil profiles, and deep sand and sandy loam soils were also modelled for the central site, Corrigin. Since the model did not account for runoff or low soil hydraulic conductivities, it was considered inappropriate to try to model a soil with a higher clay content than a sandy loam.

This study modelled a range of maximum active depths (50 cm, 100 cm, 150 cm, 200 cm, 300 cm), equivalent to a range of annual crop and pasture species. The roots were modelled to grow to their maximum active depth in stages. Different stages were used for different soil types, and were derived from maximum rooting depths measured by Hamblin and Hamblin (1985) in "deep loamy yellow earth" (called "loamy sand" in this report) and root growth data collected by Tennant (1976) for wheat roots in "deep sand" and "sandy loam". The stages are listed in Table 1. Hamblin and Hamblin (1985) did not measure the roots at intermediate growth stages so stages were chosen which reflected the early time of sowing of their experiments and were conservative in relation to excess soil water (the roots reached maximum depth quickly).

Table 1: The stages of root growth used for the three soil types modelled

Deep Sand		**Loamy Sand**		**Sandy Loam**	
Day of year	**Stage**	**Day of year**	**Stage**	**Day of year**	**Stage**
1	(start of year, January 1)	1	(start of year, January 1)	1	(start of year, January 1)
151	time of sowing	175	time of sowing	175	time of sowing
201	roots reach 50cm	231	roots reach 50cm	231	roots reach 50cm
202 – 249	roots grow to maximum depth	232 - 245	roots grow to 75 cm (except for 50cm maximum cases)	232 - 239	roots grow to 75 cm (except for 50cm maximum cases)
250 – 291	roots remain at maximum depth	246 - 294	roots grow to maximum depth	240 - 294	roots grow to maximum depth
292	roots no longer use water	295	roots no longer use water	295	roots no longer use water
365	end of year	365	end of year	365	end of year

The efficiency of water removal from the soil by either evaporation or transpiration may decrease with depth. However, in order to simplify the process for the model, it was assumed that all water within the current active depth was equally available for removal by evaporation or transpiration. For the cases where winter annual crops and pastures were modelled a MAXST equivalent to a depth of 50 cm was used outside the growing season. It is acknowledged that evaporation during the summer could affect soil deeper than this but to compensate, no reduction in water removal with depth was used. For the various root growth periods, water was also allowed to be removed from any depth of the top bucket equally. The available soil water storage of the buckets was made equivalent to the storage to the maximum depth of the roots for that growth period with no adjustment for the increasing difficulty of withdrawal with depth. This was one of the features, which made the modelling conservative with regard to recharge.

It has long been recognised that perennial plants can use more water than annuals, and one reason given for this is their ability to use rain that falls outside the period that annual crops and pastures use water (see Nulsen (1993) for example). To assess the effect of replacing annual with perennial plants on the generation of episodic recharge, perennials were modelled by making the maximum soil water storage available all year for each of the maximum active depths.

Soil water storages for loamy sand soils (ranging from 52 mm/m to 66 mm/m from the top of the profile to the bottom) were based on figures in Hamblin and Hamblin (1985). Soil water storages for deep sand and sandy loam soils were derived by using Tennant's (1976) figures for clay content down the deep sand and sandy loam profiles to calculate the maximum water storage from the relationships given in Kennett-Smith et al. (1994). The figures ranged from 38 mm/m to 68 mm/m down the deep sand profile and 108 mm/m to 165 mm/m down the sandy loam profile.

Combining the root growth stages with the soil water storages produced three "Soil-Root Models" - SRM1 (for deep sand), SRM2 (for loamy sand) and SRM3 (for sandy loam). The storages in the two "buckets" for each of the maximum active depths at the different root growth stages were than calculated.

3. Results

In addition to the results specific to episodic recharge, the modelling indicated some general points about recharge. These are presented first to provide a background to the results on episodicity (which are in Sections 3.3 to 3.7).

The general points (which are presented in detail in the following two sections (3.1 and 3.2)), show that, in line with expectations:

- total recharge increased with increasing mean annual rainfall and with decreasing root depth and soil clay content;
- most recharge was generated during the early part of winter but there were a few large summer recharge events;
- the amount of recharge from year to year was highly variable for most cases modelled;
- no recharge was generated in some of the model runs that had relatively high soil water storage or low rainfall over the 33 years for which the water balances were calculated.

3.1 General Recharge Patterns

As an indication of the general nature of recharge events the results for Corrigin SRM2 are presented in Table 2 and show that:

- even roots 300 cm deep did not prevent recharge being generated;
- both more recharge events and larger ones were generated below shallow roots than below deep roots;
- on average, even below shallow roots there were only about five recharge events per year;
- the annual amount of recharge was highly variable even for short roots;
- recharge events for the longer roots were clearly of an episodic nature (for 300 cm roots there were only six events and they occurred during only two of the 33 years).

Monthly totals for the 33 years for the 50 cm root case showed that 56 % of the recharge was produced during the months of June and July when only 33 % of the rain fell (Figure 3). Ninety-eight percent of the total recharge was generated during the months from the start of January to the end of August and the further 20 % of rain only contributed 2 % of the recharge. The number of events which generated recharge during the summer months was small but the amount of recharge per event was greater than during winter. The amount of recharge generated in April was low because rain events were smaller than during the earlier months and fewer than during the succeeding months. Of the ten largest recharge events between 1960 and 1992 (which constituted 6 % of the total number of events but produced 27 % of the recharge), four occurred from January to March and six occurred from June to August. Recharge events during January and February lasted only 1 day.

Table 2: General characteristics of recharge events* for Corrigin Soil-Root Model 2

Maximum root depth in cm	No. of recharge events	Total recharge 1960-1992 in mm	Mean recharge per event in mm	Mean no. of recharge events per year (range)	Mean annual recharge in mm (range)	No. of years in which there was recharge
50	158	1836	11.6	4.8 (0 - 14)	55.6 (0 - 147)	32
100	90	941	10.5	2.7 (0 - 12)	28.5(0-115)	23
150	49	400	8.2	1.5(0-11)	12.1(0-83)	10
200	29	184	6.4	0.9 (0 - 9)	5.6 (0 - 58)	6
300	6	35	5.8	0.2 (0 - 4)	1.1(0-27)	2

* - an "event" was defined as starting when a day with recharge followed one without, and ending when a day of recharge was followed by one without.

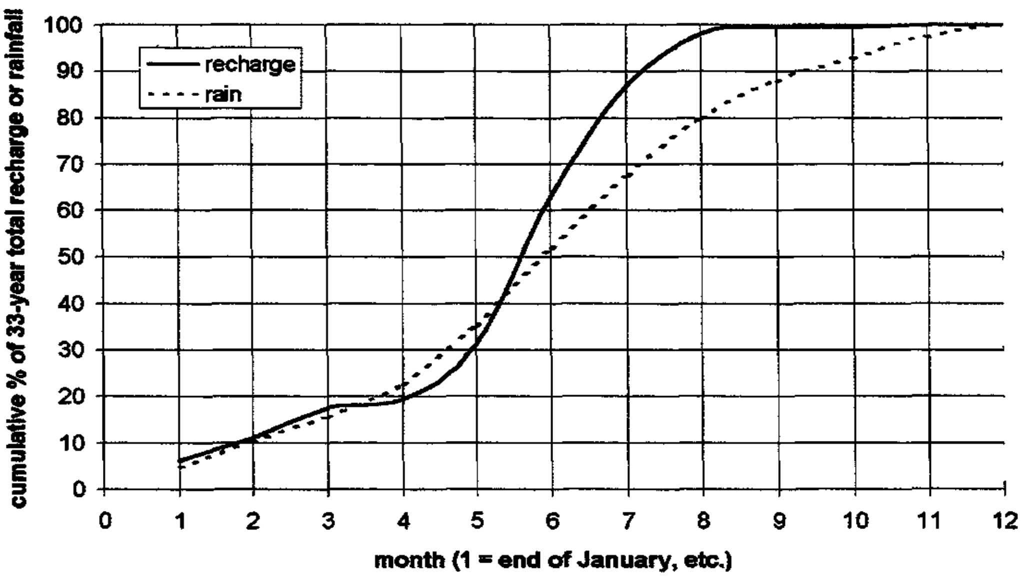


Figure 3: Cumulative % of 33-year total recharge and rain by months, Corrigin SRM2 with 50 cm roots

3.2 General Rain:Recharge Relationships

3.2.1 Annual rain and annual recharge

There was a large range in the recharge generated by a particular annual rainfall. For example, at Lake Grace for SRM2 and 50 cm roots, 300 mm rain in a year produced between 0 and 50 mm recharge. But if annual rain was greater than about 320 mm then recharge was always produced.

Similarly, there was a large range in the amount of annual rainfall resulting in a certain amount of recharge. For 50 cm deep roots for Southern Cross SRM2, 370 mm of rain in 1968 produced more recharge (110 mm) than 577 mm of rain in 1963 (97 mm). The 1968 recharge was nearly double that of 1963 as a percentage of rainfall (29.7 % as opposed to 16.8 %). The difference was related to the spread of rainfall in the two years: in 1968 the recharge occurred over 23 days while in 1963 it was spread over 88 days.

Therefore, annual rainfall was not a very good guide to the amount of recharge, which was generated. Figure 4 shows that for roots 50 cm deep, annual recharge versus annual rainfall points fell within a broad band. The upper boundary shows that in the years with relatively high recharge there was a rainfall threshold of about 170 mm. Through the middle of the band, about 270 mm of rain was required to generate recharge, and at the lower boundary of the band there was recharge after about the first 380 mm of rain. Above the thresholds about 50% of the rain became recharge. The different rainfall thresholds resulted from different rainfall conditions. It seems that the modelled results fall in the middle of a spectrum of behaviours which extends from one extreme end case where a year's rain falls in one day, and, at the opposite end of the spectrum, where the daily evapotranspiration could keep up with all the rain that fell throughout the year. The two end cases describe what could occur under extreme episodic rainfall and extreme regular rainfall regimes, respectively.

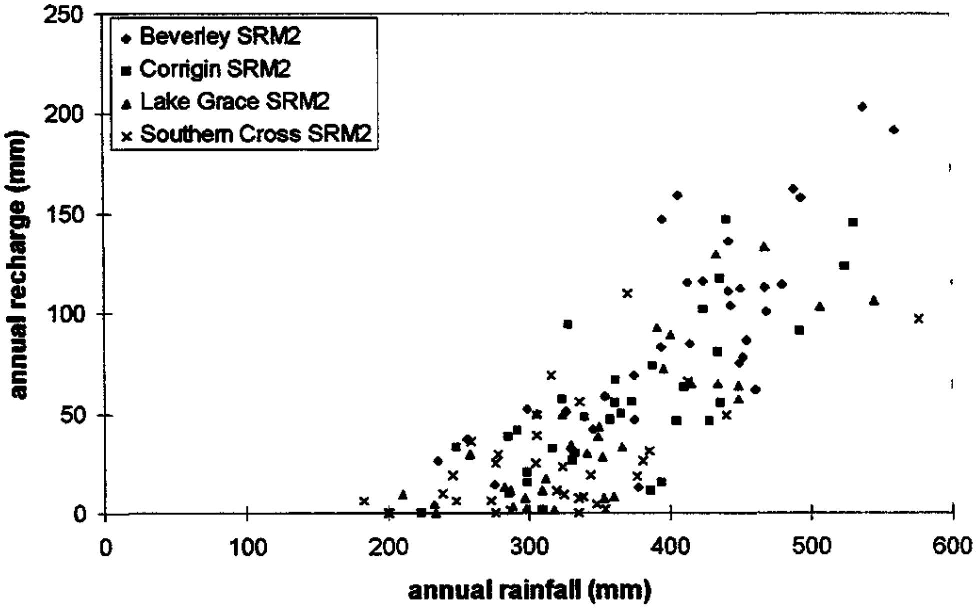


Figure 4: Annual recharge versus annual rainfall for 50 cm deep roots, 1960 to 1992

Figure 4: Annual recharge versus annual rainfall for 50 cm deep roots, 1960 to 1992

3.2.2 Mean annual rain and mean annual recharge

In Figure 5 the mean annual recharge has been plotted against the mean annual rainfall for the range of root depths for the four rainfall stations and Soil-Root Model 2. Lines marking the mean annual recharge as a percentage of the mean annual rainfall have been overlain to illustrate the range in values. This shows that the proportion of recharge to rainfall increased with rainfall and infers that making predictions of how much recharge occurs at a site based on the mean annual rainfall is even less valid for high rainfall areas than for low rainfall ones.

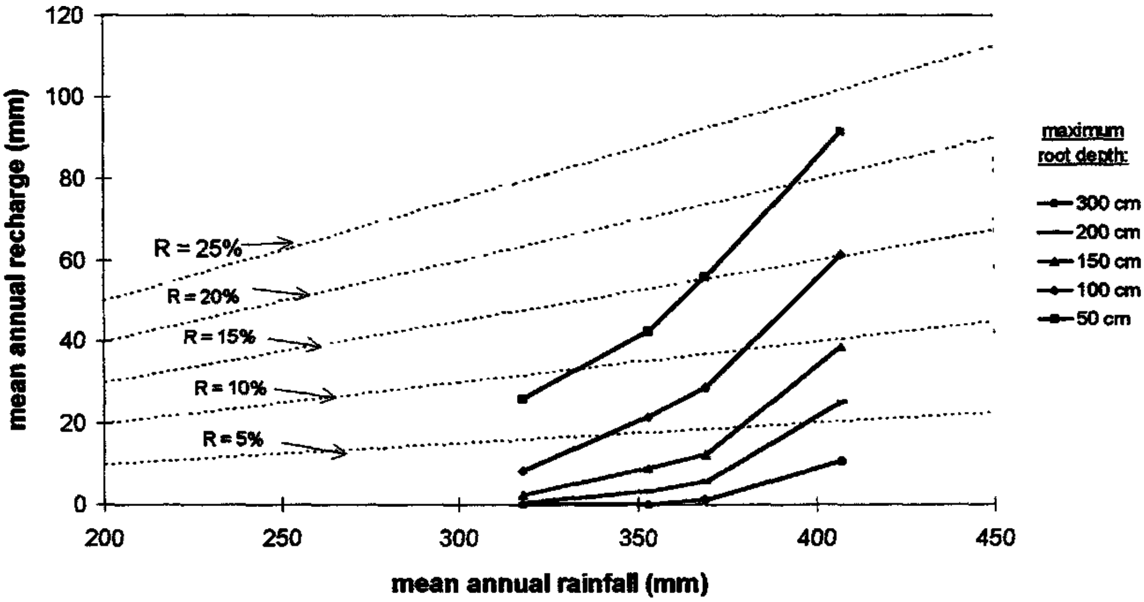


Figure 5: Mean annual recharge versus mean annual rainfall for the range of root depths for four rainfall stations, SRM2 (R - mean annual recharge as % of mean annual rainfall)

For different soil types at the same site, Figure 6 shows that mean annual recharge as a percentage of mean annual rainfall ranged from less than 1 % to nearly 16 %.

3.3 Defining Significant Episodic Recharge

Lewis (1997) described a simple method for determining whether a record of recharge contained any significant episodic events. It was based on the identification of step rises in graphs of cumulative recharge plotted against time. In a record of a regular recharge regime, the cumulative plot would rise steadily over the years, whereas a recharge regime which had significant episodic events would have noticeable irregular step rises (coinciding with the large episodic events) in the graph. Because some episodic step rises would be more important than others, a grading scale was developed which allocated a grade (decreasing in significance from grade 1 to 3) to a specific step rise. The grading scale is shown in Figure 7.

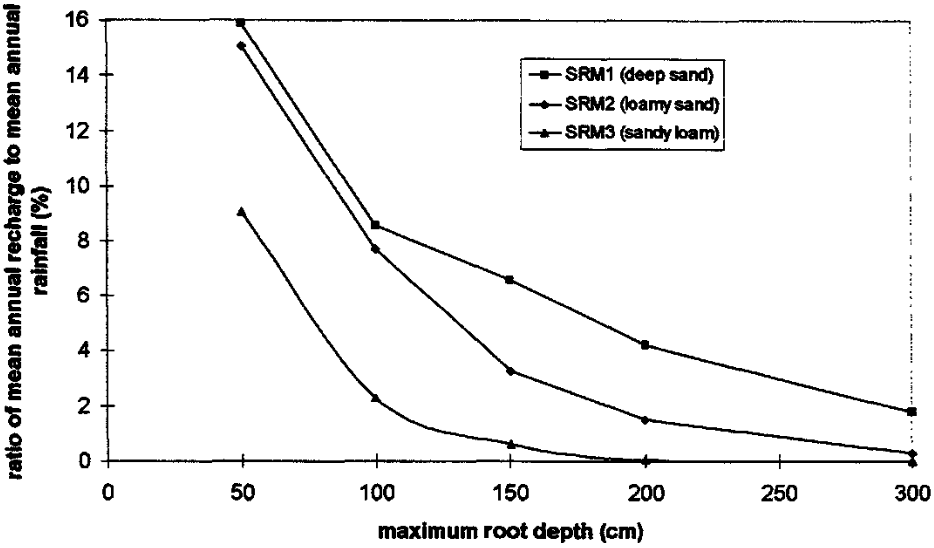


Figure 6: Effect of soil type on ratio of mean annual recharge to mean annual rainfall for a range of root depths at Corrigin

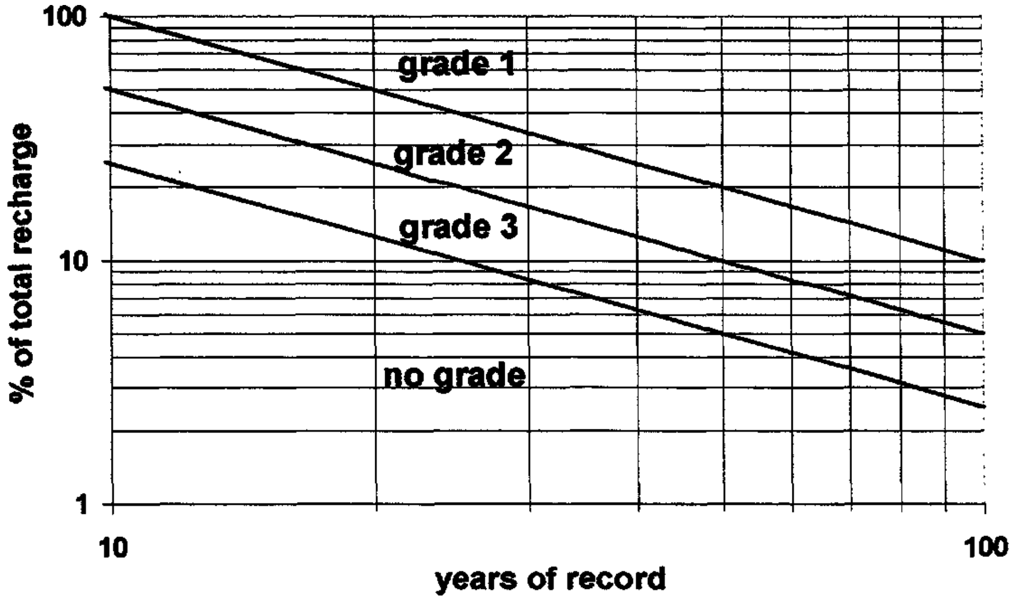


Figure 7: Grading scale for the significance of an episodic recharge step (from Lewis (1997))

The modelling results were plotted as cumulative recharge versus time graphs (Figure 8a-f). The graphs show the pattern of recharge generation over the 33 years, which were modelled. Although some of the large steps in the graphs in Figure 8a-f are due to single recharge events, most of the significant steps are the result of many closely spaced recharge events, usually during a particularly wet winter (where an "event" is defined as starting when a day with recharge follows one without, and ending when a day of recharge is followed by one without -so an event may be one or more days long). In some of the graphs recharge is clearly episodic in nature as there were only a few occasions during the 33 years when recharge occurred. In some other graphs, the slope of the line is more regular with just a few relatively large steps. In cases where there were very few recharge events, so that it could be argued that all were episodic, the grading scale in Figure 7 was used to identify those which were significant, and it is only those ones which are referred to as "episodic recharge" in the following analyses and discussions. Since the recharge results were for a 33-year period, a recharge step had to contribute at least 30.3 %, 15.2 % or 7.6 % of the total recharge to grade 1,2 or 3 respectively (Figure 7). Table 3 lists some of the major recharge steps for SRM2 at Corrigin and shows the grades of those considered to be significant recharge episodes, as an example.

In discussions of the results, the 'likelihood" of episodic recharge refers to the relative number of times episodic recharge occurred; for example, the likelihood of episodic recharge was greater for a site where there were six such episodes in a 3 3-year period than at a site where there were only two. The 'Importance" of episodic recharge refers to the relative proportion of the total recharge contributed by the episodes; for example, the importance of episodic recharge was greater at a site where episodic recharge made up 90 % of the total recharge than at a site where it made up only 30 %.

Where there was summer recharge, the decision of whether to add it to the recharge occurring later in the year was made on the basis of whether both recharge periods appeared to contribute to the same steps in the cumulative recharge graph or to different ones.

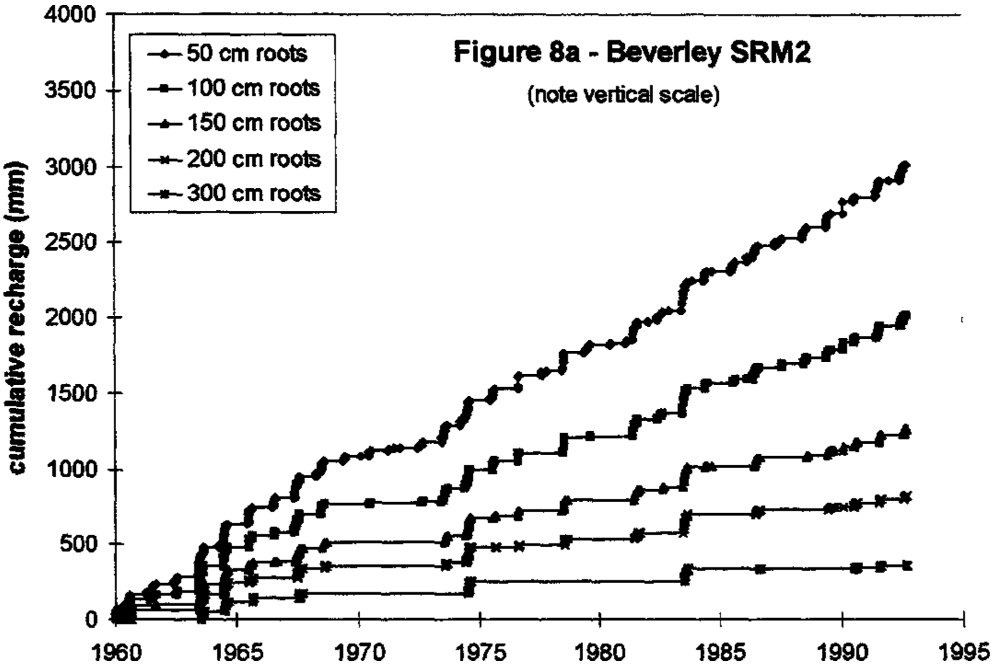


Figure 8a-f Cumulative recharge from 1960 to 1992 for five root depths

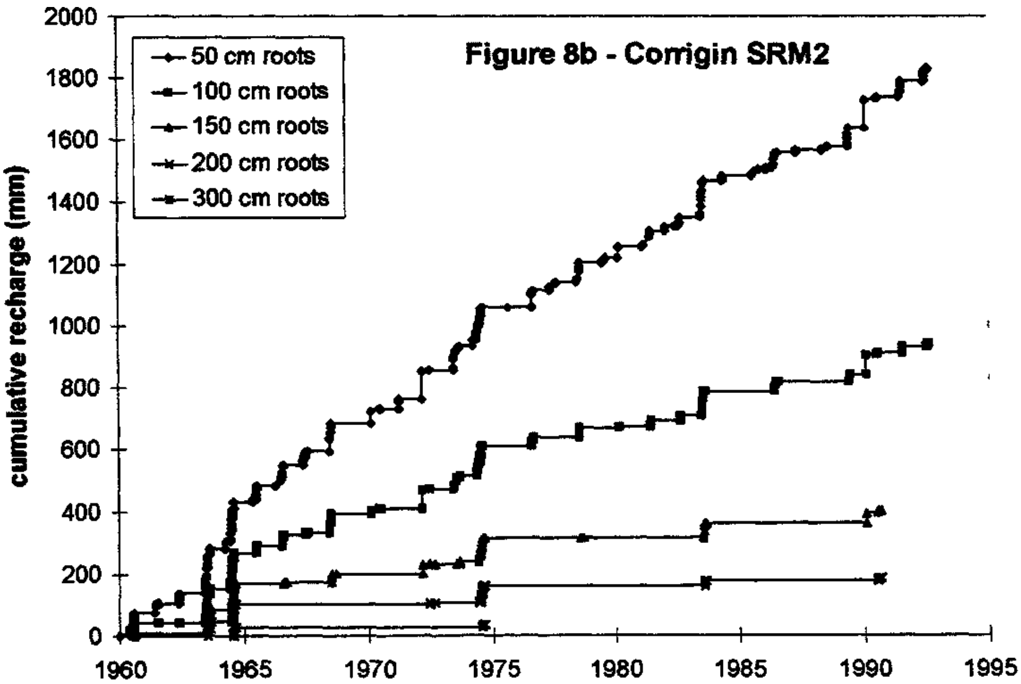
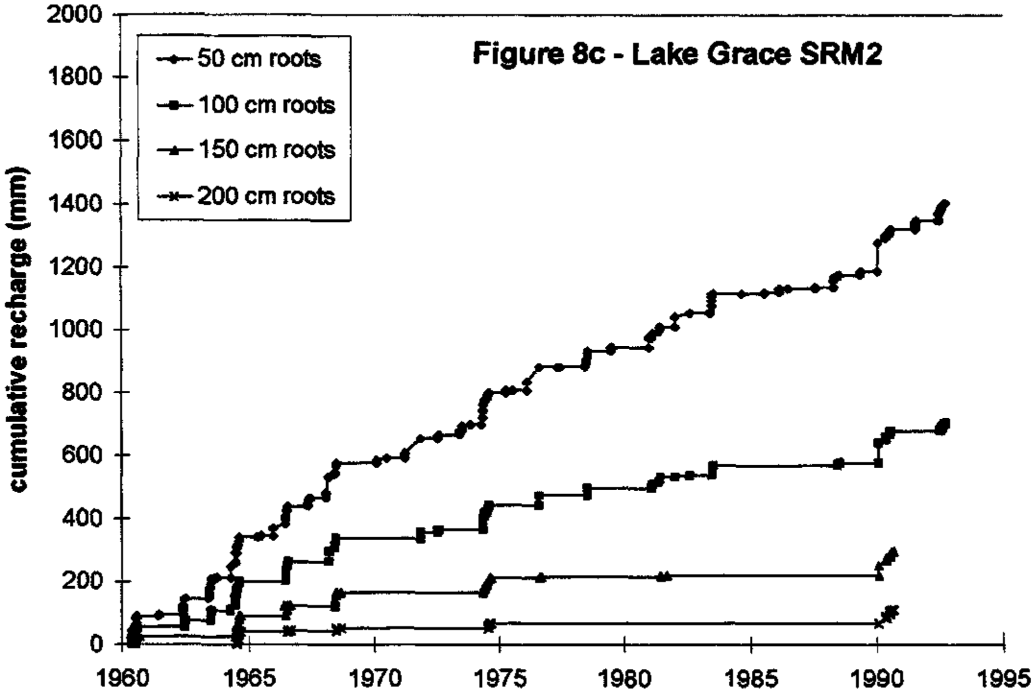


Figure 8a-f: Cumulative recharge from 1960 to 1992 for five root depths



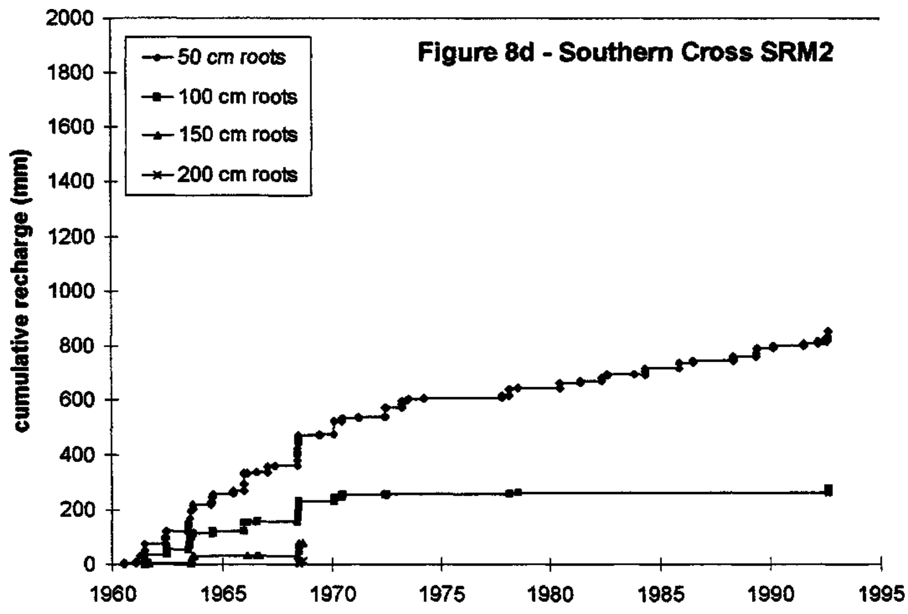


Figure 8a-f continued

Table 3: Details of the largest recharge steps for Soil-Root Model 2 at Corrigin

Root Length (cm)	Year	Months* when the recharge occurred	Duration of recharge episode (days)	Recharge amount (mm)	% of total 1960-1992 recharge	Episodic grade
50	1963	6,7,8	87	144.4	7.9	3
50	1964	4,6,7,8	124	146.6	8.0	3
50	1972	3	1	91.5	5.0	NG**
50	1974	4,5,6,7,8	131	122.4	6.7	NG**
50	1983	6,7,8	42	111.4	6.1	NG**
50	1990	1	1	92.1	5.0	NG**
100	1963	6,7,8	81	110.1	11.7	3
100	1964	6,7,8,	44	114.7	12.2	3
100	1972	3	1	59.3	6.3	NG**
100	1974	5,6,7,8	80	93.9	10.0	3
100	1983	6,7	32	78.7	8.4	3
100	1990	1	1	60.7	6.4	NG**
150	1963	7,8	52	77.1	19.2	2
150	1964	7,8	23	83.0	20.7	2
150	1972	3	1	28.1	7.0	NG**
150	1974	6,7,8	70	73.9	18.4	2
150	1983	7	22	47.6	11.9	3
150	1990	1	1	28.7	7.2	NG**
200	1963	7,8	43	45.4	24.6	2
200	1964	7,8	20	58.4	31.6	1
200	1974	7,8	41	54.0	29.2	2
200	1983	7	6	18.5	10.0	3
200	1990	7	5	7.2	3.9	NG**
300	1964	7,8	8	27.2	78.4	1
300	1974	8	8	7.5	21.6	2

* - January represented by 1, February by 2, etc.

** - NG = no grade (not a significant episodic recharge step)

3.4 How much of the total recharge generated was due to episodic recharge?

The results of the modelling runs show that where the mean annual recharge was greater than about 70 mm, episodic recharge was unimportant. Episodic recharge began to be important when the mean annual recharge was between 40 mm and 60 mm, and where the mean annual recharge was about 25 mm, then 50 % of the recharge generated was likely to be episodic in nature (Figure 9). (Because the model used is simplistic and the inputs were chosen to give conservative results with respect to the amount of recharge, the mean annual recharge values discussed above may be lower than in field situations.) For comparison, Barnes et al. (1994) assessed that the mean annual recharge in the area of central Australia that they were studying was about 20 mm and that all the recharge was episodic in nature.

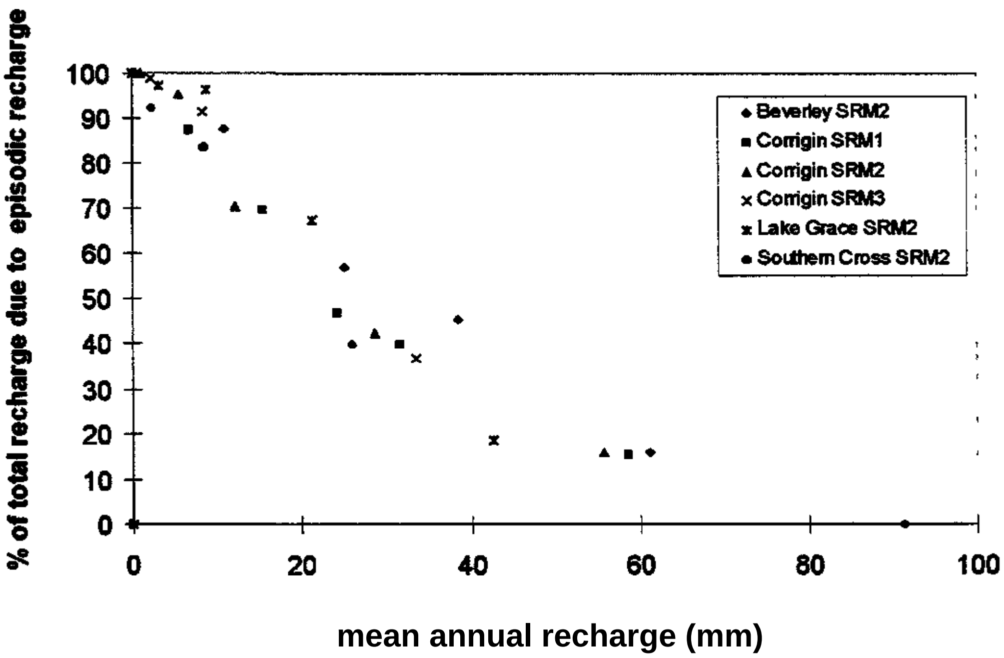


Figure 9: Percentage of total recharge due to episodic recharge versus mean annual recharge

The number of times that episodic recharge of each grade occurred for each model run are illustrated in Figure lOa-f, and Table 4 summarises the number of episodes and the percentages of the total recharge that they contributed.

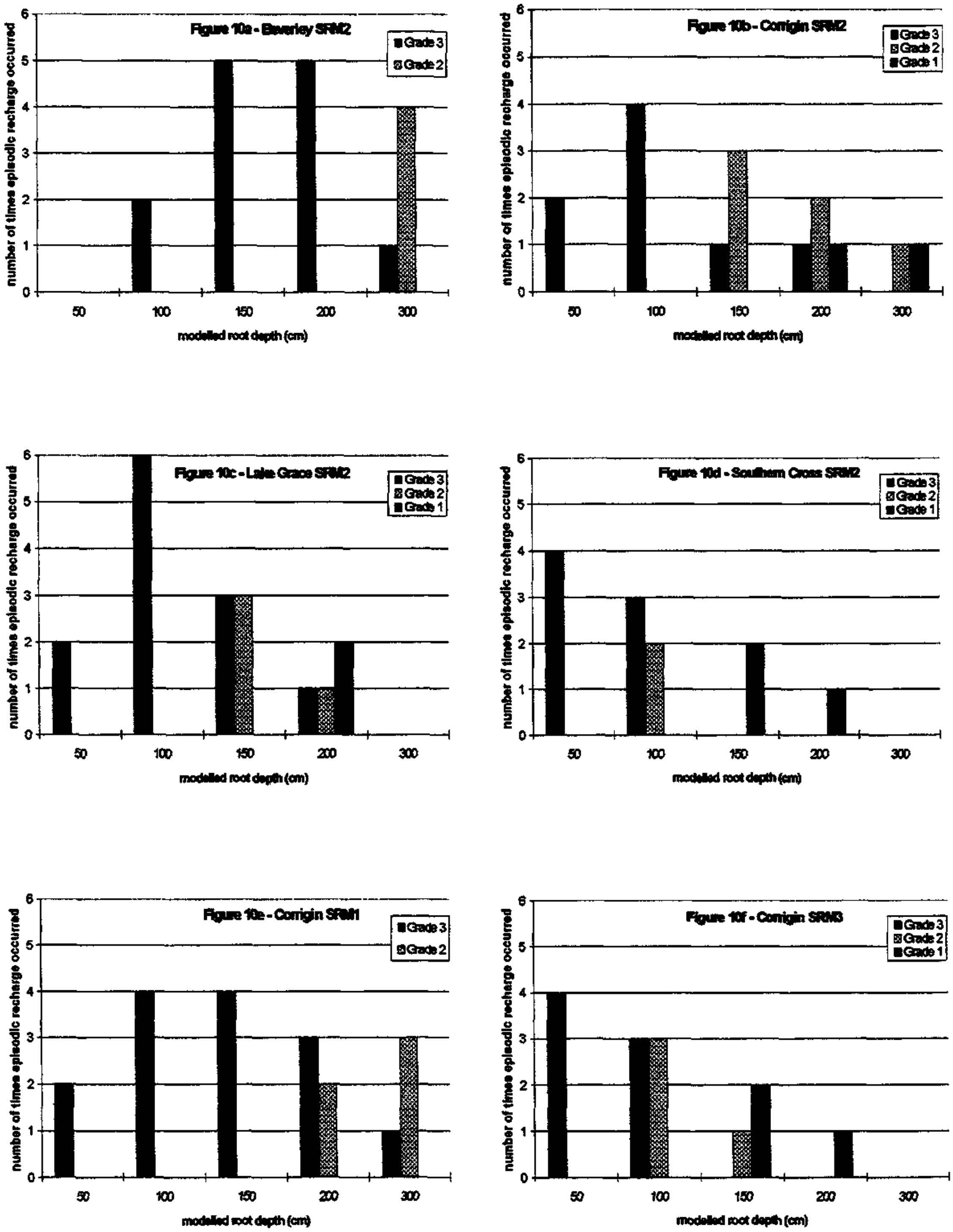


Figure lOa-f: Number of times episodic recharge occurred at each of five root depths

Table 4a: The number of times episodic recharge of all grades occurred (no. E) and the percentage of the total recharge (%) it contributed at each station modelled using Soil-Root Model 2

	Maximum Root Depth									
	50cm		100cm		150cm		200cm		300cm	
Station	**no.E**	**%**	**no.E**	**%**	**no.E**	**%**	**no.E**	**%**	**no.E**	**%**
Beverley	0	0.0	2	15.9	5	45.4	5	56.8	5	87.7
Corrigin	2	15.9	4	42.3	4	70.2	4	95.4	2	100.0
Lake Grace	2	18.7	6	67.2	6	96.5	4	97.2	NR*	NR*
Southern Cross	4	39.9	5	83.5	2	92.4	1	100.0	NR*	NR*

Table 4b: The number of times episodic recharge of all grades occurred (no. E) and the percentage of the total recharge (%) it contributed for each Soil-Root Model at Corrigin

	Maximum Root Depth									
	50cm		100cm		150cm		200cm		300cm	
Station and soil growth model	**no.E**	**%**	**no.E**	**%**	**no.E**	**%**	**no.E**	**%**	**no.E**	**%**
Corrigin SRM1	2	15.3	4	39.9	4	46.8	5	69.6	4	87.3
Corrigin SRM2	2	15.9	4	42.3	4	70.2	4	95.4	2	100.0
Corrigin SRM3	4	36.7	6	91.6	3	98.9	1	100.0	NR*	NR*

* - NR = no recharge

3.5 Effect of geographical location on generation of recharge

The inputs to the model which varied with location were rainfall and evaporation. Since the evaporation data, which were used, were the same from year to year, it was the rainfall data, which caused annual variations in the results. Table 5 shows that the mean annual rainfall decreased eastwards and the variability increased in that direction. Figure 11 shows that although there was much more winter rain in the west (Beverley) than the east (Southern Cross) and south-east (Lake Grace), (and that the rainy winter season finished earlier in the east) there was slightly more summer rain to the east and south-east. Totals for the four months from December to March from 1960 to 1992 (Table 6) increased from 1921 mm in the west (Beverley) to 2410 mm in the east (Southern Cross). Of the ten largest rain events at each site in the 33-year period, five of Southern Cross's occurred prior to May, while only three of Beverley's did. Summer rainfall events were less regular than winter ones and tended to be large and last only one day. During winters rain events were more frequent and were spread over a few days, so the large daily falls in winter tended to be smaller than the large daily falls in summer (Figure 12). Over the 33 years from 1960 to 1992, there were two years at each of Beverley, Corrigin and Lake Grace when rainfall was greater than 500 mm. At Southern Cross there was only one year, but the rainfall was the highest of all (577 mm in 1963).

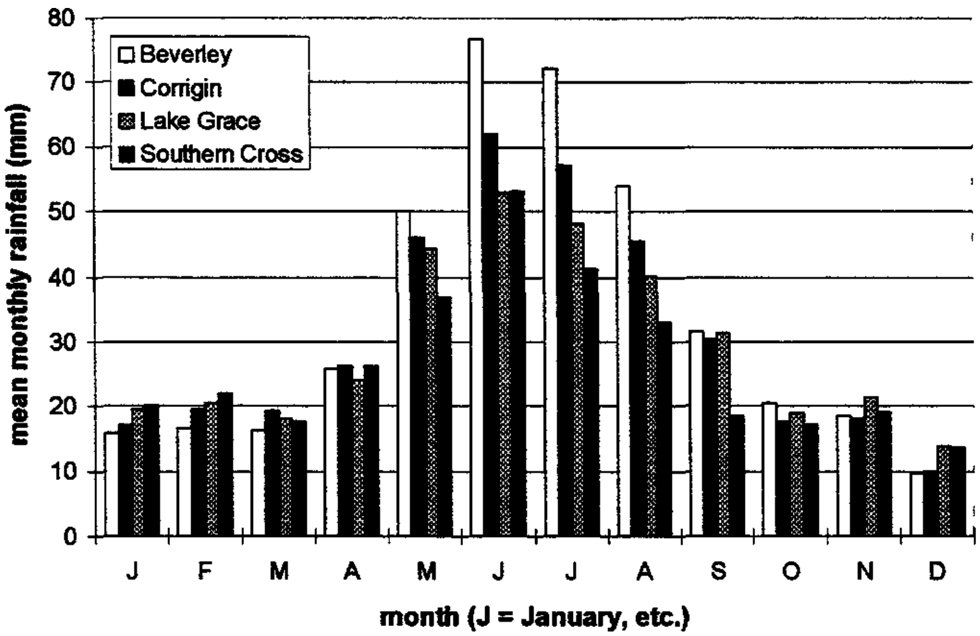


Figure 11: Mean monthly rainfall for 1960 to 1992 for the four stations modelled

Table 5: Mean, maximum and minimum annual rainfalls from 1960 to 1992 for the four stations modelled

Site	"Location" in wheatbelt	Mean annual rain 1960 - 1992 in mm	Maximum annual rain 1960 - 1992 in mm (year)	Minimum annual rain 1960 - 1992 in mm (year)
Beverley	west	407	560 (1963)	236 (1969)
Corrigin	central	369	531 (1963)	224 (1969)
Lake Grace	south east	353	545 (1968)	211(1972)
Southern Cross	east	318	577 (1963)	200 (1979)

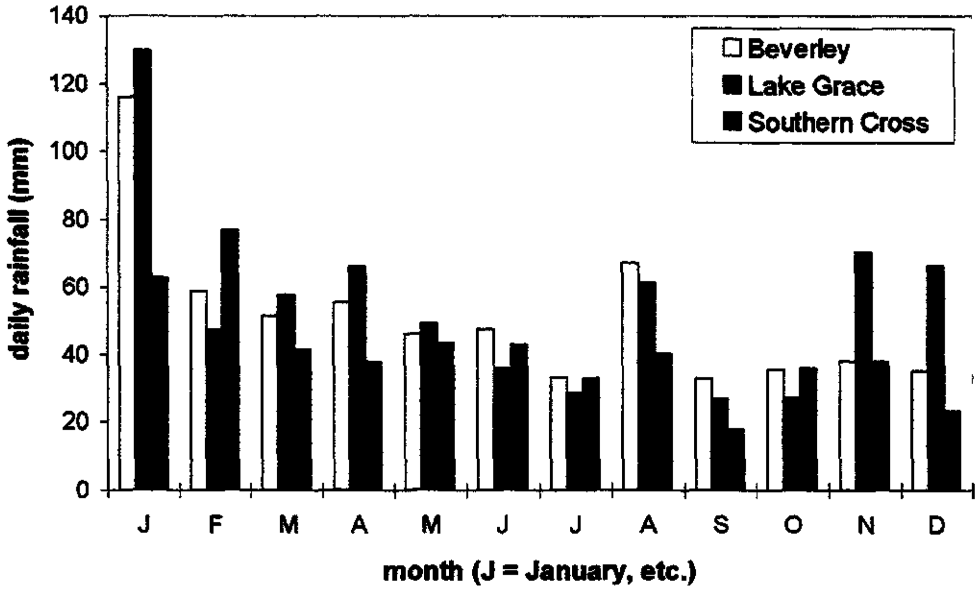


Figure 12: Maximum daily rainfall in each month for the period 1960 to 1992 for three of the stations modelled

Table 6: Comparisons of the December to March rainfall for the four stations modelled

Site	"Location" in wheatbelt	Total December, January, February, March rain, 1960 to 1992 (mm)	Total December, January, February, March rain as % of total 1960 to 1992 rain
Beverley	west	1920.9	14.3
Corrigin	central	2169.4	17.8
Lake Grace	south-east	2367.7	20.3
Southern Cross	east	2409.6	22.9

The decrease in total rainfall to the east and south-east was reflected in the amount of recharge generated (Table 7). The distribution of the recharge through the year also reflected the differences in the rainfall patterns from west to east (Figure 13 and Figure 14), with a higher proportion of the total recharge occurring during the summer at Southern Cross than at Beverley.

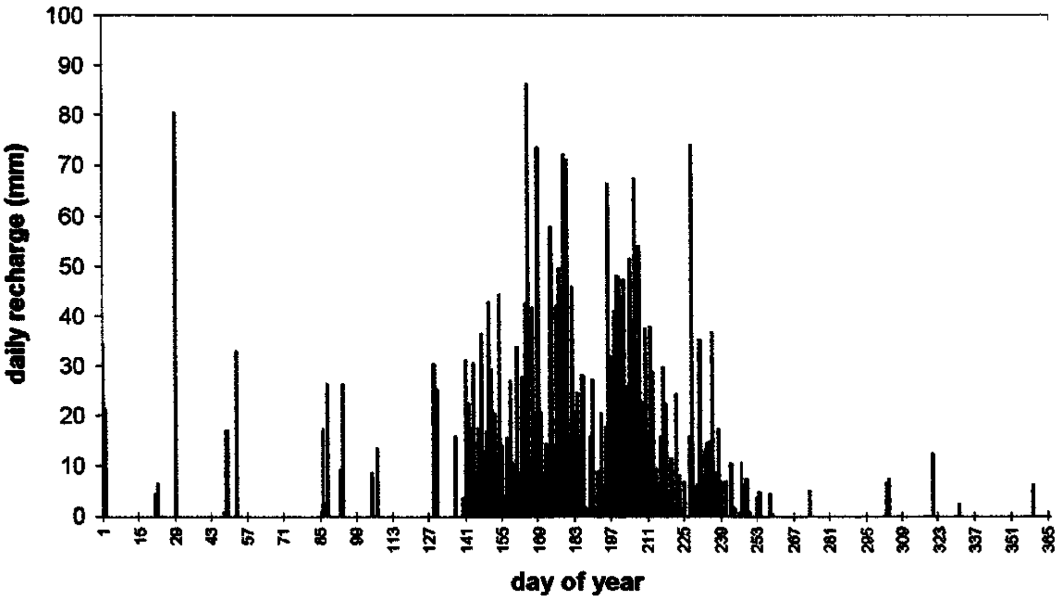


Figure 13: Total daily recharge for Beverley from 1960 to 1992 for 50 cm deep roots, SRM2

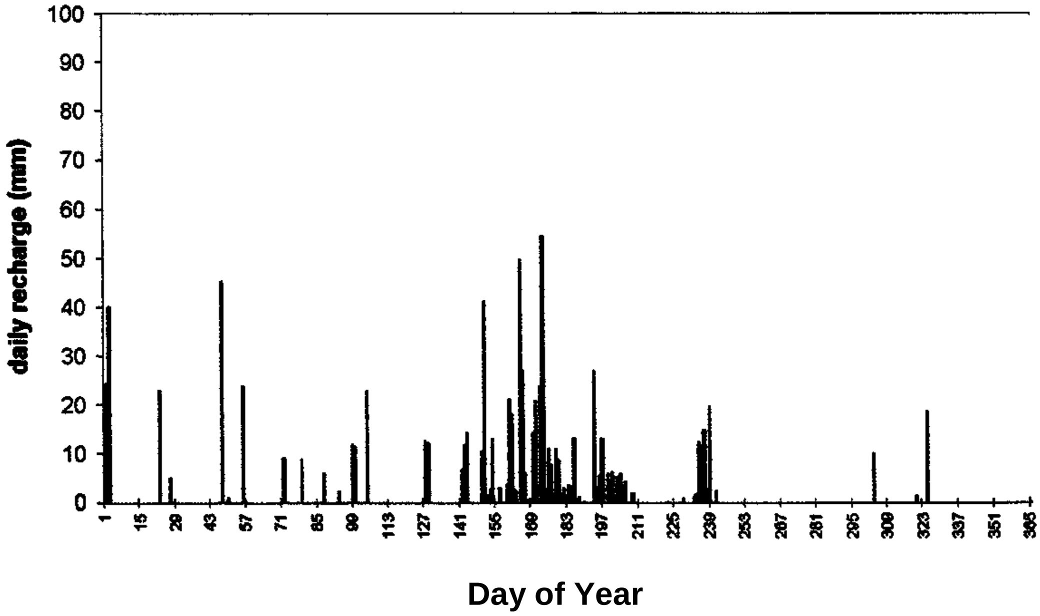


Figure 14: Total daily recharge for Southern Cross from 1960 to 1992 for 50 cm deep roots, SRM2

Table 7: Rain, recharge and episodic recharge for 150 cm deep roots and SRM2 at each of the four stations modelled

Location	Mean annual rain (mm) 1960-1992	Mean annual recharge (mm) 1960-1992	Number of times episodic recharge occurred	% of total recharge due to episodic recharge
Beverley	407	38.3	5	45.4
Corrigin	369	12.1	4	70.2
Lake Grace	353	8.9	6	96.5
Southern Cross	318	2.3	2	92.4

Rainfall amount and distribution also affected the importance of episodic recharge. Less of the recharge below a particular soil type in Beverley was episodic in nature than below a similar soil in Southern Cross (Figure 15). The importance of episodic recharge increased with decreasing mean annual rainfall; however, the number of significant recharge episodes in the 33-year period decreased eastwards but increased southwards (Table 7).

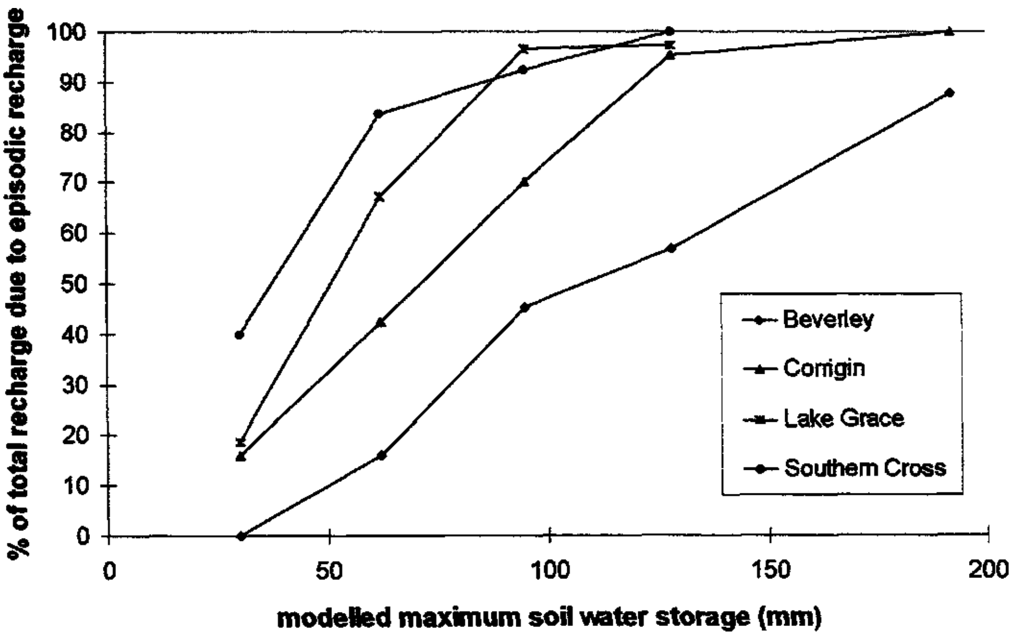


Figure 15: Percentage of total recharge due to episodic recharge versus modelled maximum soil water storage for SRM2 at four stations

Figure 16 is similar to Figure 9 except that only the SRM2 cases for the four stations are plotted and the points for each station have been joined by a line. This figure shows that this was a tendency for episodic recharge to be less important for a given amount of mean annul recharge at a lower rainfall site compared to a higher rainfall one. For example, if the mean annual recharge at a site at Southern Cross was 20 mm, then about 55 % of the total recharge was episodic, whereas at a site in Beverley with 20 mm mean annual recharge, about 68 % of the total recharge was episodic. This is because roots between 50 cm and 100 cm depth would result in a mean annual recharge of 20 mm at Southern Cross, whereas at Beverley, the roots would be greater than 200 cm deep, so the pattern of recharge is likely to be more regular at Southern Cross and more episodic at Beverley for the same mean annual recharge. However, the line for Lake Grace in Figure 16 does not follow the same trend. It does not lie neatly between those for Corrigin and Southern Cross as might be expected from its mean annual recharge. When mean annual recharge was less than about 35 mm, then episodic recharge was more important at Lake Grace than at Corrigin (this mean annual recharge corresponded to roots about 70 cm deep for Lake Grace and about 90 cm deep for Corrigin). The mean annual rainfalls at the two sites were relatively close (353 mm for Lake Grace and 369 mm for Corrigin) but at Lake Grace episodic recharge was both more likely and more important when roots were 100 cm and 150 cm deep (Table 4a and Figure lOb and c). The differences were mainly due to there being two more grade 3 episodes at Lake Grace for both root depths. For the 100 cm root depth, two of the six episodes at Lake Grace had large contributions from summer recharge, whereas none of the four grade 3 episodes at Corrigin did. For the 150 cm root depth, none of the three episodes at Lake Grace had summer recharge, but in one of the years there was 281 mm of rainfall in the first 100 days of the year, which was stored in the profile and contributed to the generation of recharge during the following winter. It appears that the more frequent large summer rainfall events that occur at

Lake Grace were at least partly responsible for the relatively high amounts and frequency of episodic recharge there.

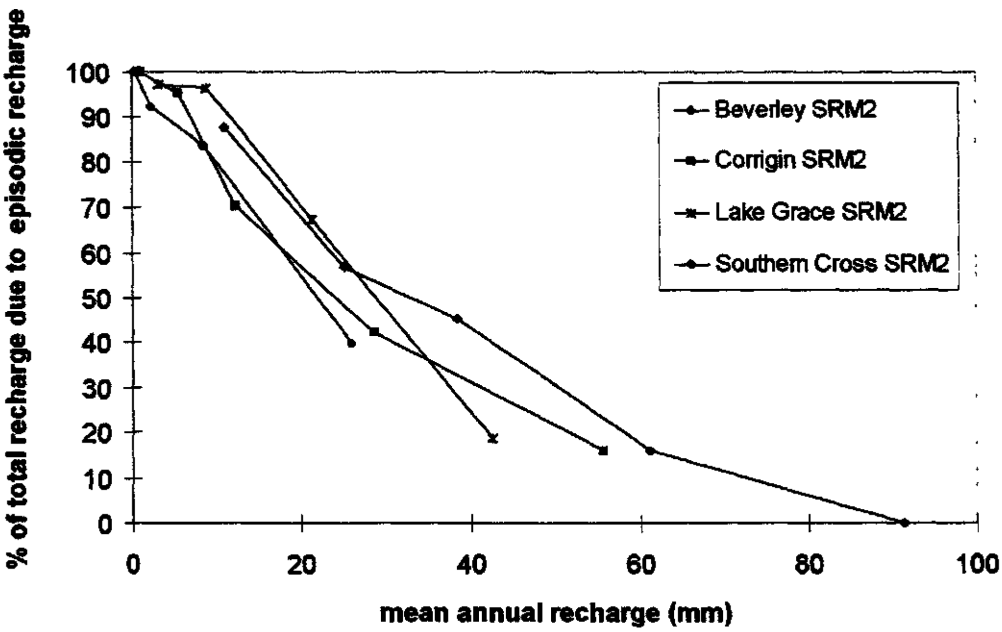


Figure 16: Percentage of total recharge due to episodic recharge versus mean annual recharge

Table 8 shows that episodic recharge did not occur across all of the four locations modelled at one time. Comparing results for SRM2, the years that were important at Corrigin were also important at Beverley, although Beverley experienced episodic recharge in two years that did not rate as episodic for Corrigin. This is not surprising because winter frontal rainfall usually moves eastwards, so goes over Beverley then Corrigin, decreasing in amount on the way. There were large summer rain events in 1972 at Corrigin and in 1990 at both Beverley and Corrigin which resulted in recharge that was noticeable on the cumulative recharge plots for all the root depths modelled, but the recharge was below grade 3 for the SRM2 cases at both Beverley and Corrigin so they were not considered to be significant episodes. However, the one-day summer rainfall event on 3 March 1972 did result in episodic recharge for SRM1 and SRM3 at Corrigin. There was 127.3 mm of rain on that day at Corrigin but only 4.3 mm in total for both 2 and 3 March 1972 at Beverley. Widespread winter episodic recharge occurred in 1963, 1964 and 1974, but for the 33 years modelled heavy winter rains resulted in episodic recharge either in the east or in the south-east, but not in both in the same year. There were two years when episodic recharge did occur at both Southern Cross and Lake Grace, but summer recharge played a part in both years. In 1966, the summer recharge at Southern Cross was graded as episodic, while at Lake Grace the summer recharge was low but contributed to the winter's total to cause an episode. In 1968 the episodic recharge at Southern Cross was due only to winter recharge whereas at Lake Grace there was again summer recharge which contributed to the winter total. In summary, the pattern for loamy sand soils (SRM2) was that in the west and central areas, episodic recharge was dominated by winter events, whereas further east and south-east, about half of the episodic recharge occurrences were due solely to winter recharge, with one-day summer rainfall events resulting in episodic recharge on one occasion in each case, and contributing to the winter totals on the others. The largest daily rainfalls occurred during summer months at all stations, so summer recharge may have been more important in deep sands (SRM1) because their lower water holding capacity meant they were less likely to be able to store all the water from a large one-day event. In sandy loam soils (SRM3), although the water holding capacity was much greater, if a one-day rain event was large enough to fill the soil profile, then although any excess may be small, it was likely to be graded as significant because the total recharge for these soils was relatively low.

Figure 8d shows that at Southern Cross there was a distinct change in the recharge rate after 1970, as a result of lower rainfall. From 1960 until then, the 50 cm roots generated 532 mm of recharge (48.4 mm/y) but from 1971 to 1992 there was only 324 mm recharge (14.7 mm/y). The corresponding rainfall figures are 3750 mm (340.9 mm/y) and 6750 mm (306.8 mm/y). No recharge was generated below the 150 cm roots after 1968. A similar effect can be seen in the results for the other three locations but it is far less marked. Table 8 also shows that the number of years with episodic recharge events decreased from six during the 1960s to three during the 1970s and only one during the 1980s.

Table 8: Years when episodic recharge occurred (X) and when summer recharge was graded as episodic (XS) (results from all modelled root depths were included)

	Beverley		Corrigin		Lake Grace	Southern Cross
Year	**SRM2**	**SRM1**	**SRM2**	**SRM3**	**SRM2**	**SRM2**
1960	X				X	
1961						X
1963	X	X	X	X		X
1964	X	X	X	X	X	
1966					X	XS
1967	X					
1968				X	X	X
1970						X
1972		XS		XS		
1974	X	X	X	X	X	
1983	X	X	X	X		
1990					XS	

To compare the relative effects of evaporation and rainfall on the results, several runs of the model were carried out with combinations of evaporation and rainfall data from different locations, for 50 cm deep roots and SRM2. Southern Cross had the lowest mean annual rainfall but the highest mean annual evaporation, and Table 9 shows how much the mean annual recharge changed when either the evaporation was decreased to that at Lake Grace, or the rainfall was increased to that at Beverley or Lake Grace. Recharge appears very sensitive to evaporation as decreasing the annual evaporation by 24 % increased the mean annual recharge by 45 %. However, increasing the rainfall by 28 % had the much greater effect of increasing the recharge by 152 %. But the relationships are not linear, as increasing the mean annual rainfall by 11 % only increased the mean annual recharge by 15 %. The implications may be that the changes in rainfall caused more of the differences in recharge regimes between the west and the east (Beverley and Southern Cross) whereas changing evaporation played a larger role from south-east to east (Lake Grace to Southern Cross). This would reflect steeper rainfall gradients from west to east than from south-east to east.

Table 9: Relative effects of rainfall and evaporation on recharge for SRM2 with 50 cm deep roots

Rainfall			Evaporation			Recharge	
Station	**Mean annual (mm)**	**% increase from Southern Cross**	**Station**	**Mean annual (mm)**	**% decrease from Southern Cross**	**Mean annual (mm)**	**% increase from Southern Cross**
Southern Cross	318	0	Southern Cross	2428	0	25.9	0
Southern Cross	318	0	Lake Grace	1854	24	37.5	45
Beveriey	407	28	Southern Cross	2428	0	65.2	152
Lake Grace	353	11	Southern Cross	2428	0	29.8	15

3.6 Effect of maximum root depth and soil type on generation of recharge

Together, the maximum root depth and the soil type define the available soil water storage, and increasing either the root depth or the clay percentage of the soil had a similar effect on reducing recharge.

The likelihood of episodic recharge occurring increased then decreased as either root depth or soil clay content increased. This pattern reflected the changes from regular recharge regimes with just a few relatively small instances of episodic recharge, through regimes with both regular and episodic recharge, to regimes with only episodic recharge. The only run of the model which produced no episodic recharge because of the regular nature of the recharge was that for 50 cm-deep roots at Beveriey (SRM2), the site with the highest mean annual rainfall. At the other end of the spectrum, with roots 300 cm deep, no recharge was produced over the 33 years below the loamy sand at either Southern Cross or Lake Grace (the two lowest average rainfall sites) nor at Corrigin below the sandy loam (Table 4). It is possible that modelling a longer sequence of years would have resulted in conditions which produced recharge in these cases.

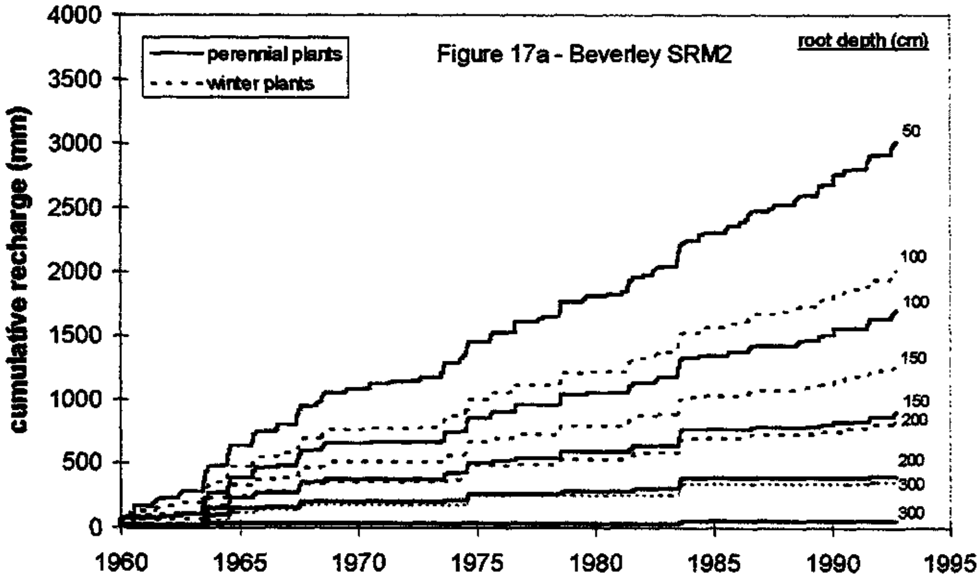
In contrast, the importance of the episodic recharge compared to the regular recharge continued to increase as root depth or soil clay content increased, even though the amount of recharge involved in the episodes became less. There were two instances where one recharge episode constituted 100 % of the recharge for the 33-year periods modelled (Table 4). Not surprisingly, the two cases were for deep roots (200 cm) and either in heavy soil (SRM3 for Corrigin) or with low rainfall (SRM2 for Southern Cross). (The 300 cm root cases at both sites had no recharge over the 33-year period).

Some of the other effects of increasing the available soil water storage (illustrated by the results for the Corrigin SRM2 run in Table 3 and Table 2) were:

- decrease in the total amount of recharge (Table 2);
- a decrease in the number of recharge events (Table 2);
- a decrease in the duration of recharge events including episodic recharge periods (Table 3);
- a delay in the start of recharge generation following the break of the season (for example, for SRM2 at Corrigin, July or August for 200 cm or 300 cm-deep roots instead of May or June for 50 cm and 100 cm-deep roots, Table 3);
- a lessening in the importance of summer recharge events (Table 3).

3.7 Effect of perennial roots

Being able to transpire stored water from the maximum root depth for the whole of the year decreased the recharge but did not generally change the pattern of recharge generation (Figure 17a to d). If annual plants did not prevent episodic recharge, then neither did perennial vegetation (when roots were less than 300 cm), but the amount of recharge was reduced. There was a decrease in the effect of perennial plants compared to winter plants from Beverley (in the west), to Corrigin (central), to Southern Cross (in the east). However, the effect of perennials at Lake Grace was greater than at even Beverley. Comparing Lake Grace to Corrigin, which has similar mean annual rainfall, shows that perennial roots at Lake Grace allowed less recharge during big episodes than at Corrigin, and prevented any recharge during low recharge periods for the winter roots, whereas at Corrigin the perennial roots appeared to reduce the size of major episodes but had little effect on smaller ones. The reason that perennials appeared to be so effective at Lake Grace was that summer rain played a greater part in causing recharge with winter plants than at Corrigin and the perennials were able to either prevent recharge occurring at all in summer, or were able to reduce the amount of stored water before more rainfall occurred in autumn or winter, and so reduced the likelihood of excess water occurring.



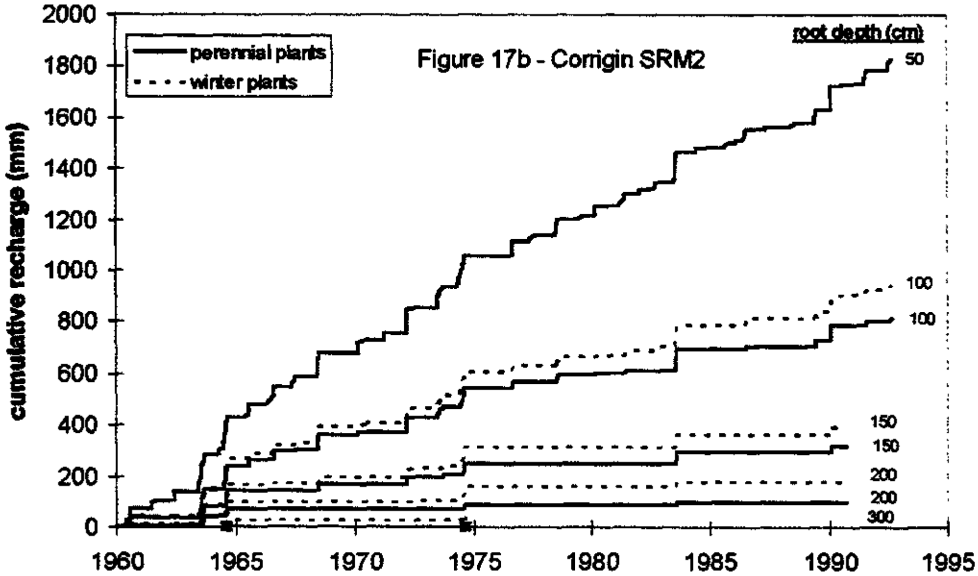
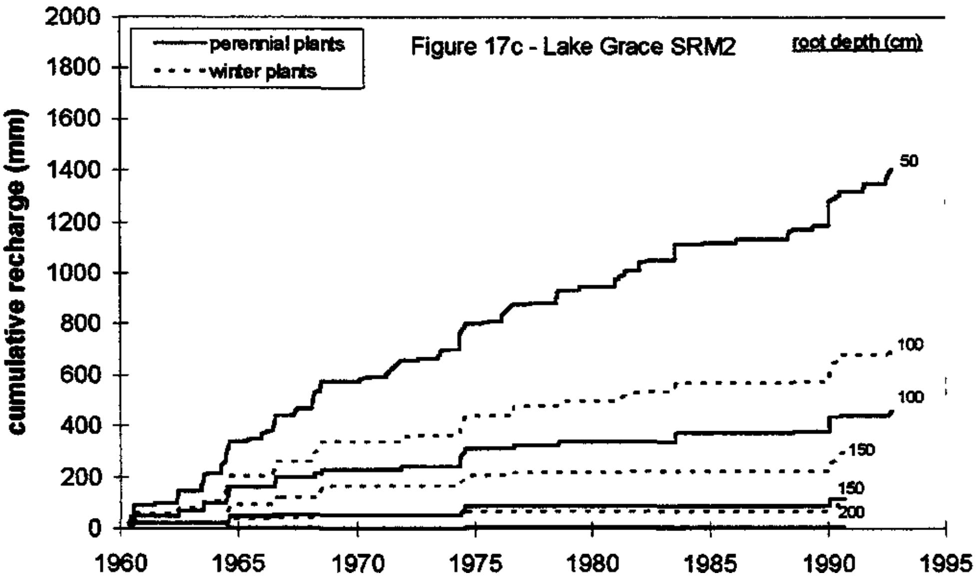


Figure 17a-d: Cumulative recharge from 1960 to 1992 for perennial and winter annual plants, SRM2



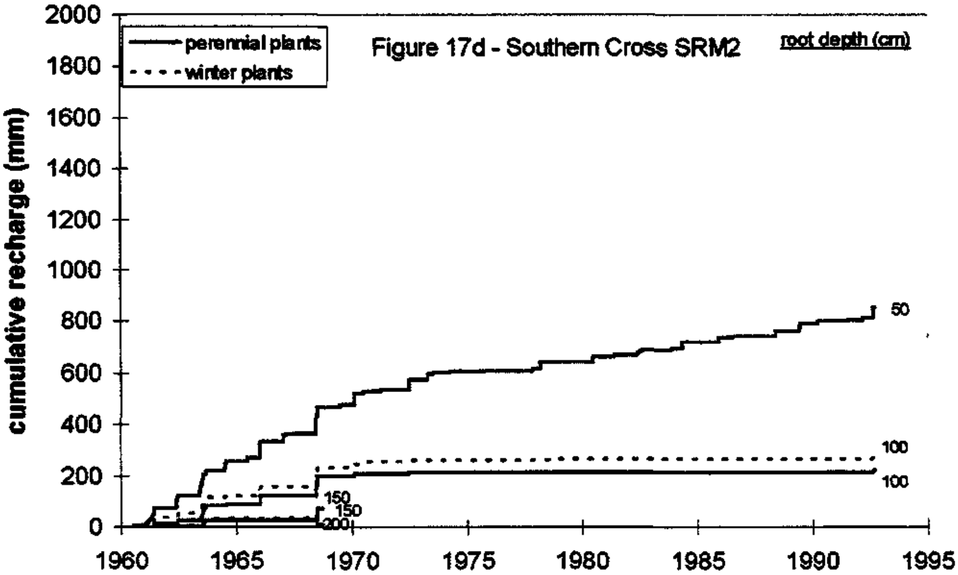


Figure 17a-d continued

Two approaches which are considered for reducing recharge below annual crop and pasture systems are increasing root depth of winter plants and replacing winter plants with perennials, which tend to have deeper roots and to be able to use water for more of the year. The relative effects of the various maximum root depths of winter plants and perennials modelled can be compared by plotting the mean annual recharge of the various situations relative to that for 50 cm roots for that site (Figure 18). This shows that at Southern Cross there was a proportionally greater effect by increasing maximum rooting depth on a loamy sand from 50 cm to 100 cm than at the other sites.

There was a greater reduction in recharge from increasing winter plant maximum root depth by 50 cm than by changing to perennial plants, although the results were similar in some cases (Lake Grace and Corrigin 150 cm perennial roots and 200 cm annual roots). There was not a great difference between the perennial plants and winter plants in the cases of 100 cm roots at Corrigin. This shows that if there are benefits from replacing annual plants with perennial ones, they are more likely to be due to the perennial's deeper root systems rather than their ability to use water throughout the year.

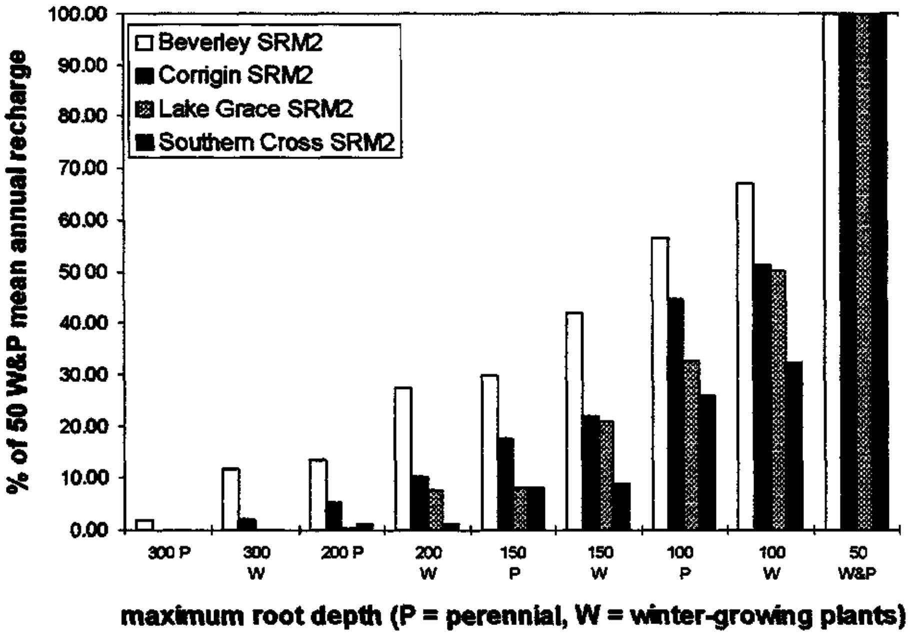


Figure 18: Mean annual recharge below perennial and winter annual plants of different maximum root depths as a percentage of those with roots 50 cm deep

4. Discussion

The results clearly show that direct episodic recharge could be a significant proportion of the direct recharge that occurs in the Western Australian wheatbelt and indicate the controlling conditions, annual patterns and long term trends of direct recharge. Because the WATBAL model used is only a simplistic representation of the water balance, the quantitative results should only be considered to be indicative.

4.1 Episodicity and aridity

The UNESCO (1979) definitions of arid and semi-arid climates are:

	Mean annual precipitation/mean annual potential evapotranspiration (p/et_p)	Annual rainfall (mm)	Interannual rainfall variability (%)
Arid	0.03 to 0.20	80 to 150	50 to 100
Semi-arid	0.20 to 0.50	200 to 500	25 to 50

Under this classification system, Beverley, Corrigin and Lake Grace fall clearly into the semi-arid zone whereas Southern Cross is in the arid zone on the basis of p/et_p and interannual rainfall variability but in the semi-arid zone based on annual rainfall. However, on the UNESCO (1979) map, all the agricultural areas are included in the semi-arid zone (it is probable that the existence of agriculture influenced how it was mapped). Aridity is characterised by "sporadic rainfall of high temporal and spatial variability" (Leraer et al. 1990, p. 4) and so would be likely to lead to recharge that is also sporadic (or episodic) and of high temporal and spatial variability. If episodic recharge is a characteristic of arid areas which becomes less distinct with decreasing aridity, then the areas modelled would be expected to fall into the grey zone between where episodic recharge is significant and where decreasing aridity results in non-episodic recharge. The results of the modelling illustrate that the wheatbelt is indeed in the transition zone. Although recharge at Southern Cross was more episodic in nature than at the other sites, recharge could be episodic at any of the sites modelled depending on the soil type and root depth of the plants being grown. Thus episodic recharge does not stop at the semi-arid/arid boundary. The Western Australian wheatbelt is at the arid end of the semi-arid spectrum and the trends of the modelling results indicate that at sites further west (with higher rainfall) episodic direct recharge would be less significant.

Barnes et al. (1994) suggested that if an arid site was subjected to climatic variations which lead to an increase in the mean annual rainfall and a decrease in variability, then the mean annual recharge could decrease. This trend did not happen in the results of this study as the mean annual recharge decreased with decreasing mean annual rainfall and increasing variability.

4.2 Episodic recharge and monitoring groundwater levels

It is clear that long term groundwater monitoring is essential to assess the salinity risk, especially in the central and eastern parts of the wheatbelt where rainfall is low, and below soils with high water holding capacities, as recharge may only occur sporadically. It may be argued that in the lower rainfall areas the volume of recharge is likely to be so low that it could be regarded as insignificant, but this is clearly not so as in many areas of the eastern wheatbelt significant secondary salinity already exist. Barnes et al. (1994) studied recharge in central Australia (which has an arid climate) and stated that using mean annual recharge figures was only meaningful when the mean is calculated over a long enough period to include a statistically significant number of extreme events. The same is true of areas receiving episodic recharge in the Western Australian wheatbelt.

4.3 Where direct episodic recharge is most likely to occur

The likelihood of episodic recharge was greatest in the middle-of-the-range cases of those modelled. Where available soil water storage was low or rainfall was high then there was so much recharge that an episode had to be particularly large to be significant. Where available soil water storage was high or rainfall was low, then there were very few (or no) recharge events during the 33 years that were modelled.

4.4 Relationship between episodic recharge and rain events

There appeared to be no clear relationship between the size of individual rainfall events and the occurrence of episodic recharge except during the summer. Similarly, there was no clear relationship between weekly or monthly rain totals in the winter months and whether recharge had an episodic nature. For a given rain total which produced winter episodic recharge, there were examples in other years of similar totals not resulting in episodic recharge. There did seem to be a weak trend that a wet July resulted in episodic recharge. In contrast, Cook (1990) used the WATBAL model for sites in South Australia and found that at Wanbi (304 mm mean annual rain) the distribution of recharge events was determined by the occurrence of very large storms at any season of the year, and that 50 % of the recharge over a 21-year period was generated on 18 days when there was more than 10 mm of recharge. This shows that groundwater trends should not be extrapolated from one area to another on the basis of mean annual rainfall.

4.5 Model results and groundwater hydro-graphs

If the general recharge patterns shown by the cumulative recharge graphs were realistic, then they would have similar forms to groundwater hydrographs from sites where there was no groundwater drainage. This appears to be the case. Examples are three piezometer hydrographs from the Morbinning Catchment (near Beverley, see Figure 1) which show (Figure 19): a steady rise (MO3); a rapid rise with a clear step in 1992 (MO69); and a level trend interrupted by a clear step in 1992 (MO63). (The steps occurred in 1992 which was a relatively wet year). Because the three piezometers are within 3 km of each other, the rainfall at each site would have been similar, and the sites are managed by the same landholder in crop and annual pasture rotations. It is not known how much lateral groundwater recharge occurs at the sites. All three sites are on slopes and have duplex soil profiles. In the absence of other information, comparison with the modelling results implies that maximum soil water storage in the root zones increases from MO3 to MO69 to MO63.

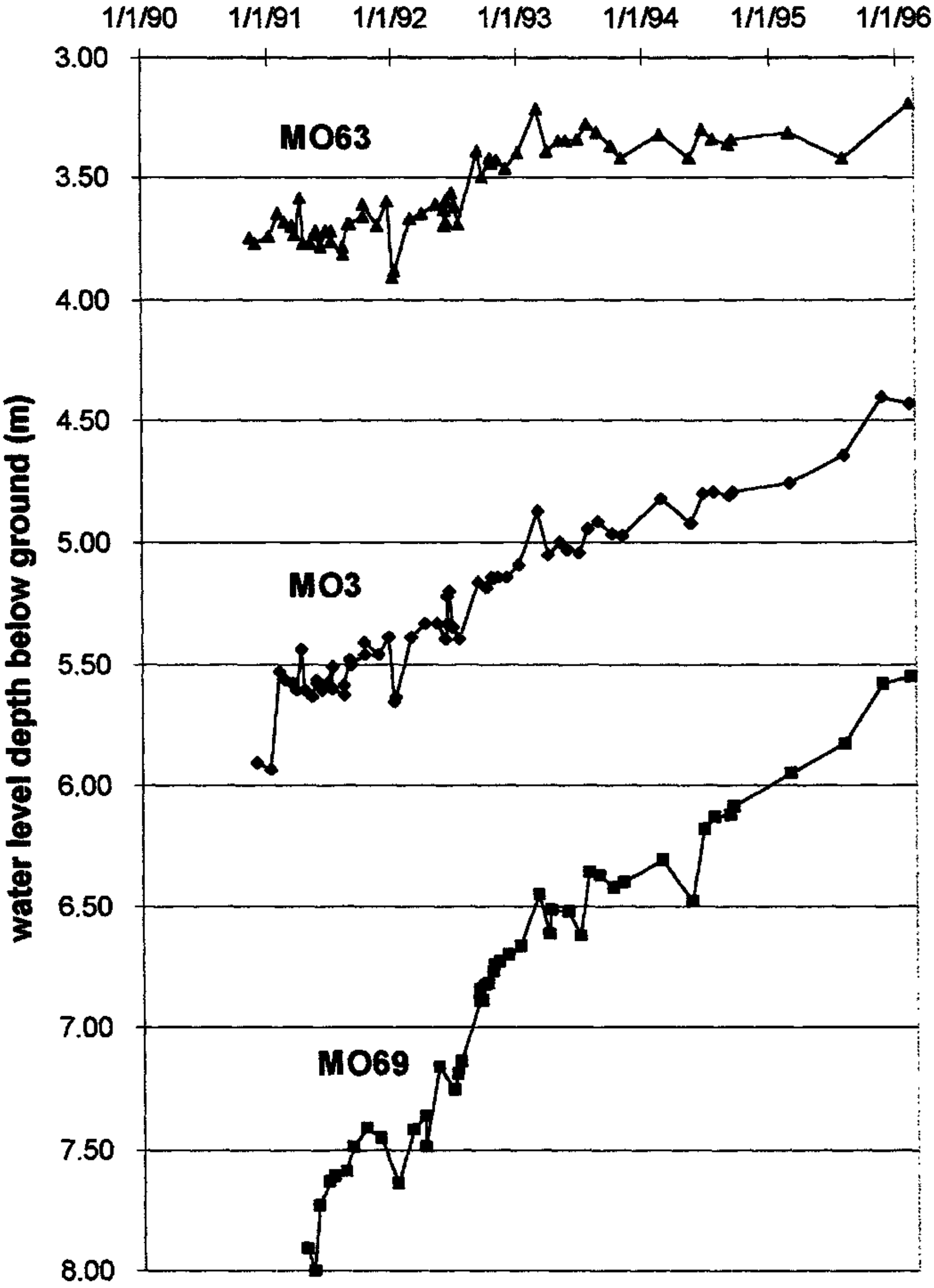


Figure 19: Groundwater hydrographs for three sites in the Morbinning Catchment near Beverley

Summer rainfall was shown by the modelling to result in recharge in the Western Australian wheatbelt and to be important in the overall total in some modelled cases. However, it only lead to significant episodic recharge at Southern Cross in the east Piezometer records show that pulses of recharge have occurred as a result of summer rain below sandy soils at a site in the east (Brown's, Figure 20; see Figure 1 for location) and below gravel soils at a site in the west (Kettlerock Gully, Figure 21, see Figure 1 for location). The piezometer at Brown's reacted markedly in early 1990 to a large rainfall event on 28 and 29 January (Corrigin had 135.8 mm and Merredin (Figure 1) had 72.2 mm). The recorded rise in the piezometer water level was large (about 50 cm) and seemed to be of the same order as the regular winter rises. Because of infrequent monitoring and a short record, it is not clear how significant the summer recharge was, but it appears possible that the total 1990 rise could have been about double what it would have been without the summer recharge pulse. (The site was planted with trees in 1986 which is why the water level fell over the years.) Further west, at Kettlerock Gully, a summer rain event (approximately 60 mm rain) in March 1993 resulted in recharge below deep gravel soil profiles and gravelly loams. Although the rain event caused water level rises up to 40 cm, the rises were small in comparison with the seasonal winter rises of two or three metres. Therefore the behaviour of these groundwater levels is similar to that predicted by the model results.

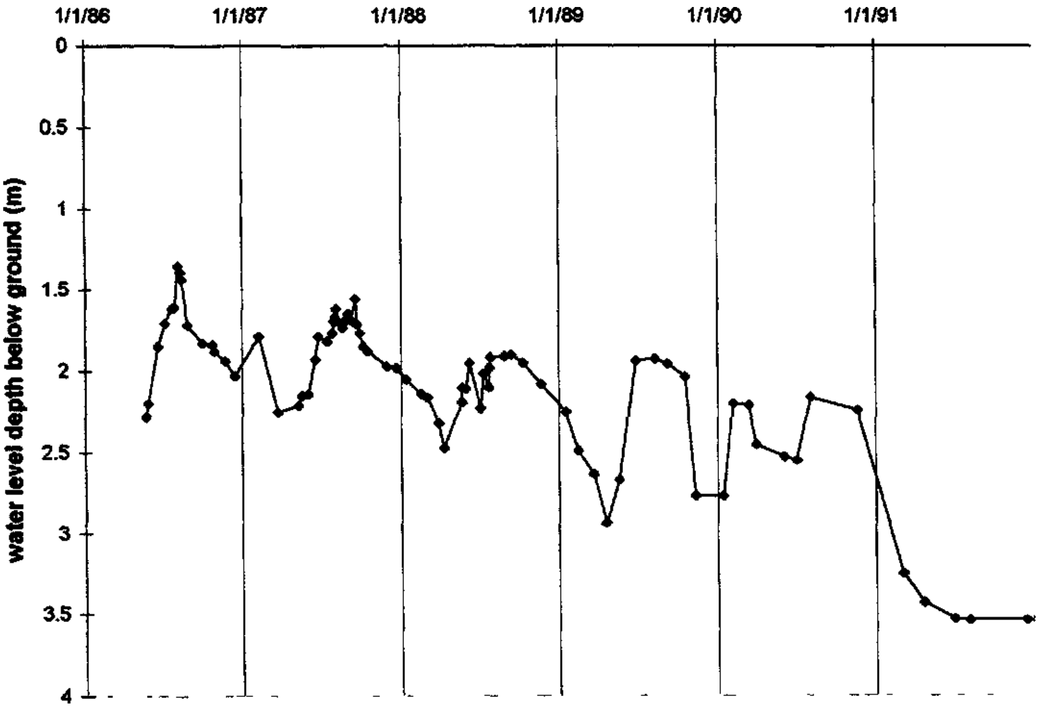


Figure 20: Effect of summer rain on groundwater hydrograph at Brown's (hydrograph provided by R. George and C. McConnell, Agriculture Western Australia)

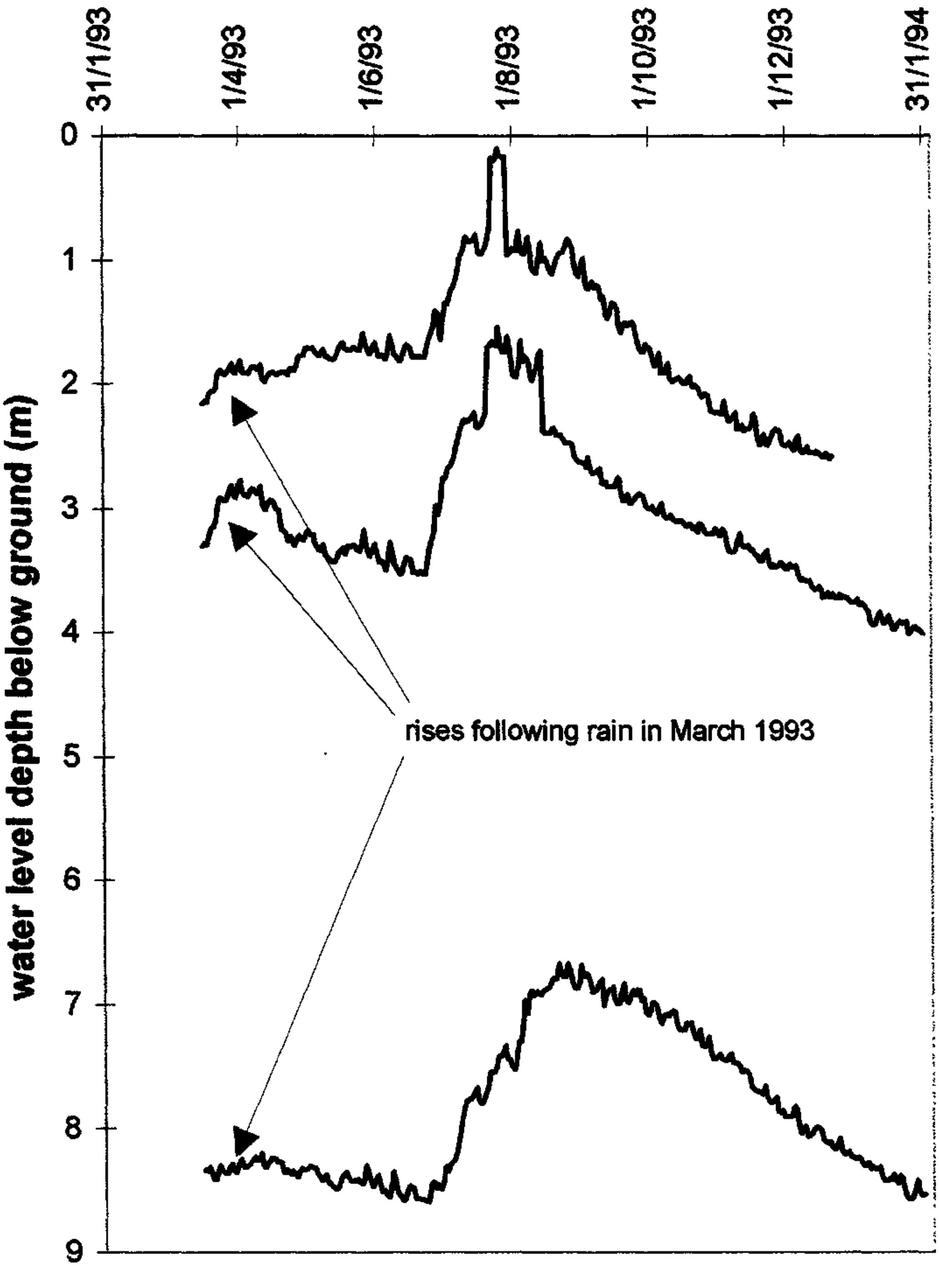


Figure 21: Effect of summer rain (19 March 1993) on groundwater hydrographs at Kettlerock Gully

4.6 Model results and water use of perennial plants

The decrease in the amount of recharge with increasing root depth indicated by the modelling is not unexpected considering the different available soil water storages used for the different depths, but the modelling shows that the change is quite dramatic and that an increase of 50 cm depth can have a greater effect than using a perennial plant with the shallower root depth. However, Nulsen (1993) attributed the greater annual water use of lucerne compared to that of wheat to the ability of lucerne to transpire all year, not to it's (assumed) deeper roots. His conclusion was influenced by measurements, which showed that wheat used more water than lucerne during the winter months even though the lucerne roots were assumed to be deeper. This shows that this simple model does not account for some important differences in plant water use characteristics between different species.

4.7 The relevance of the modelled soil types

The types of soils modelled are those which would be expected to allow most direct recharge to occur by matrix flow. Soils with significant macropore flow (for example, well-structured non-swelling clays and cleared areas with well-developed root channels from dead trees) or which are prone to significant indirect recharge (lakes and watercourses, flood-prone areas, waterlogged land) may also allow significant volumes of recharge to reach the groundwater systems, and be particularly prone to episodic recharge. The WATBAL modelling thus was only applicable to a fraction of the recharge that occurs in the Western Australian wheatbelt. Soil maps can be used to indicate the proportion of the wheatbelt with soils of the types modelled. Grealish and Wagnon (1995) and Lantzke and Fulton (undated) mapped the soil landscape units in the northern and western wheatbelt and presented the percentages of the different soil types in the mapped regions. In the northern mapped area (Grealish and Wagnon), 5 %, 9 % and 23 % of the area has soils that have similar textures to those in SRM1, SRM2 and SRM3 respectively. The corresponding figures for the areas mapped by Lantzke and Fulton (the western mapped area) were 3%, 12% and <1 %. If soils which are similar in the upper 50 cm of then- profile are included, then the areas increase dramatically hi the western area. These soils would be represented by the shallower root runs of the model. (In other areas of the wheatbelt either soil surveys did not give percentage figures covered by the different soil types, or surveys are still in progress.)

4.8 The relevance of the root depths modelled

Since the occurrence of episodic recharge appears to be related to maximum available soil water storage and thus root depth, the agricultural species in use will affect the generation of episodic recharge. Cook and Walker (1990) assumed that wheat roots were 100 to 125 cm deep and this lead them to model an active soil depth of only 50 cm because they considered the majority of the roots were concentrated in the top 50 cm of the soil. This lead to maximum available soil water storages of between 18 and 69 mm for soils with from 2 % clay to 25 % clay respectively. Kennett-Smith et al. (1994) considered that roots penetrated up to 2 m under crop and between 2 m and 4 m under perennial pastures but assumed an exponential decrease in effect of evapotranspiration with depth and modelled this effect by considering that water was only removed from the top 0.5 m and 0.5 to 1 m respectively for crop and pasture.

However Hamblin and Hamblin (1985) found that plants in their trials managed to dry out the whole profile during dry spells. Tennant et al. (1991) stated that wheat crops will dry the soil to wilting point in the upper half of the profile and to near wilting point in the lower half. Ozanne et al. (1965) measured root growth characteristics of pastures on deep sand and found that root concentration decreased exponentially with depth from 10 cm down. From the results presented in Hamblin and Hamblin (1985) and Ozanne et al. (1965) it appears that the 100 cm and 150 cm model runs probably best represent wheat. Lupins tend to have slightly deeper root systems than wheat so are probably best represented by the 150 cm runs. Annual pasture will generally be best represented by the 50 cm runs. When considering the effects of different plant species, the effect of rainfall should also be taken into account. For example, at Southern Cross there was very little recharge generated when the MAXST was greater than 125 mm whereas at Beverley the same conditions generated about 25 mm a year recharge.

4.9 Model results compared to other estimates of recharge

Although the quantitative results of the modelling are not accurate because of the simplistic assumptions used, those for loamy sands for Corrigin, Lake Grace and Southern Cross are in the range of recharge rate assessments by several authors reviewed by Nulsen (1993). He tabulated the recharge estimates which were made using a variety of methods in several locations in Western Australia. There were six locations with mean annual rainfall in the range 330 mm to 460 mm and at these sites recharge estimates ranged from 2 % to 13 % of mean annual rainfall. Most of these studies estimated the mean recharge over areas ranging from small to large catchments and therefore did not identify the direct recharge below soils with low water holding capacities. Those methods which did calculate direct recharge were at sites with soils heavier than those modelled. Therefore for all cases the estimates given in Nulsen (1993) would be expected to be lower than those modelled. Nulsen states that mean recharge is generally in the range 5 to 50 mm/y where the mean annual rain is 300 to 500 mm. The WATBAL model results for Beverley (407 mm mean annual rainfall) were higher than this (11 to 91 mm recharge per year for 300 to 50 cm deep roots in loamy sands), but the types of soils modelled would cover only part of a catchment.

4.10 Further work following from the results

The results of the simple water balance showed that the differences in rainfall regime (and to a lesser degree, in evaporation) across the central part of the wheatbelt were great enough to generate significant differences in recharge regimes. Repeating the modelling for a larger number of sites across the whole agricultural area would provide the basis for maps of relative likelihood and importance of episodic recharge. In addition, the results presented in this report were from modelling 33 years of rainfall data. Some rainfall records from Western Australian stations are continuous over longer periods. The significance of episodic recharge revealed by 33-year records at a selection of these sites could be compared to that indicated by modelling the longer records. This work is now being carried out by the author.

The modelling assessed the effect of rainfall regime on generating *direct* episodic recharge. Indirect recharge is considered to be important in both arid and semi-arid environments (Lerner et al. 1990) so information on the likelihood or importance of episodic indirect recharge is also relevant for Western Australia.. Wheatbelt valleys are prone to episodic flooding, and although very little is known about the relationship between flooding and groundwater recharge in these landscapes, it seems probable that episodic flooding results in episodic recharge. But just how significant is such recharge at a particular site, or in a particular catchment, or for the wheatbelt as a whole? These questions are also being considered by the author in work now in progress.

5. Summary and Conclusions

The aim of the study was to determine whether the rainfall regimes which occur across the Western Australian wheatbelt could lead to episodic direct recharge regimes, and the influence of root depth and soil type on the recharge regimes. The results showed that episodic direct recharge could be generated under certain circumstances at each of the four sites modelled.

The form of the impact of episodic recharge varied with rainfall regime:

- episodic recharge was *most important* at the site with the lowest mean annual rainfall and greatest rainfall variability (Southern Cross);

but

- episodic recharge contributed the *largest amounts* of recharge at the site with the greatest average annual rainfall (Beverley, Table 7);

and

- the *likelihood* of episodic recharge occurring increased with increasing average annual rainfall under some circumstances - for example, for roots from 100 cm to 200 cm deep in loamy sand (Table 4a and b).

Thus, it would be wise to assess the significance and importance of episodic recharge at any wheatbelt site where treatment to reduce recharge is being considered. Aiming to reduce recharge by only the "average" annual amount each year may have little or no effect on the spread of salinity.

6. References

Barnes, C. J., Jacobson, G. and Smith, G. D. 1994, 'The distributed recharge mechanism in the Australian arid zone.' Soil Science Society America Journal, v. 58, pp. 31-40.

Cook, P. G. and Walker, G. R. 1990, *The Effect of Soil Type on Groundwater Recharge in the Mattee Region*. Centre for Groundwater Studies Report No. 28, Glen Osmond, South Australia.

Grealish, G. and Wagnon, J. 1995, *Land Resources of the Bencubbin Area*. Land Resources Series, Agriculture Western Australia, Perth.

Hamblin, A. P. and Hamblin, J. 1985, 'Root characteristics of some temperate legume species and varieties on deep, free-draining entisols.' Australian Journal Agricultural Research, v. 36, pp. 63-72.

Keig, G. and McAlpine, J. R. 1969, WATBAL. *A Computer System for the Estimation and Analysis of Soil Moisture Regimes from Simple Climatic Data*. Technical Memorandum No. 69/9, CSIRO Australia Division of Land Research, Canberra.

Keig, G. and McAlpine, J. R. 1974, WATBAL. *A Computer System for the Estimation and Analysis of Soil Moisture Regimes from Simple Climatic Data*. Second edition, Technical Memorandum No. 74/4, CSIRO Australia Division of Land Research, Canberra.

Kennett-Smith, A. K., Cook, P. G. and Walker, G. R. 1994, 'Factors affecting groundwater recharge following clearing in the south western Murray Basin.' Journal of Hydrology, v. 154, pp. 85-105.

Lantzke, N. and Fulton, I. (undated), *Land Resources of the Northam Region*. Land Resources Series, Western Australian Department of Agriculture, Perth

Lerner, D. L., Issar, A. S. and Simmers, I. 1990, *Groundwater Recharge - A Guide to Understanding and Estimating Natural Recharge*. Heise, Hannover.

Lewis, M. F. 1997, 'The significance of episodic recharge.' Submitted to the Murray Darling Basin Workshop '97 'Groundwater - In the Balance', to be held at Toowoomba, Queensland, 26-28 August, 1997.

Nulsen, R. A. 1993, 'Opportunities and limitations for using agronomic techniques to control dryland salinity.' Proceedings of the National Conference on Land Management for Dryland Salinity Control, La Trobe University, Bendigo, pp. 24-31.

Ozanne, P. G., Asher, C. J. and Kirton, D. J. 1965, 'Root distribution in a deep sand and its relationship to the uptake of added potassium by pasture plants.' Australian Journal Agricultural Research, v. 16, pp. 785-800.

Robinson, S. and Abrecht, D. 1993, *TACT-A Seasonal Wheat Sawing Decision Aid*. User manual, Western Australian Department of Agriculture, Perth.

Tennant, D. 1976, 'Wheat root penetration and total available water on a range of soil types.' Australian Journal of Experimental Agriculture and Animal Husbandry, v. 16, pp. 570-577.

Tennant, D., Siddique, K. H. M. and Perry, M. W. 1991, 'Crop growth and water use' in *The Wheat Book. A Technical Manual for Wheat Producers*, compiled by Perry, M. W. and Hillman, B., Western Australian Department of Agriculture, Perth.

UNESCO 1979, *Map of the world distribution of arid regions: explanatory note*. MAB Technical Notes 7, 54 pp.