PART I

IS EPISODIC RECHARGE LIKELY TO BE SIGNIFICANT IN THE WHEATBELT OF WESTERN AUSTRALIA?

INTRODUCTION TO PART I

The aim of the preliminary step in this project was to assess whether episodic recharge was likely to be significant in the Western Australian Wheatbelt. Part I describes the assessment. Three approaches were used:

Approach 1. **Identify any available evidence for episodic recharge in south-western Western Australia (WA)** by inspecting publications on groundwater in agricultural areas of WA.

Approach 2. **Identify the conditions at locations where episodic recharge occurs elsewhere in the world and compare them to those in the Wheatbelt of WA** by inspecting publications on recharge from other places.

Approach 3. **Calculate the potential of rainfall regimes in south-western WA to produce episodic direct recharge** by using simple water-balance models.

Approaches 1 and 2 are presented in Chapter 2 and Approach 3 is presented in Chapter 4. The focus was broadened from the Wheatbelt to south-western WA in Approach 1 to ensure relevant information was not excluded.

A fourth approach which was considered was to determine whether areas of saline land had expanded episodically, since increases in saline land reflect increases in groundwater discharge which in turn reflect increases in recharge. However, problems with this approach included:

- insufficient reliable data or information to determine rates of spread of salinity (aerial photograph surveys were at long and inappropriate time intervals; satellite imagery coverage did not extend back far enough; Australian Bureau of Statistics survey results were unreliable (Ferdowsian et al. 1996) and too far apart);

- episodic increases in salinity could have causes other than episodic recharge - e.g. clearing and other land use changes, and aquifer storage and flow characteristics; and

- the effects of episodic recharge occurring in part of a groundwater catchment may be diluted at a discharge site by groundwater from sources with more regular regimes and by aquifer storage and transmission characteristics.
Therefore, assessments of long-term episodicity of discharge and spread of salinity were not attempted.

Approaches 1 to 3 required a system for distinguishing episodic recharge from non-episodic recharge. Some general guidelines were devised which sufficed for Approaches 1 and 2 (Sec. 2.3.2, Ch. 2), but a more objective, repeatable method was required for Approach 3. The methods which were considered and developed are described in Chapter 3.

The conclusions drawn from all of the assessments are presented at the end of Part I.
2. EPISODIC RECHARGE IN WESTERN AUSTRALIA AND ELSEWHERE: A LITERATURE REVIEW

2.1 INTRODUCTION

The objective of Part I of this thesis was to assess whether it is likely that episodic recharge is significant in the Western Australian Wheatbelt. This chapter presents two approaches to addressing that objective, both of which used reviews of published information. The approaches were:

- identifying any available evidence for episodic recharge in south-western Western Australia (WA); and
- identifying the conditions at other locations where recharge is episodic and comparing them to those the Wheatbelt of WA.

There were no systematic studies of episodic recharge or of the variability of recharge with time in south-western WA. However, several publications described relevant observations (summarised in Section 2.2) and many included groundwater hydrographs which could be assessed (Sec. 2.3).

Only a few studies elsewhere in the world directly addressed the episodicity of recharge. However, the conditions which led to large pulses of recharge were inferred from information contained in other recharge studies (described in Section 2.4). The relevance of the rainfall conditions and recharge processes to WA are discussed in Section 2.5.

The conclusions drawn from the literature review are presented in Section 2.6.

The locations of places mentioned in this chapter are shown in Figure 2-1a (Australia) and Figure 2-1b (elsewhere).

2.2 PUBLISHED OBSERVATIONS FROM SOUTH-WESTERN WESTERN AUSTRALIA

Relevant observations were found on episodicity of recharge from all regions of agricultural WA except the western coastal plains. Details of these observations and the publications in
which they appeared are summarised in Appendix 1. The observations were divided into those based on rainfall conditions and those based on site conditions.

a: (see below for caption)
In brief, several authors (e.g. Ferdowsian and Greenham 1992; Short and Skinner 1997) noted that groundwater rises were larger than normal after wet years, wet months or wet days, but few assessed their overall significance in either temporal or spatial terms. Henschke (1989) related rainfall amounts to large groundwater rises in the East Perenjori catchment in the northern Wheatbelt, but the available records were short (three years). Also, McFarlane et al. (1989) calculated the probability of rainfall exceeding that which caused large groundwater level rises in two years of a nine-year period (36% probability of exceeding the rain in May,
June and July in one of the years; 10% probability in the other year) in an area in the Lake Toolibin catchment in the central Wheatbelt.

There were a few indications that indirect recharge from floods and sporadic streamflow were related to larger than normal groundwater rises below valley floor sites (McFarlane et al. 1989; George and Frantom 1990a; George 1992a), and that waterlogged and flooded land could contribute to groundwater recharge via macropore flow (Engel et al. 1989; George and Frantom 1990b). On slopes, occasional large pulses of direct recharge from heavy summer rains occurred below coarse-grained soils (George 1992b).

Also, there were examples where agroforestry systems and forest recovering from thinning did not prevent large rises in groundwater levels in wet years (Borg et al. 1987; Raper 1997; Short and Skinner 1997). Ferdowsian and Greenham (1992) found a contrast in behaviour below natural vegetation, where there was no groundwater response, to that below nearby cleared areas, which had very large groundwater level rises, following a wet year.

2.2.1 Summary

No studies of episodic recharge in south-western WA were found, but several researchers had identified unusually large groundwater rises and associated them with periods of heavy rain and with both indirect and direct recharge processes.

2.3 GROUNDWATER HYDROGRAPHS AS INDICATORS OF EPISODIC RECHARGE

2.3.1 Introduction

Although few publications on WA commented directly on the variability of recharge over several years, many presented groundwater hydrographs which documented rises in groundwater levels. Rises in groundwater levels cannot be related directly to groundwater recharge, but the pattern of rises is likely to reflect the pattern of recharge.

This section qualitatively classifies the hydrographs to assess whether episodic recharge is a significant component of total recharge in south-western WA. The method used was subjective, but the aim was to obtain a simple overall view.
2.3.2 Method

Four-hundred-and-fifteen groundwater hydrographs from 59 publications on south-western WA were inspected for evidence of episodic recharge. The publications are listed in Appendix 2. Many hydrographs covered only short periods, and some had too few monitoring points to be useful. Only three hydrographs extended over more than 20 years. Forty-eight hydrographs covered between 10 and 20 years, and 104 hydrographs covered 5 to 10 years. Most hydrographs (260) were for periods of less than five years. Therefore, the inspection provided only an indication of the range of long-term groundwater regimes.

The hydrographs were divided into three classes. The first class was 'possibly episodic'. A hydrograph was placed in this class if:

- it had infrequent (not annual) rises markedly larger than others (Figure 2-2a shows an example) or
- there was a rising trend which had regularly rising or stable periods separated by clear steps, and the steps did not occur every year (Figure 2-2b shows an example) or
- summer rain resulted in a rise in groundwater level (because summer rain tends to be irregular in WA) or
- authors commented that groundwater level rises over a period were unusually large or were due to unusual events - e.g. floods.

It was considered valid to use the last two criteria even on very short records (three years or less). Most hydrographs which did not satisfy any of the above criteria were classified as 'probably not episodic'. Some hydrographs, particularly the very short ones (less than three years), were classed 'unclear'.

2.3.3 Results

Table 2-1 summarises the results of the hydrograph inspection.
2.3.4 Discussion

Nearly half of the hydrographs inspected were classified as 'possibly episodic', but classifications were applied only to the time period which the hydrograph represented. Any of the hydrographs might have episodic behaviour over a different or longer time period, and conversely, behaviour which seemed unusual in a short record could prove to be common over a longer time.
Table 2-1: Classes of hydrographs in publications on south-western Western Australia (publications are listed in Appendix 2)

<table>
<thead>
<tr>
<th>Length of hydrograph record (y)</th>
<th>Number of hydrographs in class</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Possibly episodic behaviour</td>
<td>Unclear</td>
</tr>
<tr>
<td>&gt;20</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>10-19</td>
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<tr>
<td>&lt;3</td>
<td>70</td>
<td>10</td>
</tr>
<tr>
<td>Totals</td>
<td>190</td>
<td>34</td>
</tr>
</tbody>
</table>

Apart from the short time-frame of many of the hydrographs, some others were poorly suited because:

- few had measurement points at intervals of one day or less, so it is possible that rapid rises and falls in water level were missed;
- in some, the measurement points were not shown, so the regularity and frequency of measurements was unclear;
- some had regular and frequent measurement points at the beginning but fewer later; this meant that it was not valid to compare rises in early and late parts of the hydrographs;
- some were drawn from minimum annual levels, plotted at a year apart; these did not show any short-term rises which may have occurred;
- many were designed to illustrate the effects of changing land management (e.g. replacing native vegetation with agricultural species, replacing agricultural species with perennial vegetation, logging and thinning forests, groundwater and surface water drainage) and these changes would confound any effects of episodic recharge;
- some of those illustrating effects of changed management showed groundwater level changes normalised to those at a control site; so if both sites reacted to an episodic recharge event by the same amount a graph would show no response, and it could even show a negative response if the effect at the control site was greater;
- in some publications groundwater level changes in several piezometers were averaged, so if any large rises occurred in only some piezometers, the effect would be reduced;
- some had been smoothed so groundwater level rises were blurred;
- they were not corrected for barometric effects, and so it was not clear which fluctuations were due to them;
• although the sample of hydrographs was a large one, it over-represented some regions and landscape positions, and under-represented others;
• as mentioned above, the length of record of most hydrographs was too short to give a true picture of the significance of episodic recharge.

2.3.5 Conclusion to Section 2.3

The hydrograph inspection gave a broad picture of the occurrence of episodic recharge although the assessments were problematic. Nearly half of the hydrographs were classed as 'possibly episodic'. Even if a large percentage of those assessments were wrong, the results imply that episodic recharge may be important below a significant proportion of south-western WA.

2.4 EPISODIC RECHARGE ELSEWHERE IN THE WORLD

2.4.1 Introduction

If episodic recharge occurs in the semi-arid areas of WA, it is likely that it also occurs in other semi-arid areas of the world, as well as in arid regions. The aim of this section of the literature review was to summarise the conditions and processes related to episodic recharge in arid and semi-arid regions, and to compare these conditions and processes to those in the south-west of WA. Information on episodic recharge from other climatic zones was included where it was thought to be relevant.

Unfortunately, many recharge studies in arid and semi-arid regions were designed to provide estimates of long-term mean recharge rates rather than to assess variations from year to year, and the term 'episodic recharge' (or any equivalent) was rarely used. Also, much of the research reported in the literature focussed on just one part of the landscape of a region or just one region of a country, and so the information available was geographically patchy.

Only one publication was found which focussed on the significance of, and the conditions leading to, episodic recharge events. This was by Jolly and Chin (1991) and related to locations in the Northern Territory of Australia (refer to Sections 2.4.2.4 and 2.4.2.5). They were interested in the implications that these pulses of recharge had for the management of groundwater resources, rather than land salinisation.
Another publication (French et al. 1996) estimated the frequency of rainfall events which could result in recharge in arid and semi-arid areas of Nevada. Their purpose was to gain information for use in contaminant transport models and on the lengths of record required to assess recharge rates. That publication considered rainfall conditions but not site conditions.

Information in many publications showed that large pulses of recharge occurred sporadically, so the conditions and processes they described were also reviewed.

The review is organised into geographical regions (Australia is considered first). Where there was sufficient information, the recharge regime, the associated rainfall regime and the processes involved are described, and then they are summarised in Section 2.4.8. The likelihood of similar conditions and processes occurring in the Wheatbelt of WA is discussed in Section 2.5.

Figures 2-1a and b show locations of places mentioned.

2.4.2 Australia

For Australia, there was relevant information from the Murray-Darling Basin (mostly from northern Victoria), and central and northern regions.

2.4.2.1 Murray-Darling Basin

A report by the Groundwater Working Group of the Murray-Darling Basin Commission (1996) contained representative groundwater hydrographs from irrigated and dryland districts throughout the Basin (which includes the parts of northern Victoria referred to in Section 2.4.2.2). Notes in the text stated that significant groundwater rises in some bores were related to wet years, floods or high river levels. The 163 hydrographs were assessed using the criteria used for the Western Australian hydrographs (Sec. 2.3). Again, the assessment was subjective, but it appears that episodic behaviour is widespread as most districts of the Basin had some episodic hydrographs. Table 2-2 summarises the results.
Table 2-2: Classes of hydrographs from the Groundwater Working Group (of the Murray-Darling Basin Commission, 1996) report on the status of groundwater

<table>
<thead>
<tr>
<th>Length of hydrograph record (y)</th>
<th>Number of hydrographs in class</th>
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<td>1</td>
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<tr>
<td>20-29</td>
<td>14</td>
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<td>22</td>
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<tr>
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<td>6</td>
<td>1</td>
</tr>
<tr>
<td>&lt;5</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Totals</td>
<td>46</td>
<td>15</td>
</tr>
</tbody>
</table>

2.4.2.2 Northern Victoria

2.4.2.2.1 The Southern Loddon Plain

Episodic recharge in dryland agricultural areas of Australia has been a topic of discussion since the phenomenon was recognised in aquifers below the Loddon Plain in northern Victoria (Macumber 1978). Regional groundwater systems in northern Victoria tend to flow northwards, away from the highlands of the Great Dividing Range, through the sedimentary aquifers of the Riverine Plain, towards regional discharge areas (Macumber 1991). The Loddon Plain is the part of the Riverine Plain associated with the Loddon River. The region has a semi-arid climate. Most rain falls in winter and annual averages are in the range of 500 to 250 mm.

Infrequent floods on the Loddon Plain result in groundwater rises much greater than those in years without floods. After a series of floods between 1973 and 1975, Macumber (1991) found that groundwater level rises in some bores were six times the usual rise. Floods were normally most extensive in the southern parts of the Plain as the rivers draining the highlands overflowed on reaching the Plain.

Macumber (1991) thought it likely that, across the Riverine Plain, direct recharge occurred on a regular basis everywhere that was not a permanent discharge zone. He also recognised that
"broad zones of preferential recharge" existed which channelled particularly large volumes of recharge to the aquifers. The alluvial nature of the Riverine Plain led to the development of such zones - there are alluvial fans at the boundary of the Plain and the highlands, and the aquitard overlying the main alluvial aquifer has "crisscrossing and interconnected shoestring sands", particularly in the southern sections of the Plain. He also noted that the recharge contribution from streams was enhanced when there were high flows as the fine sediments which usually coated the coarser streambed sediments were washed away, leaving the coarser materials more exposed to transmission losses.

2.4.2.2.2 The Northern Loddon Plain

In the northern parts of the Riverine Plain there are also areas where groundwater levels respond markedly in wet years, but Macumber (1991) reported that rises associated with the wet years of 1973 and 1974 were lower than those to the south. Below northern parts, the aquitard has shoestring sands similar to those to the south, and there are coarse marine sediments directly above the alluvial aquifer. Macumber (1991) believed that groundwater levels in the main alluvial aquifer responded to increased pressures from upbasin, and possibly also to direct recharge through overlying sediments. He did not mention whether flooding also occurred in this region of the Plain in 1973 and 1974, but floods are less likely than further south. Mean annual rainfall is much lower in the north than the south (about 250 to 350 mm compared to about 500 mm) and in 1973 and 1974 the southern part of the Plain was flooded by runoff from the highlands region. This runoff may not have reached the northern parts.

2.4.2.2.3 The Highlands

The effects of the wet years on aquifers in the highlands to the south of the Riverine Plain were not mentioned by Macumber (1978, 1991), but Reid (1995) identified episodic behaviour in a bore in sedimentary rocks below a pastured hill crest in the upper part of the Avon-Richardson Catchment, to the west of the Loddon Plain. He noted that there were 3 to 4 m rises in groundwater level during wet years, but "significant, steady declines during average to dry years". In contrast, two other bores in similar sites rose steadily over most of the monitored period, but by much lower amounts - over nine years, the average rise for the episodic bore was 45 cm/y, but was 10.5 and 7 cm/y in the other two (the former site was forested; the latter was under pasture). The behaviour in the episodic bore was related to
direct recharge. The episodic bore was in an area mapped as ‘sedimentary hills’ whereas the other two sites where mapped as ‘sedimentary rises’. The mapping methodology may have distinguished features which affected recharge regime, but the report did not describe the classification system used.

2.4.2.2.4 The Lower Avon-Richardson Catchment

The Avon-Richardson River system terminates in Lake Buloke. Reid (1995) considered that groundwater levels in both deep and shallow bores in the floodplain of the Lake had episodic rises and he suggested that they were closely associated with water levels in the Lake. Groundwater levels below nearby lunettes (crescent-shaped dunes which formed on the eastern shores of shallow lakes) also displayed episodic behaviour and Reid suggested that the groundwater could be responding to occasional flooding in the inter-lunette corridors. Upstream (approximately 40 km away), Reid identified another bore, within a 'flat clay plains' land management unit (LMU), which had episodic rises. He thought the rises resulted from flooding of the Avon River. He noted episodic behaviour in two other bores, one in a midslope site on the marine plains LMU and one in a midslope site on the Wimmera sedimentary rises LMU. He did not suggest reasons for the episodicity. Reid considered that ten out of the thirty groundwater hydrographs he presented had episodic behaviour.

2.4.2.2.5 The Mallee

Crop modelling indicated that recharge below some agricultural practices on sandy loam soils in the Mallee region of north-western Victoria could be episodic (O'Leary and O'Connell 1996). The model used daily rain data for a site where the mean annual rainfall was 338 mm. The period modelled was from 1939 to 1994, and the cropping systems used were continuous wheat and fallow-wheat, with and without stubble retention. The total water draining below the root zones of the crops ranged from 39 mm to 562 mm for the four treatments. This led O'Leary and O'Connell (1996) to conclude that agronomic management controlled drainage volume more strongly than rain. Drainage below continuous wheat without stubble retention occurred only in 7% of years (4 years out of 56), so if this drainage was to result in recharge, it would clearly be episodic. In comparison, the drainage below continuous wheat with stubble retention occurred in 59% of years (33 years out of 56). The fallow-wheat rotations resulted in more drainage than the equivalent continuous cropping. O'Leary and O'Connell did not state whether they considered any of the latter three drainage regimes to be episodic.
This simulation indicated that under conditions prevalent in the area, changing stubble management could dramatically decrease the potential groundwater recharge, and it appears that this would cause recharge to become more episodic. The paper did not comment on the differences in crop yields between the different agronomic practices.

In contrast, when Zhang et al. (1999) modelled groundwater recharge below different rotations of annual crop and annual and perennial pasture species in the Mallee region for a 32-year period, they found that water fluxes just below the modelled root zone (at 1.5 m depth) were episodic for all scenarios modelled. However, by 4 m depth the fluxes had been damped and were much less episodic.

2.4.2.3 Chowilla Anabranch system, South Australia

Jolly et al. (1994) studied the effect of a large flood on groundwater levels in an unconfined aquifer below the floodplain of the Murray River. The flood occurred in 1990 and had a return period of 1 in 13 years. It inundated much of the floodplain in the area under study (the Chowilla Anabranch), but there was little direct vertical recharge as the floodplain is covered by swelling clay, up to 5 m thick. However, below the clay is an alluvial sand deposit and hydrographs showed that groundwater levels in it rose in response to the flood, and there were indications from both groundwater rises and salinity that recharge was occurring through the bed of one of the main creeks. Jolly et al. noted that the covering of clay was absent from beds of some of the creeks and from higher areas on the floodplain. They did not state whether the higher clay-free areas played a role in recharge during the 1990 flood but they did state that only the highest elevation areas were not inundated. Thus, during a larger flood more areas without a clay seal could be inundated and so more recharge could occur.

2.4.2.4 Central Australia

Central Australia is arid - the annual mean rainfall is about 250 mm but is highly variable. At one station (Alice Springs) the annual rainfall between 1873 and 1990 ranged from 31 mm to 925 mm (mean 266 mm), while at a second station (Giles) the range between 1956 and 1990 was 100 mm to 691 mm (mean 260 mm) (Jolly and Chin 1991). Barnes et al. (1994) noted that it was not unusual for monthly totals to be ten times greater than the mean.

The groundwater in some aquifers is dominated by 'old' water (Cresswell et al. 1999a; Cresswell et al. 1999b) recharged during "favourable, wet, interglacial climatic regimes" (Cresswell et al. 1999a). The authors referred to the recharge as 'episodic', but their use of the term applied to wet climatic periods of several thousands of years when recharge occurred, separated by drier periods of tens of thousands of years.

'New' groundwater recharge is considered to be episodic (Barnes et al. 1992 and 1994) and occurs by two mechanisms: indirect recharge through beds and floodplains of ephemeral streams and rivers (Verhoeven 1977; Jacobson et al. 1989; Jolly and Chin 1991; Knighton and Nanson 1994; Harrington et al. 1998) and direct recharge below sandplains and dunes, weathered gneiss and schist, and fissured calcrete (Verhoeven 1977; Jacobson et al. 1989; Barnes et al. 1994; Harrington et al. 1998). Referring to a large part of Central Australia, Jacobson et al. (1989) considered that the amount of recharge resulting from flood events was much greater than that from direct recharge, but that it only affected aquifers over a restricted area. In contrast, Barnes et al. (1992 and 1994), referring to a relatively small part of the region, stated that the groundwater chemistry clearly showed that direct recharge was the dominant mechanism, and Harrington et al. (1998) also found direct recharge was predominant over indirect recharge in the Ti-Tree Basin to the north of Alice Springs.

Jacobson et al. (1989) found that recent recharge through joints and other fissures in sedimentary rocks was insignificant, although the mechanism had resulted in recharge in the past (carbon-14 dating of groundwater samples gave ages ranging from 12,000 to 32,500 years BP).
2.4.2.4.1 Processes of indirect recharge in Central Australia

When rivers in Central Australia flood, they tend to do it in a slow, unhurried manner. The floods last a long time, move slowly because of low gradients, and the flow volume tends to decrease en route (Knighton and Nanson 1994). Mean annual flows have extremely high coefficients of variability. A number of studies have looked at which flood events result in groundwater recharge. Jacobson et al. (1989) reported that Calf (1978) found that floodwater recharge to bedrock aquifers had occurred in two pulses at about 1400 and 5500 years BP (there is no mention of the source of the recharge nor of the actual ages of the pulses in Calf's paper). However, groundwater samples from associated aquifers were dated by Jacobson et al. (1989) and ranged in age from 0 to 5700 years BP. Stable isotope data indicated that the rainfall events which led to recharge were heavy and Jacobson et al. (1989) suggested that the climate may have been different to that at present. The groundwaters thought to have been recharged during floods showed little or no evidence of evaporation.

In contrast, hydrographs records for a shorter time period for a small fluvial basin at Alice Springs show that this aquifer has received recharge on a number of occasions since 1952 (Jolly and Chin 1991).

When the Finke River flooded in 1967 it was the largest event since at least 1895, but there were then larger floods in 1972 and 1974 (Baker et al. 1983). Jolly and Chin (1991) reported that flow records in the Todd River (which passes through Alice Springs) have been kept since 1953, and since then flows lasting more than ten days have occurred 18 times. However, 17 of the events were after 1972. Thus, large floods are not evenly distributed over the years. Baker et al. (1983) related the increase in frequency of major floods to an increase in the "influence of the north Australia monsoons and/or tropical cyclones".

Between September 1973 and August 1974 there was 925 mm of rain at Alice Springs. The Todd River flowed for 293 days during 1974, and groundwater levels in the small fluvial basin rose 6 m. Jolly and Chin (1991) calculated that the return period for the 1974 rain event was about 1 in 25 years. From the hydrograph they presented (reproduced in Figure 2-3), it appears that other individual groundwater rise events since 1952 were generally less than 2 m. (A long period of recovery from pumping between about 1964 and 1968 confounded the rises during that period.) Even though there were record flows in the Todd River during 1988, groundwater levels did not respond dramatically. Jolly and Chin explained that this was
because the rise in 1974 had effectively filled the groundwater basin. The water-level rise resulted in an increase in groundwater salinity in the small basin as the rising water dissolved salt stored in the previously unsaturated zone.

Jolly and Chin (1991) also reported the effect of the extremely wet 1973/1974 period at Docker River, to the west of Alice Springs (Figure 2-3). The aquifers there are also recharged from flows in ephemeral streams. The rainfall in the September to August water year (recorded as 690 mm at Giles, the closest rainfall station) resulted in groundwater levels rising 5 m between 1974 and 1976. This was in contrast to the total water-level rise since then to early 1990 of about 1 m.

The studies mentioned above described recharge from rivers which were relatively close to their headwater areas and had well-defined channels. The Cooper Creek between Curraweua and Nappa Merrie has a different character. It anastomises into many channels and its active width during floods can be 60 km (Knighton and Nanson 1994). Flow in the Cooper Creek
results when the monsoon in northern Australia penetrates southward and causes large rainfall events in the headwaters of the drainage system (this happens infrequently). Knighton and Nanson found that there were particularly large transmission losses (more than 75% on average) when the floodwaters overflowed the main anastomising channels along the Currareva-Nappa Merrie reach. They thought that transmission losses only contributed significant infiltration during the early stages of floodplain inundation, when there were large desiccation cracks in the clay surface. Because the clay swells on wetting, this mode of infiltration does not last long. They considered that evaporation and drainage diffusion (when lakes and depressions in the floodplain fill) caused most transmission losses. They did not discuss whether the clay formed a complete blanket across the whole floodplain area or whether, similar to the Chowilla Anabranch area on the floodplain of the Murray River described by Jolly et al. (1994) (Sec. 2.4.2.3), there were 'holes' acting as gateways to the underlying sandy aquifer. It seems unlikely that a clay blanket would be complete across such a large area, in which case, more infiltration may have occurred.

2.4.2.4.2 Processes of direct recharge in Central Australia

Near Alice Springs there are hills formed from gneiss and schist which have a thin cover of weathered material. The watercourses flowing through them are usually influent, but following record rains between 1973 and 1976, they became effluent (Verhoeven 1977). This was the result of direct recharge causing dramatic rises in groundwater levels in the small aquifers formed in the weathered materials.

Groundwater hydrographs and major ion chemistry from around Yulara indicate that direct recharge to aquifers in sequences of sandy beds underlying sand dunes is quite uniformly distributed across the area, although lesser amounts of localised recharge through beds of ephemeral streams close to hills also occurs (Barnes et al. 1992 and 1994). Only "infrequent very large events" result in significant recharge (Barnes et al. 1994). Hydrographs responded strongly to a rain event of 420 mm in March 1989 - the estimated return period for the rain was greater than 100 years. In two hydrographs presented by Barnes et al. (1994), reproduced in Figure 2-4, the 1989 groundwater rise of about 3 m was nearly three times as great as the only other one recorded, which was around the end of 1981 and beginning of 1982. The groundwater records only began in the late 1970s. Barnes et al. (1994) used rainfall records
to model groundwater responses and the results indicated that the large rain event in 1974 (see Section 2.4.2.4.1 above) resulted in a response of similar magnitude to that in 1981/1982. Barnes et al. noted that the magnitude of the 1989 groundwater rise and the timing of the response were related to the depth to the water-table at the site prior to the event - the shallower the water-table, the greater and faster the rise (Figure 2-5). For a few bores, regolith heterogeneity was considered to affect the manner in which the groundwater rose. They found that a specific amount of rain was required to make groundwater levels rise, and the effect of large rain events appeared disproportionately large. For their model they assumed that only monthly rainfall totals greater than 130 mm (about five times the monthly mean) caused groundwater recharge.

Figure 2-4: Measured and modelled groundwater levels and rainfall for near Yulara – the horizontal axis represents time and each tick is 5y, from 1965 to 1990; the left vertical axis represents water table elevation in metres; the right vertical axis represents effective rainfall (mm) (adapted from Barnes et al. 1994)

Figure 2-5: Groundwater rises for 1989 and depth to groundwater from bores near Yulara, adapted from Barnes et al. (1994)
Harrington et al. (1998) used environmental isotopes and other hydrochemical analyses to assess recharge mechanisms in the Ti-Tree Basin north of Alice Springs and came to conclusions similar to those of Barnes et al. (1994). They found that the stable isotopes in the groundwater corresponded to those in rain in months in which at least 150 to 200 mm fell (which occurs only once every 10 to 20 years (Harrington and Herczeg 1999)). They thought that most recharge was direct but that infrequent flows in rivers also contributed.

Jacobson et al. (1989) considered that macropores (discontinuities in calcrete, root channels and holes in termite mounds) channel percolating water in areas where direct recharge occurs in Central Australia. However, they also found that oxygen-18 and deuterium contents of groundwater samples indicated that the water underwent significant evaporation during the recharge process.

2.4.2.5 Northern Australia

Floodout areas as well as the beds of ephemeral streams are sources of recharge in two semi-arid areas in the Northern Territory described by Jolly and Chin (1991). At both sites (Warrabri and Tennant Creek) there was only one major groundwater rise event since the mid 1960s, when hydrograph records began. At Warrabri, the rise was 8.6 m and occurred between 1973 and 1977. Rainfall recorded at a station 90 km to the south had an annual mean of 312 mm, but from 1973 to 1977 there was an unusual sequence of high-rainfall years and the annual totals ranged from 652 to 875 mm. Jolly and Chin stated that the return period for annual rainfall greater than 600 mm was 15 years.

At Tennant Creek, groundwater levels also rose dramatically (4 m) between 1976 and 1978 (Jolly and Chin 1991). In this case the rainfall was above 600 mm in each of the three years, compared to the annual mean at Tennant Creek of 369 mm. Since 1874, the range in annual rainfall was 52 to 851 mm, and the return period for totals greater than 600 mm was 8 years. Jolly and Chin stated that a recharge rate of 1.2 mm/h had been estimated for the floodout area when it was inundated.

Further north, mean annual rainfall is higher and recharge is diffuse, occurring across much of the landscape, and rivers are more likely to act as discharge features than recharge features (Jolly and Chin 1991). Groundwater behaviour tends to be seasonal, rising during 'the wet'
(from November to March) and falling during 'the dry'. In the Douglas/Daly area, Jolly and Chin identified seasonal groundwater level rises up to 13.7 m. This largest rise occurred in the 1973 to 1974 wet season, which was part of a sequence of four years of particularly high rainfall (Figure 2-6). Jolly and Chin felt these four years resulted in elevated groundwater levels and that it was probably a long-term cyclical event. Similarly, at Gove, in the far north-east of the Northern Territory, Jolly and Chin thought the long-term cyclical rainfall event caused rises in the minimum annual groundwater levels of about 7.6 m between 1973 and 1978.

![Figure 2-6: Annual rainfall and groundwater levels from Douglas/Daly and Gove, adapted from Jolly and Chin (1991)](image)

### 2.4.3 Southern and Central Africa

#### 2.4.3.1 The Kalahari

There are deep unconsolidated sand deposits in the Botswana Kalahari, and a succession of papers has discussed the amount of groundwater recharge occurring below them.

The sand deposits overlie sedimentary rock sequences, which crop out around the boundaries of the region. The annual rainfall is extremely variable and the mean ranges from about 250 to 550 mm. De Vries (1984) presented a map which showed the coefficient of variability ranged from about 40% to 80%. The deep sandy soils are well-vegetated.
Verhagen et al. (1974) and Mazor (1982) used groundwater isotope analyses to show that groundwaters had recent components. Years which had particularly high rainfall, such as those of 1966 to 1967 and 1973 to 1974, were of "extreme importance" (Verhagen et al. 1974). Mazor stated that there could be preferred path flow through areas affected by bioturbation and through joints and fissures where the sedimentary rocks are close to the surface, especially during unusually large rain events. He did not expect recharge to be evenly distributed across the Kalahari. A geochemical study by Phofuetsile (1991) in the driest south-western part of the Kalahari also found signs of recent groundwater recharge which indicated that most of it resulted from infiltration of rain directly into fractures and joints in areas of shallow bedrock and from losses from rivers. The author thought that the recharge probably occurred "during discrete storm events or years of above average rainfall".

Verhagen (1991) summarised the results of several groundwater isotope studies which indicated that recent recharge (of about 3 mm/y) had taken place through deep sands (10 to 30 m) as well as through fractures and joints in shallow rock and through river beds. Verhagen emphasised that the "recharge is likely to be episodic, during statistical outliers in rainfall". Gieske et al. (1995) used stable isotopes and chloride mass balances to assess the flux of moisture through the deep soil profiles and found higher rates (between 9 and 15 mm/y). They stated that the recharge occurred when there were heavy rains and fast infiltration below the depth affected by evaporation.

However, interpretations of soil water-balance studies found that recharge through the deep sands was low. Foster et al. (1982) carried out balances for three different values of "near-maximum soil moisture deficit" of 185 mm, 125 mm and 50 mm. The 50 mm case resulted in excess rainfall (over the calculated evapotranspiration) in all years; the 125 mm case produced an excess in four years (mid 1966 to mid 1968, 1971 to 1972 and 1976 to 1977) and the 185 mm case had an excess in only one year (1971 to 1972), and it was only 10 mm and occurred on one day. Foster et al. noted that groundwater levels showed that widespread recharge only occurred in the 1971 to 1972 season. Also using soil water-balances, Boocock and van Stratten (1962) showed that plant roots would be able to access about 6 m of the Kalahari sand and that 80 mm of rain were required to bring this depth to field capacity (this work was reported in de Vries and von Hoyer (1988); the original publications were unavailable). Therefore, they thought that widespread direct recharge was unlikely, but that
episodic indirect recharge resulted from runoff into depressions and valley floors. They thought this type of recharge contributed only minor amounts to the aquifers.

Thus, it seems that all authors agree that any recharge that occurs in the Kalahari is episodic, and most think it can occasionally occur by direct matrix percolation below root zones in deep sands, and more frequently where the sand is shallow and bedrock close to the surface, and that indirect recharge can occur where rainwater accumulates in depressions and watercourses. The differences in opinion about the quantity of recharge may partly result from some authors (e.g. Foster et al. (1982)) basing their views on the results of water-balance analyses which did not take into account the role of preferred path flow.

2.4.3.2 Eastern Botswana

Recharge processes appear clearer in eastern Botswana. Gieske and Selaolo (1988) studied areas of fractured rock and alluvial soils east of the Kalahari sand deposits, where mean annual rainfall was about 500 mm with a variability of about 30%. Recharge was rapid through fractured-rock aquifers and coarse alluvium in ephemeral stream beds, but where there were coarse colluvial and alluvial fans at break-of-slope positions, recharge was even faster. They considered that as runoff increases as a power function of the cumulative rainfall, during the very wet years there are "exceptional" amounts of indirect recharge in areas such as depressions and watercourses, thin soils over fractures, and fissures in rocks. Under such circumstances, the infiltration rates of the soils would determine the amount of recharge. Assumptions of steady piston flow would be inappropriate. They suggested assessing the occurrence of large rainfall events using intensity-duration-frequency and depth-area-duration analyses. Further studies were described by Gieske (1992) which confirmed that recharge was episodic, occurring only in about a third to a half of years.
2.4.3.3 Namibia (South West Africa)

In Namibia (South West Africa), boreholes showed a significant rise in water level following "phenomenal" rains from 1950 to 1951, and Dr. H. Martin (unpublished, reported in Frommuzre 1953) thought that large-scale aquifer recharge only occurred when there were unusually high rainfall years (about once every ten years).

It was found by Crerar et al. (1988) that where recharge results from infiltration through river beds during floods, the amount of recharge cannot be predicted from the size of the flood as it depends on the degree of sealing that silt along the riverbed causes.

2.4.3.4 Transvaal

Hydrographs from the Transvaal presented by Bredenkamp (1988a and b) showed that there were eight major recharge events over a 33-year period for a site in a dolomite aquifer and three major recharge events over a 21-year period in fractured bedrock aquifers with thin overburden (0.6 to 7 m thick). The amount of recharge varied with the thickness and properties of the overburden materials, but he considered that the relationships between recharge and rainfall were linear above the rainfall threshold for all cases.

2.4.3.5 Zimbabwe

In Zimbabwe, "a few years with heavy rainfall are more important in producing recharge than many years of average rainfall" (Houston 1988). The aquifers are in the fissured crystalline basement rocks and in the overlying regolith (derived from weathered bedrock). Because of the temporal pattern of recharge, Houston emphasised the importance of using data from many years to make estimates of recharge. At Masvingo, in the centre of the study area, rainfall was seasonal with an annual mean of 623 mm, but annual totals ranged from 40 to 220% of the mean. Over 84 years of record there were some indications that annual rainfall amounts varied in a cyclic manner, with sequences of high rainfall years occurring about every 23 years. Houston used a recharge-runoff model to assess direct recharge over a ten-year period and the results showed that although there was a small amount of recharge in most years, there were four extremely large events in three of the years which contributed most of the recharge (the three years produced 75% of the ten-year total). Houston suggested that areas with mean annual rainfall less than 400 mm are unlikely to have recharge.
2.4.3.6 Uganda

The climate in Uganda is humid. Taylor and Howard (1996) found that the mean annual recharge of 200 mm to aquifers of the Victoria Nile Basin was related more strongly to the number of large rain events (more than 10 mm/day) than to the total annual rainfall (mean 1400 mm/y).

Comparing recharge in a catchment with deeply weathered profiles (mean annual rainfall 1576 mm) with that in a tectonically uplifted catchment where the regolith had been stripped to leave only shallow soils (mean annual rainfall 930 mm), Taylor and Howard (1999) found that the former had about 120 mm/y while in the latter, "groundwater recharge is restricted to years of exceptionally high rainfall". They referred to the former catchment having a recharge-dominated regime, and the latter, a runoff-dominated one.

2.4.3.7 Tanzania

Onodera (1993) studied the recharge rates and mechanisms through soil profiles with shallow water-tables (about 2.5 m deep) over fractured granitic bedrock, in an upland region of Tanzania (mean annual rainfall of 550 mm). Using deuterium and oxygen-18 analyses, he found that a large proportion of some rain events reached the groundwater too rapidly to be explained by matrix flow. Onodera traced the wetting front following a sequence of rains. This showed distinct deep penetration in fingers following heavy rain events (of about 50 mm), while earlier smaller rains of less than 10 mm had produced a more regular wetting front.

2.4.4 Niger

In the Sahel of Niger, pools and streams are the main sources of recharge (Desconnets et al. 1997: Leduc et al. 1997). Most surface drainage flows to seasonal pools on valley floors which have topographic catchments of about 1 to 10 km², or to pools on laterite plateaus which have catchments of only a few hectares (Desconnets et al. 1997). The centres of the pools are underlain by low-permeability clays, but around the perimeters there are sandy soils with high permeability. Some of the valley floor pools are "sinks" and drain through preferred paths, taking only a few days to become dry. While water overlies the sandy perimeters of the other pools, the water levels drop rapidly. Each pool has a stage at which the rate of lowering slows sharply, coinciding with the retreat of the water to the areas.
covered by clays. Infiltration is then still significant, but slower, and a monitored plateau pool dried out in a few weeks, while a monitored valley floor pool took about 3 months (Desconnets et al. 1997).

About 50% of the water that entered the monitored plateau pool infiltrated, and about 80% of that entering the monitored valley bottom pool (the remainders evaporated). Vegetation is dense around the pools, and Desconnets et al. (1997) considered that it used some, but not all, of the infiltrated water. Leduc et al. (1997) showed that substantial groundwater mounds formed below pools, although the height and extent of the mounds varied greatly from one pool to another. Monitoring of a valley floor pool showed that the water-table, about 16 m below the pool, began to rise a few weeks after the rainy season started, but once the groundwater levels had started to rise, they then responded to each runoff event.

Desconnets et al. found that the percentage of the rain in the catchment that entered the monitored valley bottom pool depended on the seasonal rainfall distribution. In 1992 the distribution was unusual. The rain was concentrated into two 2-week periods and runoff was high, with the result that about 20% of the rain that fell in the pool catchment infiltrated below the pool. In 1991 the total rainfall was the same (463 mm) but fell more regularly, and only about 5% of it infiltrated through the pool. Thus, it seems that seasons with unusual rainfall distributions which result in unusually high runoff could cause significant indirect episodic recharge.

2.4.5 North Africa and the Middle East

Not surprisingly for such a large region, there are differences of opinion on how significant direct recharge is across northern Africa and the Middle East. Some consider it negligible (e.g. Besbes et al. 1978) while others have found evidence of it across wide areas (e.g. Dincer et al. 1974). Indirect recharge from ephemeral streams (wadis) is accepted as a major source of groundwater in many of the areas (Besbes et al. 1978; Allemmoz and Olive 1980; Abdulrazzak et al. 1989).

In the central part of Tunisia, the timing and amount of streamflow is highly variable, and recharge is also (Besbes et al. 1978). Hydrographs recording six years of groundwater levels show that there were at least 11 recharge events, but in 1969 there was an exceptionally large
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one which coincided with a major flood. Groundwater levels were still elevated as a result of this event five years later.

A 20-year hydrograph from north-western Libya showed that the "exceptional" floods in 1964 caused a much larger pulse of recharge than any other event over the period (Allemmoz and Olive 1980). Floods in wadis discharging from a mountain range spread out over the downstream plain. Indirect recharge occurred through the beds of wadis and below flooded areas on the plain. Macropores played an important role in transporting indirect recharge to the water-table from the depressions where the water ponded and from the flood-slackening areas (Allemmoz and Olive 1980).

A study on direct recharge through coarse-grained sand dunes found evidence that it was a widespread form of recharge in north Africa and the Middle East (Dincer et al. 1974) but the amount was expected to vary greatly between years as the rainfall is not regular. From 1962 to 1972, Dincer et al. considered that recharge was only likely to have occurred during three or four winters, and it seems that it was substantial during only one of these periods. They noted that the recharge potential of a series of light rains is much less than that of an equivalent amount of rain occurring in one heavy shower.

Caro and Eagelson (1981) modelled direct recharge for areas where major aquifers crop out in central Saudi Arabia and calculated the return periods of a range of annual recharge amounts. As an indication of their results, one of the situations they modelled showed that annual recharges of 100 mm, 50 mm and 30 mm had return periods of about 50 years, 10 years and 5 years (mean annual rainfall in the areas of outcrop appeared to be between 60 and 120 mm). Dincer (1982) thought that the estimates of recharge produced by Caro and Eagelson gave the impression of much greater certainty than was warranted considering the lack of good data available to them.

2.4.6 India

There appear to be thresholds of rainfall below which recharge does not occur, and the relationship between the threshold and the mean annual rainfall changes with climatic zone (Sinha and Sharma 1988). This implies that all recharge in an area where the threshold is far above the mean annual rainfall amount will be episodic. At an arid site in India where the mean areal seasonal rainfall was 190 mm, there was no recharge in a year with rainfall 43% greater than the mean, but when rainfall was 442 mm (about 2.3 times the mean), the recharge
was 34 mm (Sinha and Sharma 1988). In a semi-arid area, there was no recharge when rainfall was average, but there was some when rainfall was 10% above average. The amount of recharge appeared to increase according to a power relationship with the amount of rainfall above the threshold. There was 14 mm of recharge when rainfall was 117 mm above the threshold and 85 mm of recharge when rainfall was 208 mm above. In a humid zone, there was recharge in most years and the amount appeared more linearly related to the rainfall.

However, in a semi-arid catchment in central India, it was not the total amount of rainfall which determined direct recharge so much as the timing of the rainfall events (Athavale and Rangarajan 1988). There were two years with similar rainfall totals and they both had two large rainfall events. In one year, the two events were several weeks apart and the resulting recharge was 32 mm; in the other year, the rainfall events were close together at the end of the rainy season and only produced 17 mm of recharge. The recharge was lower in the latter case because a greater proportion of the rainfall became runoff.

In western Rajasthan, direct recharge only occurs when rainfall is intense; such events occur only every few years (Chandrasekharan et al. 1988). Indirect recharge via infiltration through river channels is also only an occasional event as it relies on episodic floods.

2.4.7 North and Central America

2.4.7.1 Central United States of America

The Great Bend Prairie region of central Kansas has mean annual precipitation in the range of 560 mm to 740 mm (Sophocleous 1992). A drought in 1991 was followed by wet conditions in 1992 and early 1993, then during the summer of 1993 there was a sequence of heavy rains which resulted in a total that was twice the mean amount (Sophocleous et al. 1996).

Sophocleous et al. (1996) studied the effects of the large rains on groundwater levels in an aquifer underlying central Kansas. The largest rises were in areas where the water-table was shallow and these areas were the natural discharge zones of the aquifer. Groundwater level rise was also closely related to the amount of rainfall at a site. The result was that water-tables were the highest they had been since 1973 and recharge was in the range of three to more than four times greater than mean.
2.4.7.2 Western United States of America

Precipitation in arid and semi-arid areas of the United States of America (USA) tends to result from intense summer thunderstorms (which are "limited in size and rarely cover an entire basin" (Marco and Valdes 1998)) and showers associated with frontal systems in autumn and spring. The relative importance of the different types of precipitation varies from region to region. As an example, a modelling study by Kafri and Asher (1978) of recharge in southern Arizona found that the short, intense summer thunderstorms contributed less recharge than winter rainfall, even though the total of summer rain was greater (54% of the mean annual rain). Cable (1980) came to similar conclusions from measuring available soilwater at his study site, also in Arizona. He found that the differences between rainfall infiltration in summer and winter were greater for bare soil sites than for vegetated sites. The relatively small effect of summer rainfall was attributed to the higher intensities more often exceeding infiltration rates and causing more soil surface sealing, and to the higher evaporation rates depleting soilwater more rapidly. Cable also noted that in pits and swales in the landscape where surface water accumulated, soils were wet to greater depths compared to slope sites. However, Cable did not consider that water drained below depths where it could be evapotranspired. Though lower infiltration was cited as a reason for lower soilwater accumulations in summer at some sites, and ponding was cited as a cause of increased soilwater accumulations at some sites, Cable did not mention whether sites prone to ponding had greater infiltration in summer (as a result of increased runoff from adjacent slopes) than in winter.

Winograd et al. (1998) also found that summer rainfall contributes proportionally less recharge than winter precipitation (which was in the form of snowmelt) to aquifers below the Spring Mountains in southern Nevada.

Stephens (1994) stated that in semi-arid and arid areas it is possible that most recharge occurs when there are a few years of high precipitation, which may only happen about once every ten years or even once every hundred years. He thought that "research is needed to determine whether significant recharge events could be correlated to the recurrence interval of extreme precipitation events". However, French et al. (1996) assumed that there was such a correlation. Using soilwater data from less than two years (1992 and part of 1993) at two sites in Nevada, they identified occasions when "deep" penetration (>1.5 m) had occurred.
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(941, and, therefore, potential recharge). The rainfall station considered most representative of the soil measurement sites had 206 mm of rain in 1992, which had a return period of 1.3 years. Two other nearby rainfall stations had 1992 rainfalls of 434 mm and 262 mm, which had return periods of 5.1 years and 4.1 years, respectively. French et al. then used long-term rainfall records to estimate the frequency of deep water penetration. The lack of appropriate soilwater data meant that they could not assess the frequency of deep penetration from summer rainfall events, but they considered that rainfall totals for calendar years, winter periods (start of October to end of April) and 'two to three consecutive winter months' could be used to indicate whether deep penetration would occur. For the range of rainfall stations they used, the average return periods for deep moisture penetration were from 1.3 to 22 years.

2.4.7.2.1 Indirect recharge

Occasional flows in streams and rivers are important sources of groundwater recharge in arid and semi-arid regions of the western USA (Babcock and Cushing 1942; Aldridge 1970; Stephenson and Zuzel 1981; Schlehuber et al. 1989), but fluxes through soils below relatively small topographic depressions may also contribute significant amounts (Scanlon et al. 1999). The recharge rate through the streambed studied by Babcock and Cushing (1942) was greater during winter than summer because winter floods lasted longer and carried less silt than those in summer. However, the study lasted only two years so long term behaviour may be different.

Groundwater is recharged from flows on floodplains in Arizona and New Mexico (Aldridge 1970). Groundwater level rises occurred as a result of floods caused by an unusual sequence of heavy rainfall events in late 1965.

Two floods in a desert area of California illustrated that it is not just total rainfall or flood volume which determines recharge. In 1969 there was a flood with a recurrence interval of 30 years while in 1978 there was one with a recurrence interval of 20 years (Buono and Lang 1980). However, there was more recharge in the drainage basin from the 1978 event. The reasons given by Buono and Lang for the greater 1978 recharge were that precipitation in 1978 was spread evenly over several months so that there was a more uniform spread of flow in the river; that more water was retained in the basin for longer because dams had been built post-1969 and these also regulated flow; and that the groundwater level was lower prior to the 1978 flood so that there was more room for storage of recharge.
Scanlon et al. (1999) compared fluxes of water through soil profiles below interdrainage areas, drainage areas and "localized topographic depressions (fissure, gully, and borrow pit)" in the Chihuahuan Desert, Texas. They found that there was a strong relationship between geomorphic site and water flux, with low water fluxes in the interdrainage areas (0.02 to 0.05 mm/y) and high water fluxes below the depressions (approximately 100 mm/y), illustrating the importance of depression-focussed recharge. Recent fluxes below drainages were low, but there were indications that there had been higher fluxes in the past under different climatic conditions.

2.4.7.2.2 Direct recharge and redistribution

Groundwater hydrographs presented by Stephenson and Zuzel (1981) show that water levels in weathered fractured basalt at a site overlain by residual soils (about 2.1 m deep) appeared to be more prone to episodic rises than those at a site in fractured basalt without a soil cover. The sites were in a semi-arid part of south-western Idaho (mean annual rainfall 250 mm), and where there was no soil cover, groundwater levels responded more often and more rapidly to rainfall than at the sites with a soil cover. However, on one occasion during the five-year hydrograph period, the site with soil had a particularly large water level rise compared to the other rises at that site and to the rises in the soil-less site. Stephenson and Zuzel considered that direct recharge was occurring at both types of site, but that the sites with soil also acquired lateral recharge from the areas without soil.

2.4.7.3 Mexico

Hurricanes cause episodic groundwater rises in areas bordering the Gulf of Mexico. Rainfall of about 130 mm and floods resulting from a hurricane which crossed the Yucatan Peninsula caused an unusually large groundwater rise in piezometers across a wide area (Marin et al. 1990). In the two weeks before the hurricane, about 136 mm of rain had fallen and this enhanced the effect. The annual mean rainfall ranges from about 500 mm to 1000 mm across the Peninsula.
2.4.8 Summary of conditions leading to episodic recharge elsewhere in the world

Even though the geographical distribution of the areas studied was patchy, information on a variety of conditions and processes was available. The following summarises the information in terms of rainfall conditions, regolith and bedrock characteristics, recharge processes, water-table depth, rainfall thresholds and rainfall-recharge relationships.

2.4.8.1 Rainfall conditions

There does not seem to be just one type of rain event, such as tropical cyclones, which results in episodic recharge. Episodic recharge at a site may always be due to the same type of rainfall event, or there may be several meteorological situations which result in episodic recharge. The meteorological systems which have been associated with episodic recharge can be divided into two types - those which are inherently irregular, such as cyclones and summer thunderstorms, and those which are regular features with inherent variability (for example, frontal systems and monsoons) so that some events, years or cycles of years are unusually wet. From the publications reviewed it seems that areas which experience episodic recharge are:

- areas subject to tropical cyclones and deep rain-bearing depressions resulting from decayed tropical cyclones;
- areas subject to infrequent, intense spring and summer thunderstorms;
- areas on the fringes of zones with regular rainfall patterns - e.g. areas which are occasionally influenced by monsoonal or frontal activity;
- areas receiving regular rainfall from monsoons or frontal systems, but where the rainfall is markedly higher some years than others (i.e. annual and monthly rainfall totals have large coefficients of variation);
- areas where regular causes of rainfall have cyclic fluctuations - so there may be a few wet years separated by drier ones.

In regions where direct recharge is predominant, well-spaced large rainfall events may result in more recharge than many close together, as the latter situation could generate more runoff. However, this has to be balanced by the amount of water lost to evapotranspiration during the breaks between well-spaced events.
At places where indirect recharge results from surface and shallow subsurface flow, then a series of closely-spaced rainfall events is likely to result in more recharge than a well-spaced series, because of the greater runoff produced.

2.4.8.2 Regolith and rock type and recharge processes

2.4.8.2.1 Direct recharge

Direct episodic recharge has been recorded from:

- areas where fractured bedrock is at the ground surface or has only a thin soil cover;
- areas with deep sandy profiles, such as sand dunes;
- areas underlain by fissured calcrete.

Preferred path flow, resulting from fingering or from macropores (e.g. fissures in calcrete, root channels or biopores resulting from bioturbation), means that the amount of direct recharge is not necessarily uniform across areas, and that large proportions of heavy rains can become recharge quickly.

2.4.8.2.2 Indirect recharge

Perhaps the most widely recognised form of recharge in arid and semi-arid areas is that which occurs through the beds of lakes and ephemeral watercourses and pools, and through the associated floodplains.

Clay and silt deposits may control the amount of water which infiltrates. In watercourses, more recharge is likely to result from water with a low silt load, from high stream flows, and from prolonged flow periods. Pools may have clay deposits below their centres, but sandy soils below their perimeters. Although floodplains are commonly underlain by deposits of clay, there may be restricted zones with higher permeability, such as alluvial fans and shoestring sands, which become inundated during floods. These sandier profiles then act as preferential recharge zones. Because of the way that floodplains develop, the permeable deposits may be more common near the boundary between the sloping country and the plain.

The catchments for large floodplains are commonly hill or mountain ranges with relatively high rainfall. Surface water flows from them in well-defined channels, but at the boundary to the plains, the water can flood the banks or flow into distributaries, and inundate the
permeable soils. Lower parts of floodplains receive less water, so recharge tends to be concentrated at the boundary between the uplands and the plains.

2.4.8.3 Water-table depth

Infiltrating water is more likely to become recharge, and will do it more quickly, where the water-table is shallow. So, if an area receives only episodic rainfall or floods, then those sites with shallow water-tables will receive more episodic recharge. However, recharge can be limited if the water-table rises so close to ground level that there is not enough storage space for all of the potential recharge.

2.4.8.4 Rainfall thresholds and rainfall-recharge relationships

Generally, a certain amount of rainfall is required before recharge will occur at a site. This amount is the rainfall threshold. The threshold varies with landscape and regolith properties (e.g. grain size of sand dunes), land management (e.g. whether a crop is sown into retained or burnt stubble), and rainfall and soil moisture conditions (and so the water-table depth may also have an influence). The higher the threshold is above the mean annual rainfall, then the more likely it is that any recharge will be episodic. Above the threshold, either linear or power relationships between rainfall and recharge may hold.

2.5 IMPLICATIONS FOR THE SOUTH-WEST OF WESTERN AUSTRALIA

The relevance of the recharge conditions and processes found in other parts of the world to episodic recharge in WA is discussed in this section. Locations of named places are shown in Figure 2-1a and b.

2.5.1 Rainfall conditions

In terms of rainfall regime, the agricultural areas of WA fall into several of the categories of areas subject to episodic recharge (Sec. 2.4.8.1).

2.5.1.1 Tropical cyclones and deep rain-bearing depressions

Tropical cyclones originating to the north and north-west of WA tend to track south and south-east, and sometimes affect the south-west of the state (Figure 2-7). From 1830 to the mid 1990s, 24 tropical cyclones impacted on coastal areas south of Geraldton, but not all crossed the coast (Bureau of Meteorology 1995). As tropical cyclones cross the coast they
lose much of their energy, and tend to decay into deep rain-bearing depressions (Crowder 1995).

2.5.1.2 Infrequent, intense spring and summer thunderstorms

In late spring and summer, unstable air to the east of troughs of low pressure can result in intense thunderstorms over Western Australian agricultural areas (Bureau of Meteorology 1995; Keywood 1995).

![Figure 2-7: Tracks of tropical cyclones in the Australian region over a ten-year period (from Crowder 1995)](image)

2.5.1.3 Regular rainfall from frontal systems with high variability

WA is on the northern edge of a temperate cyclone belt which circles the southern polar regions. The influence of the temperate cyclones (or 'depressions') extends northwards across southern Australia in winter, and the cold fronts associated with them bring rainfall (Crowder 1995; Keywood 1995). Normally, the cyclones remain south of WA, although they sometimes cross the coast of south-eastern Australia, which results in particularly large amounts of rainfall. The cold fronts bring the regular 'seasonal' component of the south-west's rainfall. The mean annual amounts decrease inland from the south and west coasts. In most years, agricultural areas receive 60 to 70% of their rainfall between May and October (Perry 1991). Data presented by the Bureau of Meteorology shows that variability increases with
decreasing median annual rainfall (<http://www.bom.gov.au/climate/averages/tables>). At Bridgetown, the decile 9 rainfall is 126% of the median annual rainfall (i.e. 1040 mm in relation to 827 mm), whereas at Southern Cross it is 140% (388 mm in relation to 277 mm).

2.5.2 Regolith and rock type and recharge processes

2.5.2.1 Direct recharge

WA has areas with similar properties to many of those elsewhere in the world where direct episodic recharge has been recorded (Sec. 2.4.8.2.1).

2.5.2.1.1 Fractured bedrock at or close to the surface

Fractured igneous and metamorphic bedrock underlies parts of the agricultural region at shallow depths, and there are also small areas of well-jointed sedimentary bedrock covered by thin soils. However, there is also evidence from quarries that some igneous bedrock is massive, and where unweathered bedrock of this type is close to the ground surface, direct recharge is unlikely to be important compared to runoff.

2.5.2.1.2 Deep sands (and gravels)

WA is well-known for its extensive sandplain landscapes in the central, northern and eastern parts of the agricultural areas. In addition, there are deep gravel profiles (Figure 2-8) in western agricultural regions and their responses to large rainfall events could be similar to those of deep sands.

2.5.2.1.3 Fissured calcrete (and silcrete and lateritic duricrust)

Calcrete is not extensive in the Wheatbelt, but two other forms of duricrust are common. Silcrete is often found at shallow depths below valley floors, and ferricrete (lateritic duricrust) sheets are common, particularly in western areas and high in the landscape. Both of these types of duricrust have discontinuities which can act as preferred paths (Figure 2-9). Ruprecht and Schofield (1993) found that a lateritic duricrust had large holes (infilled with coarse gravel and rocks) which had saturated hydraulic conductivity values around 10 m/day and that even the 'massive' parts of the duricrust had values of around 2 m/day because of smaller holes within it.
2.5.2.1.4 Preferred path flow

The regolith in WA has several other features which favour the development of preferred path flow through the unsaturated zone. The agricultural areas were originally covered by woodlands and heath with mixtures of plants with a variety of root distributions, some deep. When the native plants were removed for agriculture, the roots remained (Figure 2-8). They gradually rotted, leaving relatively permeable channels for water movement.

Many of the clay soils in WA are well-structured. In soil pits, it is common to see roots following the cracks between ped faces, and in winter, to see water flowing along them.
Another form of preferential flow was recognised by Johnston (1987). In a forested area, he found that the regolith heterogeneity over distances of a few metres led to zones of preferential recharge. He thought that the heterogeneity was related to the structural geology of the site, and similar situations to the one he studied are common in agricultural areas.

2.5.2.2 Indirect recharge

Wheatbelt valley floors tend to have low gradients. Watercourses from the slopes become poorly-defined once they reach the valley floor and there are many shallow closed depressions. These features make valley floors prone to flooding and ponding. Shoestring sand deposits are also a common feature (Figure 2-10), as are shallow lakes. Such areas in other parts of the world with arid and semi-arid climates are important recharge zones.

In WA, floods can be flash floods resulting from very intense rainfall associated with, for example, thunderstorms, or 'general' flooding can occur as a result of widespread rainfall events (Bureau of Meteorology 1995). Between 1830 and 1982 there were at least 12 years when extensive flooding affected agricultural areas of WA. Most flooding occurred during the winter months (June and July particularly), but in three years there was flooding in January or February (Bureau of Meteorology 1995).

Therefore, there is episodic flooding in the Wheatbelt of WA and it is likely to lead to indirect episodic recharge.
2.5.3 Water-table depth

The water-table is rising below most areas of the Wheatbelt following the replacement of native vegetation with agricultural species. Infiltrating water is more likely to become recharge, and will do so more quickly, where the water-table is shallow (Sec. 2.4.8.3). This implies that if there are sites in the Wheatbelt with episodic sources of infiltration, and they coincide with areas of rising water-tables, then the areas prone to significant episodic recharge will increase. However, this may be counterbalanced by a decrease in recharge at sites where the water-table is so shallow that the ability to accept unusually large pulses of infiltration is limited.

The reverse trends in episodicity could hold where groundwater levels are falling due to pumping or change in vegetation.

Thus, where the groundwater system is not in balance, the importance of episodicity may change with time.

2.5.4 Rainfall thresholds

The rainfall threshold for a site is a convenient concept, but it will not have a fixed value. Annual thresholds, monthly thresholds and rain event thresholds can all be useful ways of describing the behaviour of a site, but they are all influenced by the conditions prior to the event being considered.

Because mean annual rainfall in WA decreases eastward from the west coast and northward from the south coast, a particular rainfall threshold is more likely to be exceeded in the south-west than in the north-east. Therefore, episodic recharge may be more widespread in the north-east. However, there is a wide variety of landscape types, regolith profiles, evapotranspiration regimes, and depths to water-table in all regions, so within a region, there are likely to be areas where thresholds are regularly exceeded, and areas where they are not.
2.6 SUMMARY AND CONCLUSIONS

Published information was reviewed to assess whether episodic recharge was likely to be significant in south-west WA. The assessment was based on:

- whether there was evidence that episodic recharge is important compared to regular recharge in south-western WA, and
- how conditions in south-western WA compare with those in other parts of the world where recharge is episodic.

A review of published groundwater hydrographs from south-western WA indicated that episodic recharge may be important below a significant proportion of the agricultural region, and comments in the literature associated large recharge pulses with periods of unusually high rainfall or floods.

Some of the rainfall conditions associated with large pulses of recharge in other regions of the world also occur in south-west WA (decayed tropical cyclones and summer storms, and temperate cyclone seasons with high variability). Some landscape characteristics (e.g. deep sands and preferred paths) which influence direct episodic recharge elsewhere are common in WA, and occasional floods, which cause episodic recharge throughout the arid and semi-arid regions of the rest of world, are also features of catchments in WA.

Thus, published information from WA and the rest of the world indicates that recharge below some parts of the landscape in the south-west of WA is likely to be episodic. There was not enough information to determine whether episodic recharge contributes a significant proportion of the total recharge.
3. HOW CAN A SIGNIFICANT EPISODIC EVENT BE IDENTIFIED?

3.1 INTRODUCTION

One of the aims of this thesis was to determine the significance of episodic recharge compared to regular recharge in the Wheatbelt of Western Australia (WA). Comparing the relative importance of the two types of recharge regimes required a repeatable, objective method of distinguishing between them and of determining how much recharge constituted a 'significant' amount. No suitable published method was found, so the aim of the investigation described in this chapter was to develop such a method.

Both water-balance modelling and groundwater hydrographs can provide information on recharge regimes. Most modelling studies are based on rainfall records, and because rainfall data is commonly available as daily readings over relatively long time periods, the models can be designed to produce recharge data as time-series for short, regular intervals, and for long time periods. Such data sets can then be graphed and visual assessments of episodicity made, but they might also be suited to statistical analyses which could provide the required objective and repeatable methods of differentiating sites.

Groundwater hydrographs usually cover much shorter periods than rainfall records, and since daily (or more frequent) groundwater level recordings have only become common since the advent of data-logging systems, the longest hydrographs tend to have infrequent and irregular monitoring intervals. In addition, hydrographs do not give a direct measurement of recharge. However, visual assessment of hydrographs can provide useful qualitative information. In Chapter 2, a simple classification system was developed to distinguish between hydrographs which were 'possibly episodic' and those which were 'probably not episodic'. Other simple classification systems could be developed to compare hydrographs from different sites and to compare the importance of different periods of groundwater level rise at a site. Three methods which were found to be useful are described in Section 3.2. However, such systems are not objective, and their repeatability is questionable. Can statistical analyses allow objective and repeatable distinctions to be made between episodic and non-episodic hydrographs?
The application of statistical methods to time-series data sets from both model output and hydrographs is complicated because of:

- the need to consider both the significance of a recharge event (which relates to its magnitude) and the episodicity of a recharge event (which relates to its frequency); and
- the characteristics of recharge data sets and groundwater hydrographs.

These constraints are discussed in Sections 3.3 and 3.4.

In developing the required method, literature on recharge time-series and other hydrological analyses, and episodic phenomena in other fields (such as recruitment of rangeland plants) was reviewed (Sec. 3.5 to Sec. 3.8). (The usage of the term 'episodic' in surface water chemistry (e.g. Eshelman 1988) and in Bradd's (1996) study of groundwater hydrographs was different to that in this thesis. In this study, the term was applied to recharge events which were infrequent, irregular and unpredictable, but Bradd (1996) and surface water researchers have used it to refer to sharp rises in groundwater level or acidification of surface water which can occur several times a year, especially in humid climates. Such rises are less rare and more predictable than the episodic events of this study. In contrast, 'episodic' has also been used to refer to periods of high recharge lasting hundreds and thousands of years (e.g. Cresswell et al. 1999a). Thus, methods of identifying episodic events that are used in those publications are not relevant to this discussion.)

Although it was found that some documented analyses could be applied to some recharge data sets, none of them satisfied all of the constraints. So, a simple grading system was also developed (Sec. 3.9). It is compared to the most appropriate visual assessment methods and descriptive statistics using example data sets in Section 3.10.

The investigation is summarised and conclusions are drawn in Section 3.11.
3.2 GROUNDWATER HYDROGRAPH GROUPINGS BASED ON VISUAL ASSESSMENTS

Although groundwater hydrographs do not necessarily represent the recharge that occurs at a site, they do record the groundwater rises, and show whether the rises at a site were episodic or regular during the period of record. There are many ways of comparing groundwater hydrographs from different sites, and three subjective ways of grouping sets of hydrographs are proposed here, each with a different use. Examples of their application are presented in Section 3.10.

3.2.1 CLEAR class

The simplest way of assessing the episodicity of a hydrograph is to subjectively decide whether it looks 'clearly episodic', 'clearly not episodic', or 'not clearly episodic during the recorded period but episodicity seems possible' - e.g. if it had large reactions to summer storms. This type of classification is similar to that described in Chapter 2, but that system incorporated information from comments in the text of publications. This system depends solely on the information in the hydrographs. It will be called CLEAR ('Clearly Looks Episodic' Assessment of Rises). The primary use of such a simple classification is to check that the results of less subjective systems (which are likely to have sharp divisions between classes) are reasonable.

3.2.2 Reaction rank

In some piezometer networks, the hydrographs can be compared and ranked by inspection according to the speed with which they react to rainfall. Some hydrographs react to small rainfall events, while others do not; some start to rise sooner and reach their peak sooner than others; some drain rapidly, some slowly or not at all. Among other things, these behaviours indicate differences in rainfall thresholds, which are relevant to episodicity. Where hydrographs have contrasting forms (e.g. if some drain well every year while others are continually rising, or if the sites being monitored are subject to different rainfall regimes) ranking may not be appropriate. Ranking for episodicity by hydrograph inspection works best between sites which receive the same rainfall events. So, this system is useful for comparing the behaviour of sites within a network, and will be called Reaction ranking.
3.2.3 TOR class

Not all episodic hydrographs look the same. The episodic events in some have large sharp rises followed by steep falls, defining narrow peaks. In others, the episodic events may result in permanent rises in the groundwater level. And the rise that looks episodic may occur over a short period - less than one year - or may result from a series of wet years. (A series of years where rises were greater than usual will be called ‘a run of high-rise years’). The large rises may just cause temporary elevations in groundwater level; over a few years of lower rises, the drainage rate may be sufficient to re-establish earlier levels. Such distinctions are important in terms of the risk of salinity developing at a site. If a site is prone to episodic pulses of recharge, but the groundwater then drains, then it is not that site, but the site which gains its drainage, which is at risk from the episodic pulses. Where episodic rises are permanent, then there is the risk that the groundwater will eventually rise to a level at that site where it would cause soil degradation.

Thus, another simple subjective hydrograph classification system was developed to divide hydrographs into those in which:

- unusual rises consisted of single steps and were permanent;
- unusual rises consisted of single steps and levels returned to previous levels (or the level which would have been expected without the unusual rise) after more than one year;
- unusual rises consisted of single peaks and levels quickly returned to those prior to the rise (before another 'normal' rise occurred);
- a run of high-rise years resulted in a permanent rise;
- a run of high-rise years resulted in a rise which returned to previous levels (or the level which would have been expected without the unusual rise) after more than one year;
- none of the above (most in this class have regular regimes).

The system will be called the TOR classification (Type Of Rise).
3.3 EPISODICITY AND SIGNIFICANCE

An episodic recharge event is one which occurs irregularly, unpredictably, and infrequently. An episodic recharge pulse may be small, in which case it may be considered insignificant. For example, at an arid location there may have been only two pulses of recharge in the last twenty years. The first may have contributed 100 mm of recharge, while the second only contributed 1 mm. They were both episodic recharge pulses, but only the first may be considered to have been significant.

Whether a recharge event is significant or not can change with the context. For example:

- an event may be statistically significant (at an accepted level of probability), but not significant for short-term land management decision making;
- an episodic recharge event affecting only a small area of a catchment may have a significant effect on the groundwater levels in that part of the catchment, but on the scale of the whole catchment and for the whole of the region, it may be insignificant;
- an episodic recharge event in the Wheatbelt of WA may be considered significant because of the effect it has on the rising groundwater levels and salinity, whereas an episodic event with similar characteristics may not be significant in a part of the world where the aquifer being recharged is used as a water resource and is pumped at a high rate relative to the recharge.

Therefore, the factors which determine whether an episodic recharge event is significant in a practical sense must be defined for the circumstances under consideration. The following sections look at ways of determining which recharge pulses are both episodic and significant in the context of salinisation of the Wheatbelt of WA.

3.4 CHARACTERISTICS OF RECHARGE DATA SETS AND APPROACHES TO ANALYSIS

Recharge data sets have certain characteristics which distinguish them from data sets from other branches of hydrology. One of the main differences is that groundwater recharge is rarely measured directly. Recharge is generally inferred from groundwater hydrographs, from measurements of water contents or movement through the unsaturated zone, from results of modelling, or from a combination of these.
Few groundwater levels in the Western Australian Wheatbelt have been monitored for even as little as ten years and available soilwater measurements are for much shorter periods. In contrast, many rainfall stations have records from the first decade of the twentieth century, and some streamflow stations are several decades old. Until recently, daily records of groundwater levels were rare. Resulting problems are discussed in Sections 3.4.1 and 3.4.2.

Probability distributions and time-series analysis are well-developed for other hydrological fields, but issues with using them for distinguishing episodic recharge events are identified below (Sec. 3.4.3; Sec. 3.4.4). However, plots of accumulated recharge may be useful for highlighting periods of high recharge (Sec. 3.4.5).

### 3.4.1 Record length – issues for recharge data

Confidence in the results of analyses increases with increasing length of record. Cook (1992) calculated the errors associated with records of different lengths when determining long-term drainage rates below root zones with drainage rate coefficients of variation ($C_v$) of either 50% or 100%, and a confidence level of 90%:

<table>
<thead>
<tr>
<th>Record Length (y)</th>
<th>$C_v = 100%$</th>
<th>$C_v = 50%$</th>
</tr>
</thead>
<tbody>
<tr>
<td>70</td>
<td>+/-20</td>
<td>+/-10</td>
</tr>
<tr>
<td>25</td>
<td>+/-35</td>
<td>+/-17</td>
</tr>
<tr>
<td>5</td>
<td>+/-90</td>
<td>+/-45</td>
</tr>
</tbody>
</table>

In calculating the above figures, Cook (1992) assumed that the annual drainage varied randomly; if it did not, then errors were even greater. The range of $C_v$ values for the sites he modelled in south-eastern South Australia was from approximately 50% (at Kybobolite, 550 mm/y mean annual rainfall) to over 100% (at Wanbi, 300 mm/y mean annual rainfall).
3.4.2 Measurement and summing intervals – issues for recharge data

The time intervals (days, 'events', weeks, months, 'seasons', or years) used in recording and summing recharge data need to be considered because:

- An 'episodic' recharge event can occur over a short, medium or long period of time. For example: the episodic recharge could be a very large pulse of water reaching the water-table within one day due to a short-lived large flood or rain event, or could extend over several months if it is caused by an unusually large number of 'normal'-sized recharge additions, or could take place over more than a year if percolation occurs along a range of pathways with differing travel times.

- The intended use of the information determines the most appropriate time periods to use. Different statistical approaches are appropriate for different time intervals. For example, consider two sites, A and B:

  At site A, recharge usually occurs on a few days during winter, but there is also an occasional very large event. So, the recharge sum on most days of the year is zero and the daily mean recharge will be low. Nearly all recharge that does occur will appear to be significantly greater than the mean daily recharge, and therefore any large episodic events may not stand out.

  At site B, all recharge is episodic, and each episode lasts only one day.

  If the aim is to identify only episodic events, then it is less important to distinguish between recharge events of different magnitudes at site B then at site A. The problem is likely to be less pronounced with annual sums of recharge as there will be relatively fewer years with zero recharge.

- In an area where there is no recharge in most years, annual recharge totals would clearly identify the years in which episodic recharge occurred. In areas where recharge events are more frequent, annual totals would still indicate years with significantly high recharge, but in neither case would annual data show whether that recharge was the result of one large short-lived pulse, several smaller pulses, or many small recharge events.

- Monthly totals would give some indication of when and for how long any episodic recharge occurred, but would still not show whether a recharge event lasted only one day or for a number of days or weeks. They would also show any regular seasonal recharge patterns.
Part I, Chapter 3: Identifying significant episodic events

- Recharge event totals would have the advantage of showing up any individual events which were significantly episodic, but if a significant volume of recharge occurred over a number of average-sized events, then it would be less likely to show up.

- Daily recharge totals would indicate large short-lived recharge events, but significant events spread over a few days would be masked.

3.4.3 Additional characteristics of recharge time-series data

Recharge time-series data may be autocorrelated, have trends (due to land management or climate changes), cyclic variations (due to seasonal rainfall or long-term rainfall cycles), random stochastic components or ‘noise’ and “rare catastrophic events which do not form part of the recognisable pattern” (Kisiel 1969). The latter component may correspond to the significant episodic (SE) events being considered, and Kisiel (1969) warned that the definition of this component "needs very careful consideration and may not be possible".

3.4.4 Issues with using probability distributions and tests of significance

One possible approach to identifying which recharge episodes were significant is to fit probability distributions to the recharge data, choose a relevant level of significance, and then determine which recharge episodes fell into the significant bracket. However, such an approach would not be straight-forward because:

- It is not clear whether episodic recharge events are just the largest members of a population which contains all of the recharge events at a site, or whether they belong to a second population of recharge events described by a different probability distribution (e.g. it could be that regular recharge results from rain produced by temperate cyclones coming towards WA from the south-west, mainly during winter, while episodic recharge results from decaying tropical cyclones).

- Distributions of recharge data sets would be strongly skewed, so the data would have to be adjusted before statistics, such as standard deviations, were calculated.

- The chosen distribution would have to adequately represent the importance of a few large events compared to many regular ones.
Part I, Chapter 3: Identifying significant episodic events

- What is the appropriate level of significance to differentiate significant episodic recharge from non-significant episodes? Figure 3-1 illustrates in a simple way why picking an arbitrary figure could lead to meaningless results.

- At sites where recharge is rare and all recharge events are significant and episodic, then using a level of significance to pick out episodic events would not identify all of them.

- At a site where all the recharge was regular, applying a level of significance may mis-identify the largest events as significantly different.

- Because episodic recharge events are not of a specific duration, events that were identified as significant for the population of annual recharge totals may not correspond with those identified from the population of event or daily recharge totals.

- Should days of zero recharge be ignored? Should years of zero recharge be ignored?

- The data sets will commonly be too small for confident statistical analyses - e.g. there may only be 10 years of annual recharge data available, or only a low number of recharge events (maybe only one or two) over a period as long as a hundred years.

![Figure 3-1: Illustration of some problems with using specific limits (0.01 and 0.05) for significance levels on a hypothetical example of ranked monthly recharge](image_url)
3.4.5 Advantages of accumulated recharge plots and step changes

The importance of large events may not be clear in simple plots. However, plots of cumulative recharge produce clear pictures because, over the long term, the plots will tend to have a linear increasing trend (unless there is no recharge at all). If there are any particularly large recharge events, they will disrupt the trend, creating step-rises. For comparison, Section 3.10 illustrates both bar graphs of annual recharge and plots of cumulative annual recharge for example data sets.

The step-rises from unusually large recharge events will be clear whether the recharge pulse occurred over only a few days (or less) or over a long period (greater than one year).

The use of statistical tests designed to identify significant step changes are limited for recharge data sets by many of the issues described in the sections above. However, the simple calculation of the percentage of the total recharge contributed by each step-rise provides a way of comparing step-rises both within one record and between records from different sites.

3.5 PUBLISHED METHODS OF ANALYSING RECHARGE

Only two methods of analysing recharge variability with time (apart from the calculation of annual means, standard deviations and coefficients of variation) were found in publications:

- plotting cumulative frequency of annual recharge (Caro and Eagelson 1981; Gieske 1992);
- plotting frequency histograms of daily recharge (Cook 1992).

Although there was scope to employ these methods on the output of recharge modelling, they were of limited use in the analysis of groundwater hydrograph records of short length and irregular monitoring intervals, and they were not designed to identify SE events.

3.6 METHODS OF ANALYSIS USED IN OTHER HYDROLOGICAL FIELDS

This section discusses the advantages and disadvantages in terms of recharge data of some relevant statistical methods in use in other hydrological fields. Section 3.6.1 looks at estimating the central tendency of a data set, methods in Section 3.6.2 are for detecting trends and step changes in time-series data, and Section 3.6.3 deals with various other approaches.
Problems associated with applying probability distribution analyses to recharge data are not included in this section as they were discussed in Section 3.4.4.

3.6.1 Central tendency and descriptive statistics

Usually, measures of central tendency are used to assess how similar one value is to the others in a population. Here, their usefulness in assessing how different one value is from the others in a population is considered.

Measures of central tendency are among the simplest analyses, but they can be meaningless and misleading if applied inappropriately. Many of the issues raised in Section 3.4 need to be considered. In particular, the measures rely on all the data points belonging to only one population (described by one probability distribution). Additional issues are mentioned in the following sections.

3.6.1.1 Deviation from and variation about the mean

One advantage of using the mean is that it is simple to calculate. Another is that it is generally meaningful even when there are few data points being averaged. However, the mean is not a good representation of data with 'outliers' (that is, particularly large or small data points) because they bias the value of the mean disproportionately. Episodic events are outliers. This leads to a further issue. Should the events which may be episodic be excluded from the calculation of the mean, so it is not biased by them? If this was done, it would require suspect episodic events to be identified prior to the calculation of the mean. The problems also apply to associated statistics such as standard deviation and coefficient of variability ($C_v$).

3.6.1.2 Deviation from the median

For data with outliers, medians are considered to be better measures of central tendency than means (Barnett and Lewis 1994). However, problems would be created by many days of zero recharge. Deviations from the median could be measured by subtracting the median from the value being questioned and dividing by either the interquartile range or the range. But again, should the extreme values under consideration be included in the calculation of the range and interquartile range?
3.6.1.3 Testing for large outliers

Outliers are "also known as wild points, rogues, fliers and Mavericks" and they are "data values that appear to be suspiciously extreme" (Ellis 1989).

Outlier analysis is usually intended to avoid rogue values distorting the picture, and to be valid the underlying probability distribution has to be identified with certainty (Barnett and Lewis 1994). Outliers may or may not be genuine members of the main population. If not, then they are called 'contaminants' from another distribution.

Barnett and Lewis (1994) also explained the difference between extreme values and outliers. The extreme values of a data set are those that have the highest and lowest values; they may or may not be outliers. This depends on whether they 'fit' with the postulated distribution model. An outlier is always an extreme value - a suspiciously extreme value.

Discordancy tests are used to detect outliers by deciding whether it is likely that an outlier belongs to the main population. Again, a level of significance has to be chosen by the operator. Discordancy tests use simple statistics of "the form N/D, where the numerator N is a measure of the separation of $x_{(10)}$ (an upper outlier in a set of ten observations) from the remainder of the sample and the denominator D is a measure of the spread of the sample" (Barnett and Lewis 1994). Examples for N are:

- the separation of $x_{(10)}$ from its nearest neighbour $x_{(9)}$;
- the separation of $x_{(10)}$ from the mean of the other nine values.

Examples of D are:

- the range of the other nine values;
- the spacing between the 8th and 9th observations;
- the standard deviation of the nine other values.

Barnett and Lewis (1994) warned that outlier tests can "mask" or "swamp" outliers where several lie close together so that none of them are identified. Gilbert (1987) described Rosner's 'many-outlier' test which can identify up to 10 outliers but it cannot be used if the number of data points is less than 25.
For time-series data, formal methods for detecting and rejecting outliers are not well developed (Barnett and Lewis 1994).

### 3.6.2 Detecting trends and step changes

Many of the time-series analyses used in streamflow and water chemistry studies are designed to detect trends and changes in trend.

Grayson et al. (1996) stressed the value of visual assessments of graphed data as the precursors of statistical tests. Plots such as ‘cusums’ (residual mass curves) and double mass curves show the points at which changes in trend occurred, and this information can then be used in planning step-change tests (there are illustrations of the two types of curves in Section 3.10).

Worked examples presented by Grayson et al. (1996, pp. 66-70) illustrated that because different trend detection tests compare different aspects of a data set, results from the various tests may point to different conclusions. Table 3-1 summarises the conclusions drawn from the worked examples, and indicates that several tests provide more information about trends in a data set than any single one.

**Table 3-1: Summary of conclusions drawn by Grayson et al. (1996, pp. 69 and 70) from different trend detection tests carried out on annual flow data for 1940 to 1989 from the Campaspe River (in Victoria)**

<table>
<thead>
<tr>
<th>Test</th>
<th>Conclusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mann test</td>
<td>&quot;Data shows an increasing trend, statistically significant at 10% level&quot;</td>
</tr>
<tr>
<td>Cumulative Deviation test</td>
<td>&quot;Mean of 1950-89 is &gt;1940-49 but not statistically significant at 10% level&quot;</td>
</tr>
<tr>
<td>Worsley Likelihood Ratio test</td>
<td>&quot;Mean of 1945-89 is &gt;1940-44 and is statistically significant at 10% level&quot;</td>
</tr>
<tr>
<td>Kruskal-Wallis test</td>
<td>&quot;Flows in certain 10 year sub-periods are different from flows in other periods, statistically significant at 5% level&quot;</td>
</tr>
<tr>
<td>Distribution Free CUSUM test</td>
<td>&quot;Flows in later years are higher than in earlier years but the difference is not statistically significant at 10% level&quot;</td>
</tr>
</tbody>
</table>
Part I, Chapter 3: Identifying significant episodic events

Some of the trend detection tests are parametric, some non-parametric; some require the operator to suggest the point at which a change occurs, others determine the change point; most are not designed for data sets with more than one step change, nor for those with an underlying trend as well as the step change, nor for autocorrelated data; some perform particularly poorly on small data sets (Ellis 1989; Grayson et al. 1996).

3.6.3 Other analyses used in hydrology

Methods have been developed for analysing extremes of rainfall and streamflow. Those mentioned below may have application to episodic recharge analysis when long records are available.

3.6.3.1 Rainfall analysis

When the highest recorded rainfalls for various durations are plotted on log-log paper, then the points are found to lie on a nearly straight line, so a relationship between duration and maximum rainfall can be derived.

Probable maximum precipitation (PMP) is a concept of an upper physical limit to rainfall amount which varies throughout the world and can be estimated using statistical or meteorological methods (Shaw 1994).

3.6.3.2 Droughts

Cusum graphs have been used to visually assess drought periods, and Herbst et al. (1966) defined droughts based on monthly rainfall deficits greater than average deficits. They also calculated the average monthly drought intensity and a severity index (intensity multiplied by drought duration).

3.6.3.3 Streamflow and surface hydrology

Gordon et al. (1994) applied predictability indices (devised for ecological studies by Colwell (1974)) to streamflow. This system addresses the frequency and intensity of flows as well as seasonality. Predictability is a measure of knowing the state at a particular time. Constancy is a measure of whether the system varies through time. Contingency is a measure of different flow states coinciding with specific times. "Predictable seasonal" streams can be separated from, say, "unpredictable unseasonal streams" (Gordon et al. 1994, p.124). It is
subjective, depending on the sample classes used and the length of record, and there is "a tendency for predictability and contingency to be biased towards high values for short periods of record". Gan et al. (1991) found that forty years of monthly data were needed to stabilise the bias.

3.7 ANALYSES USED FOR EPISODIC PHENOMENA IN OTHER FIELDS

There have been many studies on events described as 'unusual', 'rare' or 'extreme' in the fields of biology and ecology (e.g. Weatherhead 1986; Carpenter 1990; Jassby and Powell 1990; Conley et al. 1992; Gaines and Denny 1993). In a study on demographic changes in arid zone shrubs in WA, Watson et al. (1997) used the term 'episodic' to describe obvious, unpredictable changes in shrub populations which were 'event-driven' (that is, caused by drought or wet periods). There are clear parallels between such episodic ecological events and the SE recharge of this thesis.

There are two main approaches to studying the ecological phenomena. Some researchers (e.g. Carpenter 1990; Watson et al. 1997) assessed whether a known perturbation - such as a change in land use or an unusually wet period - resulted in a clear change in the system being studied (e.g. pollutant concentrations; vegetation populations). This would be equivalent to knowing when the wettest years occurred in WA and then assessing whether they produced SE recharge. The other approach is to analyse the system in question for significant changes, and then attempt to find the causes of the change (e.g. Jassby and Powell 1990; Gaines and Denny 1993). This corresponds to the approach being used in this study, which attempts to identify SE recharge, and then to determine the conditions associated with it. This approach gives more emphasis to the subject of the investigation (that is, recharge) than to the presupposed causes.

Common methods used in biology and ecology to identify the large changes in either the cause or the effect rely on time-series analysis, multivariate analysis, and Bayesian approaches, but Gaines and Denny (1993) used the statistics of extremes to predict return times of events of specific magnitudes. To be successful, all the methods need large data sets, and thus are inappropriate for short groundwater level records, although Gaines and Denny found that if short records were known to contain extremely high or low events, they could be used to predict long-term behaviour.
3.8 SUMMARY OF PUBLISHED METHODS

No published methods which could be used to differentiate between all types of episodic and regular regimes were found. However, there were approaches which could provide useful information (e.g. cusum plots and Ca, Sec. 3.10).

One problem with many established analyses is that they are only appropriate for large data sets of evenly spaced (in terms of time) points which are normally distributed and from only one population. Although recharge model output can be designed to produce suitable data sets, groundwater hydrographs and soilwater data are unlikely to comply. Other issues are that subjective choices have to be made about what degree of difference is significant and when step changes in a time-series occurred, and most time-series analyses are not appropriate for autocorrelated data.

3.9 A SIMPLE GRADING SCALE FOR IDENTIFYING SIGNIFICANT EPISODIC EVENTS

A perfect, objective, repeatable method which could be used to distinguish between episodic and non-episodic recharge in all types of data sets was not found, but a simple grading scale was developed which was useful for results of recharge modelling exercises. It was also applied to groundwater hydrographs, but for such data sets, it was more subjective. It will be called the SE grading scale (SE stands for 'significant episodic').

The grading scale (Figure 3-2) gauges both how episodic and how significant a recharge event is. It compares the percentage of recharge contributed by a particular episode to the total recharge over the period of record, and a grade is allocated. The scale takes length of record into account. A grade 1 episode is more significant than a grade 3 one. The choice of grade boundaries was subjective, but consideration was given to the character of recharge regimes and groundwater fluctuations in the Wheatbelt of WA. A grade 3 episode was considered to be equivalent to one which made up 25% of the recharge over a ten-year period; a grade 2 episode was equivalent to 50% of recharge over ten years; and a grade 1 episode was equivalent to one which contributed 100% of recharge over ten years. An event that produced only 10% of the total recharge for a ten-year period would not be significant or episodic and would plot in the ‘no grade’ region of the scale. An event which produced 10% of the recharge for a 70-year record would plot in the grade 2 region, and if there was one recharge
event in the same period which produced 20% of the total recharge, it would be a grade 1 event.

![Figure 3-2: The SE grading scale](image)

Since the grading scale uses the percentage of the total recharge, it normalises recharge between sites. The scale allows comparison between annual totals or between the magnitudes of specific events of any duration. Thus, it can be used to compare step-rises within one record or between different records. The SE grading scale is applied to some examples in Section 3.10.

The grading scale makes a sharp distinction between a grade 3 step and a 'no grade' step. It may be useful to compare the relative magnitudes of the largest recharge steps from different sites or different model runs. The ratio of the largest annual step-rise of a record to the size of the step-rise required for a grade 3 episode gives a measure of how close a step-rise is to being episodic. This ratio will be called the MG3 ratio (Maximum rise to Grade 3 rise ratio). A record with no SE steps has a ratio below one, a record with a grade 3 rise has a ratio between 1 and 2, and a record with a grade 2 rise has a ratio between 2 and 4. If a ten-year hydrograph was so regular that no year had a rise greater or less than 10% of the total, then the ratio would be 0.4.

The use of MG3 ratios is assessed in Section 3.10.
3.10 COMPARISON OF METHODS

The most appropriate visual assessment methods, classification systems and statistical analyses were applied to examples of annual recharge data sets and to groundwater level records. The aim was to compare them in terms of distinguishing between episodic and non-episodic recharge sites.

3.10.1 Recharge data sets and groundwater hydrographs

Four sets of annual recharge data and three sets of groundwater level records were used. One of the annual recharge data sets was clearly episodic (M1), one clearly regular (M4), and the other two were intermediate (M2 and M3). Each annual recharge data set covered 78 years and is illustrated in the form of a bar chart in Figure 3-3. (They were based, with some additions, on the results from four of the water-balance model runs described in Chapter 4.)

The three groundwater level records had clearly episodic (H1), regular (H3), and intermediate (H2) rise regimes (Figure 3-4). Two records consisted of periods of both irregular manual monitoring and daily data-logger records. The third consisted of only daily data-logger records. (The data used was based on three of the Western Australian records analysed in Parts II and III.) The records were of different lengths, having between 7 and 14 years of data, and one of them contained a gap of four years. These 'imperfections' (the irregularity, shortness, and gaps) are typical of the better Western Australian groundwater records, so were considered to be appropriate examples.
Part I, Chapter 3: Identifying significant episodic events

Figure 3-3: Bar charts of annual recharge data sets used in examples

Figure 3-4: Groundwater hydrographs used in examples
3.10.2 Methods

For each hydrograph, the groundwater level rise in each year was estimated (the procedure used is described in detail in Chapter 6). For these examples, only years with complete records were used.

The following plots were made for visual assessments:

- **for recharge data sets**: accumulated annual recharge as a percentage of total recharge vs. time;
- **for hydrographs**: accumulated annual groundwater rise vs. time;
- cusums (accumulated sum of deviations from the mean annual recharge or annual groundwater rise vs. time); and
- **for recharge data sets**: double mass curves of accumulated annual recharge (M1, M2 and M3 were plotted against the most regular one, M4).

The classifications systems and statistical analyses compared were:

- simple classifications (CLEAR classes, Reaction rankings and TOR classes);
- measures of central tendency (mean, standard deviation, $C_v$, median, discordancy statistics);
- SE grades and MG3 ratios.

Details of how these were applied to the example data sets are presented in Appendix 3.

3.10.3 Results

Plots are presented in Figures 3-5 to 3-9 and results of classifications and statistical analyses are listed in Table 3-2.
Figure 3-5: Accumulated annual recharge (as a percentage of total recharge) vs. time for recharge data sets

Figure 3-6: Accumulated annual groundwater rise vs. time for hydrographs
Figure 3-7: Cusums (accumulated deviation from the mean annual recharge vs. time) for recharge data sets

Figure 3-8: Cusums (accumulated deviation from the mean annual groundwater rise vs. time) for the hydrographs
Part I, Chapter 3: Identifying significant episodic events

Figure 3-9: Double mass curves (accumulated annual recharge vs. accumulated annual recharge for M4) for recharge data sets

Table 3-2: Results of classifications and statistical analyses

<table>
<thead>
<tr>
<th></th>
<th>M1</th>
<th>M2</th>
<th>M3</th>
<th>M4</th>
<th>H1</th>
<th>H2</th>
<th>H3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Record length (y)</td>
<td>78</td>
<td>78</td>
<td>78</td>
<td>78</td>
<td>11</td>
<td>14</td>
<td>7</td>
</tr>
<tr>
<td>CLEAR class</td>
<td>E</td>
<td>E</td>
<td>E</td>
<td>N</td>
<td>E</td>
<td>E</td>
<td>P</td>
</tr>
<tr>
<td>Reaction rank</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>TOR class</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>EP</td>
<td>EP</td>
<td>ET</td>
</tr>
<tr>
<td>Mean(^1)</td>
<td>2.0</td>
<td>6.8</td>
<td>20.8</td>
<td>535.1</td>
<td>0.4</td>
<td>0.3</td>
<td>1.2</td>
</tr>
<tr>
<td>sd(^{1,2})</td>
<td>12.7</td>
<td>19.0</td>
<td>31.1</td>
<td>129.2</td>
<td>0.4</td>
<td>0.2</td>
<td>0.5</td>
</tr>
<tr>
<td>Cv(^{1,2})</td>
<td>6.4</td>
<td>2.8</td>
<td>1.5</td>
<td>0.2</td>
<td>1.0</td>
<td>0.6</td>
<td>0.4</td>
</tr>
<tr>
<td>Median(^1)</td>
<td>0.0</td>
<td>0.0</td>
<td>6.5</td>
<td>510.8</td>
<td>0.2</td>
<td>0.3</td>
<td>1.1</td>
</tr>
<tr>
<td>DS(^1)</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>0.7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DS(^2)</td>
<td>0.6</td>
<td>0.4</td>
<td>0.1</td>
<td>0.3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DS(^3)</td>
<td>1.6</td>
<td>1.3</td>
<td>0.9</td>
<td>0.9</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No. SE grade 1 rises</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>No. SE grade 2 rises</td>
<td>0</td>
<td>2</td>
<td>4</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>No. SE grade 3 rises</td>
<td>0</td>
<td>1</td>
<td>6</td>
<td>0</td>
<td>2</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>MG3 ratio</td>
<td>18.4</td>
<td>7.6</td>
<td>2.5</td>
<td>0.7</td>
<td>1.1</td>
<td>1.0</td>
<td>0.7</td>
</tr>
</tbody>
</table>

1. M1 to M4 columns in millimetres; H1 to H3 columns in metres
2. sd: standard deviation; Cv: coefficient of variation
3. DS\(^1\) (discordancy statistic 1): (maximum annual recharge minus median of all values) divided by (range of all values)
3.10.4 Discussion

3.10.4.1 Visual assessments

Each of the recharge data sets had distinct patterns in each of the three plot types (Figures 3-5, 3-7 and 3-9). However, the accumulated annual recharge plots highlighted the large recharge events best. These plots were also the simplest.

The two plots used for the three sets of hydrograph data (Figures 3-6 and 3-8) also illustrated their differences in character, but contrasts between the three sets were not as great as for the recharge data sets. This was partly because the end members used as hydrograph examples were less extreme than those for the recharge data sets, partly because the records were short, and partly because of the gaps in the records.

The regular recharge data set (M4) stood out in the cusum plot (Figure 3-7) because there were three protracted periods when the recharge was either greater than or less than the mean. This is therefore an appropriate type of plot for assessing long-term trends in recharge data.

3.10.4.2 Classification systems, SE grades and MG3 ratios

Table 3-2 shows that the results of the CLEAR classifications, the SE grades and the MG3 ratios were consistent - the same data sets were identified as episodic whichever method was used.

Both the SE grades and the MG3 ratios provided information on the relative significance of the episodic events. However, the MG3 ratio would also have allowed comparison between two data sets which had the same SE grades.

In the most regular hydrograph (H3), there was one year with two large peaks instead of the usual one, because the groundwater levels reacted to high summer rainfall as well as the more regular winter rainfall. The groundwater levels did not drain to their 'normal' level before the next winter groundwater rise, so with the TOR system, this hydrograph was classed as having
an episodic temporary rise. However, the sum of the two rises was insufficient to be SE grade 3, so the year was not graded as significantly episodic.

The Reaction rank did not draw a distinction between episodic and non-episodic hydrographs, but did reflect the trends in episodicity.

3.10.4.3 Statistics

Although the mean, median and standard deviations of the recharge data sets appeared to reflect the trends in the SE grades and MG3 ratios, this was an artefact of the data sets used - the total recharge increased with decreasing episodicity. This may sometimes be the case, but it will not always be so.

The $C_v$ was a better reflection of episodicity because the absolute magnitudes of data sets are normalised when $C_v$ is calculated. So, where data sets represent single populations that can be described by normal distributions, and they have adequate data points, the $C_v$ may be a useful check for episodicity. However, because it is as strongly affected by small values as by large ones, it should only be used with caution, and in association with other methods.

Of the three discordancy tests used, only two reflected the trends in episodicity, but they were not successful in distinguishing between all of the data sets.

3.11 SUMMARY AND CONCLUSIONS

An objective and repeatable method of distinguishing between significant episodic and non-episodic recharge was required. Simple classifications for graphed time-series data were devised (CLEAR and TOR classifications and Reaction ranks) and although they are subjective, they reflect trends in episodicity between different data sets.

Plots of accumulated recharge versus time, cusums and double mass curves provide useful visual distinctions for some data sets. However, there is a lack of statistical analyses suitable for recharge data. Characteristics of recharge data sets (e.g. short records with irregular measurements) and of episodic recharge events (e.g. extremes of the main population or contaminants from another?) limit the validity of probability and time-series analyses.

The SE grading system and the MG3 ratio were developed to compare the relative significance of different events at the same site and of events at different sites. The
boundaries chosen for the SE grades were intended to identify significant episodic recharge in
the context of salinity in the Wheatbelt of WA. Checks on the results can be performed by
comparing them to the simple classifications and to simple statistics, such as the coefficient of
variation.
4. REGIONAL VARIATIONS IN LIKELIHOOD OF DIRECT EPISODIC RECHARGE, ASSESSED USING SIMPLE WATER-BALANCE MODELS

4.1 INTRODUCTION

Part I of this thesis assesses whether it is likely that episodic recharge is significant in the Western Australian Wheatbelt. Chapter 2 reviewed literature for both Western Australia (WA) and the rest of the world. One of the findings was that in other parts of the world, certain types of rain-generating meteorological systems are associated with large pulses of recharge. Similar systems occur in south-west WA (tropical cyclones and deep rain-bearing depressions; infrequent, intense spring and summer thunderstorms; regular rainfall from frontal systems with high variability). This supported the conclusion that significant episodic (SE) recharge is likely below some parts of the landscape in the south-west of WA.

However, the variability of rainfall increases as the median annual rainfall decreases, from the south-west towards the north-east of the region. This suggests that the recharge regimes may also be more variable in the drier regions in the north-eastern parts of the Wheatbelt.

The literature reviewed in Chapter 2 showed that rainfall is only one of the factors affecting the recharge regime at a site, but it seems reasonable to assume that it has a particularly strong influence. To illustrate this, consider one site where rainfall is regularly distributed throughout a year and the annual total does not vary greatly, and another at which rain falls in large events only every few years. At the first site, it is unlikely that the recharge would ever be episodic, whatever the site conditions, and at the second site, it is unlikely that the recharge regime would be regular on an annual basis (unless the groundwater system was very deep).

The main aim of this chapter is to explore how the regional trends in rainfall variability in south-western WA affect the likelihood of SE recharge. This is done using simple water-balance models.

Three sets of model runs were performed. The first one used the rainfall conditions at four locations in the Wheatbelt, along with different plant and soil conditions, with the preliminary aim of assessing whether any of the rainfall regimes had the potential to result in direct SE recharge. Since this showed that there was the potential for SE recharge, and also that there were regional differences in the resulting recharge regimes, the next set of model runs used
rainfall and evaporation data from 53 locations throughout WA to map the regional variations in importance and likelihood of SE recharge. The third set of model runs used data from northern Victoria (NV) so that the regional variations there could be compared with those in WA. This was done for two reasons. The first was that it provided a check on whether the WA trends were similar to those in another semi-arid region; the second was that it indicated the validity of transferring results of SE recharge studies between the two regions.

Section 4.2 presents the first set of model runs. The second and third sets of model runs are presented in Section 4.3, and conclusions are drawn in Section 4.4.

4.2 VARIATIONS IN DIRECT RECHARGE REGIMES BETWEEN FOUR WHEATBELT LOCATIONS

A simple water-balance model (WATBAL) was used to assess whether the rainfall regimes at four locations in the Wheatbelt had the potential to result in direct SE recharge, and how different soil types and rooting depths influenced the recharge regime.

The original WATBAL code (Keig and McAlpine 1969) used weekly precipitation and evapotranspiration figures to calculate changes in soilwater 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 soilwater 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 soilwater storage. If the soilwater storage becomes full, then the excess is simply considered to become recharge. If the evapotranspiration requirement cannot be satisfied by the day's rain, then it is taken from the soilwater store.

Although the model is a very simple one and does not take into account many hydrological processes such as interception, run-off or run-on, ponding, preferred path 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 and Kennett-Smith et al. found good general agreement between point measurements of recharge made in the field and the results of the model.
In this study the model was used to compare the occurrence of SE recharge during the 33 years from 1960 to 1992 at four locations in the Western Australian Wheatbelt (Figure 4-1). A range of maximum root depths (from 50 cm to 300 cm) for annual growth cycles was modelled at each site. At the centrally located site, 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 SE recharge regimes. In addition, the model allowed the influence of root depth and soil type on the recharge regime to be assessed.

![Figure 4-1: Locations of places mentioned in Section 4.2](image_url)

### 4.2.1 Model inputs

#### 4.2.1.1 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 4-1). 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.
4.2.1.2 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 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.

4.2.1.3 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 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 that could be stored (see Section 4.2.1.4). 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 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. All of the results presented, therefore, are from modelling runs which used a value of 5.0 for the soil parameter.
4.2.1.4 Soilwater storage

The model requires the maximum soilwater storage (MAXST) available in the active zone, which 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 4-2). (Details of growth stages are described later in this section.) 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.

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

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, were modelled. 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' here) and root growth data collected by Tennant (1976) for wheat roots in 'deep sand' and 'sandy loam'. The stages are listed in Table 4-1. Hamblin and Hamblin (1985) did not measure the roots at intermediate growth stages so ones were chosen which reflected the early time of sowing of their experiments and were conservative in relation to excess soilwater (the roots reached maximum depth quickly).
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. A MAXST equivalent to a depth of 50 cm was used outside the growing season. 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 soilwater 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.
Table 4-1: The stages of root growth used for the three soil types modelled

<table>
<thead>
<tr>
<th>Day of year</th>
<th>Stage</th>
<th>Day of year</th>
<th>Stage</th>
<th>Day of year</th>
<th>Stage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(start of year, January 1)</td>
<td>1</td>
<td>(start of year, January 1)</td>
<td>1</td>
<td>(start of year, January 1)</td>
</tr>
<tr>
<td>151</td>
<td>time of sowing</td>
<td>175</td>
<td>time of sowing</td>
<td>175</td>
<td>time of sowing</td>
</tr>
<tr>
<td>201</td>
<td>roots reach 50 cm</td>
<td>231</td>
<td>roots reach 50 cm</td>
<td>231</td>
<td>roots reach 50 cm</td>
</tr>
<tr>
<td>202 - 249</td>
<td>roots grow to maximum depth</td>
<td>232 - 245</td>
<td>roots grow to 75 cm (except for 50 cm maximum cases)</td>
<td>232 - 239</td>
<td>roots grow to 75 cm (except for 50 cm maximum cases)</td>
</tr>
<tr>
<td>250 - 291</td>
<td>roots remain at maximum depth</td>
<td>246 - 294</td>
<td>roots grow to maximum depth</td>
<td>240 - 294</td>
<td>roots grow to maximum depth</td>
</tr>
<tr>
<td>292</td>
<td>roots no longer use water</td>
<td>295</td>
<td>roots no longer use water</td>
<td>295</td>
<td>roots no longer use water</td>
</tr>
<tr>
<td>365</td>
<td>end of year</td>
<td>365</td>
<td>end of year</td>
<td>365</td>
<td>end of year</td>
</tr>
</tbody>
</table>

Soil water storage capacities 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). Tennant's (1976) figures for clay content down deep sand and sandy loam profiles were used to calculate soil water storages from relationships given in Kennett-Smith et al. (1994). The capacities 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.

4.2.2 Results

In addition to the results specific to SE 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 4.2.2.3 to 4.2.2.5).
The general points (which are presented in detail in the following Sections 4.2.2.1 and 4.2.2.2), 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;
- over the 33 years for which the water-balances were calculated, no recharge was generated in some of the model runs that had relatively high soilwater storage or low rainfall.

### 4.2.2.1 General recharge patterns

As an indication of the general nature of recharge events, the results for Corrigin SRM2 are presented in Table 4-2 and show that:

- even roots 300 cm deep did not prevent recharge being generated;
- recharge events were both more frequent and larger 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 deeper 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 4-3). Ninety-eight percent of the total recharge was generated 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 later 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>
<thead>
<tr>
<th>Maximum root depth (cm)</th>
<th>No. of recharge events</th>
<th>Total recharge 1960 - 1992 (mm)</th>
<th>Mean recharge per event (mm)</th>
<th>Mean no. of recharge events per year (range)</th>
<th>Mean annual recharge in mm (range)</th>
<th>No. of years in which there was recharge</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>158</td>
<td>1836</td>
<td>11.6</td>
<td>4.8 (0 - 14)</td>
<td>56 (0 - 147)</td>
<td>32</td>
</tr>
<tr>
<td>100</td>
<td>90</td>
<td>941</td>
<td>10.5</td>
<td>2.7 (0 - 12)</td>
<td>29 (0 - 115)</td>
<td>23</td>
</tr>
<tr>
<td>150</td>
<td>49</td>
<td>400</td>
<td>8.2</td>
<td>1.5 (0 - 11)</td>
<td>12 (0 - 83)</td>
<td>10</td>
</tr>
<tr>
<td>200</td>
<td>29</td>
<td>184</td>
<td>6.4</td>
<td>0.9 (0 - 9)</td>
<td>6 (0 - 58)</td>
<td>6</td>
</tr>
<tr>
<td>300</td>
<td>6</td>
<td>35</td>
<td>5.8</td>
<td>0.2 (0 - 4)</td>
<td>1 (0 - 27)</td>
<td>2</td>
</tr>
</tbody>
</table>

Note: 1. 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.

### 4.2.2.2 General rain:recharge relationships

#### 4.2.2.2.1 Annual rain and annual recharge

There was a large range in the recharge generated by a particular annual rainfall. For
element, 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, there was one fall of
over 20 mm in January, but most of the rest fell within a short time span in winter (and one day had over 40 mm of rain); in 1963, an unusually large number of falls (of less than 20 mm) happened during the non-winter months and so the large annual total was distributed relatively evenly throughout the year. As a result, in 1968 the recharge occurred over 23 days, while in 1963, it was spread over 88 days.

Therefore, annual rainfall was not a good guide to the amount of recharge which was generated. Figure 4-4 shows that for roots 50 cm deep, annual recharge vs. 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. Low thresholds resulted when a particular amount of rain fell in a short time period, whereas the same amount of rain falling over a longer period was likely to result in a higher threshold. This is because the amount of available soil storage and the evapotranspiration rates are more likely to store and evaporate the particular volume of rainfall when it is provided in a series of small amounts rather than as a few large doses.

Figure 4-3: Cumulative percentage of 33-year total rain and recharge (for Corrigin SRM2 with 50 cm roots) by months
Thus, there is a spectrum of thresholds possible for a particular annual rainfall. One extreme is represented by the case where all of a year's rain falls in one day, and so the threshold is extremely low and a large proportion of the rain becomes recharge. At the other extreme is the case where there is no recharge because the rainfall is spread evenly over the whole year and the soil storage plus evapotranspiration are never exceeded. These two end cases describe what could occur under extreme episodic rainfall and under regular rainfall regimes.

**Figure 4-4: Annual recharge vs. annual rainfall for 50 cm deep roots, 1960 to 1992**

4.2.2.2.2 *Mean annual rain and mean annual recharge*

In Figure 4-5 the mean annual recharge is 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 are overlain to illustrate the range in values. This shows that the proportion of recharge to rainfall increased with rainfall and implies 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.

For different soil types at the same site, Figure 4-6 shows that mean annual recharge as a percentage of mean annual rainfall ranged from less than 1% to nearly 16%.  

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Figure 4-5: Mean annual recharge vs. mean annual rainfall at a range of root depths for four rainfall stations, SRM2 (R is mean annual recharge as % of mean annual rainfall)

Figure 4-6: Ratio of mean annual recharge to mean annual rainfall at a range of root depths for three soil types at Corrigin
4.2.2.3 How much of the total recharge generated was due to SE recharge?

The 'likelihood' of SE recharge refers to the number of times SE recharge occurred. For example, the likelihood of SE recharge was greater for a site where there were six such episodes in a 33-year period than at a site where there were only two. The 'importance' of SE recharge refers to the relative proportion of the total recharge contributed by the episodes. For example, the importance of SE recharge was greater at a site where SE recharge made up 90% of the total recharge than at a site where it made up only 30%.

Cumulative recharge vs. time graphs (Figure 4-7) show the pattern of recharge generation over the 33 years which were modelled. Although some of the large steps in the graphs in Figure 4-7 are due to single recharge events, most of the significant steps result from 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 SE grading scale in Figure 3-2 was used to identify those which were significant. 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 be graded 1, 2 or 3. Table 4-3 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.

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.

The results of the modelling runs show that the importance of SE recharge increased as the mean annual recharge decreased. Where the mean annual recharge was greater than about 70 mm, SE recharge was unimportant. SE 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 4-8). (Because the model used was 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.

Table 4-3: Details of the largest recharge steps for Soil-Root Model 2 at Corrigin

<table>
<thead>
<tr>
<th>Root Length (cm)</th>
<th>Year</th>
<th>Months when the recharge occurred</th>
<th>Duration of recharge episode (days)</th>
<th>Recharge amount (mm)</th>
<th>% of total 1960-1992 recharge</th>
<th>SE grade</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>1963</td>
<td>6,7,8</td>
<td>87</td>
<td>144</td>
<td>8</td>
<td>3</td>
</tr>
<tr>
<td>50</td>
<td>1964</td>
<td>4,6,7,8</td>
<td>124</td>
<td>147</td>
<td>8</td>
<td>3</td>
</tr>
<tr>
<td>50</td>
<td>1972</td>
<td>3</td>
<td>1</td>
<td>92</td>
<td>5</td>
<td>NG²</td>
</tr>
<tr>
<td>50</td>
<td>1974</td>
<td>4,5,6,7,8</td>
<td>131</td>
<td>122</td>
<td>7</td>
<td>NG²</td>
</tr>
<tr>
<td>50</td>
<td>1983</td>
<td>6,7,8</td>
<td>42</td>
<td>111</td>
<td>6</td>
<td>NG²</td>
</tr>
<tr>
<td>50</td>
<td>1990</td>
<td>1</td>
<td>1</td>
<td>92</td>
<td>5</td>
<td>NG²</td>
</tr>
<tr>
<td>100</td>
<td>1963</td>
<td>6,7,8</td>
<td>81</td>
<td>110</td>
<td>12</td>
<td>3</td>
</tr>
<tr>
<td>100</td>
<td>1964</td>
<td>6,7,8,</td>
<td>44</td>
<td>115</td>
<td>12</td>
<td>3</td>
</tr>
<tr>
<td>100</td>
<td>1972</td>
<td>3</td>
<td>1</td>
<td>59</td>
<td>6</td>
<td>NG²</td>
</tr>
<tr>
<td>100</td>
<td>1974</td>
<td>5,6,7,8</td>
<td>80</td>
<td>94</td>
<td>10</td>
<td>3</td>
</tr>
<tr>
<td>100</td>
<td>1983</td>
<td>6,7</td>
<td>32</td>
<td>79</td>
<td>8</td>
<td>3</td>
</tr>
<tr>
<td>100</td>
<td>1990</td>
<td>1</td>
<td>1</td>
<td>61</td>
<td>6</td>
<td>NG²</td>
</tr>
<tr>
<td>150</td>
<td>1963</td>
<td>7,8</td>
<td>52</td>
<td>77</td>
<td>19</td>
<td>2</td>
</tr>
<tr>
<td>150</td>
<td>1964</td>
<td>7,8</td>
<td>23</td>
<td>83</td>
<td>21</td>
<td>2</td>
</tr>
<tr>
<td>150</td>
<td>1972</td>
<td>3</td>
<td>1</td>
<td>28</td>
<td>7</td>
<td>NG²</td>
</tr>
<tr>
<td>150</td>
<td>1974</td>
<td>6,7,8</td>
<td>70</td>
<td>74</td>
<td>18</td>
<td>2</td>
</tr>
<tr>
<td>150</td>
<td>1983</td>
<td>7</td>
<td>22</td>
<td>48</td>
<td>12</td>
<td>3</td>
</tr>
<tr>
<td>150</td>
<td>1990</td>
<td>1</td>
<td>1</td>
<td>29</td>
<td>7</td>
<td>NG²</td>
</tr>
<tr>
<td>200</td>
<td>1963</td>
<td>7,8</td>
<td>43</td>
<td>45</td>
<td>25</td>
<td>2</td>
</tr>
<tr>
<td>200</td>
<td>1964</td>
<td>7,8</td>
<td>20</td>
<td>58</td>
<td>32</td>
<td>1</td>
</tr>
<tr>
<td>200</td>
<td>1974</td>
<td>7,8</td>
<td>41</td>
<td>54</td>
<td>29</td>
<td>2</td>
</tr>
<tr>
<td>200</td>
<td>1983</td>
<td>7</td>
<td>6</td>
<td>19</td>
<td>10</td>
<td>3</td>
</tr>
<tr>
<td>200</td>
<td>1990</td>
<td>7</td>
<td>5</td>
<td>7</td>
<td>4</td>
<td>NG²</td>
</tr>
<tr>
<td>300</td>
<td>1964</td>
<td>7,8</td>
<td>8</td>
<td>27</td>
<td>78</td>
<td>1</td>
</tr>
<tr>
<td>300</td>
<td>1974</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>22</td>
<td>2</td>
</tr>
</tbody>
</table>

Notes: 1. January represented by 1, February by 2, etc. 2. NG = no grade (not a SE recharge step)
Figure 4-7a-f: Cumulative recharge from 1960-1992 for five root depths at four sites (three SRMs at Corrigin)
The numbers of times that SE recharge of each grade occurred for each model run are illustrated in Figure 4-9, and Table 4-4 summarises the number of episodes and the percentages of the total recharge that they contributed.

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

<table>
<thead>
<tr>
<th>Maximum Root Depth</th>
<th>50 cm</th>
<th>100 cm</th>
<th>150 cm</th>
<th>200 cm</th>
<th>300 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Station</td>
<td>no. E</td>
<td>%</td>
<td>no. E</td>
<td>%</td>
<td>no. E</td>
</tr>
<tr>
<td>Beverley</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>16</td>
<td>5</td>
</tr>
<tr>
<td>Corrigin</td>
<td>2</td>
<td>16</td>
<td>4</td>
<td>42</td>
<td>4</td>
</tr>
<tr>
<td>Lake Grace</td>
<td>2</td>
<td>19</td>
<td>6</td>
<td>67</td>
<td>6</td>
</tr>
<tr>
<td>Southern Cross</td>
<td>4</td>
<td>40</td>
<td>5</td>
<td>84</td>
<td>2</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Maximum Root Depth</th>
<th>50 cm</th>
<th>100 cm</th>
<th>150 cm</th>
<th>200 cm</th>
<th>300 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Station and soil growth model</td>
<td>no. E</td>
<td>%</td>
<td>no. E</td>
<td>%</td>
<td>no. E</td>
</tr>
<tr>
<td>Corrigin SRM1</td>
<td>2</td>
<td>15</td>
<td>4</td>
<td>40</td>
<td>4</td>
</tr>
<tr>
<td>Corrigin SRM2</td>
<td>2</td>
<td>16</td>
<td>4</td>
<td>42</td>
<td>4</td>
</tr>
<tr>
<td>Corrigin SRM3</td>
<td>4</td>
<td>37</td>
<td>6</td>
<td>92</td>
<td>3</td>
</tr>
</tbody>
</table>

Note: ¹ NR = no recharge

### 4.2.2.4 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 4-5 shows that the mean annual rainfall decreased eastwards and the variability increased in that direction. Figure 4-10 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 4-5) 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, and the large daily falls in winter tended to be smaller than the large daily falls in summer (Figure 4-11). 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 4-8: Percentage of total recharge due to SE recharge vs. mean annual recharge
The decrease in total rainfall to the east and south-east was reflected in the amount of recharge generated (Table 4-6). The distribution of the recharge through the year also reflected the differences in the rainfall patterns from west to east (Figure 4-12 and Figure...
4-13), with a higher proportion of the total recharge occurring during the summer at Southern Cross than at Beverley.

Table 4-5: Mean, maximum and minimum annual rainfalls and December to March (DJFM) rainfall from 1960 to 1992 for the four stations modelled

<table>
<thead>
<tr>
<th>Site</th>
<th>'Location' in Wheatbelt</th>
<th>Mean annual rain 1960-1992 (mm)</th>
<th>Maximum annual rain 1960-1992 in mm (year)</th>
<th>Minimum annual rain 1960-1992 in mm (year)</th>
<th>Total DJFM rain, 1960 to 1992 (mm)</th>
<th>Total DJFM rain as % of total 1960 to 1992 rain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beverley</td>
<td>west</td>
<td>407</td>
<td>560 (1963)</td>
<td>236 (1969)</td>
<td>1921</td>
<td>14</td>
</tr>
<tr>
<td>Corrigin</td>
<td>central</td>
<td>369</td>
<td>531 (1963)</td>
<td>224 (1969)</td>
<td>2169</td>
<td>18</td>
</tr>
<tr>
<td>Lake Grace</td>
<td>south east</td>
<td>353</td>
<td>545 (1968)</td>
<td>211 (1972)</td>
<td>2368</td>
<td>20</td>
</tr>
<tr>
<td>Southern Cross</td>
<td>east</td>
<td>318</td>
<td>577 (1963)</td>
<td>200 (1979)</td>
<td>2410</td>
<td>23</td>
</tr>
</tbody>
</table>

Table 4-6: Rain, recharge and SE recharge for 150 cm deep roots and SRM2 at each of the four stations modelled

<table>
<thead>
<tr>
<th>Location</th>
<th>Mean annual rain (mm) 1960-1992</th>
<th>Mean annual recharge (mm) 1960-1992</th>
<th>Number of times SE recharge occurred</th>
<th>% of total recharge due to SE recharge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beverley</td>
<td>407</td>
<td>38</td>
<td>5</td>
<td>45</td>
</tr>
<tr>
<td>Corrigin</td>
<td>369</td>
<td>12</td>
<td>4</td>
<td>70</td>
</tr>
<tr>
<td>Lake Grace</td>
<td>353</td>
<td>9</td>
<td>6</td>
<td>97</td>
</tr>
<tr>
<td>Southern Cross</td>
<td>318</td>
<td>2</td>
<td>2</td>
<td>92</td>
</tr>
</tbody>
</table>

Rainfall amount and distribution also affected the importance of SE 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 4-14). The importance of SE 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 4-6).

Figure 4-15 is similar to Figure 4-8 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, for the same mean annual recharge, the pattern of recharge is likely to be more regular at Southern Cross and more episodic at Beverley.
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Figure 4-10: Mean monthly rainfall for 1960-1992 for the four stations modelled

Figure 4-11: Maximum daily rainfall in each month for the period 1960-1992 for three of the stations modelled
Figure 4-12: Total daily recharge for Beverley from 1960-1992 for 50 cm-deep roots, SRM2

Figure 4-13: Total daily recharge for Southern Cross from 1960-1992 for 50 cm-deep roots, SRM2
Figure 4-14: Percentage of total recharge due to SE recharge vs. modelled maximum storage for SRM2 at four stations

Figure 4-15: Percentage of total recharge due to SE recharge vs. mean annual recharge

The line for Lake Grace in Figure 4-15 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 SE 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). Also, SE recharge was both more likely and more important at Lake Grace than at Corrigin when roots were 100 cm and 150 cm deep (Table 4-4a and Figure 4-9b and c). In about a third of the SE grade 3 events at Lake Grace, summer rainfall contributed to the recharge total, which did not happen at Corrigin. So, 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 SE recharge there.

Table 4-7 shows that SE recharge did not occur at the same time across all of the four locations modelled. Comparing results for SRM2, the years that were important at Corrigin were also important at Beverley (although Beverley experienced SE recharge in two years that did not rate as episodic for Corrigin). This is not surprising as cold fronts usually move eastwards.

Widespread winter SE recharge occurred in 1963, 1964 and 1974, but for the 33 years modelled, heavy winter rains resulted in SE recharge either in the east or in the south-east, but not in both in the same year.

In the west and central areas, SE recharge was dominated by winter events, whereas further east and south-east, about half of the SE recharge occurrences were due solely to winter recharge, with one-day summer rainfall events resulting in SE recharge on one occasion in each case, and contributing to the winter totals on the others.

Figure 4-9d 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 4-7 also shows that the number of years with SE recharge events decreased from six during the 1960s to three during the 1970s and only one during the 1980s.
Table 4-7: Years when SE recharge occurred (X) and when summer recharge was graded as episodic (XS) (results from all modelled root depths were included)

<table>
<thead>
<tr>
<th>Year</th>
<th>Beverley SRM2</th>
<th>Corrigin SRM1</th>
<th>Corrigin SRM2</th>
<th>Corrigin SRM3</th>
<th>Lake Grace SRM2</th>
<th>Southern Cross SRM2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1960</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>1961</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>1963</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>1964</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
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<td>1966</td>
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<td>X</td>
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<td>1967</td>
<td>X</td>
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<td></td>
<td>XS</td>
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<tr>
<td>1968</td>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>1970</td>
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<td></td>
<td></td>
<td></td>
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<td>X</td>
</tr>
<tr>
<td>1972</td>
<td></td>
<td>XS</td>
<td></td>
<td></td>
<td>XS</td>
<td></td>
</tr>
<tr>
<td>1974</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>1983</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>1990</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>XS</td>
</tr>
</tbody>
</table>

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 4-8 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%. 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 4-8: Relative effects of rainfall and evaporation on recharge for SRM2 with 50 cm deep roots

<table>
<thead>
<tr>
<th>Station</th>
<th>Rainfall Mean annual (mm)</th>
<th>% increase from Southern Cross</th>
<th>Station</th>
<th>Evaporation Mean annual (mm)</th>
<th>% decrease from Southern Cross</th>
<th>Recharge Mean annual (mm)</th>
<th>% increase from Southern Cross</th>
</tr>
</thead>
<tbody>
<tr>
<td>Southern Cross</td>
<td>318</td>
<td>0</td>
<td>Southern Cross</td>
<td>2428</td>
<td>0</td>
<td>26</td>
<td>0</td>
</tr>
<tr>
<td>Southern Cross</td>
<td>318</td>
<td>0</td>
<td>Lake Grace</td>
<td>1854</td>
<td>24</td>
<td>38</td>
<td>45</td>
</tr>
<tr>
<td>Beverley</td>
<td>407</td>
<td>28</td>
<td>Southern Cross</td>
<td>2428</td>
<td>0</td>
<td>65</td>
<td>152</td>
</tr>
<tr>
<td>Lake Grace</td>
<td>353</td>
<td>11</td>
<td>Southern Cross</td>
<td>2428</td>
<td>0</td>
<td>30</td>
<td>15</td>
</tr>
</tbody>
</table>

### 4.2.2.5 Effect of maximum root depth and soil type on generation of recharge

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

The likelihood of SE recharge occurring increased then decreased as either root depth or soil clay content increased. This pattern reflected the changes passing from regular recharge regimes, through regimes with both regular and SE recharge, and then through regimes with only SE recharge, and finally to regimes with no recharge during the period considered. The only run of the model which produced no SE recharge because of the regular nature of the recharge was that for 50 cm-deep roots at Beverley (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 4-4). It is possible that modelling a longer sequence of years would have resulted in conditions which produced recharge in these cases.

Clearly, the importance of SE recharge relative to total recharge increased 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 4-4). Not surprisingly, the two cases were for deep roots (200 cm) and either in the heaviest 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 soilwater storage (illustrated by the results for the Corrigin SRM2 run) were:

- a decrease in the total amount of recharge (Table 4-2);
- a decrease in the number of recharge events (Table 4-2);
- a decrease in the duration of recharge events including SE recharge periods (Table 4-3);
- a delay in the start of recharge generation following the break of the season (e.g. 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 4-3);
- a lessening in the importance of summer recharge events (Table 4-3).

4.2.3 Discussion

Even though the model used was simplistic, it is clear that the rainfall regimes can lead to direct SE recharge, and such recharge could be a significant proportion of the direct recharge that occurs in the Western Australian Wheatbelt. The model also indicated 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 be considered to be only indicative.

4.2.3.1 Where direct SE recharge is most likely to occur

The likelihood of SE recharge was greatest in the middle-of-the-range cases of those modelled. Where available soilwater 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 soilwater storage was high or rainfall was low, then there were very few (or no) recharge events during the 33 years that were modelled.
4.2.3.2 Relationship between SE recharge and rain events

There appeared to be no clear relationship between the size of individual rainfall events and the occurrence of SE recharge except during summer. Similarly, there was no clear relationship between weekly or monthly rain totals in the winter months and the episodicity of recharge. For a given rain total which produced winter SE recharge, there were examples in other years of similar totals not resulting in SE recharge. There did seem to be a weak trend that a wet July resulted in SE 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.

4.2.3.3 Model results and groundwater hydrographs

If the general recharge patterns shown by the cumulative recharge graphs are realistic, then groundwater hydrographs from sites where there is no groundwater drainage should have similar rise patterns. This appears to be the case. Examples are three piezometer hydrographs from the Morbinning Catchment (near Beverley, see Figure 4-1) which show (Figure 4-16): 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 flow 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 soilwater storage in the root zones increases from MO3 to MO69 to MO63.

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 led to SE 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 4-17; see Figure 4-1 for location) and below gravel soils at a site in the west (Kettlerock Gully, Figure 4-18, see Figure 4-1 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 4-1) 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 4-16: Groundwater hydrographs for three sites in the Morbinning Catchment near Beverley
4.2.3.4 The relevance of the modelled soil types

The three soil types modelled have low water holding capacities compared to other, more clay-rich, soil types in the Wheatbelt. Therefore, in terms of matrix flow, one would expect the amount of direct recharge through these soils to be greater than through other types. However, soils with significant macropore flow (e.g. well-structured non-swelling clays and...
cleared areas with well-developed root channels from dead trees) or which may have significant indirect recharge (lakes and watercourses, floodplain areas, waterlogged land) may also allow significant volumes of recharge to reach the groundwater systems, and be particularly prone to SE 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 assess 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. The corresponding figures for the areas mapped by Lantzke and Fulton were 3%, 12% and <1% (if soils which are only similar in the upper 50 cm of their profile are included, then the areas increase dramatically). 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.

4.2.3.5 The relevance of the root depths modelled

Since the occurrence of SE recharge appears to be related to maximum available soilwater storage and thus root depth, the agricultural species in use will affect the generation of SE recharge. Cook and Walker (1990) assumed that wheat roots were 100 to 125 cm deep and this led 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 led to maximum available soilwater storages of between 18 and 69 mm for soils with from 2% clay to 25% clay. 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. They modelled this effect by considering that water was only removed from the top 0.5 m for crop and 0.5 to 1 m for 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.

**4.2.3.6 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 WA. 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 heavier soils than those modelled. Therefore, one would expect all estimates given in Nulsen (1993) to be lower than the model results. Nulsen stated 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.
4.3 REGIONAL VARIATIONS IN MODELLED DIRECT SE RECHARGE, WESTERN AUSTRALIA AND NORTHERN VICTORIA

The simple daily water-balance carried out for Beverley, Corrigin, Lake Grace and Southern Cross (Sec. 4.2) illustrated that their rainfall regimes could lead to SE recharge and that the significance and likelihood of SE recharge changed with location in the Wheatbelt. (The two factors that changed with location in the simple water-balance model were rainfall and evaporation.) The results indicated that if similar water-balances were carried out (for a particular value of soilwater storage) for enough stations, then maps of likelihood of direct SE recharge, based on rainfall and evaporation regimes, could be drawn. This was done for both WA and NV, with the aim of mapping the regional variations in recharge regimes for different site conditions.

Note that such maps would not account for SE recharge resulting from indirect processes involving waterlogging, streamflow, flooding or lakes, nor from direct infiltration and percolation which involved preferred path processes.

4.3.1 The model

As this study aimed to concentrate on the effects of rainfall regime, the daily water-balance model described in Section 4.2 was simplified further. In the first model, there were two ‘buckets’ in which the available water capacity changed during the year as active rooting depth changed. In this study, the available water holding capacity was constant. Another difference was that the previous study used BASIC code whereas this study used an EXCEL spreadsheet, adapted from one prepared by H. Cresswell (Division of Land and Water, CSIRO, Canberra).

4.3.1.1 Rainfall data

Daily rainfall data was required for enough locations to determine boundaries between areas which behaved differently. A selection of Bureau of Meteorology stations was made based on whether there were complete, or nearly complete, records for 30-year periods. (Lavery et al. (1992) listed a set of rainfall stations with high-quality data, and this study used all the relevant ones. Even in these records, there were some substantial gaps.) Stations relatively close together were chosen in regions with steep isohyet gradients and also in one area of the Western Australian Wheatbelt to test the change in behaviour on a finer scale.
Records from 53 rainfall stations in WA and 42 in NV were used (the stations are listed and mapped in Appendix 4).

For WA, the main period modelled was from 1950 to 1979 (inclusive) as this coincided with a full rainfall cycle for most of the agricultural area (identified by Nicholls and Lavery (1992)). For those stations with sufficient data, the 30 years from 1920 to 1949 and the 18 years from 1980 to 1997 were also modelled. Results for the three periods 1950 to 1979; 1920 to 1949; and 1920 to 1997 were compared. The average rainfall for each period is listed in Appendix 4.

For NV, two 30-year periods were modelled: 1930 to 1959 and 1960 to 1989. The first of these periods corresponded to a clear rainfall cycle in central NV (Nicholls and Lavery 1992). The average rainfall for each period is listed in Appendix 4.

4.3.1.2 Evaporation data and potential and actual evapotranspiration

As in the previous study (Sec. 4.2), monthly mean evaporation figures for the locations were obtained from the ESOCLIM computer program (Centre for Resource and Environmental Studies, Australian National University, Canberra) and these were converted into daily evaporation figures with a smoothing routine. The data was generated by I. Foster (Agriculture Western Australia, South Perth). Note that the daily evaporation figures were based on mean monthly figures and so the daily data used in the model did not vary from year to year. The annual evaporation at each station is listed in Appendix 4.

Potential and actual evapotranspiration were calculated in the same way as described in Section 4.2.

4.3.1.3 Available water storage in the root zone

The values of maximum soilwater storage available in the root zone (MAXST) used were based on loamy sands and sandy loams (such a simple water-balance model is inappropriate for soils with higher soilwater storage capacities as they tend to have low hydraulic conductivity). MAXST values were calculated in the same way as those in Section 4.2 for active root zones of 50 cm and 100 cm deep. Table 4-9 lists the values used.
Table 4-9: Values of maximum soilwater storage available in the active root zone (MAXST) used in the simple water-balance model

<table>
<thead>
<tr>
<th>Active root zone depth (cm)</th>
<th>MAXST (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Loamy Sand</td>
</tr>
<tr>
<td>50</td>
<td>30</td>
</tr>
<tr>
<td>100</td>
<td>60</td>
</tr>
</tbody>
</table>

Thus, runs of the model were carried out for MAXST of 30 mm, 60 mm and 140 mm to assess the effect of rainfall regime on a small range of soil types with two root depths.

4.3.1.4 Assessing significance and likelihood of SE recharge

SE grades for calendar years were calculated. Records were inspected to check whether using calendar years resulted in significant steps being missed if they occurred over a two-year period or spanned the end of the year. It was not a common problem.

For each MAXST, the percentage of the 30-year (and 78-year for WA) recharge which was graded as SE recharge, the number of years over which the SE recharge occurred, and the number of SE grade 1 recharge events were calculated. For the MAXST of 60 mm from 1950 to 1979 in WA, for each station which had SE recharge, the percentage of the SE recharge which occurred in each season of the year was calculated.

4.3.2 Results and discussion

Details of the results are presented in Appendix 4.

The modelling results gave a clear picture of the regional trends in SE direct recharge based on rainfall and evaporation regimes (Figure 4-19 and Figure 4-20). Contour lines were not drawn on the maps because there were a few anomalies which would have distorted them. Results and their discussion are presented separately for WA and NV.
a: 30 mm MAXST

b: 60 mm MAXST
c: 140 mm MAXST

Figure 4-19: SE recharge as % of total recharge at Western Australian stations, 1950-1979; MAXST values a: 30 mm; b: 60 mm; c: 140 mm

a: 30 mm MAXST
4.3.2.1 Western Australia

The importance of direct SE recharge increased from unimportant (zero SE recharge) in the wet south-west, north-eastwards through regions where it was important, to the drier regions east and north of the agricultural areas where it was either extremely important (near to 100% of recharge was episodic) or unimportant (zero SE recharge for some sites with MAXST of 140 mm). There are different reasons for the unimportance of SE recharge in the wetter south-west and where it was indicated in the drier north-east. In the wetter south-west, there
was little likelihood of SE recharge because there was recharge in most years and rainfall regimes were less variable than further east and north. In the dry zones, the reason for zero SE recharge at some stations was that recharge was rare and there were no episodes during the modelled period - it is possible that with longer or different modelling periods SE recharge would occur.

The importance of SE recharge also increased from the high rainfall areas in the south-west north-eastwards towards the drier regions in the centre of WA.

Even for the low MAXST of 30 mm, there were several stations in the central and eastern Wheatbelt where SE recharge made up about 20% to 43% of the total recharge. At most of these stations there were between one and three SE events in the 30-year period. For MAXST of 60 mm, SE recharge was important across a large proportion of the agricultural areas, and generally occurred in from three to six years. In the east and south, nearly all recharge was significant and episodic for the higher MAXST of 140 mm, and at many places there was just one SE grade 1 event during the 30 years.

The regional trends were the same for the different periods modelled, but in the north-eastern Wheatbelt there was less recharge and it was more episodic during the earlier period (1920 to 1949).

In the northern central Wheatbelt, several close stations were compared. The years in which the greatest recharge occurred tended to be the same (and occurred in wet winters), but there was more variety in the timing of moderate recharge years (which were influenced by summer storms). Similarly, in the northern Wheatbelt, there were differences between nearby stations because of the localised nature of 1-day rainfall events in summer and autumn months.

Comparing the results for Perenjori near the northern boundary and Southern Cross near the eastern boundary of the agricultural area showed that although the mean annual rainfall at Perenjori was lower, the total recharge was greater and the importance of SE recharge (33% of the total recharge) was less than at Southern Cross (63%). The years which generated recharge were different between the two regions.

A surprising result was, for the conditions modelled, the similarity between the results for the semi-arid parts of the agricultural areas and arid parts of WA. For example, for Giles (in the
Part I, Chapter 4: Regional variations in likelihood

arid region - mean annual rainfall over the modelled period of 260 mm) SE recharge was not clearly more important, nor were there clearly fewer episodic events during the modelled period, nor were there more SE grade 1 events, than in the north-eastern Wheatbelt. This suggests that rainfall regimes in semi-arid regions are as likely to produce direct SE recharge as those in arid areas. This is supported when the coefficients of variation (Cv) of recharge are compared (Figure 4-21a). Although annual rainfall is less variable in the Wheatbelt, the variability of the annual recharge at stations in arid and semi-arid parts are similar.

This similarity was investigated further by comparing the variability of recharge in just those years which received recharge - that is, years with no recharge were ignored. Again, the variability of recharge was as great in semi-arid areas as in arid areas (Figure 4-21b).

The total recharge in semi-arid areas was lower than in arid areas, but was spread over a similar number of years. The lower average recharge explained the similarity in the Cv values - in arid areas the standard deviation of annual recharge was generally higher than in semi-arid areas, and since Cv is calculated by dividing the standard deviation by the mean, the semi-arid and arid regions had similar Cv values. (This indicates that if the standard deviation was used as a measure of variability rather than the Cv, then the recharge in the arid areas would be considered more variable than in the semi-arid areas.)

The pattern of daily recharge showed that in arid areas most recharge was generated from very large rainfall events, most of which were in summer. In the semi-arid agricultural regions, there were a few years when recharge was generated by large summer storms, but most occurred over a few days in winter months.

These results only indicate the episodicity of direct recharge, not indirect recharge. Although indirect recharge is considered to be the dominant form in arid and semi-arid regions (see Chapter 2), it is not clear whether indirect episodic recharge is relatively more important in arid than in semi-arid areas.
a: all years from 1950-1979 for WA and 1960-1989 for Victoria

b: only years from 1950-1979 which had recharge were included in Cv calculations

Figure 4-21: Variability of annual rainfall vs. variability of annual recharge for Western Australian (WA) (1959-1979) and northern Victorian (1960-1989) stations. Non-agricultural stations in WA with greater than 280 mm mean annual rainfall are not plotted. MAXST 60 mm

Generally, agricultural areas which had direct SE recharge had between about 20 and 50% of it during January, February and March (Figure 4-22); northern WA (where rain is
monsoonal) and arid areas had from 50 to 99% of their episodic recharge during those same months.

![Map with color legend](image)

**Figure 4-22**: Percentage of SE recharge that occurred during January, February and March, Western Australia, 1959-1979, MAXST 60 mm; small black symbols represent stations which had no SE recharge

### 4.3.2.2 Northern Victoria

In NV, the importance of SE direct recharge increased northwards. Towards the north-west of the state, more than 50% of the total recharge was episodic for the MAXST of 60 mm. The regional trends for the two 30-year periods modelled were similar, although at some stations total rainfall and recharge increased from the earlier to the later period, while it decreased at others.

The relationships between the variability of recharge and of rainfall were similar to those for the semi-arid areas of WA, although there was a tendency for rainfall of a certain variability to produce slightly more variable recharge in the Western Australian Wheatbelt (Figure 4-21a). If average annual rainfall is used as a guide to how much recharge is episodic, then, for MAXST of 60 mm, the results for WA and NV are similar, although the points plot within very broad bands.
4.4 SUMMARY AND CONCLUSIONS

The main aim of this chapter was to explore how the regional trends in rainfall variability in south-western WA affect the likelihood of SE recharge, using simple water-balance models. Firstly, a preliminary set of runs for four Wheatbelt locations aimed to assess whether the rainfall regimes had the potential to result in SE recharge regimes under the soil and root conditions modelled. Then the rainfall records from a large number of stations throughout WA and NV were used, with the aim of mapping the regional variations in recharge regimes for different site conditions.

The results of the preliminary modelling showed that SE recharge occurred at each of the four Wheatbelt locations under some of the modelled conditions. The importance of SE recharge increased with decreasing mean annual rainfall, but the amount of SE recharge increased with increasing mean annual rainfall.

Commonly, SE recharge occurred in different years in different parts of the Wheatbelt.

The annual rainfall at a site is not a good guide to the amount of recharge generated. A year with a low rainfall concentrated into short periods could result in more recharge than a year with much more total rainfall spread more evenly throughout the year.

Modelling the recharge for a large number of sites in WA and NV enabled regional trends in potential episodicity to be seen. The intermediate case modelled (MAXST of 60 mm) showed that SE recharge was important throughout the Wheatbelt of WA and central and eastern parts of NV.

The year with the greatest amount of recharge tended to be the same at nearby stations. In the WA Wheatbelt, it was commonly the result of several periods of heavy winter rain rather than large summer falls. Summer rain contributed to many of the smaller SE events, but the years in which summer rain was important varied from station to station.

The potential of rainfall of a particular annual variability to cause SE recharge was similar in the WA Wheatbelt and northern Victoria. But even though the rainfall regimes in the semi-arid Wheatbelt of WA were less variable than those of the arid regions to the east, the modelling indicated that recharge regimes could be just as variable. It seems that very large
summer storms led to most SE recharge in the arid areas, whereas SE recharge in the semi-arid areas was more often associated with wet winters.
CONCLUSION TO PART I

Part I presented assessments of the likelihood of recharge being episodic in the Wheatbelt of WA, which were made as a preliminary to planning a research project into SE recharge.

Several publications on south-western WA identified unusually large groundwater rises and associated them with periods of heavy rainfall and with both indirect and direct recharge processes. Nearly half of the published groundwater hydrographs which were inspected were classed as 'possibly episodic'.

Although very few studies elsewhere in the world have focussed on SE recharge, studies with other purposes provided information on rainfall and site conditions associated with unusually large pulses of recharge. Many of the common conditions can be found in WA (e.g. irregular large rainfalls produced by decayed tropical cyclones and summer storms; variable winter rainfall from temperate cyclone systems; deep sand profiles; preferred path flow through unsaturated soils; occasional floods).

Simple water-balances showed that the rainfall regimes in the WA Wheatbelt and northern Victoria could produce SE recharge regimes under some of the conditions modelled (only direct recharge processes through high-permeability soil types were modelled).

Thus, the conclusion is that SE recharge is likely to contribute a significant proportion of the total recharge in some parts of the Western Australian Wheatbelt, and that both direct and indirect recharge processes could be involved.
Author/s: Lewis, Marjorie Fay

Title: The significance of episodic recharge in the wheatbelt of Western Australia

Date: 2000-11


Publication Status: Unpublished

Persistent Link: http://hdl.handle.net/11343/39438

File Description: Pt. 1

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