The significance of episodic recharge in the Wheatbelt of Western Australia

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ABSTRACT

Groundwater levels in the Wheatbelt of Western Australia are rising and causing severe and widespread land salinisation. Evidence from northern Victoria showed that episodic recharge pulses following floods had caused significant groundwater rises. The aim of this study was to determine:
1. whether episodic recharge was significant compared to regular recharge in the Wheatbelt;
2. the conditions under which episodic recharge occurs.

These aims were addressed in three stages. Part I assessed the likelihood of episodic recharge being significant in the Wheatbelt by reviewing published information and by investigating whether Wheatbelt rainfall patterns could lead to episodic recharge (using simple water-balance models). The assessments showed that significant episodic recharge was likely, and that both direct and indirect processes could be involved. The likelihood of episodic recharge increased north-eastwards, reflecting trends in decreasing mean annual rainfall, increasing rainfall variability, and increasing evaporation.

Since there were no suitable methods of distinguishing between episodic and non-episodic recharge in the literature, several indices were developed.

Part II aimed to identify sites where episodic recharge had occurred, so that the conditions at them could be compared to those at sites with regular recharge regimes. Three methods were used: analysis of long-term groundwater hydrographs from three piezometer networks, analysis of groundwater chemistry (principally deuterium and oxygen-18 ratios), and piezometer monitoring at flood-prone sites. None of the methods identified episodic recharge sites, but sites with significant episodic groundwater rises were successfully identified using the long-term hydrographs. These identifications were relevant because salinisation results from groundwater level rises.

The 'long-term' hydrographs were short (all <16 years) and covered only a limited range of landscape locations, so they were augmented with records from northern Victoria. Even then, very few sites had more than one significant episodic rise during the period of record.
Part III aimed to determine which rainfall and site conditions were associated with significant episodic groundwater rises. A surprising finding was that most significant episodic rises did not occur during the years with the highest rainfall. Rainfall pattern during the year was more influential. It was clear that floods were not essential to generate episodic recharge and many of the irregular, large groundwater rises occurred below slopes.

The short Western Australian groundwater records did not show the expected increase in episodicity towards the north-east. Significant episodic groundwater rises occurred in the south-western piezometer network but not the north-eastern one. The long-term (~70 years) rainfall records showed that, during the periods of groundwater records, rainfall was relatively low in the south-west but relatively high in the north-east. Thus, long-term mean annual rainfall is not a good indicator of the likelihood of episodicity over the short-term.

Episodic recharge is not restricted to particular regolith, bedrock or landscape conditions, but can occur under most areas. Groupings of piezometers were identified, based on similarities in hydrograph forms and the years in which large rises occurred. It was found that episodicity increased with groundwater level depth within some groups and that the processes causing this varied. So, episodicity changed from one part of a landscape to another, reflecting groundwater level depth. An additional implication is that at a site where there are long-term groundwater rises, then episodicity also changes with time.

Based on the results of the research, simple conceptual models for predicting how recharge regimes change in response to changes in rainfall and site factors were developed.
DECLARATION

This is to certify that

(i) the thesis comprises only my original work,

(ii) due acknowledgement has been made in the text to all other material used,

(iii) the thesis is less than 100,000 words in length, exclusive of tables, maps, bibliographies, appendices and footnotes.

Marjorie Fay Lewis
PREFACE

Some of the work described in Chapters 3 and 4 was also presented in a conference paper and documented in a technical report:


Although Dr. Glen Walker was my principal supervisor throughout, I was initially enrolled (part-time and off-campus) at Flinders University in South Australia. The early planning for the research in this thesis was carried out at that stage, but the majority of the work was carried out during my enrolment at the University of Melbourne.

All sources of the information used in this thesis are cited in the text.
ACKNOWLEDGEMENTS

I have thoroughly enjoyed the time spent on this PhD and am sorry that it is coming to an end. I would not have felt like this if I had not had generous funding and support from many people.

I am grateful to the Cooperative Research Centre for Catchment Hydrology for the scholarship and project funding, and to Agriculture Western Australia who gave me study leave and operational support.

I was extremely fortunate in having Dr. Glen Walker as my principal supervisor. He manages to be authoritative without being arrogant, and I have appreciated his broad knowledge, clear-thinking and ideas. He was generous with his time - he persisted in pulling my focus back to the questions I was supposed to be addressing, and he patiently and subtly trained me to organise my writing.

I would also like to thank my two other supervisors, Dr. Bob Nulsen and Dr. Q.J. Wang. Although they are both under pressure from too much work, they found time to give me support and advice when asked, and Bob Nulsen reviewed the final draft of the thesis.

Much of the work in this thesis depended on data collected by others. In Western Australia, Greg Bartle and Jim Prince supplied the groundwater level data from the Cuballing, East Perenjori and Wallatin Creek networks. Both of them were as helpful as anyone could wish, and they spent time ensuring that the quality of the data they provided was as high as possible. Leah McCloy, Cec McConnell and Peter Lacey were also key people in field data collection in Western Australia. David Hall willingly provided Esperance data and showed me the sites.

In Victoria, Mark Reid and David Heislers delved into their databases with gusto and provided the bulk of the hydrograph records used in this project. In addition, Phil Cooke and his associates gathered together maps of the piezometer locations and provided useful hints on how to find them.

The dye-tracer experiments could not have been done without the rainfall simulator and all who helped me prepare it and use it. In particular, I owe thanks to Peter Hanson, Hernan
Ortiz, Jim Prince and Ed Solin, and to Dave Imrie who let me dye his laboratory blue with hardly any complaints. Soil pit discussions and descriptions were of high quality because of the presence of Noel Schocknecht, Paul Galloway, Bill Verboom and Mir Frahmand.

Megan le Fournour, Fred Leaney, John Dighton, Andrew Holub, Kerry McEwan and Corinne Le Gal La Salle all tried very hard to train me in the arts of deuterium and oxygen-18 analyses. That none of them lost their tempers is testament to their patient and generous personalities. Jeff Turner was as helpful as usual when he gave me rainfall isotope data.

The water-balance models I used were based on programs supplied by Ashleigh Kennett-Smith and Hamish Creswell, and Ian Foster, Les Heinrich, the staff at the Bureau of Meteorology and Tam Hoang took time to provide me with evaporation and rainfall data.

One of the many good things about being granted time for PhD research is the ability to read the literature without feeling you should be doing something else instead. So, I would like to thank all those who reported their research in accessible publications, and especially to those who did it on interesting topics in exotic places, who did it clearly, who were honest about the assumptions they employed, and who reported all sides of the story, not just the bits that fitted their agendas.

I would have had much less to read if the superb staff at the library at Agriculture WA had not been so helpful and so good at tracking down the things I was after. Also, many people generously loaned me relevant publications or provided copies.

I should also thank Phil Dyson and Phil Macumber. I can't remember which one of them first said "episodic recharge" to me, but they must both bear some responsibility for the topic of this thesis.

Friends have been wonderful. In particular, I want to thank Deb O'Connell for her sharp eyes, questioning mind and encouraging comments, and for her dedication to reading the thesis when she could have been playing with Jaslyn instead. And thankyou Jaslyn for your artistic comments. Very special thanks are also due to Naomi Segal, Jenny Davis, Ian Bennett and Tony Proffitt who have been particularly empathetic and encouraging.
And finally, thankyou Bruce Mattinson for the typically unique ways in which you provided all sorts of support, and inspiration too ("What's the problem? Just finish it.").
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1. INTRODUCTION

1.1 EPISODIC RECHARGE

The term 'episodic recharge' will be used to describe infrequent and irregular pulses of groundwater recharge. In arid regions, both rainfall and recharge tend to be episodic. In semi-arid regions the importance of episodic recharge compared to regular recharge is less clear. This thesis evaluates the significance of episodic recharge in semi-arid agricultural areas of Western Australia. In these areas, reducing groundwater recharge is an important step in reducing land degradation caused by salinity.

1.2 BACKGROUND

1.2.1 Agriculture and groundwater recharge in Western Australia

Since 1830, 18 million hectares of natural vegetation have been cleared and replaced with agricultural species in south-western Western Australia (Figure 1-1). The natural vegetation was predominantly perennial and deep-rooted. Most of the agricultural species are winter annuals - shallow-rooted, legume pastures and grain and legume crops.

The change in vegetation has dramatically affected the hydrological cycle. The most marked effects are decreases in evapotranspiration and increases in groundwater recharge. Groundwater levels have risen throughout the region and groundwater discharge has increased. This has caused land and stream salinisation, which is spreading rapidly. In 1996, a situation statement on salinity was produced (Anon. 1996) which reported the range of groundwater level rises observed in different parts of the agricultural region, and estimated the amount of recharge responsible (Table 1-1). Ferdowsian et al. (1996) estimated that in 1994 salinity caused by elevated groundwater levels affected about 9% of the land cleared for agriculture, and that between about 2010 and 2020 (depending on rainfall conditions), 17% could be affected. They predicted that an area equivalent to more than 30% of the cleared land could eventually be salt-affected.
1.2.2 Reducing groundwater recharge

Reducing the volume of groundwater recharge is one approach to dealing with salinisation. Since it is assumed that groundwater levels were not rising before the land was cleared, one would expect that returning the land to the original native vegetation mix, or to a mixture of other plants with a similar range of water-use characteristics, would reduce recharge rates to levels which the 'natural' discharge systems could accommodate. However, there are presently few or no plants available which have economic potential as well as the appropriate water-use characteristics. Therefore, most land managers who wish to reduce the salinity hazard are aiming to increase the water-use of the plants that they have traditionally grown. The impact of this approach is likely to be greatest in the drier agricultural areas, such as the eastern Wheatbelt (Figure 1-1, Figure 1-2), where the amount of recharge is thought to be relatively small - estimates are of the order of 10 to 40 mm/y (Table 1-1). However, it is an approach people would like to be able to rely on in areas with higher rainfall too.

Table 1-1: Estimated annual recharge and observed annual rise of groundwater levels in agricultural areas of Western Australia, compiled from information in Anon. (1996), page 7 and Table 4.1

<table>
<thead>
<tr>
<th>Rainfall zone (mm/y)</th>
<th>Estimated range of annual recharge under current agriculture (mm)</th>
<th>Observed range of annual rise of groundwater levels1 (mm)</th>
</tr>
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<tr>
<td>&lt;350</td>
<td>10 to 40</td>
<td>20 to 300</td>
</tr>
<tr>
<td>350 to 500</td>
<td>20 to 150</td>
<td>50 to 500</td>
</tr>
<tr>
<td>&gt;500</td>
<td>50 to 300</td>
<td>150 to 1500</td>
</tr>
</tbody>
</table>

Note: 1. at sites away from groundwater discharge areas
Figure 1-1: South-western Western Australia. This vegetation index image from March 1996 (produced by Department of Land Administration from NOAA imagery) indicates relative 'greenness' (and by implication, relative evapotranspiration rates). The areas which were greenest are coloured purple and blue, intermediate areas are in green and yellow, and the areas which were least green are coloured red. The image clearly delineates the agricultural areas because they had no green plants at that time of year. The Wheatbelt had the deepest shades of red. In contrast, areas with natural vegetation to the west and east still had green vegetation in late summer. A/P: agricultural/pastoral (or 'rangeland') boundary. The faint white lines are boundaries of shires, some of which are named in faint white type.
1.2.3 Regular or episodic recharge?

The approach of increasing annual pasture and crop water-use would work best where the relatively small amount of average annual recharge is spread evenly over the years, that is, it is regular. The distribution of recharge from year to year is likely to depend to a large degree on the rainfall regime. Most of the Western Australian agricultural region has a semi-arid climate, and rainfall in semi-arid areas may be characterised by "sporadic rainfall of high temporal and spatial variability" (Lerner et al. 1990, p. 4). Therefore, recharge could also be highly variable temporally. It is possible that a site with a mean annual recharge of 10 mm/y receives 100 mm in one year and nothing in the next nine years (i.e. episodic recharge). It is unlikely that this type of recharge would be controlled by the improvements which could be achieved in increasing the water-usage of annual crops and pastures.

The possible role of episodic recharge in Western Australia was considered following its recognition in aquifers below the plains of northern Victoria. Macumber (1991) showed that
groundwater pressures below southern section of the plains have regular seasonal patterns of fluctuations (of about 0.6 m amplitude) unless flooding occurs. A series of floods between 1973 and 1975 resulted in groundwater pressure rises more than six times higher than the 'regular' fluctuation amplitude at some sites. Groundwater hydrographs he presented (two are reproduced in Figure 1-3) spanned various periods between 1969 and 1986 and the recharge events in the three years from 1973 to 1975 clearly dominated the 17-year period. He suggested that similar large events may have occurred in 1954 and 1964 (Macumber 1991, p. 108). Western Australian Wheatbelt valleys are prone to occasional flooding, which raised the question of whether similar pulses of flood-related recharge were an important source of groundwater in lower parts of the landscape.

Figure 1-3: Two figures from Macumber (1991) showing hydrographs with large episodic pulses of recharge following floods

1.2.3.1 Episodic recharge in agricultural Western Australia?

Good-quality, long-term groundwater level records from the Western Australian Wheatbelt are rare, but from the mid 1980s onwards a large number of piezometers were installed. A few of these were monitored regularly and by the early 1990s there appeared to be some evidence of episodic behaviour (Figure 1-4). Surprisingly, some of the sites were on slopes, and not likely to be affected by recharge from flood events. This suggested that direct recharge processes (see Section 1.4.2) could also lead to episodic recharge.
The few apparently episodic hydrographs had short records - was the behaviour really episodic over the long term, and how significant was the episodic recharge compared to the more regular seasonal recharge? And was the behaviour widespread?

Although it became accepted that episodic recharge might be a factor in the agricultural areas of Western Australia (e.g. Nulsen 1993), no systematic analyses of where and when it occurred, and how important it was in the overall picture of groundwater recharge and salinity were carried out. This meant that no steps were taken to address any deleterious impacts. Policy continued to encourage resources to be committed to reducing recharge assuming it was regular and occurred in relatively small amounts in winter (Anon. 1996). If this assumption is wrong, it could lead to two problems:

- the resources committed to reducing small quantities of regular winter recharge would be wasted as they would be ineffective against occasional large pulses;
- a site which had stable groundwater levels for a few years could be interpreted as having no significant long-term recharge, when in fact a few more years of monitoring could show that recharge was substantial.

Figure 1-4: Example of a hydrograph from a mid-slope site in the Western Australian Wheatbelt (Lewis, M.F. 1998, unpublished data) which appears to have episodic rises (bgl: below ground level)
1.3 RESEARCH AIMS AND OUTLINE

This thesis reports research carried out to determine:

1. the significance of episodic recharge compared to regular recharge in the Wheatbelt of Western Australia;

2. the conditions under which episodic recharge occurs.

There were three main purposes behind the second aim. One was to provide a means of extrapolating the groundwater level records at sites with only short records; the second was to have a way of assessing the likelihood of episodic groundwater rises occurring at sites for which no groundwater information was available; and the third purpose was to provide a sound basis for designing management options to decrease those episodic rises which threaten to worsen land degradation.

The aims were addressed in three stages. As a preliminary, the first stage (Part I of the thesis) assessed the likelihood of episodic recharge being significant in the Western Australian Wheatbelt by reviewing published information on recharge in Western Australia and elsewhere in the world (Ch. 2), and by calculating the potential for the rainfall regimes in Western Australia to cause episodic recharge, using a simple water-balance model (Ch. 4). Methods of distinguishing significant episodic from regular recharge were also investigated (Ch. 3). These investigations indicated that episodic recharge is likely to occur in Western Australia, so further research was warranted. However, the review of publications found only one (Jolly and Chin 1991) which focussed on episodic events and the conditions associated with them (it was based on four sites in the Northern Territory of Australia), although there were many publications which mentioned, or showed hydrographs of, large unusual pulses of recharge. Since there was no foundation of prior studies into episodic recharge, and no established approaches for investigating the conditions associated with it, the research described in this thesis is the first step in understanding its role in the agricultural areas of Western Australia.

The aim of the second stage of this thesis (Part II) was to identify sites where episodic recharge had occurred. Firstly, the sites considered are described (Ch. 5) and then the three approaches which were used are presented (Ch. 6: analysis of long-term hydrographs; Ch. 7:
analysis of groundwater chemistry (principally deuterium and oxygen-18 ratios); Ch. 8: monitoring groundwater levels at sites considered to be prone to episodic recharge). It was necessary to identify episodic recharge sites so that they could be compared to sites with regular recharge. This was done in Part III, the third stage of the thesis. Firstly, the rainfall conditions associated with episodic recharge were investigated (Ch. 9) and then differences between site factors and recharge processes at episodic and non-episodic recharge sites were examined (Ch. 10).

The thesis is summarised and implications are discussed in Chapter 11.

1.4 USAGE OF THE TERMS 'RECHARGE REGIME', AND 'DIRECT' AND 'INDIRECT' RECHARGE

1.4.1 Recharge regimes

For rivers, the term 'regime' is used to describe "the expected pattern of river flow during a year" (Shaw 1994, p. 289). Adapting this, 'recharge regime' is used in this thesis to describe the pattern of recharge at a site. However, because of the nature of episodic events, the term is used to describe the long-term pattern of recharge, rather than the expected annual one. Examples of qualitative descriptions of recharge regimes are:

- all recharge occurs in winter and the amount is uniform from year to year over a long period (Figure 1-5a);
- all recharge occurs in winter, but the amount is variable from year to year (Figure 1-5b);
- there is always recharge during winter and the amount is uniform from year to year, but in some years there is a significant amount of summer recharge too (Figure 1-5c);
- recharge occasionally occurs during winter, and even more occasionally during summer and the amount of recharge in any year is highly variable (Figure 1-5d).

1.4.2 Direct and indirect recharge

The term 'direct recharge' is used to refer to recharge that results from rainfall at, or close to, the site. 'Indirect recharge' describes recharge resulting from water that moves laterally before reaching the groundwater system. Stream and river flow, flood water and lake water can be sources of indirect recharge. One aquifer can contribute water to another. In Western Australia, water in perched groundwater systems (shallow 'waterlogging' systems and deeper
systems in sand lenses) may flow laterally before draining vertically to a deeper aquifer. These types of aquifer recharge are included in the ‘indirect’ definition.

Figure 1-5: Examples of recharge regimes: a. uniform winter recharge regime; b. variable winter recharge regime; c. uniform winter with variable summer recharge regime; d. occasional recharge regime