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## Table of Contents



Cover photograph: Noel Paselaqua's property "Jayfields", Upper Billabong Creek catchment.

## Abstract

This work was conducted to test whether generic relationships could be developed for assessing the impact of land-use change on recharge. Over 80 studies across Australia were reviewed, although only 41 were used to generate a database. Studies were characterised on the basis of broad soil type (sand or non-sand), land-use (annual, perennial or trees) and annual rainfall. Developing quantitative recharge relationships was only partially successful due to the studies limited geographical coverage, lack of details on the recharge studies and variability in the data. For annual vegetation on sandy soils, recharge clearly increases with increasing annual rainfall. In the case of non-sandy soils, the relationship between recharge and rainfall was poor, although the general distribution suggests that potential recharge will be lower than on sandy soils. Of the three recharge technique groups, piezometric methods appeared to produce the best relationships. Apart from the disparity in techniques, reasons for the variation in the data include: coarse soil categories, ignoring land management factors, complications due to macropores and shallow water tables. The data were biased towards areas of winter dominant rainfall and low annual rainfall, so the general relationships could not be used to estimate recharge in areas with summer dominant rainfall (i.e. northern Australia) or areas in high rainfall zones. Additionally it is expected that areas for which the relationships will not apply include: areas where preferential pathway flow dominates (e.g. lateritic profiles, limestone, fractured rock), areas with shallow water tables and areas with soil of very low water holding capacity (e.g. skeletal soils, very deep coarse sands). Collectively, the results 1) confirm that recharge is higher under shallow-rooted annual vegetation than deep-rooted vegetation; 2) highlight the lack of annual recharge measurements under perennial vegetation and; 3) provide a platform upon which generic recharge relationships can be explored in the future using modelling tools or once more data becomes available.

## 1 Introduction

Increased recharge is generally accepted as a major cause of secondary dryland salinity in Australia. Thus, quantitative estimation of recharge is important in assessing alternative land management options, as well as for providing input into groundwater models that assess impacts on groundwater systems. While a number of studies have estimated recharge for specific areas or groundwater systems, there has never been an integrated review of Australian recharge studies in a way that allows general predictions of recharge for sites elsewhere. This paper presents the results of many recharge studies from across Australia and outlines preliminary efforts to develop simple empirical relationships that can be applied in a generic way across a range of landscapes.

If they can be established, generic relationships should enable preliminary estimates of recharge or deep drainage in the absence of detailed field work. The ability to develop and use such relationships is dependent on there being some simple relationships between deep drainage and factors such as soil type, rainfall and land-use, as well as on our ability to map these factors. However, previous work has shown that there is variability in deep drainage even within a paddock (Cook *et al.* 1989) and hence there is likely to be a level of complexity associated with a multitude of factors such as land management, plant disease and micro-topography. More complex models may be able to include such factors but since the key parameters are unknown over any sizeable area, their general application is limited.

Generic relationships can be developed at a number of scales. Some previous studies have developed generic relationships between annual recharge and annual or seasonal precipitation for a catchment or region (e.g. Sinha and Sharma 1988, Bredenkamp 1990, Houston 1990). These relationships often contain thresholds below which none of the rainfall contributes to recharge. The threshold reflects the ability of the soil and/or landscape to absorb rainfall events and is related to the vegetation rooting depth, soil water holding capacity and water table depth. These factors vary spatially. For drier climates, rainfall is likely to be more 'episodic' and hence thresholds may actually apply to single events (Barnes *et al.* 1994). The type of threshold relationship developed may depend, not only on the temporal scale under consideration, but also the spatial scale. Within a paddock, key spatial variables may be soil texture and crop rotation; at a sub-regional scale, they may be soil types and land-use; and at a larger scale perhaps geomorphic features or a simple division of vegetation type may dominate spatial recharge.

Because of the complexity and expense of obtaining recharge estimates, there are still relatively few measurements across Australia. These have been made by different methods at different spatial and temporal scales and over different depths at which deep drainage is considered. Because of the small number of studies and the high degree of variability likely in the predominantly point scale data, ‘relationships’ developed may indicate no more than a broad band within which recharge values may be expected to lie for a given rainfall, soil grouping and vegetation type.

Whether or not simple relationships can be developed depends on there being dominant, controlling factors. For example, evapotranspiration in low rainfall zones is controlled by rainfall, whereas for higher rainfall zones it is limited by available energy. Relationships can be developed using such controlling factors (e.g. Zhang *et al*. 1999). The threshold concept described earlier represents one limiting factor in lower rainfall zones. It is also known that the rainfall minus the evapotranspiration estimated by Zhang *et al.* (1999) should form an estimate of excess water and hence approximates the upper limit for deep drainage. For the higher rainfall zones, it is expected that recharge will be limited by the permeability of the unsaturated zone, and that a relatively high proportion of flow will move laterally into streams. Finally, in areas with shallow water tables or aquifers with low storage capacity, recharge may be limited by the ability of the aquifer to store and discharge the water. In some cases, simple relationships with only one limiting factor may exist. However, at the continental scale, the situation is likely to be considerably more complicated with there being several limiting factors.

For this study, we considered the three primary factors controlling recharge in semi-arid Australia to be land-use, soil type and climate (e.g. Kennett-Smith *et al.* 1994). Data were reviewed and collated from previous studies across Australia, with no additional measurements taken for this study. This approach necessitated an assessment of the techniques and associated estimates as part of this study’s analysis. While effort has been directed into developing relationships for the larger continental scale, there is an emphasis on the application of the findings to salinity management.

The aim of bringing together the results of many recharge studies allows us to test whether:

1. These results collectively confirm tenets of salinity management such as the use of trees;
2. It is possible to develop quantitative relationships to predict the impact of land-use change on recharge using simple land-use and soil divisions;
3. We understand the causes of the variability in recharge estimates;
4. It is necessary to target future studies to improve our understanding of recharge.

The term ‘recharge’ is used here to describe the amount of water that is actually added to an aquifer. The terms ‘potential recharge’ or ‘deep drainage’ refer to water fluxes (measured or inferred) at some depth within the unsaturated zone, and need not be equivalent to the actual amount of water entering the aquifer at that time. Most techniques 'infer' recharge from measurements made of other parameters, which can be related to recharge (e.g. water table rise or chloride distribution in the profile). In many previous studies and in this paper, the term 'measured' covers both directly measured and inferred recharge values.

## 2 Method

From more than 80 recharge studies reviewed in the literature only those studies (41) in which recharge was actually measured or inferred from measurement of other parameters, were included. The literature included journal articles, technical reports, conference papers and unpublished data.

A database was developed to summarise information from all 41 'selected' papers; the main inputs being the amount of recharge, method used, land-use, soil type and annual rainfall.

### *2.1 Site description*

As illustrated in Fig. 1 the data are heavily biased towards southern Australia and low to medium rainfall zones. This is largely related to the importance of salinity as a land degradation issue in these areas.

The studies collated estimated recharge at sites with a wide range of environments. Rainfall ranged from 100mm/year to 1150mm/year, while soil types varied from very coarse sands to heavy clays (i.e. clay contents higher than 65%). Land-use also varied widely, from deep-rooted vegetation such as Mallee scrub, Banksia, Jarrah and Pine plantations, to perennials such as Lucerne, Medicago sativa, and native shrubs (e.g. Blue Mallee) to annual vegetation like Wheat, Oats, Clover and Ryegrass (with a large combination of rotations and lengths of fallow). The recharge measurement, rainfall, land-use, soil group and recharge estimation technique used for each study are summarised in Table 1 and the means by which data were discarded and categorised is outlined in the analysis procedure below.

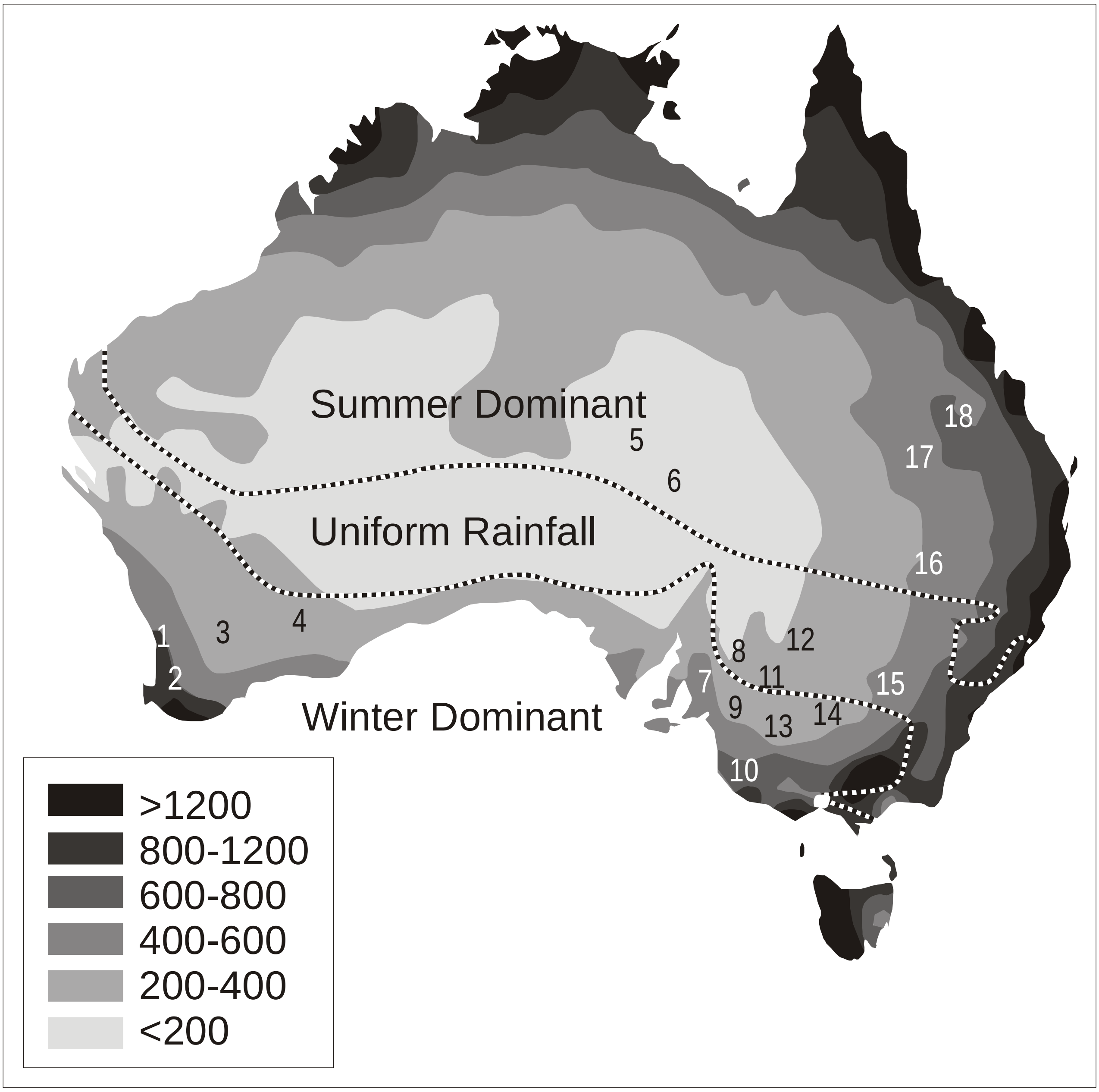


**Figure. 1.** Median annual rainfall (mm/yr) and seasonality map of Australia. Numbers indicate recharge study site location and correspond with the third column in Table 1. Information derived from The Ausmap Atlas of Australia, AUSLIG.

**Table 1** Summary of site description and data used in analysis.

| Author | Location[1] | Site No.[2] | Rainfall[3] | Soil Group[4] | Land-use | No. estimates[5] | Recharge Technique[6] |
|---|---|---|---|---|---|---|---|
| Allison 1987 | New Kalimurina, Central Australia | 6 | 100 | Sand | Tree | 1 | 1 |
| Allison and Hughes 1972 | Gambier Plain (SA) | 10 | 700 | Non-sand | Tree | 1 (11) | 4 |
| Allison and Hughes 1978 | Gambier Plain (SA) | 10 | 710-760 | Sand, Non-sand | Annual | 21 | 1,4 |
| Allison and Hughes 1983 | Walpeup (Vic.) | 11 | 335 | Sand | Annual, Tree | 2 (6) | 1,2 |
| Allison *et al*. 1985 | Mallee (SA) | 8 | 300 | Sand, Non-sand | Annual, Tree | 6 | 1,3,4 |
| Allison *et al*. 1990 | Maggea (SA)<br>Kulkami (SA) | 8 | 270<br>370 | Sand<br>Sand | Annual, Tree<br>Annual, Tree | 11<br>23 | 1,2<br>1,2 |
| Baker, P.J. pers. Comm. 2000 | Mitchell (Qld) | 17 | 567 | Non-sand | Annual, Tree | 2 | 1,2 |
| Barker *et al*. 1995 | Albury (NSW) | 15 | 300# | Non-sand | Tree | 1 | 6 |
| Brinkley *et al* 1997 | Goulburn catchment (Vic.) | 14 | 621<br>629<br>660<br>976<br>1038 | Non-sand | Annual, Tree | 1 (33)<br>1 (20)<br>1 (23)<br>1 (4)<br>1 (14) | 6 |
| Carbon *et al*. 1982 | Gnangara Mound (WA)[7] | 1 | 669#<br>668#<br>803# | Sand | Annual, Perennial Tree | 11 | 11 |
| Colville and Holmes 1972 | Mt Gambier (SA) | 10 | 483#<br>805#<br>617# | Sand | Tree | 3 | 7 |
| Cook *et al*. 1989 | Borrika (SA) | 8 | 340 | Sand | Annual, Trees | 12 | 1,3 |
| Cook *et al*. 1990 | Woolpunda Groundwater Mound (SA) | 8 | 270 | Sand | Annual | 1 (7) | 1 |
| Ellis, T., pers comm. 1999 | Dergholm (Vic.) | 12 | 701 | Sand | Tree | 1 | 1 |
| George, R., pers comm. 1999 | East Belka (WA)<br>Eastern Wheatbelt (WA) | 2 | 330<br>330 | Non-sand<br>Non-sand | Annual<br>Annual, Tree | 2 (N/A)<br>4 (N/A) | 6<br>1,6 |
| George and Frantom 1990 | Merredin Catchment (WA) | 3 | 328 | Sand Non-sand | Tree | 2 | 1 |
| Gordon, I. *et al*. pers. comm. 1999 | Liverpool Plains (NSW) | 16 | 550<br>750 | Non-sand | Annual | 7 | 10 |
| Harrington *et al*. 1999 | Ti-Tree (NT) | 5 | 300 | Sand | Tree | 2 (63) | 1,8 |
| Holmes and Colville 1970a | Mt Gambier (SA) | 10 | 600 | Sand | Tree | 6 | 11 |

*Table 1 cont.*

| Author | Location[1] | Site No.[2] | Rainfall[3] | Soil Group[4] | Land-use | No. estimates[5] | Recharge Technique[6] |
|---|---|---|---|---|---|---|---|
| Holmes and Colville 1970b | Mt Gambier (SA) | 10 | 566[#]<br>438[#]<br>566[#]<br>463[#]<br>805[#]<br>617[#] | Sand | Annual | 12 | 9 |
| Johnston 1987c | Don, Ernie, Lemon, (WA) | 2 | 800 | Non-sand | Tree | 1 (20) | 1 |
| | Salmons, Wrights, (WA) | | 1150 | Non-sand | Tree | 1 (12) | 1 |
| Johnston 1987b | Salmons, (WA) | 2 | 1150 | Non-sand | Tree | 9 | 1 |
| Kennett-Smith *et al*. 1990 | Buronga(NSW) | 12 | 310 | Non-sand | Annual | 24 | 2 |
| | Balranald (NSW) | | 322 | Non-sand | Annual | 6 | 2 |
| | Euston (NSW) | | 312 | Sand<br>Non-sand | Annual | 10 | 2 |
| Kennett-Smith *et al*. 1992a | Mallee (NSW) | 12 | 255 | Sand<br>Non-sand | Annual | 17 | 1,2,3 |
| | | | | Non-sand | Tree | 21 | |
| Kennett-Smith *et al*. 1992b | Glendook (Vic) | 11 | 430 | Sand | Annual, Tree | 14 | 1,2,3 |
| | Eureka (Vic) | | 430 | Sand<br>Non-sand | Annual, Tree | 10 | 1,2,3 |
| Kennett-Smith *et al*. 1993 | Goroke (Vic) | 13 | 526 | Non-sand | Annual, Tree | 26 | 1,2,3 |
| Kennett-Smith *et al*. 1994 | Balranald (NSW) | 12 | 322 | Non-sand | Annual | 4 | 2 |
| | Borrika (SA) | 8 | 340 | Sand<br>Non-sand | Annual | 28 | 2 |
| | Maggea (SA) | 8 | 270 | Sand<br>Non-sand | Annual | 5 | 2 |
| | Cooke Plain (SA) | 8 | 380 | Sand<br>Non-sand | Annual | 2 | 2 |
| | Walpeup (Vic) | 11 | 340 | Non-sand | Annual | 2 | 2 |
| | Buronga (NSW) | 12 | 295 | Non-sand | Annual | 3 | 2 |
| Leaney and Allison 1986 | Mallee near Morgan (SA) | 8 | 300 | Sand | Tree | 2 (33) | 8,1 |
| Leaney *et al.* 1995 | South East (SA) | 9 | 490 | Non-sand | Annual, Tree | 2 | 1,2 |
| | | | 530 | Sand | Annual, Tree | 2 | 1 |
| Leaney and Herczeg 1999 | SW Murray Basin | 9 | 390-500 | Sand, Non-sand | Annual | 9 | 1 |

*Table 1 cont.*

| Author | Location[1] | Site No.[2] | Rainfall[3] | Soil Group[4] | Land-use | No. estimates[5] | Recharge Technique[6] |
|---|---|---|---|---|---|---|---|
| Loh and Stokes 1981 | Wrights (WA) | 2 | 1150 | Non-sand | Annual | 1 (N/A) | 6 |
| | Lemon (WA) | | 750 | Non-sand | Annual | | 6 |
| | Bingham (WA) | | 725 | Non-sand | Annual | | 6 |
| | Batalling (WA) | | 650 | Non-sand | Annual | | 6 |
| | Bakers Hill (WA) | | 490 | Non-sand | Annual | | 6 |
| | Lake Toolabin (WA) | | 410 | Non-sand | Annual | | 6 |
| | Salmon Gums (WA) | | 390 | Non-sand | Annual | | 6 |
| O'Connell *et al*. 1997 | Walpeup (Vic.) | 11 | 338 | Sand | Annual, Tree | 4 | 2,3 |
| | Timberro South (Vic.) | 13 | 338 | Sand | Annual, Tree | 16 | 2,3 |
| | Wimmera (Vic.) | 13 | 420 | Non-sand | Annual, Tree | 9 | 2,3 |
| Pakrou and Dillon 2000 | Mt Gambier (SA) | 10 | 714#<br>985#<br>642#<br>625# | Non-sand | Annual | 4 | 9 |
| Salama *et al*. 1993 | Cuballing, (WA) | 2 | 462 | Non-sand | Annual, Tree | 4 | 1,2,6 |
| Sharma *et al*. 1991 | Gnangara Mound (WA)[7] | 1 | 770-800<br>756#<br>798#<br>1227# | Sand | Annual, Tree | 26 | 1,11,12 |
| Thorburn *et al*. 1991 | NE Australia (Qld) | 18 | 630 | Non-sand | Annual, Tree | 3 | 10 |
| Thorpe 1987 | Gnangara Mound (WA)[7] | 1 | 830 | Sand | Tree | 8 | 1,4 |
| Turner *et al*. 1994 | Kalgoorlie (WA) | 4 | 250 | N/A | Tree | 1 | 8 |
| Walker *et al*. 1987 | Tatiara (SA) | 9 | 489 | Non-sand | Annual | 1 | 5 |
| | Binnum (SA) | | 524 | Non-sand | Annual | 1 | 5 |
| | Joanna (SA) | | 582 | Sand<br>Non-sand | Annual | 4 | 5 |
| Walker *et al.* 1992a | Upper SE (SA) | 9 | 530 | Sand | Annual, Tree | 4 | 1,2,3 |
| Walker *et al*. 1992b | Cooke Plains (SA) | 7 | 380 | Sand | Annual, Perennia lTree | 4 | 1 |

Notes on Table 1

1. The letters in brackets are abbreviations for states and territories of Australia, i.e., WA, SA, VIC, NSW, QLD, NT correspond with Western Australia, South Australia, Victoria, New South Wales, Queensland and Northern Territory, respectively.

2. The site numbers correspond with those in Fig. 1. The numbers illustrate the general location in which the study was conducted.

3. Rainfall is presented as the long-term annual average. A '#' next to a rainfall value indicates that this is a single year value.

4. Soils were divided into two broad soil groupings, i.e., sand and non-sand.

5. 'No. estimates' is the number of recharge estimates that were plotted from each study in Fig. 4. Reasons for data being discarded are indicated under *Data Handling and Analysis Procedure*. Brackets indicate that the recharge estimates were reported as an average value. The numbers in the brackets correspond with the number of measurements taken to produce the average value. Where N/A appears, the authors did not report this information.

6. The numerals in the 'Recharge Technique' column correspond with recharge techniques listed in Table 3.

7. Data from the Gnangara Mound (WA) are not included in Fig. 3. This data is presented separately in Fig. 4.

## *2.2 Data handling and analysis procedure*

From the 41 selected studies, data were discarded where:

- The data had already been reported in another study (e.g. Kennett-Smith *et al*. 1994);
- Measurements were deemed unrepresentative by the authors of the cited paper (e.g. Pakrou and Dillon (2000), observed that their repacked lysimeters produced considerably higher estimates of drainage than their monolith lysimeters);
- Rainfall and recharge were measured/presented as a seasonal total rather than an annual total (e.g. Nulsen and Baxter 1982; Lane 1996, Smith *et al*. 1998);
- Recharge was estimated under trees of less than 5 years of age (e.g. Barker *et al*. 1995).

In addition to these points, several studies reporting 'measured' annual recharge values were not analysed because:

- They were in rainfall zones very different to the majority of other studies (e.g. 4239 mm / yr in the case of Bonell *et al*. 1983);
- Site runoff characteristics had been altered (e.g. Ridley *et al*. 1997).

Data from Gnangara Mound in Western Australia are presented separately. This region is covered by very deep coarse sands and recharge estimates were considerably higher (i.e. sometimes an order of magnitude) than any of those found in the literature from other parts of Australia. It would appear that there are different factors limiting transpiration/recharge (e.g. soil water holding capacity, nutrition) to those applied generally in this study.

Because of the limited number of recharge studies encountered in the literature, it was necessary to keep the number of categories for land-use and soil small to ensure that there were a reasonable number of data values available for each category. Also, lack of documentation made it difficult to further sub-divide the categories.

Land-use was divided into three broad categories; *annuals* (shallow-rooted annual crops or pasture), *perennials* (perennial pastures and native herbaceous vegetation) and *trees* (very deep-rooted vegetation).

Soils were ultimately divided into two very broad textural groups, *sand* and *non-sand*. The non-sand group comprised sites with a clay content greater than 10%. Initial inclusion of a third soil group, *loam* (10-20% clay), revealed that it did not improve the certainty of the result. The group to which a soil was allocated was partially dependent upon vegetation type (i.e. rooting depth). For a soil planted with annual vegetation the clay content in the top 2 m of the soil profile was considered in categorising the soil, for perennials the clay content of the top 3 m was considered in categorising the soil and for trees the clay content of the top 5 m was considered. Where a qualitative soil description was presented the authors drew upon personal experiences and the experience of others in the area or with similar soils to help categorise the data.

The matrix in Table 2 illustrates the number of soil - land-use combinations encountered in the literature.

**Table 2**. Number of recharge estimates for different soil – land-use combinations (numbers in brackets indicate number of studies that estimated recharge for each particular soil – land-use combination).

| Vegetation | Sand | Loam | Clay |
|---|---|---|---|
| Annual | 110 (18) | 48 (7) | 111 (16) |
| Perennial | 5 (2) | - | 1 (1) |
| Tree | 87 (20) | 12 (4) | 55 (17) |

All rainfall and recharge values are annual totals. Data have been divided into long-term average values and single year values. Where site specific rainfall data were not presented for a long-term average recharge measurement, the authors of this paper allocated the site a rainfall value using information from the Bureau of Meteorology or from other studies conducted in the same area. Where necessary, long-term annual rainfall was interpolated from sites with known rainfall values.

## *2.3 Recharge estimation techniques*

The collated data represent estimates of recharge at different temporal and spatial scales as well as at different depths in the profile (see Table 3). To enable useful comparisons between different studies, the recharge data were divided into three groups, based upon the measurement technique used, particularly with reference to depth of measurement.

Group 1 techniques are those that infer recharge at depths many metres below the root zone. Measurements are generally made at a point scale over many metres of depth and recharge is averaged over decades. Group 2 techniques are those that infer recharge from changes in the water table. Recharge estimates are at the paddock to catchment scale and the time scale of measurement may vary from an event basis to an annual basis. Group 3 techniques are those that estimate potential recharge immediately below the root zone. These techniques are generally at the point scale and measurements are at short time intervals (i.e. days or even hours). For Group 1 and 2 measurements the annual totals are long-term/historical averages, while the yearly totals for Group 3 techniques are for a single year.

*Selection of data for generic relationships*

To investigate the effect of soil texture on potential recharge and hence develop generic relationships for assessing the impact of land-use change on recharge, it was necessary to eliminate the variation caused by different recharge measurement techniques and time scales. This was initially tested using Group 1 techniques because more data were available than for other techniques, and it was thought that long term average data would be less variable than single year data. Data using Group 2 and Group 3 techniques were discarded for this component of the analysis. Recharge estimates were also discarded where:

- They were markedly influenced (on the basis of being mentioned in the cited paper) by secondary factors (e.g. aspect, slope, depth to water table, preferential flow, impervious horizons and episodicity), as they were considered likely to introduce error into the relationships. Preferential flow was the secondary factor that most commonly led to data being discarded.
- One of the three controlling factors discussed in the introduction was absent e.g. skeletal soils (Allison and Hughes 1978) or fallow land (Thorburn *et al*. 1991);
- The cited study failed to specify soil or vegetation type (e.g. O'Connell *et al*. 1997).

This process resulted in a subset of 28 studies (from the initial selection of 41) being used in the development of generic relationships.

Brief descriptions of the techniques for recharge estimation that were used as input to the database are given below.

*Physical methods for estimating recharge*

Lysimetry: A lysimeter is a vessel containing a volume of soil which is isolated hydrologically from the surrounding soil and upon which vegetation may be planted, which is representative of the surrounding environment. Lysimeters are generally weighed to provide direct measurement of changes in water storage. Inputs of precipitation and outputs of drainage are measured directly, thus enabling closure of the water balance. Non-weighing lysimeters determine drainage in the same way as weighing lysimeters. However, they measure changes in water storage (e.g. using neutron probes) to infer evapotranspiration. Bond (1998) provides a more comprehensive discussion.

Soil water mass balance method: The amount of water stored in the soil profile under sites of both original land-use and a changed use are measured and compared, to estimate the amount of water that has infiltrated since the change (e.g. clearing) occurred. The validity of this technique hinges on the similarity of physical structure of the two soil profiles being compared. A more detailed description can be found in Kennett-Smith *et al.* (1992a).

Water balance: This technique estimates drainage from changes in the soil water profile, where drainage is generally estimated as the difference between rainfall and the measured evapotranspiration and change in profile soil water storage. Changes in water storage are evaluated by integrating soil water content measurements. These measurements are often made using Time Domain Reflectometry or Neutron moisture meters. Zegelin *et al*. (1992) and Greacen (1981) provide a more detailed description of this technique.

Piezometric rise: Groundwater records can be analysed to determine the relationship between the amount of rainfall and groundwater response. The main assumption is that the water table rise is due to event-based recharge. This technique can only be applied in areas where the water table is fairly shallow. The main advantage is that the groundwater hydrograph is an integrator of all the processes occurring in the unsaturated zone. Difficulties with this method include accounting for lateral flow and estimating specific yield. This technique is discussed further in Armstrong and Narayan (1998).

Ratio of groundwater hydrograph amplitudes: The groundwater hydrograph amplitudes of two similar land units under different land-uses are compared, where recharge under one of the land-uses has already been established using an alternative technique. Based upon the ratio of the hydrograph amplitudes of the two areas, recharge is then estimated for the second area. While this technique is relatively inexpensive and easy to apply, it encompasses errors that may be associated with the initial method as well as the lateral flow distortions associated with piezometric methods. A more detailed description of this technique and an example of its application can be found in Colville and Holmes (1972).

*Chemical methods for estimating recharge*

Tracers can be divided into three broad categories: *environmental tracers*, *historical tracers* and *artificial tracers*. In nearly all cases, the tracer is used to follow water movement and hence should move with the water. Recharge is inferred from the rate of movement or the spatial distribution of the tracer. Most tracer techniques rely on one-dimensional vertical flow and some rely on piston flow. Advantages of tracers over other recharge estimation methods include: usefulness in arid and semi-arid areas where water fluxes are small; less-frequent field visits and; can estimate long-term mean water fluxes. Tracer techniques can fail where preferred-pathway recharge is evident or where conditions of one-dimensional flow are not satisfied. Some tracers are also susceptible to anion exclusion and vegetation uptake.

Environmental tracers occur naturally in the landscape and recharge is inferred from the spatial pattern or the overall mass balance of the tracer. The most commonly used environmental tracer is chloride. Chloride techniques can be either steady-state (e.g. *Chloride Mass Balance Approach (CMBA)*) where land-use has remained unchanged for a very long period of time (i.e. > 100 years) or transient (e.g. *Generalised Chloride Front Displacement (CDFM), SODICS model*) where land-use has been recently modified.

Artificial tracers such as *Bromide* are applied on or just below the soil surface. Recharge is inferred by monitoring the tracer as it is leached down by infiltrating water. The most appropriate use of an artificial tracer is where recharge rates are high and the time scale of leaching through the root zone is less than one year.

Historical tracers infer recharge from the rate of movement of a highly concentrated tracer that has resulted from a historical event. Historical tracers have an advantage over artificial tracers in that there can be a longer time for the tracer to move. A common subset of historical tracers are 'bomb' tracers. The most common bomb markers are $^{3}H$ and $^{36}Cl$, which resulted from nuclear fallout between 1952 and 1965.

See Walker (1998) for a more detailed discussion on tracers.

**Table 3** Recharge techniques and their depth and scales of measurement.

| Recharge Technique[1] | Scale of Measurement | | Depth of Measurement | What does it measure? |
|---|---|---|---|---|
| | Spatial | Temporal | | |
| Group 1 | | | | |
| Environmental Tracers<br>1) CMBA (25)<br>2) CDFM (12) | Point | Historical average | Unsaturated zone (i.e. below root zone) | Infers potential recharge |
| 3) Soil Water Mass Balance (7) | Point | Historical average | Unsaturated zone (i.e. below root zone) | Infers potential recharge |
| Historical Tracers<br>4) Tritium (4)<br>5) Cl-36 (1) | Point | Historical average | Unsaturated zone (i.e. below root zone) | Infers potential recharge |
| Group 2 | | | | |
| 6) Piezometeric rise (5) | Catchment | Event | Water table | Infers recharge |
| 7) Ratio of hydrograph amplitudes (1) | Paddock | N/A | Water table | Infers recharge |
| 8) C-14 (3) | Catchment | Historical average | Water table | Infers recharge |
| Group 3 | | | | |
| 9) Lysimeters (2) | Point | Seasonal/ Annual | Root zone | Measures potential recharge |
| 10) SODICS (2) | Point | Annual | Root zone | Infers potential recharge |
| 11) Water Balance (3) | Point | Seasonal/ Annual | Root zone | Infers potential recharge |
| 12) Bromide (1) | Point | Seasonal/ Annual | Root zone | Infers potential recharge |

1. Numbers in brackets indicate the number of studies using this technique to estimate recharge.

### 2.4 Excess water curve

To place the recharge values into context with other components of the water balance, recharge values are compared to estimates of 'excess water' by Zhang *et al.* (1999), who developed a rational function approach to evapotranspiration based on mean annual rainfall and vegetation cover. By studying over 250 catchments from many parts of the world, Zhang *et al.* (1999) showed that, for a given vegetation type, there is a good relationship between long-term average evapotranspiration and rainfall. The relationship between the annual non-transpired (or excess) water, and annual rainfall is shown in Fig. 2 and will be referred to as the *rational function approach to excess water*. It should be noted that these 'average' curves take no account of soil type. Hence, recharge estimates at sites with sandy-soils (i.e. low water holding capacity) and few surface drainage features, may lie above the excess water curve because the vegetation may not be able to transpire as much water as on clay soils.

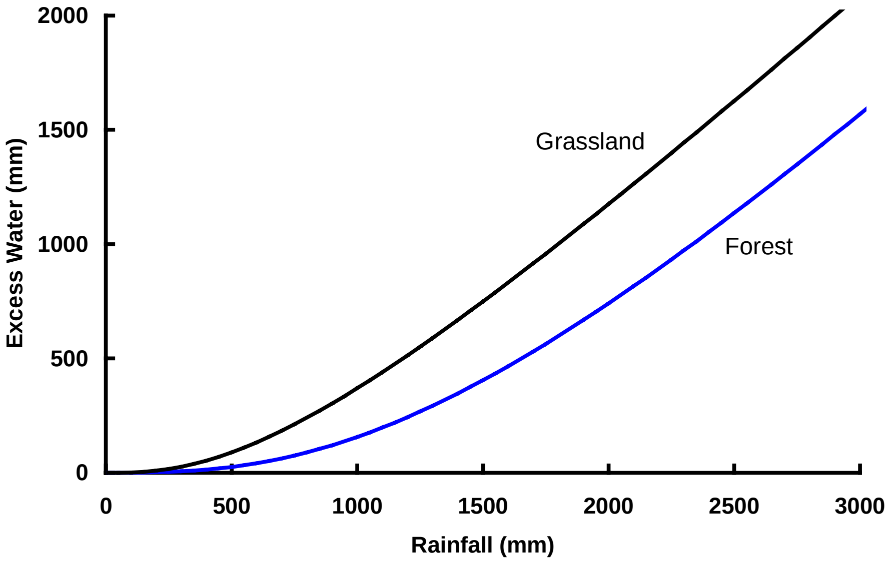


**Figure 2.** Relationship between excess water and rainfall for different vegetation types (Source: Zhang *et al.* 1999).

In their present form, the curves in Fig. 2 estimate the upper limit of water that can recharge underlying aquifers ('excess water' includes both recharge and runoff).

## 3 Results

Fig. 3 shows the recharge data that were collated from the subset of 41 studies that measured recharge or recharge related parameters. In Fig. 3 each symbol represents either an individual measurement or an area-averaged estimate of recharge. Solid symbols represent long-term average data and hollow symbols represent single year data. Data from the Gnangara Mound has not been included in this figure. The excess water curves shown in Figs. 3-7, should only be used as an approximate upper limit of recharge for the long-term average recharge estimates. It is inappropriate to compare single year recharge values with a curve generated from mean long-term data. Fig. 4 shows recharge values measured at Gnangara Mound, WA. Figs. 5 and 6 illustrate different land-uses on sand textured soils and non-sand textured soils respectively. These figures are sub-sets of Fig. 3, and they exclude data estimated using Group 2 and 3 techniques or considered to be affected by secondary factors (see under Method). Fig. 7 is also a subset of Fig. 3 and compares recharge estimates made using different techniques. However, only annual vegetation data were included and estimates influenced by secondary factors (as mentioned in the cited paper) were discarded.

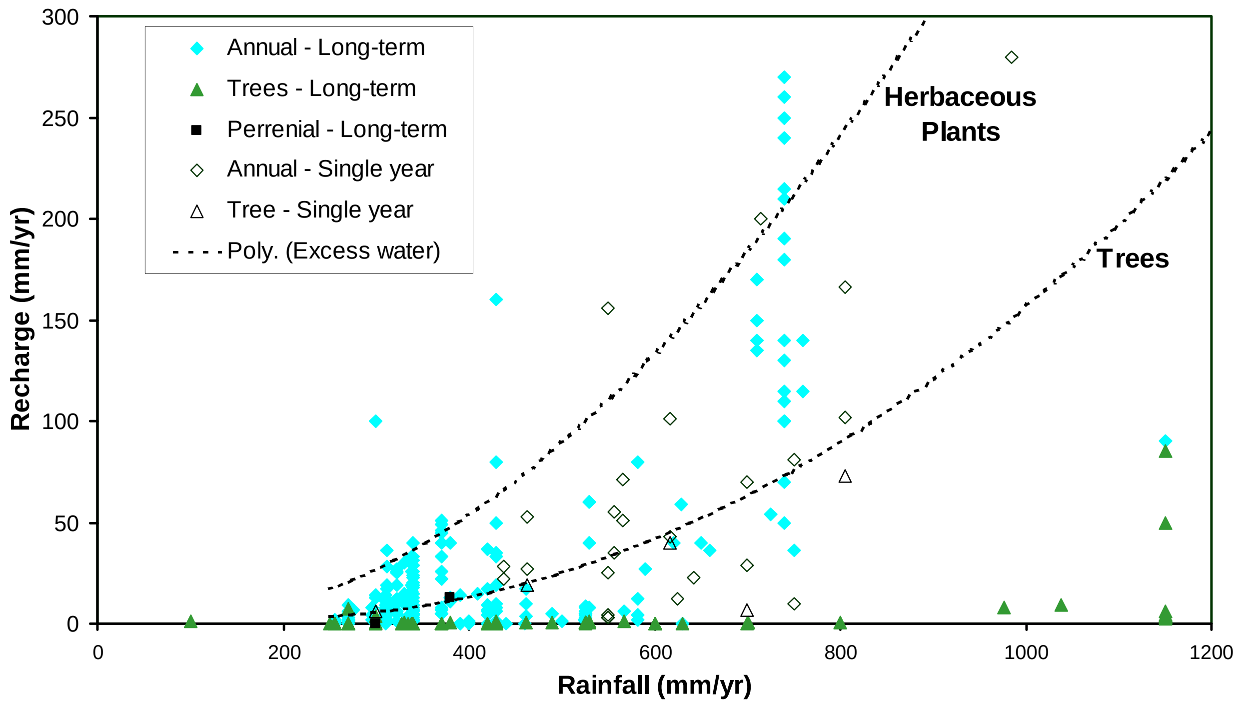


**Figure 3.** Annual recharge versus annual rainfall for different vegetation types and time scales of measurement.

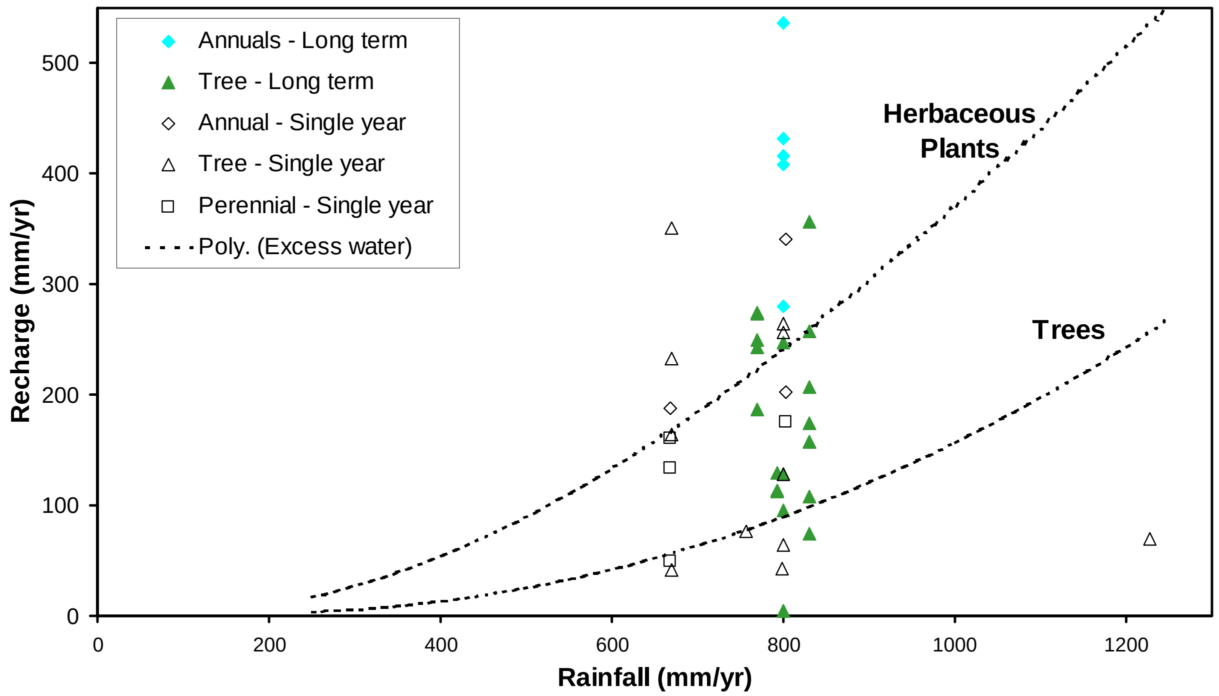


**Figure 4.** Annual recharge versus annual rainfall for different vegetation types and time scales of measurement at the Gnangara Mound, Western Australia.

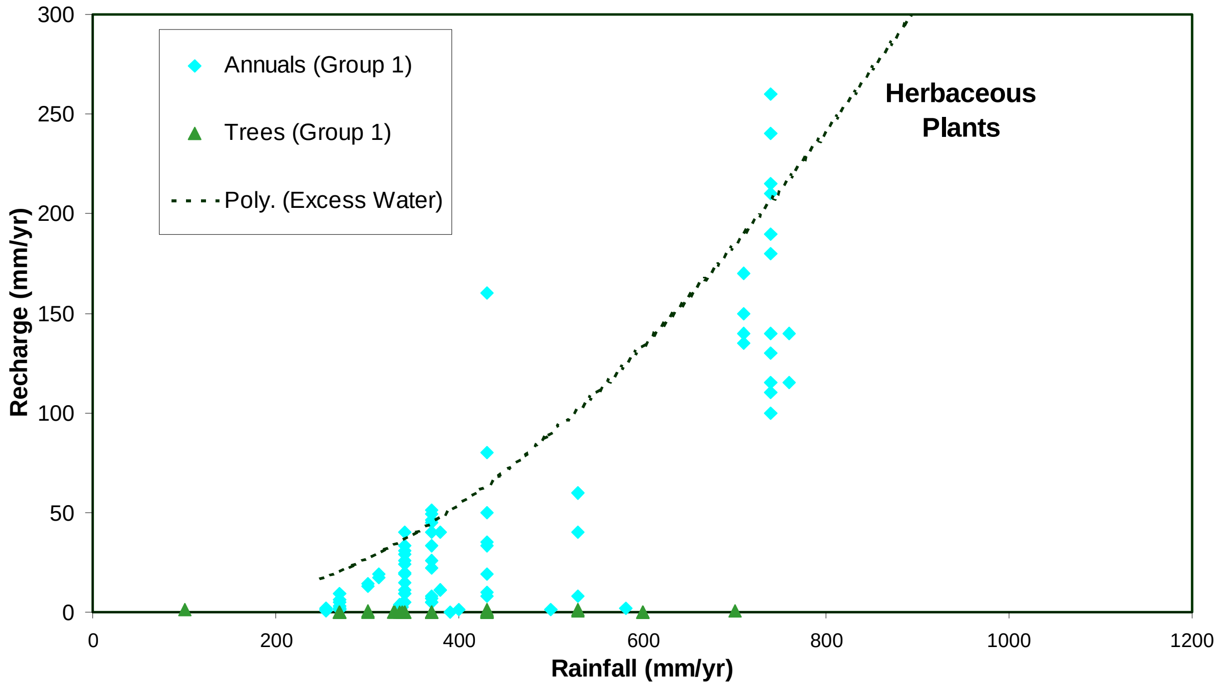


**Figure 5.** Annual recharge versus annual rainfall for different vegetation types on sandy soil using Group 1 data.

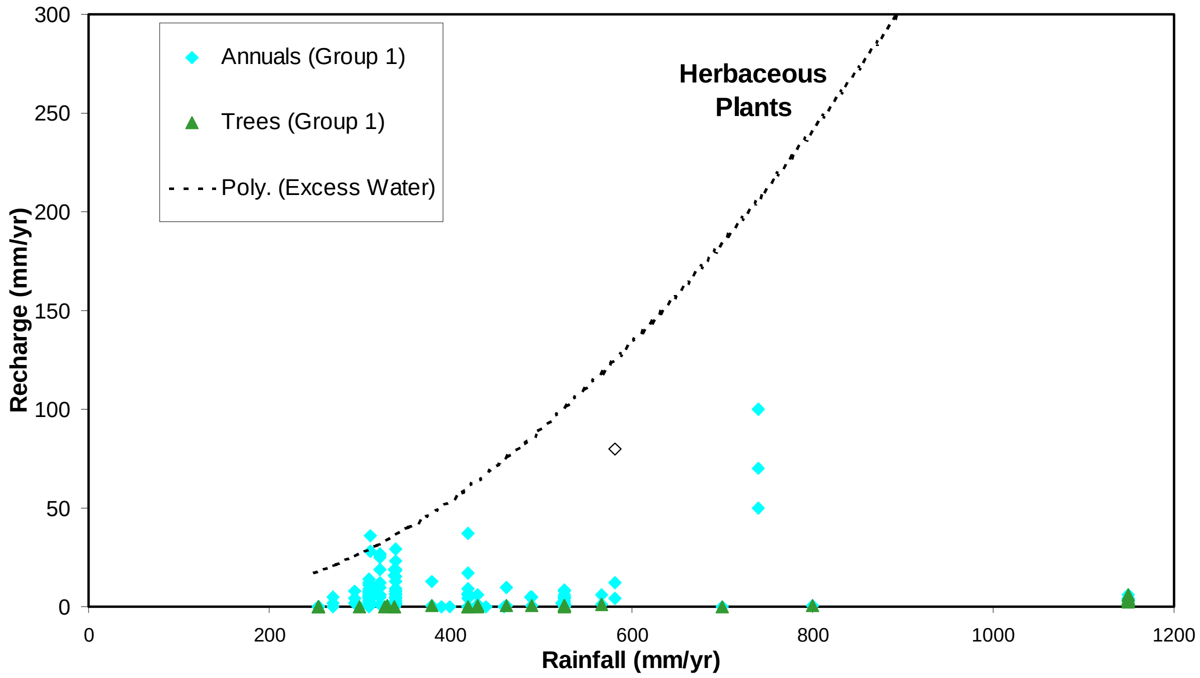


**Figure 6.** Annual recharge versus annual rainfall for different vegetation types on non-sand soil using Group 1 data. The non-shaded data point is a site with a shallow watertable.

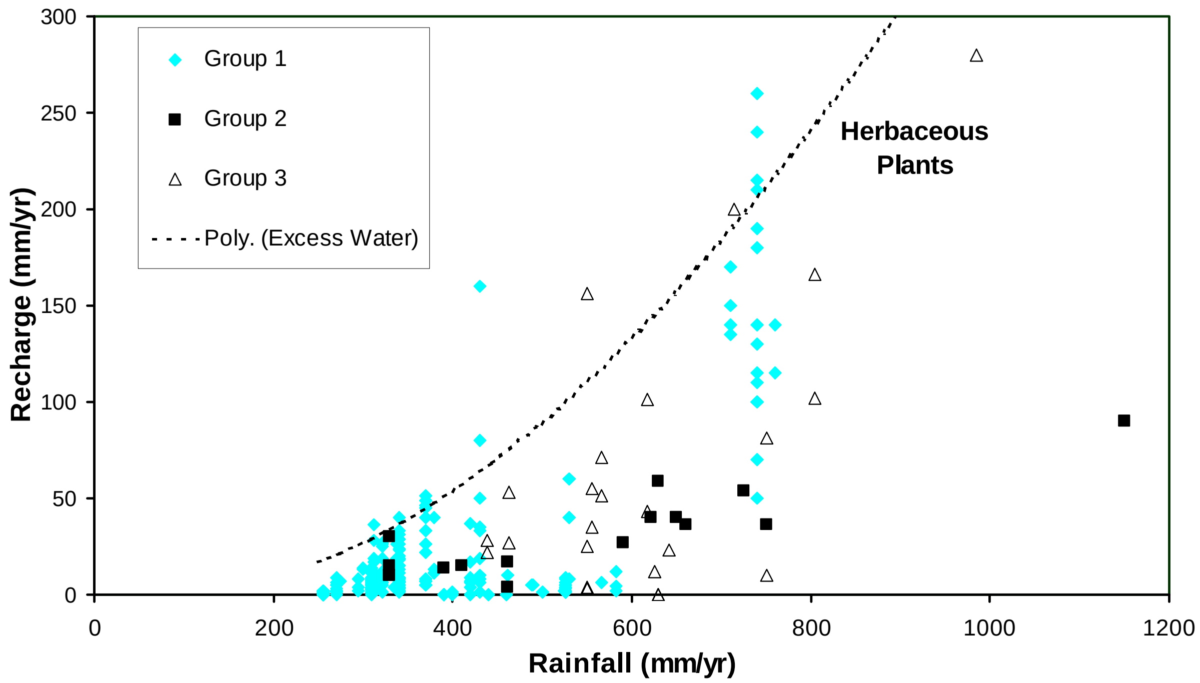


**Figure 7.** Annual recharge versus annual rainfall for annual vegetation using different recharge estimation techniques.

From Fig. 3, it can be seen that the majority of the studies reviewed have estimated recharge under annual crops/pastures in low to medium rainfall zones. Few studies were encountered in which recharge was estimated under perennials. There was also a deficiency of data on recharge under trees in medium and high rainfall zones and for annuals in high rainfall zones.

The data indicate that:

1. Despite the high variation within the data presented in Fig. 3, the broad categories and different scales of measurement, it is clear that the recharge under annuals was greater than that under trees.
2. The general distribution of the data shows that as the rainfall increases, so does the recharge. The long-term average recharge data appear to be limited by the rational function estimate of 'excess water', which forms the hypothetical upper bound on recharge.
3. Fig. 5 shows that recharge increases faster as rainfall increases for sandy soils, compared to non-sand soils (Fig. 6). It indicates a rainfall threshold of approximately 250mm for annuals on sandy soils and that around 30% of rainfall above this threshold will become recharge. It should be noted that many of the estimates of recharge that were used to develop this relationship were from the Mallee and south-east South Australia. Hence the level of confidence in this relationship is higher in that region. While the absolute range of recharge estimates within the non-sand textured soils was no less than that within the sandy soil category, the relative range was higher. Because of this, a relationship between rainfall and recharge on non-sand soils is less apparent.
4. The general trend observed in the data was a movement away from the rational function approach to excess water curve, as the soil texture becomes finer, as the vegetation changes from shallow to deeper rooted and as the rainfall increases.
5. Fig. 7 indicates that there is less variability in the recharge measurements made using Group 2 techniques than Group 1 or 3 techniques.
6. There were insufficient data on perennial vegetation to allow an analysis of this land-use category.

## 4 Discussion

Lerner *et al.* (1990) suggest that the accuracy of recharge estimates is prone to four types of error: an *incorrect conceptual model*, *neglect of spatial and temporal variability*, *measurement error* and *calculation error*. In this study, possible error within the data due to measurement / calculation and inappropriate choice of conceptual models was ignored, on the basis that information allowing an assessment of these errors is rarely presented and secondly that for a large data set, measurement / calculation errors will tend to balance out. It was assumed that the variation in the data arose mainly from natural spatial and temporal variability.

### *4.1 Reasons for variation in estimates*

Part of the scatter in recharge estimates is likely to be due to *different techniques for estimating recharge* amongst the studies. As discussed earlier, this is likely to be due to the different techniques 'measuring' recharge at different depths and different temporal and spatial scales.

That Fig. 7 indicates there is less variability in the Group 2 data than the Group 1 or 3 data should not be surprising, because a number of studies have shown a strong relationship between rise in groundwater level and rainfall (e.g. Armstrong and Smith 1974, Sophocleous 1992). Piezometric response techniques are integrators of the processes occurring in the unsaturated zone at the larger scale and hence are not subject to the same spatial variability as point scale measurements. They provide an inference of the actual amount of water reaching the water table and hence data account for both matrix and preferential flow. Piezometric techniques can only be applied where there is a quick groundwater response to rainfall, and hence the areas of application may restrict some of the variability.

The three *land-use categories adopted* in this study accounted for large differences in the recharge data. However, within land-use categories there was marked variation – a result of a wide range of vegetation types, management practices and other factors (e.g. soil). For example, the annual vegetation included both pasture and cropping, as well as differing management practices, such as fallow, fertilisation and grazing. Such differences are known to cause variation (e.g. Kennett-Smith 1992a; O'Connell *et al.* 1995). Even within the tree category there can be high variation. Sharma *et al.* (1991) compared the groundwater recharge to an unconfined aquifer under different land-uses on the Swan Coastal Plain (Fig. 4). Recharge was greater under the native Banksia vegetation than under pine trees. It was also noted that recharge was higher under a 'sparse' pine plantation than under a dense pine plantation, and higher under young pines than mature pines. Little can be done to further account for the variation caused by broad land-use groupings used in this paper because more detailed land-use information is seldom available for the individual studies.

Variation in recharge estimates can be introduced by *ignoring temporal rainfall distribution*. Data reported in large time-steps, such as annual rainfall, introduce scatter by failing to distinguish the differences in temporal variation within years. It is well documented that the duration and intensity of rainfall events are of equal or greater importance to recharge, as the total annual rainfall (Leaney *et al.* 1995). This is particularly the case in semi-arid regions where rainfall can be very episodic in nature and much of a year's rain can fall within a short space of time causing greater recharge than would occur if the same volume of rainfall was spread over an entire year. Some piezometric hydrographs show particularly large rises after large rainfall events (Lewis 1997). Because of this high degree of episodicity, it is often misleading to talk of a mean annual recharge. Mean annual recharge data are more useful if the mean has been derived over a long period that contains a statistically significant number of extreme events (Barnes *et al.* 1994). The variability caused by ignoring the temporal distribution of rainfall events is likely to be greater for single year estimates of recharge (i.e. Group 3) than for long-term averages (i.e. Group 1). This is because single year values will be affected by the temporal variability in rainfall between years as well as the temporal variability between sites.

The *soil categorisation* adopted for this study was very coarse. The relationship between recharge and annual rainfall for annual vegetation seen in Fig. 5 suggests that division based on texture was partially successful for sandy soils. However, the relationship between rainfall and recharge for non-sand soils was less consistent (Fig. 6), and it appears that this category was too broad. An additional textural division was attempted, where a soil was categorised as a loam if it had a clay content between 10% and 20%. However, the relationship between recharge and annual rainfall in the loam category was poor and the relationship for the clay category failed to improve. It appears that in soils with clay contents higher than 10%, the influence of soil texture on soil water movement becomes negligible, or may be confused by clay type and properties. It is likely that soil structure becomes more important for these higher clay content soils but such information was not available for these studies.

In the preceding discussion, a number of *secondary factors* were introduced, associated with the three primary factors. These were land management, episodicity and seasonality of rainfall (Thorburn *et al.* 1991) and soil structure. Other secondary factors include shallow water tables (Allison and Hughes 1972; Colville and Holmes, 1972; Sophocleous, 1992) and preferred pathways, both of which can vary both spatially and temporally.

Evidence of the effect of depth to water table can be seen in Fig. 6 (data value has no background colour). Walker *et al.* (1987) estimated recharge at a site in the Naracoorte Ranges (annual rainfall 582 mm / yr) with a water table depth of just two metres to be 80 mm/yr. This is almost an order of magnitude higher than other recharge estimates in the same region with deeper water tables. In a study done in central Kansas by Sophocleous (1992), depth to water table during the spring months was found to be one of the most influential variables affecting recharge. However, at many sites in Australian where recharge measurements have been taken, the water table has been very deep (e.g. Allison *et al*. 1985; Johnston 1987b; Cook *et al*. 1989; O'Connell *et al*. 1997). Hence, depth to water table is not thought to be a key factor affecting recharge over large parts of southern Australia.

For some areas, recharge through preferential flow pathways can be a major form of recharge (Johnston 1987a,b,c). These pathways are caused by macropores like cracks and old root channels as well as larger scale sink holes and geological discontinuities, which enable water to flow more rapidly than through the soil matrix (Allison and Hughes 1983). In conditions of such *preferential flow*, the influence of land-use, rainfall and soil texture is reduced e.g. Allison *et al.* (1985); Johnston (1987b). The ability of such channels to transmit recharge depends on the depth of vegetation rooting (Johnston 1987c; Allison *et al.* 1990) and the likelihood of continuous macropores to the water table (Walker 1998). It would be expected that recharge in areas of preferential flow recharge will be much more dependent on the temporal variability of rainfall than in areas where matrix flow dominates. It is likely that such preferred pathways will be important in areas of fractured hard rock, dissolution features in limestone and in areas of shallow water tables.

Techniques for estimating recharge in these areas include hydrograph methods (although specific yield in these areas may be poorly known) and groundwater tracers (Cook and Herczeg 1999). The scale and frequency of distribution of preferential flow paths is such that they are often missed by measurements. It is difficult to foresee any relationship that could be applied to such an area because of the difficulty of mapping such features.

The <u>*excess water curves*</u> appear to indicate an approximate upper limit to the long-term average recharge. Where recharge values lie above the excess water curve (Fig. 3), recharge has either been estimated on sandy-soils with few drainage features (e.g. Allison and Hughes 1978; Kennett-Smith *et al.* 1992b) or the site has been influenced by secondary factors (e.g. Allison *et al.* 1985).

### *4.2 Application of the generic relationships*

When applying generic relationships it is important to consider their limitations and the assumptions that were involved in their development. The main assumption when using relationships developed from deep drainage measurements is that deep drainage will become recharge. The main limitations are:

- Studies reporting high numbers of recharge estimates have a stronger influence than those reporting few;

- Greater errors in estimates of recharge are likely to occur in higher rainfall regions because of the greater number of studies encountered for low rainfall regions;
- The generic relationships developed from this review can be used only where matrix flow conditions are dominant, or they may underestimate recharge. This is because estimates of recharge where preferential flow was reported were not included in the analysis.
- The lack of data from summer dominant rainfall regions means the relationships may not be applicable in areas where evapotranspiration exceeds rainfall most of the year round.

The acceptable level of error is dependent on the task and the situation. The level of detail required to make management decisions is difficult to estimate *a priori.*

The most appropriate situation in which to use the results in Figs. 3-7 for estimating recharge, are where long-term, "first cut" estimates of recharge are required over a regional scale. Provided there are spatial data available on the parameters, these results are well suited for use in a GIS to show qualitative spatial patterns in recharge.

The application of these results to a regional scale can involve difficulties since most of the data were effectively point scale measurements. This may be appropriate in some catchments, but generally the water balance of a particular section of a landscape is not independent of the upslope data (Hatton 1998). In landscapes where lateral hydraulic gradients are high and subsurface flow is significant, the results in Figs. 3-7 may be unreliable. Even in landscapes where the results are applicable, it is important to recognise the scatter apparent in the data and to use it to gain an indication of uncertainty.

Data from Australian recharge studies, viewed collectively, can provide a basis from which generic recharge relationships may be derived for future use and in a wider context. It is proposed that the value of the information presented here may be enhanced by:

- Using results of this study to identify gaps in knowledge and hence to target vital areas for future research, such as recharge measurements beneath perennial vegetation;
- Exploring the variation within the data using modelling tools;
- Complementing the measurements of recharge utilised here with the results of the many existing modelling studies.

## 5 Conclusions

This is the first collation of recharge studies across Australia. The collective results of the collated recharge studies confirm that recharge is higher under shallow-rooted annual vegetation than deep-rooted vegetation.

The ability to develop quantitative relationships using simple land-use and soil divisions was only partially successful:

- For annual vegetation on sandy soils (Fig. 5), recharge clearly increases with increasing rainfall. Under these conditions there appears to be a rainfall threshold of 250mm and about 30% of rainfall above this threshold will become recharge;
- In the case of non-sandy soils (Fig. 6), the relationship between annual rainfall and recharge is less consistent, although the general distribution of the data suggest that potential recharge will be considerably lower than on sandy soils. It appears that where the clay content was higher than 10%, soil texture has no influence on recharge;
- This study identified a lack of recharge measurements beneath perennial vegetation. Additionally few studies measured recharge under trees in medium and high rainfall zones (i.e. >600 mm / yr);
- The estimator of Zhang *et al*. (1999) for ‘excess water’ provides an upper limit to the long-term average recharge measurements in Fig. 3. However, it is inappropriate to use these curves at the Gnangara mound (Fig. 4) in Western Australia where there appears to be other factors limiting transpiration;
- Preliminary results indicate that there appears to be less variability among recharge measurements made using Group 2 techniques than using Group 1 and 3 techniques.

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