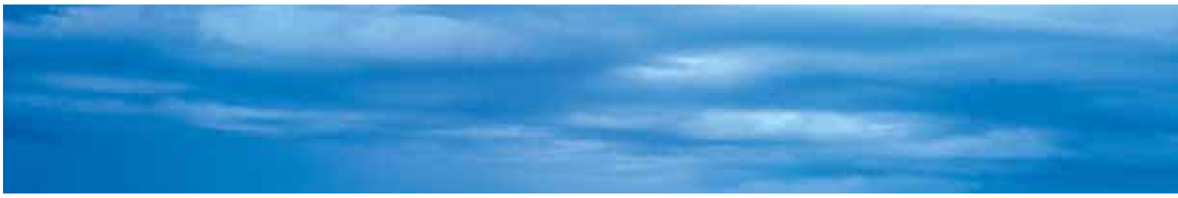
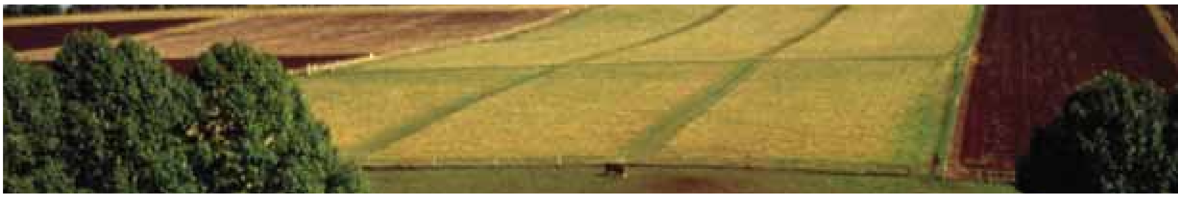
ESTIMATING EXTRACTABLE SOIL MOISTURE CONTENT FOR AUSTRALIAN SOILS

TECHNICAL REPORT
Report 04/3

June 2004

Tony Ladson / James Lander / Andrew Western / Rodger Grayson





COOPERATIVE RESEARCH CENTRE FOR
CATCHMENT HYDROLOGY

Estimating Extractable Soil Moisture Content for Australian Soils

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ISBN 1 920813 08 X

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631.4320994

Keywords

Soil moisture
Soil water balance
Field tests
Soil properties
Time series
Soil profiles
Soil water relations

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Preface

This report uses an unconventional approach to estimating plant available water content for Australian soils. Instead of using laboratory measurements of soil properties, these authors have collected actual measurements of soil moisture from a wide range of field studies around Australia. In total, extractable soil water capacity is presented for 180 locations that include the six States and two Territories. They have also compared estimates of extractable soil moisture from field measurements with those from the Atlas of Australian Soils.

The 'active' soil store - the amount of water than can be evaporated from soils or used by plants - is a key parameter in hydrologic models. The work presented here is an important contribution to the catchment modelling effort that is core business of the Cooperative Research Centre (CRC) for Catchment Hydrology. I commend this report to anyone interested in the interaction between water and Australian soils.

Geoff Podger, Program Leader
Predicting Catchment Behaviour
CRC for Catchment Hydrology

List of Figures

List of Tables

1. Introduction

The amount of water that can be stored in soil and evaporated or used by plants is a key parameter in hydrologic models, weather prediction models and is important for crop and pasture production. Broad scale estimates of the dynamic soil store are available using data from the Atlas of Australian Soils (AAS) but there has been limited validation of the results. This report describes the collection of soil moisture storage data, based on field measurements, and a comparison with AAS values.

1.1 Extractable Soil Moisture

A key feature of this project is the estimation of extractable soil moisture from field measurements. This contrasts with the standard approach where the maximum available soil water store is determined from parameters estimated in a laboratory. Generally, soil samples are analysed in a laboratory to determine the moisture content at the lower limit of availability to plants (–15 bar) and at "field capacity" (commonly –0.10 bar to –0.33 bar). The difference between these values, often called plant available water (PAW), gives an estimate of the maximum amount of water that can be stored in the soil and used by plants, provided a soil (or rooting) depth is assumed. It is common for relationships to be formed between laboratory derived PAW, and soil properties such as soil texture. This procedure, known as the pedo-transfer approach, allows information from standard soils maps to be used to infer, and map, PAW (Williams, 1983).

The concept of a maximum soil store is also important in hydrologic models. In these models, the soil water store is often represented by a bucket that receives water from rain and loses water to evaporation, evapotranspiration and deep drainage. Surface runoff occurs if the bucket overflows. In spatially explicit models the maximum soil store at any grid cell will depend on the soil properties at that location. Often the plant available water is used as an estimate of the size of the bucket and a good estimate of this value is important if models are to behave in a way that matches known physical processes.

Ritchie (1981) noted the practical problems associated with the estimation of plant available water using the standard approach. Accurate estimates depend on knowledge of field capacity, permanent wilting point and bulk density for the whole profile within the root zone. In reality these parameters are likely to change vertically within the profile and between profiles. Estimates of the rooting depth are also likely to be subject to error. There is also the issue of which soil water potentials used in the analysis actually correspond to 'true' field capacity and permanent wilting point.

As an alternative approach, Ritchie (1981) suggested the concept of extractable soil moisture as a practical way of overcoming some of the problems associated with estimating available soil moisture from laboratory measurements. The extractable moisture is defined as the difference between the highest measured volumetric water content in the field and the lowest measured volumetric water content. This could occur for example when plants are very dry and leaves are either dead or dormant, or in fallow conditions following a long period of dry weather. Extractable soil water takes the root distribution into account provided the measured soil moisture profile is deeper than the rooting depth. Estimates do not require soil water content/potential relationships for each soil depth where physical properties change. Ritchie (1981) found that field measurements of the total extractable water are often less variable spatially than available water estimated from water content-potential measurements.

Ratliff *et al.,* (1983) compared field and laboratory measurements of the limits of soil water availability. Field measured wettest and driest profiles were compared with laboratory measurements of soil moisture content at –15 bar (401 observations) and –0.33 bar (282 observations). Results showed laboratory measurements of the lower limit of soil moisture availability underestimated the field values for sands, silt loams and sandy clay loams and overestimated values for loams, silty clays, and clays. For the upper limit, laboratory estimates were less than the field measurements for sands, sandy loams, and sandy clay loams and were greater than laboratory measurements for silt loams, silty clay loams, and silty clays. They concluded that field estimates of soil water availability should be preferred over laboratory measurements for water balance calculations.

2. Our Approach to Estimating Extractable Soil Moisture

Our approach has been to estimate extractable soil moisture capacity from field measurements of soil moisture content. A time series of soil moisture values over the depth of the soil, shows the actual changes in soil moisture so the extractable soil moisture can be estimated from the difference between the wettest and driest profiles.

In simple terms, our methodology involved:

- Obtaining a time series of profile soil moisture data; and
- Defining the 'wettest' and 'driest' profiles and using these to estimate extractable soil moisture.

The extractable soil moisture depends on the soil type and the vegetation type. Deeper-rooted vegetation will be able to extract larger amounts of soil moisture because it has access to more of the soil profile. Conversely, even fallowed soils will experience wettest and driest profiles so it is possible to estimate a value for extractable soil moisture when there is no vegetation.

2.1 Searching for Soil Moisture Data

There have been many, perhaps hundreds, of projects in Australia that have involved measurement of soil moisture. These include studies of the performance of crop types, cropping systems, water balance studies, analysis of recharge associated with salinity investigations and studies of water yield following fires or forest cutting. Profile soil moisture measurements have been measured using Neutron Moisture Meters, Time Domain Reflectometry, and Gravimetric Sampling. Originally we intended to track down raw data from a large number of studies where there were long time-series of profile measurements of soil moisture. This turned out to be impossible. Although over 90 researchers were contacted (see Appendix 1), and we received excellent cooperation, few usable datasets were obtained (see Appendix 2).

Commonly, the data used by hydrologists are measured and managed by organisations with a particular mandate, and the resources necessary to archive and make available their information. Meteorological and streamflow data are two obvious examples. But information where there are no coordinated monitoring networks is difficult to track down. Much of the information we have been seeking was collected as part of individual research projects by a researcher, or a small group of researchers. The motivations in these sorts of projects are to answer some specific questions and make the results available through publications. Indeed we have gained a lot of the information we need from published papers and reports. However, the basic data normally reside in field books or computer media of different sorts, depending on the age of the study. These data have been used by the research team at the time, but, from the point of view of the researchers (and likely the clients), once the appropriate analysis and publications have been completed, there is little need to do anything more. That makes the data difficult for others to obtain and use, especially when corporate memory starts to fade.

In this project, the way forward was to use soil moisture data and results from published reports and journal articles. Generally these data are well documented and cleaned up, although probably only a small amount of the total data collected is available. Over 200 journal articles were examined and information from about 75 articles contributed to our database. A particularly valuable source of data was the work of Agricultural Production Systems Research Unit in Toowoomba, Queensland, which has published an extensive guide to soil water availability for southern Queensland. In all, storage capacities were obtained for 180 unique soil, crop, location, combinations (Figure 1).

2.2 Types of Soil Moisture Data Available

There are three types of data available that could be used to calculate the extractable soil moisture content.

1. A time series of profile measurements that show how the soil moisture varies with depth;
2. A time series of the total amount of moisture in a particular depth of soil at a site; and
3. Information on profile moisture content where a soil had been artificially manipulated to be as wet and as dry as possible.

2.2.1 Time Series of the Soil Moisture Profile Measurements

A time series of soil moisture profiles can provide information on the extractable soil moisture. If profiles are measured on a number of dates, the wettest and driest profiles can be identified and the difference between them used to estimate extractable soil moisture and active soil depth. An example is show in Figure 2. Soil moisture storage was measured about every two weeks in the top 2.2 m of the soil profile under a Pinus radiata plantation near Lidsdale, NSW (33.43S, 150.07E) between October 1968 and April 1971 (Smith, 1972). Soils are hard setting loams with mottled yellow clayey subsoil derived from both Devonian and Permian parent material: Northcote (1966) classifications Dy 3.41 and Dy 2.61.

The driest profile occurred on the 4th February 1969 and the wettest profile on the12th February 1971. The maximum active soil moisture store is the difference between the wettest and driest profiles (Figure 2) i.e. 234 mm.

An active soil depth can also be defined. For this example, most of the soil moisture change occurs in the upper part of the profile. Below about 1200 mm there is little change so we define 1200 mm as the active depth (Figure 2). Our estimate of the extractable soil store is the difference between the wettest and driest profile between the soil surface and the active depth.

There are two features of this data set that are worth noting and which mean the estimate of extractable soil moisture, is this case, is likely to be accurate.

1. The active depth can be clearly defined, that is, there is little soil moisture change in the profile below the depth of 1100 mm; and
2. The active depth occurs within the range of soil that was measured i.e. the top 2.2 m.

Not all the profile measures we used share these desirable features. In fact, we divided the profile measurements into four types depending how accurately the active soil store and active depth could be estimated. These four profile types are listed and defined in Table 1. In addition, to the four profile types, there were two other sources of soil moisture data which are discussed in the next sections and defined in Table 1.

2.2.2 Time Series of the Total Moisture Content in a Soil Profile

Extractable soil moisture is estimated, with varying accuracies, from the four types of profile measurements, as explained above. A time series of total soil moisture data is the fifth type of data that was used (Table 1) to estimate the active soil storage. An example of this type of data is shown in Figure 3 which is a time series of moisture storage at Lidsdale (Smith, 1972). For Lidsdale, time series of both the soil profiles and the total moisture content were available, but for most sites this type of information was not provided as only a summary is recorded in the journal papers or reports that we could access.

From the time series, the driest conditions occurred on the 4th February 1969 and the wettest on the 12th February 1971. An estimate of the extractable soil moisture is the difference between the soil moisture storage on these dates i.e. 234 mm, the same as the value calculated from the difference in the soil profiles (Figure 2).

If only a time series is available then there is no indication of the active depth of soil. The measurement depth may be reported but the active depth and the measurement depth may not coincide. In these cases, the measured depth is recorded as the active depth in the data base.

If the true active depth happens to be greater than the measurement depth, our estimate of extractable soil moisture will be less than the true value since some of the soil store is unmeasured.

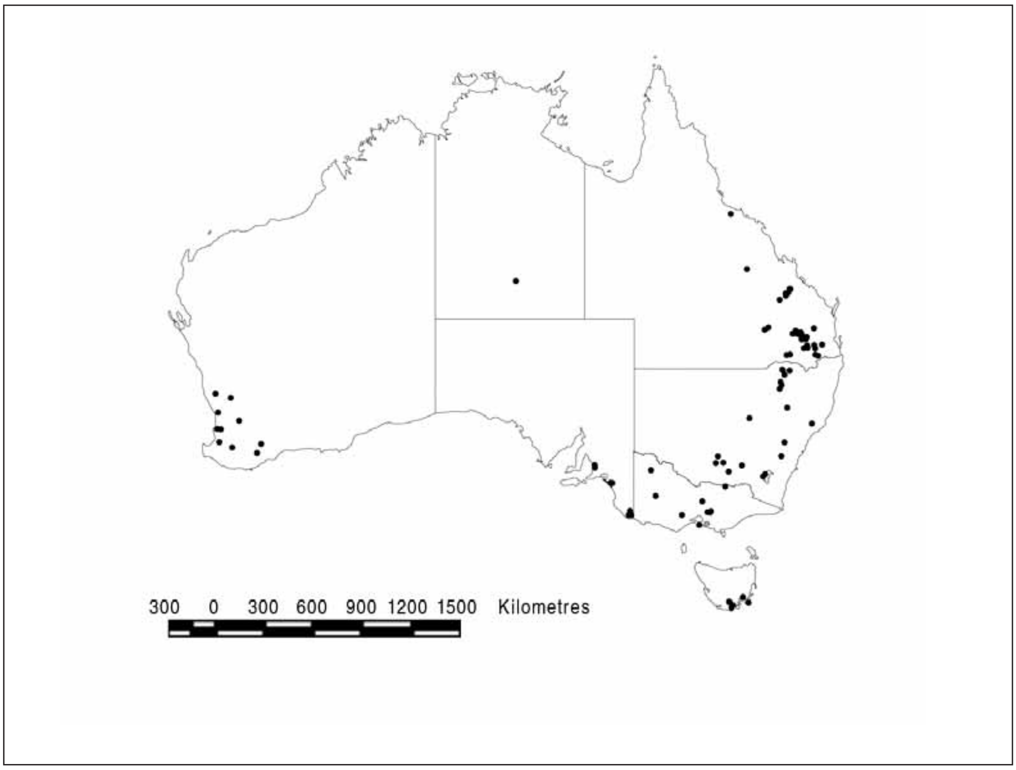


Figure 1 Sites where Extractable Soil Moisture Estimates are Available

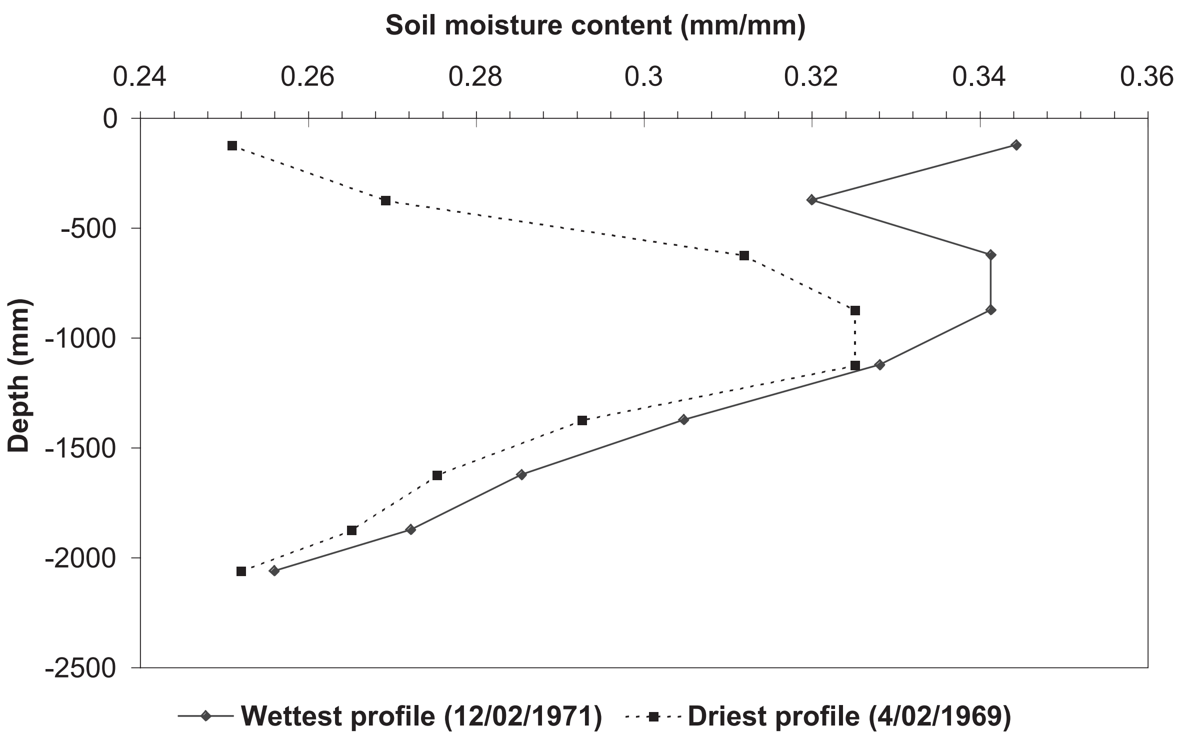
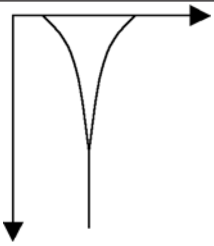
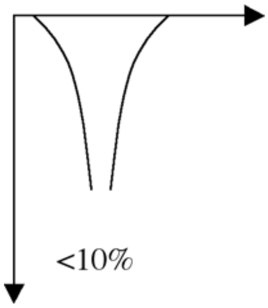
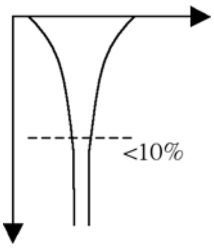
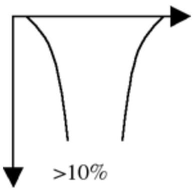
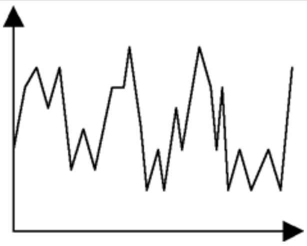


Figure 2 Wettest and Driest Soil Moisture Profiles for Lidsdale, NSW

Table 1 Types of Soil Moisture Information

No	Definition	Profile Type
1	Active depth < measured depth. Clearly defined active depth with no active storage below this depth. This type of profile provides the most accurate estimate of the extractable soil moisture.	
2	Active depth > measured depth but there is limited storage below the measured depth. Measurement of soil moisture within the profile was made at an insufficient depth to capture the whole active storage. However, the difference between the wettest and driest profiles at the maximum measured depth is less than 10%. This type of profile provides a reasonable but underestimate of the extractable soil moisture and the active depth.	
3	Active depth is defined as being less than measured depth. Soil moisture differences between wettest and driest profiles occur down to the bottom of the measured profile, but there is little change below a particular depth (-------). This depth was defined as the active depth for this soil type. Extractable soil moisture was calculated for the soil between the surface and the active depth.	
4	Active depth > measured depth and there is a substantial storage below the measured depth. Values of extractable soil moisture and active depth from these profiles will be underestimates.	
5	Time series of soil moisture measurements. Active soil storage can be estimated from the difference between the wettest and driest measurements but, without additional information, the active depth can not be estimated (see Section 2.2.1).	
6	Artificial manipulation to produce maximally wet or dry soils. Extractable soil moisture can be estimated from soil profiles that have been manipulated to be maximally wet or dry (see Section 2.2.3).	

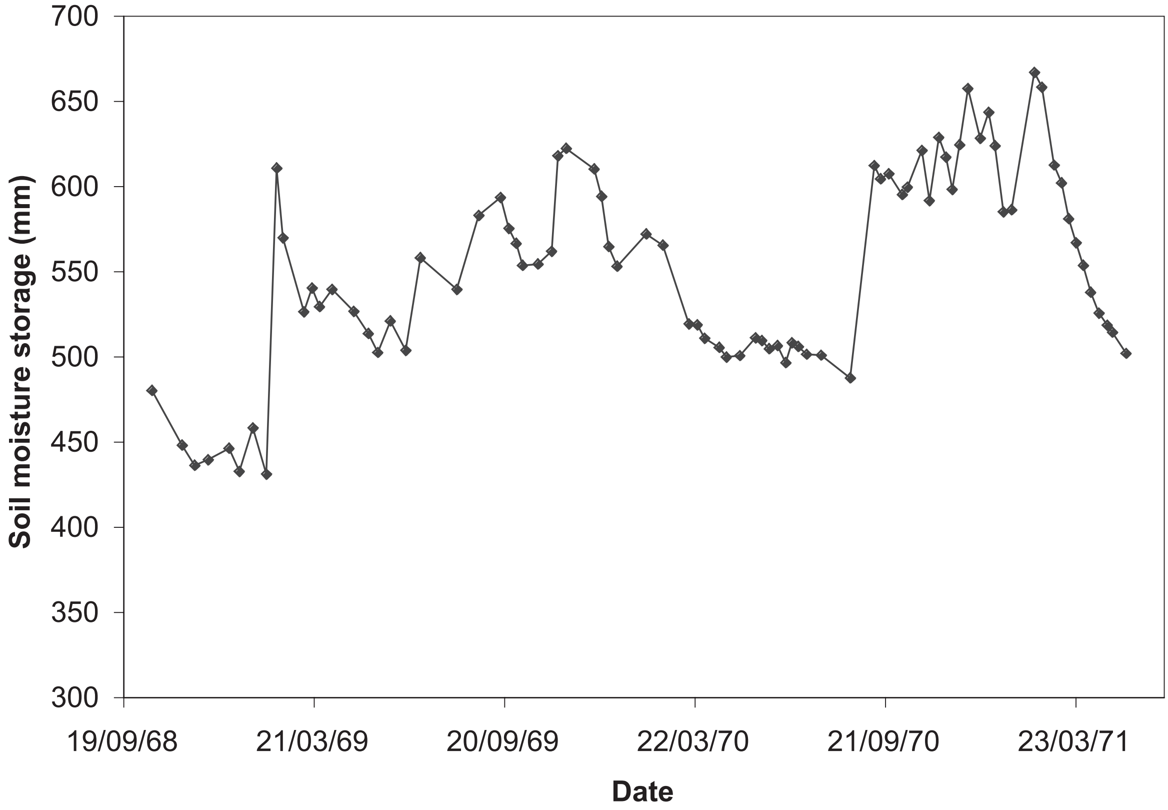


Figure 3 Time Series of Soil Moisture Storage for Lidsdale, NSW

2.2.3 Artificial Manipulation to Produce Maximally Wet or Dry Soils

The sixth type of data we have used is where there is information on soil moisture profiles in soils that have been artificially wetted or dried to obtain an estimate of the maximum active soil store, or where there is opportunistic sampling of what is believed to be the wettest and driest profiles. The Agricultural Production Systems Research Unit in Toowoomba, Queensland, has routinely collected this type of data. Procedures for wetting the soil to determine the Drained Upper Limit include ponding water on the surface, which is suitable for light textured soils, or trickle irrigation at just below the surface infiltration rate, for heavier soils. Dry profiles can be obtained by excluding rain from a vigorously growing crop and then sampling the profile at flowering and crop maturity (Dalgliesh and Cawthray, 1998). This type of data does provide information on active soil depth because profiles are measured under wettest and driest conditions.

Of the 180 active soil moisture storage measurements in our database, 91 are based on time series measures of profiles or total soil storage. The other 89 values are from situations where the soil was artificially wetted and dried to obtain an estimate of the maximum active soil store.

3. How Dry is Dry And How Wet is Wet?

Field measurements of the wettest and driest profiles, which occur under natural conditions, will only give a good estimate of the total active soil moisture store if these profiles are indeed close to the wettest and driest the soils are likely to get. Extreme profiles will largely depend on the weather conditions during the measurement period. Clearly, the longer the measurement period the more likely that extremes will be encountered. For this reason, where we based the active soil store estimate on a time series of soil moisture measurements, a minimum of two years of data has been used.

We have also analysed the rainfall during the measurement period. For each of the locations (91 measurements at 45 sites), the rainfall during the measurement period was compared to long-term rainfall data. Comparisons were made using sixty years of monthly rainfall data (1940 to 1999), provided by the Bureau of Meteorology. These data come from a monthly rainfall gridded dataset, which has been developed by the Bureau, where rainfall has been estimated for square cells of 0.25 degrees (approximately 25 km x 25 km) depending on latitude).

The median, 25th and 75th percentile rainfalls for the period 1940 to 1999 were compared to the rainfall during the soil moisture measurement period at the 45 sites (see Appendix 3). For example, the rainfall during the 31 months when soil moisture was collected at Lidsdale, NSW (October 1968 to May 1971) can be compared to summary statistics for January 1940 to December 1999 for the grid cell centred on the Lidsdale site (see Figure 4).

The wettest and driest months during the measurement period were also compared to the long-term rainfall data. The rank of the wettest and driest month was calculated based on the 720 months of long-term data. For example, at Lidsdale, only 0.4% of months between 1940 and 1999 were drier than the driest month during the measurement period, and only 4% of months were wetter than the wettest month. Extreme ranks increase the likelihood that the measured wettest and driest profiles are close to the extreme values so that the estimate of the soil moisture store is approximately correct. For the 45 sites where ranks were calculated, 82% of the driest months were in the driest 5% of all months and 87% of wettest months where in the wettest 5% of all months (Figure 5 and Figure 6). The difference between the rank of the wettest and driest months was also calculated such that a difference of 100% would mean the highest ranked wettest and the highest ranked driest months occurred during the measurement period. Eighty nine percent of sites had a difference in ranks of greater than 90% (Figure 7).

One limitation of this analysis is specification of the start and end of the measurement period. This was taken from the source documents where possible. If only the start and end year were specified, the starting and ending months were taken to be January and December respectively, which may lead to an underestimation of the ranks of the wettest and driest month. Full results of the analysis of rainfall are listed in Appendix 4. A macro was developed in Microsoft Excel to facilitate the analysis.

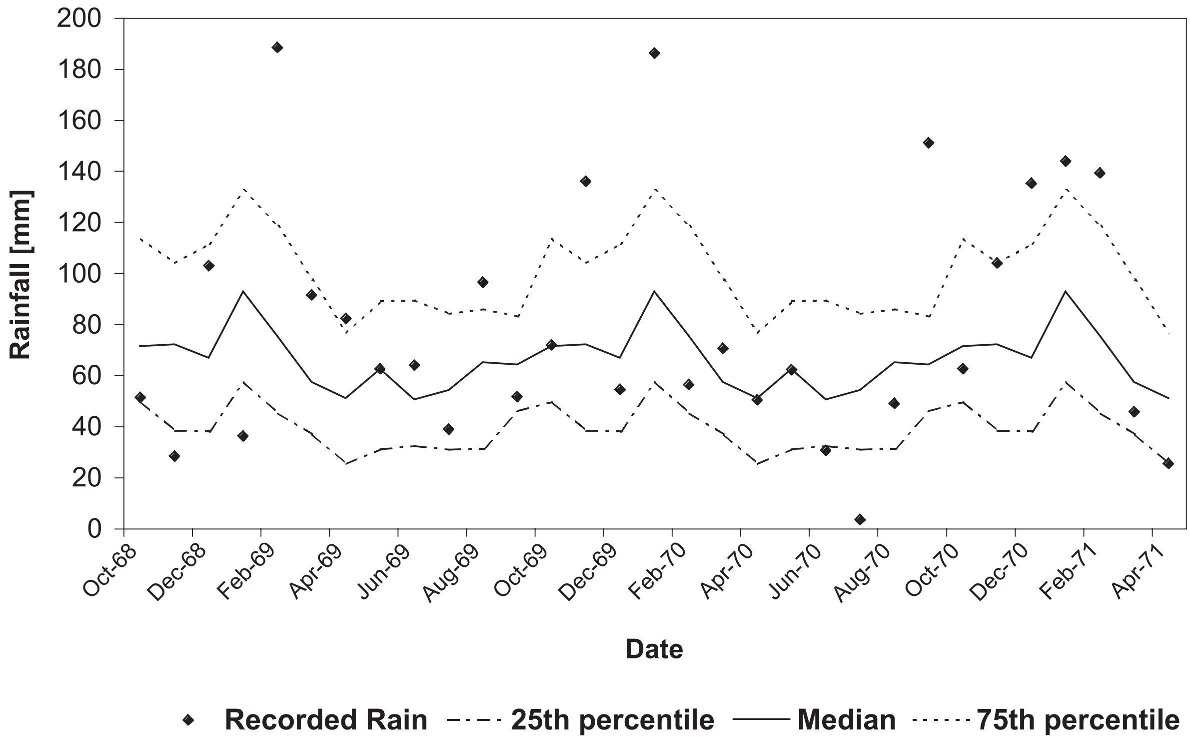


Figure 4 Monthly Rainfall During the Period of Measurement at Lidsdale (October 1968 to April 1971) Compared to the 25th, and 75th Percentiles, and the Median, for Monthly Rainfall from January 1940 to December 1999.

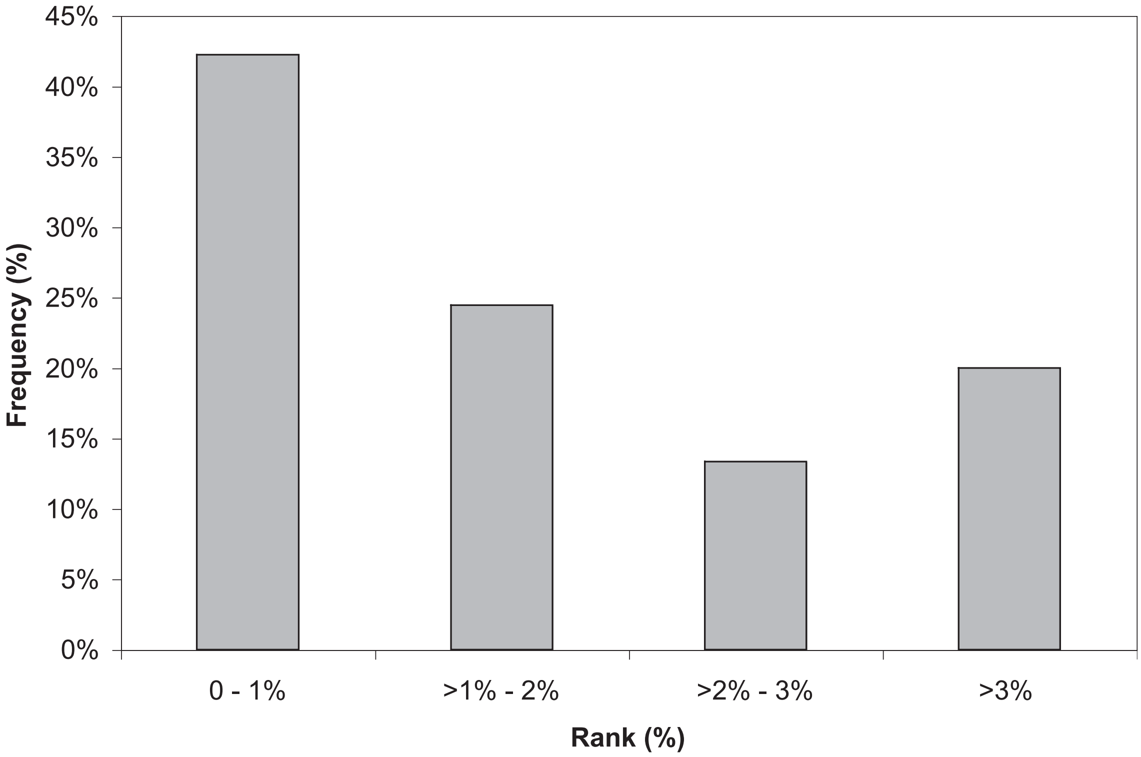


Figure 5 Rank of the Driest Month when Comparing Rainfall During the Period when Soil Moisture was Measured with 60 Years of Rainfall Data (1940 – 1999). Results are for 45 Locations.

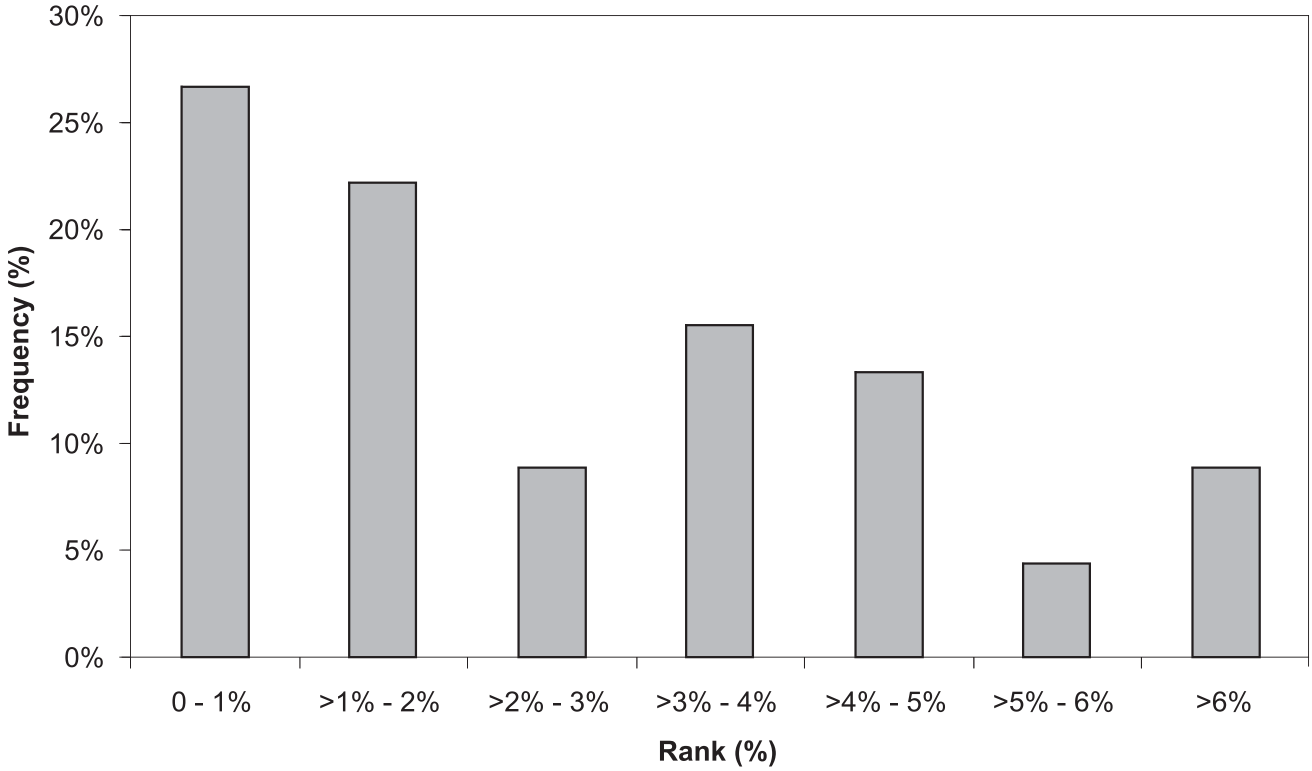


Figure 6 Rank of the Wettest Month when Comparing Rainfall during the Period when Soil Moisture was Measured with 60 Years of Rainfall Data (1940 – 1999). Results are for 45 Locations.

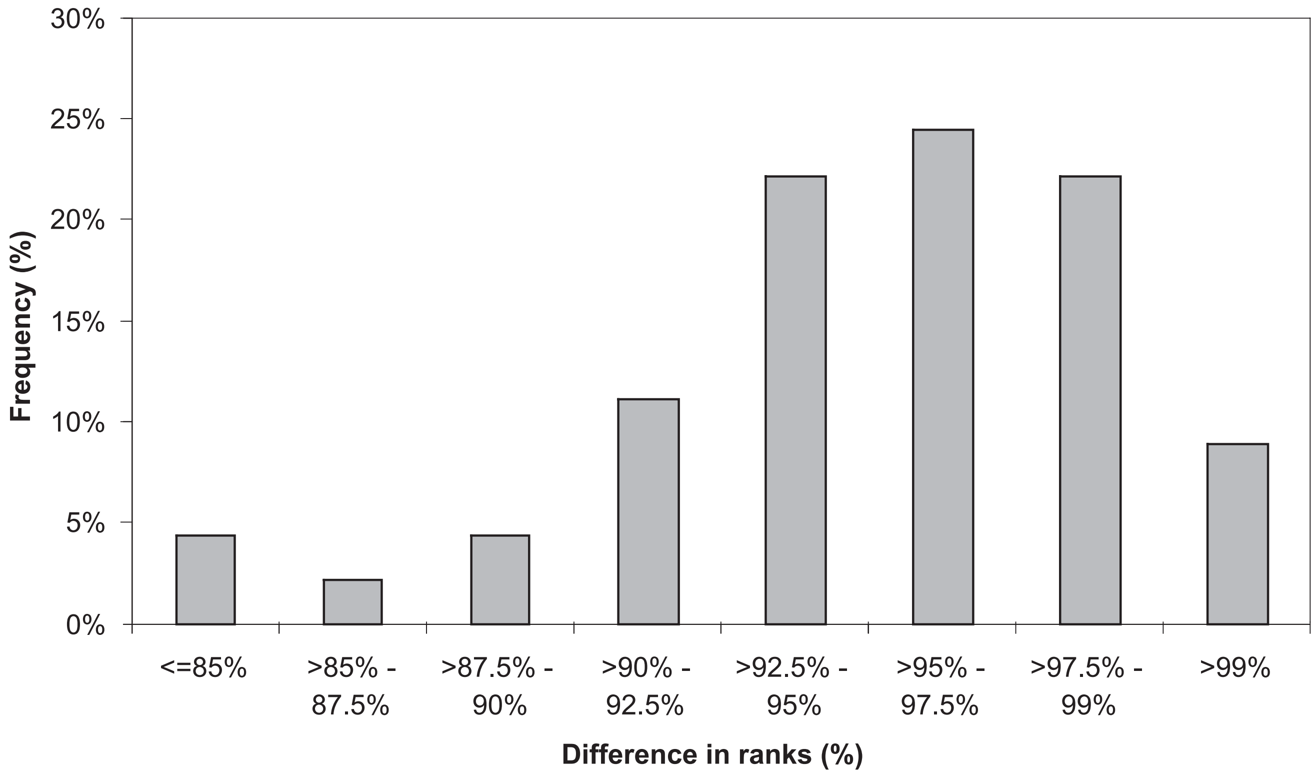


Figure 7 Difference in Rank of Wettest and Driest Months for the 45 Sites (where 100% would mean the highest-ranked wettest and the highest- ranked driest months occurred during the measurement period).

4. A Database of Soil Moisture Store Information

4.1 General Information about the Database

Information on soil moisture has been collected in a Microsoft Access database. This information is mainly based on journal articles, conference papers and reports as noted in Section 2.

4.2 Description of Database Fields

There are 25 fields in the database for each record as detailed in Table 2. Each record corresponds to a particular combination of soil type, vegetation type and location.

Table 2 Fields in the Database (continued next page)

Field	Brief Explanation
Site location	The name of the site as referred to the source documentation
State	Australian state or territory
Latitude	Latitude in decimal degrees
Longitude	Longitude in decimal degrees
Reliability of location	1 – reliable location as determined from the source document or measured directly from a map. 2 – location may be unreliable as there was limited information in the source document
Site map	Is a site map available in the source document? (Yes/No)
Vegetation type	Vegetation type as recorded in the source document
Generalised vegetation type	1 - Trees 2 - Crops 3 - Pasture 4 - Fallow
Land use	Land use as noted in the source document
Terrain	Terrain as noted in the source document
Soil type	Soil type as noted in the source document
Data type	Type of soil moisture information as documented in Table 1.
Horizon depth	Is information on horizon depth recorded in the source document? (Yes/No)
Porosity/bulk density	In information on porosity and/or bulk density recorded in the source document? (Yes/No)
Soil depth	Soil depth as noted in the source document, or the depth of measurement

Table 2 Fields in the Database (cont.d)

Field	**Brief Explanation**
Stored soil moisture	The total stored soil moisture as determined from the source document
Active soil depth	Best estimate of active soil depth based on soil moisture data provided in the source document (see Section 2.2.1 for details of analysis)
Active soil moisture store	Best estimate of the active soil moisture store (the extractable soil moisture). In some cases this may be different from the stored soil moisture, particularly for profiles of type 3 (see Table 1 and Section 2.2.1)
Missing water	Was the whole active soil moisture store measured (Yes/No). This refers particularly to profiles of type 4 (Table 1) where the active storage appears to extend below the measured depth
Start/Stop	The beginning and end of the measurement period. This information comes from the source document. The month and year is listed where it is available in the source document
Rainfall	Has rainfall data been used to test the representativeness of the period when soil moisture was measured (see section 3 for details)? This test was done wherever possible that is, where dates of soil moisture measurements were noted in the source document
Rank of the driest month	This is the rank (scaled between 0 and 1) of the driest month in the period when the soil moisture was measured compared to all the monthly rainfal1 in 740 months between 1940 and 1999 (see Section 3). The driest month between 1940 and 1999 is ranked as zero
Rank of the wettest month	This is the rank (scaled between 0 and 1) of the wettest month in the period when the soil moisture was measured compared to all the monthly rainfal1 in 740 months between 1940 and 1999 (see Section 3). The wettest month between 1940 and 1999 is ranked as zero
Monitoring frequency	Frequency that soil moisture was measured as noted in the source document
References	Reference to source document(s)

4.3 Example

An example is presented below for extractable soil moisture data from Lidsdale, NSW

Site location: Lidsdale

State: NSW

Latitude: 33.43 S

Longitude: 150.07W

Reliability of location: 1 - reliable

Site map: True (available)

Vegetation type: Radiata pine

Generalised vegetation type: Forestry

Terrain: Hills

Soil type: Dy 3.41/Dy 2.61 (Northcote)

Data type: 3

Information on Horizon depth: True (Yes)

Information on Porosity/bulk density: False (No)

Soil depth: 2.2 m

Stored soil moisture: 234 mm

Active soil depth: 1200 mm

Active soil moisture store: 234

Missing water: False

Start/Stop: October 1968 to April 1971

Rainfall: True (Rainfall data is available and has been used to test representativeness of the measurement period)

Rank of the driest month: 0.004 (scaled from 0 to 1, where 0 implies driest on record)

Rank of the wettest month: 0.041 (scaled from 0 to 1, where 0 implies the wettest on record)

Monitoring frequency: Weekly

References: Pilgrim *et al.,* (1982), Smith *et al.,* (1974), Smith (1974)

5. Comparison with the Atlas of Australian Soils

The Atlas of Australian Soils (Northcote *et al.,* 1960-1968) provides spatial information on soil landscapes for the whole of Australia based on soil characteristics that can be observed in the field. This has been an important resource for over three decades, and remains the only consistent source of data for the whole continent. However until recently it has not been straightforward to use the Atlas to establish the soil physical properties that are important for hydrologic analysis.

McKenzie *et al.,* (2000) (following from McKenzie and Hook, 1992) have addressed this problem and provide data on soil physical properties for the 725 soils in the Digital Atlas of Australian Soils (BRS, 1991). Soil properties have been estimated using a simple two-layer soil model consisting of A and B horizons. Soil water retention properties were calculated for each soil, based on estimates of thickness, texture, bulk density and pedality, using Williams (1983) approach. The available water capacity for each layer was calculated from fitted soil water retention curves assuming upper and lower limits of –0.1 bar and –15 bar respectively.

The Digital Atlas of Australian Soils provides data for polygons (there are 22,560 in total) that represent soils in particular regions. Each of the polygons is attributed with one of 3060 soil landscape types, many of which occur more than once. For each map unit, the dominant soil type is described (referred to as the dominant Principle Profile Form) along with any subdominant Principle Profile Forms. McKenzie *et al.,* (2000) records up to five Principle Profile Forms for each soil landscape. Each of the Principle Profile Forms includes an estimate of solum thickness (the sum of the depth of the A and B horizons) and the available water capacity over that depth. When interrogating the data on soil physical properties, specifying a location, will link to a polygon and return information on the dominant and subdominant Principle Profile Forms.

Our estimates of the active soil moisture store, based on field measurements, provide an opportunity for comparison with the available water capacity from the interpretation of the Atlas of Australian Soils information. For each of the locations in our database (Figure 1) the available water capacity estimated for corresponding dominant Principle Profile Form was compared to the extractable soil moisture store (Figure 8). In several cases, there is more than one estimate of extractable soil moisture store for a particular location because measurements were made under more than one vegetation type. All the available estimates have been included in Figure 8. The outlying high storage value shown in Figure 8 of 680 mm is from a site in the Brindabellas, ACT where soil moisture was measured under a mixed Eucalypt forest during a drought (Talsma and Gardner, 1986).

The results show that the soil moisture store from the Atlas of Australian Soils is generally smaller than the estimate from field measurements. A comparison of the ratio of the differences (Figure 9) showed that 42% of the estimates of extractable soil moisture were greater than twice the value from the Atlas of Australian Soils. In general, estimates of available water capacity from McKenzie *et al.,* (2000) could be considered a reasonable lower bound on field-based estimates of the actual dynamic soil moisture store. It should be noted that the information on location in our database is of variable quality and depends on the precision in the original reference, supplemented where appropriate (and possible) by direct discussions with researchers. Errors in location will contribute a small amount of the variance shown in Figure 8.

The comparison in Figures 8 and 9 is made using the dominant Principle Profile Form for each polygon that matches a particular location. In most cases there will also be subdominant Principle Profile Forms with their own associated estimates of available water capacity. These provide a greater spread of estimates as shown in Figure 10 where the extreme variability is apparent, although the extractable soil moisture store is still generally much larger than the estimate using AAS data.

Estimates of the available water capacity provided by McKenzie *et al.,* (2000) are the product of the depth of the soil profile and the soil moisture storage capacity per unit depth. Equivalent parameters are also available from our database where an active soil depth

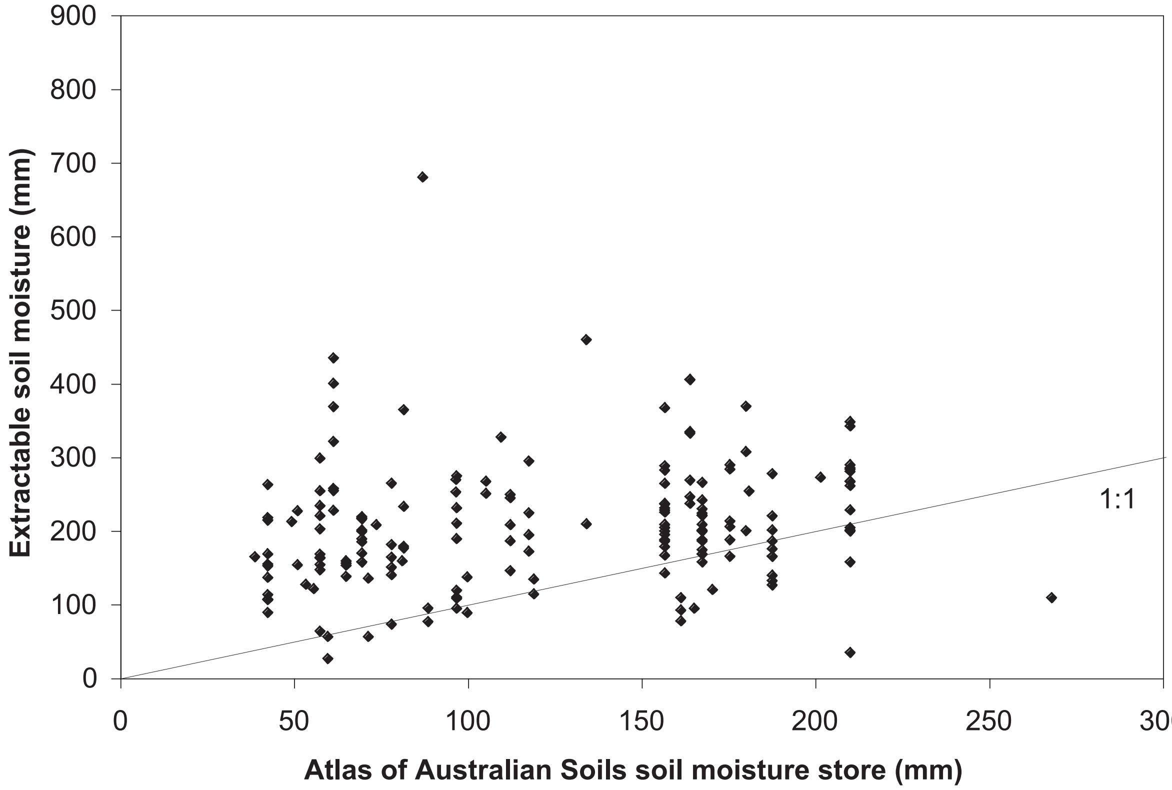


Figure 8 Comparison of Soil Moisture Stores from the Atlas of Australian Soils with Field-based Estimates of Extractable Soil Moisture

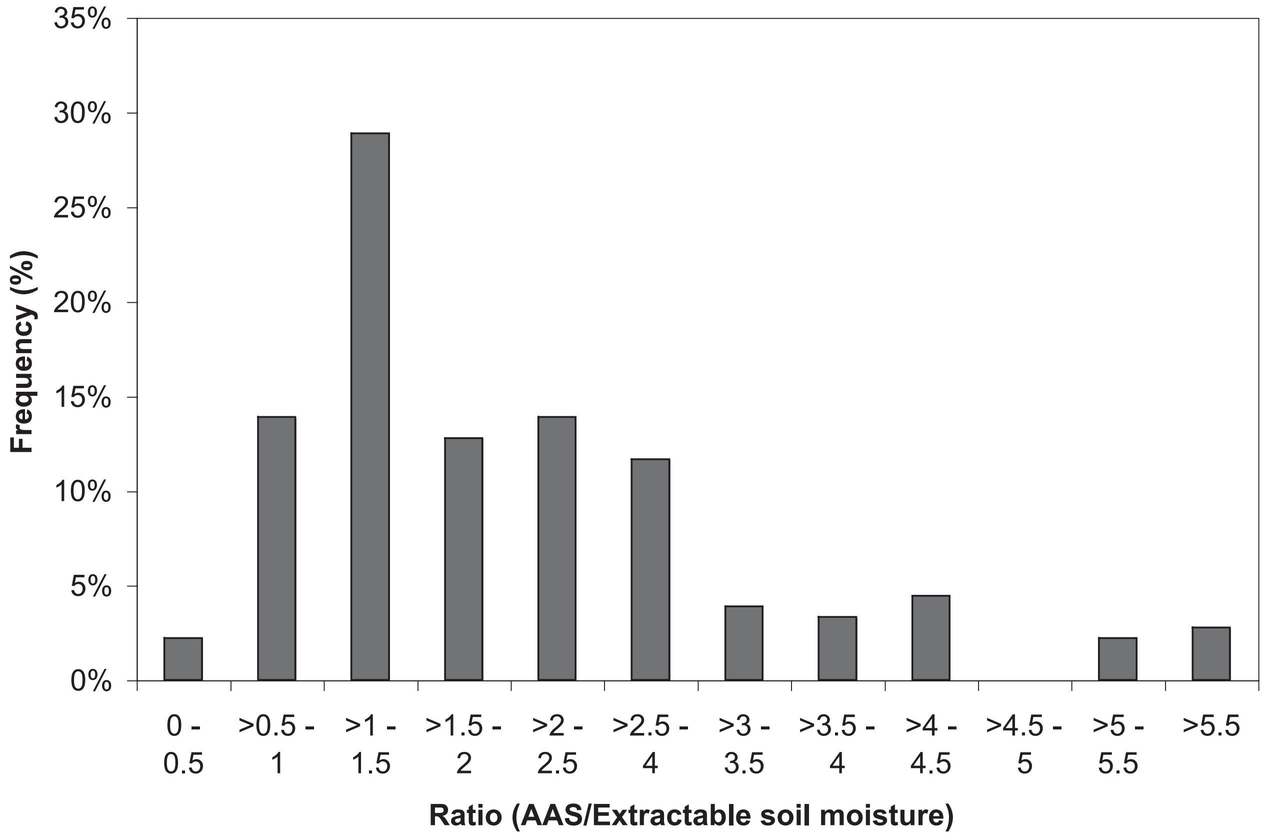


Figure 9 Ratio of Estimates of Soil Moisture Store from the Atlas of Australian Soils and Field Measurements of Extractable Soil Moisture

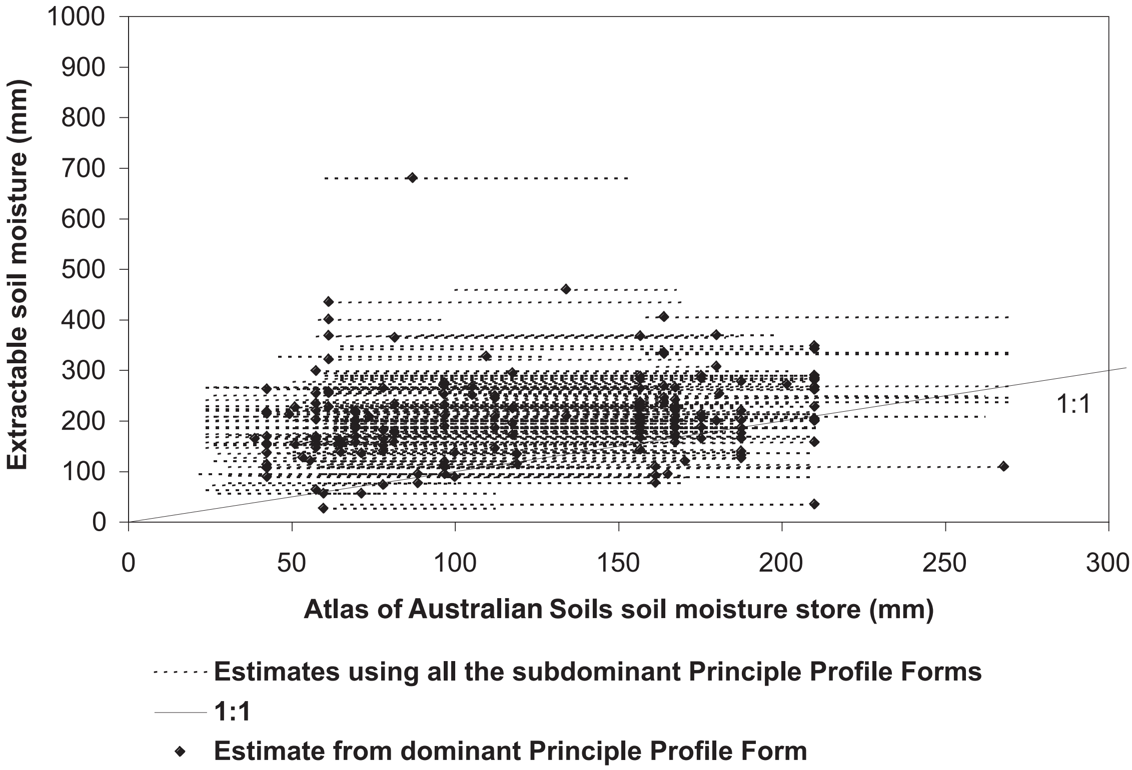


Figure 10 Comparison of Field-based Estimates of Extractable Soil Moisture with the Estimates of Available Water Capacity from the Atlas of Australian Soils. Estimates for the Dominant and Subdominant Principle Profile Forms are shown for each Location

is defined based on where the wettest and driest profiles meet or the maximum depth of soil moisture measurement; whichever is less (Table 1).

The soil moisture store per unit depths are compared in Figure 11 using only the dominant Principle Profile Form for each location. In this case the estimates from McKenzie *et al.,* (2000) and the field measurements cluster around the 1:1 line suggesting reasonable agreement, although clearly the scatter is large.

The active soil depth from field measurements, and the solum thickness from the Atlas of Australian Soils are compared in Figure 12. Active soil depths are generally much larger than solum thickness estimates. It is the underestimate of active soil depth that explains the low estimate of soil moisture store from the AAS interpretation shown in Figure 8.

McKenzie *et al.,* (2000) acknowledges that solum thickness estimates are likely to be subject to error. Unfortunately, the thickness of individual soil layers, and the depth of the soil profile, are often not recorded as part of the Northcote classification and there is only imprecise definition of the depth of soil that can be exploited by plants. Often plants will extract moisture from below the A and B horizons and historical datasets do not provide any consistent information on deeper soil layers. Data in existing soils databases also tends to be censored because of the method used to collect soil profile information, for example, soil pits and augers, are often restricted to one to two metres. Often soil surveys for agricultural purposes restrict examination to the first 1 m of the soil profile and some Principle Profile Forms are only comprised of an A horizon, yet roots can penetrate deeper soils (McKenzie *et al.,* 2000).

Clearly, estimates of available water capacity could be improved by better soil descriptions but it is also necessary to use appropriate estimates of active soil depth. The active soil depth is partly determined by rooting depth of vegetation but it is also possible for moisture to be withdrawn from the soil under fallow conditions. Estimates of active soil depth from our database for trees, crops, grass and fallow are shown in Figure 13.

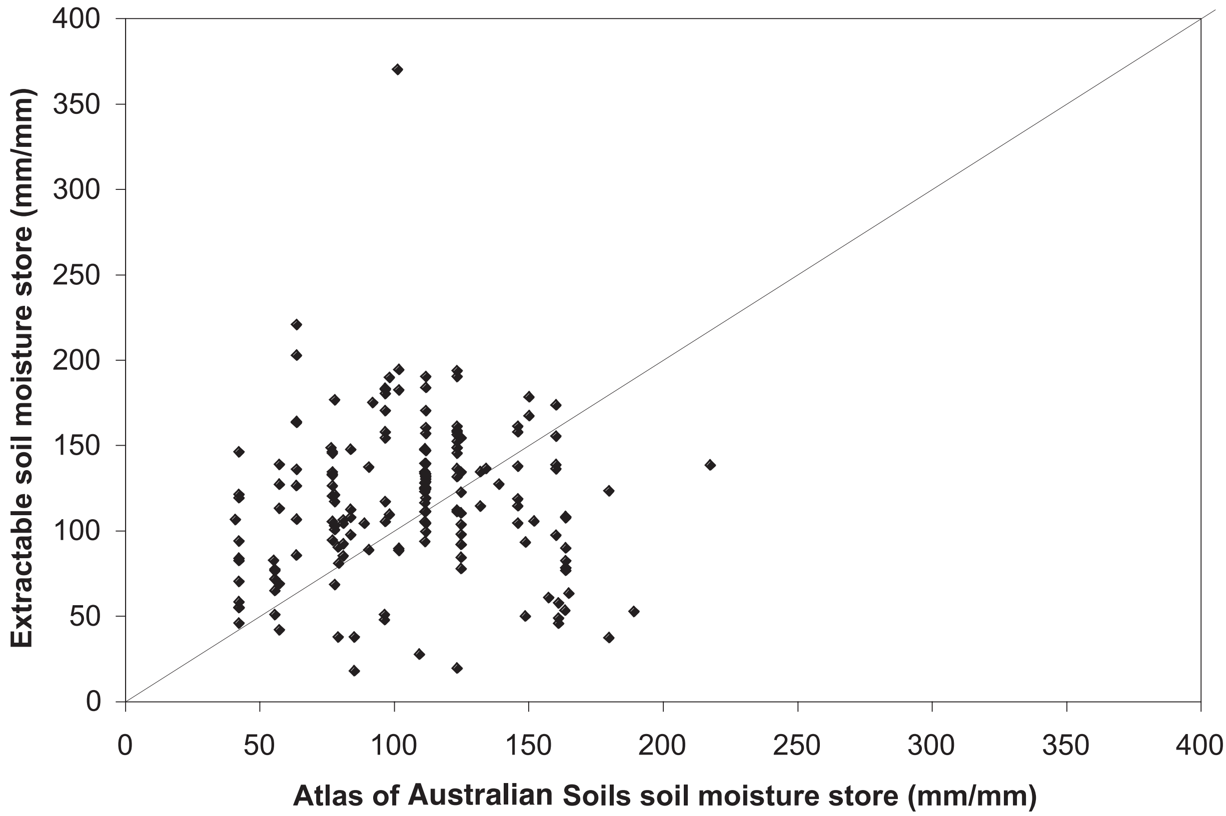


Figure 11 A Comparison of Soil Moisture Store Per Unit Depth

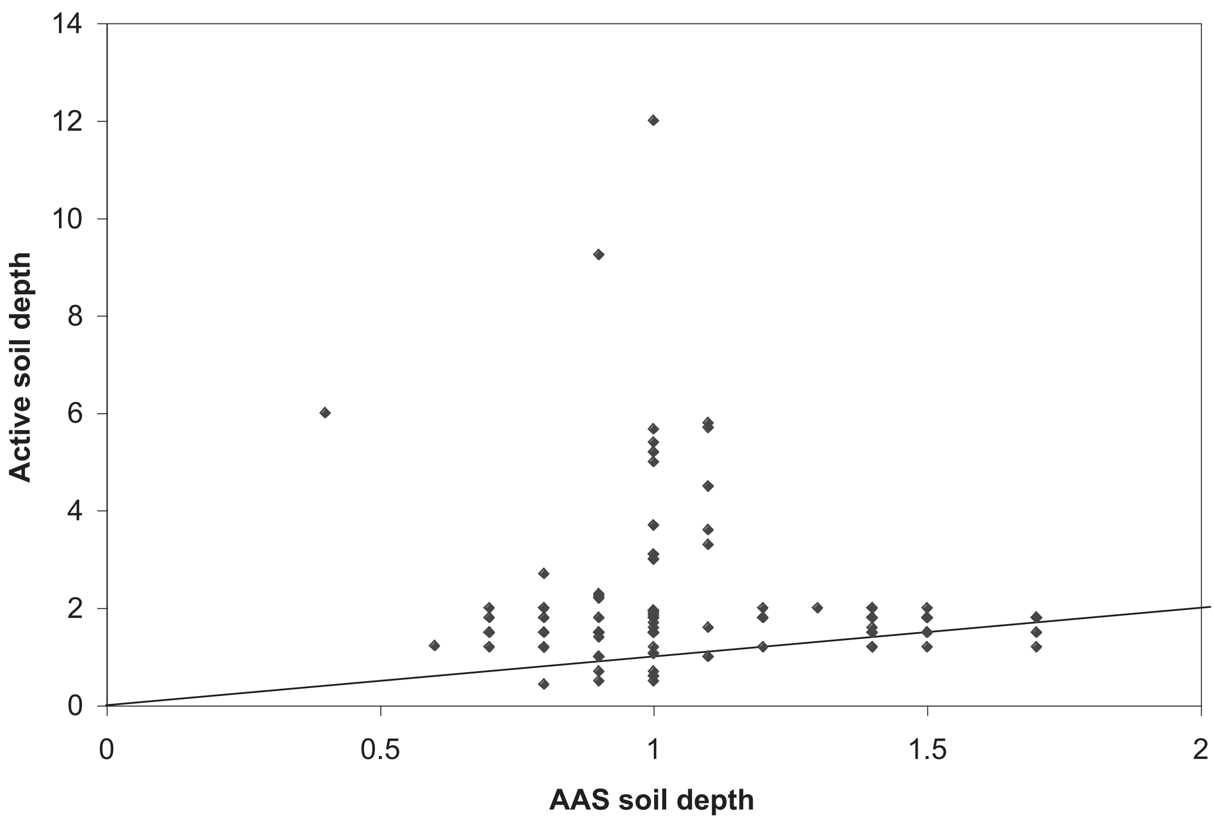


Figure 12 A Comparison of Solum Depth from the Atlas of Australian Soils and Active Soil Depth from Field Measurements

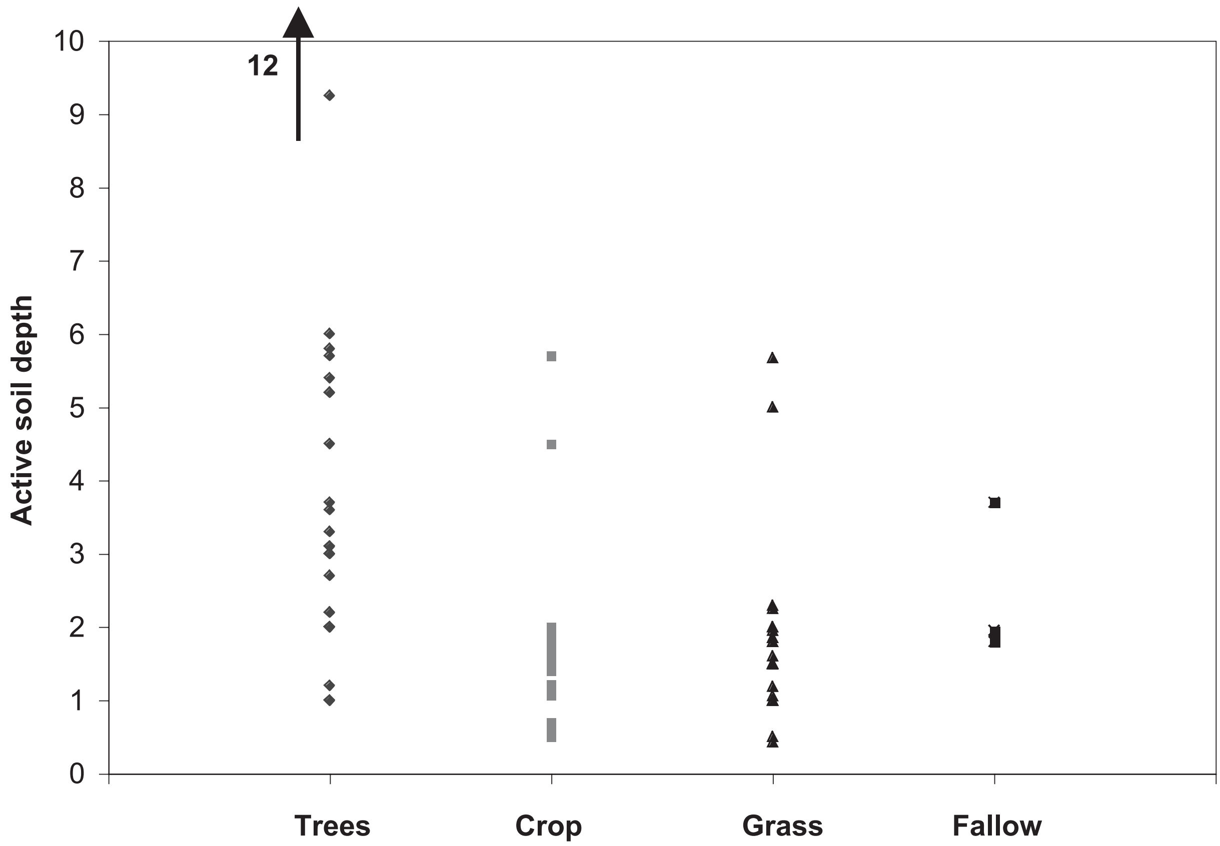


Figure 13 Active Soil Depths based on Field Measurements of Extractable Soil Moisture for three Vegetation Types and Fallow Conditions

The active soil depth for crop, grass, and fallow are generally one to two metres with some outliers that are probably explained by soil type. Our data suggests that wherever there are deep sandy soils active depths may be very large. For example, the two active soil depths for crop, (of about 5 m) are for Lucerne grown on deep sandy soils near Keith, South Australia (Holmes, 1960). The active soil depths for grass of around five metres were measured on deep sands near Pinjarra, WA (75 km south of Perth) (Carbon *et al.,* 1982) and the high active soil depth for fallow conditions (of about 3.7 m) was for a deep sandy soil near Wongan Hills in Western Australia about 170 km north-east of Perth where there may have been interaction with groundwater.

The active soil depth for trees is more variable than for crop, grass and fallow, ranging from 1 to 12 m. Again, the largest active depths are for deep sandy soils. Further work is required before the active soil depth can be predicted from soil types and tree taxa.

6. Conclusion

Information on extractable soil moisture has been gathered for 180 unique combinations of location, soil and vegetation types. This dataset provides estimates of the soil moisture storage based on field measurements of wettest and driest soil moisture profiles.

Our search for this profile information revealed deficiencies in the way data from experimental studies is archived in Australia. For parts of the hydrologic cycle, such as rainfall and streamflow, there is accurate current and historical information that is easily accessible. This contrasts with soil moisture data that are usually gathered for specific projects so there is little incentive to archive it in a form that can be interpreted by others. Most of the data we have gathered were from published sources, which probably represents only a small proportion of the soil moisture measurements that have been collected but is also probably the proportion that researchers are most confident in.

Analysis of rainfall during the periods when soil moisture was measured, suggests that observed driest and wettest profiles are good estimates of the minimum and maximum storage values. In over 80% of cases, the wettest and driest months during the measurement periods were ranked within 5% of the wettest and driest months of a 60-year rainfall record (1940 to 1999). Around 40% of the time they were ranked within the top 1%.

The extractable soil moisture stores were compared with the available water capacity estimated by McKenzie *et al.,* (2000) for the Atlas of Australian Soils (AAS). Preliminary results show that data from the Atlas of Australian Soils provide a useful lower bound for measured dynamic soil moisture storage, but of the sites examined, 42% had extractable stores greater than two times the AAS values. Our analysis shows that estimates of available water capacity from the Atlas of Australian Soils must be treated with caution particularly where there are trees. There is the potential of using information on vegetation type to better estimate active soil depths but further work is needed to quantify these relationships.

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Appendix 1 - Information Sources

The following people were contacted regarding soil moisture

Haralds Alksnis, CSIRO Land and Water, Canberra

Mohammed Bari, Water and Rivers Commission Western Australia

Geoff Beale, Department of Land and Water Conservation

Geoff Beecher, NSW Agriculture

Craig Beverly, DPI

Martin Bluml, DPI CLPR

Leith Bowya, Water and Rivers Commission, Western Australia

Andrew Bradford, CSIRO

Leon Bren, The University of Melbourne

Joost Brouwer, now based in the Netherlands

Ken Bubb, Queensland Forestry Research Institute, Gympie

Bruce Carey, QNR Toowoomba

Greg Chapman, DIPNR

Colin Chartres, AGSO Canberra

David Chittleborough, Waite, University of Adelaide

Brendan Christy, DPI

David Connor, The University of Melbourne

John Cooke, DPI Mildura

Peter Crapper, CSIRO Land and Water

Hamish Creswell, CSIRO

Trevor Daniels, University of Adelaide

Peter Dowling, NSW Agriculture

Frank Dunin, CSIRO

Derek Eamus, University of Technology Sydney (CRC for Tropical Savannas)

Richard Eckard, DPI Dairy Research Centre

Brian Finlayson, The University of Melbourne

David Freebairn, Queensland Natural Resources, Mines and Energy

Guy Geeves, DIPNR Cowra

Iain Grierson, University of Adelaide

Peter Hairsine, CSIRO Land and Water, Canberra

Barry Hart, Monash University

D. Hall, NSW Agriculture

Keith Hellier, NSW Agriculture

Bill Heslop, Goulburn-Murray Water

Cliff Hignett, former CSIRO now consulting

Robert Hoogers, NSW Agriculture

John Hornbuckle, CSIRO

Ian Hume, CSIRO

Lindsay Hutley, CRC Savannas, Northern Territory University

Ron Hutton, NSW Agriculture

Andrew Johnson, CSIRO

Bill Johnson, DIPNR

Patrick Lane, DSE

Alan Lavis, Goulburn-Murray Water

Mark Littleboy, DIPNR

Greg Lodge, NSW Agriculture

Alicia Lucas, DSE

Warwick McDonald, National Land and Water Resources Audit

David McKenzie, (former CSIRO)

Neil McKenzie, CSIRO

Tom McMahon, The University of Melbourne

Russell Mein, Monash University

Wayne Meyer, CSIRO Land and Water, Glen Osmond

Geoffrey Miller, NSW Agriculture

Peter Milthorpe, NSW Agriculture

Angela Murray, CSIRO Sustainable Ecosystems Townsville

Sean Murphy, NSW Agriculture

Nanda Nandadumar, DIPNR

David Nash, DPI, Victoria

Sam North, NSW Agriculture

Garry O'Leary, CSIRO

Cuan Petheran, CSIRO Land and Water

Geoff Podger, DIPNR

Derek Poulton, Goulburn-Murray Water

Mike Raupach, CSIRO Land and Water

Harald Richter, Bureau of Meteorology

Anna Ridley, DPI

John Ruprecht, Water and Rivers Commission, Western Australia

Mark Sallaway, Natural Resources Mines and Energy, Bundaberg Qld

P. Sandford, Agriculture Western Australia

Mark Silburn, APSRU, Queensland Natural Resources, Mines and Energy

Murugesu Sivapalan, University of Western Australia

Keith Smettem, University of Western Australia

Chris Smith, CSIRO Land and Water, Canberra

Richard Stirzaker, CSIRO

John Thompson, NSW Agriculture

Hugh Turral, The University of Melbourne

Narendra Tuteja, DIPNR Queanbyan

Nick Uren, Latrobe University

Robert van de Graaff, Melbourne

Rob Vertessy, CSIRO Land and Water

Glen Walker, CRC for Catchment Hydrology, Glen Osmond, SA

QJ Wang, DPI Tatura

Phil Ward, CSIRO

Ian Watson, Melbourne Water

Bob White, The University of Melbourne

Des Whitfield, DPI

Mark Wood, Goulburn-Murray Water

Clive Yates, Frank Wise Research Institute, Kununurra

Rick Young, NSW Agriculture

Steve Zegelin, CSIRO

Lu Zhang, CSIRO

Databases Searched

The following databases have been searched to locate projects that measured profile soil moisture:

- CSIRO database of scientific publications for 1990-2000;
- CSIRO database of technical reports for 1997-2000;
- AGRICOLA;
- Australian Journal of Soil Research 1997-2000;
- All electronic journals in The University of Melbourne database.

Models

Several models have been developed to describe soil wetting and drying and moisture availability. Some of these have been calibrated or developed by analysing soil moisture data sets. Despite searching for the calibration data from the following models nothing was found that contributed to the database developed for this project.

PERFECT

PERFECT - Productivity Erosion Runoff Functions to Evaluate Conservation Techniques (Littleboy *et al.,* 1992). A users guide has been published as a computer simulation model of Productivity Erosion Runoff Functions to Evaluate Conservation Techniques, Queensland Department of Primary Industries Bulletin, QB 89005 (Littleboy *et al.,* 1989). PERFECT was reviewed by Littleboy (1997). PERFECT requires information on plant available water content as related to soil properties. PAWCER is one model that has been used to provide the soil moisture submodel of PERFECT.

APSIM

Agricultural Production System Simulator - see http://apsim-help.tag.csiro.au/main_what_is_apsim.asp. APSIM requires information about soil-water properties for each soil type. These include the drained upper limit, the -15 bar lower limit of soil moisture and the saturated water content (APSIM, 2002). Not likely to be a source of information for this project.

PAWCER

PAWCER - Plant Available Water Capacity Estimation Routine developed by Mark Littleboy as part of his Ph.D. thesis (Littleboy, 1997, p151). Available soil moisture is partly based on laboratory measurements of the -15 bar water content so data is not likely to be relevant for direct estimates of extractable soil moisture although calibration of the PAWCER model was based on estimation of plant available water capacities from field measurements on 63 soils (Littleboy, 1997). These measurements have been included in our database where the information was available.

WAVES

CSIRO model of water, carbon and energy see http://www.clw.csiro.au/waves. As part of the WAVES project there was extensive data collection in the Mallee region of NSW and Victoria, at Hilston and Walpeup. The Walpeup data has been included in the extractable soil moisture database. The Hilston data was not in a form that could be used.

Appendix 2 - Issues with the Collection and Archiving of Soil Moisture Data

Published in *Catchword* (Cooperative Research Centre for Catchment Hydrology Newsletter, April 2001).

In search of the perfect profile…

Report by Tony Ladson, Rodger Grayson and Andrew Western

Background

Back in October 2000, we began looking for research sites around Australia where there were measurements of root-zone soil moisture storage. This information is of general importance to many modelling studies and will help us specifically with the modelling being undertaken in CRC Project 2.3 (on predicting catchment water yield and salinity under different vegetation and climate scenarios), and CRC Project 5.2 (which aims to improve the land surface component in the Bureau of Meteorology's Numerical Weather Prediction model).

Finding the wettest and driest profile at any particular site gives an indication of the soil water storage for that soil and vegetation type - provided spatial and temporal scales of sampling are appropriate. We plan to compare measured soil profile information with the soil hydraulic characteristics from other work such as the commonly used "pedotransfer function" (PTF) approach. In PTF approaches, physical characteristics of soil, such as the percentage of sand, silt and clay, are used to estimate hydraulic characteristics, including soil water storage.

Soil moisture data

Tony Ladson and James Lander are now tracking down as much soil moisture information as possible by talking to researchers, reviewing the literature, and searching for technical reports. We have received excellent assistance from many CRC for Catchment Hydrology personnel, and others from within organizations party to the CRC. To date we have contacted over 100 individuals, collected 35 relevant papers and reports from which we can derive the information of interest, and received 10 data sets. We are expecting to receive several more data sets soon, and many others have been mentioned, but as yet their availability is unclear. While we will continue to chase more information, we have enough now to begin a pilot study to see whether the comparisons yield useful results. We hope to get this pilot phase complete by the middle of the year.

Timing and issues

The search for information has taken a lot longer than we expected and has raised some interesting philosophical and practical issues that are of wider relevance to the CRC for Catchment Hydrology, its partners and beyond. These largely relate to data archiving and management. The assistance we have had from all concerned to date has been terrific, but there are some broader issues that warrant discussion.

Data from individual research

Commonly, the data we use as hydrologists are measured and managed by organisations with a particular mandate, and the resources necessary, to archive and make available their information. Meteorological and streamflow data are two obvious examples. But information where there are no coordinated monitoring networks is difficult to track down. Much of the information we have been seeking has been collected as part of individual research projects by a researcher, or small group of researchers like ourselves. The motivations in these sorts of projects are to answer some specific questions and make the results available through publications. Indeed we have gained a lot of the information we need from published papers and reports. However, the basic data normally reside in field books or computer media of different sorts, depending on the age of the study.

These data have been used by the research team at the time, but, from the researcher (and likely the client's) point of view, once the appropriate analysis and publications have been completed, there is little need to do anything more with them. We have found this problem with our own work especially where we never envisaged any further use for data, and usually the clients at the time were not funding us to archive it in any special way. It is also difficult to retrieve information from studies that are stored on out-of-date media like 'unexercised' magnetic tapes or even 5 1/4 inch discs. These problems must ring true for many of you.

Rescuing data

This is not a unique issue for CRC researchers. For example between 1965 and 1978 there was a vast deployment of seismometers in parts of the US to monitor Soviet nuclear tests. All data were stored on tapes but, given they had served their purpose, the custodian intended to dump them, until "rescued" by some USGS personnel (Anon., 2000). We need not look overseas to see disappointing losses of information. Many of the river cross-sections surveyed during the late 1930s in Victoria have been lost, including all those for the Mitchell River, along with the complete photo collection of the Mitchell that was held by the Rivers and Streams Section of the Rural Water Commission. In our own group, we would be hard pressed to locate the data from any post-graduate study that was undertaken more than 10 years ago, unless the original data ended up in a thesis appendix. Our experience from talking with individuals in other organisations is that the chances of locating data are very slim once those who did the collection or measurement move on. Even where specific databases have been established they can be lost because of changes in computer systems and personnel.

Resources for archiving data

From the point of view of individual researchers or research groups, it is difficult to justify the expense and time needed to archive and maintain data beyond the initial analysis and reporting. This is a task that must be tackled at a higher level. The obvious success in data management of groups like the BoM has come from major investments in the business of storing and maintaining data. There has been a vast amount of information collected over the last century or more as part of graduate projects, university, agency and CSIRO studies, but it is largely inaccessible today – simply because it was never envisaged that it might be useful later, and/or there were no resources available and/or the responsibility for archiving and maintenance activities was unclear.

'Data notes'

There are however some encouraging developments. Leading international journals such as Water Resources Research, now have a form of publication called "data notes". These provide a vehicle for writing up and making generally available, data sets from field studies. These serve not only to maximise use of the results of (expensive) field studies, but also, being journal publications, provide motivation and 'brownie points' for researchers. There is a steady increase in the number of "data notes" which has to be a good sign. There are also World and National (US) Data Centres that are committed to 1) providing open access to scientists, 2) archiving data sets indefinitely (or to migrating the data to a permanent archive if the centre ceases operation) and 3) providing services at reasonable cost. For more information see <http://www.agu.org/pubs/datacent.html>.

Managing data for future use

Do we need some archiving and data maintenance capability for research projects within the CRC for Catchment Hydrology? Should the CRC for Catchment Hydrology become a data centre for some of the key data that we measure and process? A consortium of researchers is ideally placed to develop storage protocols and procedures. The CRC for Coastal Zone, Estuary and Waterway Management is developing a centralised approach to data storage including development of protocols and rules for data access, and the CRC for Catchment Hydrology is currently exploring ways to be involved. Alternatively, should we lobby for a Federal Government Data Centre dedicated to archiving data from government (and other) funded research projects. Depositing data (maybe with an appropriate quarantine period preventing access by competitors) could be a condition of funding and appropriate Meta Data requirements could ensure continued usefulness of the data.

In twenty year's time when someone wants data from a CRC for Catchment Hydrology project they'd read about in a journal or report, what chance would they have of getting a copy?

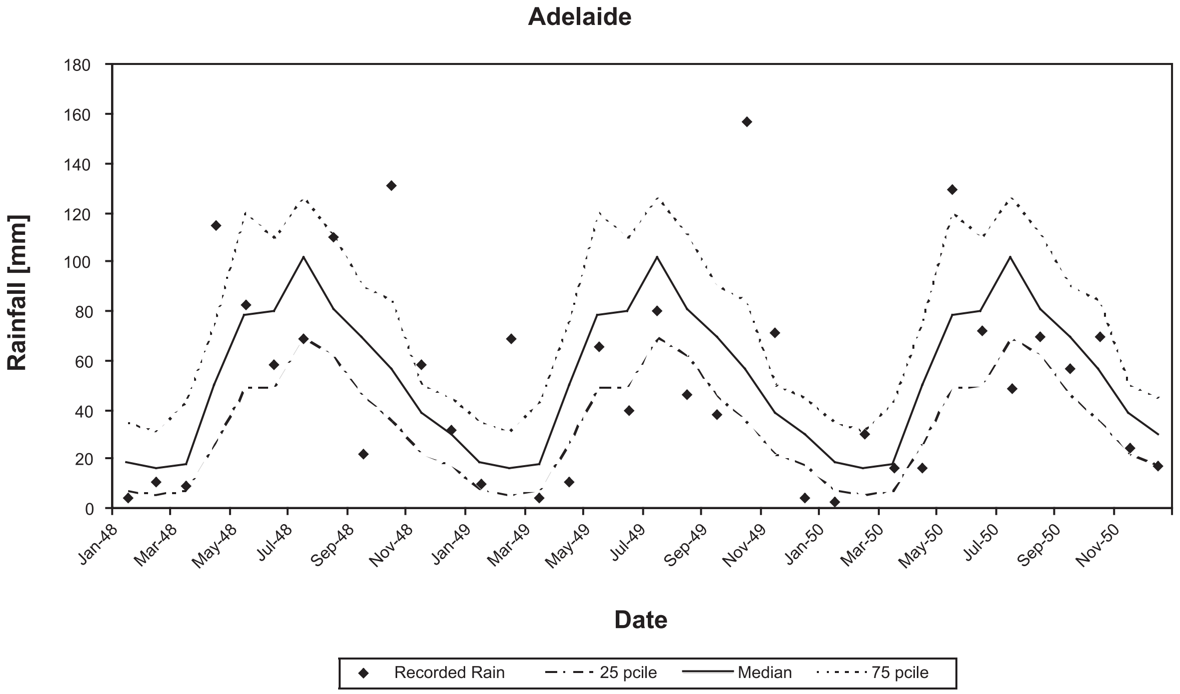
References

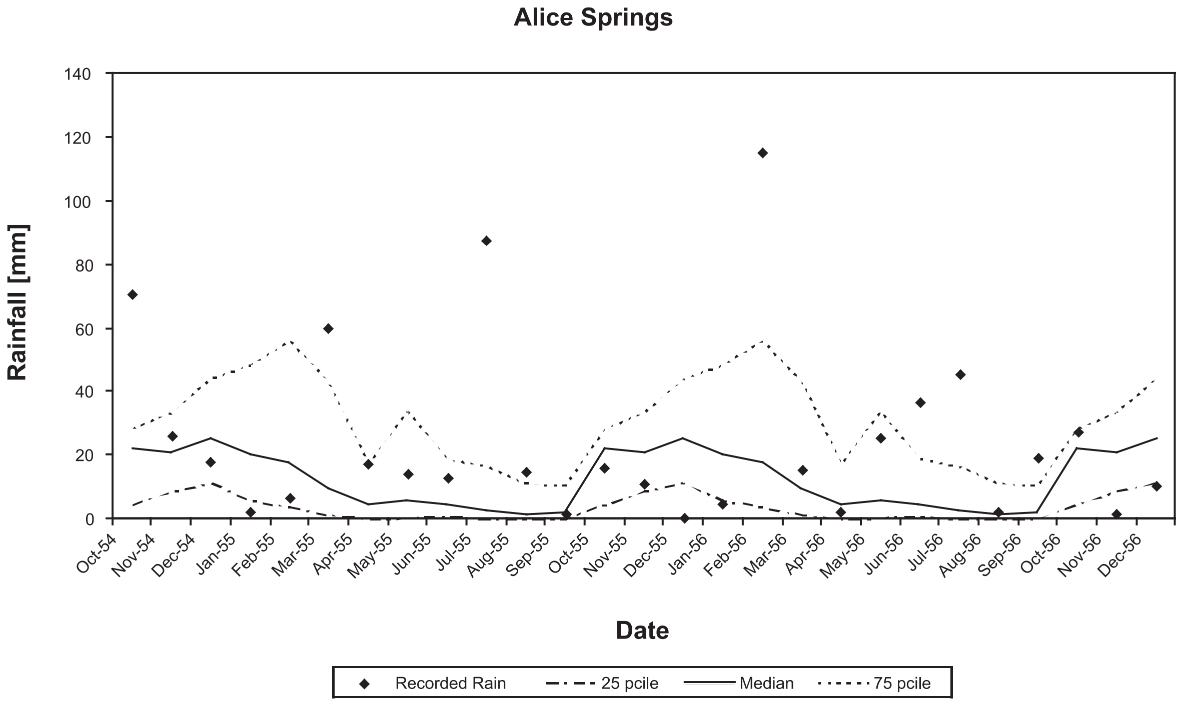
Anon. (2000) "Journey to the centre of the earth" American Scientist, Vol 88 No.5:p 401-402.

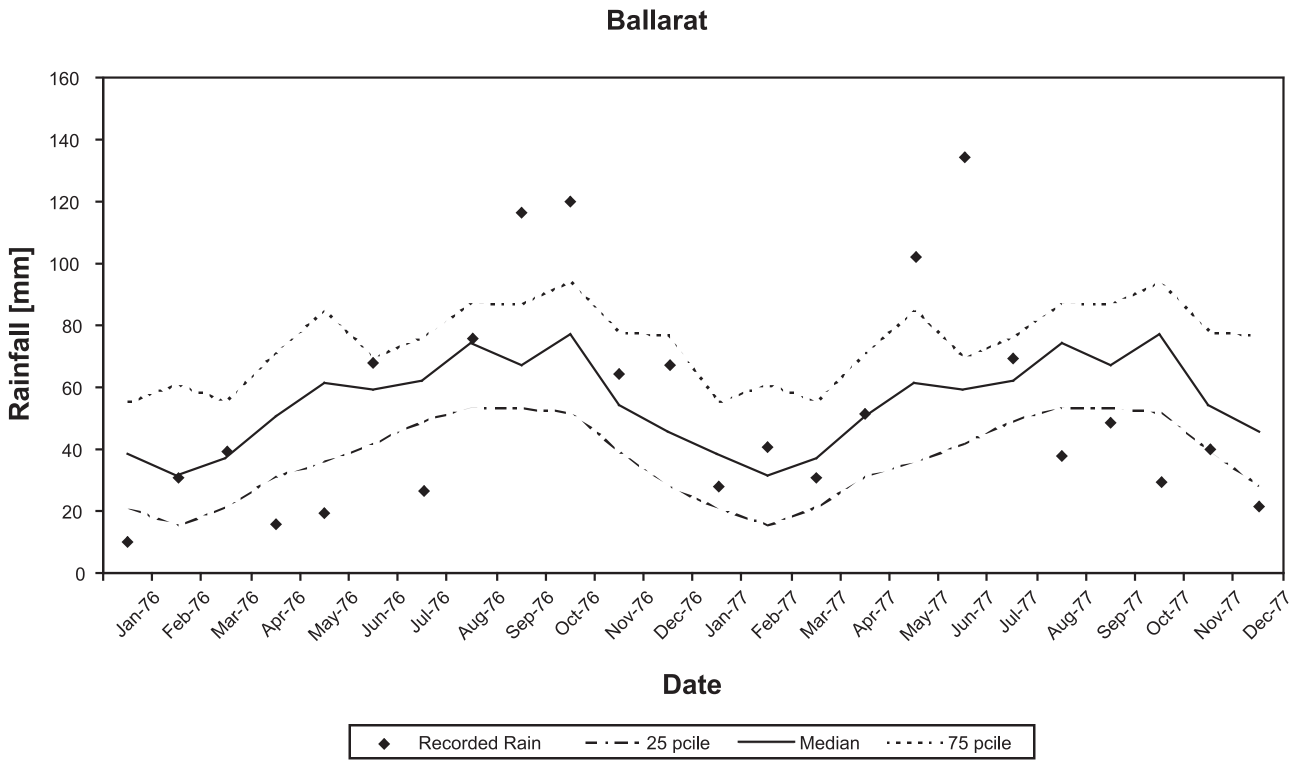
Appendix 3 - Analysis of Rainfall Data

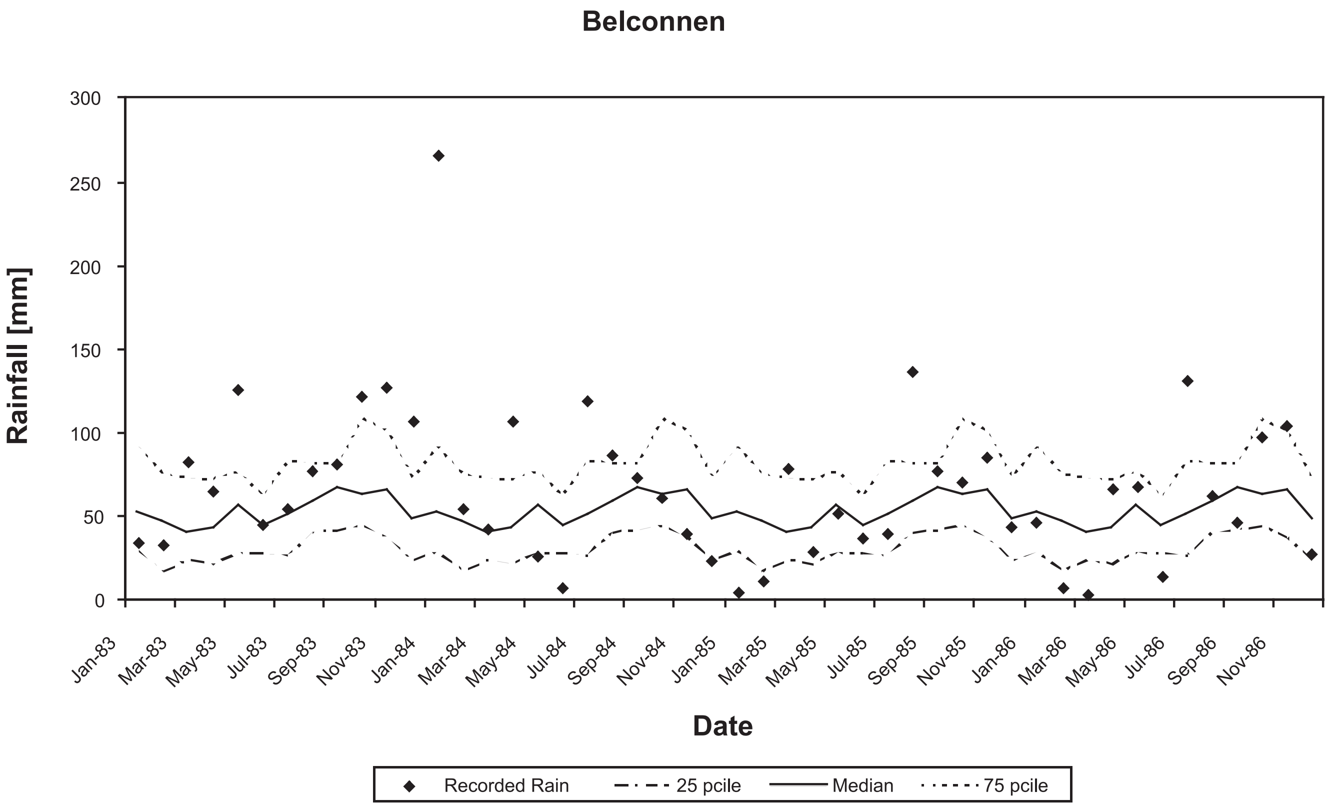
For each of the sites where a time series of soil moisture measurements was available the extractable soil moisture was estimated from the difference between the wettest and driest recorded profiles. This will only result in an accurate estimate if the measured wetted and driest profiles are close to the maximally wet and dry profiles that occur at this site.

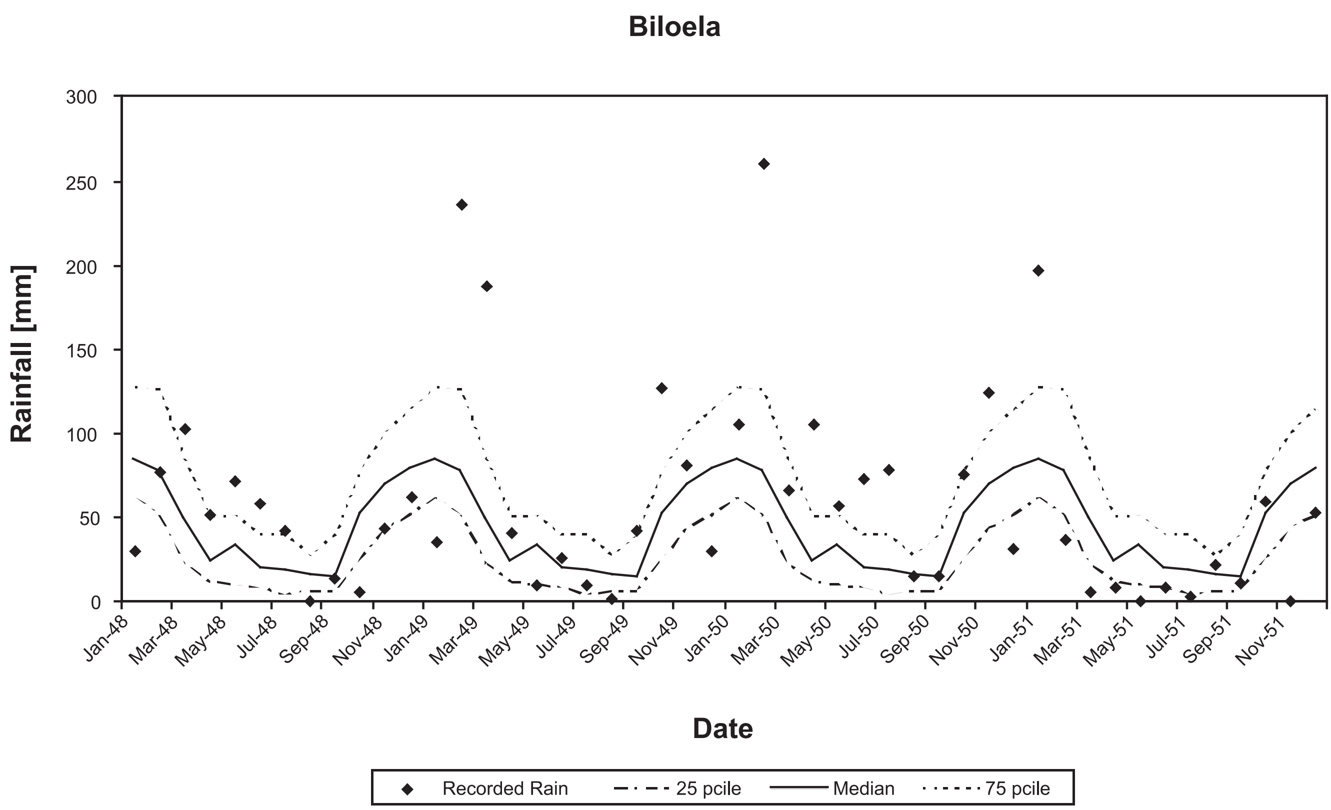
An indication of how extreme the wettest and driest profiles are likely to be can be determined from the monthly rainfall at the site in comparison with the long-term rainfall. In this appendix, the 25th, median and 75th percentile rainfalls are compared to rainfall recorded at the sites during the period the soil moisture was measured. The percentiles are based on monthly rainfall from 1940 to 1999. Sites are listed in alphabetical order based on the "Site Location" field in the database. Dates are based on the "Start/Stop" field (see Table 1). For further discussion of this analysis see Section 3.

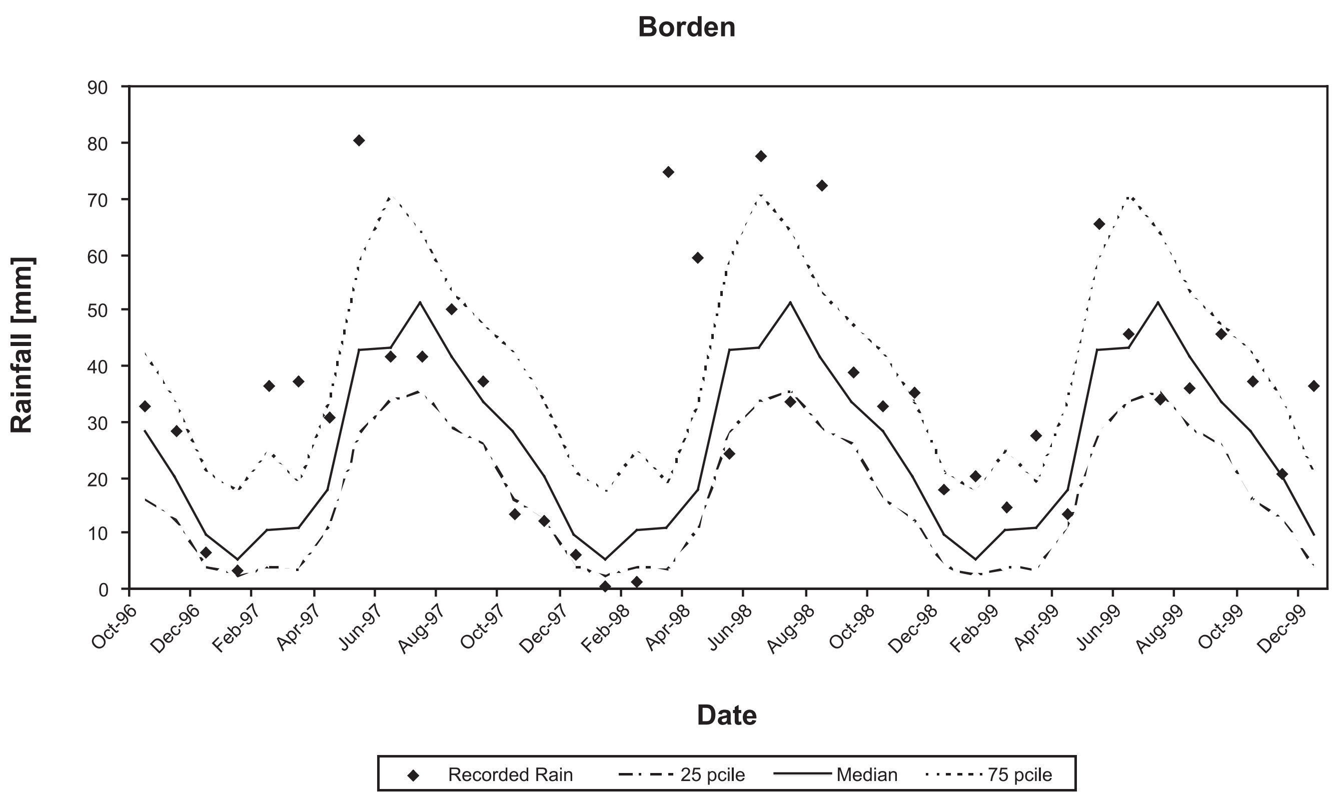


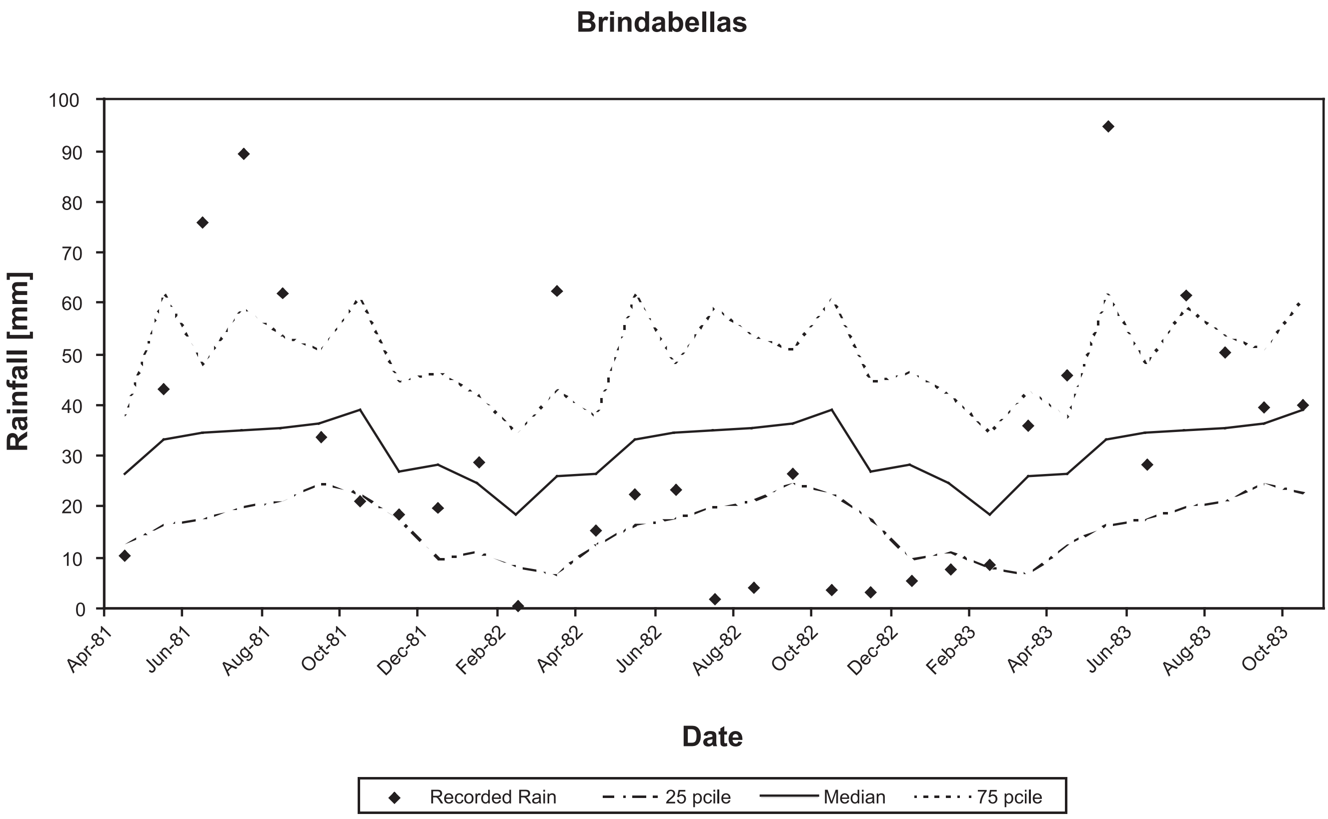


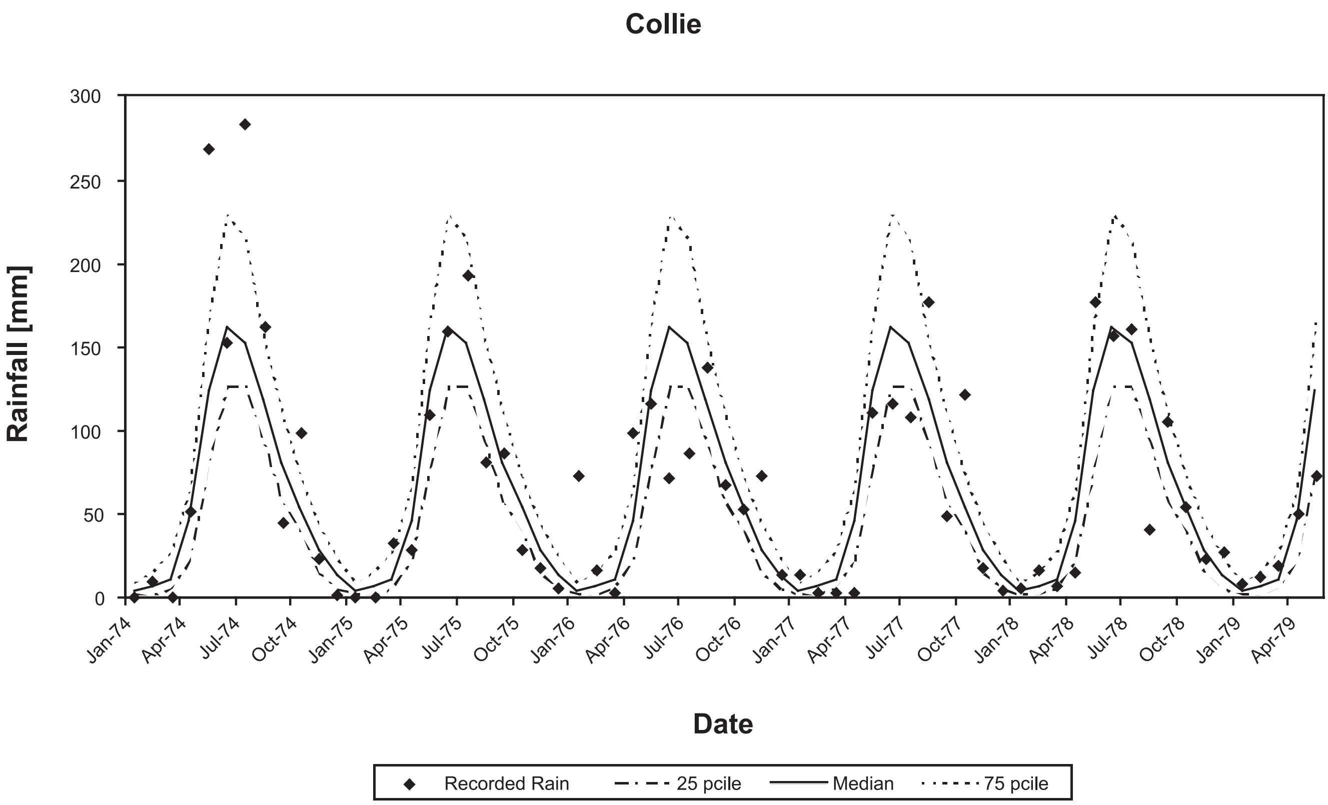

Ballarat
Rainfall [mm]
160
140
120
100
80
60
40
20
0
Jan-76
Feb-76
Mar-76
Apr-76
May-76
Jun-76
Jul-76
Aug-76
Sep-76
Oct-76
Nov-76
Dec-76
Jan-77
Feb-77
Mar-77
Apr-77
May-77
Jun-77
Jul-77
Aug-77
Sep-77
Oct-77
Nov-77
Dec-77
Date
Recorded Rain
25 pcile
Median
75 pcile

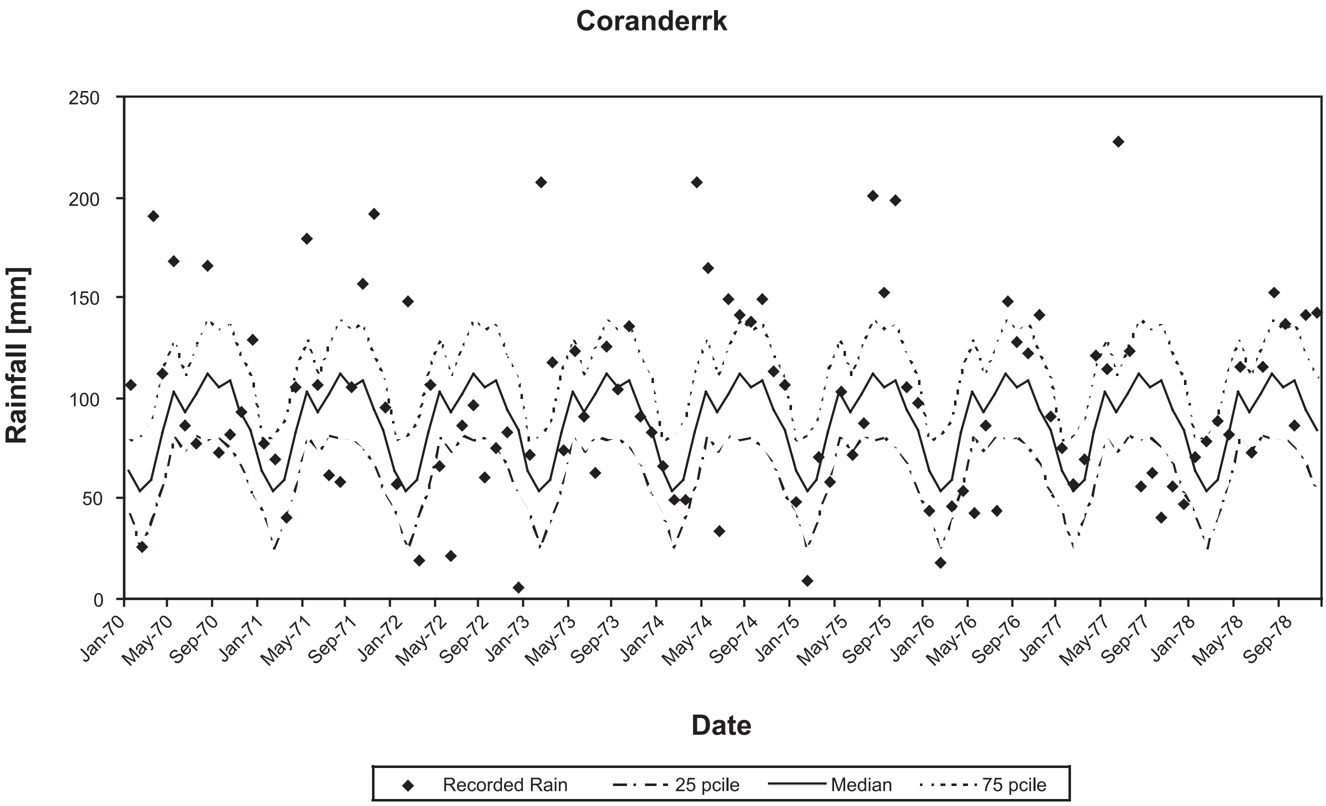

Belconnen
Rainfall [mm]
300
250
200
150
100
50
0
Jan-83
Mar-83
May-83
Jul-83
Sep-83
Nov-83
Jan-84
Mar-84
May-84
Jul-84
Sep-84
Nov-84
Jan-85
Mar-85
May-85
Jul-85
Sep-85
Nov-85
Jan-86
Mar-86
May-86
Jul-86
Sep-86
Nov-86
Date
Recorded Rain
25 pcile
Median
75 pcile

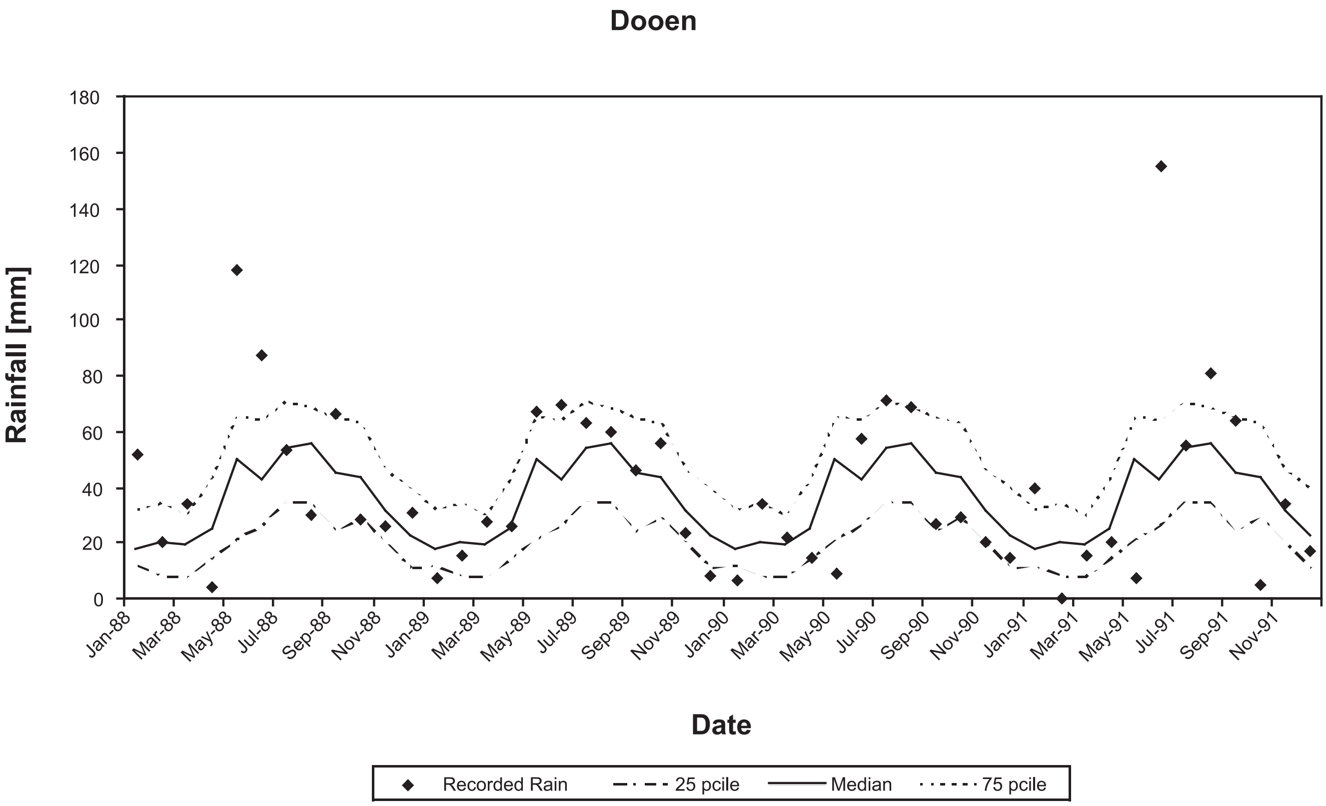

Biloela
300
250
200
150
100
50
0
Rainfall [mm]
Jan-48
Mar-48
May-48
Jul-48
Sep-48
Nov-48
Jan-49
Mar-49
May-49
Jul-49
Sep-49
Nov-49
Jan-50
Mar-50
May-50
Jul-50
Sep-50
Nov-50
Jan-51
Mar-51
May-51
Jul-51
Sep-51
Nov-51
Date
Recorded Rain
25 pcile
Median
75 pcile


Borden
90
80
70
60
50
40
30
20
10
0
Rainfall [mm]
Oct-96
Dec-96
Feb-97
Apr-97
Jun-97
Aug-97
Oct-97
Dec-97
Feb-98
Apr-98
Jun-98
Aug-98
Oct-98
Dec-98
Feb-99
Apr-99
Jun-99
Aug-99
Oct-99
Dec-99
Date
Recorded Rain
25 pcile
Median
75 pcile

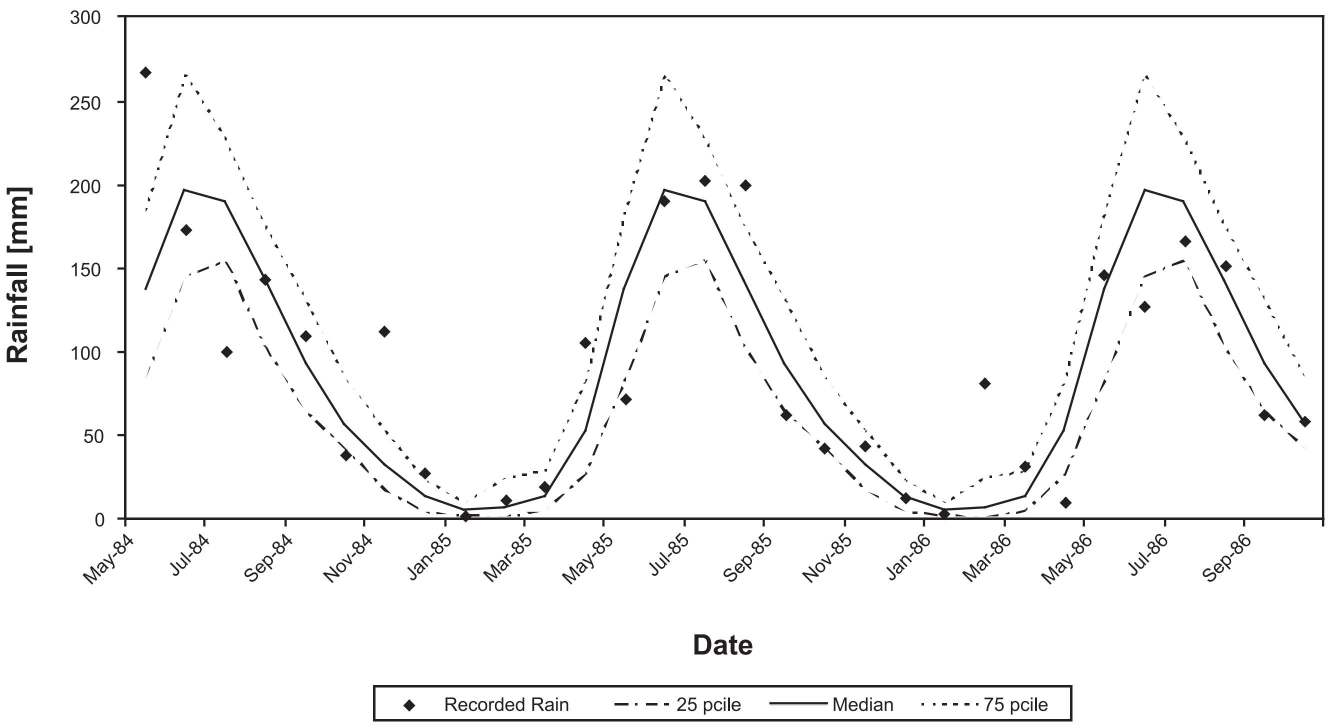

Brindabellas
Rainfall [mm]
100
90
80
70
60
50
40
30
20
10
0
Apr-81
Jun-81
Aug-81
Oct-81
Dec-81
Feb-82
Apr-82
Jun-82
Aug-82
Oct-82
Dec-82
Feb-83
Apr-83
Jun-83
Aug-83
Oct-83
Date
Recorded Rain
25 pcile
Median
75 pcile


Collie
Rainfall [mm]
300
250
200
150
100
50
0
Jan-74
Apr-74
Jul-74
Oct-74
Jan-75
Apr-75
Jul-75
Oct-75
Jan-76
Apr-76
Jul-76
Oct-76
Jan-77
Apr-77
Jul-77
Oct-77
Jan-78
Apr-78
Jul-78
Oct-78
Jan-79
Apr-79
Date
Recorded Rain
25 pcile
Median
75 pcile

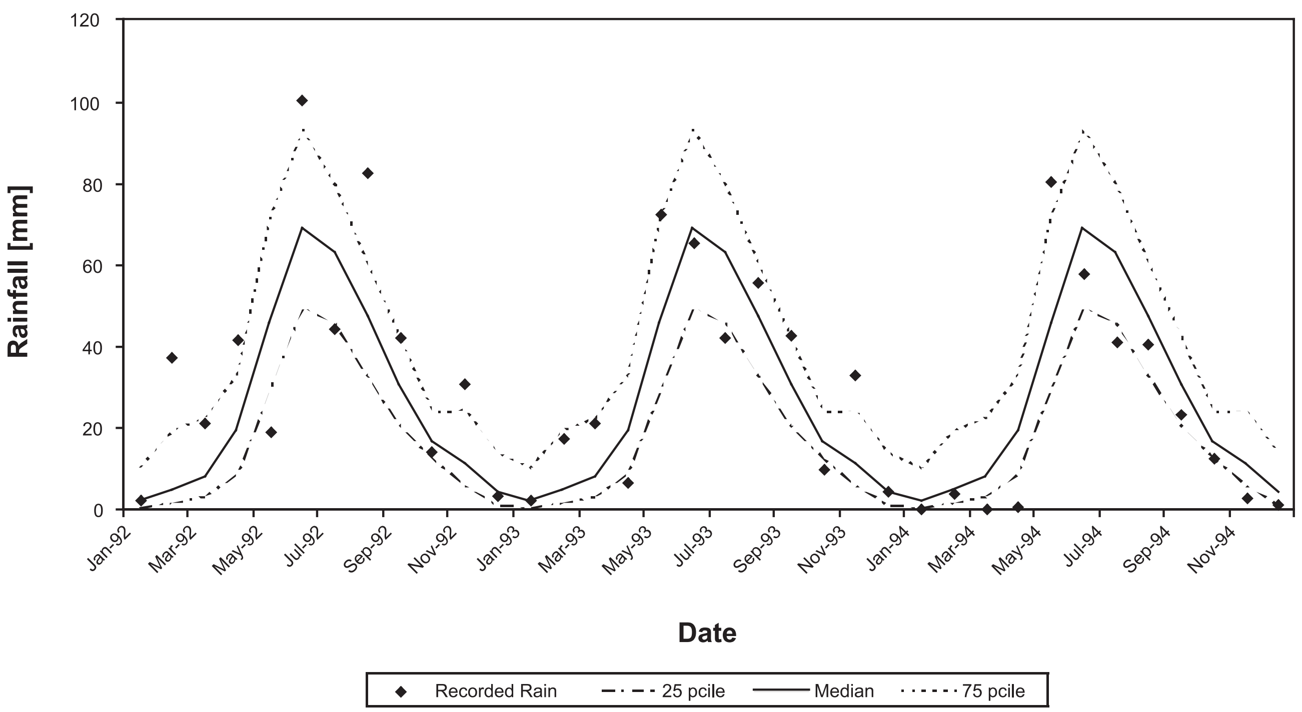

Coranderrk
Rainfall [mm]
0
50
100
150
200
250
Jan-70
May-70
Sep-70
Jan-71
May-71
Sep-71
Jan-72
May-72
Sep-72
Jan-73
May-73
Sep-73
Jan-74
May-74
Sep-74
Jan-75
May-75
Sep-75
Jan-76
May-76
Sep-76
Jan-77
May-77
Sep-77
Jan-78
May-78
Sep-78
Date
Recorded Rain
25 pcile
Median
75 pcile

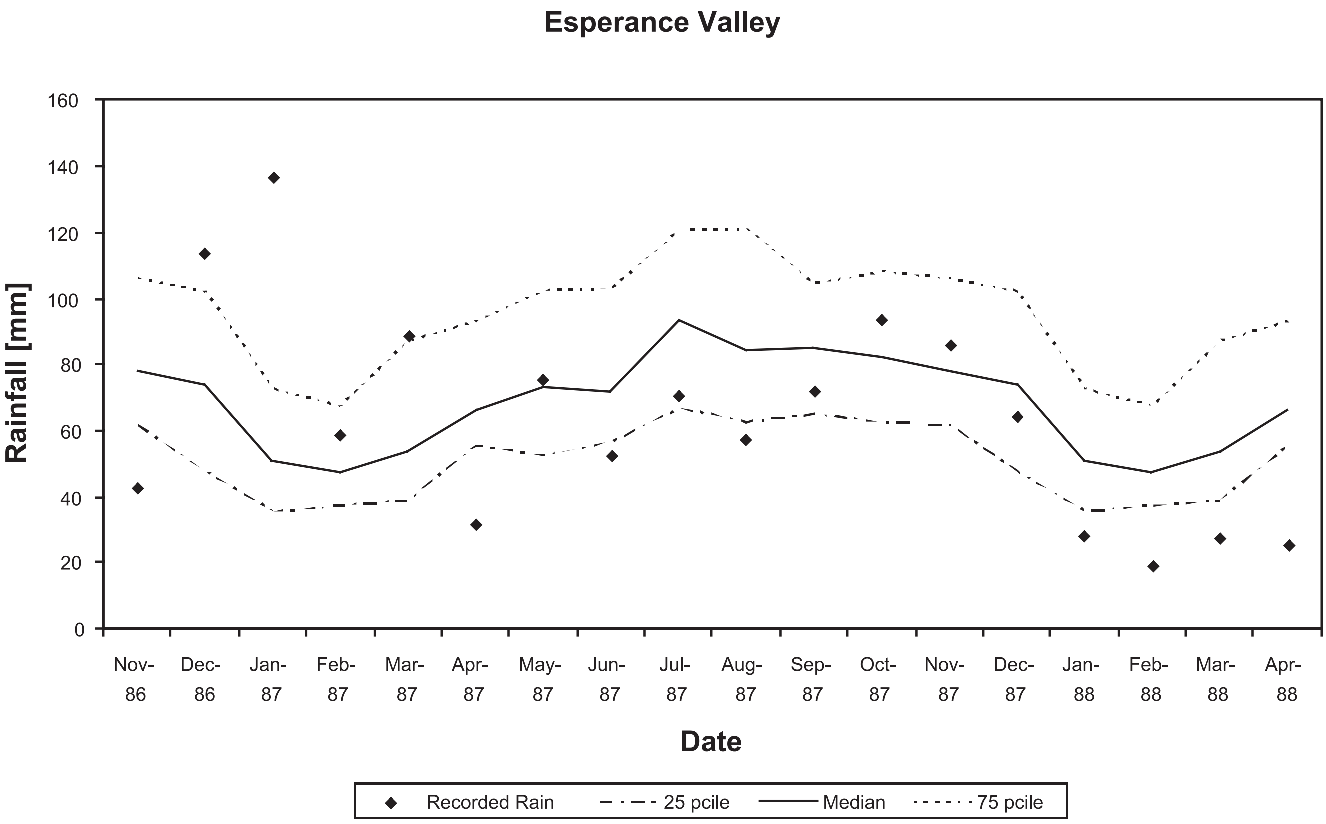

Dooen
Rainfall [mm]
0
20
40
60
80
100
120
140
160
180
Jan-88
Mar-88
May-88
Jul-88
Sep-88
Nov-88
Jan-89
Mar-89
May-89
Jul-89
Sep-89
Nov-89
Jan-90
Mar-90
May-90
Jul-90
Sep-90
Nov-90
Jan-91
Mar-91
May-91
Jul-91
Sep-91
Nov-91
Date
Recorded Rain
25 pcile
Median
75 pcile

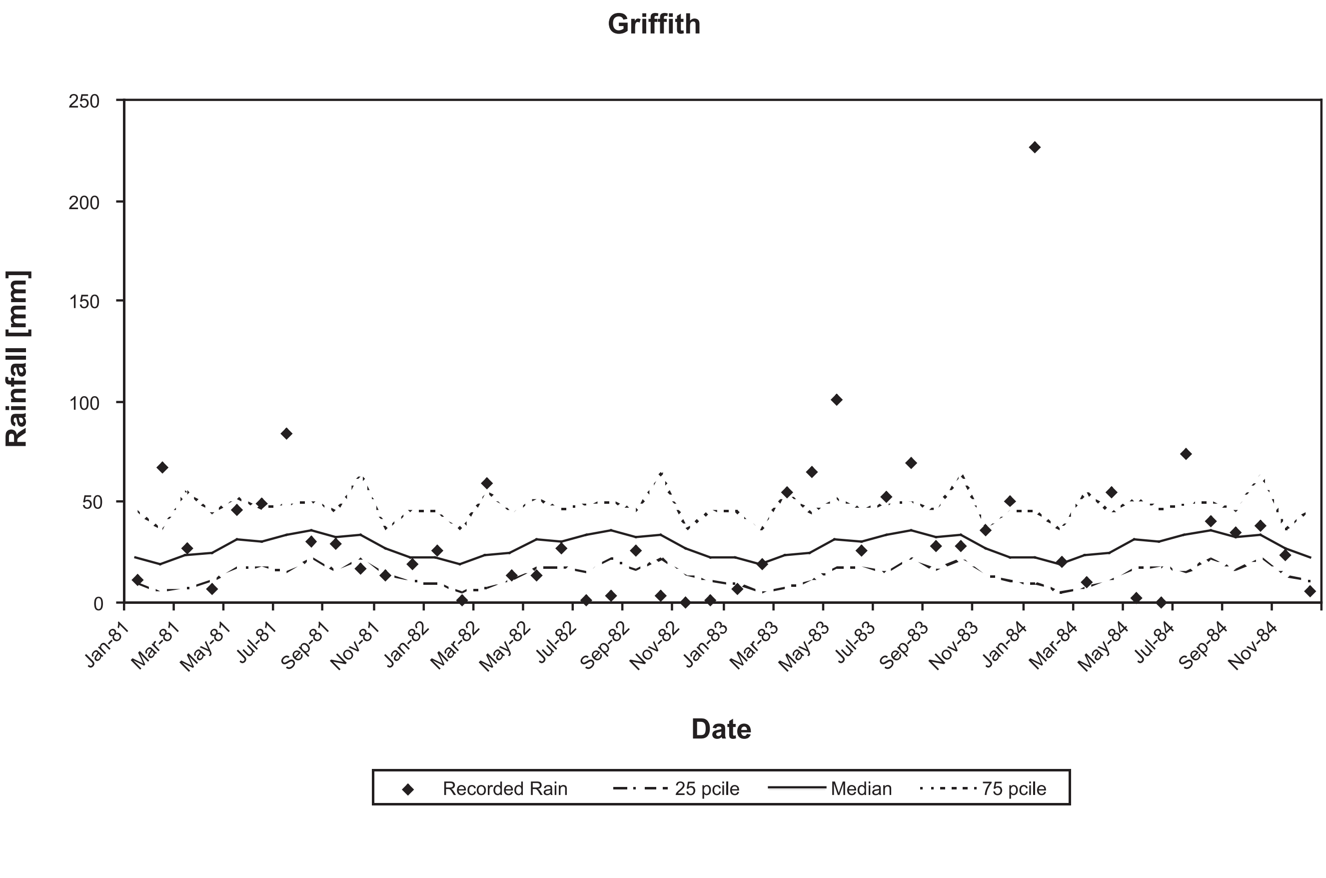
Dwellingup (upslope)

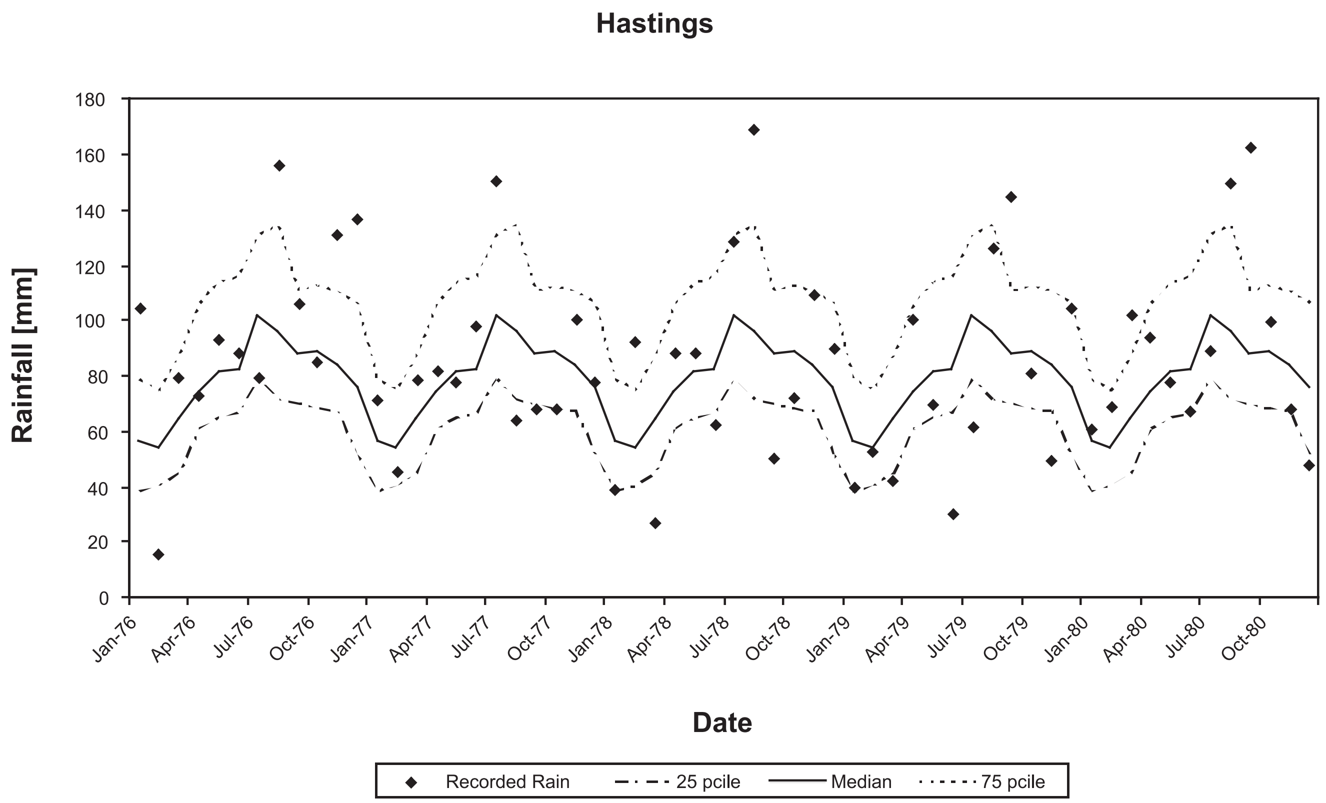


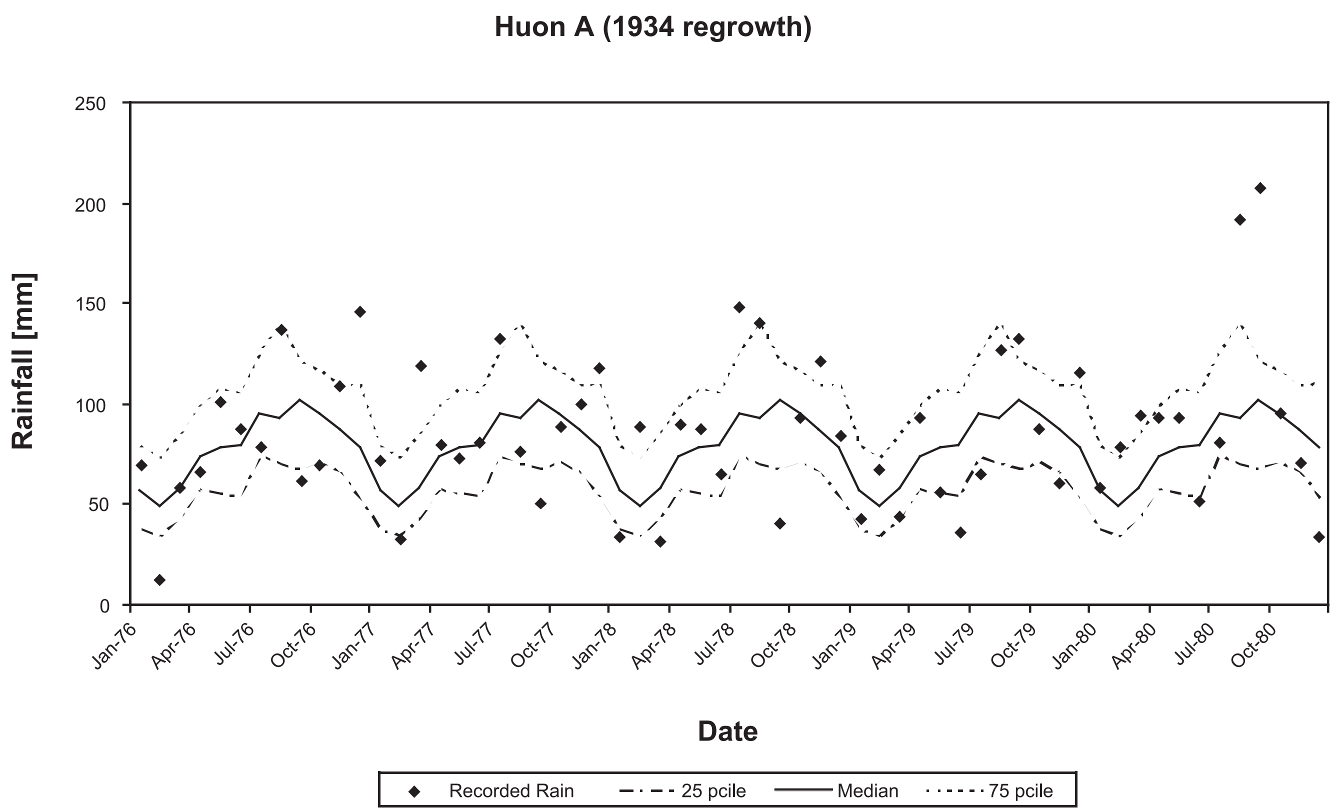
East Beverly

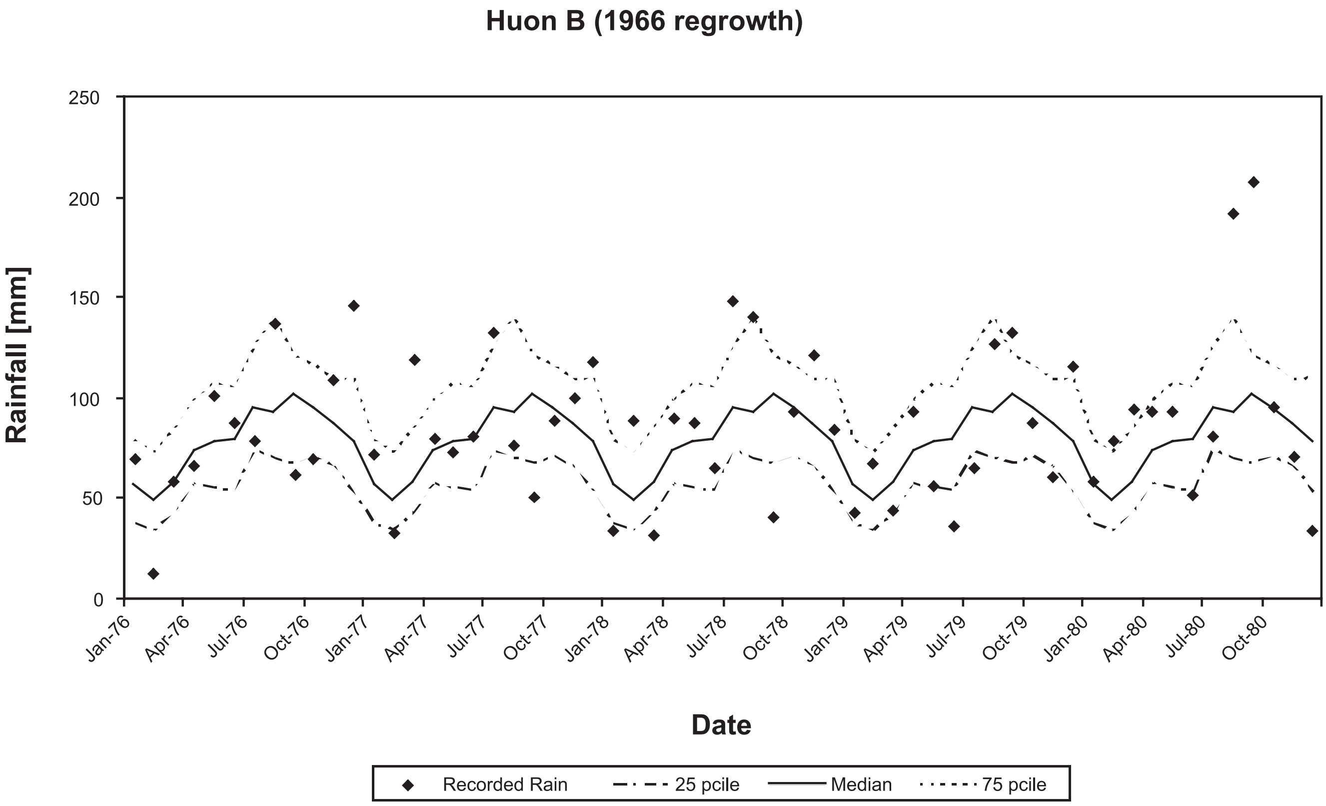


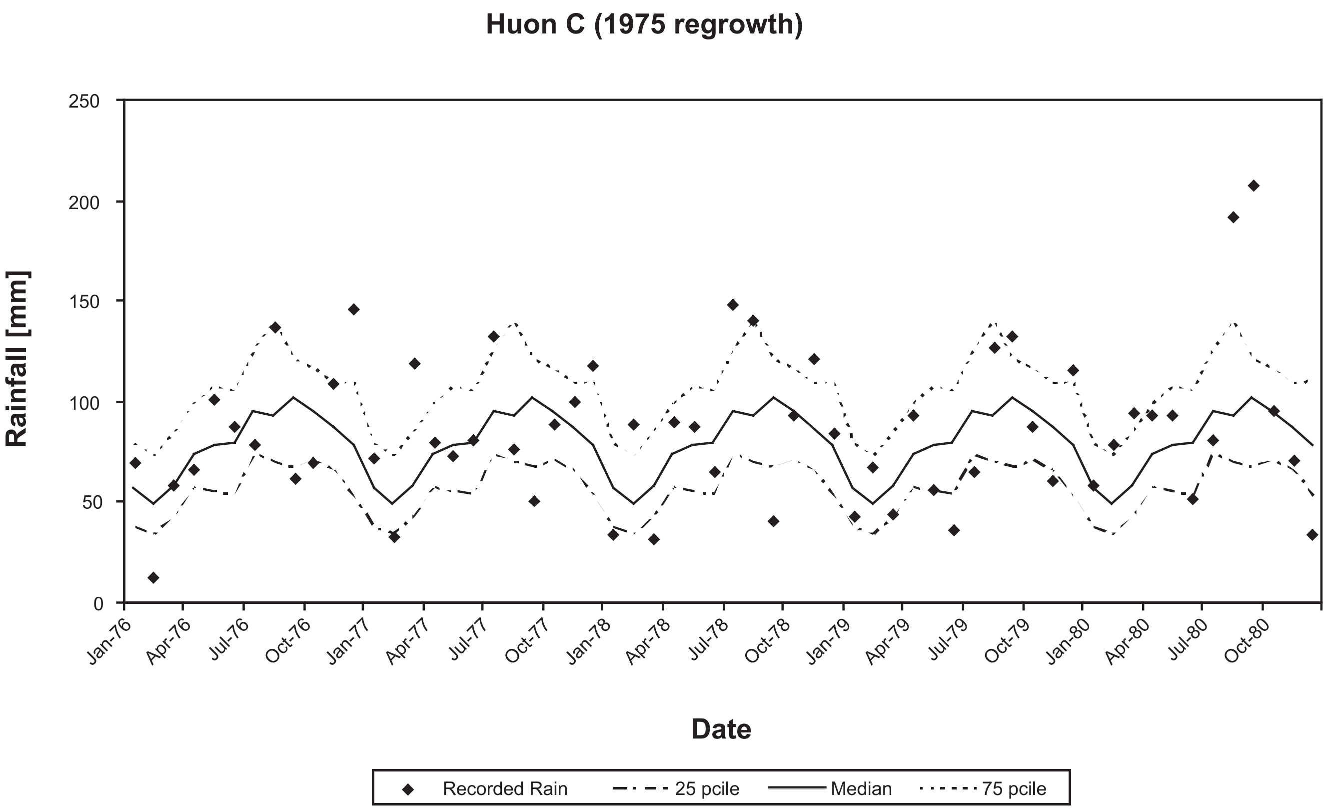

Esperance Valley
Rainfall [mm]
160
140
120
100
80
60
40
20
0
Nov-86
Dec-86
Jan-87
Feb-87
Mar-87
Apr-87
May-87
Jun-87
Jul-87
Aug-87
Sep-87
Oct-87
Nov-87
Dec-87
Jan-88
Feb-88
Mar-88
Apr-88
Date
Recorded Rain
25 pcile
Median
75 pcile

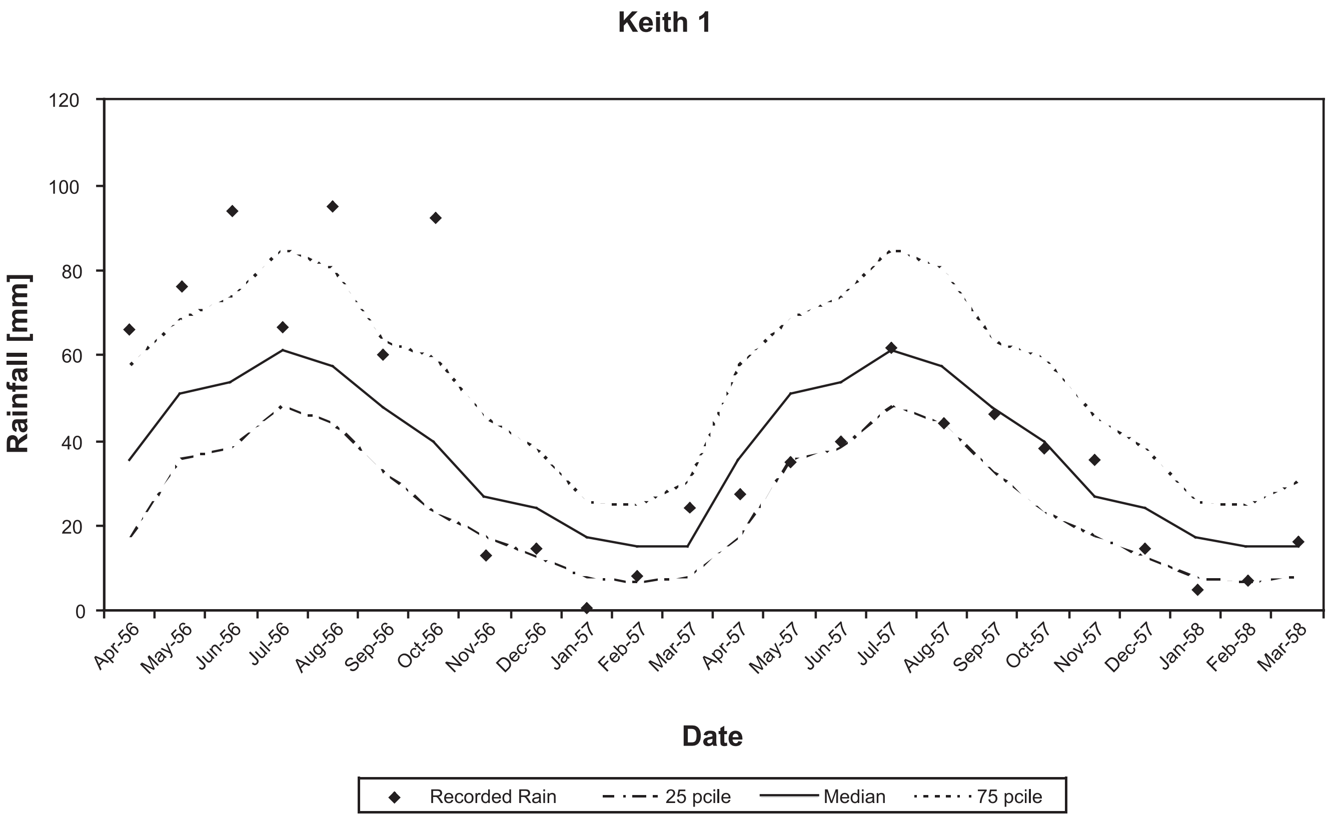

Griffith
Rainfall [mm]
250
200
150
100
50
0
Jan-81
Mar-81
May-81
Jul-81
Sep-81
Nov-81
Jan-82
Mar-82
May-82
Jul-82
Sep-82
Nov-82
Jan-83
Mar-83
May-83
Jul-83
Sep-83
Nov-83
Jan-84
Mar-84
May-84
Jul-84
Sep-84
Nov-84
Date
Recorded Rain
25 pcile
Median
75 pcile

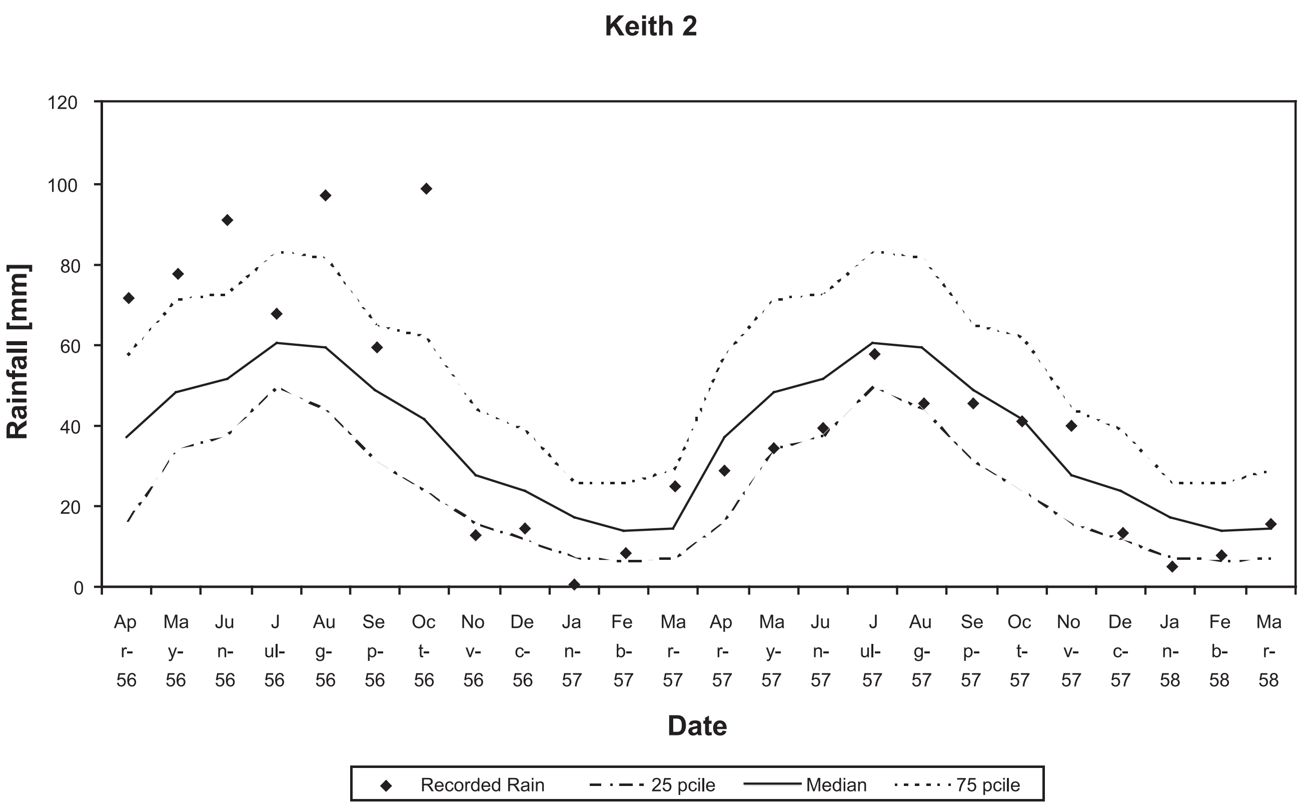

Hastings
180
160
140
120
100
80
60
40
20
0
Rainfall [mm]
Jan-76
Apr-76
Jul-76
Oct-76
Jan-77
Apr-77
Jul-77
Oct-77
Jan-78
Apr-78
Jul-78
Oct-78
Jan-79
Apr-79
Jul-79
Oct-79
Jan-80
Apr-80
Jul-80
Oct-80
Date
Recorded Rain
25 pcile
Median
75 pcile

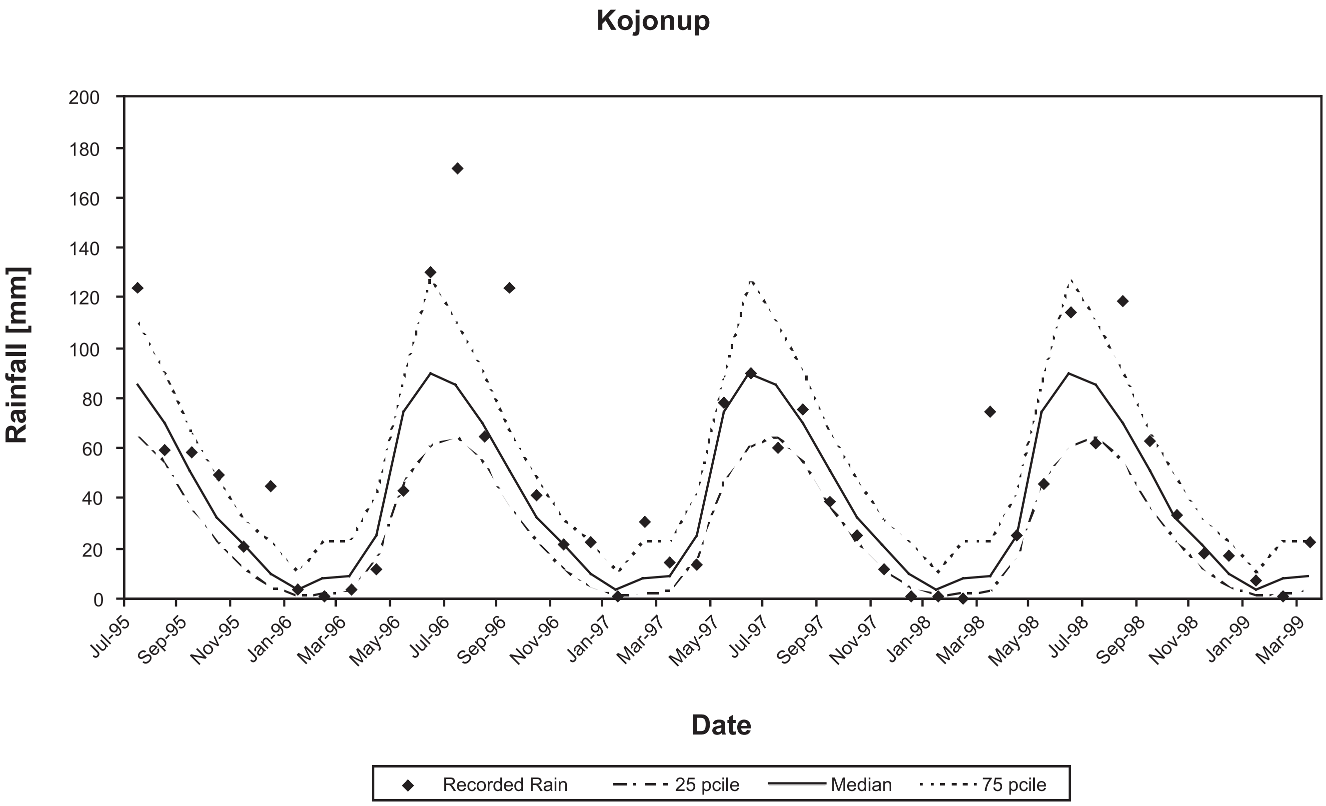

Huon A (1934 regrowth)
250
200
150
100
50
0
Rainfall [mm]
Jan-76
Apr-76
Jul-76
Oct-76
Jan-77
Apr-77
Jul-77
Oct-77
Jan-78
Apr-78
Jul-78
Oct-78
Jan-79
Apr-79
Jul-79
Oct-79
Jan-80
Apr-80
Jul-80
Oct-80
Date
Recorded Rain
25 pcile
Median
75 pcile

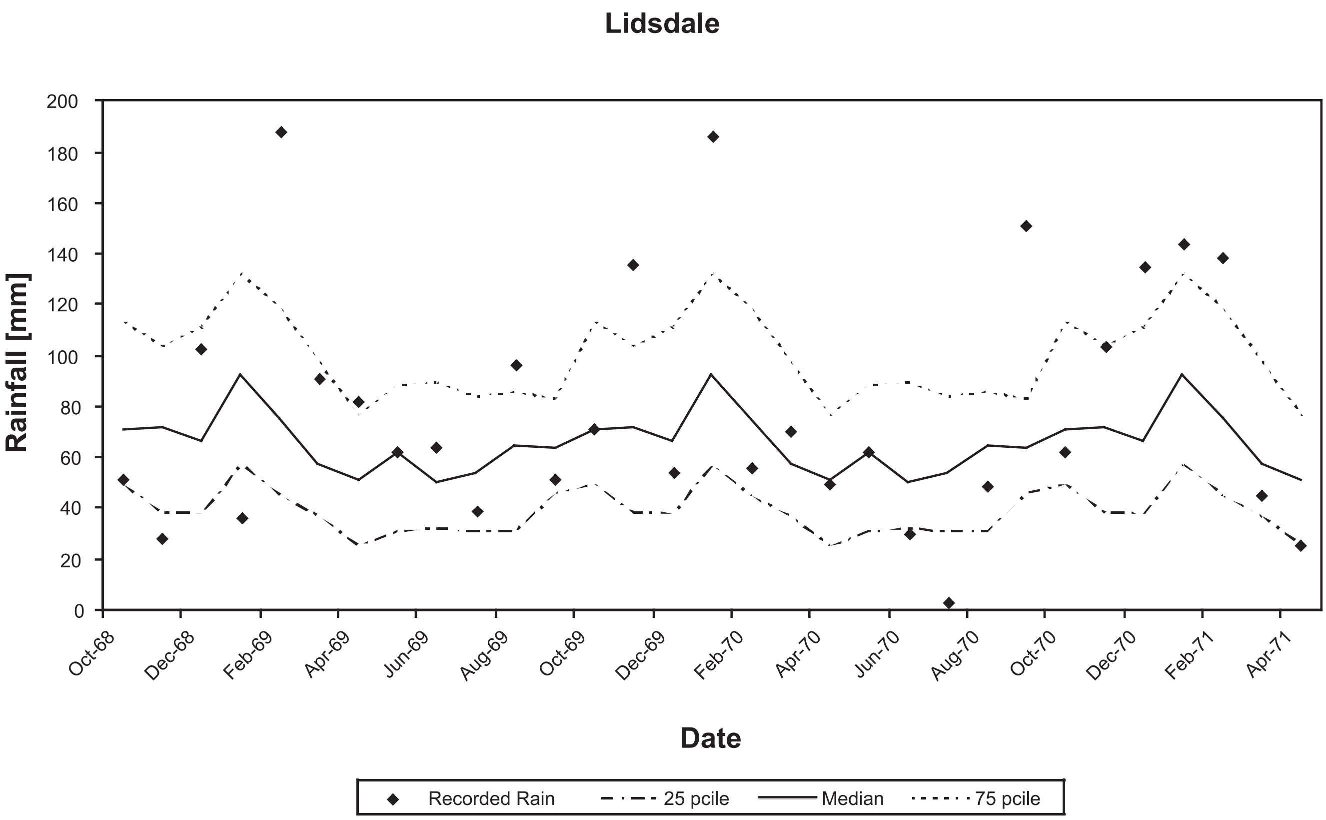

Huon B (1966 regrowth)
Rainfall [mm]
250
200
150
100
50
0
Jan-76
Apr-76
Jul-76
Oct-76
Jan-77
Apr-77
Jul-77
Oct-77
Jan-78
Apr-78
Jul-78
Oct-78
Jan-79
Apr-79
Jul-79
Oct-79
Jan-80
Apr-80
Jul-80
Oct-80
Date
Recorded Rain
25 pcile
Median
75 pcile

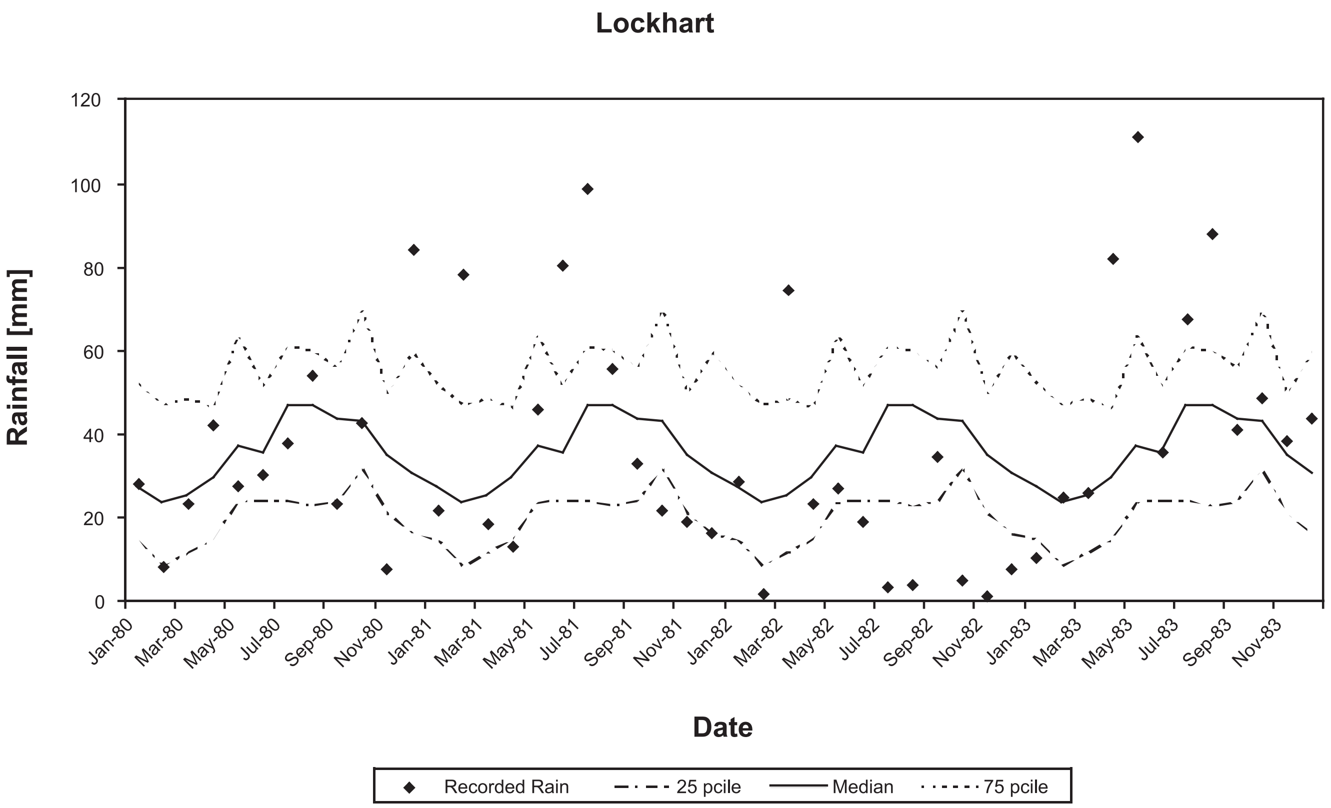

Huon C (1975 regrowth)
Rainfall [mm]
250
200
150
100
50
0
Jan-76
Apr-76
Jul-76
Oct-76
Jan-77
Apr-77
Jul-77
Oct-77
Jan-78
Apr-78
Jul-78
Oct-78
Jan-79
Apr-79
Jul-79
Oct-79
Jan-80
Apr-80
Jul-80
Oct-80
Date
Recorded Rain
25 pcile
Median
75 pcile

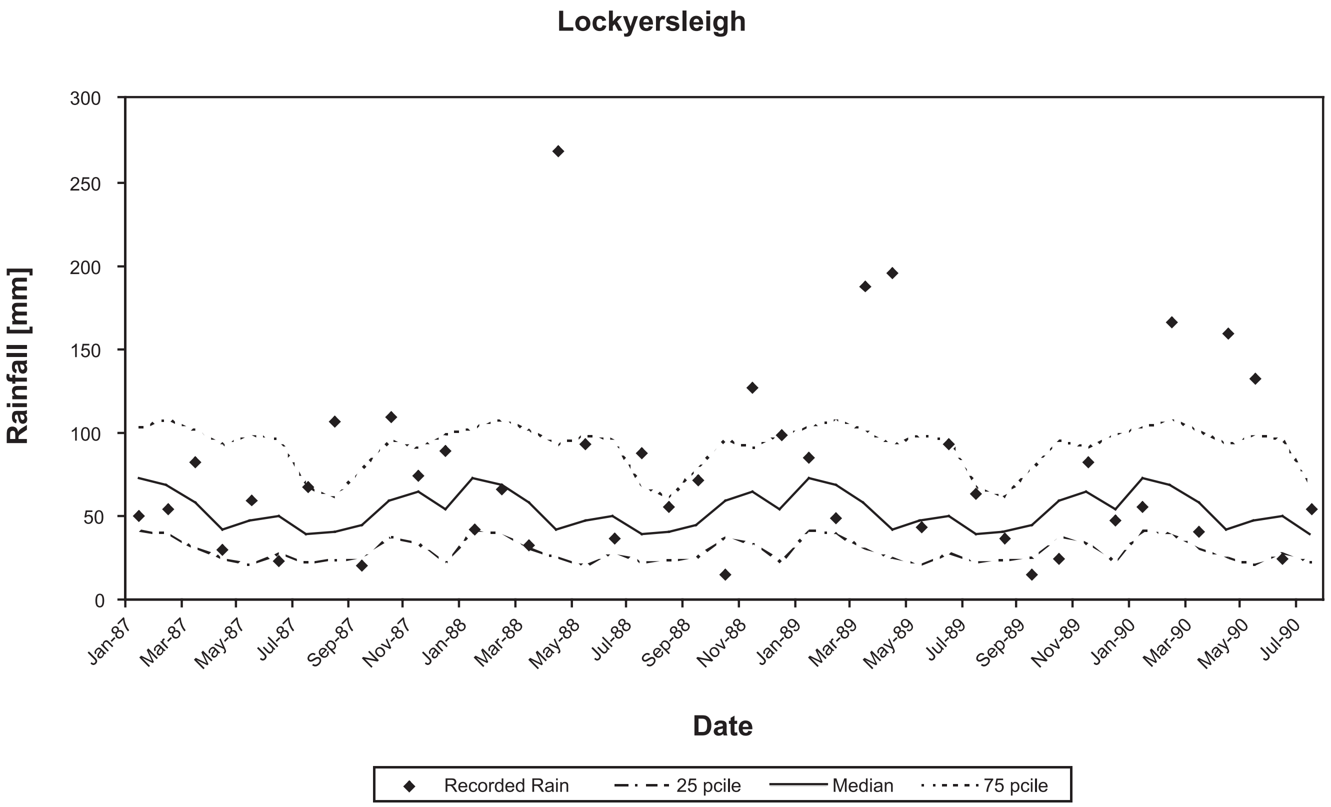

Keith 1
120
100
80
60
40
20
0
Rainfall [mm]
Apr-56 May-56 Jun-56 Jul-56 Aug-56 Sep-56 Oct-56 Nov-56 Dec-56 Jan-57 Feb-57 Mar-57 Apr-57 May-57 Jun-57 Jul-57 Aug-57 Sep-57 Oct-57 Nov-57 Dec-57 Jan-58 Feb-58 Mar-58
Date
Recorded Rain
25 pcile
Median
75 pcile

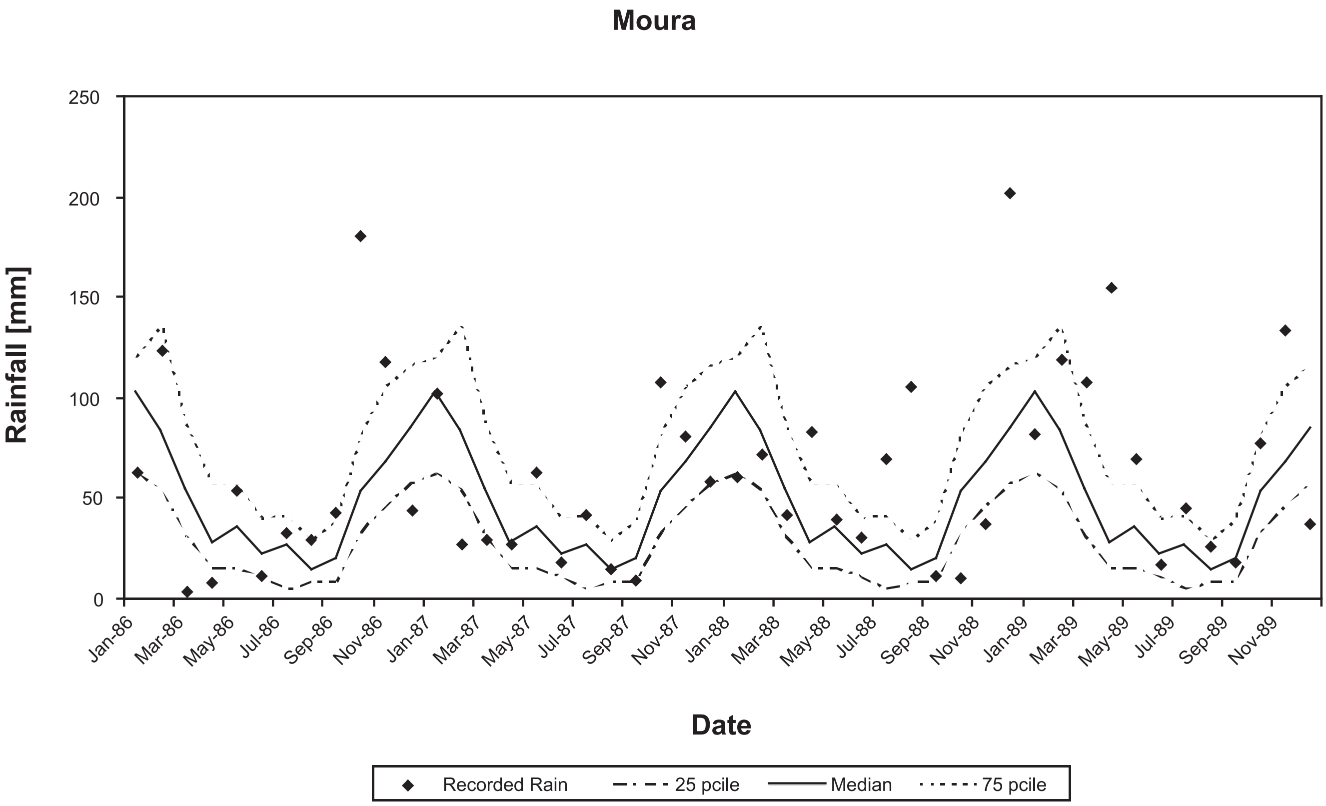

Keith 2
120
100
80
60
40
20
0
Rainfall [mm]
Apr-56 May-56 Jun-56 Jul-56 Aug-56 Sep-56 Oct-56 Nov-56 Dec-56 Jan-57 Feb-57 Mar-57 Apr-57 May-57 Jun-57 Jul-57 Aug-57 Sep-57 Oct-57 Nov-57 Dec-57 Jan-58 Feb-58 Mar-58
Date
Recorded Rain
25 pcile
Median
75 pcile

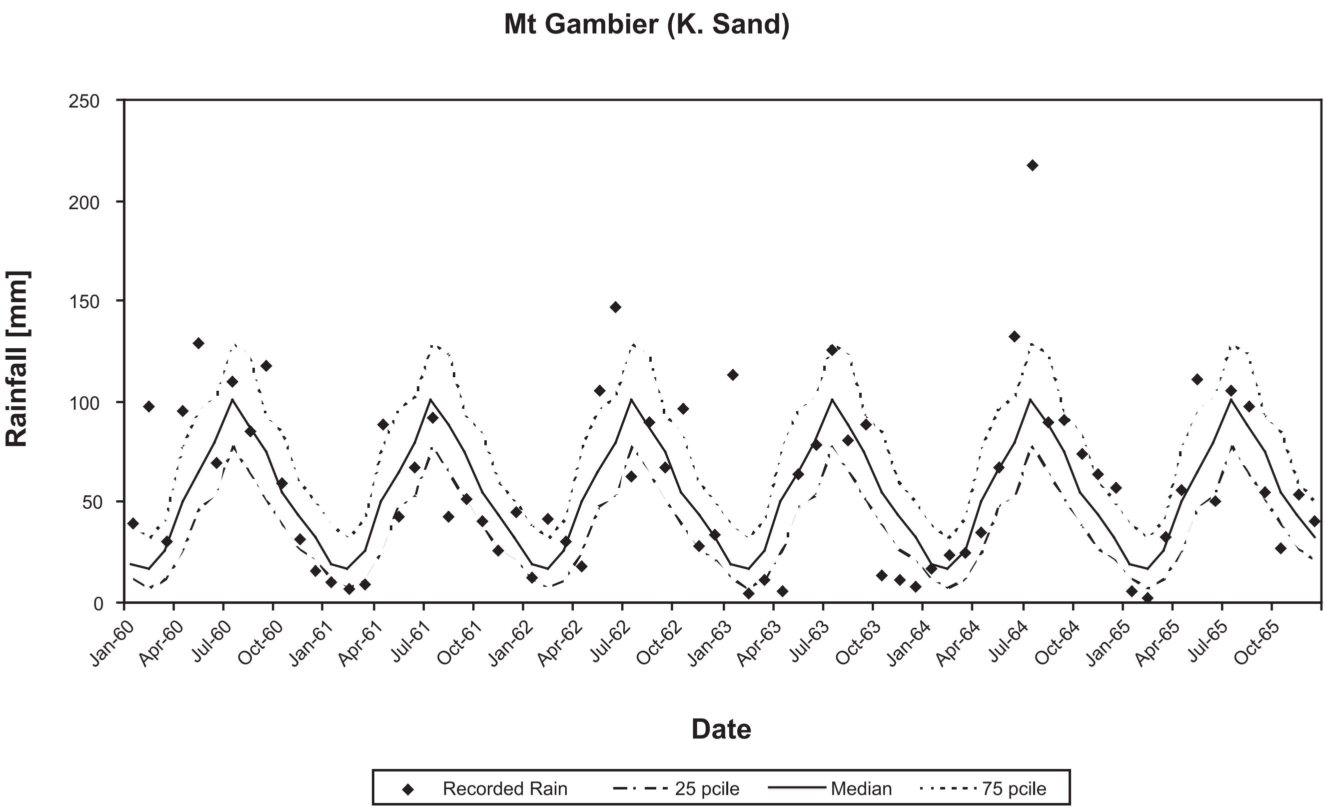

Kojonup
200
180
160
140
120
100
80
60
40
20
0
Rainfall [mm]
Jul-95
Sep-95
Nov-95
Jan-96
Mar-96
May-96
Jul-96
Sep-96
Nov-96
Jan-97
Mar-97
May-97
Jul-97
Sep-97
Nov-97
Jan-98
Mar-98
May-98
Jul-98
Sep-98
Nov-98
Jan-99
Mar-99
Date
Recorded Rain
25 pcile
Median
75 pcile

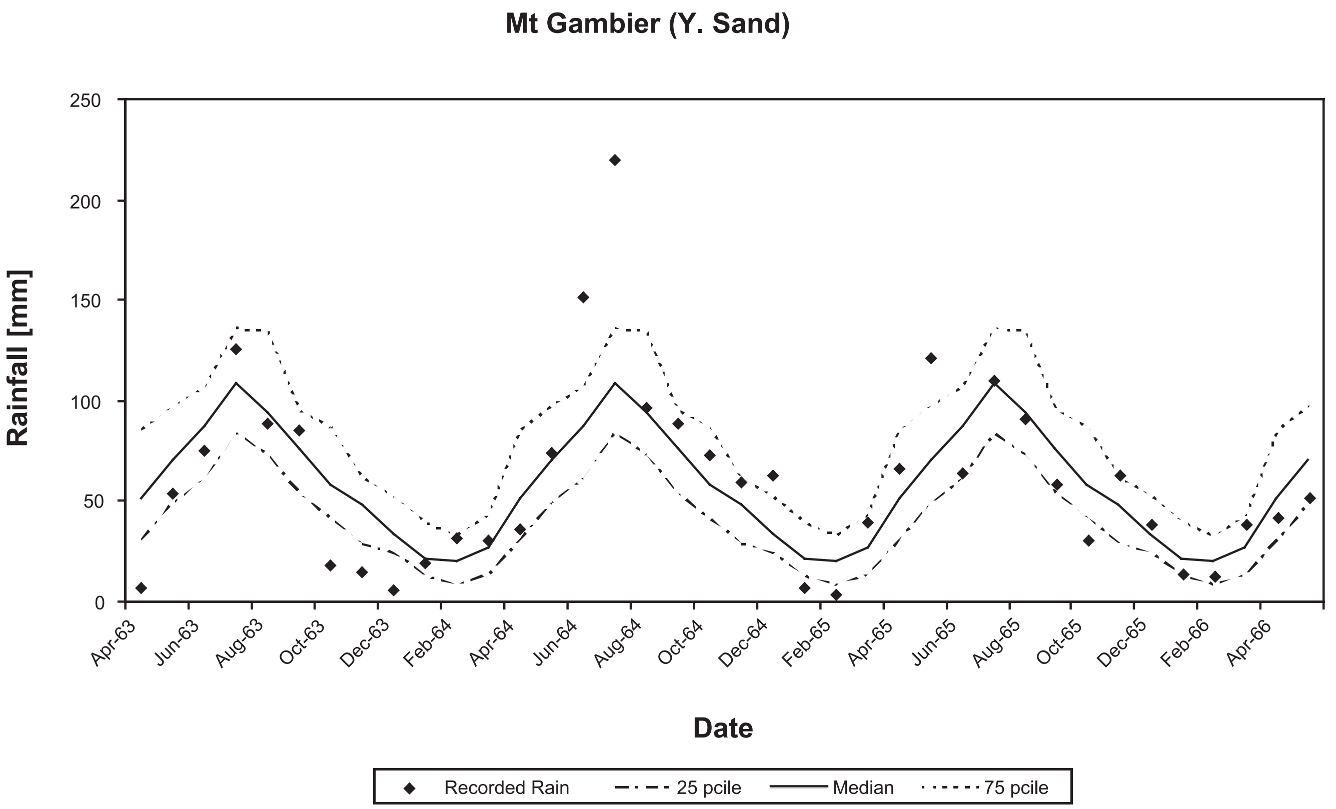

Lidsdale
200
180
160
140
120
100
80
60
40
20
0
Rainfall [mm]
Oct-68
Dec-68
Feb-69
Apr-69
Jun-69
Aug-69
Oct-69
Dec-69
Feb-70
Apr-70
Jun-70
Aug-70
Oct-70
Dec-70
Feb-71
Apr-71
Date
Recorded Rain
25 pcile
Median
75 pcile

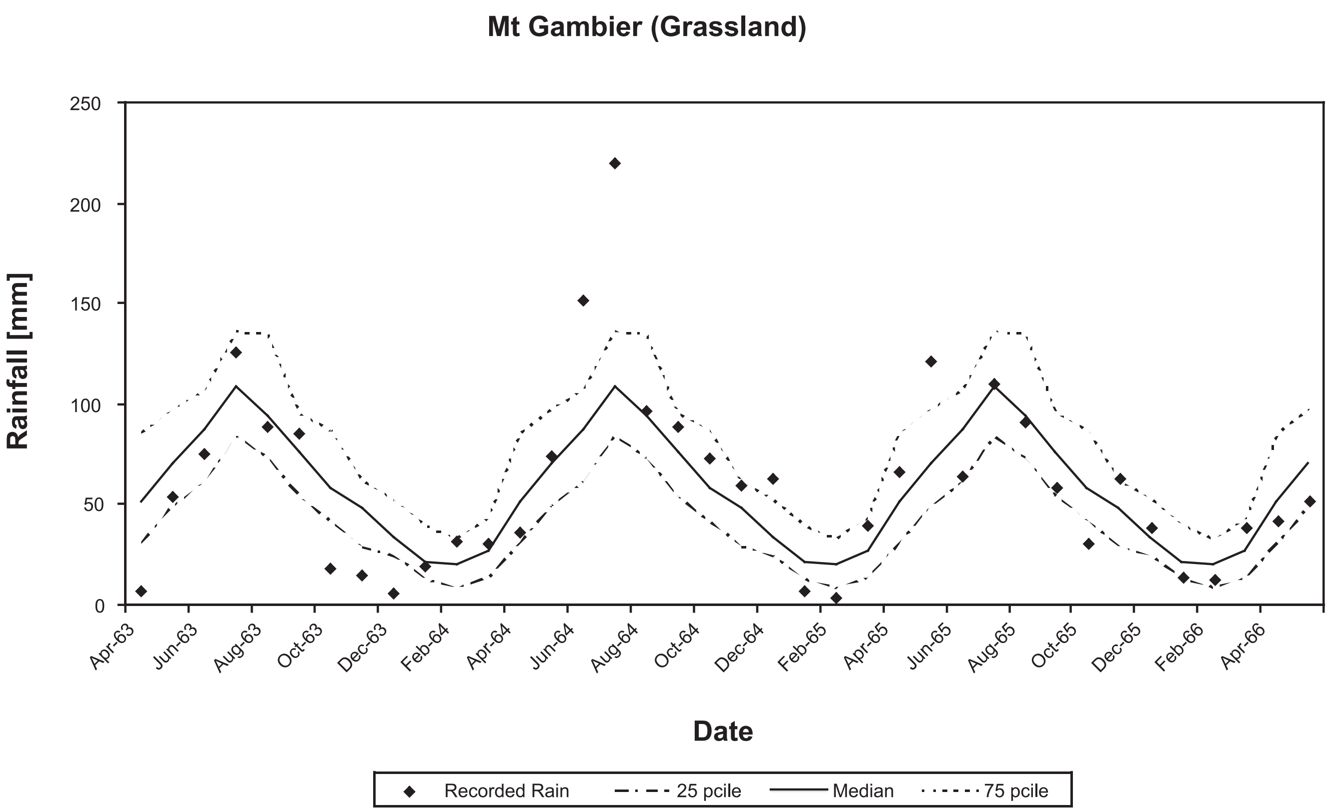

Lockhart
Rainfall [mm]
0
20
40
60
80
100
120
Jan-80
Mar-80
May-80
Jul-80
Sep-80
Nov-80
Jan-81
Mar-81
May-81
Jul-81
Sep-81
Nov-81
Jan-82
Mar-82
May-82
Jul-82
Sep-82
Nov-82
Jan-83
Mar-83
May-83
Jul-83
Sep-83
Nov-83
Date
Recorded Rain
25 pcile
Median
75 pcile

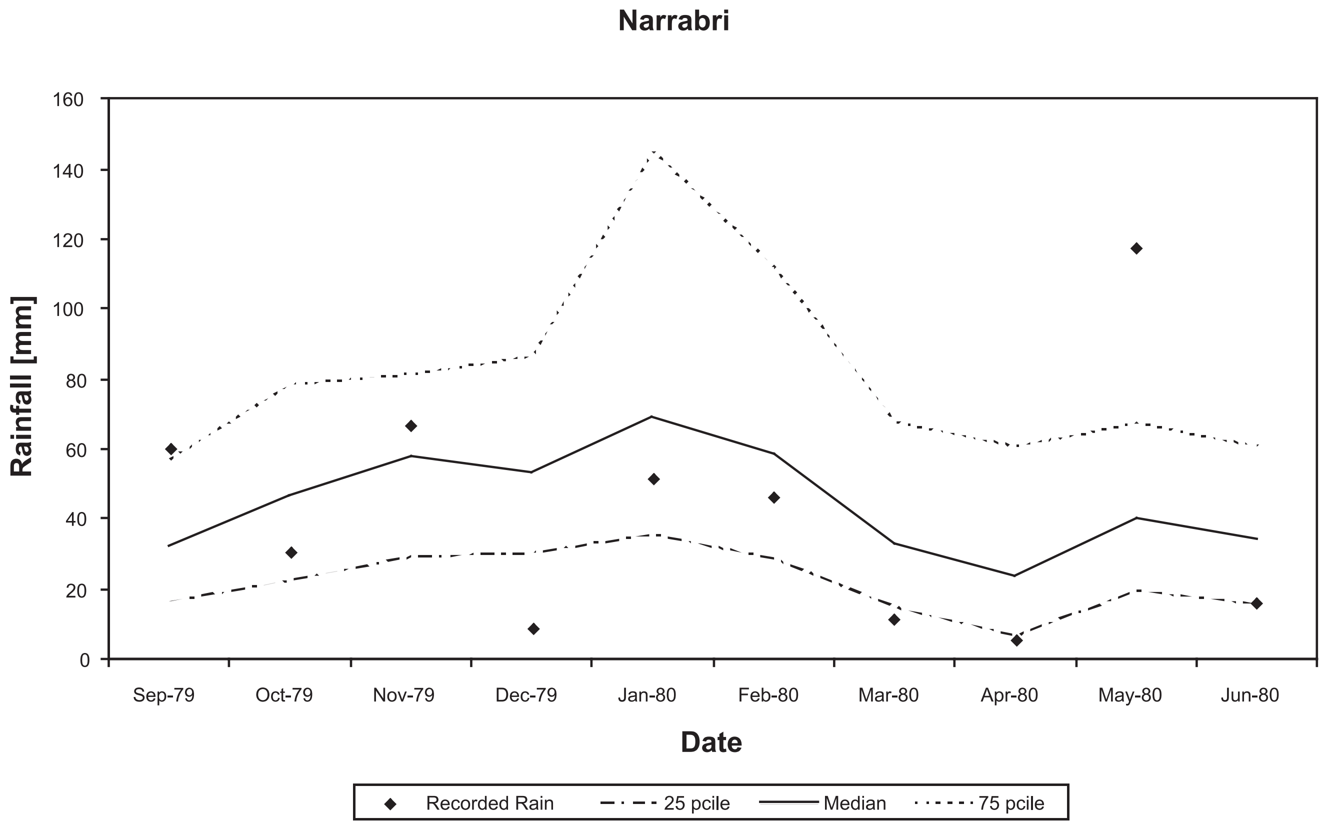

Lockyersleigh
Rainfall [mm]
0
50
100
150
200
250
300
Jan-87
Mar-87
May-87
Jul-87
Sep-87
Nov-87
Jan-88
Mar-88
May-88
Jul-88
Sep-88
Nov-88
Jan-89
Mar-89
May-89
Jul-89
Sep-89
Nov-89
Jan-90
Mar-90
May-90
Jul-90
Date
Recorded Rain
25 pcile
Median
75 pcile

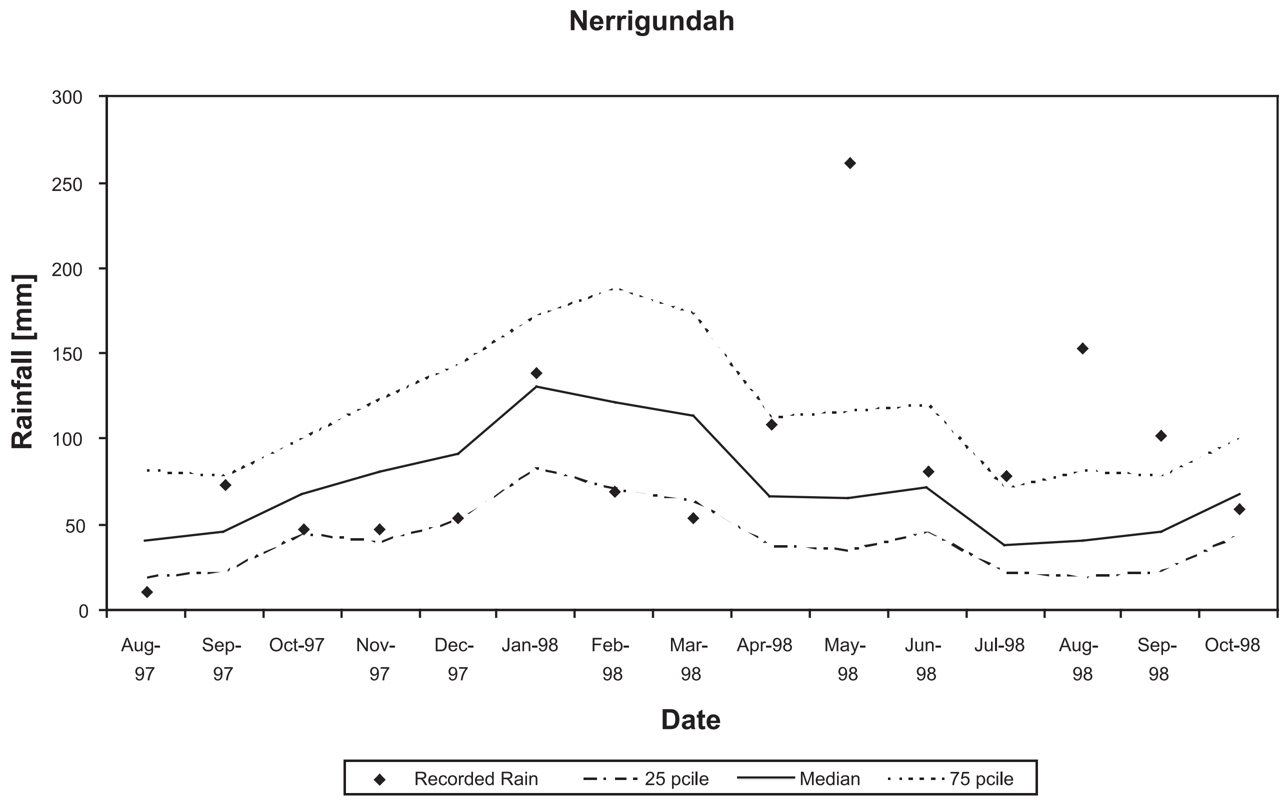

Moura
250
200
150
100
50
0
Rainfall [mm]
Jan-86
Mar-86
May-86
Jul-86
Sep-86
Nov-86
Jan-87
Mar-87
May-87
Jul-87
Sep-87
Nov-87
Jan-88
Mar-88
May-88
Jul-88
Sep-88
Nov-88
Jan-89
Mar-89
May-89
Jul-89
Sep-89
Nov-89
Date
Recorded Rain
25 pcile
Median
75 pcile

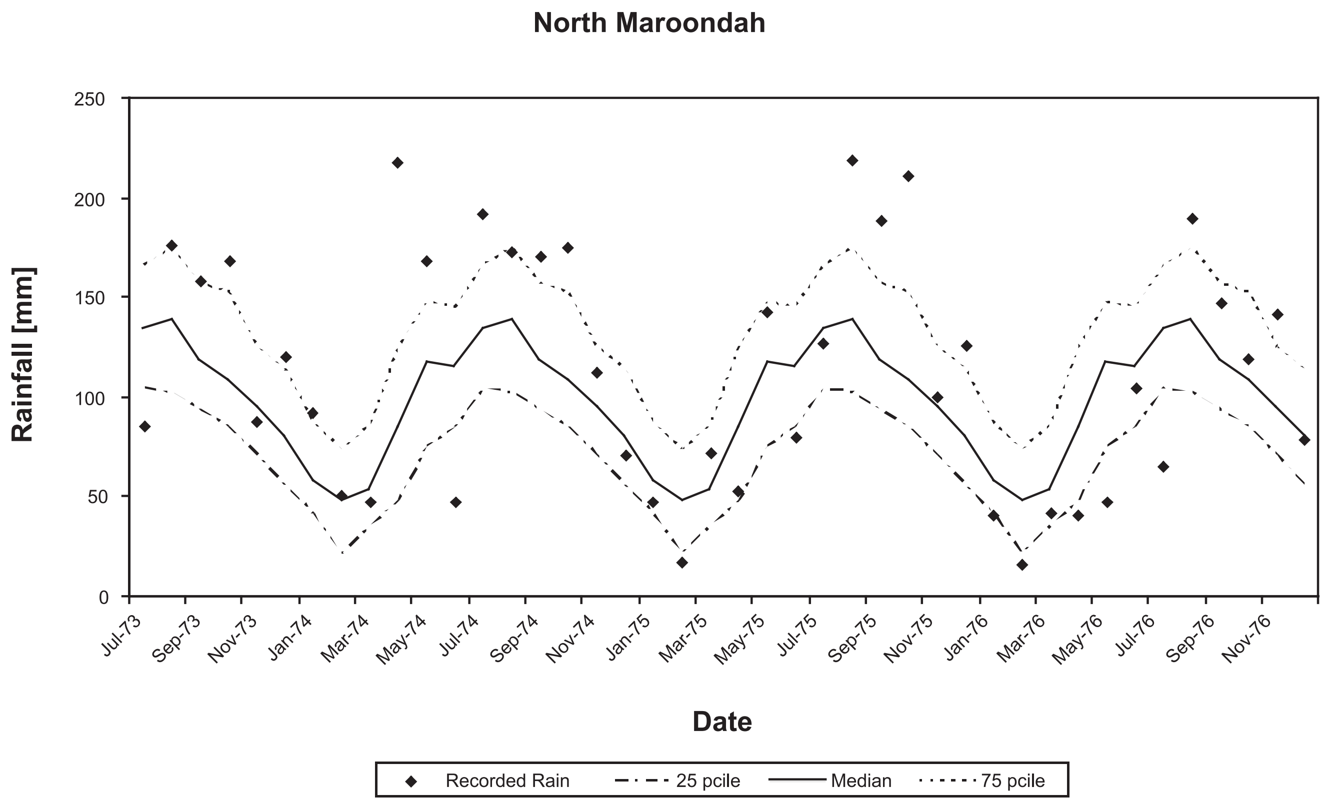

Mt Gambier (K. Sand)
250
200
150
100
50
0
Rainfall [mm]
Jan-60
Apr-60
Jul-60
Oct-60
Jan-61
Apr-61
Jul-61
Oct-61
Jan-62
Apr-62
Jul-62
Oct-62
Jan-63
Apr-63
Jul-63
Oct-63
Jan-64
Apr-64
Jul-64
Oct-64
Jan-65
Apr-65
Jul-65
Oct-65
Date
Recorded Rain
25 pcile
Median
75 pcile

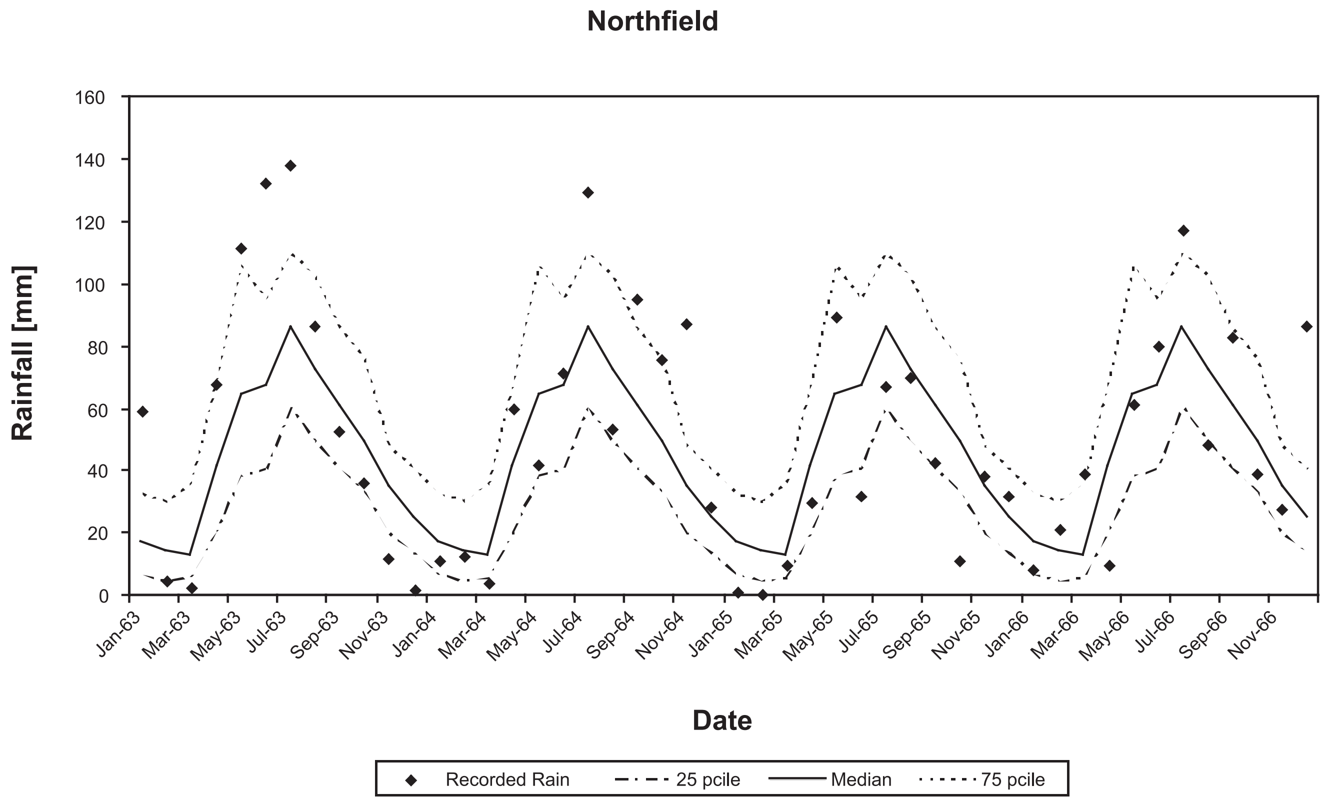

Mt Gambier (Y. Sand)
Rainfall [mm]
250
200
150
100
50
0
Apr-63
Jun-63
Aug-63
Oct-63
Dec-63
Feb-64
Apr-64
Jun-64
Aug-64
Oct-64
Dec-64
Feb-65
Apr-65
Jun-65
Aug-65
Oct-65
Dec-65
Feb-66
Apr-66
Date
Recorded Rain
25 pcile
Median
75 pcile

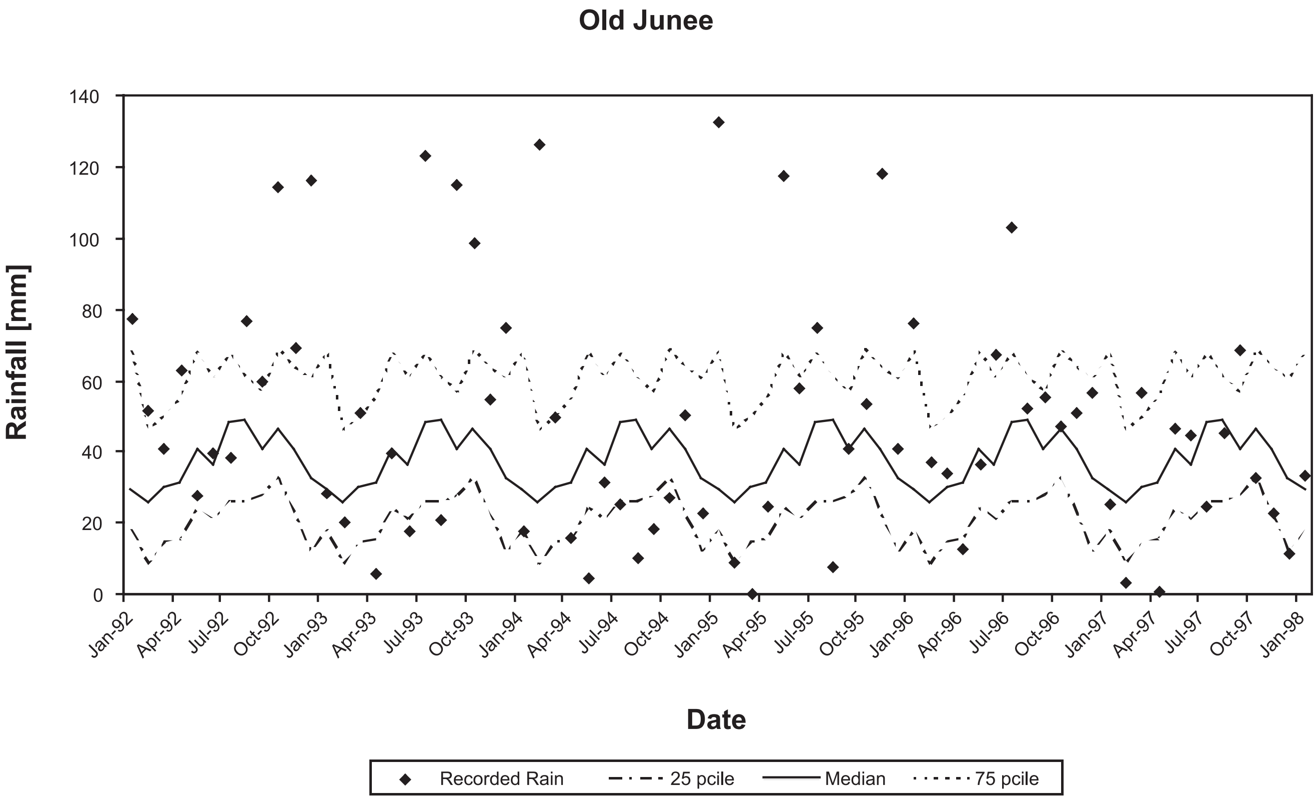

Mt Gambier (Grassland)
Rainfall [mm]
250
200
150
100
50
0
Apr-63
Jun-63
Aug-63
Oct-63
Dec-63
Feb-64
Apr-64
Jun-64
Aug-64
Oct-64
Dec-64
Feb-65
Apr-65
Jun-65
Aug-65
Oct-65
Dec-65
Feb-66
Apr-66
Date
Recorded Rain
25 pcile
Median
75 pcile

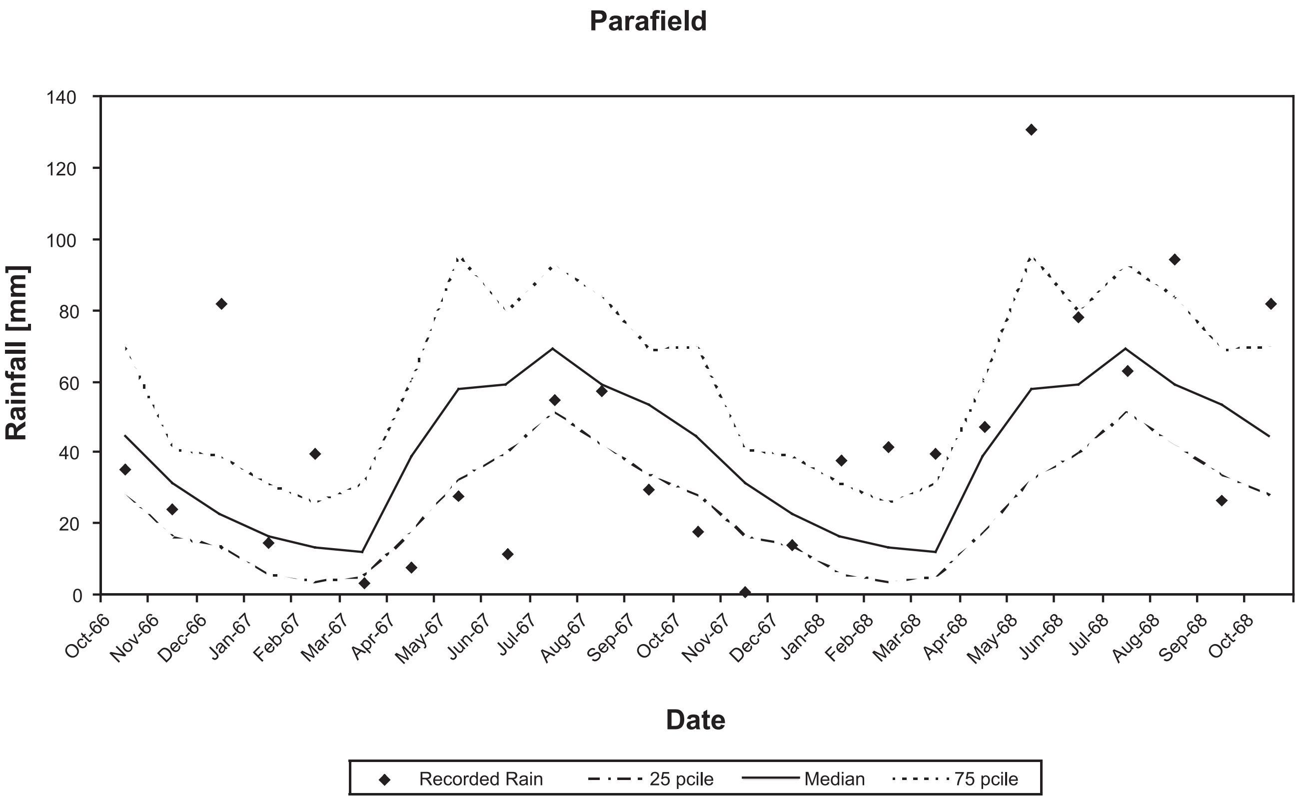

Narrabri
160
140
120
100
80
60
40
20
0
Rainfall [mm]
Sep-79
Oct-79
Nov-79
Dec-79
Jan-80
Feb-80
Mar-80
Apr-80
May-80
Jun-80
Date
Recorded Rain
25 pcile
Median
75 pcile

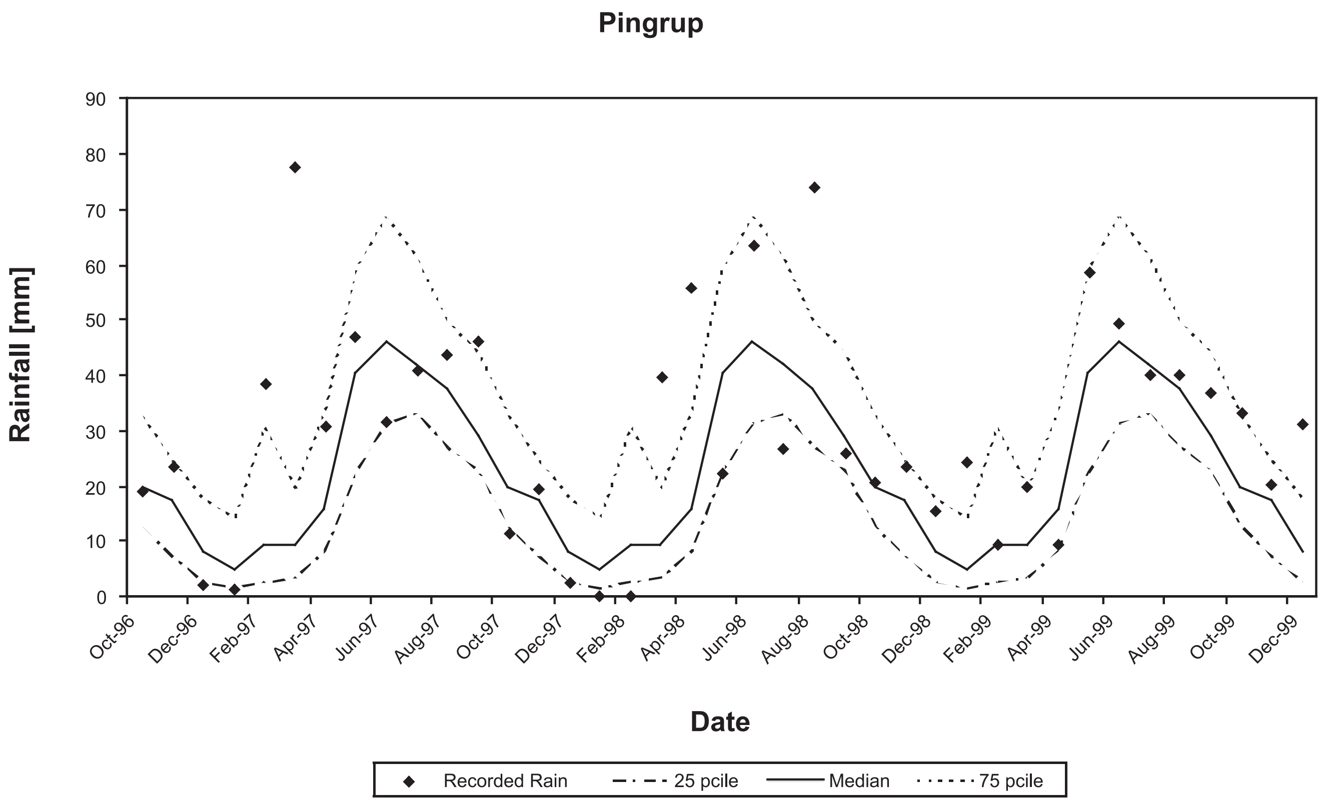

Nerrigundah
300
250
200
150
100
50
0
Rainfall [mm]
Aug-97
Sep-97
Oct-97
Nov-97
Dec-97
Jan-98
Feb-98
Mar-98
Apr-98
May-98
Jun-98
Jul-98
Aug-98
Sep-98
Oct-98
Date
Recorded Rain
25 pcile
Median
75 pcile

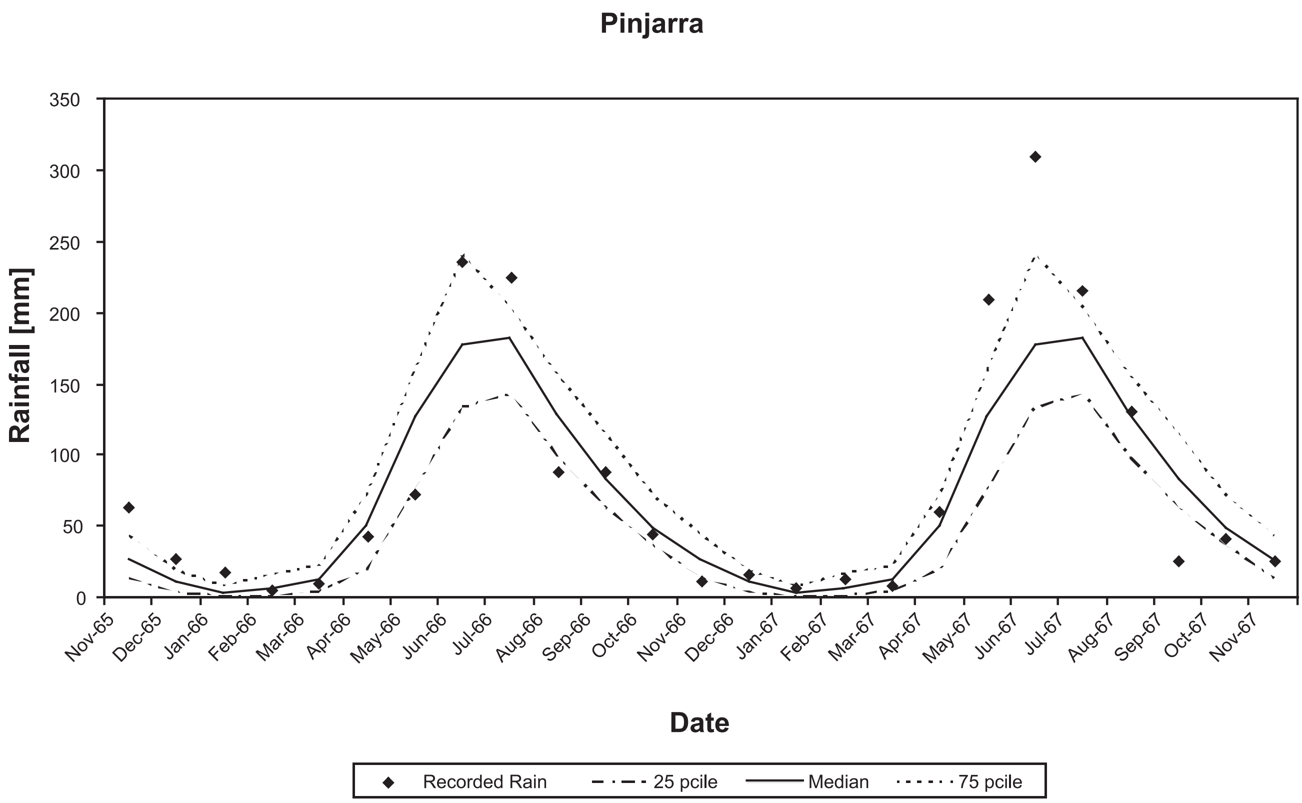

North Maroondah
Rainfall [mm]
250
200
150
100
50
0
Jul-73
Sep-73
Nov-73
Jan-74
Mar-74
May-74
Jul-74
Sep-74
Nov-74
Jan-75
Mar-75
May-75
Jul-75
Sep-75
Nov-75
Jan-76
Mar-76
May-76
Jul-76
Sep-76
Nov-76
Date
Recorded Rain
25 pcile
Median
75 pcile

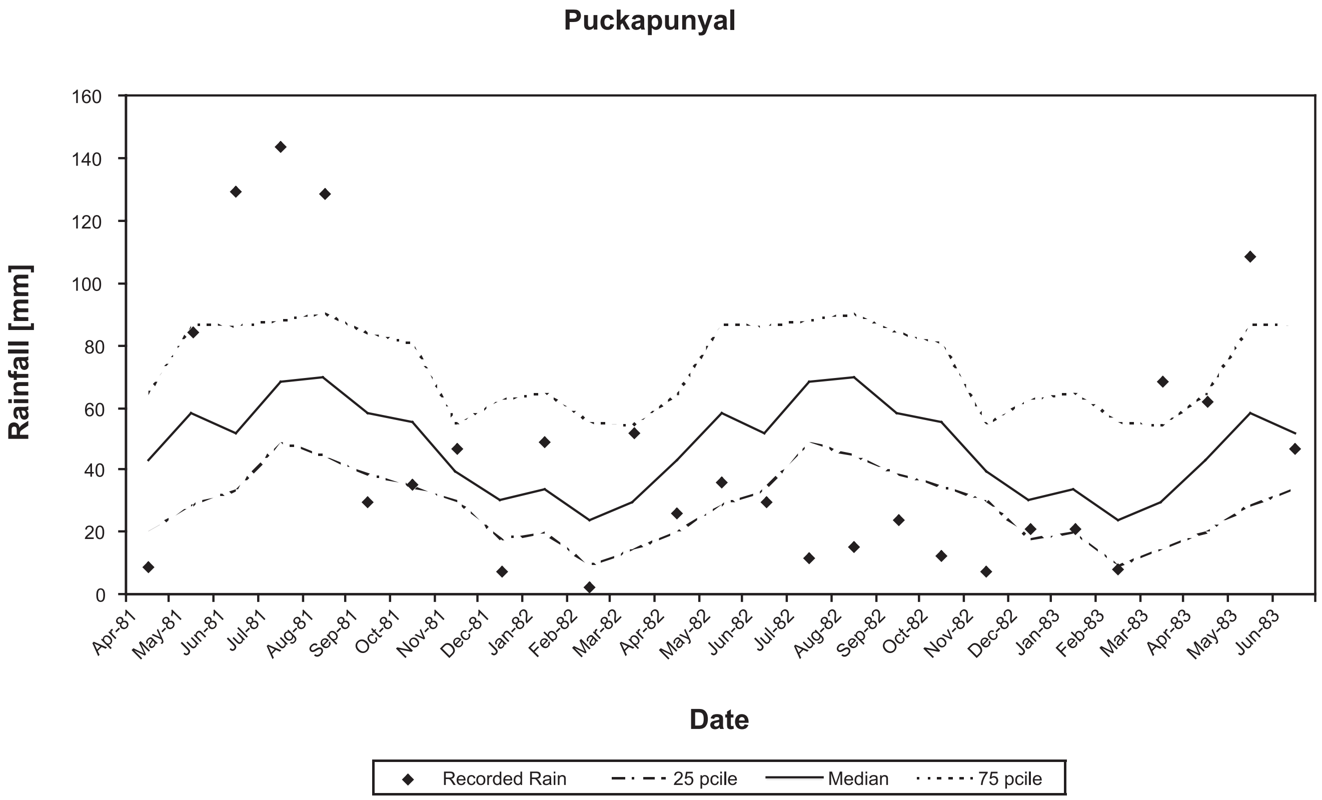

Northfield
Rainfall [mm]
160
140
120
100
80
60
40
20
0
Jan-63
Mar-63
May-63
Jul-63
Sep-63
Nov-63
Jan-64
Mar-64
May-64
Jul-64
Sep-64
Nov-64
Jan-65
Mar-65
May-65
Jul-65
Sep-65
Nov-65
Jan-66
Mar-66
May-66
Jul-66
Sep-66
Nov-66
Date
Recorded Rain
25 pcile
Median
75 pcile

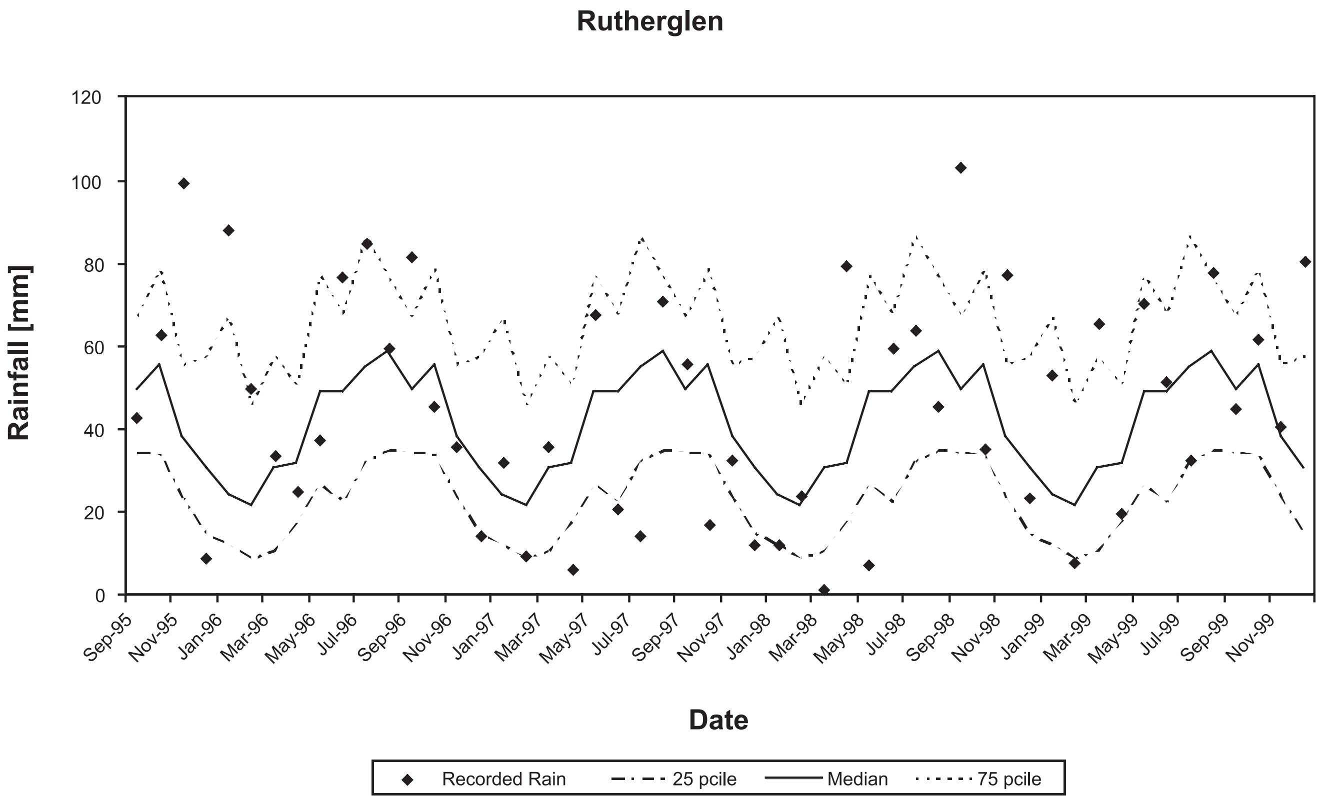

Old Junee
Rainfall [mm]
140
120
100
80
60
40
20
0
Jan-92
Apr-92
Jul-92
Oct-92
Jan-93
Apr-93
Jul-93
Oct-93
Jan-94
Apr-94
Jul-94
Oct-94
Jan-95
Apr-95
Jul-95
Oct-95
Jan-96
Apr-96
Jul-96
Oct-96
Jan-97
Apr-97
Jul-97
Oct-97
Jan-98
Date
Recorded Rain
25 pcile
Median
75 pcile

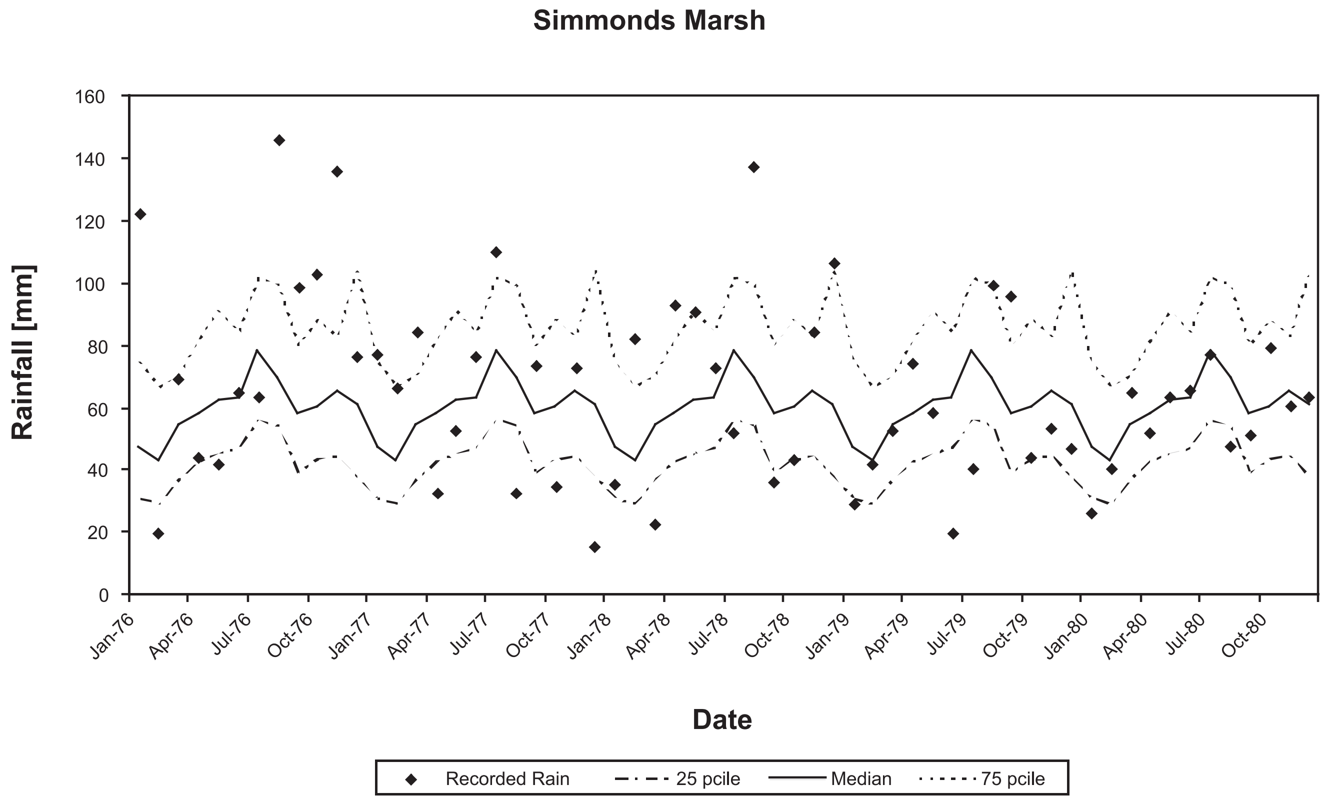

Parafield
Rainfall [mm]
140
120
100
80
60
40
20
0
Oct-66
Nov-66
Dec-66
Jan-67
Feb-67
Mar-67
Apr-67
May-67
Jun-67
Jul-67
Aug-67
Sep-67
Oct-67
Nov-67
Dec-67
Jan-68
Feb-68
Mar-68
Apr-68
May-68
Jun-68
Jul-68
Aug-68
Sep-68
Oct-68
Date
Recorded Rain
25 pcile
Median
75 pcile

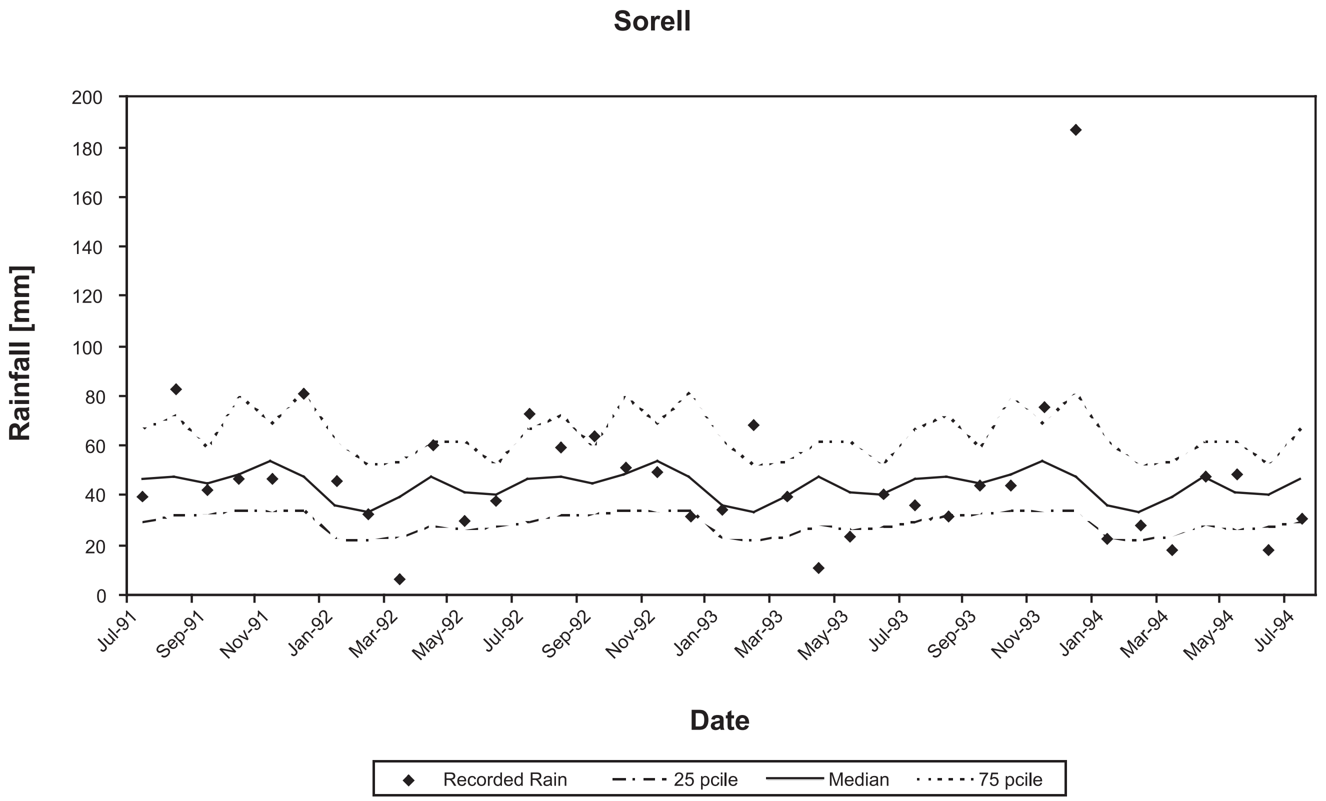

Pingrup
Rainfall [mm]
90
80
70
60
50
40
30
20
10
0
Oct-96
Dec-96
Feb-97
Apr-97
Jun-97
Aug-97
Oct-97
Dec-97
Feb-98
Apr-98
Jun-98
Aug-98
Oct-98
Dec-98
Feb-99
Apr-99
Jun-99
Aug-99
Oct-99
Dec-99
Date
Recorded Rain
25 pcile
Median
75 pcile

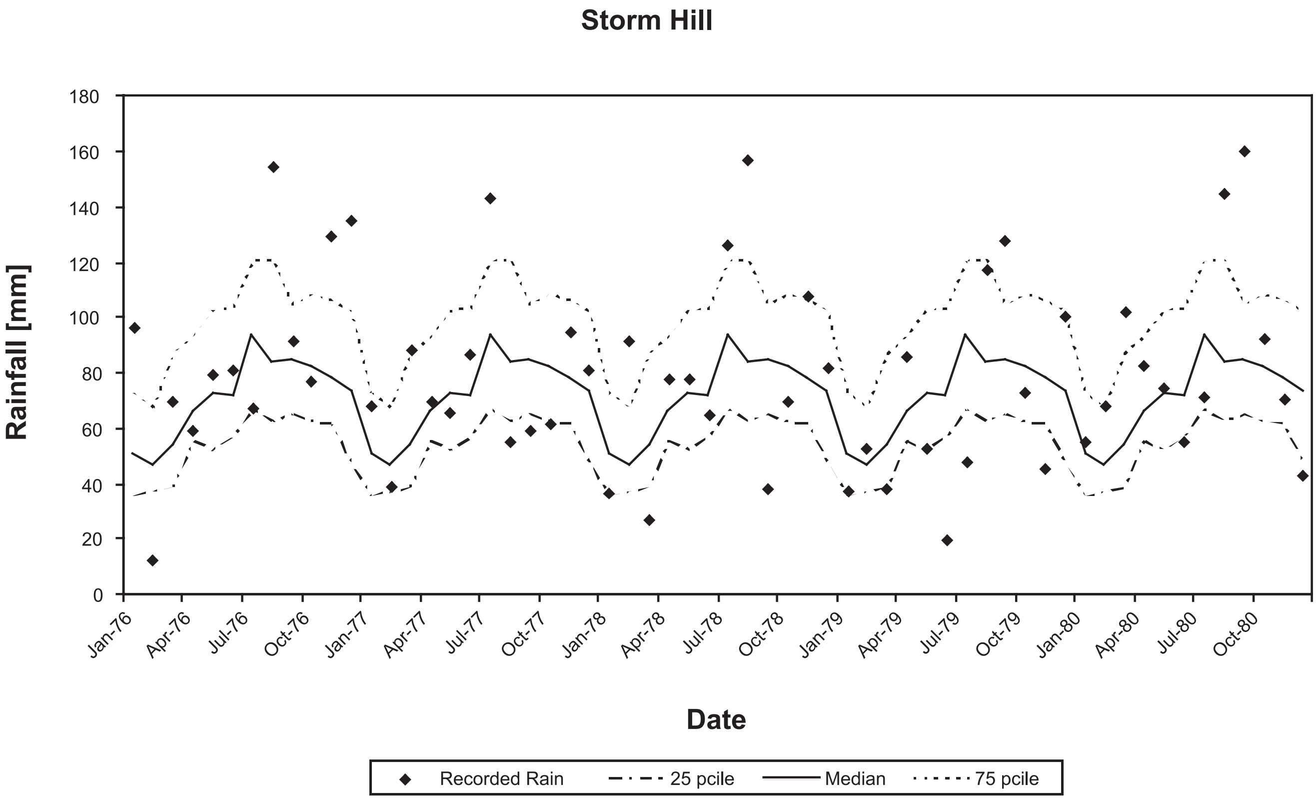

Pinjarra
Rainfall [mm]
350
300
250
200
150
100
50
0
Nov-65
Dec-65
Jan-66
Feb-66
Mar-66
Apr-66
May-66
Jun-66
Jul-66
Aug-66
Sep-66
Oct-66
Nov-66
Dec-66
Jan-67
Feb-67
Mar-67
Apr-67
May-67
Jun-67
Jul-67
Aug-67
Sep-67
Oct-67
Nov-67
Date
Recorded Rain
25 pcile
Median
75 pcile

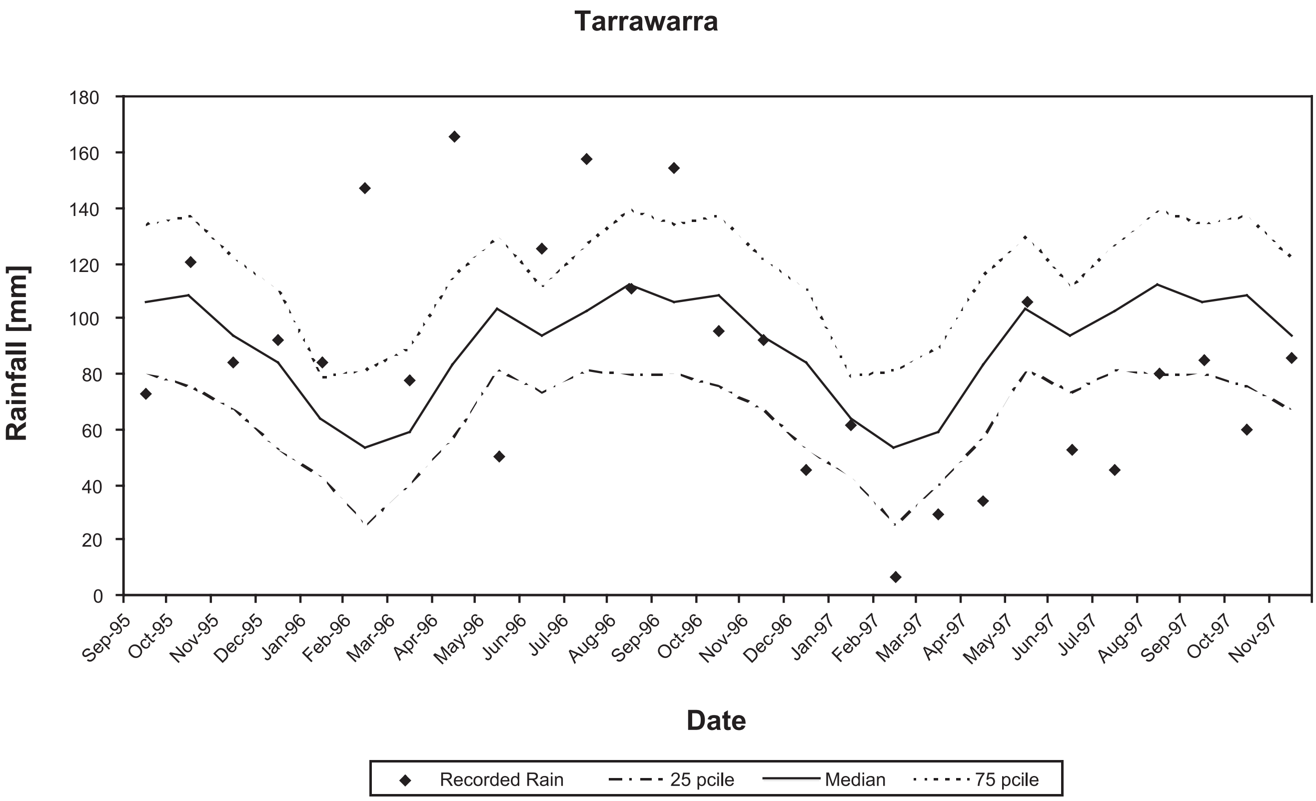

Puckapunyal
Rainfall [mm]
160
140
120
100
80
60
40
20
0
Apr-81
May-81
Jun-81
Jul-81
Aug-81
Sep-81
Oct-81
Nov-81
Dec-81
Jan-82
Feb-82
Mar-82
Apr-82
May-82
Jun-82
Jul-82
Aug-82
Sep-82
Oct-82
Nov-82
Dec-82
Jan-83
Feb-83
Mar-83
Apr-83
May-83
Jun-83
Date
Recorded Rain
25 pcile
Median
75 pcile

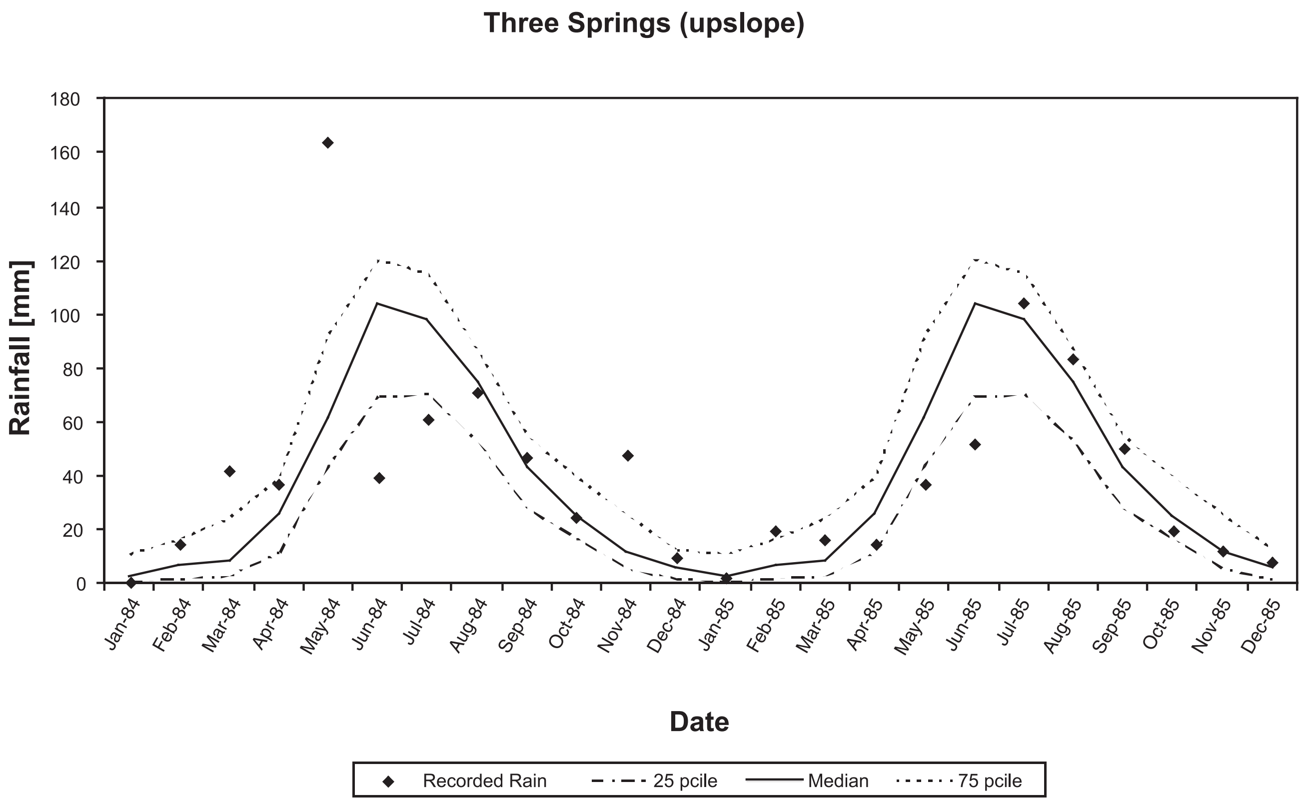

Rutherglen
Rainfall [mm]
120
100
80
60
40
20
0
Sep-95
Nov-95
Jan-96
Mar-96
May-96
Jul-96
Sep-96
Nov-96
Jan-97
Mar-97
May-97
Jul-97
Sep-97
Nov-97
Jan-98
Mar-98
May-98
Jul-98
Sep-98
Nov-98
Jan-99
Mar-99
May-99
Jul-99
Sep-99
Nov-99
Date
Recorded Rain
25 pcile
Median
75 pcile

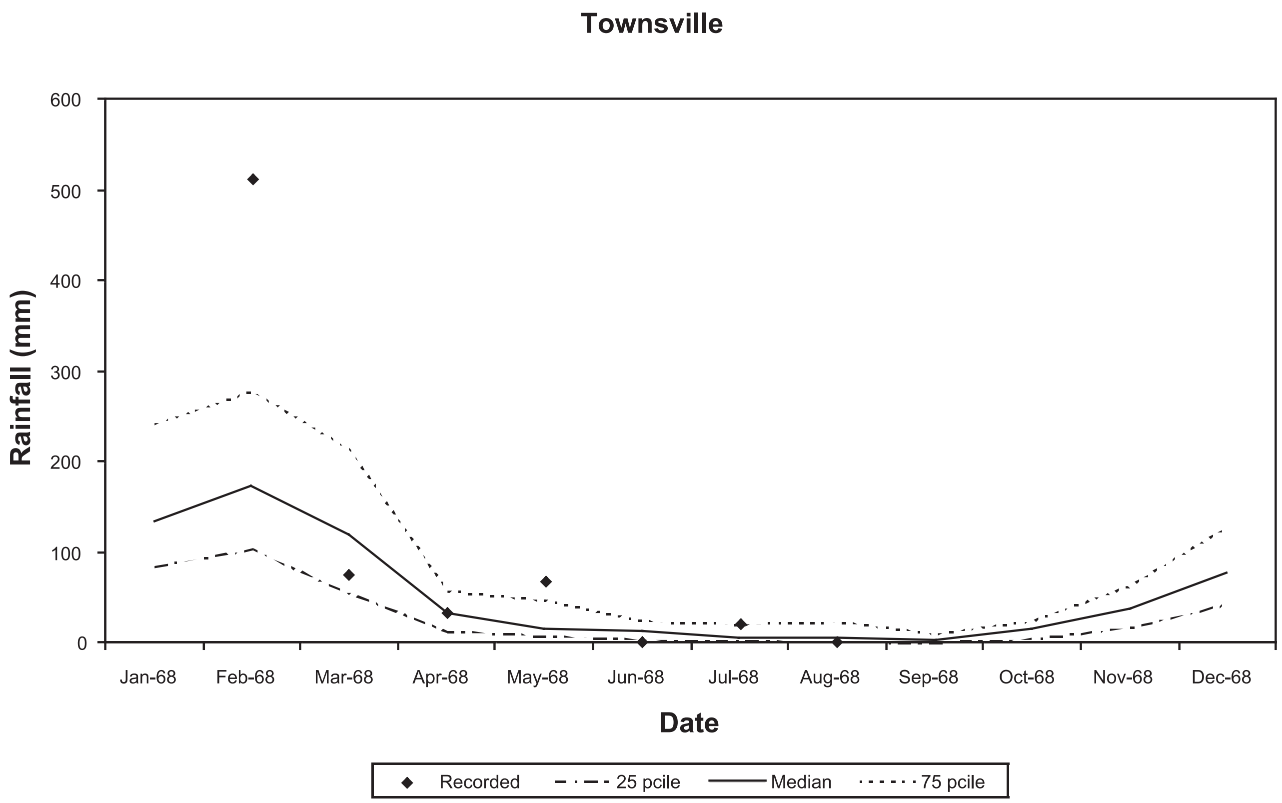

Simmonds Marsh
160
140
120
100
80
60
40
20
0
Rainfall [mm]
Jan-76
Apr-76
Jul-76
Oct-76
Jan-77
Apr-77
Jul-77
Oct-77
Jan-78
Apr-78
Jul-78
Oct-78
Jan-79
Apr-79
Jul-79
Oct-79
Jan-80
Apr-80
Jul-80
Oct-80
Date
Recorded Rain
25 pcile
Median
75 pcile

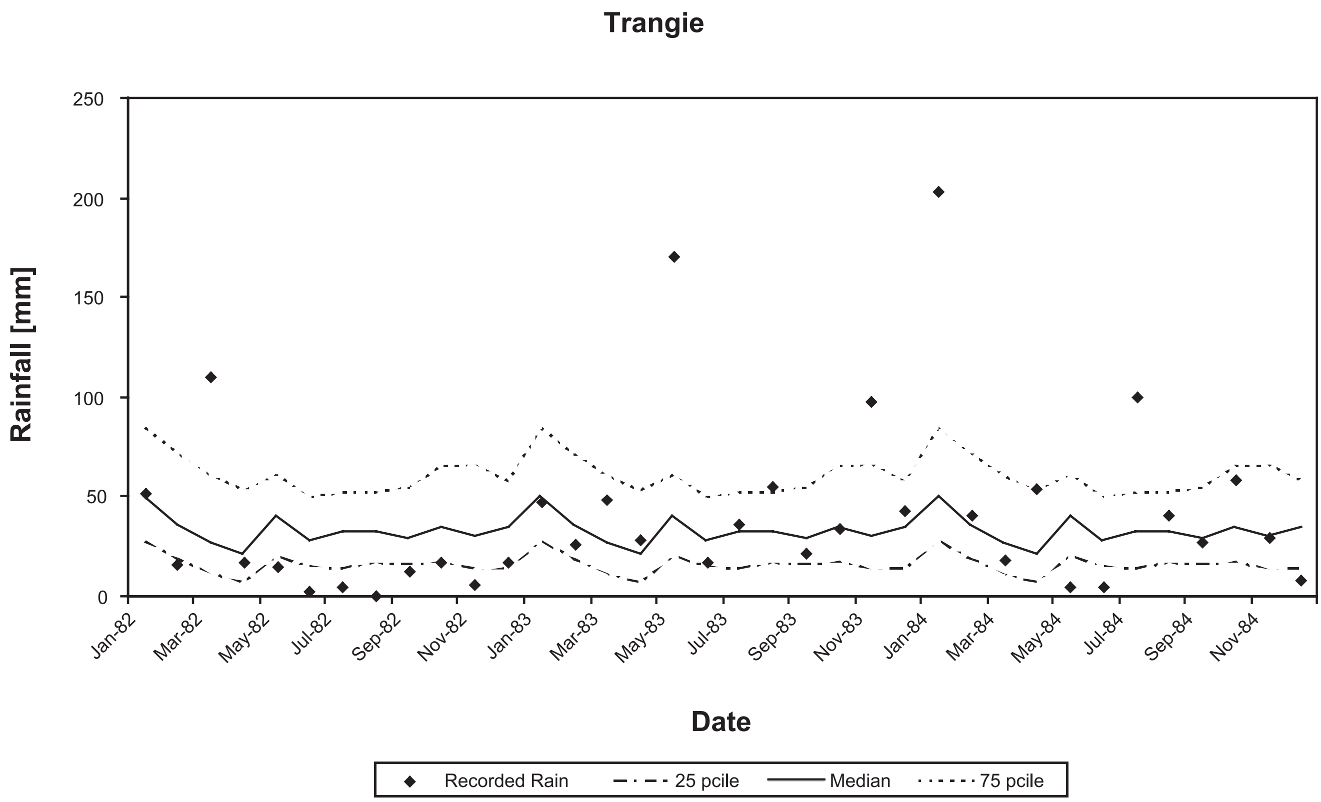

Sorell
200
180
160
140
120
100
80
60
40
20
0
Rainfall [mm]
Jul-91
Sep-91
Nov-91
Jan-92
Mar-92
May-92
Jul-92
Sep-92
Nov-92
Jan-93
Mar-93
May-93
Jul-93
Sep-93
Nov-93
Jan-94
Mar-94
May-94
Jul-94
Date
Recorded Rain
25 pcile
Median
75 pcile

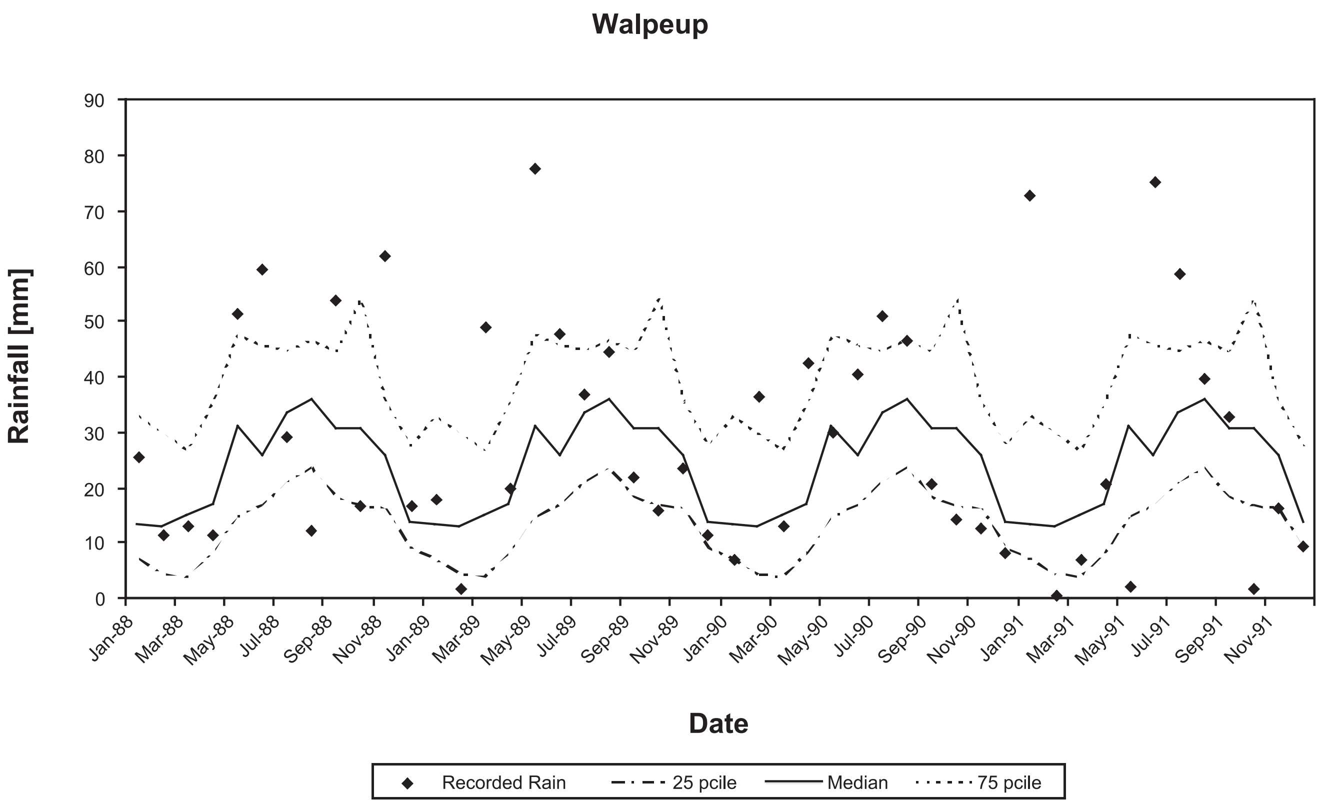

Storm Hill
Rainfall [mm]
Date
Recorded Rain
25 pcile
Median
75 pcile

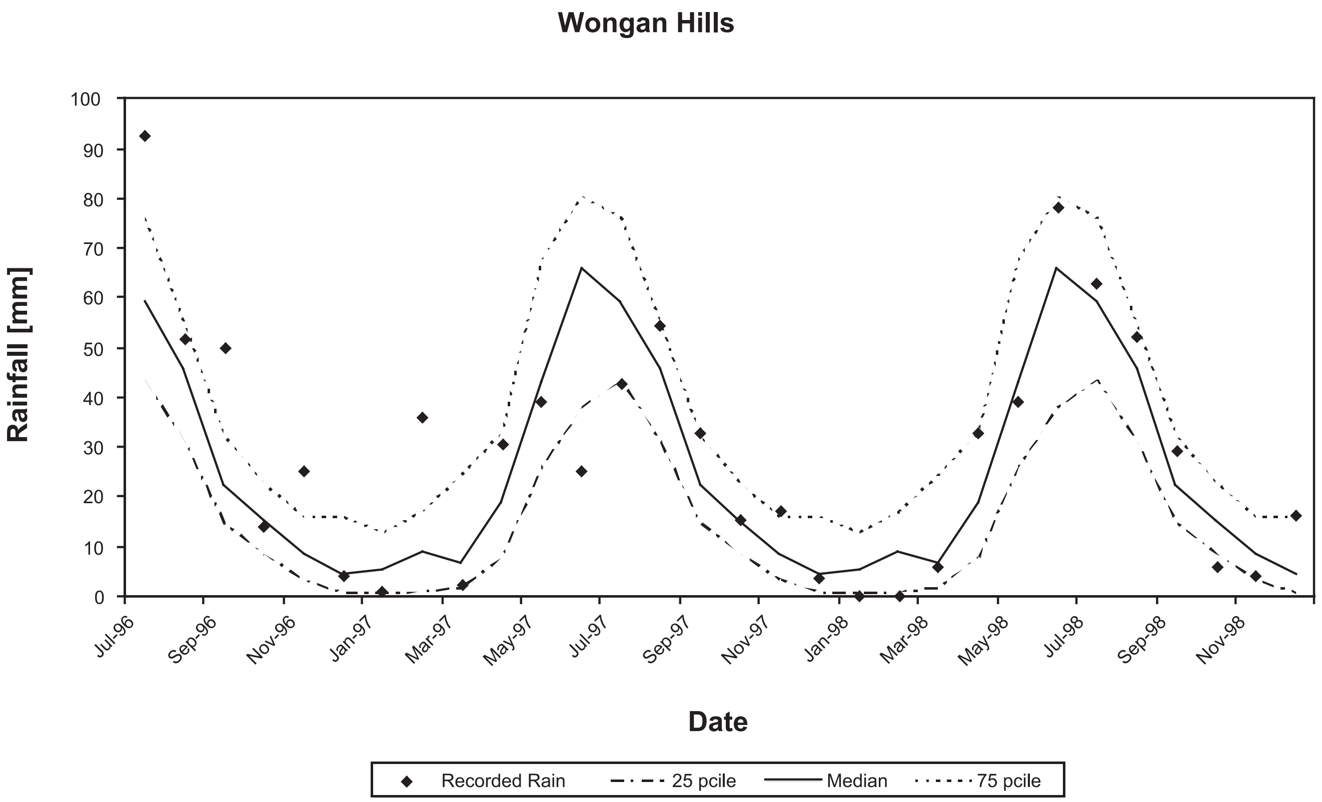

Tarrawarra
Rainfall [mm]
Date
Recorded Rain
25 pcile
Median
75 pcile

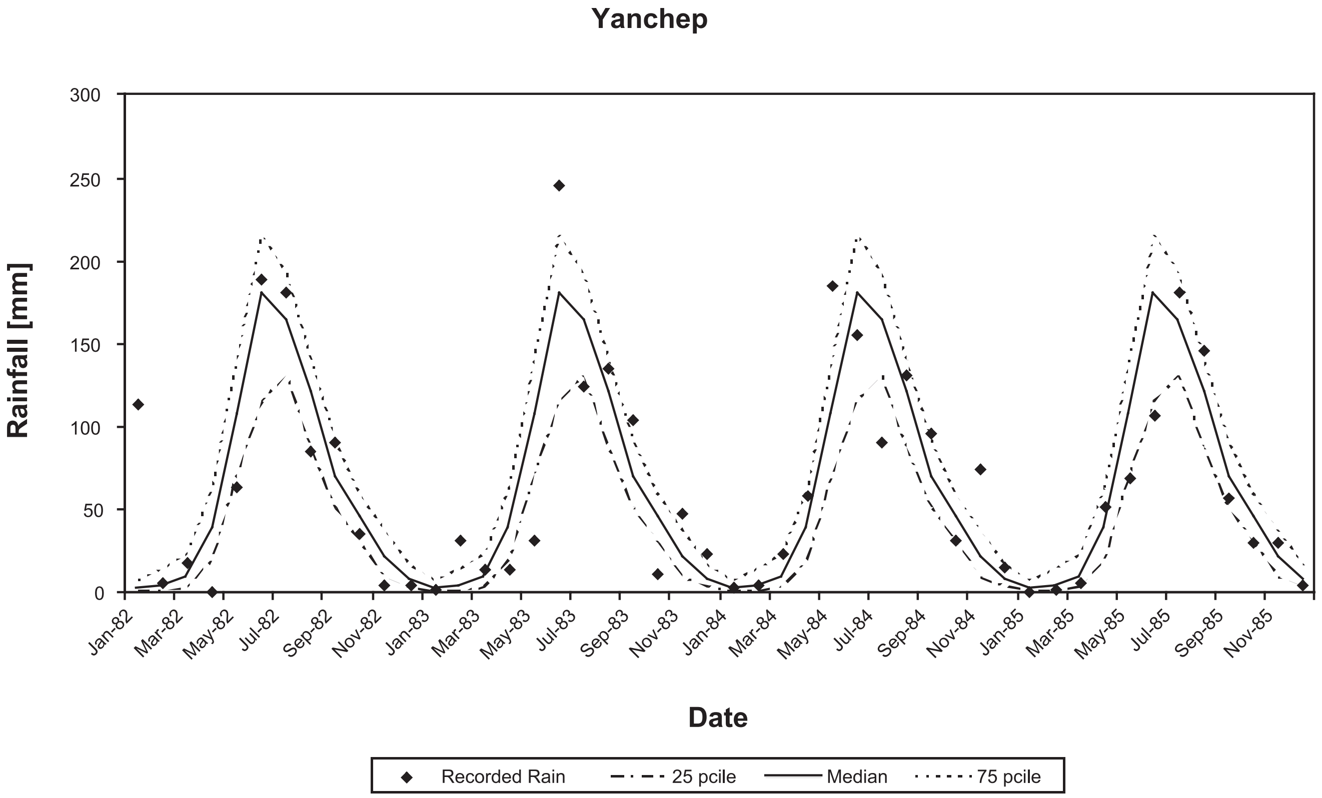

Three Springs (upslope)
180
160
140
120
100
80
60
40
20
0
Rainfall [mm]
Jan-84
Feb-84
Mar-84
Apr-84
May-84
Jun-84
Jul-84
Aug-84
Sep-84
Oct-84
Nov-84
Dec-84
Jan-85
Feb-85
Mar-85
Apr-85
May-85
Jun-85
Jul-85
Aug-85
Sep-85
Oct-85
Nov-85
Dec-85
Date
Recorded Rain
25 pcile
Median
75 pcile

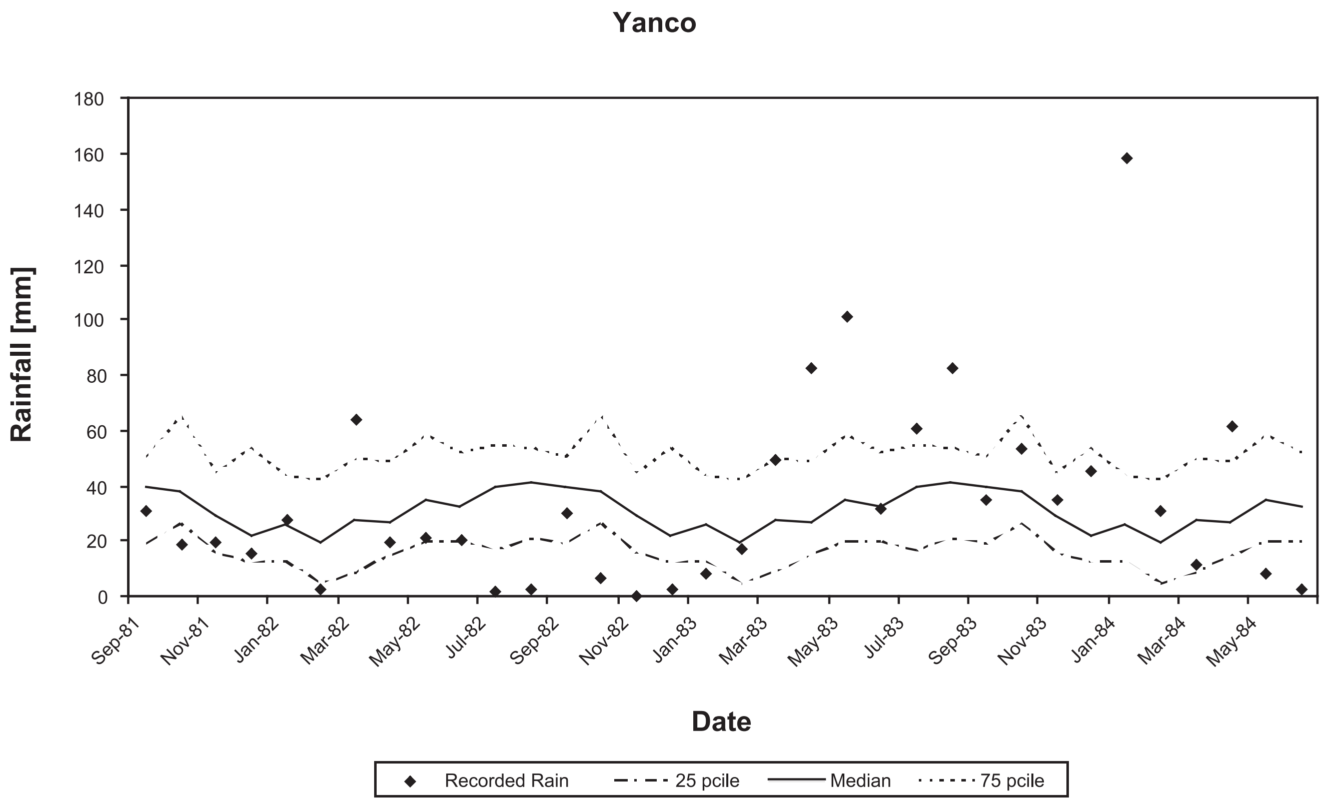

Townsville
600
500
400
300
200
100
0
Rainfall (mm)
Jan-68
Feb-68
Mar-68
Apr-68
May-68
Jun-68
Jul-68
Aug-68
Sep-68
Oct-68
Nov-68
Dec-68
Date
Recorded
25 pcile
Median
75 pcile

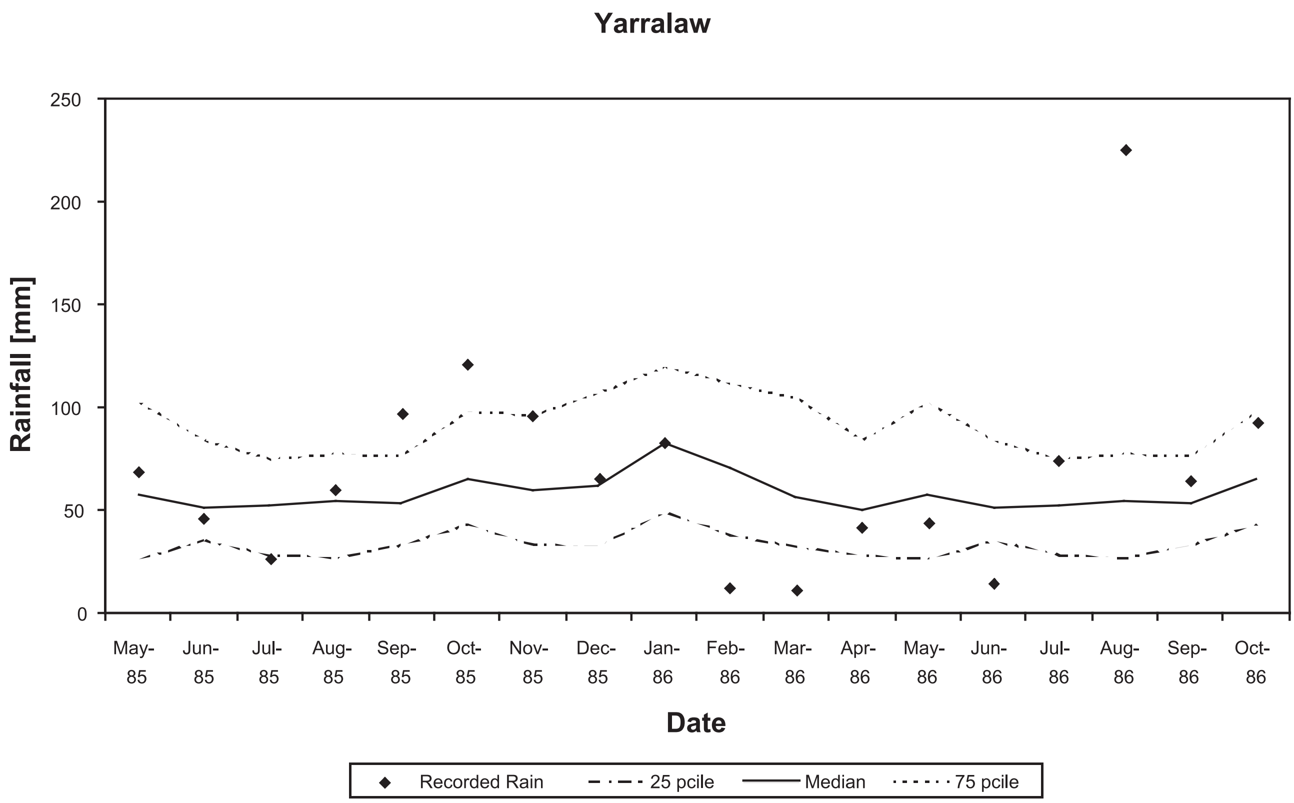

Trangie
Rainfall [mm]
250
200
150
100
50
0
Jan-82
Mar-82
May-82
Jul-82
Sep-82
Nov-82
Jan-83
Mar-83
May-83
Jul-83
Sep-83
Nov-83
Jan-84
Mar-84
May-84
Jul-84
Sep-84
Nov-84
Date
Recorded Rain
25 pcile
Median
75 pcile


Walpeup
Rainfall [mm]
90
80
70
60
50
40
30
20
10
0
Jan-88
Mar-88
May-88
Jul-88
Sep-88
Nov-88
Jan-89
Mar-89
May-89
Jul-89
Sep-89
Nov-89
Jan-90
Mar-90
May-90
Jul-90
Sep-90
Nov-90
Jan-91
Mar-91
May-91
Jul-91
Sep-91
Nov-91
Date
Recorded Rain
25 pcile
Median
75 pcile


Wongan Hills
Rainfall [mm]
Date
Recorded Rain
25 pcile
Median
75 pcile


Yanchep
Rainfall [mm]
Date
Recorded Rain
25 pcile
Median
75 pcile


Yanco
Rainfall [mm]
180
160
140
120
100
80
60
40
20
0
Sep-81
Nov-81
Jan-82
Mar-82
May-82
Jul-82
Sep-82
Nov-82
Jan-83
Mar-83
May-83
Jul-83
Sep-83
Nov-83
Jan-84
Mar-84
May-84
Date
Recorded Rain
25 pcile
Median
75 pcile


Yarralaw
Rainfall [mm]
250
200
150
100
50
0
May-85
Jun-85
Jul-85
Aug-85
Sep-85
Oct-85
Nov-85
Dec-85
Jan-86
Feb-86
Mar-86
Apr-86
May-86
Jun-86
Jul-86
Aug-86
Sep-86
Oct-86
Date
Recorded Rain
25 pcile
Median
75 pcile

Appendix 4 - Extractable Soils Database

Site location	State	Latitude	Longitude	Reliability of location	Site map	Vegetation type	Generalised veg type	Landuse	Terrain	Soil type	Data type	Info on horizon depth
Adelaide (Black Earth)	SA	-34.97	138.63	1	FALSE	grassland/pasture	3	Grazing	Gentle Slopes	Black Earth	3	TRUE
Adelaide (Red-Brown Earth)	SA	-34.97	138.63	1	FALSE	annual pasture	3	Grazing	Gentle Slopes	Red-Brown Earth	3	TRUE
Alice Springs	NT	-23.7	133.87	2	FALSE	grassland	3	Grazing	Undulating Plains	Gradational	5	TRUE
Ballarat	VIC	-37.83	143.88	1	TRUE	pasture	3	Grazing	Undulating Plains	Dd 1.72/Dy 5.23	5	TRUE
Banana	QLD	-24.43	150.14	1	FALSE	sorghum	2	Cropping	Plains	Dark	2	FALSE
Banana 2	QLD	-24.43	150.14	1	FALSE	sorghum	2	Cropping	Plains	Brown Clay	4	FALSE
Banana 3	QLD	-24.58	150.15	1	FALSE	maize	2	Cropping	Plains	Black Vertosol	4	FALSE
Banana 3	QLD	-24.58	150.15	1	FALSE	sunflower	2	Cropping	Plains	Black Vertosol	4	FALSE
Banana 3	QLD	-24.58	150.15	1	FALSE	wheat	2	Cropping	Plains	Black Vertosol	4	FALSE
Belconnen	ACT	-35.35	148.9	2	FALSE	radiata pine	1	Forestry	Hilly	Sandy Yellow Podzolic	4	TRUE
Beverly	QLD	-27.18	151.1	1	FALSE	cotton	2	Cropping	Plains	Grey Vertosol	1	FALSE
Beverly	QLD	-27.18	151.1	1	FALSE	chickpea	2	Cropping	Plains	Grey Vertosol	1	FALSE
Beverly	QLD	-27.18	151.1	1	FALSE	wheat	2	Cropping	Plains	Grey Vertosol	1	FALSE
Billa Billa	QLD	-28.17	150.2	1	FALSE	wheat	2	Cropping	Plains	Red Chromosol	4	FALSE
Biloela	QLD	-24.4	150.3	1	FALSE	wheat	2	Cropping	Alluvial Plain	Alluvial Clay Loam	5	FALSE
Bongeen	QLD	-27.63	151.4	1	FALSE	cotton	2	Cropping	Plains	Black Vertosol	4	FALSE
Bongeen	QLD	-27.63	151.4	1	FALSE	sorghum	2	Cropping	Plains	Black Vertosol	4	FALSE
Bongeen 2	QLD	-27.6	151.44	1	FALSE	mungbean	2	Cropping	Plains	Black Vertosol	1	FALSE
Bongeen 2	QLD	-27.6	151.44	1	FALSE	sorghum	2	Cropping	Plains	Black Vertosol	4	FALSE
Bongeen 2	QLD	-27.6	151.44	1	FALSE	cotton	2	Cropping	Plains	Black Vertosol	4	FALSE
Bongeen 3	QLD	-27.7	151.46	1	FALSE	cotton	2	Cropping	Plains	Black Vertosol	4	FALSE
Bongeen 3	QLD	-27.7	151.46	1	FALSE	sorghum	2	Cropping	Plains	Black Vertosol	4	FALSE
Borden	WA	-34.08	118.25	2	FALSE	lucerne	2	Gropping/Grazing	Plains	Solodic (Dg 2.33)	5	FALSE
Borden	WA	-34.08	118.25	2	FALSE	clover	3	Cropping/Grazing	Plains	Solodic (Dg 2.33)	5	FALSE
Brindabellas	ACT	-35.5	148.77	2	TRUE	eucalypt dominated	1	Forestry	Mountain Range	Yellow Earth (Gn 2.24)	3	TRUE
Brookstead	QLD	-27.74	151.46	1	FALSE	mungbean	2	Cropping	Plains	Grey Vertosol	1	FALSE
Brookstead	QLD	-27.74	151.46	1	FALSE	cotton	2	Cropping	Plains	Grey Vertosol	4	FALSE
Brookstead	QLD	-27.74	151.46	1	FALSE	sorghum	2	Cropping	Plains	Grey Vertosol	4	FALSE
Capella	QLD	-22.97	147.8	1	FALSE	wheat	2	Cropping	Plains	Black Vertosol	2	FALSE
Chances Plains	QLD	-26.73	150.78	1	FALSE	wheat	2	Cropping	Plains	Grey Vertosol	4	FALSE
Chances Plains	QLD	-26.73	150.78	1	FALSE	chickpea	2	Cropping	Plains	Grey Vertosol	1	FALSE
Chances Plains 2	QLD	-26.7	150.74	1	FALSE	wheat	2	Cropping	Plains	Grey Vertosol	1	FALSE
Chances Plains 2	QLD	-26.7	150.74	1	FALSE	sorghum	2	Cropping	Plains	Grey Vertosol	4	FALSE
Collie	WA	-33.42	115.98	1	TRUE	eucalyptus dominated	1	Forestry	Dissected Lateritic Plateau	Duplex	1	TRUE
et **Coranderrk** (Blue Jacket)	VIC	-37.68	145.58	1	TRUE	eucalyptus dominated	1	Forestry	Hilly	Loam over Clay	5	FALSE
Coranderrk (Picaninny)	VIC	-37.68	145.58	1	TRUE	eucalyptus dominated	1	Forestry	Hilly	Loam over Clay	5	FALSE

Porosity/ bulk density	Soil depth (m)	Stored soil moisture (mm)	Active soil depth (m)	Active soil moisture store (mm)	Missing water	Start/stop	Rainfall	Rank of driest month	Rank of wettest month	Monitoring frequency	References
FALSE	2.4	164.3	1.85	154.5	FALSE	1948 - 1950	TRUE	0.025	0.026	Weekly/Daily	Aitchison and Holmes (1953), Aitchison and Holmes (1952)
FALSE	3.1	180.4	1.85	152.1	FALSE	1948 - 1950	TRUE	0.025	0.026	Weekly/Daily	Aitchison and Holmes (1953), Aitchison and Holmes (1952)
FALSE	1.5	94.43	1.5	94.43	FALSE	Oct 1954-Dec 1956	TRUE	0.171	0.032	Weekly	Winkworth (1970), Winkworth (1967)
FALSE	2	212.4	2	212.4	FALSE	1976 - 1977	TRUE	0.029	0.016	Fortnightly	Williamson (1979)
TRUE	1.8	244.5	1.8	244.5	FALSE	N/A	FALSE	#N/A	#N/A	N/A	Dalgleish and Foale (1998)
TRUE	1.2	186	1.2	186	TRUE	N/A	FALSE	#N/A	#N/A	N/A	Dalgleish and Foale (1998)
TRUE	0.6	109.5	0.6	109.5	TRUE	N/A	FALSE	#N/A	#N/A	N/A	Dalgleish and Foale (1998)
TRUE	0.6	94.5	0.6	94.5	TRUE	N/A	FALSE	#N/A	#N/A	N/A	Dalgleish and Foale (1998)
TRUE	0.6	108	0.6	108	TRUE	N/A	FALSE	#N/A	#N/A	N/A	Dalgleish and Foale (1998)
TRUE	2	272.2	2	272.2	TRUE	1983 - 1986	TRUE	0.016	0.002	Fortnightly	Dewar (1997), Meyers and Talsma (1992)
TRUE	1.8	277.5	1.8	277.5	FALSE	N/A	FALSE	#N/A	#N/A	N/A	Dalgleish and Foale (1998)
TRUE	1.8	165	1.8	165	FALSE	N/A	FALSE	#N/A	#N/A	N/A	Dalgleish and Foale (1998)
TRUE	1.8	186	1.8	186	FALSE	N/A	FALSE	#N/A	#N/A	N/A	Dalgleish and Foale (1998)
TRUE	1.4	185	1.4	185	TRUE	N/A	FALSE	#N/A	#N/A	N/A	Dalgleish and Foale (1998)
FALSE	1.22	126.88	1.22	126.88	FALSE	1948 - 1951	TRUE	0.006	0.006	Fortnightly	Fitzpatrick and Nix (1969), Allen and George (1956)
TRUE	1.8	280.5	1.8	280.5	TRUE	N/A	FALSE	#N/A	#N/A	N/A	Dalgleish and Foale (1998)
TRUE	1.8	285	1.8	285	TRUE	N/A	FALSE	#N/A	#N/A	N/A	Dalgleish and Foale (1998)
TRUE	1.8	157.5	1.2	157.5	FALSE	N/A	FALSE	#N/A	#N/A	N/A	Dalgleish and Foale (1998)
TRUE	1.8	261	1.8	261	TRUE	N/A	FALSE	#N/A	#N/A	N/A	Dalgleish and Foale (1998)
TRUE	1.8	348	1.8	348	TRUE	N/A	FALSE	#N/A	#N/A	N/A	Dalgleish and Foale (1998)
TRUE	1.8	342	1.8	342	TRUE	N/A	FALSE	#N/A	#N/A	N/A	Dalgleish and Foale (1998)
TRUE	1.8	267	1.8	267	TRUE	N/A	FALSE	#N/A	#N/A	N/A	Dalgleish and Foale (1998)
FALSE	1.5	135.16	1.5	135.16	FALSE	Oct 1996-Dec 1999	TRUE	0.025	0.049	Every 3 Months	Latta *et al.,* (2001)
FALSE	1.5	56.04	1.5	56.04	FALSE	Oct 1996-Dec 1999	TRUE	0.025	0.049	Every 3 Months	Latta *et al.,* (2001)
FALSE	10	871.1	6	828.5	FALSE	Apr 1981-Oct 1983	TRUE	0.004	0.048	Monthly	Talsma and Gardner (1986), Talsma (1983)
TRUE	1.8	142.5	1.2	142.5	FALSE	N/A	FALSE	#N/A	#N/A	N/A	Dalgleish and Foale (1998)
TRUE	1.8	288	1.8	288	TRUE	N/A	FALSE	#N/A	#N/A	N/A	Dalgleish and Foale (1998)
TRUE	1.8	282	1.8	282	TRUE	N/A	FALSE	#N/A	#N/A	N/A	Dalgleish and Foale (1998)
TRUE	1.5	145.5	1.5	145.5	FALSE	N/A	FALSE	#N/A	#N/A	N/A	Dalgleish and Foale (1998)
TRUE	1.8	223.5	1.8	223.5	TRUE	N/A	FALSE	#N/A	#N/A	N/A	Dalgleish and Foale (1998)
TRUE	1.8	186	1.5	186	FALSE	N/A	FALSE	#N/A	#N/A	N/A	Dalgleish and Foale (1998)
TRUE	1.8	157.5	1.5	157.5	FALSE	N/A	FALSE	#N/A	#N/A	N/A	Dalgleish and Foale (1998)
TRUE	1.8	169.5	1.8	169.5	TRUE	N/A	FALSE	#N/A	#N/A	N/A	Dalgleish and Foale (1998)
FALSE	14	332.05	12	327.1	FALSE	Jan 1974-May 1979	TRUE	0.02	0.013	Monthly/3 Months	Peck and Williamson (1987), Johnston (1987), (seasonal) Sharma *et al.,* (1987), Sharma al. (1982)
TRUE	3.1	237.01	3.1	237.01	FALSE	1970 - 1978	TRUE	0.005	0.005	2-6 Weeks	Howard and Langford (1971), Langford and O' Shaughnessy (1980)
TRUE	3.1	334.5	3.1	334.5	FALSE	1970 - 1978	TRUE	0.005	0.005	2-6 Weeks	Howard and Langford (1971), Langford and O' Shaughnessy (1980)

Site location	State	Latitude	Longitude	Reliability of location	Site map	Vegetation type	Generalised veg type	Landuse	Terrain	Soil type	Data type	Info on horizon depth
Coranderrk (Slip)	VIC	-37.68	145.58	1	TRUE	eucalyptus dominated	1	Forestry	Hilly	Loam over Clay	5	FALSE
Croppa Creek	NSW	-29.1	150.38	1	FALSE	chickpea	2	Cropping	Plains	Grey Vertosol	4	FALSE
Croppa Creek	NSW	-29.1	150.37	1	FALSE	fabas	2	Cropping	Plains	Grey Vertosol	4	FALSE
Croppa Creek	NSW	-29.1	150.37	1	FALSE	cotton	2	Cropping	Plains	Grey Vertosol	4	FALSE
Croppa Creek	NSW	-29.1	150.37	1	FALSE	wheat	2	Cropping	Plains	Grey Vertosol	4	FALSE
Dalby	QLD	-27.12	151.3	1	FALSE	sorghum	2	Cropping	Plains	Black Vertosol	4	FALSE
Dalby	QLD	-27.12	151.3	1	FALSE	cotton	2	Cropping	Plains	Black Vertosol	4	FALSE
Dalby	QLD	-27.12	151.3	1	FALSE	barley	2	Cropping	Plains	Black Vertosol	1	FALSE
Dooen	VIC	-36.67	142.3	2	FALSE	wheat	2	Cropping	Undulating Plains	Grey Cracking Clay (Ug 5.2)	4	FALSE
Dwellingup	WA	-32.65	116.07	2	FALSE	eucalyptus dominated	1	Forestry	Hillslope	Sand (coarse textured)	1	FALSE
East Beverly (good growth soil)	WA	-32.13	117.17	1	FALSE	barley and wheat	2	Cropping	Plain	Dy 2.82	3	TRUE
East Beverly (poor growth soil)	WA	-32.13	117.17	1	FALSE	barley and wheat	2	Cropping	Plain	Dy 2.82	1	TRUE
Edgeroi	NSW	-29.99	149.89	1	FALSE	wheat	2	Cropping	Plains	Brown Clay	1	FALSE
Edgeroi	NSW	-29.99	149.89	1	FALSE	cotton	2	Cropping	Plains	Brown Clay	3	FALSE
Esperance Valley	TAS	-43.3	146.92	2	FALSE	eucalypt forest (E. nitens)	1	Forestry	Assumed Hilly	Yellow Podzolic	5	TRUE
Greenmount	QLD	-27.77	151.92	1	FALSE	wheat	2	Cropping	Plains	Black Vertosol	4	FALSE
Griffith	NSW	-34.28	146.05	1	FALSE	wheat	2	Cropping	Plains	Hanwood Loam	3	FALSE
Gurley	NSW	-29.8	149.83	1	FALSE	wheat	2	Cropping	Plains	Box/Belah	4	FALSE
Hastings	TAS	-43.42	146.88	1	FALSE	eucalypt forest	1	Forestry	Undulating	Yellow Podzolic	5	FALSE
Haystack	QLD	-26.84	150.85	1	FALSE	wheat	2	Cropping	Plains	Grey Vertosol	1	FALSE
Hermitage	QLD	-28.21	152.1	1	FALSE	sorghum	2	Cropping	Plains	Brown Vertosol	3	FALSE
Hopelands	QLD	-26.87	150.56	1	FALSE	chickpea	2	Cropping	Plains	Grey Vertosol	1	FALSE
Hopelands	QLD	-26.87	150.56	1	FALSE	wheat	2	Cropping	Plains	Grey Vertosol	1	FALSE
Hopelands	QLD	-26.87	150.56	1	FALSE	cotton	2	Cropping	Plains	Grey Vertosol	2	FALSE
Hopelands 2	QLD	-26.86	150.64	1	FALSE	sorghum	2	Cropping	Plains	Grey Vertosol	4	FALSE
Hopelands 2	QLD	-26.86	150.64	1	FALSE	cotton	2	Cropping	Plains	Grey Vertosol	4	FALSE
Hopelands 2	QLD	-26.86	150.64	1	FALSE	wheat	2	Cropping	Plains	Grey Vertosol	1	FALSE
Hopelands 2	QLD	-26.86	150.64	1	FALSE	chickpea	2	Cropping	Plains	Grey Vertosol	1	FALSE
Huon A (1934 regrowth)	TAS	-43.05	146.72	1	FALSE	eucalypt forest	1	Forestry	Assumed Hilly	Krasnozem	5	FALSE
Huon B (1966 regrowth)	TAS	-43.1	146.77	1	FALSE	eucalypt forest	1	Forestry	Assumed Hilly	Krasnozem	5	FALSE
Huon C (1975 regrowth)	TAS	-43.08	146.73	1	FALSE	eucalypt forest	1	Forestry	Assumed Hilly	Krasnozem	5	FALSE
Jambin	QLD	-24.18	150.37	1	FALSE	wheat	2	Cropping	Plains	Cracking Clay	4	FALSE
Jambin 2	QLD	-24.18	150.43	1	FALSE	wheat	2	Cropping	Plains	Scrub	1	FALSE
Jandowae	QLD	-26.79	151.05	1	FALSE	wheat	2	Cropping	Plains	Grey Vertosol	1	FALSE
Jandowae	QLD	-26.79	151.05	1	FALSE	cotton	2	Cropping	Plains	Grey Vertosol	4	FALSE
Jandowae	QLD	-26.79	151.05	1	FALSE	sorghum	2	Cropping	Plains	Grey Vertosol	2	FALSE
Jandowae 2	QLD	-26.87	151.09	1	FALSE	barley	2	Cropping	Plains	Grey Vertosol	1	FALSE

Porosity/ bulk density	Soil depth (m)	Stored soil moisture (mm)	Active soil depth (m)	Active soil moisture store (mm)	Missing water	Start/stop	Rainfall	Rank of driest month	Rank of wettest month	Monitoring frequency	References
TRUE	3.1	332.3	3.1	332.3	FALSE	1970 - 1978	TRUE	0.005	0.005	2-6 Weeks	Howard and Langford (1971), Langford and O' Shaughnessy (1980)
TRUE	1.8	205.5	1.8	205.5	TRUE	N/A	FALSE	#N/A	#N/A	N/A	Dalgleish and Foale (1998)
TRUE	1.8	187.5	1.8	187.5	TRUE	N/A	FALSE	#N/A	#N/A	N/A	Dalgleish and Foale (1998)
TRUE	1.8	289.5	1.8	289.5	TRUE	N/A	FALSE	#N/A	#N/A	N/A	Dalgleish and Foale (1998)
TRUE	1.8	283.5	1.8	283.5	TRUE	N/A	FALSE	#N/A	#N/A	N/A	Dalgleish and Foale (1998)
TRUE	1.8	199.5	1.8	199.5	TRUE	N/A	FALSE	#N/A	#N/A	N/A	Dalgleish and Foale (1998)
TRUE	1.8	283.5	1.8	283.5	TRUE	N/A	FALSE	#N/A	#N/A	N/A	Dalgleish and Foale (1998)
TRUE	1.8	204	1.5	204	FALSE	N/A	FALSE	#N/A	#N/A	N/A	Dalgleish and Foale (1998)
TRUE	2	367	2	367	TRUE	1988 - 1991	TRUE	0	0.002	Irregular	O'Leary and Connor (1997), O'Leary and Connor (1996)
FALSE	15	519.19	9.25	459.2	FALSE	May 1984 -Oct 1986	TRUE	0.062	0.034 (upslope)	Fortnightly/Weekly	Ruprecht and Schofield (1990), Ruprecht and Schofield (1990)
FALSE	1.5	84.1	0.7	76.5	FALSE	1992 - 1994	TRUE	0.023	0.039	Fortnightly	Gregory (1998), Gregory *et al.,* (1992), Tennant *et al.,* (1992)
FALSE	1.5	94.7	0.5	94.7	FALSE	1992 - 1994	TRUE	0.023	0.039	Fortnightly	Gregory (1998), Gregory *et al.,* (1992), Tennant *et al.,* (1992)
TRUE	1.8	208.5	1.5	208.5	FALSE	N/A	FALSE	#N/A	#N/A	N/A	Dalgleish and Foale (1998)
TRUE	1.8	240	1.2	228	FALSE	N/A	FALSE	#N/A	#N/A	N/A	Dalgleish and Foale (1998)
FALSE	1.2	232.88	1.2	232.88	FALSE	Nov 1986-Apr 1988	TRUE	0.011	0.098	Fortnightly	Honeysett *et al.,* (1992)
TRUE	1.5	267	1.5	267	TRUE	N/A	FALSE	#N/A	#N/A	N/A	Dalgleish and Foale (1998)
TRUE	1.7	180.5	1.6	172	FALSE	1981 - 1984	TRUE	0.012	0	Weekly	Meyer (1992), Meyer *et al.,* (1990), Meyer *et al.,* (1987)
TRUE	1.8	175.5	1.8	175.5	TRUE	N/A	FALSE	#N/A	#N/A	N/A	Dalgleish and Foale (1998)
FALSE	3	369.05	3	369.05	FALSE	1976 - 1980	TRUE	0.002	0.048	2-3 Weeks	Nicolls *et al.,* (1982)
TRUE	1.8	220.5	1.5	220.5	FALSE	N/A	FALSE	#N/A	#N/A	N/A	Dalgleish and Foale (1998)
TRUE	1.8	216	1.2	208	TRUE	N/A	FALSE	#N/A	#N/A	N/A	Dalgleish and Foale (1998)
TRUE	1.8	157.5	1.5	157.5	FALSE	N/A	FALSE	#N/A	#N/A	N/A	Dalgleish and Foale (1998)
TRUE	1.8	174	1.5	174	FALSE	N/A	FALSE	#N/A	#N/A	N/A	Dalgleish and Foale (1998)
TRUE	1.8	168	1.8	168	FALSE	N/A	FALSE	#N/A	#N/A	N/A	Dalgleish and Foale (1998)
TRUE	1.8	220.5	1.8	220.5	TRUE	N/A	FALSE	#N/A	#N/A	N/A	Dalgleish and Foale (1998)
TRUE	1.8	229.5	1.8	229.5	TRUE	N/A	FALSE	#N/A	#N/A	N/A	Dalgleish and Foale (1998)
TRUE	1.8	208.5	1.5	208.5	FALSE	N/A	FALSE	#N/A	#N/A	N/A	Dalgleish and Foale (1998)
TRUE	1.8	201	1.5	201	FALSE	N/A	FALSE	#N/A	#N/A	N/A	Dalgleish and Foale (1998)
FALSE	2	178.6	2	178.6	FALSE	1976 - 1980	TRUE	0	0.017	2-3 Weeks	Nicolls *et al.,* (1982)
FALSE	2	253.8	2	253.8	FALSE	1976 - 1980	TRUE	0	0.017	2-3 Weeks	Nicolls *et al.,* (1982)
FALSE	2	176.25	2	176.25	FALSE	1976 - 1980	TRUE	0	0.017	2-3 Weeks	Nicolls *et al.,* (1982)
TRUE	1.5	156	1.5	156	TRUE	N/A	FALSE	#N/A	#N/A	N/A	Dalgleish and Foale (1998)
TRUE	1.8	138	1.5	138	FALSE	N/A	FALSE	#N/A	#N/A	N/A	Dalgleish and Foale (1998)
TRUE	1.8	199.5	1.5	199.5	FALSE	N/A	FALSE	#N/A	#N/A	N/A	Dalgleish and Foale (1998)
TRUE	1.8	241.5	1.8	241.5	TRUE	N/A	FALSE	#N/A	#N/A	N/A	Dalgleish and Foale (1998)
TRUE	1.8	199.5	1.8	199.5	FALSE	N/A	FALSE	#N/A	#N/A	N/A	Dalgleish and Foale (1998)
TRUE	1.8	186	1.5	186	FALSE	N/A	FALSE	#N/A	#N/A	N/A	Dalgleish and Foale (1998)

Site location	State	Latitude	Longitude	Reliability of location	Site map	Vegetation type	Generalised veg type	Landuse	Terrain	Soil type	Data type	Info on horizon depth
Jandowae 2	QLD	-26.87	151.09	1	FALSE	cotton	2	Cropping	Plains	Grey Vertosol	3	FALSE
Jimbour	QLD	-26.98	151.12	1	FALSE	chickpea	2	Cropping	Plains	Black Vertosol	4	FALSE
Jimbour	QLD	-26.98	151.12	1	FALSE	cotton	2	Cropping	Plains	Black Vertosol	4	FALSE
Jimbour	QLD	-26.98	151.12	1	FALSE	wheat	2	Cropping	Plains	Black Vertosol	1	FALSE
Kaimkillenbun	QLD	-27.07	151.41	1	FALSE	wheat	2	Cropping	Plains	Black Vertosol	4	FALSE
Kaimkillenbun	QLD	-27.07	151.41	1	FALSE	sorghum	2	Cropping	Plains	Black Vertosol	4	FALSE
Keith 1	SA	-35.88	139.58	2	FALSE	lucerne 2	2	Cropping/Grazing	Dunes	Sand	3	TRUE
Keith 1	SA	-35.88	139.58	2	FALSE	lucerne 1	2	Cropping/Grazing	Dunes	Sand	4	TRUE
Keith 2	SA	-35.9	139.68	2	FALSE	heath 4	1	Not Specified	Dunes	Sand	2	TRUE
Keith 2	SA	-35.9	139.68	2	FALSE	heath 1	1	Not Specified	Dunes	Sand	3	TRUE
Keith 2	SA	-35.9	139.68	2	FALSE	heath 3	1	Not Specified	Dunes	Sand	3	TRUE
Keith 2	SA	-35.9	139.68	2	FALSE	heath 2	1	Not Specified	Dunes	Sand	3	TRUE
Kojonup	WA	-33.75	116.75	1	FALSE	perennial pasture	3	Cropping/Grazing.	Plains	Sandy Duplex Soil (Dy 5.52)	5	TRUE
Kojonup	WA	-33.75	116.75	1	FALSE	annual pasture	3	Cropping/Grazing	Plains	Sandy Duplex Soil (Dy 5.52)	5	TRUE
Koomamurra	QLD	-27.22	151.36	1	FALSE	barley	2	Cropping	Plains	Grey Vertosol	4	FALSE
Koomamurra	QLD	-27.22	151.36	1	FALSE	cotton	2	Cropping	Plains	Grey Vertosol	4	FALSE
Koomamurra	QLD	-27.22	151.36	1	FALSE	sorghum	2	Cropping	Plains	Grey Vertosol	4	FALSE
Kupunn	QLD	-27.23	151.11	1	FALSE	chickpea	2	Cropping	Plains	Grey Vertosol	1	FALSE
Kupunn	QLD	-27.23	151.11	1	FALSE	cotton	2	Cropping	Plains	Grey Vertosol	2	FALSE
Kupunn	QLD	-27.23	151.11	1	FALSE	wheat	2	Cropping	Plains	Grey Vertosol	1	FALSE
Lawes	QLD	-27.54	152.34	1	FALSE	sorghum	2	Cropping	Plains	Black Vertosol	4	FALSE
Lawes	QLD	-27.54	152.34	1	FALSE	chickpea	2	Cropping	Plains	Black Vertosol	2	FALSE
Lawes 2	QLD	-27.54	152.34	1	FALSE	chickpea	2	Cropping	Plains	Prarie Soil	3	FALSE
Lawes 2	QLD	-27.54	152.34	1	FALSE	wheat	2	Cropping	Plains	Prarie Soil	1	FALSE
Lemon Tree	QLD	-27.75	151.24	1	FALSE	cotton	2	Cropping	Plains	Brown Clay	4	FALSE
Lemon Tree	QLD	-27.75	151.24	1	FALSE	barley	2	Cropping	Plains	Brown Clay	3	FALSE
Lidsdale (Catchment 2)	NSW	-33.43	150.07	1	TRUE	radiata pine	1	Forestry	Hills	Dy 3.41/Dy 2.61	4	TRUE
Lidsdale (Catchment 6)	NSW	-33.43	150.07	1	TRUE	eucalyptus dominated	1	Forestry	Hills	Dy 3.41/Dy 2.61	4	TRUE
Lockhart	NSW	-35.2	146.7	2	FALSE	wheat	2	Cropping	Plains	Red-Brown Earth	2	TRUE
Lockyersleigh (site A)	NSW	-34.69	145.92	1	TRUE	grassland	3	Grazing	Undulating Plains	Duplex	6	TRUE
Lockyersleigh (site B)	NSW	-34.69	145.92	1	TRUE	grassland	3	Grazing	Undulating Plains	Duplex	6	TRUE
Lockyersleigh (site C)	NSW	-34.69	145.92	1	TRUE	grassland	3	Grazing	Undulating Plains	Duplex	6	FALSE
Massie	QLD	-28.14	151.93	1	FALSE	sorghum	2	Cropping	Plains	Black Vertosol	4	FALSE
Moura	QLD	-24.83	149.78	1	FALSE	Zero Tillage	4	Cropping	Plains	Sandy Clay Loam (Dy 3.33/Db 2.33)	6	TRUE
Moura	QLD	-24.83	149.78	1	FALSE	Reduced Tillage	4	Cropping	Plains	Sandy Clay Loam (Dy 3.33/Db 2.33)	6	TRUE
Moura	QLD	-24.83	149.78	1	FALSE	Conventional Tillage	4	Cropping	Plains	Sandy Clay Loam (Dy 3.33/Db 2.33)	6	TRUE
Mt Carmel	QLD	-28.13	150.4	1	FALSE	sorghum	2	Cropping	Plains	Mt Carmel	4	FALSE
Mt Carmel	QLD	-28.13	150.4	1	FALSE	faba bean	2	Cropping	Plains	Mt Carmel	1	FALSE
Mt Carmel	QLD	-28.13	150.4	1	FALSE	wheat	2	Cropping	Plains	Mt Carmel	1	FALSE

Porosity/ bulk density	Soil depth (m)	Stored soil moisture (mm)	Active soil depth (m)	Active soil moisture store (mm)	Missing water	Start/stop	Rainfall	Rank of driest month	Rank of wettest month	Monitoring frequency	References
TRUE	1.8	207	1.2	204	FALSE	N/A	FALSE	#N/A	#N/A	N/A	Dalgleish and Foale (1998)
TRUE	1.8	201	1.8	201	TRUE	N/A	FALSE	#N/A	#N/A	N/A	Dalgleish and Foale (1998)
TRUE	1.8	267	1.8	267	TRUE	N/A	FALSE	#N/A	#N/A	N/A	Dalgleish and Foale (1998)
TRUE	1.8	228	1.5	228	FALSE	N/A	FALSE	#N/A	#N/A	N/A	Dalgleish and Foale (1998)
TRUE	1.8	34.5	1.8	34.5	TRUE	N/A	FALSE	#N/A	#N/A	N/A	Dalgleish and Foale (1998)
TRUE	1.8	289.5	1.8	289.5	TRUE	N/A	FALSE	#N/A	#N/A	N/A	Dalgleish and Foale (1998)
FALSE	5.7	262.2	4.5	227.3	FALSE	Apr 1956-Mar1958	TRUE	0.004	0.039	Every 3 Weeks	Holmes (1960)
FALSE	5.7	434.52	5.7	434.52	TRUE	Apr 1956 -Mar 1958	TRUE	0.004	0.039	Every 3 Weeks	Holmes (1960)
FALSE	5.7	368.2	5.7	368.2	TRUE	Apr 1956-Mar 1958	TRUE	0.004	0.039	Every 3 Weeks	Holmes (1960)
FALSE	5.7	287.5	3.3	254.4	TRUE	Apr 1956-Mar 1958	TRUE	0.004	0.039	Every 3 Weeks	Holmes (1960)
FALSE	5.7	324.3	4.5	321	FALSE	Apr 1956-Mar 1958	TRUE	0.004	0.039	Every 3 Weeks	Holmes (1960)
FALSE	5.7	282.8	3.6	257.3	TRUE	Apr 1956-Mar 1958	TRUE	0.004	0.039	Every 3 Weeks	Holmes (1960)
FALSE	1	136.97	1	136.97	FALSE	July 1995-Mar 1999	TRUE	0.009	0.014	2-5 Weeks	Dolling (2001)
FALSE	1	88.49	1	88.49	FALSE	July 1995-Mar 1999	TRUE	0.009	0.014	2-5 Weeks	Dolling (2001)
TRUE	1.8	187.5	1.8	187.5	TRUE	N/A	FALSE	#N/A	#N/A	N/A	Dalgleish and Foale (1998)
TRUE	1.8	225	1.8	225	TRUE	N/A	FALSE	#N/A	#N/A	N/A	Dalgleish and Foale (1998)
TRUE	1.8	178.5	1.8	178.5	TRUE	N/A	FALSE	#N/A	#N/A	N/A	Dalgleish and Foale (1998)
TRUE	1.8	192	1.5	195	FALSE	N/A	FALSE	#N/A	#N/A	N/A	Dalgleish and Foale (1998)
TRUE	1.8	231	1.8	231	FALSE	N/A	FALSE	#N/A	#N/A	N/A	Dalgleish and Foale (1998)
TRUE	1.8	163.5	1.5	166.5	FALSE	N/A	FALSE	#N/A	#N/A	N/A	Dalgleish and Foale (1998)
TRUE	1.8	189	1.8	189	TRUE	N/A	FALSE	#N/A	#N/A	N/A	Dalgleish and Foale (1998)
TRUE	1.8	210	1.8	210	FALSE	N/A	FALSE	#N/A	#N/A	N/A	Dalgleish and Foale (1998)
TRUE	1.8	234	1.5	231	FALSE	N/A	FALSE	#N/A	#N/A	N/A	Dalgleish and Foale (1998)
TRUE	1.8	274.5	1.5	274.5	FALSE	N/A	FALSE	#N/A	#N/A	N/A	Dalgleish and Foale (1998)
TRUE	1.8	153	1.8	153	TRUE	N/A	FALSE	#N/A	#N/A	N/A	Dalgleish and Foale (1998)
TRUE	1.8	162	1.5	159	FALSE	N/A	FALSE	#N/A	#N/A	N/A	Dalgleish and Foale (1998)
FALSE	2.2	233.9	2.2	233.9	TRUE	Oct 1968-Apr 1971	TRUE	0.004	0.041	Weekly	Pilgrim *et al.,* (1982), Smith et al. (1974), Smith *et al.,* (1974)
FALSE	2.2	298.4	2.2	298.4	TRUE	Oct 1968-Apr 1971	TRUE	0.004	0.041	Weekly	Pilgrim *et al.,* (1982), Smith et al. (1974), Smith *et al.,* (1974)
TRUE	1.6	164	1.6	164	TRUE	1980 - 1983	TRUE	0.005	0.032	Weekly	Mason and Fischer (1986)
TRUE	1.5	150.4	1.5	150.4	FALSE	Jan 1987-Jul 1990	TRUE	0.114	0.009	1-2 Weekly	Kalma *et al.,* (1995), Alksnis et al. (1990)
TRUE	1.5	264.5	1.5	264.5	FALSE	Jan 1987-Jul 1990	TRUE	0.114	0.009	1-2 Weekly	Kalma *et al.,* (1995), Alksnis et al. (1990)
TRUE	1.5	181.1	1.5	181.1	FALSE	Jan 1987-Jul 1990	TRUE	0.114	0.009	1-2 Weekly	Kalma *et al.,* (1995), Alksnis et al. (1990)
TRUE	1.8	249	1.8	249	TRUE	N/A	FALSE	#N/A	#N/A	N/A	Dalgleish and Foale (1998)
TRUE	1.8	264	1.8	264	FALSE	1986 - 1989	TRUE	0.062	0.024	6 Weeks	Lawrence *et al.,* (1994)
TRUE	1.8	237	1.8	237	FALSE	1986 - 1989	TRUE	0.062	0.024	6 Weeks	Lawrence *et al.,* (1994
TRUE	1.8	236	1.8	236	FALSE	1986 - 1989	TRUE	0.062	0.024	6 Weeks	Lawrence *et al.,* (1994)
TRUE	1.8	216	1.8	216	TRUE	N/A	FALSE	#N/A	#N/A	N/A	Dalgleish and Foale (1998)
TRUE	1.8	157.5	1.5	157.5	FALSE	N/A	FALSE	#N/A	#N/A	N/A	Dalgleish and Foale (1998)
TRUE	1.8	219	1.5	219	FALSE	N/A	FALSE	#N/A	#N/A	N/A	Dalgleish and Foale (1998)

Site location	State	Latitude	Longitude	Reliability of location	Site map	Vegetation type	Generalised veg type	Landuse	Terrain	Soil type	Data type	Info on horizon depth
Mt Carmel	QLD	-28.13	150.4	1	FALSE	cotton	2	Cropping	Plains	Mt Carmel	1	FALSE
Mt Gambier (Grassland)	SA	-37.83	140.83	1	FALSE	pasture	3	Grazing	Plains	Dy 5.42	6	TRUE
Mt Gambier (Kalangadoo Sand)	SA	-37.58	140.75	2	FALSE	monterey pine	1	Forestry	Plains	Dy 5.42	1	FALSE
Mt Gambier (Young Sand)	SA	-37.83	140.67	2	FALSE	monterey pine	1	Forestry	Plains	Uc 2.33	1	TRUE
Narrabri	NSW	-30.22	149.78	1	FALSE	cotton	2	Cropping	Plains	Ug 5.25	4	FALSE
Nerrigundah	NSW	-32.3	151.72	2	TRUE	pasture	3	Grazing	Undulating	Loam Based	5	TRUE
North Maroondah (Black Spur 1)	VIC	-37.6	145.63	1	TRUE	mountain ash	1	Forestry	Hilly	Krasnozem	5	FALSE
North Maroondah (Black Spur 2)	VIC	-37.6	145.63	1	TRUE	mountain ash	1	Forestry	Hilly	Krasnozem	5	FALSE
North Maroondah (Black Spur 3)	VIC	-37.6	145.63	1	TRUE	mountain ash	1	Forestry	Hilly	Krasnozem	5	FALSE
North Maroondah (Black Spur 4)	VIC	-37.6	145.63	1	TRUE	mountain ash	1	Forestry	Hilly	Krasnozem	5	FALSE
North Moree	NSW	-29.09	149.97	1	FALSE	cotton	2	Cropping	Plains	Grey Vertosol	4	FALSE
North Moree	NSW	-29.09	149.97	1	FALSE	wheat	2	Cropping	Plains	Grey Vertosol	1	FALSE
North Moree 2	NSW	-29.04	149.93	1	FALSE	barley	2	Cropping	Plains	Grey Vertosol	2	FALSE
North Moree 2	NSW	-29.04	149.93	1	FALSE	chickpea	2	Cropping	Plains	Grey Vertosol	1	FALSE
North Moree 2	NSW	-29.04	149.93	1	FALSE	faba bean	2	Cropping	Plains	Grey Vertosol	1	FALSE
Northfield	SA	-34.85	138.63	2	FALSE	plain fallow	4	Cropping/Grazing	Plains	Black Earth (Ug 5.11)	5	TRUE
Northfield	SA	-34.85	138.63	2	FALSE	fallow then wheat	2	Cropping/Grazing	Plains	Black Earth (Ug 5.11)	5	TRUE
Northfield	SA	-34.85	138.63	2	FALSE	plain grassland	3	Cropping/Grazing	Plains	Black Earth (Ug 5.11)	5	TRUE
Northfield	SA	-34.85	138.63	2	FALSE	grassland then wheat	2	Cropping/Grazing	Plains	Black Earth (Ug 5.11)	5	TRUE
Old Junee	NSW	-34.83	147.5	2	FALSE	annual pasture	3	Cropping/Grazing	Undulating Plains	Red-Brown Earth (Dr 2.42)	5	FALSE
Old Junee	NSW	-34.83	147.5	2	FALSE	lucerne	2	Cropping/Grazing	Undulating Plains	Red-Brown Earth (Dr 2.42)	5	FALSE
Old Junee	NSW	-34.83	147.5	2	FALSE	wheat	2	Cropping/Grazing	Undulating Plains	Red-Brown Earth (Dr 2.42)	5	FALSE
Pallamallawa	NSW	-29.36	150.07	1	FALSE	wheat	2	Cropping	Plains	Brown Clay	2	FALSE
Parafield	SA	-34.8	138.62	2	FALSE	grassland then wheat	2	Cropping/Grazing	Plains	Dr 2.13	5	TRUE
Parafield	SA	-34.8	138.62	2	FALSE	fallow + straw then wheat	2	Cropping/Grazing	Plains	Dr 2.13	5	TRUE
Parafield	SA	-34.8	138.62	2	FALSE	fallow then wheat	2	Cropping/Grazing	Plains	Dr 2.13	5	TRUE
Parafield	SA	-34.8	138.62	2	FALSE	fallow and straw	4	Cropping/Grazing	Plains	Dr 2.13	5	TRUE
Parafield	SA	-34.8	138.62	2	FALSE	fallow	4	Cropping/Grazing	Plains	Dr 2.13	5	TRUE
Parafield	SA	-34.8	138.62	2	FALSE	grassland	3	Cropping/Grazing	Plains	Dr 2.13	5	TRUE
Pingrup	WA	-33.53	118.5	2	FALSE	lucerne	2	Cropping/Grazing	Plains	Solodized Solonetz (Db 4.33)	5	FALSE
Pingrup	WA	-33.53	118.5	2	FALSE	medic	3	Cropping/Grazing	Plains	Solodized Solonetz (Db 4.33)	5	FALSE
Pinjarra	WA	-32.62	115.87	2	FALSE	pasture (Eragrostis curvula)	3	Cropping/Grazing	Plains	Spearwood Sand	1	FALSE
Pinjarra	WA	-32.62	115.87	2	FALSE	pasture (Bromus Mollis)	3	Cropping/Grazing	Plains	Spearwood Sand	1	FALSE
Point Nepean	VIC	-38.42	144.92	1	TRUE	pasture	3	Grazing	Undulating	Sand Based (Uc 1)	2	FALSE
Puckapunyal (Depression)	VIC	-37	145.12	2	FALSE	forest	1	Forestry	Undulating	Not Stated	4	TRUE
Puckapunyal (Depression)	VIC	-37	145.12	2	FALSE	grassland	3	Grazing	Undulating	Not Stated	2	TRUE

Porosity/ bulk density	Soil depth (m)	Stored soil moisture (mm)	Active soil depth (m)	Active soil moisture store (mm)	Missing water	Start/stop	Rainfall	Rank of driest month	Rank of wettest month	Monitoring frequency	References
TRUE	1.8	217.5	1.5	217.5	FALSE	N/A	FALSE	#N/A	#N/A	N/A	Dalgleish and Foale (1998)
FALSE	2.25	209	2.25	209	FALSE	1960 - 1965	TRUE	0.006	0	Monthly	Holmes and Colville (1970), Holmes and Colville (1970)
FALSE	7.5	642.9	2.7	400	FALSE	Apr 1963 May 1966	TRUE	0.006	0	Monthly	Holmes and Colville (1970), Holmes and Colville (1970)
FALSE	8.7	233	5.4	200	FALSE	Apr 1963-May 1966	TRUE	0.006	0	Monthly	Holmes and Colville (1970), Holmes and Colville (1970)
TRUE	1.5	199.4	1.5	199.4	TRUE	Sept 1979 June 1980	TRUE	0.083	0.102	Every 6 Weeks	Hodgson and Chan (1987), Chan and Hodgson (1981)
FALSE	0.43	159	0.43	159	TRUE	Aug 1997-Oct 1998	TRUE	0.045	0.039	Weekly/Fortnightly	Walker (1999)
FALSE	5.2	405.22	5.2	405.22	TRUE	July 1973 - 1976	TRUE	0.027	0.031	Monthly/Weekly	Creaner (1988), Langford and O' Shaughnessy (1977)
FALSE	3	246.05	3	246.05	TRUE	July 1973 - 1976	TRUE	0.027	0.031	Monthly/Weekly	Creaner (1988), Langford and O' Shaughnessy (1977)
FALSE	5.2	405.02	5.2	405.02	TRUE	July 1973 - 1976	TRUE	0.027	0.031	Monthly/Weekly	Creaner (1988), Langford and O' Shaughnessy (1977)
FALSE	3	268.55	3	268.55	TRUE	July 1973 - 1976	TRUE	0.027	0.031	Monthly/Weekly	Creaner (1988), Langford and O' Shaughnessy (1977)
TRUE	1.8	220	1.8	220	TRUE	N/A	FALSE	#N/A	#N/A	N/A	Dalgleish and Foale (1998)
TRUE	1.8	201	1.5	201	FALSE	N/A	FALSE	#N/A	#N/A	N/A	Dalgleish and Foale (1998)
TRUE	1.8	165	1.8	165	FALSE	N/A	FALSE	#N/A	#N/A	N/A	Dalgleish and Foale (1998)
TRUE	1.8	132	1.2	132	FALSE	N/A	FALSE	#N/A	#N/A	N/A	Dalgleish and Foale (1998)
TRUE	1.8	126	1.5	126	FALSE	N/A	FALSE	#N/A	#N/A	N/A	Dalgleish and Foale (1998)
FALSE	1.8	168.4	1.8	168.4	FALSE	1963 - 1966	TRUE	0.002	0.021	2-3 Weekly	Schultz (1971)
FALSE	1.8	214	1.8	214	FALSE	1963 - 1966	TRUE	0.002	0.021	2-3 Weekly	Schultz (1971)
FALSE	1.8	262.5	1.8	262.5	FALSE	1963 - 1966	TRUE	0.002	0.021	2-3 Weekly	Schultz (1971)
FALSE	1.8	217.7	1.8	217.7	FALSE	1963 - 1966	TRUE	0.002	0.021	2-3 Weekly	Schultz (1971)
FALSE	2	194.5	2	194.5	FALSE	Jan 1992-Jan 1998	TRUE	0	0.019	Twice Yearly	Angus *et al.,* (2001)
FALSE	2	224.3	2	224.3	FALSE	Jan 1992-Jan 1998	TRUE	0	0.019	Twice Yearly	Angus *et al.,* (2001)
FALSE	2	294.5	2	294.5	FALSE	Jan 1992-Jan1998	TRUE	0	0.019	Twice Yearly	Angus *et al.,* (2001)
TRUE	1.8	139.5	1.8	139.5	FALSE	N/A	FALSE	#N/A	#N/A	N/A	Dalgleish and Foale (1998)
FALSE	1.95	106.9	1.95	106.9	FALSE	Oct 1966 -Oct 1968	TRUE	0.015	0.01	2-3 Weeks	Schultz (1972)
FALSE	1.95	113.2	1.95	113.2	FALSE	Oct 1966-Oct 1968	TRUE	0.015	0.01	2-3 Weeks	Schultz (1972)
FALSE	1.95	88.8	1.95	88.8	FALSE	Oct 1966-Oct 1968	TRUE	0.015	0.01	2-3 Weeks	Schultz (1972)
FALSE	1.95	136.4	1.95	136.4	FALSE	Oct 1966-Oct 1968	TRUE	0.015	0.01	2-3 Weeks	Schultz (1972)
FALSE	1.95	106.4	1.95	106.4	FALSE	Oct 1966-Oct 1968	TRUE	0.015	0.01	2-3 Weeks	Schultz (1972)
FALSE	1.95	106.5	1.95	106.5	FALSE	Oct 1966-Oct 1968	TRUE	0.015	0.01	2-3 Weeks	Schultz (1972)
FALSE	1.5	56.04	1.5	56.04	FALSE	Oct 1996-Dec 1999	TRUE	0.011	0.053	Every 3 Months	Latta *et al.,* (2001)
FALSE	1.5	26.3	1.5	26.3	FALSE	Oct 1996-Dec 1999	TRUE	0.011	0.053	Every 3 Months	Latta *et al.,* (2001)
FALSE	6	250.3	5	252.6	FALSE	Nov 1965-Nov 1967	TRUE	0.137	0.01	Every 6 Weeks	Carbon *et al.,* (1982)
FALSE	6	265.2	5.67	269.3	FALSE	Nove 1965-Nov 1967	TRUE	0.137	0.01	Every 6 Weeks	Carbon *et al.,* (1982)
TRUE	2.29	120	2.29	120	FALSE	Sept 1998-Feb 2000	TRUE	#N/A	#N/A	Monthly/2 Monthly	Andrew Western (pers.comm.)
FALSE	1	220.4	1	220.4	TRUE	Apr 1981-Jun 1983	TRUE	0.012	0.017	Fortnightly	Burch *et al.,* (1983)
FALSE	1	163	1	163	TRUE	Apr 1981-Jun 1983	TRUE	0.012	0.017	Fortnightly	Burch *et al.,* (1983)

Site location	State	Latitude	Longitude	Reliability of location	Site map	Vegetation type	Generalised veg type	Landuse	Terrain	Soil type	Data type	Info on horizon depth
Puckapunyal (Lower Slope)	VIC	-37	145.12	2	FALSE	grassland	3	Grazing	Undulating	Not Stated	4	TRUE
Puckapunyal (Lower Slope)	VIC	-37	145.12	2	FALSE	forest	1	Forestry	Undulating	Not Sated	4	TRUE
Redvale	QLD	-26.54	151.84	1	FALSE	peanuts	2	Cropping	Plains	Red Ferrosol	4	FALSE
Roma Res Stn	QLD	-26.63	148.87	1	FALSE	wheat	2	Cropping	Plains	Brown Vertosol	4	FALSE
Rutherglen	VIC	-36.1	146.5	1	FALSE	continuous lucerne	2	Cropping/Grazing	Plains	Red-Brown Earth (Dr 3.22)	5	TRUE
Rutherglen	VIC	-36.1	146.5	1	FALSE	annual pasture	3	Cropping/Grazing	Plains	Red-Brown Earth (Dr 3.22)	5	TRUE
Simmonds Marsh	TAS	-43.12	147.9	1	FALSE	eucalypt forest	1	Forestry	Flat	Krasnozem	5	FALSE
Sorell	TAS	-42.78	147.57	1	FALSE	eucalypt forest (E. globus)	1	Forestry	Undulating	Chocolate Soil	5	FALSE
Sorell	TAS	-42.78	147.57	1	FALSE	eucalypt forest (E. nitens)	1	Forestry	Undulating	Chocolate Soil	5	FALSE
Spring Ridge	NSW	-31.33	150.23	1	FALSE	sorghum	2	Cropping	Plains	Black Vertosol	3	FALSE
Spring Ridge	NSW	-31.33	150.23	1	FALSE	sunflower	2	Cropping	Plains	Black Vertosol	2	FALSE
Storm Hill	TAS	-43.28	146.97	1	FALSE	eucalypt forest	1	Forestry	Assumed Hilly	Krasnozem	5	FALSE
Tarrawarra	VIC	-37.65	145.43	1	FALSE	pasture	3	Grazing	Undulating Hills	Duplex/Gradational	6	TRUE
Three Springs (upslope)	WA	-30.5	115.75	1	FALSE	wheat	2	Cropping	Plains	Sand Based (site dependent)	1	TRUE
Three Springs (upslope)	WA	-30.5	115.75	1	FALSE	lupin	2	Cropping	Plains	Sand Based (site dependent)	4	TRUE
Three Springs (upslope)	WA	-30.5	115.75	1	FALSE	cereal rye	2	Cropping	Plains	Sand Based (site dependent)	4	TRUE
Townsville (soil 1)	QLD	-19.65	146.83	2	FALSE	townsville stylo pods, legumes, annual grasses	3	Grazing	Plains	Landsdown Sandy Loam (Solodized Solonetz)	3	TRUE
Townsville (soil 2)	QLD	-19.65	146.83	2	FALSE	townsville stylo pods, legumes, annual grasses	3	Grazing	Plains	Stockyard Loam (Solodic)	2	TRUE
Townsville (soil 3)	QLD	-19.65	146.83	2	FALSE	townsville stylo pods, legumes, annual grasses	3	Grazing	Plains	Double Barrel Loam (Red Podzol)	4	TRUE
Trangie	NSW	-31.98	147.95	1	FALSE	soybean	2	Cropping	Plains	Grey-Brown Clay (Ug 6.3)	1	TRUE
Wallumbilla	QLD	-26.49	149.1	1	FALSE	wheat	2	Cropping	Plains	Brown Sodosol	4	FALSE
Wallumbilla	QLD	-26.49	149.1	1	FALSE	buffel/medic	2	Cropping	Plains	Brown Sodosol	4	FALSE
Walpeup	VIC	-35.12	142.02	1	FALSE	wheat	2	Cropping	Undulating Plains	Sandy Loam (Gc 1.22)	4	FALSE
Warra	QLD	-26.9	150.9	1	FALSE	cotton	2	Cropping	Plains	Grey Vertosol	3	FALSE
Wellcamp	QLD	-27.57	151.86	1	FALSE	wheat	2	Cropping	Plains	Black Vertosol	1	FALSE
West of Brigalow	QLD	-26.82	150.75	1	FALSE	wheat	2	Cropping	Plains	Grey Vertosol	3	FALSE
West of Brigalow	QLD	-26.82	150.75	1	FALSE	cotton	2	Cropping	Plains	Grey Vertosol	4	FALSE
Wongan Hills	WA	-30.75	116.67	1	FALSE	tagasaste	1	Forestry/Grazing	Plains	Sand	5	TRUE
Wongan Hills	WA	-30.75	116.67	1	FALSE	fallow	4	Cropping/Grazing	Plains	Sand	5	TRUE
Yanchep	WA	-31.63	115.9	1	FALSE	banksia	1	Not Specified	Plains	Garvin Sand	5	TRUE
Yanco	NSW	-34.66	146.38	2	FALSE	wheat	2	Cropping	Gentle Slope	Red-Brown Earth	3	TRUE
Yarralaw	NSW	-34.27	149.88	1	TRUE	grassland	3	Grazing	Undulating Plains	Duplex	4	TRUE

Porosity/ bulk density	Soil depth (m)	Stored soil moisture (mm)	Active soil depth (m)	Active soil moisture store (mm)	Missing water	Start/stop	Rainfall	Rank of driest month	Rank of wettest month	Monitoring frequency	References
FALSE	1	163.6	1	163.6	TRUE	Apr 1981-Jun 1983	TRUE	0.012	0.017	Fortnightly	Burch *et al.,* (1983)
FALSE	1	202.4	1	202.4	TRUE	Apr 198 -Jun 1983	TRUE	0.012	0.017	Fortnightly	Burch *et al.,* (1983)
TRUE	1.8	109	1.8	109	TRUE	N/A	FALSE	#N/A	#N/A	N/A	Dalgleish and Foale (1998)
TRUE	0.7	119	0.7	119	TRUE	N/A	FALSE	#N/A	#N/A	N/A	Dalgleish and Foale (1998)
FALSE	1.8	226.76	1.8	226.76	FALSE	Sept 1995-Dec 1999	TRUE	0.018	0.07	Fortnightly	Ridley *et al.,* (2001), Ridley *et al.,* (1997)
FALSE	1.8	153.52	1.8	153.52	FALSE	Sept 1995-Dec1999	TRUE	0.018	0.07	Fortnightly	Ridley *et al.,* (2001), Ridley et al. (1997)
FALSE	2	164.5	2	164.5	FALSE	1976 - 1980	TRUE	0.015	0.041	2-3 Weeks	Nicolls *et al.,* (1982)
FALSE	1	134.12	1	134.12	FALSE	July 1991-July 1994	TRUE	0.004	0.006	Fortnightly	Honeysett *et al.,* (1996)
FALSE	1	114.12	1	114.12	FALSE	July 1991-July 1994	TRUE	0.004	0.006	Fortnightly	Honeysett *et al.,* (1996)
TRUE	1.8	171	1.2	165	FALSE	N/A	FALSE	#N/A	#N/A	N/A	Dalgleish and Foale (1998)
TRUE	1.8	213	1.8	213	FALSE	N/A	FALSE	#N/A	#N/A	N/A	Dalgleish and Foale (1998)
FALSE	2	364.25	2	364.25	FALSE	1976 - 1980	TRUE	0.001	0.058	2-3 Weeks	Nicolls *et al.,* (1982)
TRUE	1.19	208	1.19	208	FALSE	Sept 1995-Nov 1997	TRUE	0.008	0.073	Fortnightly	Western *et al.,* (1999), Western and Grayson (1998)
TRUE	1.9	72.7	1.7	77.3	FALSE	Jan 1984-Dec1985	TRUE	0.050	0.019	Fortnightly	Hamblin *et al.,* (1988)
TRUE	1.9	92.1	1.9	92.1	FALSE	Jan 1984-Dec 1985	TRUE	0.050	0.019	Fortnightly	Hamblin (upslope) *et al.,* (1988)
TRUE	1.9	108.9	1.9	108.9	FALSE	Jan 1984-Dec 1985	TRUE	0.050	0.019	Fortnightly	Hamblin *et al.,* (1988)
FALSE	0.87	73.03	0.5	63.4	FALSE	Feb 1968-Aug 1968	TRUE	0.02	0.013	Weekly	McCown *et al.,* (1976), McCown (1971)
FALSE	1.06	146.8	1.06	146.8	TRUE	Feb 1968- Aug 1968	TRUE	0.02	0.013	Weekly	McCown *et al.,* (1976), McCown (1971)
FALSE	1.49	168.1	1.49	168.1	TRUE	Feb 1968-Aug 1968	TRUE	0.02	0.013	Weekly	McCown *et al.,* (1976), McCown (1971)
FALSE	1.2	72.9	1.07	72.9	FALSE	1982 - 1984	TRUE	0.006	0.01	not stated	McKenzie *et al.,* (1990)
TRUE	1.5	199	1.5	199	TRUE	N/A	FALSE	#N/A	#N/A	N/A	Dalgleish and Foale (1998)
TRUE	1.5	189	1.5	189	TRUE	N/A	FALSE	#N/A	#N/A	N/A	Dalgleish and Foale (1998)
TRUE	1.5	121	1.5	121	FALSE	1988 - 1991	TRUE	0.004	0.027	Irregular	O'Leary and Connor (1997), O'Leary and Connor (1996)
TRUE	1.8	207	1.5	201	FALSE	N/A	FALSE	#N/A	#N/A	N/A	Dalgleish and Foale (1998)
TRUE	1.8	250.5	1.5	250.5	TRUE	N/A	FALSE	#N/A	#N/A	N/A	Dalgleish and Foale (1998)
TRUE	1.8	190.5	1.5	187.5	FALSE	N/A	FALSE	#N/A	#N/A	N/A	Dalgleish and Foale (1998)
TRUE	1.8	265.5	1.8	265.5	TRUE	N/A	FALSE	#N/A	#N/A	N/A	Dalgleish and Foale (1998)
FALSE	3.7	254	3.7	254	FALSE	July 1996-Dec 1998	TRUE	0	0.041	Monthly/Fortnightly	Lefroy *et al.,* (2001)
FALSE	3.7	154	3.7	154	FALSE	July 1996-Dec 1998	TRUE	0	0.041	Monthly/Fortnightly	Lefroy *et al.,* (2001)
FALSE	5.8	307.31	5.8	307.31	FALSE	Aut 1982-Aut 1985	TRUE	0.022	0.02	Monthly	Sharma *et al.,* (1989), Sharma and Craig (1989), Farrington and Bartle (1989)
TRUE	1.4	143	1.2	140	FALSE	Sept 1981-June 1984	TRUE	0.011	0.006	Weekly	Fischer *et al.,* (1988)
FALSE	1.6	168.5	1.6	168.5	TRUE	May 1985-Oct 1986	TRUE	0.052	0.014	Weekly	Bullock and Neil (1990), Bullock (1987)

Appendix 5 – Conference Paper

Ladson, A. R., Lander, J., Western, A., Grayson, R. B., Zhang, L. (2002) Estimating extractable soil moisture content for Australian Soils. 27th Hydrology and Water Resources Symposium. Melbourne. May 2003. (Conference proceedings published on CD). Institution of Engineers, Australia

ESTIMATING EXTRACTABLE SOIL MOISTURE CONTENT FOR AUSTRALIAN SOILS

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Abstract

The amount of water that can be stored in soil and actively used by plants, is a key parameter in hydrologic models and is important for crop and pasture production. Often the active soil moisture store is estimated from laboratory measurements of soil properties. An alternative approach, described in this paper, is to estimate the extractable soil moisture capacity from direct measurements of soil moisture content in the field. A time series of soil moisture values, over the depth of the soil, shows the actual changes in water content. The difference between the wettest and driest profiles is an estimate of the dynamic soil moisture store. We have gathered data on extractable soil water capacity for 180 locations over Australia and have compared our values with published results from the Atlas of Australian Soils, derived from profile descriptions and pedo-transfer functions. Preliminary results show that data from the Atlas of Australian soils provide a useful lower bound for measured dynamic soil moisture storage, but of the sites examined, 42% had extractable stores greater than two-times the AAS values. This was due to estimates of total soil depth that were underestimated in the AAS results compared to the active depths apparent in the data. These depths were strongly related to vegetation type.

Key Words: extractable soil moisture, soil water, dynamic soil store, Atlas of Australian Soils.

Introduction

The amount of water that can be stored in soil and actively used by plants is a key parameter in hydrologic models, weather prediction models and is important for crop and pasture production. Broad scale estimates of the dynamic soil store are available using data from the Atlas of Australian Soils (AAS) but there has been limited validation of the results. This paper describes the collection of soil moisture storage data, based on field measurements, and a preliminary comparison with AAS values.

Extractable Soil Moisture

A key feature of this project is the estimation of extractable soil moisture from field measurements. This contrasts with the standard approach where, the maximum available soil water store is determined from parameters estimated in a laboratory. Generally, soil samples are analysed in a laboratory to determine the moisture content at the lower limit of availability to plants (–15 bar) and at "field capacity" (commonly –0.10 bar to -0.33 bar). The difference between these values, often called plant available water (PAW), gives an estimate of the maximum amount of water that can be stored in the soil and used by plants, provided a soil (or rooting) depth is assumed. It is common for relationships to be formed between laboratory derived PAW, and soil properties such as soil texture. This procedure, known as the pedo-transfer approach, allows information from standard soils maps to be used to infer, and map, PAW (Williams, 1983).

Ritchie (1981) noted the practical problems associated with the estimation of plant available water using this approach. Accurate estimates depend on knowledge of field capacity, permanent wilting point and bulk density for the whole profile within the root zone. In reality these parameters are likely to change vertically within the profile and between profiles. Estimates of the rooting depth are also likely to be subject to error.

There is also the issue of which soil water potentials used in the analysis actually correspond to 'true' field capacity and permanent wilting point.

As an alternative approach, Ritchie (1981) suggested the concept of extractable soil moisture as a practical way of overcoming some of the problems associated with estimating available soil moisture from laboratory measurements. The extractable moisture is defined as the difference between the highest measured volumetric water content in the field (after drainage) and the lowest measured volumetric water content when plants are very dry and leaves are either dead or dormant. Extractable soil water takes the root distribution into account provided the measured soil moisture profile is deeper than the rooting depth. Extractable soil moisture does not require soil water content/potential relationships for each soil depth where physical properties change. Ritchie (1981) found that field measurements of the total extractable water are often less variable spatially than available water estimated from water content-potential measurements.

Ratliff *et al.,* (1983) compared field and laboratory measurements of the limits of soil water availability. Field measured wettest and driest profiles were compared with laboratory measurements of soil moisture content at –15 bar (401 observations) and –0.33 bar (282 observations). Results showed laboratory measurements of the lower limit of soil moisture availability underestimated the field values for sands, silt loams and sandy clay loams and overestimated values for loams, silty clays, and clays. For the upper limit, laboratory estimates were less than the field measurements for sands, sandy loams, and sandy clay loams and were greater than laboratory measurements for silt loams, silty clay loams, and silty clays. They concluded that field estimates of soil water availability should be preferred for water balance calculations.

Our Approach to Estimating Extractable Soil Moisture

The approach we have used is to obtain the extractable soil moisture capacity from field measurements of soil moisture content. A time series of soil moisture values over the depth of the soil, shows the actual changes in soil moisture so the extractable soil moisture can be estimated from the difference between the wettest and driest profiles.

In simple terms, our methodology involved:

- Obtaining time series of profile soil moisture data; and
- Defining the 'wettest' and 'driest' profiles and using these to estimate extractable soil moisture.

The extractable soil moisture depends on the soil type and the vegetation type. Deeper-rooted vegetation will be able to extract larger amounts of soil moisture because it has access to more of the soil profile. Conversely, even fallowed soils will experience wettest and driest profiles so it is possible to estimate a value for extractable soil moisture when there is no vegetation.

Searching for Soil Moisture Data

There have been many, perhaps hundreds, of projects in Australia that have involved measurement of soil moisture. These include studies of the performance of crop types, cropping systems, water balance studies, analysis of recharge associated with salinity investigations and studies of water yield following fires or forest cutting. Profile soil moisture measurements have been measured using Neutron Moisture Meters, Time Domain Reflectometry, and Gravimetric Sampling. Originally we intended to track down raw data from a large number of studies where there were long time-series of profile measurements of soil moisture. This turned out to be impossible. Although over 90 researchers were contacted, and we received excellent cooperation, few usable datasets were obtained. Commonly, the data used by hydrologists are measured and managed by organisations with a particular mandate, and the resources necessary, to archive and make available their information. Meteorological and streamflow data are two obvious examples. But information where there are no coordinated monitoring networks is difficult to track down. Much of the information we have been seeking was collected as part of individual research projects by a researcher, or small group of researchers. The motivations in these sorts of projects are to answer some specific questions and make the results available through publications. Indeed we have gained a lot of the information we need from published papers and reports. However, the basic data normally reside in field books or computer media of different sorts, depending on the age of the study. These data have been used by the research team at the time, but, from the researcher (and likely the client's) point of view, once the appropriate analysis and publications have been completed, there is little need to do anything more with them. That makes the data difficult for others to obtain and use, especially when corporate memory starts to fade.

In this project, the way forward was to use soil moisture data and results from published reports and journal articles. Generally these data are well documented and cleaned up, although probably only a small amount of the total data collected is available in this form. Over 200 journal articles were examined and information from about 75 articles contributed to our database. A particularly valuable source of data was the work of Agricultural Production Systems Research Unit in Toowoomba, Queensland, which has published an extensive guide to soil water availability for southern Queensland. In all, storage capacities were obtained for 180 unique soil, crop, location, combinations (Figure 1).

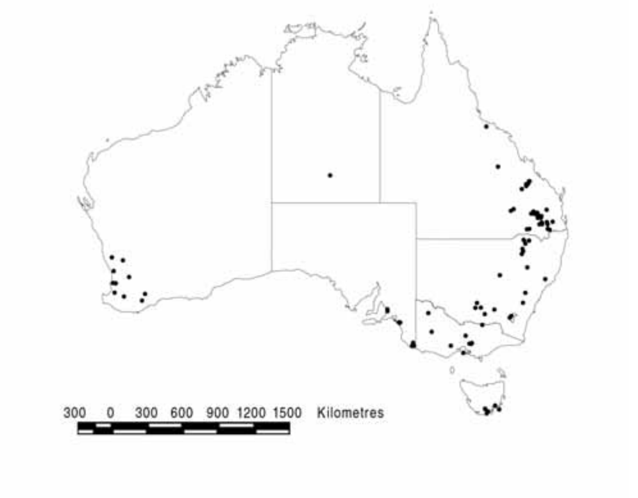

Figure 1 Sites Where Extractable Soil Moisture Estimates are Available

An example of the data we have used is shown in Figure 2, which is a time series of moisture storage in the top 2.2 m of the soil profile under a Pinus radiata plantation near Lidsdale, NSW (33.43S, 150.07E) between October 1968 and April 1971 (Smith, 1972).

Soil moisture measurements were made about every 2 weeks. Soils are hard setting loams with mottled yellow clayey subsoil derived from both Devonian and Permian parent material: Northcote (1966) classifications Dy 3.41 and Dy 2.61.

From the time-series, the driest conditions occurred on 4 February 1969 and the wettest on 12 February 1971. In this case, soil moisture profile data were available for the wettest and driest observations and are shown on Figure 3. More commonly, only a small subset of the measured data was included in the sources we used to populate our database.

The maximum active soil moisture store is the difference between the maximum and minimum values in the time series of soil moisture data (Figure 2), which is equivalent to the difference between the wettest and driest profiles (Figure 3) i.e. 234 mm.

Of the 180 active soil moisture storage measurements in our database, 91 are based on similar data to that shown in Figures 2 and 3. That is, the soil moisture was measured under natural climatic conditions with the wettest and driest profiles determined by the weather and cropping cycle. The other 89 values are from situations where the soil was artificially wetted and dried to obtain an estimate of the maximum active soil store. Field procedures are documented in Dalgiesh and Foale (1998) for the artificially manipulated conditions.

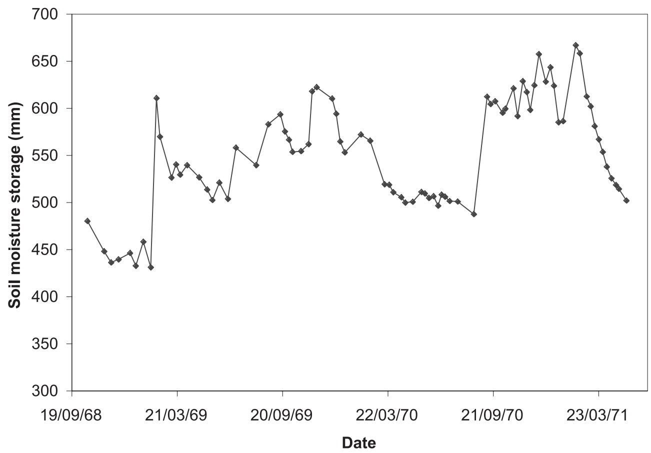

Figure 2 Time Series of Soil Moisture Storage for Lidsdale, NSW

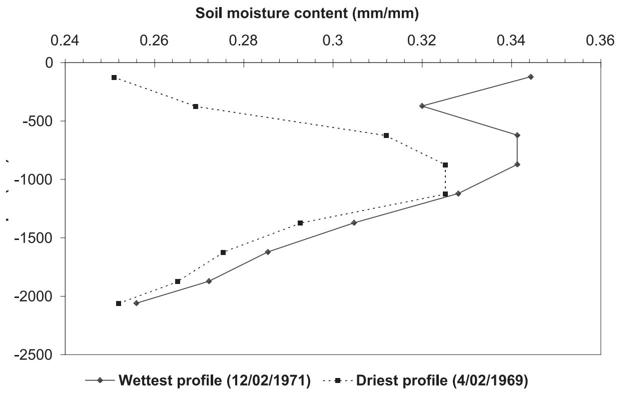

Figure 3 Wettest and Driest Soil Moisture Profiles for Lidsdale, NSW

The database also includes information on: location, vegetation type, landuse, soil type, active soil moisture store, soil depth, horizon depth, porosity, bulk density, dates when soil moisture measurements where made, soil moisture monitoring frequency, and the references used to derive the data. There is also an assessment of the accuracy of the soil moisture measurements in terms of their ability to represent the soil moisture store.

How dry is dry and how wet is wet?

Field measurements of the wettest and driest profiles, which occur under natural conditions, will only give a good estimate of the total active soil moisture store if the weather was wet and dry during the measurement period. For this reason, where we based the active soil store estimate on a time-series of soil moisture measurements, a minimum of 2 years of data have been used. For each of these locations (45 sites), the rainfall during the measurement period was compared to long-term rainfall data. Comparisons were made using sixty years of monthly rainfall data (1940 to 1999), provided by the Bureau of Meteorology. These data come from a monthly rainfall grided dataset, which has been developed by the Bureau, where rainfall has been estimated for square cells of 0.25 degrees (approximately 25 km depending on latitude).

The median, 25th and 75th percentiles were compared to the rainfall during the soil moisture measurement period at the 45 sites. For example, the rainfall during the 31 months when soil moisture was collected at Lidsdale, NSW (October 1968 to May 1971) can be compared to summary statistics for January 1940 to December 1999 (see Figure 4).

The wettest and driest months during the measurement period were also compared to the long-term rainfall data. The rank of the wettest and driest month was calculated based on the 720 months of long-term data. For example, at Lidsdale, only 0.4% of months between 1940 and 1999 were drier than the driest month during the measurement period, whereas 96% of months were drier than the wettest month. Extreme ranks increase the likelihood that the active soil moisture storage has been captured by the measured data. For the 45 sites where ranks were calculated, 82% of the driest months were in the driest 5% of all months and 87% of wettest months where in the wettest 5% of all months. The distribution of the ranks of the driest months is shown in Figure 5. Data for the wettest months is similar. Only 5 sites had a difference between the wettest and driest ranks of less than 90%. These results provide justification for using the difference between the wettest and driest profiles, in our dataset, as an estimate of the active soil store.

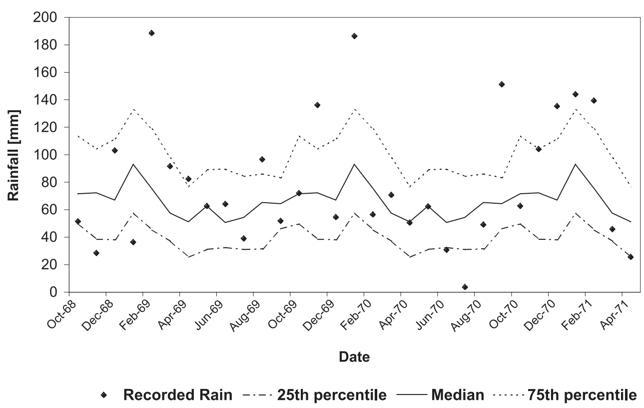

Figure 4 Rainfall During the Period of Measurement at Lidsdale (October, 1968 to April 1971) Compared to the 25th, and 75th Percentiles, and the Median, for Data from January 1940 to December 1999.

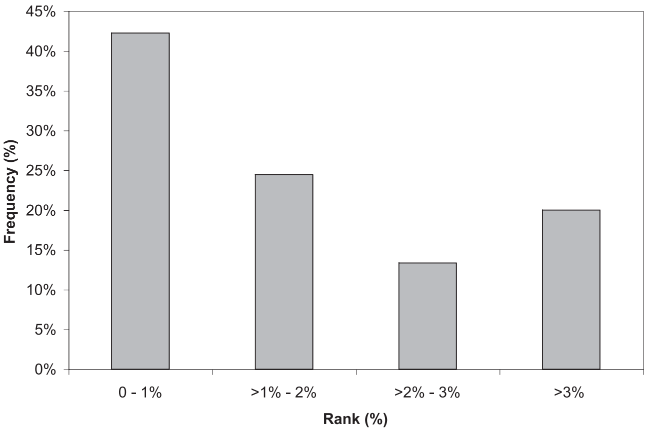

Figure 5 Rank of the driest month when comparing rainfall during the period when soil moisture was measured with 60 years of rainfall data (1940 – 1999). Data are for 45 locations.

Comparison with the Atlas of Australian Soils

The Atlas of Australian Soils (Northcote *et al.,* 1960-1968) provides spatial information on soil landscapes for the whole of Australia based on soil characteristics that can be observed in the field. This has been an important resource for over three decades, and remains the only consistent source of data for the whole continent. However until recently it has not been straightforward to use the Atlas to establish the soil physical properties that are important for hydrologic analysis.

McKenzie *et al.,* (2000) (following from Hooke & McKenzie, 1992) have addressed this problem and provide data on soil physical properties for the 725 soils in the Digital Atlas of Australian Soils (BRS, 1991). Soil properties have been estimated using a simple two-layer soil model consisting of A and B horizons. Soil water retention properties were calculated for each soil, based on estimates of thickness, texture, bulk density and pedality (using Williams (1993) approach). The available water capacity for each layer was calculated from fitted soil water retention curves assuming upper and lower limits of –0.1 bar and –15 bar respectively.

The Digital Atlas of Australian Soils provides data for polygons (there are 22,560 in total) that represent soils in particular regions. Each of the polygons is attributed with one of 3060 soil landscape types, many of which occur more than once. For each map unit, the dominant soil type is described (referred to as the dominant Principle Profile Form) along with any subdominant Principle Profile Forms. McKenzie *et al.,* (2000) records up to 5 Principle Profile Forms for each soil landscape. Each of the Principle Profile Forms includes an estimate of solum thickness (the sum of the depth of the A and B horizons) and the available water capacity over that depth. When interrogating the data on soil physical properties, specifying a location, will link to a polygon and return information on the dominant and subdominant Principle Profile Forms.

Our estimates of the active soil moisture store, based on field measurements, provide an opportunity for comparison with the available water capacity from the interpretation of the Atlas of Australian Soils information. For each of the locations in our database (Figure 1) the available water capacity estimated for corresponding dominant Principle Profile Form was compared to the extractable soil moisture store (Figure 6). In several cases, there is more than one estimate of extractable soil moisture store for a particular location because measurements were made under more than one vegetation type. All the available estimates have been included in Figure 6. The outlying high storage value shown Figure 6 of 680 mm is from a site in the Brindabellas, ACT where soil moisture was measured under a mixed Eucalypt forest during a drought (Talsma & Gardner, 1986).

The results show that the soil moisture store from the Atlas of Australian Soils is generally smaller than the estimate from field measurements. A comparison of the ratio of the differences (Figure 7) showed that 42% of the estimates of extractable soil moisture were greater than twice the value from Atlas of Australian Soils. In general, estimates of available water capacity from McKenzie *et al.,* (2000) could be considered a reasonable lower bound on field-based estimates of the actual dynamic soil moisture store. It should be noted that the information on location in our database is of variable quality and depends on the precision in the original reference, supplemented where appropriate (and possible) by direct discussions with researchers. Errors in location will contribute a small amount of the variance shown in Figure 6.

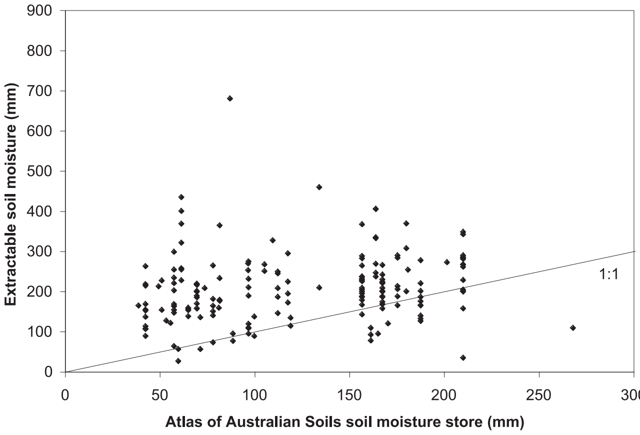

Figure 6 Comparison of Soil Moisture Stores from the Atlas of Australian Soils with Field-based Estimates of Extractable Soil Moisture

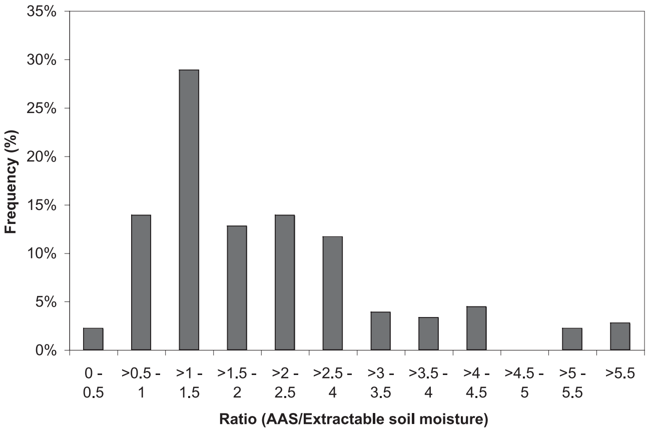

Figure 7 Ratio of Estimates of Soil Moisture Store from the Atlas of Australian Soils and Field Measurements of Extractable Soil Moisture

The comparison in Figures 6 and 7 is made using the dominant Principle Profile Form for each polygon that matches a particular location. In most cases there will also be subdominant Principle Profile Forms with their own associated estimates of available water capacity. These provide a greater spread of estimates as shown in Figure 8 where the extreme variability is apparent, although the extractable soil moisture store is still generally much larger than the estimate using AAS data.

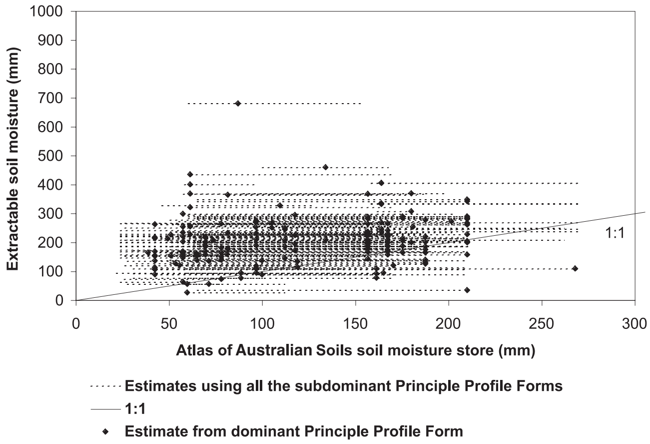

Figure 8 Comparison of Field-based Estimates of Extractable Soil Moisture with the Estimates of Available Water Capacity from the Atlas of Australian Soils. Estimates for the Dominant and Subdominant Principle Profile Forms are Shown for Each Location

Estimates of the available water capacity provided by McKenzie *et al.,* (2000) are the product of the depth of the soil profile and the soil moisture storage capacity per unit depth. Equivalent parameters are also available from our database where an active soil depth is defined based on the where the wettest and driest profiles meet or the maximum depth of soil moisture measurement; which ever is less (Figure 3).

The soil moisture store per unit depths are compared in Figure 9 using only the dominant Principle Profile Form for each location. In this case the estimates from McKenzie *et al.,* (2000) and the field measurements cluster around the 1:1 line suggesting reasonable agreement, although clearly the scatter is large.

The active soil depth from field measurements, and the solum thickness from the Atlas of Australian Soils are compared in Figure 10. Active soil depths are generally much larger than solum thickness estimates. It is the underestimate of active soil depth that explains the low estimate of soil moisture store from AAS interpretation shown in Figure 6.

McKenzie *et al.,* (2000) acknowledges that solum thickness estimates are likely to be subject to error. Unfortunately, the thickness of individual soil layers, and the depth of the soil profile, are often not recorded as part of the Northcote classification and there is only imprecise definition of the depth of soil that can be exploited by plants. Often plants will extract moisture from below the A and B horizons and historical datasets do not provide any consistent information on deeper soil layers. Data in existing soils databases also tends to be censored because of the method used to collect soil profile information, for example, soil pits and augers are often restricted to 1 to 2 metres. Often soil surveys for agricultural purposes restrict examination to the first 1 m of the soil profile and some Principle Profile Forms are only comprised of an A horizon, yet roots can penetrate deeper soils (McKenzie *et al.,* 2000).

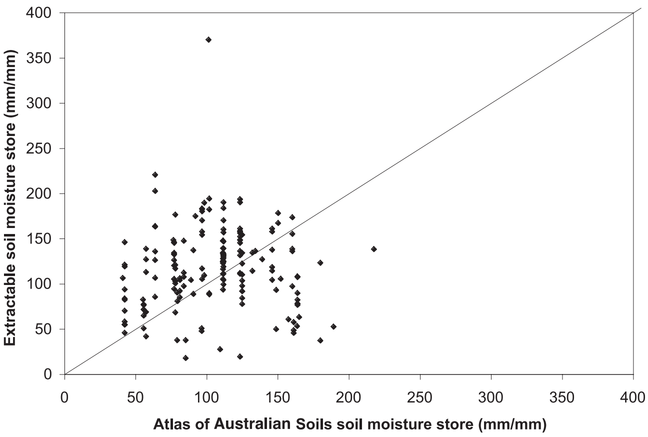

Figure 9 A Comparison of Soil Moisture Store Per Unit Depth

Clearly, estimates of available water capacity could be improved by better soil descriptions but it is also necessary to use appropriate estimates of active soil depth. The active soil depth is partly determined by rooting depth of vegetation but it is also possible for moisture to be withdrawn from the soil under fallow conditions. Estimates of active soil depth from our database for trees, crops, grass and fallow are shown in Figure 11. The active soil depth for crop, grass, and fallow are generally one to two metres with some outliers that are probably explained by soil type. For example, the two large active soil depths for crop, (of about 5 m) are for lucerne grown on deep sandy soils near Keith, South Australia (Holmes, 1960). The active soil depths for grass of around 5 metres were measured on deep sands near Pinjarra, WA (75 km south of Perth) (Carbon *et al.,* 1982) and the high active soil depth for fallow conditions (of about 3.7 m) was for a deep sandy soil near Wongan Hills in Western Australia about 170 km north-east of Perth where there may have been interaction with groundwater.

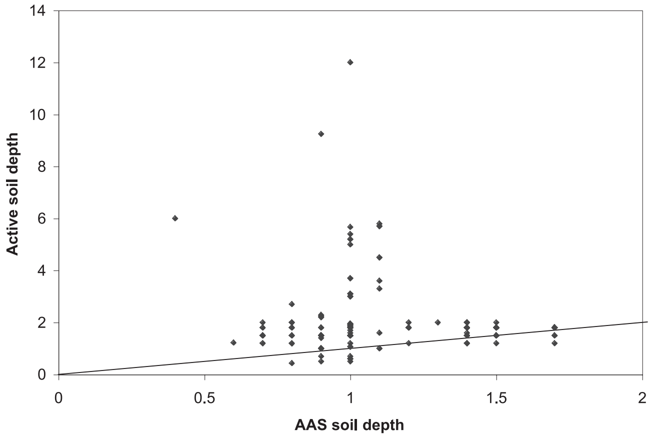

Figure 10 A comparison of solum depth from the Atlas of Australian Soils and active soil depth from field measurements

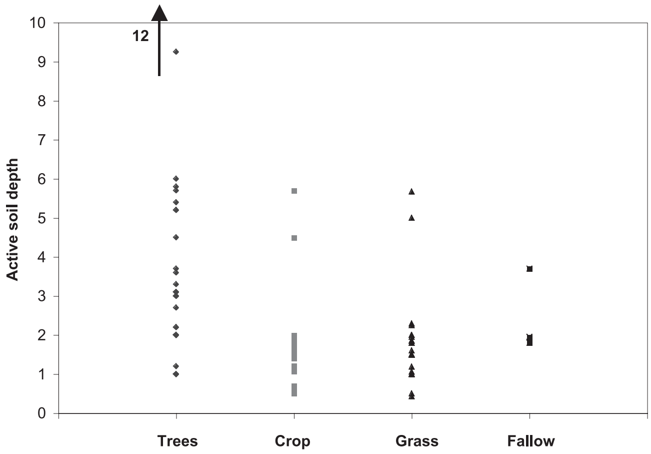

Figure 11 Active Soil Depths Based on Field Measurements of Extractable Soil Moisture for 3 Vegetation Types and Fallow Conditions

The active soil depth for trees is more variable than for crop, grass and fallow, ranging from 1 to 12 m. Again, the largest active depths are for deep sandy soils. Further work is required before the active soil depth can be predicted from soil types and tree taxa.

Conclusion

Information on extractable soil moisture has been gathered for 180 unique combinations of location, soil and vegetation types. This dataset provides estimates of the soil moisture storage based on field measurements of wettest and driest soil moisture profiles.

Our search for this profile information revealed deficiencies in the way data from experimental studies is archived in Australia. For parts of the hydrologic cycle, such as rainfall and streamflow, there is accurate current and historical information that is easily accessible. This contrasts with soil moisture data that are usually gathered for specific projects so there is little incentive to archive it in a form that can be interpreted by others. Most of the data we have gathered was from published sources, which probably represents only a small proportion of the soil moisture measurements that have been collected.

Analysis of rainfall during the periods when soil moisture was measured, suggests that observed driest and wettest profiles are good estimates of the minimum and maximum storage values. In over 80% of cases, the wettest and driest months during the measurement periods were ranked within 5% the wettest and driest months of a 60-year rainfall record (1940 to 1999). Around 40% of the time they were ranked within the top 1%.

The extractable soil moisture stores were compared with the available water capacity estimated by McKenzie *et al.,* (2000) for the Atlas of Australian Soils (AAS). Preliminary results show that data from the Atlas of Australian soils provide a useful lower bound for measured dynamic soil moisture storage, but of the sites examined, 42% had extractable stores greater than two-times the AAS values.

In the future we plan to compare estimates of extractable soil moisture with data from Australia Soil Resource Information System (ASRIS) that is being prepared as part of the National Land and Water Resources Audit and is planned for release in 2002. ASRIS will provide detailed information on soil properties in the intensively used areas of Australia and will include information that has been collected since the preparation of the Atlas of Australian Soils during the 1960s (NLWRA, 1999). However, the Atlas of Australian Soils and additional interpretations such as those by McKenzie *et al.,* (2000) will remain the best sources of information for much of Australia. Our analysis shows that estimates of available water capacity from the Atlas of Australian Soils must be treated with caution particularly where there are trees. There is the potential of using information on vegetation type to better estimate active soil depths but further work is needed to quantify these relationships

Acknowledgements

The assistance of the Bureau of Meteorology in providing rainfall data is gratefully acknowledged. The cooperation of all the people who provided access to data or reports is acknowledged with thanks. This work is funded through the CRC for Catchment Hydrology.

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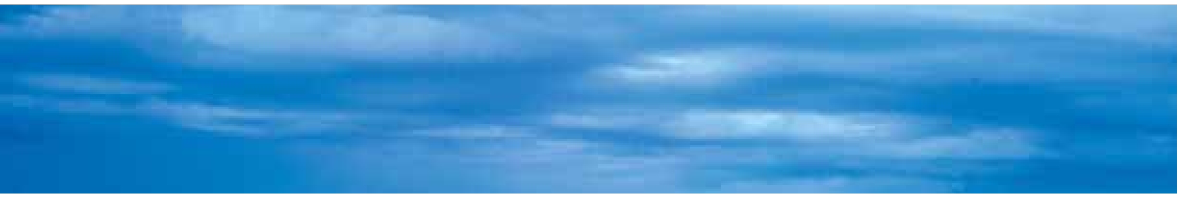

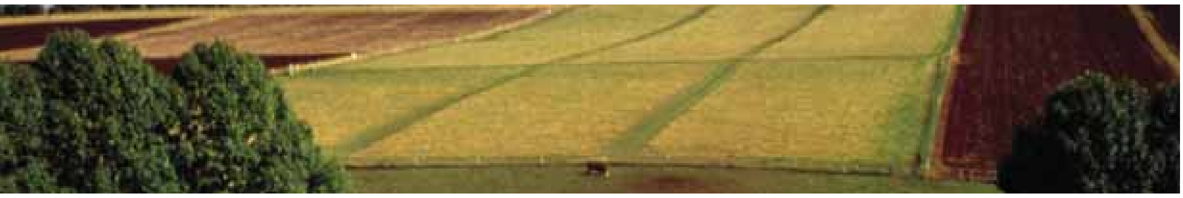

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- Water Corporation of Western Australia

RESEARCH AFFILIATES:

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- National Institute of Water and Atmospheric Research, New Zealand
- Sustainable Water Resources Research Center, Republic of Korea
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- Earth Tech
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Established and supported under the Australian Government's Cooperative Research Centre Program

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