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Complete List of Authors:	Acworth, Richard; Connected Waters Initiative Research Centre, School of Civil and Environmental Engineering, UNSW Australia Rau, Gabriel; University of New South Wales, Water Research Laboratory Cuthbert, Mark; University of Birmingham, Earth Sciences; University of New South Wales, Water Research Laboratory; Jensen, Evan; Connected Waters Initiative Research Centre, School of Civil and Environmental Engineering, UNSW Australia Leggett, Keith; Fowlers Gap Arid Zone Research Station, School of Biology, Earth and Environmental Sciences, UNSW Australia
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Long-term spatio-temporal precipitation variability in arid-zone Australia and implications for groundwater recharge

R. Ian Acworth[1,*], Gabriel C. Rau[1], Mark O. Cuthbert[2], Evan Jensen[1], Keith Leggett[3]

1. *Connected Waters Initiative Research Centre (CWI), School of Civil and Environmental Engineering, UNSW Australia, King Street, MANLY VALE 2093, Australia.*

2. *School of Geography, Earth and Environmental Sciences, University of Birmingham, Edgbaston, Birmingham, B15 2TT, UK*

3. *Fowlers Gap Arid zone Research Station, UNSW, New South Wales*

* Corresponding author:

Ian Acworth (riacworth@gmail.com), Tel: +61 2 80719826, Fax: +61 2 99494188

Abstract

Quantifying dryland groundwater recharge as a function of climate variability is becoming increasingly important in the face of a globally depleted resource, yet this remains a major challenge due to lack of adequate monitoring and the complexity of processes involved. A previously unpublished and unique dataset of high density and frequency rainfall measurements is presented, from the Fowlers Gap Arid Zone Research Station in western New South Wales (Australia). The dataset confirms extreme spatial and temporal variability in rainfall distribution which has been observed in other dryland areas and is generally explained by the dominance of individual storm cells. Contrary to previous observations, however, this dataset contains only a few localised storm cells despite the variability. The implications of spatiotemporal rainfall variability on the estimation of groundwater recharge is assessed and show that the most likely recharge mechanism is through indirect and localised, rather than direct, recharge. Examples of rainfall and stream gauge height illustrate runoff generation when a spatially averaged threshold of 15–25 mm (depending on the antecedent moisture conditions) is exceeded. Preliminary assessment of groundwater levels illustrates that the regional water table is much deeper than anticipated, especially considering the expected magnitude of indirect and localised recharge. A possible explanation is that pathways for indirect and localised recharge are inhibited by the large quantities of Aeolian dust observed at the site. Runoff readily occurs with water collecting in surface lakes which slowly dry and disappear. Assuming direct groundwater recharge under these conditions will significantly overestimate actual recharge.

1. Introduction

1.1 Background

As groundwater resources are globally depleted (Wada et al., 2010), water scarcity, the gap between demand and supply, is a critical concern especially in arid and semi-arid climate zones (Taylor, 2014). Arid and semi-arid zones are inhabited by an estimated 35% of the global population with the great majority (90%) occurring in developing countries (UNEP, 2011). In these regions, the population growth, and therefore also the water demand, is faster than in any other region (UNDDD, 2015). Aquifers are the most important source of water in arid and semi-arid zones as the result of their ability to act as a buffer during dry periods (de Vries and Simmers, 2002; Taylor et al., 2012b; Taylor, 2014) as long as recharge actively occurs during wetter periods. It has also recently been shown that groundwater may have been an important control on human evolution in dryland environments of East Africa (Cuthbert and Ashley, 2014).

The determination of recharge in arid and semi-arid zones has long been recognized as a priority, see for example Lerner et al. (1990), de Vries and Simmers (2002) or Scanlon et al. (2006) but has been found to be extremely dificult to estimate. The reasons for this include the lack of an appropriate conceptual model of recharge and also, frequently, a complete lack of appropriate observations, either of rainfall, run-off or the groundwater level response. In this paper, the potential for groundwater recharge to occur is examined, along with the available evidence for its likely mode of occurrence, in what is considered to be a typical arid zone located in western New South Wales (NSW), Australia. A previously unpublished record of 44 years of rainfall measurements collected from 17 rain gauges spread evenly accross the 385 km^2 Fowlers Gap Arid Zone Research Station (Fig.1) is examined. The average rainfall at a tipping-bucket gauge maintained by the Australian Bureau of Meteorology (BoM) at FGAZRS, for the 44 years of record between 1970 and 2014, was 246 mm/year.

Conceptual models for groundwater recharge were proposed by Lloyd (1986) based upon observations of processes in various arid zones including Northern Chile and the Middle East. These processes are illustrated in Figure 2 (adapted from Lloyd, 1986) and form much of the basis for recharge studies by later workers (Lerner et al., 1990, de Vries and Simmers 2002, or Scanlon et al., 2006). Here, the term 'direct' is used for any recharge occurring diffusively over large areas due to infiltration from precipitation. Recharge that is more focused spatially as a result of losses from a surface water body is referred to as 'indirect' if it is due to infiltration from stream channels, or 'localised' if routed via localised ponding (Fig. 2). These terms are consistent with definitions given by Lloyd (1986) and more recently re-iterated by Healy (2010). In this paper, the evidence for direct, indirect or localised groundwater recharge to occur at Fowlers Gap is examined.

The starting point for estimation of recharge by direct, indirect or localised pathways must always rely upon the measurement of rainfall (Fig. 2). For this reason, the characteristics (frequency and intensity) of the rainfall record are first examined in detail as they directly impact upon the probable recharge process. The 44 year record of daily rainfall for a dense group of gauges in the arid zone makes this data set a significant and valuable resource, adding to the global pool of sparse hydrological monitoring in the arid zone.

1.2 The Fowlers Gap Arid Zone Research Station (FGAZRS)

The FGAZRS extends 385.5 km^2 and is located approx. 110 km north-east from Broken Hill at longitude of 142 ºE and latitude of 31°S in the arid zone of western New South Wales, Australia (Figure 1a). The lease for the station had initially been gazetted in 1885 after Charles Sturt reported good prospects for agriculture in the area during his travels in 1844-1845. In 1966 the NSW State Government handed the lease for the property to the University of South Wales (UNSW Australia) to undertake research work pertinent to the pastoral industry west of the Darling River. The FGAZRS was established in the same year by UNSW Australia, and it has been the location for a wide range of arid zone research ever since. The research has included significant projects into stocking capacity, fauna and flora. The interested reader is referred to a summary of published research (Macdonald, 2000) which is also documented and available to download on the station website (FGAZRS, 2015).

The climate at FGAZRS is arid with potential evaporation greatly exceeding rainfall. Bell (1973) reported a 3-year record of mean pan evaporation of 3,613 mm/year for the period 1969-1971. The climate can be described as a warm arid (BWh) climate using Koppen's (1936) classification or arid mesothermal (EB') using Thornthwaite's (1948) classification.

Rainfall tends to occur in wet spells of between one and six days of measured rainfall, separated often by long dry spells of between a few weeks to several months. Bell (1973) also reported that the wet spells are due to strong inflows of moist air associated with one of the following conditions:

- intense tropical cyclones or depressions in the vicinity of Queensland (QLD) during the summer months (December to February)
- extra-tropical depressions over southern inland Australia or the Great Australian Bight, generally during the winter months (June to August) or
- strongly developed low pressure systems in the upper atmosphere which can bring heavy rainfall over wide areas of the inland in any season.

It was considered that rainfall in wet spells would have a greater areal extent but have a more uniform distribution as compared to single convective storm cells. However, the great spatial variability in rainfall was noted at an early stage of the investigation (Bell, 1973; Macdonald, 2000).

Cordery et al., (1983) reported hydrological characteristics of the FGAZRS based upon 7 years of monitoring during the period 1975 to 1982. They established run-off plots on a variety of land surfaces and installed recording rain gauges. From the results of these observations they concluded that rainfall associated with convective storm cells accounted for much less of the total annual rainfall than that associated with depressions or upper atmosphere troughs. This was contrary to most of the literature (Osborne et al., 1979) that suggested arid zone rainfall was dominated by convective storm cell events.

Runoff was observed to occur after 35 mm of rain falling on very dry ground and a median value of initial losses of only 15 mm was established based upon measurements from 46 run-off producing storms measured in 6 run-off plots. These initial results were updated by Cordery (2004) who argued that arid zone surface runoff was a significant resource. Unfortunately, the infrastructure installed at FGAZRS as part of this study was not maintained after the study.

The FGAZRS area and Fowlers Gap creek catchment are located at the south-western fringe of the endorheic (internally draining) Bancannia Basin with approx. area of 23,270 km² (Fig. 1a). The southern part of the catchment is drained by Fowlers Gap Creek, which rises south west of the station and traverses the Barrier Ranges in two water gaps and then floods out on the alluvial plains to the east and northeast (Fig. 1c). Fowlers Gap Creek has a catchment area of approximately 384.4 km^2 upstream of the gauging station (Figs. 1b & 1c). The drainage in the north of the station includes Sandy Creek with an open upper catchment above Sandstone Tank that narrows through a gorge in the Barrier Ranges (locations shown in Fig. 1).

Although the Lake Bancannia (115 m Australian Height Datum (AHD) Fig. 1Cc) is currently endorheic, there is only a limited ridge of 5 m in height to the northwest separating this drainage from the regional system draining to Lake Frome approximately 180 km to the west (Fig. 1a). The elevation of Lake Frome is only 1 m AHD and there are extensive playas and dune fields immediately east of Lake Frome that can act as a significant source of dust.

The geomorphology of FGAZRS is described by Mabbutt (1973) and comprises three physiographic domains which can be readily detected on the satellite image for the area (Fig.1b):

- undulating lowland with low ridges in the west – mainly 180 m to 240 m AHD and typically with a relief of 10-30 m
- a central belt of ranges and foothills with up to 100 m relief locally and attaining a maximum of 432 m above sea level in the south-west, these are part of the Barrier Ranges (Fig. 1b)
- an eastern section consisting of gently dipping alluvial sand and clay plains which descend from about 170 m at the rock bar gauging station to 115 m at Lake Bancania (Fig 1.c). A line of what are playa lakes extends to the south east close to the North Mandelman rain gauge site (Fig. 1c). These may be old discharge lakes for the groundwater system. As they have an elevation of approx. 130 m AHD, some further recent subsidence is probable for the creation of the internal drainage at Lake Bancannia.

The geology of the Station is complex and a brief summary was provided by Ward and Sullivan (1973) as follows: The western part of the Station is comprised of Upper Precambrian rocks consisting of strongly folded shale, dolomite, limestone and quartzite accompanied by low-grade regional metamorphism. Structures are particularly clearly seen on the satellite image that demarks the Barrier Ranges (Fig. 1b). Along the eastern edge of the Barrier Ranges, quartzose sandstones with associated red-brown and grey-green shales of probable Devonian age unconformably overlie the older rocks. Further to the east, the Devonian sandstones are again unconformably overlain by a sequence of lower Tertiary sands and clays with a thin sequence of lower Cretaceous sediment at their base. Drilling for oil in 1967 proved in excess of 3,000 m of Devonian red-bed sediments at a borehole (Planet Oil) on the eastern alluvial plains (Fig. 1c) before proving Precambrian basement at 3,527 m depth. The red beds crop out in the hills and the formation dips at approximately 6.5 degrees to the south east towards the Planet Oil bore. The geological sequence recorded is presented in Table 1 and a geological sketch section is shown in Figure 3.

The groundwater resources of the FGAZRS have been investigated as part of the original station establishment (Beavis et al., 1984). There are three groundwater units present:

1. The Precambrian metamorphic rocks – dominated by shallow weathered aquifers and fractures. These have not provided useful supplies of groundwater.

2. The Devonian sandstones which are fractured and have zones with reasonable porosity (>10%) interbedded with shales.

3. The sequence of unconsolidated Cenozoic sediments that form the eastern part of the Station and which contain permeable sands with some gravels between clay aquitards.

The Sandstone Bore in the hills close to the sandstone bore rain gauge (Fig. 1b) has groundwater at approximately 80 m AHD (standing water level (SWL) = 100 m below ground (BG)) and is pumped for stock water. This same unit possibly occurs at Planet Oil Bore at > 800 m but is too deep for useful development. The Cenozoic sediments have provided the most useful supplies of water. Smith's Bore (Fig 1b) has groundwater at approx. 85 m AHD (SWL = 75 m BG). There are limited shallower sand deposits beneath Fowlers Gap Creek with groundwater at approximately 18 to 20 m depth. Recent drilling indicates that groundwater in these sands is confined. The relationship between these different units is shown as a section in Fig. 3.

2. Methodology

2.1 Long-term rainfall monitoring

Early work was carried out to develop secure watering points in each of the paddocks at FGAZRS. To predict the likely vegetation growth and forecast the sheep stocking rate, a standard rain gauge (comprising a 200 mm funnel and collecting jar) was placed in each of 17 paddocks commencing in 1970. Figures 1b and 1c contain details about location and Table 2 contains data on gauge location and record length. The monitoring density of 1 gauge per ~23 km^2 greatly exceeds the minimum density of both one per 1,500 km^2 as recommended by the World Meteorological Organization (WMO,

1969) or ~5.27 gauges over 400 km^2 as required by U.S. National Weather Service for arid and semi-arid regions (Soliman, 2010).

Rain days are often grouped and the rain gauges were emptied manually the day after each rain event had stopped. This was a result of the difficulty of visiting all the gauges during wet weather as most of them were off-road (track) and sometimes only accessible on foot or by motorbike. Each time the rain gauges were emptied the total rainfall for each station was recorded on paper. Frequently, rainfall occurred over a few days rather than as a single storm cell event so that some water would have been lost by evaporation. This loss amount has not been quantified but is considered to be likely uniform across all gauges. It is important to note that, rather than the more conventional rainfall accumulated to 09:00 each day, the total rainfall from each period of wet weather (rain event) was recorded. The rainfall data were transcribed from the paper record to rainfall year books at the research station and were recently transcribed from hardcopy to electronic records for analysis.

In addition to the manual devices, a tipping-bucket rain gauge has been operated by the Australian Bureau of Meteorology at FGAZRS over the same time period at Fowlers Gap (BoM, 2015). This gauge (the BoM rainfall gauge) was monitored in the standard manner with results recorded to 09:00 each day and is used as a reference for the manual gauges

In 2013, all 17 standard rain gauges were replaced by automatic (tipping bucket) rain gauges. Date and time of each bucket tip is recorded on one file while rainfall is totalled every 15 min and the totals relayed daily through a dedicated radio network to a base logger and updated daily to a database in Sydney where they are publically available for download (NCRIS, 2015). The location of each rainfall gauge and the available years of record are given in Table 2.

2.2 Streamflow monitoring

To establish a data based relationship between rainfall, run-off and groundwater recharge, significant infrastructure was established at the FGAZRS in 2013. In addition to the replacement of rain gauges, a climate station and 3 level gauges were installed (Bubbler system, Hydrological Services Pty Ltd, Australia):

- A level gauge was installed on Homested Creek at a site where previous instrumentation had been installed (Cordery et. al., 1983). The catchment of Homestead Creek lies completely within the FGAZRS and the rain gauge network covers this catchment completely. Homestead Creek drains into Fowlers Gap Creek.

- A level gauge was also installed in Freidslich Dam which lies in the upper reaches of Homestead Creek.

- A third level gauge was installed at a constriction on Fowlers Gap Creek formed by a silcrete rock bar crossing the creek. The constriction is downstream of the Barrier Ranges and allows the height in the creek to be monitored before the waters begin to dissipate over the flood plain. The Fowlers Gap Creek catchment exceeds the FGAZRS boundary (shown in Fig. 1c) and extends southwards outside of the area covered by the FGAZRS raingauge network.

The level gauges record water levels every 15 minutes. The data are then transmitted daily via the mobile data network to a database which is publically available (NCRIS, 2015). While the infrastructure has only been monitoring since 2013 there are already a few ephemeral streamflow events on record that will be presented in this paper. However, longer-term monitoring will be required to establish a robust relationship between rainfall, runoff and groundwater recharge at this arid zone field site.

2.3 Rainfall data analysis

All daily data were assembled in a spreadsheet for analysis. The BoM rainfall gauge data were used to determine the likely number of rain days and the actual days upon which rain fell. The manual entries made for the other 17 gauges were originally recorded on the day that the measurement was made, rather than the day that the rain fell. This occurred because access to all sites was often not possible on the same day. For this reason, rainfall over FGAZRS was shown over two or possibly more days when, in fact, it occurred on a single day. The BoM rainfall gauge data were used to establish which day the rain fell and the other records moved to that day as appropriate.

A time series of annual data for the BoM rainfall gauge was used to determine the mean annual rainfall and deviation from the mean for the available data (1970 to 2013). Annual totals were also calculated for all gauges and rainfall distribution plots for each year prepared using the default kriging options in Surfer v13 (Golden Software, Colorado, US). The geo-location of each gauge was determined in the field using a differential positioning system (R8, Trimble Navigation Ltd, US).

The annual variability in rainfall distribution across the site was calculated by creating a data series where cumulative annual rainfall totals were summed for each year and the mean, standard deviation and coefficient of variation (standard deviation divided by the mean) calculated for each year. At a shorter time frame, the cumulative rainfall for individual rainfall events was calculated for the 2013 – 2014 years by summing individual tips from the tipping-bucket rain gauges.

3. Results

3.1 Long-term summaries of the Fowlers Gap rainfall record

Mean annual rainfall for the BoM rainfall gauge measured over a 43-year period (1970 to 2013) was 243.8 mm/year. Figure 4 shows the cumulative departure from the mean of the annual rainfall for the years 1970 to 2013. Table 3 demonstrates that summer rainfall dominates, although rain can be expected in any month. Whereas there is a clear month in which the maximum occurs (January), the minimum is less well defined. The variation between years (standard deviation) is lowest for the winter rainfall and highest during the summer. The coefficient of variation is also highest in the summer months and lowest during the winter. The annual total rainfall for each year and the number of rain days occurring in that year are shown in Table 4.

3.2 Characteristics of rainfall at Fowlers Gap

Examples of the data recovered from the rainfall year books are presented in Table 5. The table is split into a number of sections to illustrate different rainfall events. The first two data entries (24/07/04 and 26/11/02 single wide-spread storm events) represent by far the most common occurrence in the record where rainfall has been recorded at each gauge across the catchment on a particular day. Single localised storm events are not frequently recorded. The two included here (12/08/03 and 02/09/03) actually occurred during the winter time when frontal systems delivering more general rain would be expected. Isolated cumulonimbus cells are more anticipated in the summer months but examples were sparse in the data set. Note that there is considerable spatial variability in the long-term totals across the catchment.

The multi-day events are more complex and indicate that rain producing conditions lasted over a period of days presumably associated with the passage of an upper atmosphere depression. Under those conditions, the rain gauges were only emptied when the operatives could get to the sites. The implication of this observation is that the absolute values for the storm event will be close to correct (less evaporation) but the timing of the event will be incorrect. Clearly, in the first example (16-17 Dec 2009) rain fell over two days at various times but the gauges were only emptied at the end of the event. Conditions are less clear for the event period 28/02/83 to 08/03/83 but illustrate the same principles as the earlier data. In the last multi-day event example (3), rain producing conditions occurred continuously over 3 days, as shown by the daily totals at the BoM gauge, but were only totalled for the other gauges on the last day of the event. In each case, the data from the BoM gauge, emptied at 09:00 each day, can be used to indicate the timing of the event.

Data from a 3-day event recorded on the tipping-bucket array are also shown in Table 5 (Tipping-bucket array - Example 1). These data have been totalled from the individual tip records for each gauge and will be discussed further below.

3.3 Temporal and spatial variability of rainfall

The initial part of the record is characterised by a very wet period with annual rainfall in 1974 of 809.5 mm (Table 4) and 71 days of recorded rainfall. This was more than 3 times the average rainfall. This initial (for the available record) period of wet weather was followed by a drying spell (1978 to 1986) and then a return to more uniform conditions for the period 1988 to 2000. The drought period of the first decade of this century (The Millenium Drought) is clearly shown between 2002 and 2009 with a return to wetter conditions for the years 2010 and 2011 before the onset of drought again in 2013. The plot of deviation from the mean (Fig. 4) clearly indicates these variations.

Maps showing 32 years of annual isohyets for FGAZRS (1982 – 2013) were prepared (not shown). A suitable subset of 6 maps was selected by forming a ranked series of average annual rainfalls across FGAZRS. Years with rankings of 2, 11, 19, 29, 37 and 43 are shown in Figure 5 with average and standard deviations indicated for each of the ranked years shown. In this manner, the variability of the annual rainfall distribution across FGAZRS can be better appreciated for the full range of climate conditions. The data for the period 1970 to 1981 is excluded as not all the gauges were installed before 1982 (refer to Table 2).

To test the hypothesis that by adding successive annual totals to a cumulative total, the spatial distribution should become more uniform, the time evolution of the coefficient of spatial variation was plotted in Figure 6. This was calculated by taking the yearly average rainfall across FGAZRS commencing in 1990 and calculating the mean, standard deviation and coefficient of variation. A new data set was then calculated by adding the rainfall for 1991 to the 1990 data and repeating the statistical calculations. The 1992 data were then added to the 1990+1991 data and so on.

The period from 1990 to 2013 is chosen as all gauges included have these years of data available (Table 2). This analysis demonstrates that the spatial variability in the data set reaches an irreducible minimum after 6 years of approximately 7.5% and then slowly increases with the addition of more years of data.

3.4 Recent examples of runoff-generating rainfall

As an example for runoff-generating rainfall, Figure 7a shows the 24 hr totals on 14-16 August 2014 as well as the 3-day cumulative totals. The data used here are drawn from the tipping-bucket network established in 2013. The spatial variability identified in the annual series is again reflected in this rain event that lasted over 3 days in August 2014. It can be seen that the spatial variation evolves as the event continues, and that a number of rainfall cells were embedded in the overall event. Figure 7b shows the hyetographs constructed from the times of the bucket tips at a representative selection of rainfall gauges. The daily data for all gauges is shown in Table 5. Shortly after 25 mm of rainfall had accumulated, runoff was recorded at the Rock Bar gauging station at the outlet of the Fowlers Gap Creek catchment (Fig. 1b and 1c), where the level rose by more than 1.5 m in less than 15 minutes. The same period of rainfall also gave a peak on the Homestead Creek gauge. Interestingly, this creek, which is upstream of the Rock Bar gauge and on a tributary creek, commenced flowing 16 hours before, during an earlier part of the storm.

As a comparison with the more frequently recorded multi-day rain events, the rainfall distribution for the single storm on 24 September 2014 is shown in Figure 8a. Again, individual station data are shown in Table 5. Rainfall lasted for approximately 7 hrs during this event, coincidentally stopping just as the flood peak reached the monitoring gauge (Figure 8a). Rain began falling, and stopped falling, at about the same time across all gauges. However, for this single event the rainfall totals are spatially variable with values between 26 and 41 mm (Table 5).

4. Discussion

4.1 Implications of rainfall distributions at Fowlers Gap for the calculation of direct recharge

Figure 2 illustrates the steps involved in the calculation of direct recharge using a standard soil moisture balance model (SMBM) methodology. The conceptual model is one dimensional and relies upon the assumption that only vertical fluxes occur. Received rainfall and actual evapotranspiration are inputs to a finite soil moisture store that overflows to become direct recharge when the soil moisture store is full. Evapotranspiration draws down on the soil moisture store. This simple approach has met with considerable success and Kowal and Kassam (1978) provide an early example of the SMBM method application in their regional analysis of recharge in the savannah areas of Northern Nigeria. Run off can be accommodated as a percentage of rainfall and deducted before the balance is calculated if appropriate measurements are available. Acworth (1981) used a modification of the SMBM to predict runoff as occurring when both the soil moisture store was full and groundwater was close to the surface. This approach required an estimate of the specific yield of the soil and also underlines an important precondition for the successful use of the method in that it is assumed that unconfined conditions exist that allow the excess rainfall to penetrate downwards to the water table in an unconfined aquifer.

Acworth (1981) compared the output of a SMBM to observed conditions for the same Nigerian savannah environment and concluded that the distribution of rainfall in both time and space is important when calculating direct recharge. Crosbie et al., (2008) in their review of groundwater recharge in the Murray Darling Basin (MDB), noted that an increase in rainfall always leads to an increase in recharge. However, Acworth (1981) noted that the grouping of rain storms in time had a significant impact on the total recharge predicted, with greater recharge possibly occurring from close grouping of storms (in time), even where the total amount (annual) rainfall was less. SMBM modelling of recharge by Acworth (1981) showed a correlation coefficient of only 0.75 between annual rainfall and predicted recharge, with 946 mm of rainfall producing 405 mm recharge in one year compared to 991 mm of rainfall producing only 228 mm recharge in another year. Allen et al. (1998) and Rushton (2003) give detailed descriptions of such SMBM methods for estimating direct recharge (also known as deep drainage in the soils literature).

The SMBM method works well in humid regions where moisture is frequently available in the soil profile. The average annual rainfall for the savannah areas of Nigeria was 1076 mm per year (SD 153 mm; n = 38) (Acworth, 1981). However, average rainfall for FGAZRS is much less (Table 2, last column) with the average for the BoM station being only 244 mm.

There are therefore several problems to using the SMBM method to calculate direct recharge at FGAZRS:

1. The poor distribution in rainfall (both in time and in space),

2. The difficulty in averaging soil data sufficiently to determine the available soil volume and

3. The presence of large quantities of clay in the profile can significantly inhibit direct recharge.

The great variability in the distribution of rainfall in both space and time means that it is not possible to determine an appropriate or meaningful average rainfall for input to the soil moisture balance without a density of precipitation monitoring that is impractical and unaffordable at regional scales at which water resources assessments are carried out. This is especially so in areas with very low density population. The FGAZRS data demonstrate that even for a relatively small area, the spatial distribution of rainfall is widely variable over periods of less than 3 years (Fig. 6). When it is appreciated that Howard and Lloyd (1979) proposed a water balance to be run at least daily to provide an accurate prediction of recharge by the direct method, then the scale of the problem can be appreciated. It is possible that much higher rainfall in the past, perhaps during the Pleistocene, may have led to direct recharge at FGAZRS.

It is clear from the description of the skeletal soils present over large parts of the FGAZRS that there is no appropriate soil volume that can be used to carry out a SMBM analysis. Observations of rapid runoff, as shown in Figures 7 or 8, and as noted by Cordery (2004), may indicate rapid saturation of a very small soil moisture store or rainfall rates that exceed the hydraulic conductivity of the thin and dry soil profile. However, rapid runoff seems to be a general condition occurring even for less intense rainfall events and another explanation is also possible.

The FGAZRS area has extensive deposits of dust transported from the Lake Frome area to the west (Fig. 1) (Keys et al., 2011; de Dekker et al., 2014; Schaetzl & Thompson, 2015). Dust is clearly seen in pictures captured during extremely dry conditions (Fig. 9 b and c). This dust is washed from the surface during rainfall events and is most likely carried down into cracks and fissures in the weathered zone where it must reduce the hydraulic conductivity of the soil. Thick sequences of dust may also serve to confine groundwater in deeper horizons.

The estimation of direct recharge by the SMBM at FGAZRS, while possible to conduct, is not likely to produce meaningful results. This does not preclude the possibility of direct recharge occurring. However, if it does occur, it will be very difficult to quantify. An indication as to whether direct recharge does actually occur can only be made based upon analysis of groundwater level responses to rainfall and long-term monitoring of groundwater levels has been established at FGAZRS with this in mind.

4.2 Possibility of localised recharge at Fowlers Gap

Figure 2 provides a conceptual model for localised recharge that was adapted from Lloyd (1986). It seems very probable that localised recharge will occur in the sandstone hills of FGAZRS (Fig. 9c). There are joint sets observable in the sandstone that could provide conduits for localised recharge.

However, the depth to groundwater at the Sandstone Bore (Fig. 2) of greater than 100 m below ground level does not indicate localised recharge to be a regionally significant process. Localised recharge that does occur to perched water tables must be later used by the sparse vegetation, leaving little or no moisture to percolate downward to the regional water table.

4.3 Indirect recharge at Fowlers Gap

The observations at FGAZRS have shown that significant runoff is rapidly generated across the catchment for rainfall events exceeding a spatial average of 15-25 mm. The size of this runoff-producing threshold will depend upon the antecedent conditions. For example, under very dry conditions, as much as 40 mm is required, while under catchment wet conditions, as little as 10 mm is enough to generate runoff.

The runoff data reported by Cordery (2004) and the stream hydrographs presented in Figs. 7 and 8 strongly indicate that the majority of rainfall concentrates as runoff and becomes channel (wadi) flow with transmission losses and flood flow down creeks rapidly removing water from the area. It is therefore highly likely that indirect recharge is then a significant process.

The estimation of the quantity of indirect recharge (Fig. 2) is notoriously difficult (Shanafield and Cook, 2014). That losses to evapotranspiration occur (Fig. 2) is evident by the presence of mature river red gums (*Eucalyptus camaldulensis*) which line the banks of the Fowlers Gap Creek and also grow in the creek bed (Fig 1). Losses to evaporation are also inevitable as the humidity frequently rapidly falls to levels of between 30-40% after periods of wet weather. Some evapotranspiration also occurs from flood plains inundated with water where grasses grow rapidly (Fig. 9d) after over-bank flows.

The quantity of vertical infiltration remains difficult to estimate. New groundwater monitoring boreholes have been drilled in transects across Fowlers Gap Creek to detect groundwater mounding after major flow events, however, at the end of 2014, no significant flows had been recorded. The drilling encountered dry conditions beneath the creek bed with the shallowest perched water occurring at 17 m and a deeper confined aquifer at 70 m in the Cenozoic sediments beneath the plain (at Smith's Bore - Fig. 1). This poses the question as to how deep the red gums are rooting or whether the investigation has missed shallower perched aquifers.

At present there is little information available from which to deduce groundwater conditions at FGAZRS. The water level in the Sandstone Borehole (Fig 1c) lies at approximately 100 m BG (Fig. 2) and does not indicate frequent and distinct groundwater head increases due to recharge. However, due to such a thick unsaturated zone, this is perhaps not surprising since recharge pulses, even if infrequent, would be expected to be highly damped (perhaps beyond recognition) and peaks lagged in time before they reach the water table. Thus, the lack of head response should not necessarily be interpreted as a lack of recharge (Cuthbert, 2010). Water table fluctuations may be of little use in estimating recharge unless the groundwater recession characteristics (see Cuthbert, 2014) reveal themselves during a long drought. Consequently, the climatic and hydrogeological conditions at

FGAZRS seem to offer unresolved and new challenges for the assessment and quantification of groundwater recharge in arid zone environments. This highlights the need for increased global monitoring of hydrogeological parameters, such as rainfall, evaporation and groundwater levels, in dryland areas.

5. Conclusion

A 40+ year record of daily rainfall measured in 18 rain gauges within the 385 km^2 Fowlers Gap Arid Zone Research Station has demonstrated that the distribution of rainfall in space and time is highly variable. While this is consistent with findings in other semi-arid environments, it had been considered likely (Bell, 1973) that winter rainfall associated with frontal systems would have a more even distribution. This would have offered the possibility that direct recharge to groundwater could be reasonably estimated using SMBM type methods. While a component of direct recharge cannot be discounted where soil moisture deficits are locally overcome, the new field data indicate clearly that estimations using SMBMs would be highly misleading in such environments. For the FGAZRS, the available evidence suggests that the recharge that does occur will result predominantly from indirect or localised processes.

Cumulonimbus storm cells are expected to predominate in these latitudes during the summer months. It is a characteristic of cumulonimbus cells that they generate wide variation in rainfall rates over time with great spatial variation in rainfall totals (Sharon, 1981). Some gauges would be expected to record no rainfall, with adjacent gauges perhaps receiving heavy rainfall. Based upon these characteristics, it would be expected that there would be many events during the summer months at FGAZRS with rainfall recorded at only a few gauges. A surprising result from this study is that the great majority of storm events have produced rainfall in all gauges, yet the temporal and spatial distribution remains very great. The reason for this is unclear.

Observations of flow in Fowlers Gap Creek indicate that runoff commences after approximately 15-25 mm of rainfall. Exact figures depend upon the degree of wetness in the catchment. High surface flows are rapidly generated indicating that infiltration is low and runoff represents a high proportion of the rainfall. Under these conditions, indirect recharge is anticipated beneath the creeks. A lack of significant flow for many years has made it difficult to fully assess these conditions, however recent drilling indicates dry conditions to 17 m BG immediately adjacent to the creek with confined groundwater at 70 m BG. Extensive River Red Gums along the creek channels indicate that moisture must be stored in the unsaturated zone closer to the ground surface or that the trees have developed deep root systems. Localised recharge is anticipated in the hills, particularly where Devonian sandstones crop out and are fissured. However, even here, the groundwater is approximately 100 m BG and significant recharge seems unlikely.

The FGAZRS soils are generally thin and skeletal on parent rock and often have high clay content close to the surface. These observations indicate long weathering of the parent rock on the Barrier Ranges and the location of the FGARZS close to one of the primary dust producing centres in

Australia. The implications of the presence of the dust on possibly inhibiting drainage clearly require further work. It may be that no amount of additional rain, as envisaged in some climate models (Taylor et al., 2012a) will actually increase recharge in areas where the soil profile is significantly impacted by dust. The current indications are that groundwater recharge is not as widespread at this semi-arid site as that recorded beneath wadi systems in other parts of the world.

Acknowledgements

The team at Fowlers Gap Arid Zone Research Station (https://www.fowlersgap.unsw.edu.au) are thanked for their support, for allowing their records to be digitised and for escorting us around the endless tracks of the station to find the rain gauges. The NCRIS National Research Infrastructure for Australia scheme of the Australian Federal Government provided the funding to establish the network of tipping-bucket rain gauges. MOC was supported by funding from the European Community's Seventh Framework Programme [FP7/2007-2013] under grant agreement n°299091. The UNSW Australia Water Research Laboratory provided the data warehouse facilities (http://datawarehouse.wrl.unsw.edu.au). Geoscience Australia is acknowledged for the digital elevation dataset used for catchment delineation and mapping, and eAtlas (http:\\eatlas.org.au) for the Bancannia Basin outline used in Figure 1.

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Table 1. Geological succession recorded at the Planet Oil bore (Fig. 1c) annotated with notes from Mabbutt (1973).

Depth (m)	Lithology	Age
0 - 75	Stiff brown clay with layers of sandy gravel. Layers of swelling clay towards the base. Small feeds of water associated with sand layers.	Cenozoic
75 – 130	Clay interbedded with bands of quartz sand,. Clay layers include lignite and thin dolomites. Sand horizons produce good quality stock water with yields of between 0.6 and 1.25 L/s.	
130 - 155	Grey-brown shale	Lower Cretaceous
155 – 191	White sand with a piezometric head rising to 37m below ground surface. Age determined by palynology sample from 161.5m	
191 - 214	Grey-green to brown shale	
214 - 237	Red-brown shale	Carboniferous (?)
237 - 830	Shale and siltstone (aquitard)	Devonian
830 - 1222	Upper sandstone of the Nundooka Sandstone formation	
1222 - 3527	Red beds. Good porosity between 1448m and 1609m.	
3527 – 3409 (base)	Dacite or andesite volcanics	Lower Cambrian

Table 2. Details of the arid-zone rainfall ga-uge network and yearly average measurement.

Station No.	Station Name	Easting [m]	Northing [m]	Elevation [m AHD]	Record length [years]	Average annual rainfall [mm/year]
1	Mandelman Bore	579968	6566145	141	44	181.6
2	Gap Creek	562219	6557144	192	42	205.1
3	Nelia Dam	570688	6556159	197	44	204.5
4	Warrens Tank	576188	6559590	154	44	201.5
5	Bald Hills	568571	6573795	240	42	196.1
6	Sandstone Bore	570253	6566321	180	22	210.6
7	Johnston's Tank	572572	6569435	167	36	172.6
8	Freislich Dam	564060	6562672	214	36	205.8
9	South Sandstone	563594	6564981	225	32	194.7
10	Air Strip	564367	6561214	213	32	180.6
11	Homestead Creek	566118	6561071	189	36	192.2
12	Beadle	564493	6571434	239	32	215.4
13	Mating	574534	6561476	161	24	118.5
14	Saloon Tank	579580	6562919	137	24	170.1
15	North Mandelman	585776	6569466	125	41	195.2
16	Gap Hills	573430	6575929	149	43	210.2
17	Sandstone Tank	565560	6568887	230	44	213.2
18	Met. Station	566933	6568887	182	44	243.8

Table 3 Average monthly rainfall, standard deviation and coefficient of variation at the BoM rainfall gauge.

Parameter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average monthly rainfall (mm)	33.7	28.5	19.7	12.5	23.8	15.4	19	14.9	16.5	19.2	20.2	20.4
Standard deviation (mm)	51.9	37.7	34.6	26.9	30.9	16.8	19.9	16.1	17.9	19.0	23.1	30.5
Coefficient of variation (%)	154	132	176	215	130	88	104	108	108	98	114	149

Table 4. Average annual rainfall, rank and number of rain days at the BoM rainfall gauge (1970 – 2013).

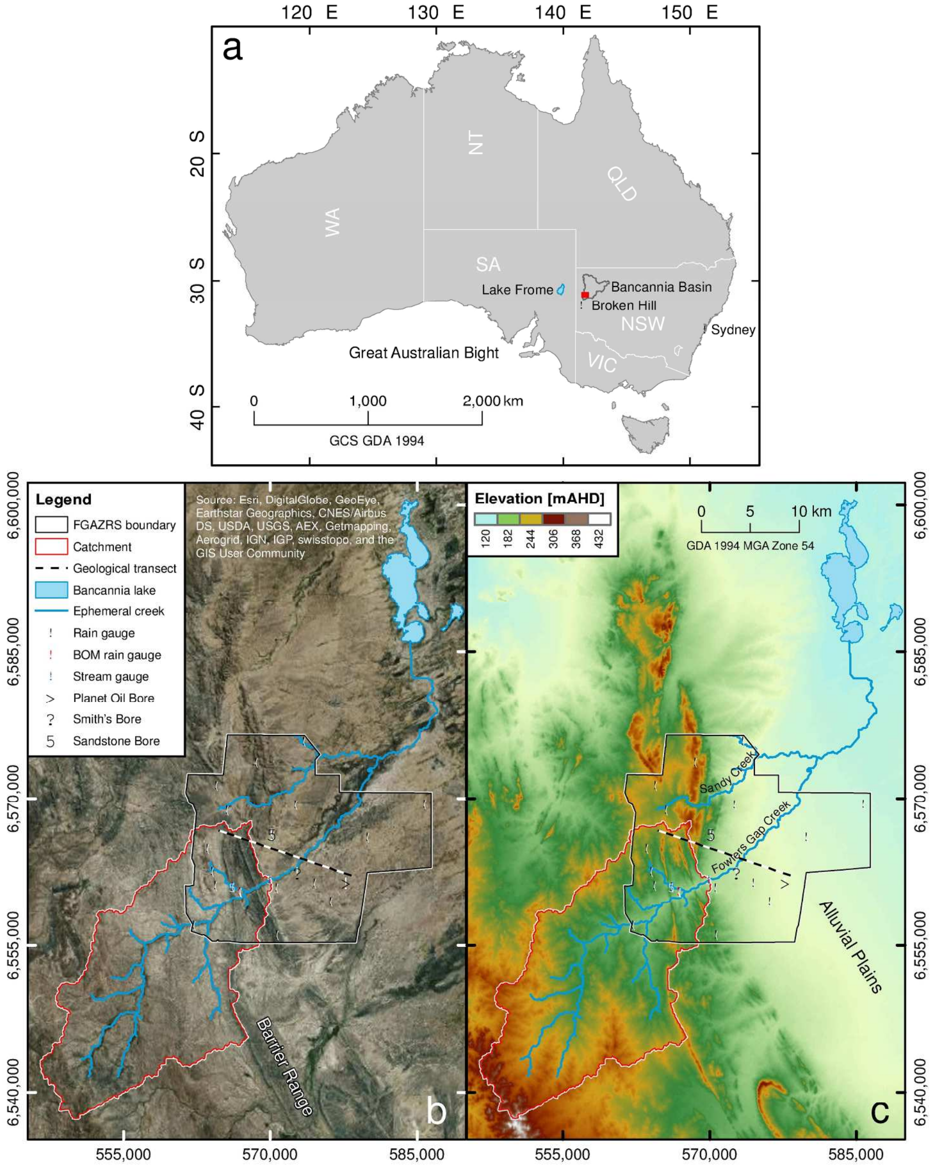
Year	Total rain [mm]	Rank	Rain days
1970	120.6	8	16
1971	302.1	34	42
1972	108.8	7	23
1973	244.6	25	52
1974	809.5	44	71
1975	329.0	37	61
1976	266.0	26	41
1977	30.3	1	13
1978	298.6	32	63
1979	275.7	30	57
1980	146.2	11	41
1981	221.5	21	55
1982	94.0	3	24
1983	223.5	23	58
1984	276.4	31	47
1985	199.5	18	44
1986	189.2	15	33
1987	405.6	41	44
1988	271.8	28	39
1989	341.4	39	51
1990	206.2	19	53
1991	134.0	10	37
1992	329.8	38	47
1993	379.2	40	34
1994	95.0	5	22
1995	195.8	16	27
1996	301.3	33	29
1997	275.4	29	27
1998	305.0	35	41
1999	239.0	24	36
2000	236.8	23	38
2001	175.8	13	33

2002	66.4	2	16
2003	269.6	27	21
2004	163.8	12	14
2005	199.0	17	44
2006	105.6	6	34
2007	210.8	20	48
2008	188.6	14	44
2009	125.6	9	37
2010	522.8	42	71
2011	526.2	43	63
2012	331.6	36	41
2013	94.6	4	30

Table 5. Example daily rainfall data (mm) from the farm year-book records. Note that rainfall data are rounded to facilitate

comparison of totals. Station 18 is the BoM rainfall gauge.

Date	**Station**																	
-	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**
Single wide-spread storm events																		
24/07/04	16	21	21	19	17	15	22	18	19	18	20	20	20	17	16	17	18	19
26/11/02	7	11	12	11	6	9	6	12	12	9	10	9	10	8	6	6	9	10
Single localised storm events																		
12/08/03	-	-	-	-	33	40	41	33	33	28	29	48	-	-	-	40	39	29
02/09/03	-	21	26	18	-	-	-	-	-	2	-	18	20	18	18	-	-	-
Multi-day event: example 1																		
16/12/99	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	14
17/12/99	19	26	28	39	45	45	41	50	42	42	40	63	43	33	16	45	45	26
Multi-day event: example 2																		
28/02/83	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-
01/03/83	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.2	-	-	-
02/03/83	9	15	21	13	14	13	8	-	18	21	-	21	-	-	9	12	9	21
04/03/83	-	-	-	-	-	-	-	24	-	-	23	-	-	-	-	-	-	6
05/03/83	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
06/03/83	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	6
07/03/83	-	3	11	9	-	-	-	-	-	-	-	-	-	-	-	-	-	-
08/03/83	3	-	-	-	2	1	1	7	3	10	5	4	-	-	1	4	5	-
Multi-day event: example 3																		
05/07/93	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	5
06/07/93	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	22
07/07/93	36	48	42	47	45	48	35	50	42	47	46	46	46	44	43	40	39	22
Tipping-bucket data for all gauges: example 1																		
14/08/14	9	11	9	15	6	5	12	10	9	12	6	17	10	13	8	10	19	11
15/08/14	16	18	22	17	19	23	16	15	14	19	19	14	27	17	15	16	14	16
16/08/14	18	14	8	17	20	12	18	20	21	16	13	20	10	16	12	13	20	13
Tipping-bucket data for all gauges : example 2																		
24/09/14	34	24	27	38	39	27	37	32	29	26	26	35	33	31	39	41	30	27



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218x262mm (300 x 300 DPI)

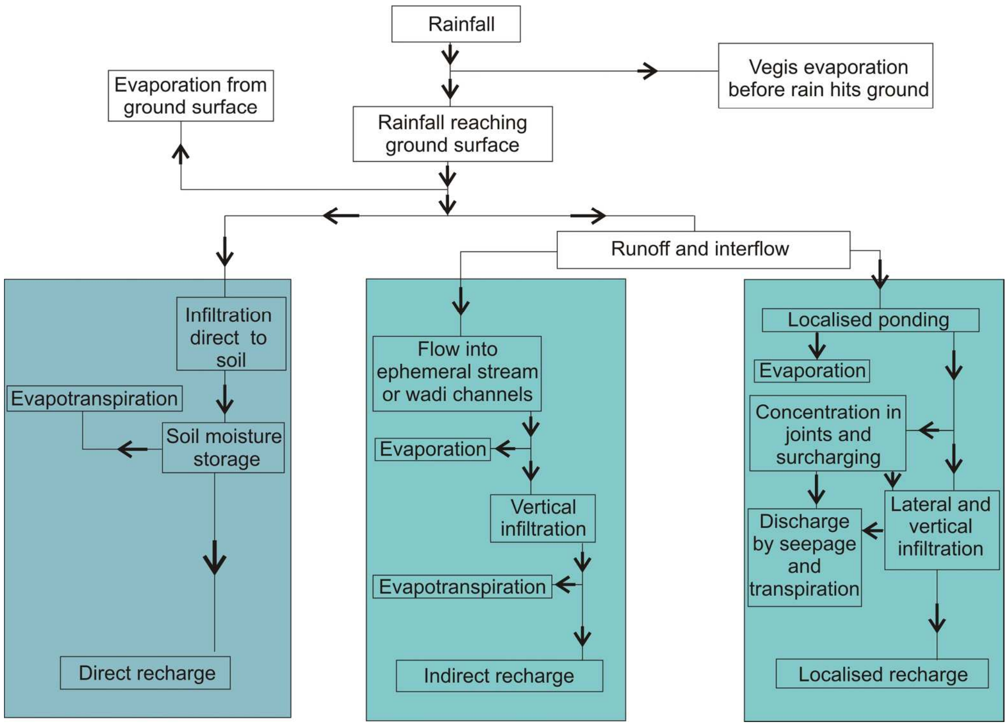


Fig. 2 Conceptual model depicting recharge processes in arid and semi-arid zones (modified after Lloyd, 1986).
176x126mm (300 x 300 DPI)

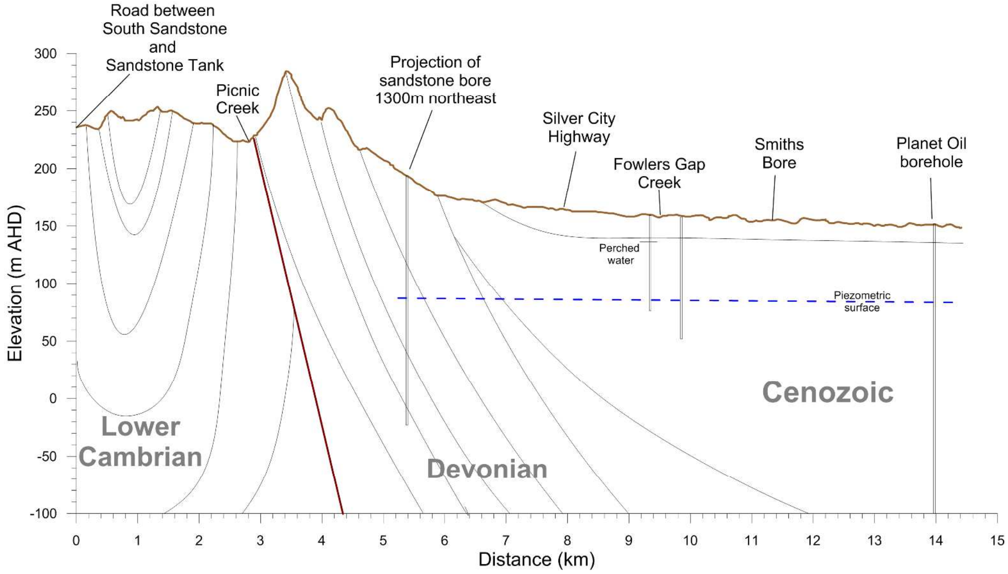


Figure 3: Sketch section showing general geological units and basic groundwater level data at FGAZRS. Line of section is shown in Figure 1b.
260x148mm (300 x 300 DPI)

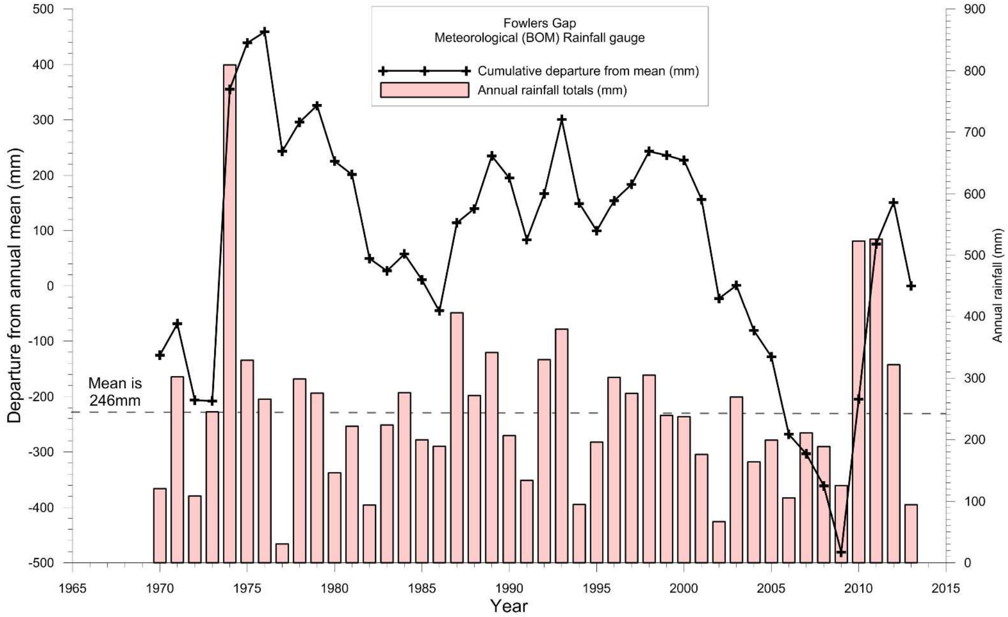


Figure 4: Cumulative departure from the mean for the Australian Bureau of Meteorology (BoM) rainfall gauge annual rainfall series.
274x168mm (300 x 300 DPI)

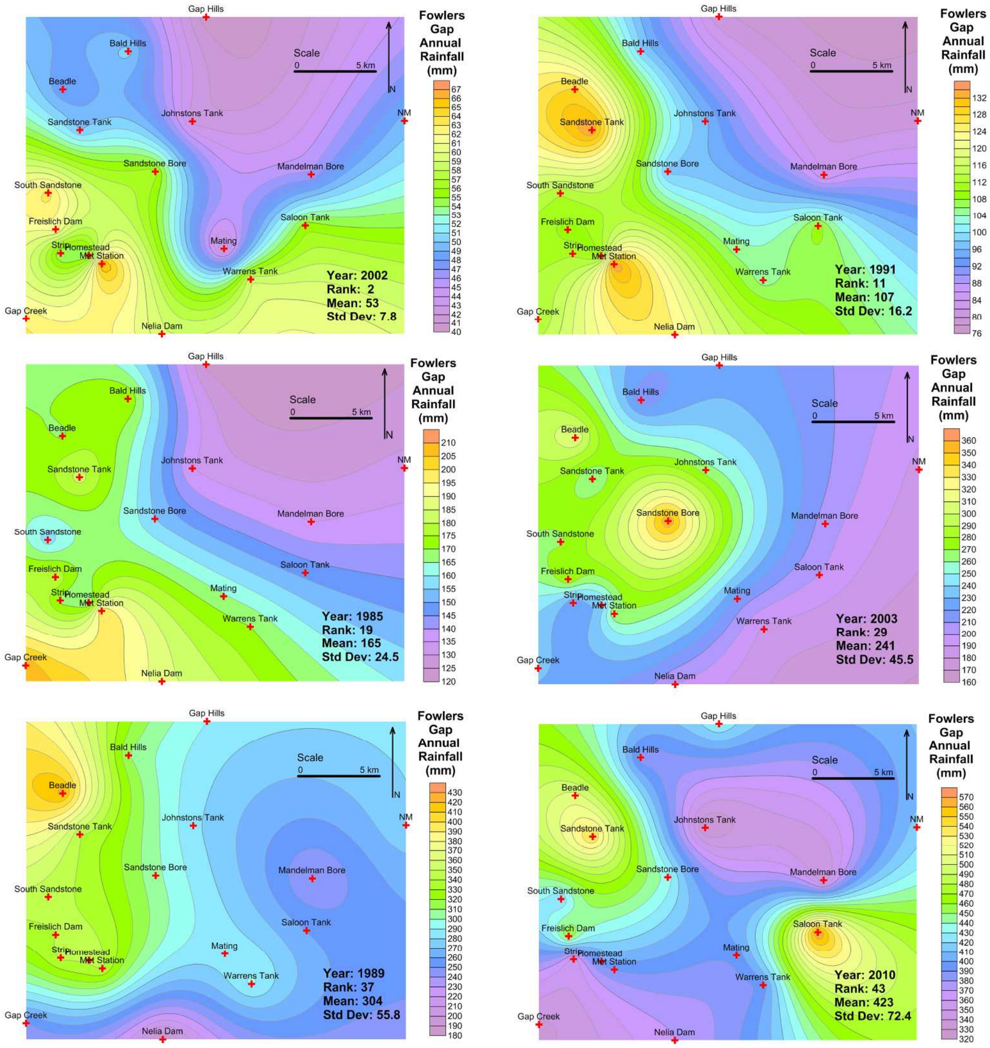


Figure 5: Total rainfall distribution across FGAZRS for representative rainfall years, selected from a ranked series of annual average rainfall.
203x214mm (300 x 300 DPI)

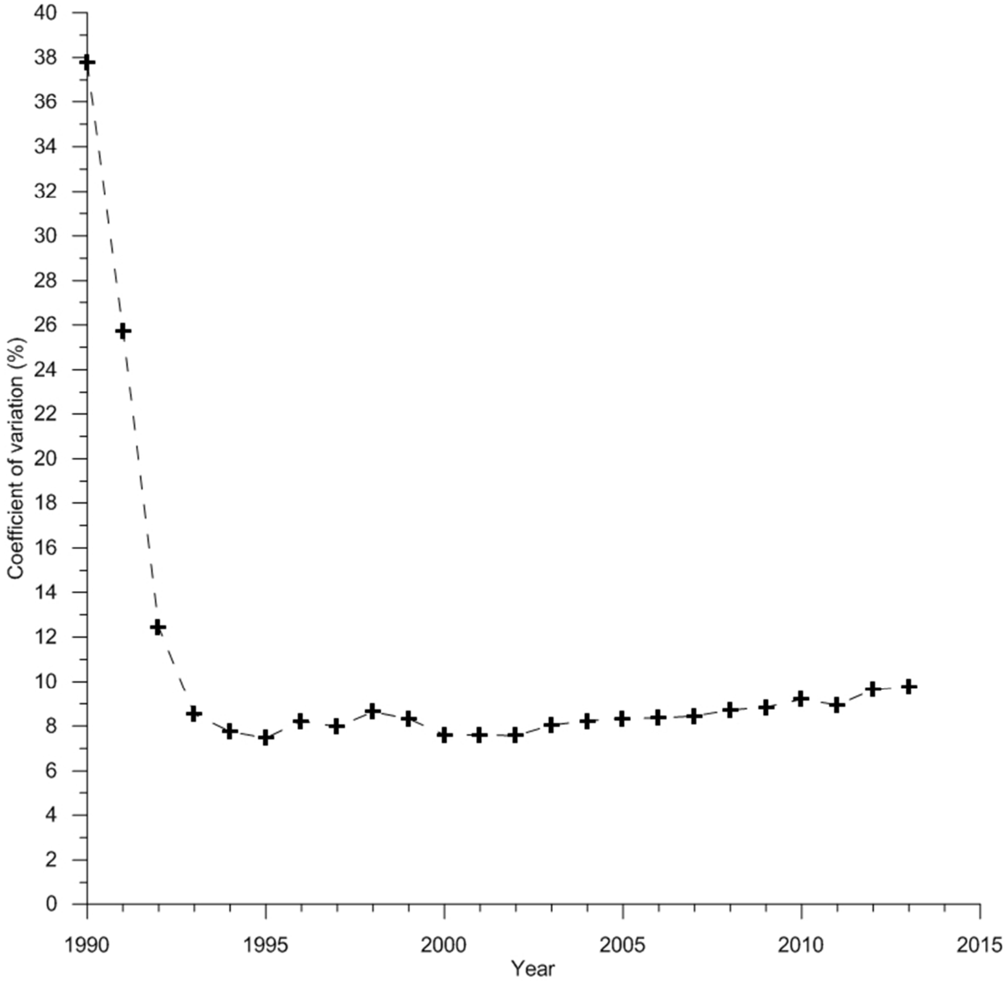


Figure 6: Coefficient of variation for the cumulative annual total rainfalls.
172x168mm (119 x 119 DPI)

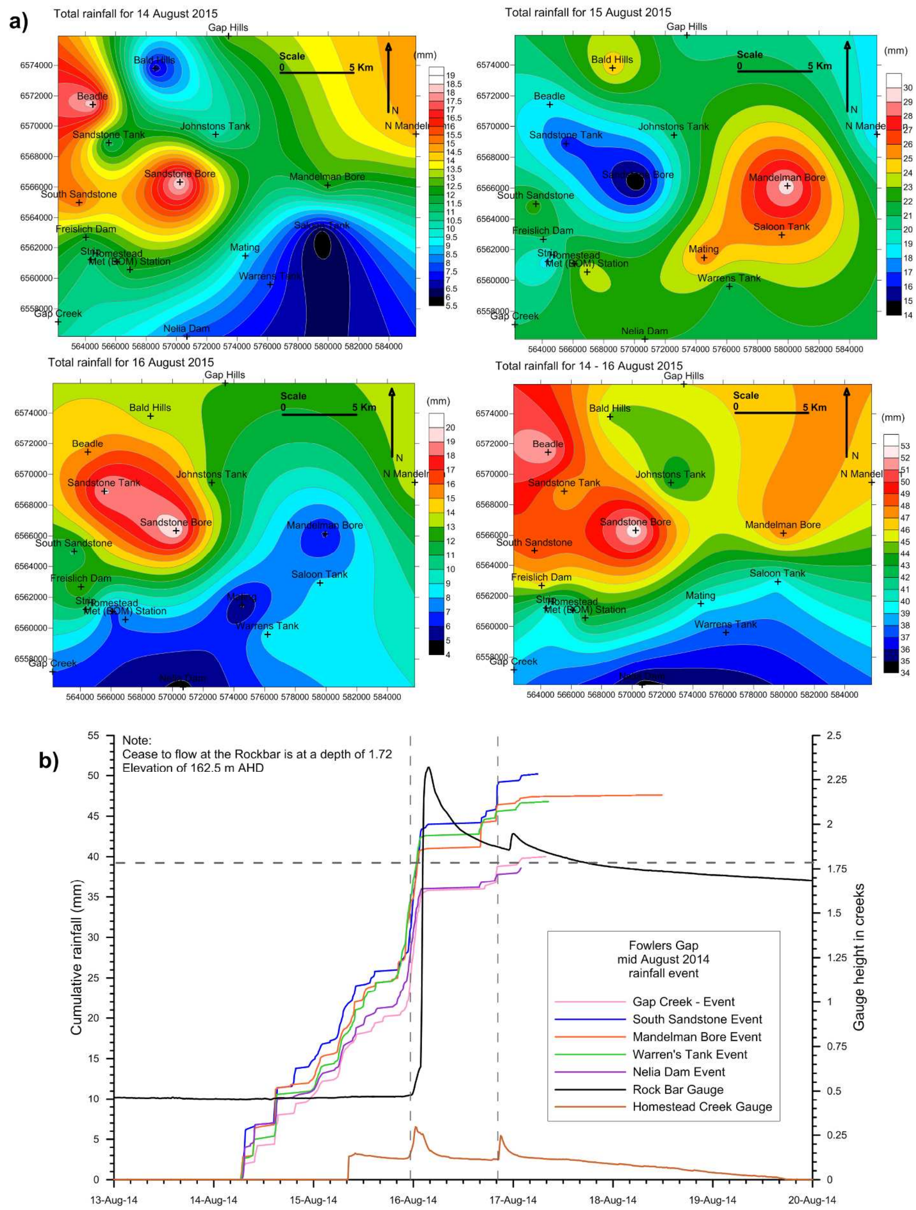


Fig. 7 a) Rainfall distributions over a 3-day event in August 2014. b) Hyetographs and run off at the Rock Bar and Homestead Creek stream gauges (refer to Figure 1b and 1c).
200x265mm (300 x 300 DPI)

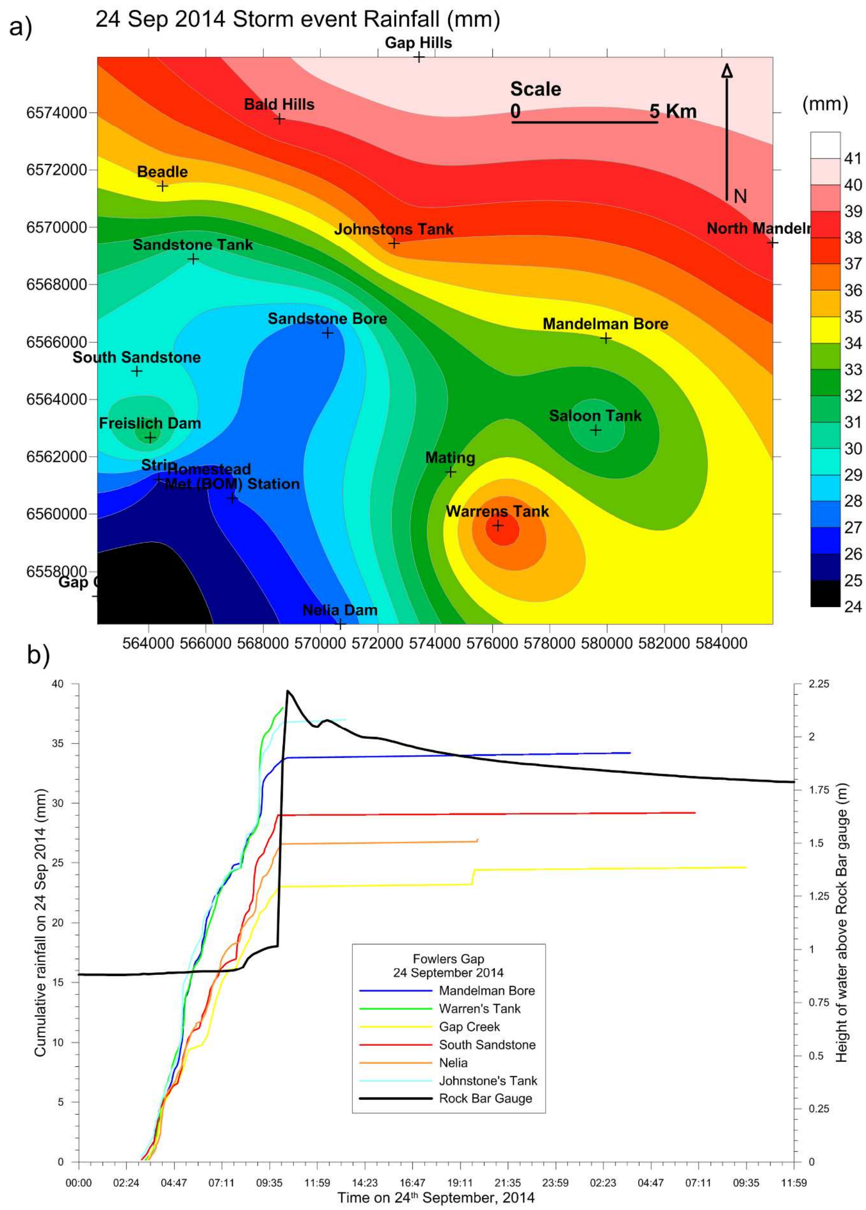
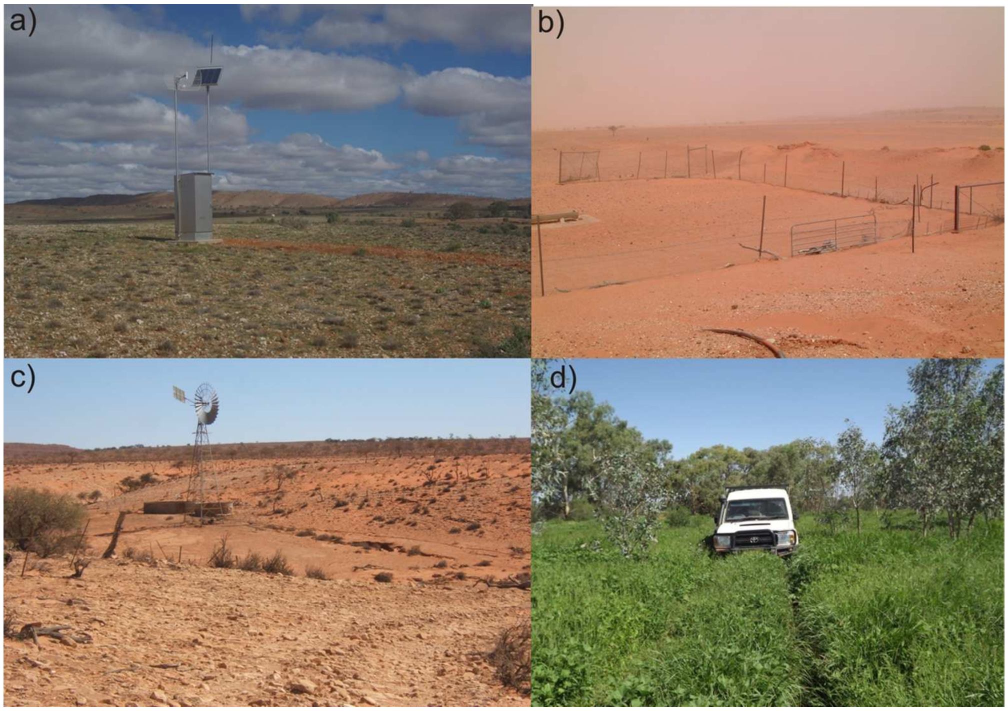


Fig. 8 a) Rainfall distributions over a 1-day event on 24 September 2014. b) Hyetographs and runoff measured at Fowlers Gap stream gauge (refer to Figure 1b and 1c).
182x256mm (300 x 300 DPI)



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112x78mm (300 x 300 DPI)