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On the uncertainties associated with using gridded rainfall data as a proxy for observed

C. R. Tozer, A. S. Kiem, and D. C. Verdon-Kidd

Environmental and Climate Change Research Group, School of Environmental and Life Sciences, Faculty of Science and IT, University of Newcastle, NSW, Australia

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Correspondence to: C. R. Tozer (carly.tozer@uon.edu.au)

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Abstract

Gridded rainfall datasets are used in many hydrological and climatological studies, in Australia and elsewhere, including for hydroclimatic forecasting, climate attribution studies and climate model performance assessments. The attraction of the spatial coverage provided by gridded data is clear, particularly in Australia where the spatial and temporal resolution of the rainfall gauge network is sparse. However, the question that must be asked is whether it is suitable to use gridded data as a proxy for observed point data, given that gridded data is inherently "smoothed" and may not necessarily capture the temporal and spatial variability of Australian rainfall which leads to hydroclimatic extremes (i.e. droughts, floods)? This study investigates this question through a statistical analysis of three monthly gridded Australian rainfall datasets – the Bureau of Meteorology (BOM) dataset, the Australian Water Availability Project (AWAP) and the SILO dataset. To demonstrate the hydrological implications of using gridded data as a proxy for gauged data, a rainfall-runoff model is applied to one catchment in South Australia (SA) initially using gridded data as the source of rainfall input and then gauged rainfall data. The results indicate a markedly different runoff response associated with each of the different sources of rainfall data. It should be noted that this study does not seek to identify which gridded dataset is the "best" for Australia, as each gridded data source has its pros and cons, as does gauged or point data. Rather the intention is to quantify differences between various gridded data sources and how they compare with gauged data so that these differences can be considered and accounted for in studies that utilise these gridded datasets. Ultimately, if key decisions are going to be based on the outputs of models that use gridded data, an estimate (or at least an understanding) of the uncertainties relating to the assumptions made in the development of gridded data and how that gridded data compares with reality should be made.

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Uncertainties associated with using gridded rainfall data

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1 Introduction

Rainfall data is a crucial component in many engineering applications. It is required, for example, to carry out rainfall/runoff modelling to estimate inflows into a reservoir, determine the size of rainwater tanks for water sensitive urban design, or calculate the size of levees for flood mitigation strategies. Similarly, those in the climate community use rainfall data to develop and test seasonal forecasting schemes, perform climate attribution studies and verify climate model outputs. However, it is often the case, particularly in Australia due to low population densities and the relatively short history of observational recordings (especially away from the eastern seaboard), that observational rainfall data does not exist at the specific location of interest for such hydrological or climatological investigations. The sparseness of the rainfall observation network means that the gauge closest to the point of interest may be several kilometres away and therefore not representative of the climate patterns at the required location (Jeffrey et al., 2001).

In order to overcome this problem, and also due to the increasing development and popularity of Geographical Information Systems (GIS) software and grid based climate and hydrological models, significant efforts have been made into spatially interpolating data so as to fill the "gaps" in the observational network (e.g. Jeffrey et al., 2001; Hapuarachchi et al., 2008; Kiem et al., 2008; Jones et al., 2009). There are currently two Australia-wide monthly gridded rainfall datasets available. These are the Australian Water Availability Project (AWAP) dataset (http://www.eoc.csiro.au/awap/) and the SILO dataset (www.longpaddock.qld.gov.au). The AWAP dataset superseded the Bureau of Meteorology's former operational gridded rainfall dataset (referred to as the BOM dataset henceforth) in early 2010. While the BOM, AWAP and SILO gridded datasets were developed with the same objective in mind (i.e. complete spatial coverage of rainfall data for Australia), the methods used to produce the various gridded datasets differ in many aspects (refer to Sect. 2.1 for details). All three datasets have been used in recent hydrological and climatological studies. For example, the BOM

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gridded rainfall data was used in recent studies undertaken by Verdon-Kidd and Kiem (2009) and Evans et al. (2009) and the SILO dataset was used in hydrological modelling for the Murray Darling Basin Sustainable Yields and Tasmania Sustainable Yields projects (see Chiew et al., 2008; Viney et al., 2009) and is widely used in industry (e.g. environmental consulting, government agencies, water authorities). AWAP data was used in the modelling undertaken for the Climate Futures for Tasmania project (Grose et al., 2010) and also in several projects being undertaken as part of the South Eastern Australian Climate Initiative: Phase 2 (www.seaci.org).

As discussed, due to the spatially and temporally incomplete nature of the observational network in Australia (and many other places in the world), continuous century (or greater) long, monthly and daily rainfall data that covers the whole of Australia is immensely attractive – as demonstrated by the widespread use of various sources of gridded data. However, it must be remembered that gridded data is in essence "virtual data" and that numerous assumptions underlie the spatial interpolation techniques used to produce the gridded data and that these assumptions differ across the various gridded data products. Given the "virtual" nature of gridded data, and the different techniques used to produce it, differences between (a) gridded data and observed station data and (b) the different gridded datasets will exist. Beesley et al. (2009) reviewed the AWAP and SILO error statistics and found that across Australia there is a negative/positive bias in the gridded datasets for higher/lower rainfall areas. Similar results were found by Silva et al. (2007) and Ensor and Robeson (2008) in their comparisons of gridded and gauged data in Brazil and Midwestern USA, respectively.

The aim of this study is therefore to determine where and when the differences between gridded and gauged monthly, seasonal and annual data occur and to quantify the magnitude of the disagreements (Sect. 4). South Australia (SA) is chosen as the case study as it is a region with limited gauged data and its water resources have also recently become a research focus with the establishment of the Goyder Institute (http://www.goyderinstitute.org/index.php). Studies into SA's water resources require rainfall data but limited work has been done on analysing the pros and cons of various

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sources of rainfall data for SA. Of particular interest are the potential implications of using gridded rainfall data as a proxy for gauged data in hydrological modelling in SA (Sect. 5). It should be noted that this study does not seek to identify which gridded dataset is the "best" – it is unlikely this is even possible given that all data sources, including observed station data, have their strengths and weaknesses (e.g. Lavery et al., 1997). Rather, the intention here is to quantify differences between various gridded data sources, and how they each compare with observed point data, such that these differences can be considered and accounted for in the increasing number of studies that utilise gridded data.

2 Data

2.1 Gridded rainfall data

The BOM, AWAP and SILO Australia-wide gridded datasets provide spatially interpolated monthly (and daily, in the case of AWAP and SILO) rainfall grids at a resolution of $0.05^\circ \times 0.05^\circ$ (i.e. approximately 25 km^2).

The BOM dataset was produced using the Barnes successive correction technique (Jones and Weymouth, 1997). In this technique grid values are derived from nearby observation stations whose influence on a grid point is determined based on the distance between the two points. Several iterations are performed to decrease the difference between the grid points and the observed data until a high resolution grid is produced (Jones and Weymouth, 1997). Over 5000 gauging stations across Australia are used in the interpolation. This process produced grids at a 0.25° longitude-latitude resolution (Jones and Weymouth, 1997; Fawcett et al., 2010). Spline interpolation analysis was used to achieve a grid resolution of 0.05°. BOM gridded data is available from 1900 to 2009 and is no longer updated, as it was superseded by the AWAP dataset in early 2010 (Fawcett et al., 2010). It should be noted that only BOM data from 1900 to 2008 was available to the authors at the time this analysis was undertaken.

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The AWAP dataset is produced as part of the Australian Water Availability Project, a joint initiative of the BOM and the Commonwealth Scientific and Industrial Research Organisation (CSIRO). In the daily/monthly AWAP dataset the observed daily/monthly rainfall from approximately 7500 stations is decomposed into a monthly average and associated anomaly (Jones et al., 2009). These daily/monthly anomalies are then interpolated using the Barnes successive correction technique (as utilised in the BOM gridded dataset), whilst the monthly climatological averages are interpolated using three-dimensional smoothing splines (Jones et al., 2009). The rainfall grids are produced by multiplying the monthly climate average grids and daily/monthly anomaly grids. An unexplained microscale variance term is used in AWAP to allow for observational or measurement error, such that exact reproduction of gauged values at each gauge location is not expected. AWAP rainfall grids are freely available from 1900 onwards at http://www.eoc.csiro.au/awap/. It is noted that the AWAP product is undergoing constant improvement and development – in this study AWAP Version 3 daily interpolated and monthly interpolated datasets (CSIRO March 2010 reformat of the Bureau of Meteorology AWAP Version 3 monthly rainfall surfaces) were used.

The SILO dataset is produced by the Queensland Department of Environment and Resource Management. Two SILO products are available: the data drill product (i.e. gridded data) and the patched point data product. In this analysis the daily and monthly data drill product (i.e. gridded data), available from 1890 onwards from www.longpaddock.qld.gov.au, was used. To generate the monthly gridded SILO rainfall dataset, the observed data from nearly 5000 BOM stations is normalised and then interpolated using ordinary kriging. The observed data is cross validated and stations with high residuals are removed. The updated dataset is reinterpolated using ordinary kriging and the monthly rainfall surfaces are generated by reversing the normalisation (Jeffrey et al., 2001; Jeffrey, 2006). It is important to note that the process used to create the SILO datasets is set to accurately reproduce the observed data (i.e. exact interpolation).

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2.2 Observed rainfall data

Gauged monthly rainfall totals were extracted for 16 stations across SA (see Fig. 1) so that a gridded and gauged data comparison could be undertaken. The stations encompass a range of elevations and locations (coastal and inland) throughout SA and cover various timeframes. Station details are provided in Table 1. Five of the 16 stations are considered "high quality" as defined by Lavery et al. (1997), who developed a list of 379 rainfall stations across Australia that did not show inhomogeneities or spurious trends in their data records (Lavery et al., 1997; Gallant and Karoly, 2010). These five "high quality" stations (highlighted in Table 1) also have records greater than 70 years. The additional eleven stations, five "long record" (>70 years) and six "short record" (<50 years), although not rated as "high quality" based on the Lavery et al. (1997) definition, are on average 91 % complete and therefore suitable for this analysis. As discussed earlier, the process used to create the SILO grids is set to enforce exact interpolation. Given this, the SILO gridded dataset is likely to be a better fit to the observed data (Beesley et al., 2009) compared with the BOM and AWAP gridded datasets.

2.3 Data utilised for hydrological model

Daily observed streamflow (gauge number A4260504, obtained from the Department for Water's Surface Water Archive: http://e-nrims.dwlbc.sa.gov.au/swa/) and daily rainfall (gauge number 23808 obtained from http://www.bom.gov.au/climate/data/) within the Finniss River catchment in SA (see Fig. 3) and mean monthly areal potential evapotranspiration (from maps provided at http://www.bom.gov.au/climate/averages/climatology/evapotrans/) were used to calibrate the hydrological model (see Sect. 5 for details).

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3 Methodology

3.1 Intercomparison of gridded rainfall datasets

Given that the three gridded datasets (BOM, AWAP, and SILO) are produced using different methods, some differences between them are to be expected. However, the gridded datasets are intended to represent the same observed (or real) situation and therefore it is hoped that these differences are minimal. As a first step in understanding how the three gridded datasets compare, the percentage differences in annual averages between SILO and AWAP gridded datasets and BOM and AWAP gridded datasets for the whole of SA were determined. The same comparison was undertaken at a randomly selected ungauged point location within SA (see Fig. 1 for point location). Note that AWAP was used as the reference point here as this dataset is widely used by Government agencies and the general public due to its free availability on the BOM website.

3.2 Comparison of gridded rainfall datasets against gauged rainfall

The gridded datasets were compared to gauged data records across SA on a monthly, seasonal and annual scale with seasonal and annual data gained via aggregation of the monthly totals. For all analyses, any seasons or years with missing monthly gauged data were excluded from the analyses. The statistics were calculated for the gauged periods presented in Table 1. The following analyses were performed:

1. Comparison of BOM, AWAP, and SILO grids that correspond with each gauged site (from Table 1) with the actual gauged data on a monthly, seasonal and annual basis using the Nash Sutcliffe Efficiency (NSE) (Eq. 1). Note only seasonal NSE results are shown in Sect. 4.

$$\mathrm{NSE} = 1 - \frac{\sum_{i=1}^{n}(\mathrm{Gridded}_i - \mathrm{Observed}_i)^2}{\sum_{i=1}^{n}(\mathrm{Observed}_i - \overline{\mathrm{Observed}})^2} \quad (1)$$

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2. Comparison of BOM, AWAP and SILO grids that correspond with each gauged site (from Table 1) with the actual gauged data on a monthly, seasonal and annual basis using the Root Mean Square Error (RMSE) (Eq. 2). Note only annual RMSE results are shown in Sect. 4.

$$\text{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(\text{Gridded}_i - \text{Observed}_i)^2} \quad (2)$$

3. Comparison of the number of zero rainfall months and the 99th percentile (i.e. wettest 1 %) monthly rainfall recorded at each gauge shown in Table 1 with the corresponding BOM, AWAP and SILO grids.

The above analyses compare the rainfall recorded at a single station with the rainfall produced, using either the BOM, AWAP or SILO process, for the grid within which the station sits. Some grids, however, encompass several rainfall stations that have recorded data over the same period. This situation presented an opportunity to determine how the rainfall recorded at each gauge compares with the gridded rainfall produced, particularly given that the rainfall recorded at one station is likely to be different than the rainfall recorded at another station within the grid. For example, do the rainfall totals produced for the gridded data simply sit in the middle of the gauged rainfall totals? To investigate this, four grids in SA which contain multiple rainfall gauges were selected and the annual totals for three high rainfall years and three low rainfall years recorded at the stations within each grid were compared with the corresponding BOM, AWAP and SILO annual totals (Fig. 2). To select the high rainfall years the annual timeseries for each gauge within the grid were plotted and three high rainfall years common to at least two of the gauges within the grid were selected. The same process was undertaken to select the low rainfall years.

3.3 Hydrological modelling implications

To investigate the hydrological modelling implications of using gridded rainfall data as a surrogate for gauged data, a simple rainfall runoff model was developed. This

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modelling exercise aimed to highlight the sensitivities of hydrological modelling to changes in the rainfall input and therefore the potential issues associated with using gridded data for such an application. A daily rainfall-runoff model was developed using SIMHYD (i.e. the SIMple HYDrology model) for the upper Finniss River catchment in SA (Fig. 3). SIMHYD is a daily rainfall-runoff model which uses daily rainfall and areal potential evapotranspiration data to estimate daily stream flow (refer to Peel et al., 2000, for further information on SIMHYD).

4 Results

4.1 Intercomparison of gridded rainfall datasets

Figure 4a and b shows the percentage differences in annual average rainfall in SA for the period 1900 to 2008 between the SILO and AWAP and BOM and AWAP gridded datasets, respectively. Figure 4a shows that the SILO dataset has a tendency to have a lower annual average compared to AWAP for most of the State for the period 1900 to 2008 with differences in the order of −5 % to −20 % difference between the two datasets. The BOM and AWAP datasets appear to be more similar with most of the differences ranging between −5 % and 5 %, although there are some regions of the State that display differences outside these bounds (Fig. 4b). It is interesting to note that the BOM/AWAP difference map seen in Fig. 4b appears "smoother" than the SILO/AWAP map seen in Fig. 4a. This may be due to the AWAP and BOM datasets being produced using similar methods compared with the process used to create the SILO dataset. Overall, Fig. 4a and b confirm that the three datasets are indeed different for SA.

Figure 5 compares the three gridded datasets at a randomly selected ungauged point in SA (see Fig. 1 for point location) and it is found that the differences across the three gridded data sets are marked, ranging from approximately +80 % to −40 %. It should be noted that there is no way of telling which of the gridded datasets is most representative of the real rainfall data at this point, since the random point was deliberately

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chosen so as not to overlap with an observation station. It is clear, however that, for the selected location, the three gridded datasets (BOM, SILO, AWAP) rarely agree (i.e. the lines are rarely on 0 %) and importantly there does not seem to be any systematic pattern to the disagreement (i.e. the differences appear to be random). This raises the questions, what is the true rainfall timeseries at the chosen point since 1900? Which (if any) of the gridded datasets is a suitable representation of the gauged data, which itself is an approximation of the actual climate conditions?

4.2 Comparison of gridded rainfall datasets against gauged rainfall

4.2.1 Annual rainfall totals

The RMSE of the annual rainfall totals for each gridded dataset are presented as a percentage of the annual gauge mean in Table 2. Note that the RMSE gives an indication of the average "error" (or difference) between the gridded and gauged datasets, but not the direction of the error. The green cells highlight the gridded dataset which best matches the gauged data, and the second closest match is highlighted in yellow.

It is evident from Table 2 that the RMSE values determined for SILO tend to be lower than those calculated for AWAP and BOM. Indeed, ten of the sixteen stations have RMSE values of less than 5 % for SILO. Another notable result is observed at the gauge with the highest elevation (23736) where all gridded datasets (including SILO) recorded high RMSE values (between approximately 15 and 20 %) indicating the gridded data may be unreliable at higher elevations or that there are steeper rainfall gradients and therefore higher rainfall variability. However larger errors (up to around 30 %) were recorded for the AWAP and BOM datasets at other gauges.

4.2.2 Annual rainfall extremes

Figure 2 shows the location of the four SA grids investigated in the annual rainfall extremes assessment and the stations within each grid. These grids were selected

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as they contained several rainfall gauges with overlapping records between 1900 and 2009. Figure 6 shows the annual rainfall recorded at each station (where the data is available for that year) and the corresponding gridded rainfall data for three high rainfall and three low rainfall years (as determined from the gauged data as described in Sect. 3.2). Although there are some "outliers" (e.g. SILO in Grid 2, high rainfall event in 1923), the gridded annual totals tend to sit in between the gauged totals. A clear example is seen in Grid 4 (low rainfall event in 1982) where the gridded datasets essentially capture the midpoint between the two gauges. Ultimately the results suggest that the gridded datasets do not accurately capture the gauged extremes.

4.2.3 Seasonal rainfall totals

The seasonal NSE values calculated in the comparison of the gridded and gauged at each of the 16 gauges selected are presented in Table 3. Again, the green cells highlight the gridded dataset which best matches the gauged data, and the second closest match is highlighted in yellow. The NSE gives an indication of the agreement between the observed and gridded data (see Eq. 1). A NSE value of 1 indicates that the gridded data exactly matches the observed data (Chiew, 2006; Peel et al., 2000).

Table 3 shows that SILO is a better match to gauged data compared to AWAP and BOM (a result consistent with the RMSE analysis), with NSE values generally close, if not equal to 1. This is generally expected given that SILO data is produced through exact interpolation of the observed data (Jeffrey et al., 2001). Although the SILO data is "fitted" to the observed data, it is not an exact match. This is shown in the annual RMSE results as well as in the seasonal NSE results, particularly at the high elevation gauge, 23736. Another interesting result is that AWAP outperforms BOM during spring at most stations, yet during summer BOM tends to record higher NSE values compared to AWAP. Interestingly, AWAP and BOM both perform very poorly in autumn and winter for gauges 17125 and 20050, respectively, however there is no clear reason for the very low NSE values calculated.

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To investigate if the gridded data performs worse at higher elevations (as suspected based on the RMSE results), seasonal NSE values calculated for each gauge for each gridded dataset were plotted against gauge elevation. The spring results are shown in Fig. 7. It is evident that the values determined for SILO congregate around an NSE value of 1, whereas the values determined for AWAP and BOM are much more scattered. There is no obvious trend in NSE value and elevation; however there is a clear outlier, which corresponds to the highest gauge, 23736 (elevation 727 mAHD). The readings taken for this gauge ceased in 1956, thus it is not clear whether the significantly lower NSE values recorded for this site are due to topographical issues or temporal issues (since all three data sets perform poorly at this location).

4.2.4 Monthly rainfall extremes

An important aspect of the gridded data is the ability to capture the high and low rainfall extremes, since it is often the extremes that are of interest in hydrological and climatological studies. To explore this issue further Table 4 shows the number of months over the gauged period that each dataset records a zero rainfall month along with the 99th percentile monthly rainfall (in mm) for all datasets. Again the gridded dataset that most closely matches gauged is highlighted in green and the second closest in yellow. Table 4 shows that both the BOM and AWAP datasets often significantly underestimate the number of gauged zero rainfall months, whereas SILO matches the gauged data reasonably well. This result indicates that the AWAP and BOM datasets are likely to overestimate the low rainfall months. On the other end of the scale, it is also evident that the gridded datasets do not match the gauge at the higher rainfall months (i.e. 99th percentile rainfall). At more than half of the stations, all three gridded datasets underestimate the 99th percentile gauged monthly rainfall. This finding fits with results of Beesley et al. (2009) who, in their review of daily AWAP and SILO error statistics, found that there is a negative/positive bias in the gridded datasets for higher/lower rainfall areas. Similar results were found by Silva et al. (2007) and Ensor and Robeson (2008) in their comparisons of gridded and gauged data in Brazil and Midwestern

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USA, respectively, which indicates that the "smoothing out" of extreme rainfall events is a common issue with gridded datasets.

5 Implications of using gridded rainfall data as a surrogate for observed in hydrological modelling

Table 5 shows the calibration and verification statistics for the SIMHYD model developed for the Finniss River catchment in SA (Fig. 3). A reasonable calibration was obtained that was considered suitable for the purpose of this comparative study, noting that natural streamflow data is particularly difficult to obtain for SA due to diversions, extractions and interbasin transfers (B. Murdoch, personal communication, 22 September 2010). Following calibration of the model, flow was simulated for the period 1970 to 2002 using the gauged daily rainfall (23808) and AWAP daily gridded rainfall extracted at the gauge location. Figure 8 shows a comparison of the simulated flow aggregated to an annual timestep. It is evident from Fig. 8 that the flow simulated using the AWAP gridded rainfall data tends not to reach the high flow extremes of the gauged flow. This is particularly obvious during the period 1985 to 1990. On the other end of the scale the low gauged flows tend to be overestimated by the AWAP simulated flow. The results obtained using SILO data (not presented) were consistent with this pattern, although to a lesser degree given the closer agreement between SILO gridded rainfall data and gauged rainfall.

Annual, seasonal and monthly NSE statistics for (1) AWAP rainfall data compared with gauged rainfall data (gauge number 23808) and (2) flow simulated using AWAP data and the gauged flow data (A4260504) for the period January 1970 to December 2002 are presented in Table 6. The results clearly demonstrate that although the NSE values for rainfall are relatively high, they markedly decrease in the flow comparison. The results of the analysis shown in Fig. 5 and Table 6 align with suggestions that a change (or error) in rainfall will lead to a greater change (or error) in streamflow (Chiew, 2006). In the example outlined above the results show that a one percent

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difference between gauged rainfall and gridded rainfall for station 23808, leads to approximately a four percent error in streamflow, demonstrating that even a small discrepancy in rainfall can lead to a large difference in streamflow estimates. Importantly, this result highlights the need for caution when using gridded data in hydrological applications, a point that is further discussed below.

As mentioned in Sect. 2.3 the hydrological model was calibrated using gauged rainfall data, and as such, it is expected that flow calculated using gauged rainfall as an input will more closely match the observed flow than flow simulated using gridded rainfall (i.e. a dataset that was not calibrated for). However, the point here is to illustrate the differences between gridded and gauged data and to test the assumption that gridded data can be used as a proxy for observed point data. If it were the case that gauged data was well represented by gridded data then simulated flow should also be similar, regardless of which data source was used for calibration. Clearly this is not the case, hence implying that currently available gridded rainfall datasets may not be a suitable proxy for gauged rainfall data for hydrological modelling in SA.

6 Discussion

The results of this study have shown that the SILO, AWAP and BOM gridded datasets are not an exact match to gauged rainfall. Gauges at different elevations and spatial scales were tested at different temporal scales (monthly, annual and seasonal) and the differences between the gridded datasets and between each gridded data set and gauged observations do not appear to be systematic. SILO is a much better fit to the gauged data but this is to be expected as the method used to develop the SILO database involves a step that directly "fits" the gridded data to the gauged observations. In reality, assessing the fit of the AWAP and BOM datasets to a gauged point location is not a fair comparison given that the methods used to create these datasets aim to produce an accurate picture of the area average rainfall, not necessarily rainfall at individual points (Jones and Weymouth, 1997). The procedure used to create the SILO

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dataset on the other hand is set to enforce exact interpolation of the observed data (Jeffrey et al., 2001), however, even this does not mean it is possible that a SILO grid value will be identical to the rainfall at all sites within that grid. There are suggestions, however, that exact interpolation can be misleading as it assumes that there is no error in the observed data (e.g. that results from errors in measurement) (Hutchinson, 1993). Furthermore, there is no simple way of assessing how accurately the SILO dataset, or any gridded dataset, captures the rainfall in ungauged areas.

Another point to consider is how the processes used to produce the gridded rainfall datasets account for a changing rainfall observation network and the potential biases this may introduce. For example, Fawcett et al. (2010) show that the BOM gridded rainfall dataset is subject to network driven inhomogeneities in Tasmania (i.e. the BOM grids show artificial changes in rainfall as the number of stations providing data each month/year changes) but that the AWAP gridded dataset substantially reduces the inhomogeneities (Fawcett et al., 2010). Although the focus is of Fawcett et al. (2010) was on western Tasmania, it is likely that similar issues apply in areas where there are few rainfall gauges or where significant changes in the gauge network occur over time. This is the case for SA where, as illustrated in Fig. 9, the gauge network in has changed markedly over time and there are large ungauged areas. Future analysis should be focused on assessing inhomogeneities in the gridded data resulting from these network issues and quantifying the uncertainties that emerge.

The point of this investigation, however, is not necessarily to compare the performance of the gridded datasets in how they mimic gauged data or compare them to each other, but rather to highlight that gridded data is interpolated gauged data and should be considered as such (and made explicitly clear in studies that use this data) and the implications of this considered (i.e. gridded data is not observed data and is not necessarily indicative of the real situation, particularly with respect to extremely wet and dry conditions). The results of the hydrological modelling (Sect. 5) demonstrate one implication of the issues associated with using the gridded data as a surrogate for observed (i.e. for every 1 % difference between gridded and observed rainfall inputs

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there was a corresponding 4 % difference between observed and simulated flow).

Of major concern is that gridded data is being used as a proxy for observed data in studies aiming to downscale and/or bias-correct climate model outputs with the expectation that this brings the climate model outputs closer to "reality". However, this is not the case at all, rather such exercises just force the climate model outputs to more closely match the gridded data which, as demonstrated here, is sometimes significantly different to the observations (particularly with respect to extremes) which themselves may or may not be "real" (Hutchinson, 1993). Another issue is the use of gridded rainfall data in studies seeking to attribute patterns or trends to physical climate mechanisms – the attribution studies will be flawed if the data the patterns or trends are based on do not accurately reflect reality, especially in relation to climatic extremes. Ultimately, if key decisions are going to be based on the outputs of models that use interpolated data, an estimate, or at least an understanding, of the uncertainties relating to the assumptions made in the development of gridded data and how that gridded data compares with reality should be made (Jeffrey et al., 2001). There should be (a) error analysis between observed and gridded data undertaken as a matter of course, and (b) ensembles of gridded data surfaces with associated stochastic uncertainty quantification in both space (e.g. due to limited gauged information at the some grid locations) and time (e.g. due to variable quality and completeness of observed records in the past and the potential non-stationarity in the relationships between rainfall stations within a grid).

7 Conclusions

The attractiveness of spatially and temporally complete data coverage provided by gridded data (such as BOM, SILO, AWAP) for use in hydroclimatological research, modelling and analysis is obvious. However, it must be remembered that despite the fact that the various gridded datasets are "based" on observed data the spatial interpolation methods employed to produce the gridded data (a) will always introduce some artificiality and (b) make it difficult to verify the "realness" of the gridded data in areas or epochs

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with no or sparse observation stations. This is not to say that gridded data should not be used, rather, the fact that gridded data will not always accurately represent "real" spatial and temporal variability should be acknowledged and the uncertainties associated with this should be quantified and accounted for in any study that uses "virtual" data. There is no such thing as bad data – just poor uncertainty quantification!

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Table 1. Gauge details. Asterisks indicates High Quality station as given in Lavery et al. (1997). Cells highlighted in yellow indicate stations used in hydrologic model.

Site no.	Site name	Record start	Record end	Years	Elevation (mAHD)
16031	Tarcoola (Mulgathing)	Jan 1934	Open	75.5	198
16055*	Yardea	Nov 1877	Open	124.9	260
16083*	Hamilton Station	Feb 1931	Open	70.5	170
16086	Moonaree (Kangaroo Well)	Mar 1986	Open	24	275
17052	Gammon Ranges (Wertaloona)	Jun 1906	Open	100.3	100
17125	Innamincka (Bookabourdie)	Jul 1997	Open	11.9	45
17132	Marree (Etadunna)	May 1998	Open	11.9	30
18069*	Elliston	Feb 1882	Open	126.3	7
18146	Tar 639 Mile	Jul 1941	Dec 1968	27	150
19001*	Appila	Feb 1882	Open	120.4	369
19047	Booleroo Centre (Willowie)	Feb 1898	Open	109.1	316
20050	Plumbago	Dec 1970	Open	38.5	260
21027	Jamestown	Jan 1878	Open	123.3	455
23318	Tanunda	Feb 1870	Open	120.2	250
23721*	Happy Valley Reservoir	Mar 1864	Open	118.8	170
23736	Mount Lofty Summit	Apr 1956	Aug 2005	49.7	727
23808	Yundi	Feb 1969	Feb 2003	33.9	262
A4260504	Finniss River	Apr 1969	Open	43	203

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Table 2. Annual Root Mean Square Error (RMSE) as percentage of gauged data. Green highlighted cells indicate the closest match to gauged, yellow cells indicate the second closest match to gauged.

	% RMSE (annual)		
Station	BOM	SILO	AWAP
16031	8.97	0.99	14.36
16055*	16.65	1.20	8.69
16083*	24.51	13.69	29.22
16086	16.24	1.20	18.30
17052	15.26	15.65	20.30
17125	24.65	3.21	23.11
17132	6.89	1.16	11.91
18069*	6.95	1.24	8.27
18146	24.03	1.42	10.45
19001*	12.00	1.94	16.35
19047	10.18	3.25	11.05
20050	28.28	1.16	28.44
21027	9.61	5.24	7.79
23318	7.38	6.20	7.65
23721*	8.72	6.48	8.25
23736	18.49	14.46	19.55

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Table 3. Seasonal NSE values of gridded vs. gauged data. Green highlighted cells indicate the closest match to gauged, yellow cells indicate the second closest match to gauged.

	Summer			Autumn			Winter			Spring		
Station	BOM	SILO	AWAP	BOM	SILO	AWAP	BOM	SILO	AWAP	BOM	SILO	AWAP
16031	0.94	1.00	0.92	0.98	1.00	0.95	0.97	1.00	0.95	0.85	1.00	0.84
16055*	0.90	1.00	0.91	0.87	1.00	0.94	0.80	1.00	0.94	0.85	1.00	0.93
16083*	0.90	0.97	0.79	0.72	0.96	0.72	0.94	0.93	0.92	0.88	0.95	0.91
16086	0.90	1.00	0.84	0.90	1.00	0.92	0.80	1.00	0.73	0.63	1.00	0.90
17052	0.90	0.82	0.80	0.98	1.00	0.97	0.96	0.98	0.92	0.90	1.00	0.95
17125	0.96	1.00	0.94	−2.20	0.97	−0.11	0.95	1.00	0.92	0.90	1.00	0.93
17132	0.98	1.00	0.95	0.83	1.00	0.91	0.95	1.00	0.85	0.71	1.00	0.91
18069*	0.94	1.00	0.92	0.94	0.99	0.92	0.94	1.00	0.92	0.88	1.00	0.95
18146	0.79	1.00	0.98	0.58	1.00	0.97	0.81	1.00	0.95	0.69	1.00	0.91
19001*	0.95	1.00	0.94	0.92	1.00	0.88	0.68	1.00	0.35	0.75	1.00	0.89
19047	0.93	0.99	0.94	0.93	0.99	0.92	0.88	0.99	0.85	0.82	0.99	0.93
20050	0.91	1.00	0.93	0.92	1.00	0.92	−0.12	1.00	−0.09	0.61	1.00	0.76
21027	0.94	0.99	0.93	0.96	0.98	0.97	0.85	0.96	0.91	0.75	0.98	0.93
23318	0.94	0.98	0.94	0.92	0.96	0.93	0.94	0.95	0.93	0.87	0.98	0.93
23721*	0.96	0.98	0.96	0.90	0.96	0.91	0.87	0.94	0.88	0.75	0.95	0.93
23736	0.75	0.91	0.77	0.62	0.81	0.62	0.67	0.76	0.61	0.59	0.73	0.52

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Table 4. Number of zero rainfall months and 99th percentile monthly rainfall recorded for each dataset. Green highlighted cells indicate the closest match to gauged, yellow cells indicate the second closest match to gauged.

	Number of zero rainfall months				99th percentile monthly rainfall (mm)			
Station	Gauged	BOM	SILO	AWAP	Gauged	BOM	SILO	AWAP
16031	162	75	162	105	89.9	86.6	91.1	85.5
16055*	100	11	98	19	97.3	74.4	94.4	83.7
16083*	548	353	447	298	120.1	124.2	121.3	147.7
16086	41	9	39	6	87.8	72.5	86.8	70.0
17052	448	36	442	136	140.5	121.6	119.4	116.2
17125	49	30	48	27	106.0	95.5	107.1	108.4
17132	44	17	44	22	85.5	82.1	83.2	88.7
18069*	34	10	33	21	136.0	132.2	135.6	133.4
18146	58	8	58	36	100.2	89.3	99.3	91.8
19001*	36	11	33	12	115.3	118.6	113.7	125.2
19047	83	25	70	23	103.1	103.8	101.3	108.6
20050	88	30	88	32	139.8	144.8	138.9	145.6
21027	25	11	20	12	132.2	114.6	130.5	119.6
23318	30	12	20	14	143.8	135.6	146.7	135.0
23721*	9	1	8	3	169.2	172.8	162.6	171.6
23736	3	0	0	0	330.6	277.3	281.7	264.7

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Table 5. Calibration statistics for SIMHYD model.

	Calibration period (Jan 1970–Dec 1986)	Verification period (Jan 1987–Dec 2002)
NSE (monthly)	0.89	0.85
Relative difference between gauged and estimated flow (daily)	4.4 %	9.7 %

Table 6. NSE values for AWAP vs gauged data (1970 to 2002).

	Annual	Monthly	Summer	Autumn	Winter	Spring
AWAP rainfall vs. gauged rainfall (23808)	0.86	0.96	0.94	0.95	0.79	0.95
AWAP simulated flow vs. gauged flow (A4260504)	0.74	0.78	0.75	0.67	0.57	0.82

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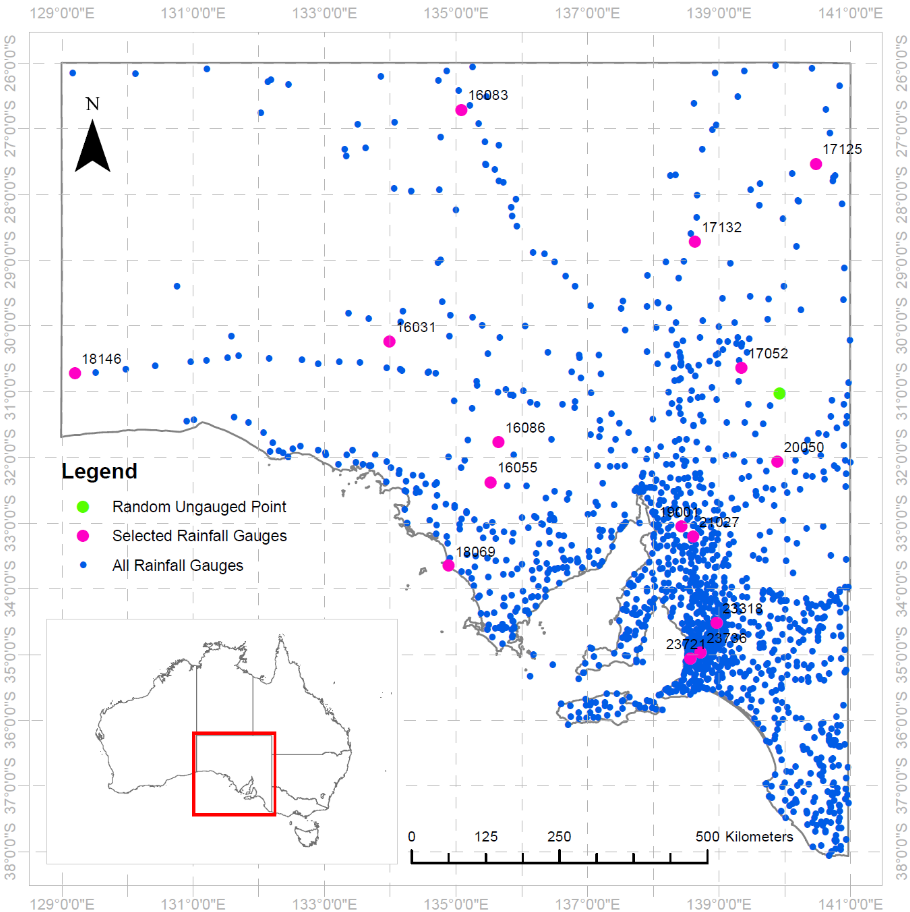

Fig. 1. Indication of all rainfall gauges in SA (blue dots), gauges selected for analysis (pink dots) and the random ungauged point.

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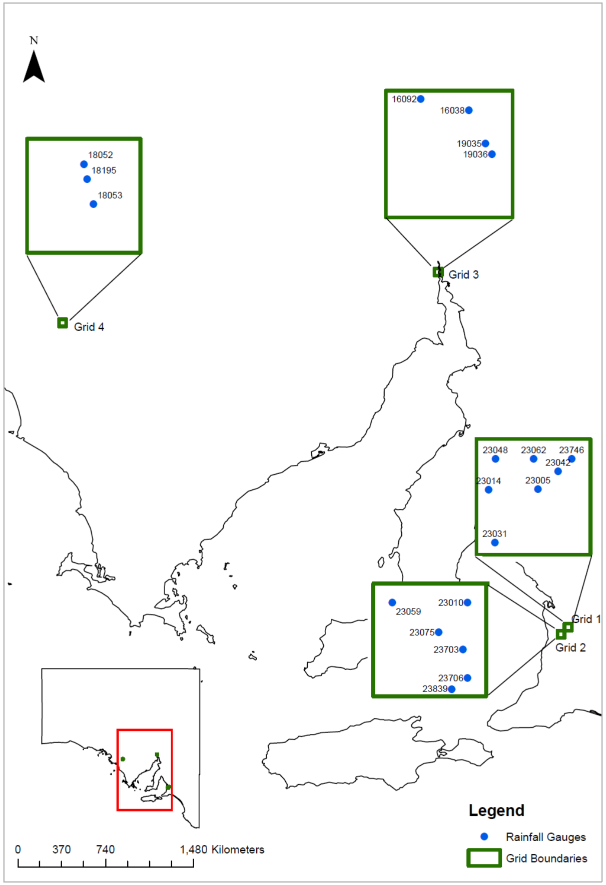

Fig. 2. Location of grids selected for annual rainfall extremes analysis.

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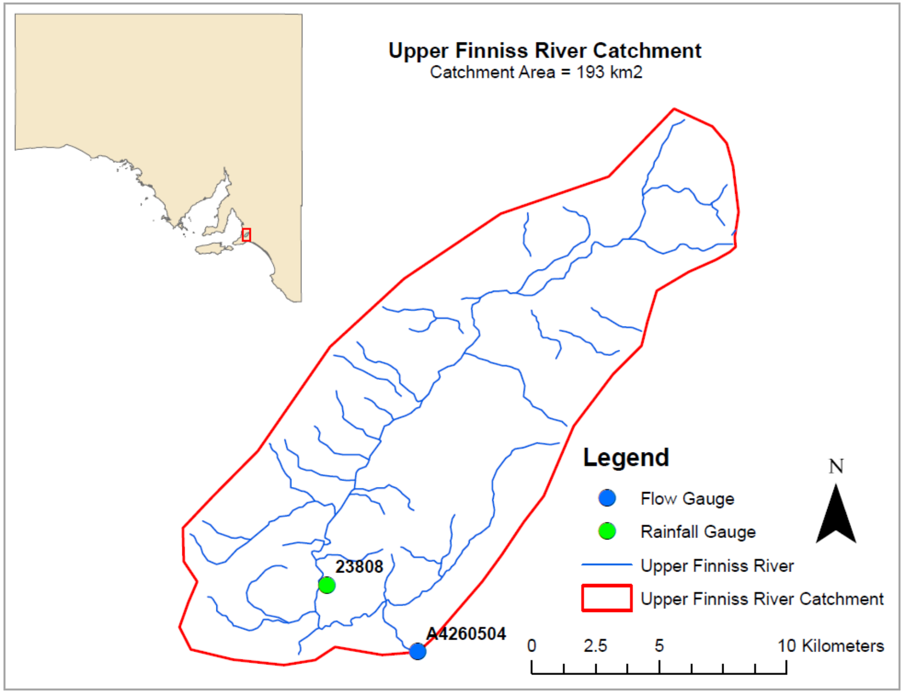

Fig. 3. Location map of Finniss River catchment.

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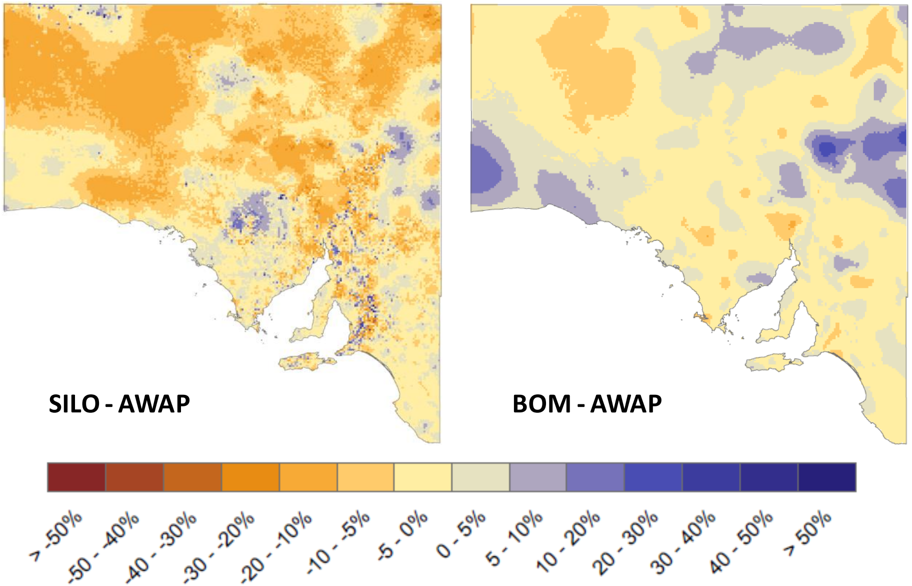

Fig. 4. Percentage difference between annual average (1900–2008) of the three gridded datasets.

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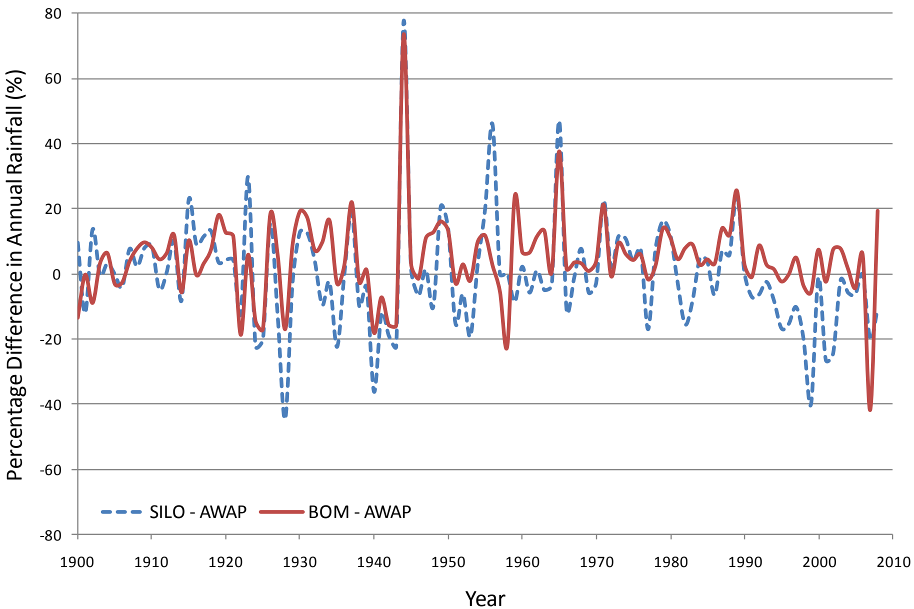

Fig. 5. Comparison between gridded datasets at a random location in SA.

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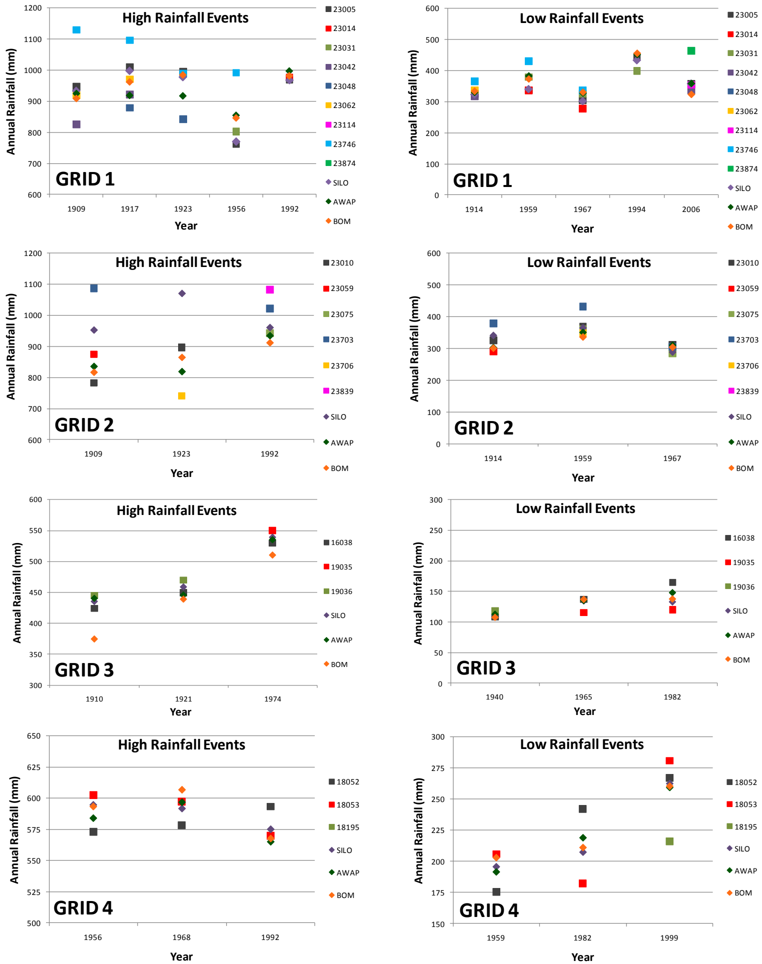

Fig. 6. Gauged versus gridded annual rainfall data for high and low rainfall events in four grids in SA.

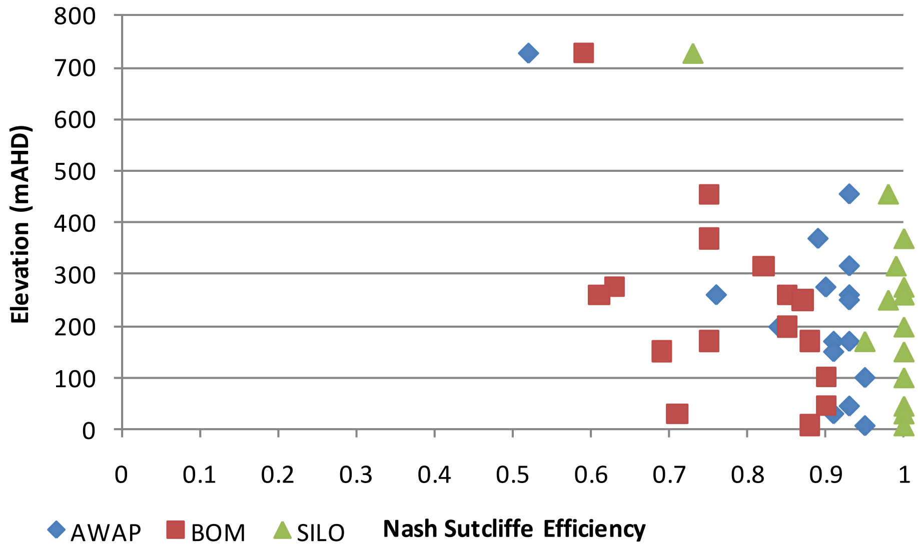

Fig. 7. Comparison of NSE values and gauge elevation for Spring (SON).

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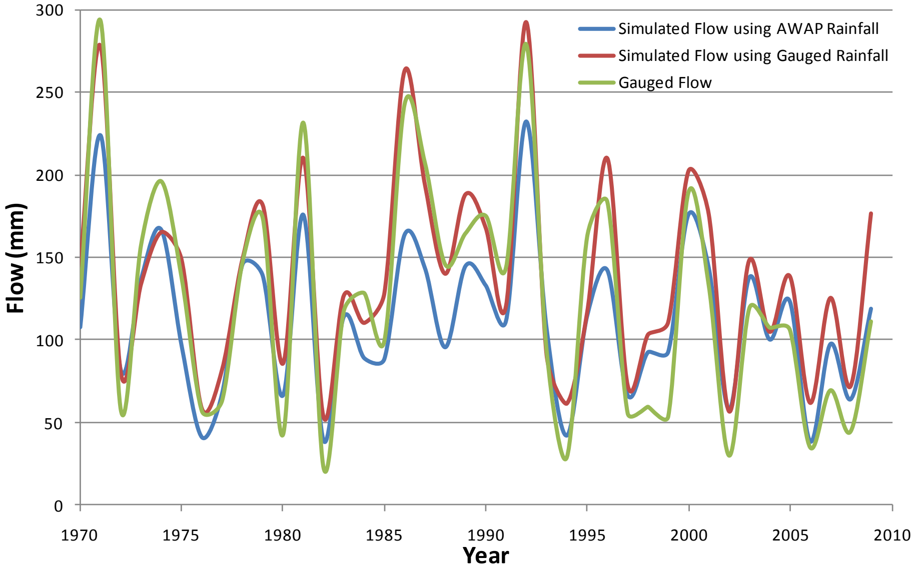

Fig. 8. Comparison of the gauged flow (A4260504), simulated flow using gauged rainfall (23808) and simulated flow using AWAP rainfall.

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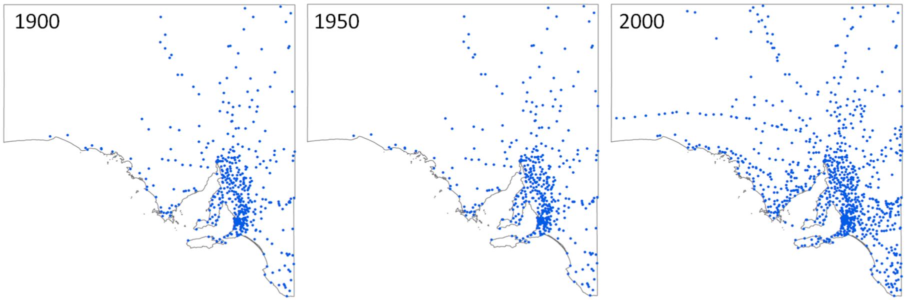

Fig. 9. Rainfall stations open in South Australia in 1900, 1950 and 2000 as indicated.