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An Investigation into the Efficacy of Australian Rainfall & Runoff 2016 Procedures in the Mount Lofty Ranges, South Australia

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Summary

This report presents the results of an application of the 2016 Australian Rainfall and Runoff (ARR2016) procedures for flood flow estimation in 25 of the catchments in the Mount Lofty Ranges of South Australia that were used to derive the procedures. Where a good rating curve and a long period of record exists then a flood frequency analysis (FFA) conducted at a site provides the most reliable estimate of flood magnitude as it directly incorporates all of the catchment characteristics. For this reason, all other flood estimation techniques are parameterised, calibrated and validated to the FFA. Direct comparison of the other flood estimation technique flows to the at-site flows will give an indication of both the bias of the methodology (is it consistently under or over estimating?) and overall the accuracy of the predictions, determined by the level of fit of the comparison. It can be assumed that the bias and accuracy will be similar for ungauged sites, not used in the derivation of the procedures.

In this study RORB model flows derived using ARR2016 procedures were compared with at-site flood frequency flows at the sites used to derive the regional flood frequency estimate (RFFE). The RFFE itself was also used for comparison. A simplified RORB catchment model was used at all sites.

It has been found that the RFFE estimates were reasonable, but the RORB estimates using ARR 2016 procedures were poor, particularly for frequent events, and showed a bias to underestimate flows. The RORB model estimates derived using the ARR 2016 procedures were worse also than those estimated using the 1987 version of Australian Rainfall and Runoff. The reasons for this are discussed, but it could be due to the application of the Monte Carlo approach to catchments producing small flows in frequent events. It is also possible that the RORB model cannot adequately describe the catchment response for the full range of Annual Exceedance Probabilities (AEPs) and that baseflow extraction and estimation for the range of AEPs is inadequate.

The report concludes with recommendations for practitioners in South Australia in the prediction of flood flows in rural catchments. It is intended that more detailed recommendations will be made in a separate report once other methodologies for the estimation of floods has been undertaken.

Contents

1. Introduction

With the release of the 2016 version of Australian Rainfall and Runoff (ARR2016) (Ball et al, 2016), the way design floods are estimated in Australia has changed significantly. A Regional Flood Frequency estimation (RFFE) procedure was developed that aims to provide an estimate of design flows for all ungauged catchments. Flood estimation by runoff routing was also changed to include the use of a joint probability approach rather than a design flood approach, so that the variability and interaction of flood producing factors are better allowed for.

The Office of Environment and Heritage, New South Wales has recently published a review of the ARR2016 design inputs for New South Wales, as a result of perceived bias in flood estimates in that state (WMA Water, 2019). Although there has been some testing during the development of ARR2016 the procedures have not been tested on a significant number of catchments within any other region.

The Mount Lofty Ranges are located in South Australia and are characterised by humid conditions in comparison with most of the state. Annual rainfall varies from 350mm to a maximum of 1100 mm, and defined watercourses are present. The ranges are also the South Australian region with the most significant development and thus infrastructure.

This report presents the findings of an investigation into the efficacy of ARR2016 by comparing the results of the RFFE and RORB model peak flow predictions using ARR2016 procedures for gauged catchments in the Mount Lofty Ranges. Although this is not an independent set of catchments, it can be assumed that the results would be similar if the adopted approach was applied to the same number of ungauged catchments within the region, as there is no bias in the selection of catchments.

This report is structured as follows:

- The background of both flood regional frequency estimation and runoff routing modelling is given, with a summary of how these are applied in ARR2016.
- The investigation uses a simplified model structure for the RORB model, which saves significant time in the derivation of results, enabling a large number of catchments to be examined. The background and justification for the use of this approach is given by comparing the flow predictions of a simple model based on the Laurenson Runoff Routing Model (LRRM) with RORB.
- Both the ARR2016 RFFE and RORB model estimates are then compared with the at-site estimates, to assess the bias and accuracy.
- A comparison is then made with the performance of the previous 1987 version of Australian Rainfall and Runoff (ARR1987)
- Possible reasons for the change in performance between ARR1987 and ARR2016 is then discussed. Recommendations are made for practitioners in South Australia in the prediction of flood flows in rural catchments.

It is intended that more detailed recommendations will be made in a separate report once other methodologies for the estimation of floods has been undertaken.

2. Regional Flood Frequency Estimation

Background

Obtaining an accurate estimation of the relationship between flood flows and their associated recurrence intervals becomes complicated if the length of the available streamflow gauging record at the site of concern is shorter than the recurrence interval of interest. Even greater difficulty occurs if there is no flow record available at the site of interest. To compensate for data records of insufficient length or where no flow records are available, a trade-off is made between the spatial and the temporal characterisation of extreme flood flows. This can be done through the use of regional flood frequency analysis (RFFA), which relates flood flow quantiles of interest to various characteristics of the drainage basins using regression analysis.

The accuracy of the prediction depends on the reliability of the at-site estimates, the degree to which the selected catchment variables relate to the actual streamflow behaviour and the ability of the selected technique to incorporate this behaviour. Hence, in order to achieve the ultimate objective of acceptable regional flood frequency analysis, techniques need to be improved in:

- Making accurate at-site flood quantile estimates;
- Selecting appropriate catchment characteristics; and
- Selecting an appropriate regression procedure.

At-site Flood Frequency Analyses

At-site estimates of flood quantiles are made using flood frequency analysis. In practice, the true probability distribution of the floods is not known. According to Hosking and Wallis (1997), even if it were, its functional representation would probably have too many parameters to be of much practical use. Hence, the practical issue is how to select a reasonable and simple distribution to describe the phenomenon of interest which allows estimation of the distribution's parameters, and thus enable the practitioner to make reliable quantile estimation.

An empirical approach to determine the form of the theoretical probability distribution of floods is to fit several theoretical distributions to observed Annual Maximum (AM) series data and to decide, by suitable criteria, which distribution fits the data best (Matalas, 1963). This method is called the probability distribution method and has the advantage that it can be automated using computers. Furthermore, the approach can be facilitated by restricting the number of possible theoretical probability distributions to those which comply with practical statistical and physical considerations. Analytical goodness-of-fit criteria are useful for gaining an appreciation of whether the lack of fit is likely to be due to sample-to-sample variability, or whether a particular departure of the data from a model is statistically insignificant (Stedinger et al., 1992).

When statistical analysis is used to estimate the frequency of extreme events (defined by Wang, 1997 as the upper part of the probability distribution) or estimate the magnitude of a quantile at low probabilities, the interpolation and extrapolation of a record to the required recurrence interval ought to be made by following the trend shown by the more extreme events in the record (Wang, 1996). Hosking and Wallis (1997) recommended that the trend of extreme events can usually be fitted reasonably well by a smooth distribution function such as the Generalized Extreme Value (GEV) distribution. Wang (1997) found the GEV distribution to be a robust frequency distribution function of extreme flood data from catchments selected world-wide.

Regional Flood Frequency Analyses

When the probability distribution method is used for RFFA, several fundamental issues arise in selecting and fitting a distribution function to sample data as it is important to know if the proposed distribution is consistent with the available data for a site. The problem is more complicated when the proposed distribution needs to be consistent with the regional data in order to make reliable estimates of risk from the regional frequency analysis.

This statistical problem in regional flood frequency analyses is often solved by applying a goodness-of-fit test with two considerations. First, the available data are not a single random sample but a set of samples from different sites; and second, the chosen distribution should not merely fit the data well but should also yield quantile estimates that are robust to physically plausible deviations of the true frequency distribution from the chosen frequency distribution.

ARR2016 RFFE

The aim of ARR2016 RFFE has been to overcome the above issues and make more reliable flood quantile estimates for ungauged catchments. Book 3 Chapter 3 of ARR2016 presents the RFFE method for use at ungauged catchments. It uses a region-of-influence generalised least squares regression model to estimate the mean, standard deviation and skewness of log transformed AM series using catchment attributes as predictors.

3. Runoff Routing

Background

A runoff routing model is used to convert rainfall on a catchment to catchment outflow, by first subtracting losses to convert the total rainfall to catchment runoff, and then accounting for storage and translation effects as this runoff moves through the catchment to the outlet. This paper will focus on the RORB model (Laurenson et al, 2010), with the use of an initial – continuing loss model, as is commonly used for flood hydrograph estimation in Australia. The RORB runoff routing model was selected for the investigation of losses for ARR2016 as regional prediction equations for its parameterisation are readily available for most regions in Australia (Hill et al, 2014). The selected Mount Lofty ranges catchments can be considered to be fully rural, with the towns within them making only a small contribution to flood runoff.

Book 4, chapter 2 of ARR2016 summarises runoff processes that occur in a catchment, and RORB assumes that the dominant processes are baseflow and surface flow. Only a single runoff process is modelled by RORB, with baseflow being extracted before modelling, and added to the hydrograph predicted by the model to produce a total hydrograph. Runoff routing models within RORB simulate translation and attenuation effects by catchment sub-division, and the use of a number of non-linear storages located along the stream lines.

Prior to ARR2016, a design event approach was used to estimate flows, with the assumption that the application of design rainfall events with a known probability to a catchment with average conditions would result in a predicted flow of the same probability. The procedures in ARR2016 now include a Monte Carlo approach. Weinmann et al (2002) discuss the advantages of the Monte Carlo approach, which takes account of varying catchment conditions. It is argued that substantial improvements in design flood estimates are only possible if the variability and interaction of flood producing factors are better allowed for. The Monte Carlo approach was tested by Rahman et al (2001) and Caballero and Rahman (2013) on three catchments in Victoria and three catchments in New South Wales respectively. It was found that the Monte Carlo approach gave good results. Charalambous et al (2013) applied the approach to the North Johnstone River in north Queensland, where it was found to give a better result than the design storm approach. In all cases it was applied to gauged catchments with fitted storage and loss parameters. Table 1 provides a summary of catchment statistics for the catchments used for verification. It can be seen that most of these have significantly greater annual rainfall totals than most of the Mount Lofty Ranges catchments, where the average annual rainfall ranges from approximately 350mm to 900mm.

Table 1 Stations used for Verification of Monte Carlo Approach

Station Name	Station Number	Area (km^2)	Annual rainfall (mm)
Boggy Creek at Angleside	403226	108	1020
Tarwin River at East Branch	227226	127	1020
Avoca River at Amphitheatre	408202	78	745
Oxley River at Eungella	201001	213	1857
Bielsdown Creek at Dorrigo No.2 & No.3	204017	76	1862
Belar Creek at Warkton	420003	133	690
North Johnstone at Tung Oil	112004A	925	3000

It is noted that Kuczera et al (2017) applied the ARR2016 procedures to 26 non-urban catchments across Australia and concluded that the application of RORB with Monte Carlo simulation produced a result that “should rightfully shake the confidence of any user of ARR2016”, and that “Clearly there is much ‘unfinished business”. Since the Monte Carlo approach is now the recommended approach in ARR2016 to flood estimation by runoff routing models and a rigorous assessment to local conditions is warranted.

Description of Two Runoff Routing Models Used in Australia

LRRM

The commonly used RORB (Runoff Routing for a Burroughs Computer) model is a development of the LRRM (Laurenson Runoff Routing Model), as described by Laurenson (1964). According to Laurenson the model should provide for:

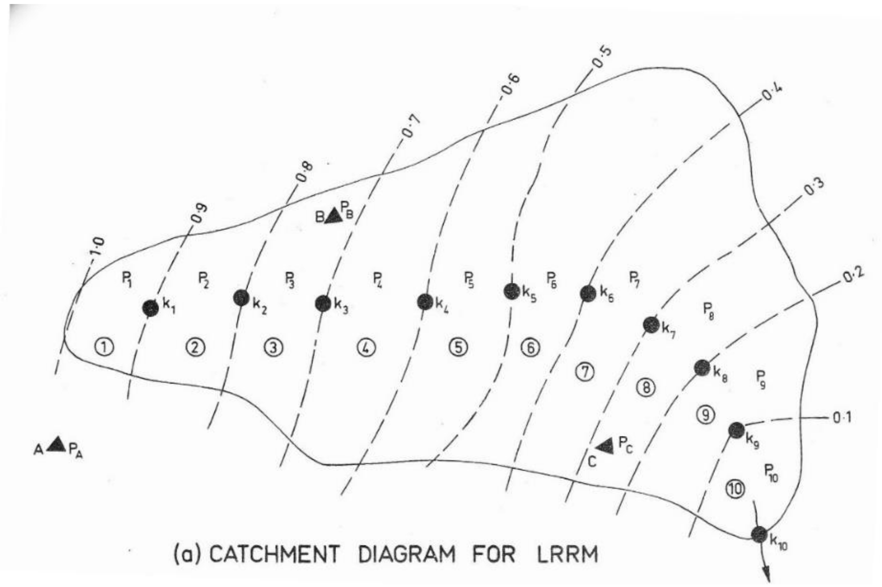
- Temporal variation in rainfall excess;
- Areal variation in rainfall excess;
- The fact that different elements of rainfall excess pass through different amounts of storage;
- The fact that catchment storage is distributed rather than concentrated; and
- The fact that in general the relationship between stream discharge and catchment storage is non-linear.

The LRRM divides the catchment into a number of sub-areas (typically 10) on the basis of equal travel time to the catchment outlet (isochrones). However, it assigns a separate storage to each of the sub-areas, and runoff from a sub-area is then routed through the series of downstream storages to the catchment outlet. The division into sub-areas and the detailed representation of travel time in the catchment allows the effects of spatial variation of catchment rainfall to be modelled explicitly.

Figure 1 shows the structure of the LRRM model, with k representing the concentrated storage for each sub-area and P being the rainfall total for each sub-area. The model uses nonlinear storages, with the relationship between discharge and storage in each reach being represented by a power function, as expressed by Equation 1.

$$S = k\,Q^{m} \qquad \text{Equation 1}$$

The catchment representation in the LRRM can be regarded as a linear network of ten rainfall input nodes, ten routing links (each with a nonlinear concentrated storage) and one output node. Laurenson assumed that the storage delay time for the last storage was equal to half that of the other nine. A single node of the xprafts model is a LRRM model with ten equal sub-areas, instead of being divided by isochrones (XP Software 2009).



(a) CATCHMENT DIAGRAM FOR LRRM

Figure 1 Structure of the LRRM Model (Aitken, 1975)

RORB

The first version of the RORB program was released as a program named RORT in 1975 (Laurenson, 1975). Many further versions have been released since then, but the basic difference from the LRRM model is that the catchment is represented by a distributed network of sub-areas and channel reaches rather than by isochrones as in Figure 1. A detailed description of the model can be found in the user manual (Laurenson et al, 2010).

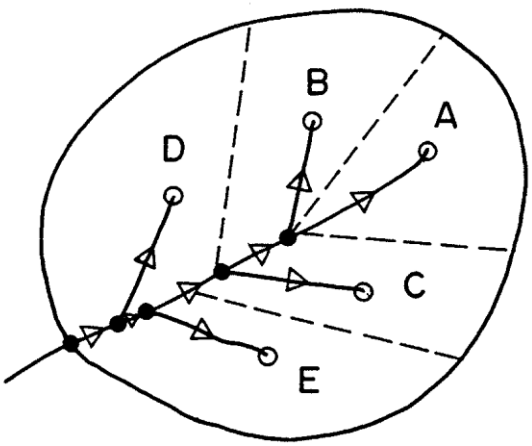


Figure 2 Structure of the RORB Model (Laurenson et al, 2010)

Rainfall is applied at the centroid of each sub-area, and runoff then calculated by subtracting losses. Baseflow is not modelled but must be separated from the total hydrograph. The resultant hydrograph is then routed through each channel reach by a storage of the form of Equation 1, where the value of k is determined as the overall catchment kc, multiplied by the relative delay time (= d/dav), where d is the length of the individual storage reach, and dav is the mean flow distance in the catchment.

Comparison of LRRM and RORB Model Design Flow Prediction

Given the finding of Kemp (2017) that a LRRM model is an adequate representation of the catchment for the three catchments and six events examined it was decided to model larger number of catchments with RORB by both a catchment file representing the LRRM model with ten equal sized sub-areas (a template file) and the normal RORB catchment sub-division to determine design flows, using the procedures of ARR2016, for catchment rainfalls, temporal patterns, losses and storage parameter values. Monte Carlo simulation was used. Baseflow was not included in the estimation.

A total of 11 rural catchments was used, including eight in the Mount Lofty and Flinders Ranges, plus three sample catchments described in the RORB user manual (Laurenson et al, 2010) or used in RORB training. Those shown as DPTI were developed by the South Australian Government Department of Planning, Transport & Infrastructure or its predecessors.

For each catchment a template catchment file was edited to give the correct total catchment area. A typical catchment file is shown below, in this case for the Torrens River at Mount Pleasant:

```
Torrens River at Mount Pleasant area = 26km^2
C Only for rural catchments, natural reaches
1, All reaches natural
1,1.0,-99
2,1.0,-99
2,1.0,-99
2,1.0,-99
2,1.0,-99
2,1.0,-99
2,1.0,-99
2,1.0,-99
2,1.0,-99
2,0.5,-99
7, print resultant hydrograph
hydrograph at outlet
0
C All areas of equal size.  Change for other catchments
2.6,2.6,2.6,2.6,2.6,2.6,2.6,2.6,2.6,2.6,-99
0,-99, No impervious area
```

Note that there are nine reaches of the same length, plus one of half the length, as per the LRRM model. Note that the reach lengths do not have to be edited, as they are only used to determine the relative delay time of each storage (= d/dav). The catchment dav is the total catchment length is 5, or half of the total catchment reach length of ten, as would be expected in a normal RORB model catchment sub-division.

For each catchment, flows were derived for Annual Exceedance Probabilities (AEPs) of between 1:2 years and 1:50 years following ARR2016 procedures. The Monte Carlo simulations were undertaken using both the standard RORB catchment file and the template file edited only to apply the correct catchment area.

Table 1 Comparison of Peak Flow Values for RORB and LRRM

Catchment/station	Catchment Area (km^2)	Ratio template (LRRM) peak flow / RORB peak flow for AEP (1:Y years)				
		2	5	10	20	50
Torrens River at Mount Pleasant (A5040512)	26.0	1.05	0.92	0.95	0.94	1.00
Myponga Creek (A5020502)	74.4	1.00	0.93	0.96	0.92	0.93
Arcoona Creek (A0040520)	49.8	1.00	1.00	0.89	0.90	0.93
South Creek (RORB)	89.7	0.97	0.95	0.90	0.93	0.93
Baker Creek at Brooklands (RORB)	290	0.99	1.02	1.00	1.01	1.00
Thomson River at the Narrows (RORB)	519	1.26	1.08	1.04	1.01	0.97
Rocky River at Stone Hut (DPTI)	202	1.00	1.17	1.02	1.00	0.99
Biggs Flat Creek (DPTI	22.6	0.49	0.99	1.05	1.08	1.13
Pedler Creek at Stump Hill Road (DPTI)	87.4	1.00	1.08	1.03	1.01	0.97
Brown Hill Creek at Scotch College (A5040901)	18.0	1.00	0.98	1.02	0.94	0.95
Gorge Creek on Palmer – Murray Bridge Road (DPTI)	42.1	1.00	0.91	1.00	0.93	0.98
Mean ratio		0.98	1.00	0.99	0.97	0.98
Standard deviation		0.181	0.081	0.054	0.055	0.057

Note: station number is given apart from catchments sourced from DPTI that were developed by the South Australian Government Department of Planning, Transport & Infrastructure or its predecessors, and those shown as RORB which are RORB sample catchment files.

Table 1 summarises the comparison and indicates that there is a very close agreement between the two models. Manual catchment sub-division is not required for RORB modelling unless there is a need for flows at internal points within the model, or if there is more than one loss model, rainfall or storage parameter input. It should be noted however that Kemp (2017) has shown that the RORB model is not internally consistent. The structure of the model has an impact on predicted flows both within the model and at the model's outlet. As the LRRM has a standard number of sub-catchments flow prediction cannot be affected by the model structure.

4. Application of ARR2016 Procedures to Mount Lofty Ranges Catchments

A description of the development of the RFFE in South Australia is provided in the ARR2016 project reports (Rahman et al, 2015a and 2015b). A total of 28 catchments were selected from the humid area of South Australia. This includes 27 catchments in the Mount Lofty Ranges, and one catchment on Kangaroo Island. The record lengths of annual maximum flood series of these 28 stations range from 20 to 63 years (mean: 36.64 years, median: 37 years and standard deviation 9.15years). The catchment areas of the selected 28 catchments range from 0.6km^2 to 708km^2 (mean: 161km^2 and median: 63km^2). The geographical distribution of the selected 28 catchments is shown in Figure 3.

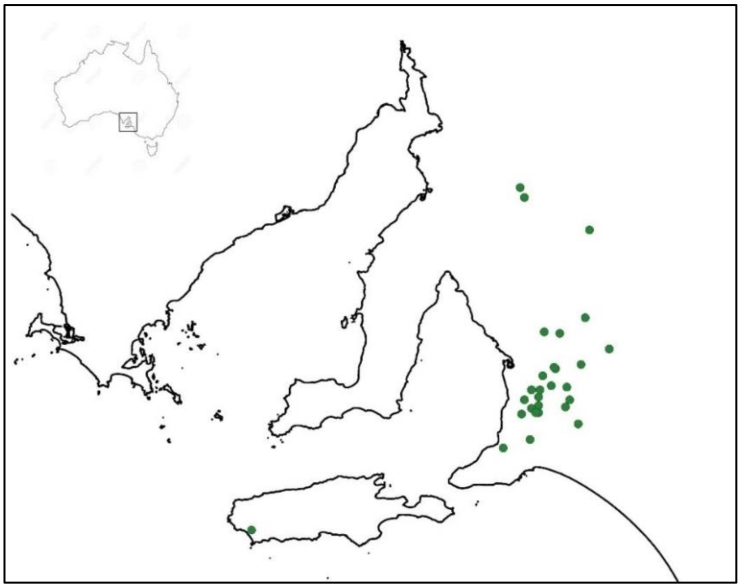


Figure 3 South Australia Humid Catchments Used for RFFE Derivation

ARR2016 (Ball et al, 2016) provides an online data hub that provides all the information necessary to estimate hydrographs using a RORB model including:

- Rainfall intensity-frequency-duration information;
- Areal reduction factors;
- Temporal patterns;
- Baseflow factors;
- Losses; and
- Storage parameters.

The RORB model includes the ability to model a single storm, an ensemble of storms or to carry out Monte Carlo simulation using a number of generated storms of varying duration and intensity, on a catchment where losses are also varied. The simulation results can be analysed directly using frequency analysis. The RORB software (version 6.32) has the ability to import data from the data hub.

A template catchment file was developed for each of the 28 catchments, and was used with RORB version 6.32 to determine peak flows. In accordance with the ARR2016 recommendations Monte Carlo analysis was used to determine estimated catchment outflow for a range of Annual Exceedance Probabilities (AEPs), using the online data hub to obtain all the required data. The RORB storage parameter kc was derived for each catchment based on the findings of Kemp (1993), that is $kc = 0.89A^{0.55}$. Baseflow was added to the peak flow, also in accordance with the ARR2016 recommendations.

5. Comparison of RFFE and RORB RESULTS with At-site Quantiles

Approach

For this investigation it was assumed that the at-site quantiles were a good representation of the true flood quantiles. In fact, it is known that there is uncertainty in the flood quantile estimates, both aleatory and epistemic (Kuczera et al, 2017). Aleatory uncertainty refers to the intrinsic uncertainty of the system and is usually described using probability models. Epistemic uncertainty, on the other hand, refers to uncertainty arising as a result of lack of information or knowledge about the system.

Comparison with the at-site quantiles will produce an estimate of the efficacy of the RFFE that is greater than that if ungauged catchments are being used, as epistemic uncertainty will be at a minimum.

The ARR2016 RFFE software produces at-site quantiles and initially these were to be used for the comparison of at-site quantiles with the RORB and RFFE results. However, with one site having estimated quantiles an order of magnitude greater than expected (Mount Barker Creek, A4260557), the quantiles were questioned, and it was revealed that incorrect annual maximum flow data had been used in their derivation. For this reason, at-site flood quantiles have been independently derived for this investigation. The RFFE software will need to be updated with correct annual data.

A table of the sites used and their quantiles derived as part of this investigation is given in Appendix A.

For further analysis Mount Barker Creek and Burnt Out Creek (A5030529) have been removed from the comparison; Mount Barker Creek because it has a significant and expanding urban area and Burnt Out Creek because it is a small research catchment subject to bushfire and regrowth, so would not have a stationary time series (Greenwood and Cresswell, 2007). In addition, the flow quantiles for Rocky River (AW5130501) cannot be calculated with the current version of RFFE (version 2016v1) as the site lies outside the zones for which the software can be used.

At-site flood quantiles were estimated using the Log Pearson III (LP III) distribution model fitted to the AM series by the method of moments (MOM) as given in ARR2016 Book 3. Due to its simplicity and the ease of use, the Log Pearson Type III (LP III) distribution is still widely used and accepted in many countries including USA and Australia. For example, Book 3 Chapter 3 of ARR2016 recommends the use of LP3 for flood frequency analyses. The TUFLOW FLIKE software was used.

Results

For each AEP, estimated RFFE and RORB flows were plotted against the at-site estimates, with trendlines indicating the level of fit. The trendlines were forced through the origin, so that any bias can be seen in the slope of the trendline. Appendix A presents at-site flood quantiles along with the ratios of ARR-RFFE/LP III and ARR-RORB/LP III at 5 selected AEPs.

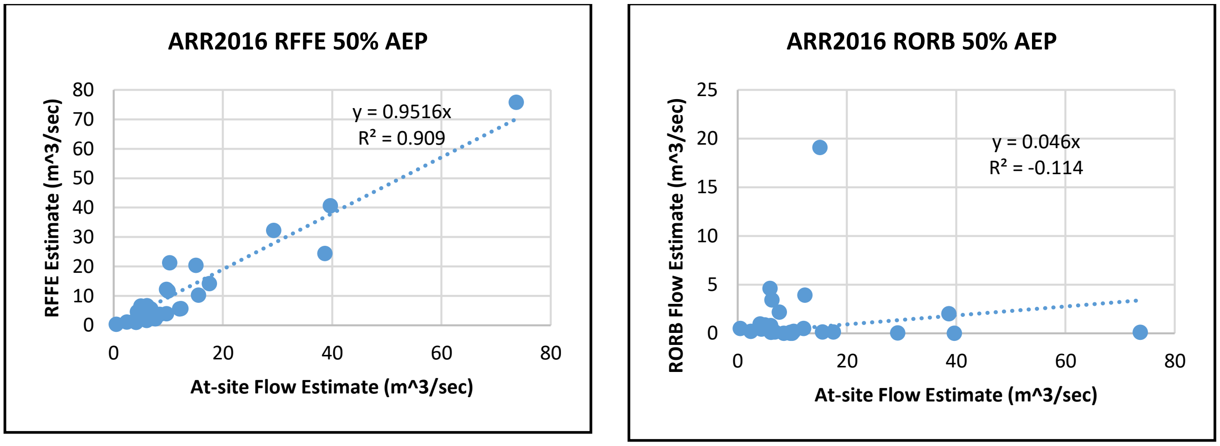


Figure 4 Comparison of ARR2016 50% RFFE and RORB Estimates With at-site Quantiles

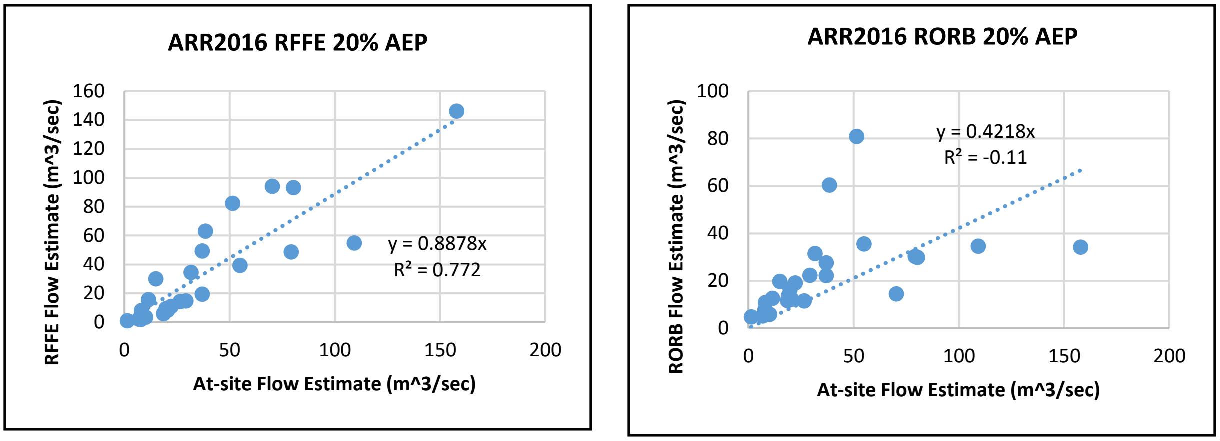


Figure 5 Comparison of ARR2016 20% RFFE and RORB Estimates With at-site Quantiles

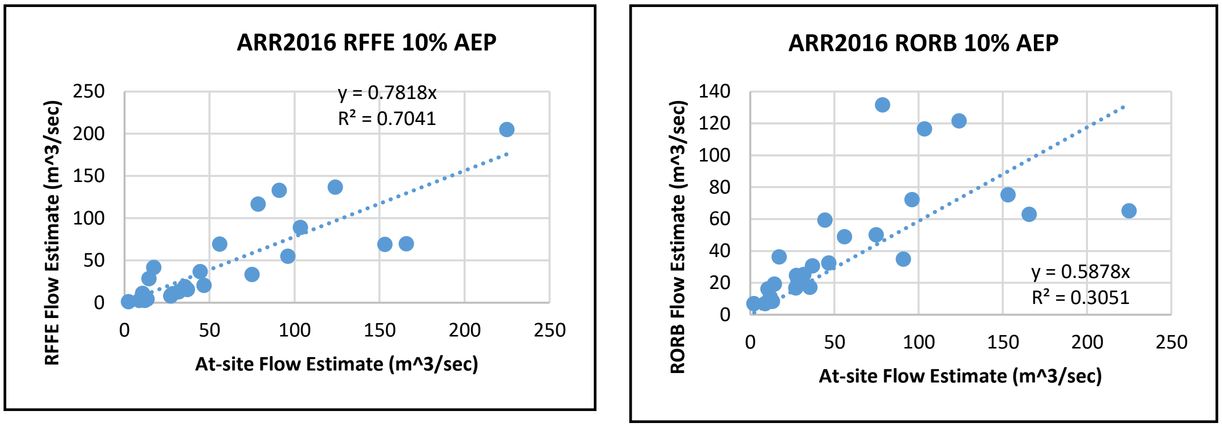


Figure 6 Comparison of ARR2016 10% RFFE and RORB Estimates With at-site Quantiles

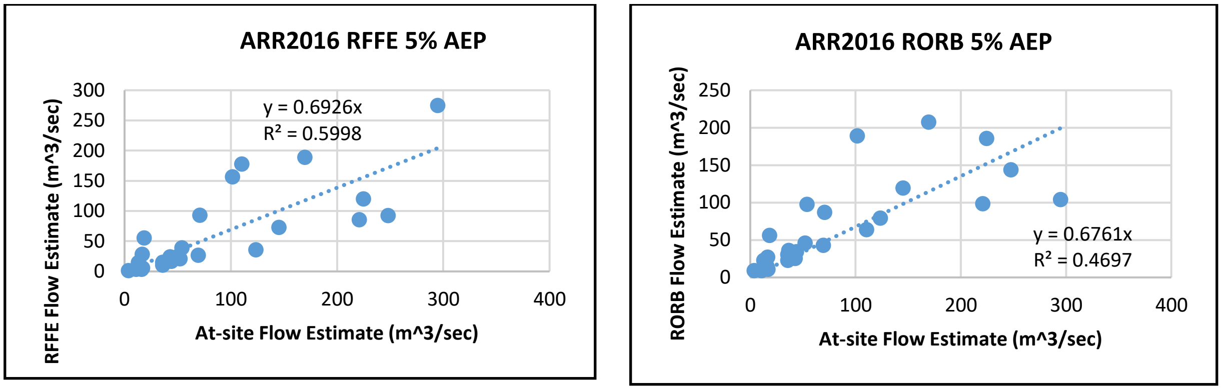


Figure 7 Comparison of ARR2016 5% RFFE and RORB Estimates With at-site Quantiles

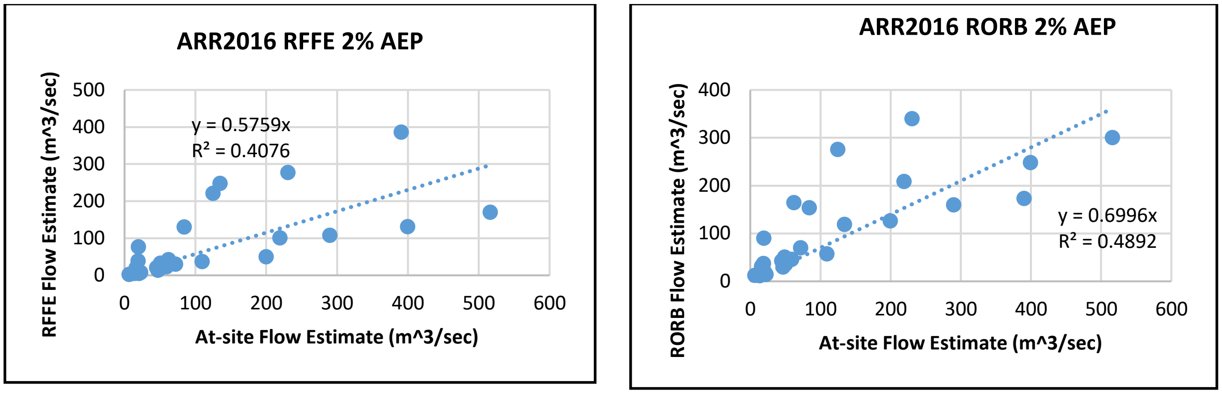


Figure 8 Comparison of ARR2016 2% RFFE and RORB Estimates With at-site Quantiles

The results of the comparison of at-site estimates and RFFE and RORB flows can be summarised as follows:

- The ARR2016 RFFE provides a good estimate of the 50% AEP flows from the Mount Lofty Ranges catchments, and reasonable estimates for other AEPs, although the skill of RFFE reduces with reducing AEP.
- The ARR2016 RORB model performs less well than the RFFE, and only for the 2% AEP does it outperform RFFE.
- Neither RFFE nor RORB provide estimates without bias. In the case of RORB the performance is particularly poor for frequent events, but improves as the AEP of the flood reduces. RFFE provides less bias for frequent events, but this increases as the AEP reduces.
- The level of correlation between at-site flows and the estimates reduces with decreasing probability for RFFE and increases for RORB. Only for the 2% AEP does RORB produce a better level of fit than RFFE.
- A negative value of R2 for the RORB 50% and 20% AEP estimates indicates that the RORB model provides no skill in predicting flows of these probabilities in the Mount Lofty Ranges.

Comparison with 1987 Australian Rainfall & Runoff RORB Predictions

Because of the poor predictive ability of the ARR2016 RORB procedures it was decided to undertake an analysis of the catchments using the procedures from the 1987 version of ARR, using a simple approach. The following were used:

- ARR1987 rainfall intensities;
- Design storms from 3 to 72 hours;
- Unfiltered temporal patterns; and
- An initial loss of 30 mm and a continuing loss of 1 mm/hr (see Table 3.4 in ARR1987).

Baseflow was ignored, as is the usual practice in South Australian flood hydrology. The same 25 catchments were modelled, using the simplified template catchment model. Figure 9 shows the comparison of the ARR1987 estimates with at-site estimates, with the ARR1987 estimate for an Average Recurrence Interval plotted against the at-site estimate for the closest AEP.

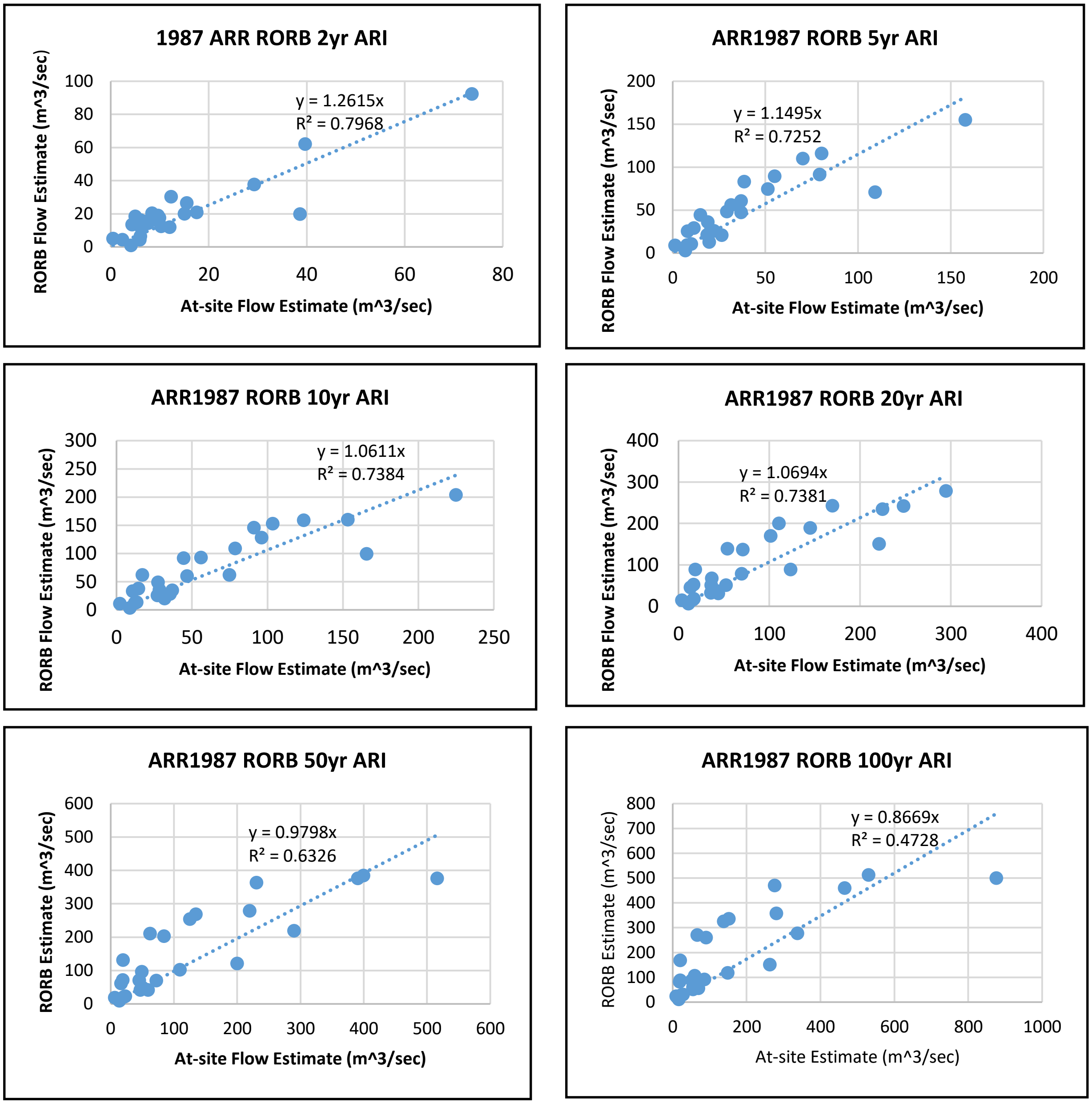


Figure 9 Comparison of At-site and ARR1987 RORB Flow Prediction

It can be seen that the ARR1987 RORB model predictions are much better than the ARR2016 predictions for all AEPs, both in the level of correlation and the bias. For lower AEPs they are also better than the RFFE predictions.

6. Discussion

The Performance of RFFE and RORB

The study results indicate that flow prediction in ARR2016 for the Mount Lofty Ranges is poor. Reduction in the skill of RFFE with decreasing AEP could reflect the difficulty of prediction of rare events, indicated by increasing error bands. Improving prediction by RORB with decreasing AEP indicates that the model is performing better under high flows.

RFFE

The performance of RFFE is reasonable, even with the data that was used being in error. It performs best for frequent flows, which is expected given that it was derived using parameter regression rather than quantile regression. This means that the mean, standard deviation and skew were used in the derivation of the regression rather than the flood quantiles themselves. Parameter regression gives emphasis to the mean and thus frequent flows.

Monte Carlo Simulation

ARR1987 RORB approach performs much better than ARR2016 RORB approach, and for low AEPs better than RFFE. The reasons for this are unclear, but the main difference in the RORB modelling has been the move from a design storm approach to a joint probability approach using Monte Carlo simulation. Monte Carlo simulation in flood hydrology involves random sampling of inputs including rainfall duration, intensity, temporal and areal patterns with a random sampling of catchment loss to produce a large number of estimates, from which flood peaks of various AEPs can be extracted.

Weinmann et al (2002) argues that “substantial improvements in flood estimates are only possible if the variability and interaction of flood producing factors are allowed for”, and “the proposed Monte Carlo simulation approach can overcome these limitations”. Unfortunately, this paper has shown that for the Mount Lofty Ranges this is not the case. More investigation is required before the Monte Carlo approach can be used for this region.

Runoff Processes

Another possible explanation of the poor ARR2016 performance lies with the limitation of RORB in that only one runoff process is modelled, and that this is the dominant process in the production of flood flows. In the Mount Lofty Ranges, it is possible that frequent flows (up to 10% AEP) are dominated by baseflow in most catchments, which is not modelled by RORB. Traditional runoff routing models such as RORB are event-based models, considering only one runoff process, with one catchment response time or lag. All routing is assumed to occur within the stream channels, with the out of channel runoff being assumed to have little or no lag time. Catchment runoff processes have been the subject of numerous studies. Published evidence (Jayatalika and Connell, 1996, Dunne and Black, 1970, Gillham, 1984, Hewlett and Hibbert, 1967) indicates that generally three distinct runoff processes can occur in a catchment, depending on climate and physical characteristics. Kemp (2002) found that the dominant runoff process in the Mount Lofty Ranges was not surface flow, as assumed in the RORB model, but an interflow through surface soil layers.

The Effect of Ignoring Multiple Runoff Processes

Monte Carlo simulation assumes that there is a consistent transfer function between the input, in this case rainfall excess or runoff and the output hydrograph. However, in reality any catchment may behave in a different manner, depending on catchment condition, and what processes dominate.

In many catchments baseflow or other processes may occur, that are not modelled by the RORB model, meaning RORB cannot fully describe the total flood hydrograph. Monte Carlo simulation cannot provide a reasonable flood hydrograph, where there may be three or more processes occurring at once, all of which do not occur stochastically, but depend on catchment condition.

ARR1987 with its much simplified design storm approach does not reflect the reality of catchment behavior, but does work for the Mount Lofty Ranges, possibly because it reflects average catchment conditions, and not the true complexity that is involved.

Baseflow

Baseflow may be significant in some catchments, particularly for frequent flows, however in respect to baseflow Ladson et al (2013) pointed out that:

The limitation of the digital filtering approach is that the derived series do not reflect any underlying physical processes in shape, timing or quantum so it is not possible to make quantitative inferences; and

We tested several different software packages all claiming to use the Lyne and Hollick filter but there was substantial variation in the estimated BFI. There are also different approaches used in Hydstra and IQQM (Hydstra, 2006; Simons et al, 1996). This means that comparison of baseflow indices between studies and over time are difficult and this reduces confidence in the approach. We suggest the Lyne and Hollick filter is still useful but a standard approach to its application is required.

Baseflow separation by filter then not only does not reflect underlying physical processes but is subject to substantial variation dependent on the approach used.

Summary

RORB models just one of many runoff processes that may be occurring in any catchment and may therefore not reliably predict full flood hydrographs when used with Monte Carlo simulation. The treatment of baseflow in ARR2016 does not reflect underlying processes and cannot given the limitations described by Ladson et al (2013). Little is known about how to predict what processes may occur within a catchment and therefore what the catchment response to rainfall is. Catchment outflow given a rainfall input is most likely not a stochastic response. Although Kuczera et al (2017) make the statement that “the physics of transference of rainfall to runoff is reasonably well understood” we conclude that this is the main source of epistemic error in hydrology.

7. Recommendations for Practitioners

The findings in this report give rise to the need for recommendations for practitioners. Unfortunately the 2016 update of ARR has not provided methodologies that are a significant improvement on the previous 1987 ARR. The authors are continuing to work towards the improvement of flood flow prediction, and will provide updates as work continues. **Error! Reference source not found.** and Figure 9 give an indication of what approach will give the most reasonable estimate for each AEP (and ARI). Based on this the RFFE gives the best estimate for 50% and 20% AEP, but for less frequent events (ARI = 10 years to 100 years) it is suggested that the 1987 ARR should be used with the RORB model until a further recommendation is made. The following should be used with the RORB model:

- ARR1987 rainfall intensities;
- Design storms from 3 to 72 hours;
- Unfiltered temporal patterns; and
- An initial loss of 30 mm and a continuing loss of 1 mm/hr (see Table 3.4 in ARR1987).
- The RORB storage parameter k_c was derived for each catchment based on the findings of Kemp (1993), that is $k_c = 0.89A^{0.55}$.
- Assume zero baseflow.

Work is continuing on the assessment of flows for ungauged rural catchments, and will be further reported. In the meantime it is suggested that:

- Observed data from gauging stations should be used as the first basis for analysis. If record periods are short, then results should be compared with regional information such as the Regional Flood Frequency Estimation (RFFE) for frequent events and ARR1987 RORB for 10 year ARI and less frequent.
- Design flows predicted from any calibrated runoff-routing model should be consistent with flood frequency analysis of observed data, or in the absence of observed data, RFFE and ARR1987 RORB predictions.

8. Conclusions

It has been shown that a simple LRRM model with ten equal sub-areas predicts peak flows that are very similar to those of a RORB model of the same catchment and can thus be used in the quick estimation of peak flows for multiple catchments, with a large saving in time.

It has been found that the annual data series used in the derivation of RFFE2016 in South Australian catchments is incorrect, and thus RFFE for South Australia has to be redone. Comparison of the estimates of RFFE and ARR2016 RORB on South Australian catchments has shown that although RFFE (given the above finding) is reasonable, ARR2016 RORB estimates are poor, particularly for frequent flows. One explanation of this is the inability of RORB to handle the wide range of processes that may occur in any catchment. However, more work is required to determine the actual cause, and whether RORB with Monte Carlo as recommended by ARR can be made to provide reasonable estimates, or if a more complex model, capable of modelling several runoff processes is required.

ARR1987 RORB has been found to provide much better estimates than ARR2016 and should be used in preference until further recommendations are made as to the ARR2016 joint probability Monte Carlo approach.

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Appendix A – At-site quantiles with ratios of ARR2016 RFFE and ARR2016 RORB estimates

	50% AEP			20% AEP			10% AEP			5% AEP			2% AEP		
Station ID	LP III Flow (m^3/sec)	RFFE/ LPIII	RORB/ LPIII	LP III Flow (m^3/sec)	RFFE/ LPIII	RORB/ LP III	LP III Flow (m^3/sec)	RFFE/ LPIII	RORB/ LP III	LP III Flow (m^3/sec)	RFFE/ LPIII	RORB/ LP III	LP III Flow (m^3/sec)	RFFE/ LPIII	RORB/ LP III
A4260504	39.7	1.02	0.00	70.3	1.34	0.21	91.0	1.46	0.38	110	1.61	0.54	135	1.84	0.80
A4260529	9.94	1.17	0.01	37.0	1.33	0.57	56.0	1.24	0.90	70.7	1.32	2.17	84.0	1.55	1.83
A4260533	29.3	1.10	0.00	80.4	1.16	0.38	124	1.10	0.93	170	1.11	1.12	230	1.20	1.44
A4260536	5.00	1.30	0.12	38.5	1.64	1.50	103	0.86	1.18	225	0.53	0.81	516	0.33	0.59
A4260558	6.27	0.98	0.52	22.2	0.49	0.89	36.9	0.43	0.84	52.2	0.40	0.87	71.9	0.41	0.96
A5020502	9.66	1.26	0.01	15.0	2.00	1.30	17.2	2.44	2.19	18.5	2.99	3.18	19.6	3.91	4.69
A5030502	6.07	1.09	0.02	11.5	1.35	0.99	14.4	1.97	1.42	16.7	1.70	1.68	18.9	2.05	1.92
A5030503	8.45	0.43	0.01	18.9	0.35	0.79	27.5	0.33	0.94	36.6	0.33	1.02	49.2	0.34	1.07
A5030504	73.7	1.03	0.00	158	0.92	0.20	225	0.91	0.28	295	0.93	0.35	391	0.99	0.44
A5030506	9.69	0.40	0.01	20.5	0.40	0.61	28.4	0.38	0.77	35.9	0.42	0.85	45.2	0.45	0.93
A5030507	7.61	0.29	0.33	18.6	0.31	0.61	27.2	0.29	0.63	35.8	0.29	0.64	44.0	0.30	0.63
A5030508	2.40	0.45	0.77	7.78	0.25	1.03	12.0	0.22	0.92	15.9	0.22	0.94	20.4	0.23	0.93
A5030509	6.06	0.26	0.11	10.0	0.33	0.60	13.3	0.34	0.65	17.0	0.34	0.65	22.8	0.33	0.65
A5030526	4.12	0.25	0.21	6.79	0.29	0.75	8.79	0.30	0.81	10.8	0.32	0.84	13.7	0.33	0.81
A5040500	38.7	0.63	0.05	109	0.50	0.34	166	0.42	0.39	221	0.39	0.44	290	0.37	0.53
A5040512	5.94	0.43	0.78	19.7	0.48	0.81	31.8	0.41	0.80	44.0	0.38	0.79	59.2	0.39	0.80
A5040517	0.46	0.74	1.22	1.30	0.68	3.70	2.30	0.52	3.15	3.75	0.41	2.51	6.59	0.30	1.93
A5040518	4.34	1.04	0.08	8.06	1.01	1.31	10.7	1.05	1.52	13.1	1.11	1.78	16.2	1.23	2.01
A5040523	12.3	0.45	0.28	29.2	0.51	0.81	46.7	0.44	0.69	69.4	0.39	0.62	109	0.34	0.53
A5040525	12.0	0.46	0.04	26.5	0.54	0.46	35.5	0.54	0.52	42.9	0.57	0.60	50.6	0.64	0.70
A5050502	15.5	0.66	0.01	55.0	0.71	0.66	96.1	0.57	0.78	145	0.50	0.81	219	0.46	0.93
A5050504	17.5	0.81	0.01	79.3	0.61	0.38	153	0.45	0.51	248	0.37	0.61	400	0.33	0.63
A5050517	6.78	0.82	0.02	36.9	0.52	0.74	74.9	0.44	0.71	124	0.29	0.65	200	0.25	0.64
A5070500	10.3	2.06	0.11	31.6	1.09	1.16	44.5	0.83	1.59	53.9	0.72	2.04	62.2	0.67	2.91
A5070501	15.1	1.35	1.37	51.4	1.60	1.60	78.5	1.49	1.61	102	1.54	1.84	125	1.77	2.20