

Development of a regional flood frequency estimation model for Pilbara, Australia

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Abstract: This paper presents the development of regional flood frequency estimation (RFFE) models for Pilbara, Western Australia as a part of Australian Rainfall and Runoff (ARR) revision. The Pilbara is an economically important arid region, which is rich in natural resources and mining activities. A total of 11 catchments are selected from the Pilbara region to develop the RFFE models. The selected catchments are arid with average annual rainfall values are in the range of 200 and 350 mm. For each of the selected catchments, flood quantiles are estimated for 6 annual exceedance probabilities (AEPs), which are 50%, 20%, 10%, 5%, 2% and 1% using two estimation approaches: (i) annual maximum flood series (AMS): Log Pearson Type 3 (LP3) distribution-Bayesian procedure and (ii) partial duration series (PDS) (with average number of events per year equal to 0.5): Generalised Pareto distribution and L moments procedure. The AMS consists of maximum discharge value in each calendar year; however, the PDS consists of all the independent peak flows over a certain threshold. Two different RFFE models are developed (using AMS and PDS data) using an index flood method where the 10% AEP flood quantile (Q_{10}) is used as the index variable and a dimensionless growth factor for AEP of $x\%$ (GF_x) is used to estimate Q_x (where, $x = 50\%, 20\%, 10\%, 5\%, 2\%$ and 1%). The prediction equation for the index flood is developed using an ordinary least squares regression with two predictor variables (catchment area and design rainfall intensity). The results demonstrate that the performance of the two RFFE models is quite similar. For AEPs of 50% to 1%, the absolute median relative error values of the estimated flood quantiles are found to be in the range of 23% to 46% and 42% to 56% for AMS and PDS based RFFE models, respectively. The results reveal that both the models are able to generate flood quantiles with a good accuracy; however the AMS-based RFFE model outperforms the PDS-based model.

Keywords: Pilbara, RFFE, ARR, arid region, semi-arid region, floods

1. INTRODUCTION

About three quarters of Australian land is considered to be semi-arid and arid where mean annual rainfall is very low. Several Australian studies (e.g. Pilgrim *et al.*, 1988; Ruprecht, 1996; Cordery, 2004) have demonstrated that these arid and semi-arid areas have noticeably different flood hydrology than the humid areas. In these areas, rainfall is highly variable and dry antecedent conditions often lead to little or no runoff from majority of the rainfall events. However, even in these semi-arid and arid areas, severe floods do happen causing significant damage. The geomorphology of the semi-arid and arid areas is distinctly different to the humid areas, which is characterised by a shallow stream system with ill-defined and non-perennial channels that shift courses erratically, high transmission loss, lack of vegetation and high erosion rate (Zaman *et al.*, 2012).

The national guideline for flood estimation in Australia, Australian Rainfall and Runoff (ARR1987) developed regional flood frequency analysis (RFFA) methods for the semi-arid and arid areas of Australia using streamflow data from a handful of catchments (I. E. Aust., 1987). Since the publication of ARR1987, there has been no update of these RFFA methods. More recently, the National Committee on Water Engineering (Engineers Australia) has initiated upgrading the regional flood methods in Australia. In this regard, under Project 5: Regional Flood Methods, significant research endeavours have been carried out (e.g. Rahman *et al.*, 2009, 2011; Palmén and Weeks, 2011; Haddad and Rahman, 2012; Zaman *et al.*, 2012; Haque *et al.*, 2014; Micevski *et al.*, 2015; Rahman *et al.*, 2015). In the ARR Project 5, the semi-arid and arid areas have been separated from the higher rainfall areas by 500 mm mean annual rainfall (MAR) contour line (i.e. if the MAR is less than 500 mm, the area is considered to be semi-arid and arid). The semi-arid and arid areas have also been divided into two regions, (i) Pilbara region in Western Australia and (ii) other arid areas (Rahman *et al.*, 2015).

The Pilbara is an important mining region in Western Australia. It is often recognised as the engine room of the nation due to its massive reserve of natural resources (e.g. iron ore, base metals, oil and gas). Being one of the world's most ancient natural landscapes covering around 500,000 km², it is also considered as a region of high environmental significance (HVAC&R Nation, 2015). However, in this area, stream gauging records are very limited to perform hydrological and flood frequency analyses (Weeks *et al.*, 2015). In addition, there has been limited flood frequency analysis. Rahman *et al.* (2012a) investigated the flood frequency analysis in Pilbara area using the PDS data and Quantile Regression Technique (QRT).

Rahman *et al.* (2012b) and Zaman *et al.* (2012) investigated the flood frequency analysis for the semi-arid and arid areas of Australia by forming a single fixed region with all the arid catchments (i.e. 57 catchments in Rahman *et al.* (2012b) and 45 catchments in Zaman *et al.* (2012)). They adopted the index flood method based on the PDS data similar to ARR1987. Flavell (2012) developed a flood estimation model for the Pilbara region using PDS data from 16 catchments by adopting a multiple linear regression and index flood method. For smaller flood quantiles (50% to 5% AEPs), he adopted a multiple linear regression technique to estimate design floods and for higher flood quantiles (2% and 1% AEPs), a frequency factor based on 5% AEP was used. Davies and Yip (2014) developed flood estimation models based on the index flood method where design discharge for AEP of 20% was used as the index flood. They used the annual maximum series (AMS) data from 10 catchments including 5 from Gascoyne region and 5 from Pilbara region in Western Australia. They grouped the catchments based on the catchment areas (small catchments: up to 1000 km², medium catchment: 1000 – 10,000 km² and large catchment: more than 10,000 km²) and developed three prediction equations.

The focus of this study is to develop a RFFE model for Pilbara based on the most up-to-date flood data. It compares the AMS and PDS series based RFFE models and recommends a RFFE model for the Pilbara region. The remainder of the paper is organised as below. Study area and data are presented in Section 2, which is followed by presentation of results and conclusion.

2. STUDY AREA AND DATA

The Pilbara region, located within 20-24°S and 115-122°E, is generally hot and dry. Seasonality in climate is characterised with hot summers (average daily minimum and maximum temperatures are around 25°C and 36°C, respectively) and mild winters (average daily minimum and maximum temperatures are around 12°C and 27°C) (Reeves *et al.*, 2007). Rainfall is highly variable and localised, and mainly happens during the summer months. This region is also subject to cyclones and thunderstorms during the summer months. Being an arid region, the annual potential evaporation is about 10 times higher than the annual rainfall (i.e. evaporation to rainfall ratio: 10 to 1).

In the ARR Project 5, higher rainfall areas of Australia have been divided into five different regions (Regions 1 to 5), and the semi-arid and arid areas have been divided into two different regions (Regions 6 and 7) where Region 6 is the Pilbara region. To develop the data set for RFFE 2015, an upper limit of catchment size of 1,000 km² was adopted and the cut-off record length was selected as 19 years to maximise the number of catchments. A total of 11 catchments from the Pilbara region (Table 1) satisfy the criteria. The rating curves were examined for these stations as part of data quality check; however, no station in Pilbara was removed based on rating curve extrapolation error due to the availability of very few catchments in this region.

The selected catchments have an average annual rainfall in the range of 200 to 350 mm. The catchment areas range from 0.1 to 885 km² (median: 174 km²) and streamflow record lengths for AMS series range from 26 to 33 years (median: 28 years). Both PDS and AMS data of the selected 11 catchments have been extracted and utilised to develop RFFE models. During extraction of PDS data, the average number of events per year was set as 0.5. In extracting the AMS and PDS, only the good quality data were considered.

3. METHOD

At-site flood quantiles are estimated adopting two different models: (1) AMS model where FLIKE software (Kuczera, 2001) is used to fit the LP3 distribution with the Bayesian procedure (Rahman *et al.*, 2015); and (2) PDS model where Generalised Pareto distribution and L moments procedure are adopted. Flood quantiles are estimated for 6 different annual exceedance probabilities (AEPs) (i.e. 50%, 20%, 10%, 5%, 2% and 1%).

In order to develop the RFFE model, an index flood method is adopted where the 10% AEP flood quantile (Q_{10}) is used as the index variable. A dimensionless growth factor for AEP of $x\%$ is used to estimate Q_x , where $x = 50\%, 20\%, 10\%, 5\%, 2\%$ and 1% AEPs. The prediction equation is developed for Q_{10} as a function of two predictor variables (catchment area and design rainfall intensity of 6-hour duration and 50% AEP).

Table 1. Selected study catchments from Pilbara (Western Australia).

Station ID	Station name	River name	Catchment area (km ²)	AMS record length (years)	Period of record
701003	Nokanena Brook	Wootachooka	235.2	28	1973 - 2000
701005	Robb Crossing	Arrowsmith	809.8	30	1972 - 2001
701006	Buller	Buller	33.9	27	1974 - 2001
701601	Wearbe	Nokanena Brook Catch	0.1	29	1971 - 1999
706207	Mt Samson	Hardey	250.3	33	1968 - 2001
707001	Palra Springs	Robe	174.3	32	1968 - 1999
708009	Fish Pool	Kanjenjie Ck Trib.	41.1	28	1973 - 2001
708227	Recorder Pool	Portland	553.4	33	1968 - 2001
709006	Blue Dog Pool	Tanberry Ck	128.1	26	1975 - 2001
709007	Marmurrina Pool U-South	Harding	49.4	26	1974 - 1999
709010	Pincunah	Turner	885	27	1985 - 2012

4. RESULTS

The fitted flood frequency curves at each of the selected gauging stations for the AMS and PDS cases are checked visually (examples can be seen in Figures 1 and 2). The fit is found to be better generally for the AMS case than the PDS one – this is largely attributed to the censoring of potentially influential low flows in the Bayesian AMS procedure. The median growth factors are estimated to be 0.214, 0.614, 1.00, 1.456, 2.116 and 2.639 for AEPs of 50%, 20%, 10%, 5%, 2% and 1% AEPs (for the AMS case). The median growth factors for the PDS case are 0.329, 0.858, 1.00, 1.813, 2.404 and 3.192, respectively.

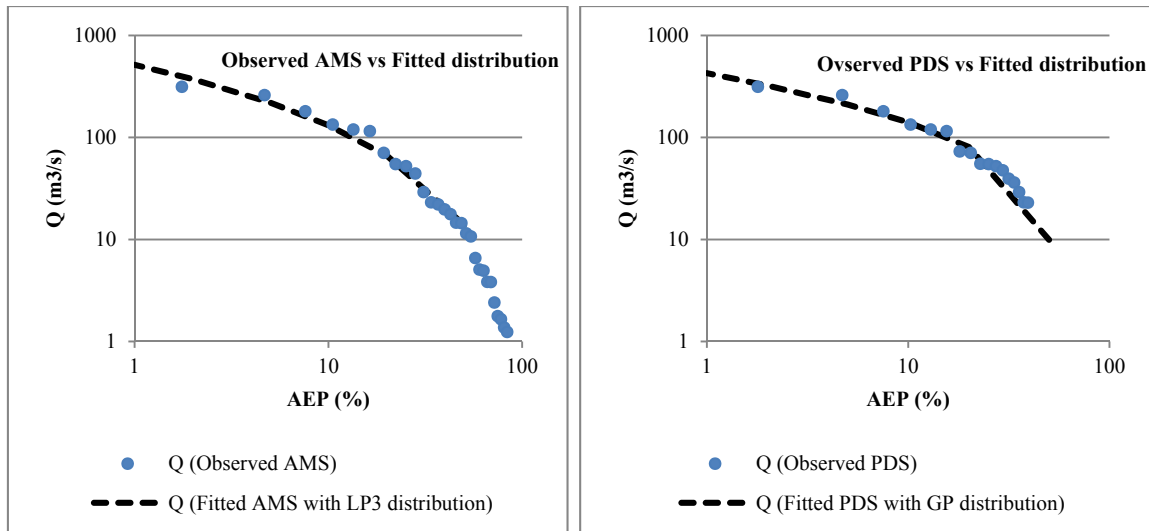


Figure 1. Fitted probability distributions for the AMS and PDS cases (Station 706207).

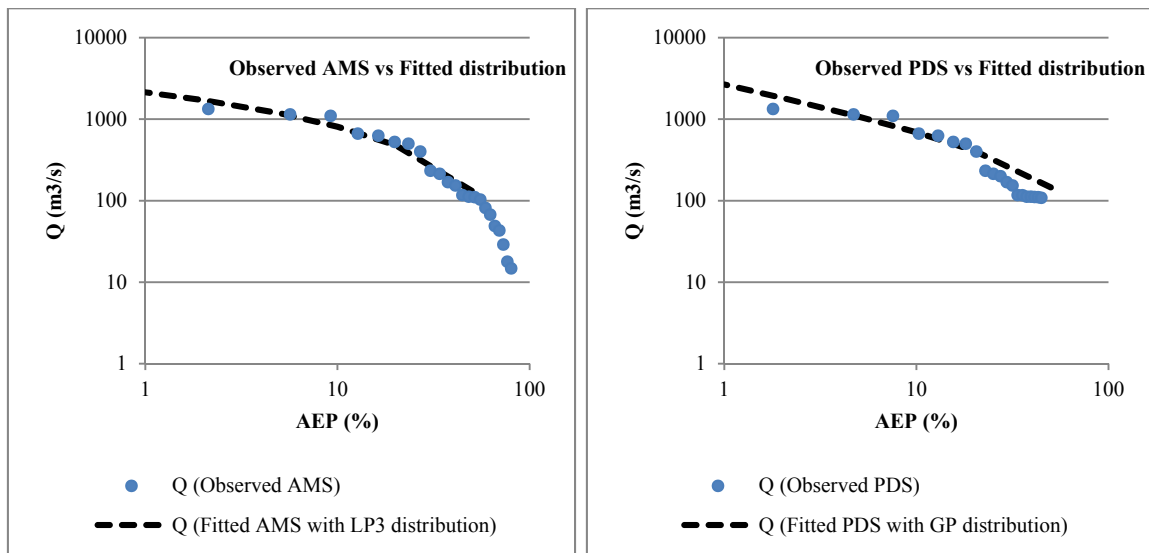


Figure 2. Fitted probability distributions for AMS and PDS cases (Station 709010).

Results of regression analysis in relation to the development of the prediction equation for 10% AEP flood (Q_{10}) are summarised in Table 2. It can be seen that the developed regression equations have coefficient of determination (R^2) values above 90% and the standard error of estimate values are quite low. The predictor variables (catchment area and the design rainfall intensity) are found to be statistically significant in both the equations with the p -values smaller than 0.01. The observed (estimated by at-site flood frequency analysis) vs. predicted flood quantiles by the developed RFFE models are presented in Figure 3, which shows a good agreement between the observed and predicted flood quantiles. The regression equations satisfy the least squares model assumption quite well e.g. the residuals are normally distributed.

Comparison of the median relative error (RE) values (which is estimated ignoring the sign of the RE values at individual sites) for both the models are presented in Figure 4. It can be seen that the median RE values are 42% to 56% for the PDS based RFFE model, and 23% to 46% for the AMS based RFFE model. These results reveal that AMS based RFFE model outperforms the PDS based RFFE model for all the six AEPs.

Table 2. Summary of regression equations for Q_{10}

Model	AMS			PDS		
Dependent variable	log10(Q ₁₀)			log10(Q ₁₀)		
N	11			11		
<u>Independent variables</u>	Coefficients	SE of coefficients	<i>t</i> -statistics (<i>P</i> value)	Coefficients	SE of coefficients	<i>t</i> -statistics (<i>P</i> value)
Constant	-2.597	0.485	-5.35(0.001)	-2.331	0.4763	-4.89(0.001)
log10(A)	0.549	0.066	8.32(0.000)	0.479	0.065	7.40(0.000)
log10(I _{6_50%})	4.04	0.595	6.79(0.000)	3.921	0.584	6.71(0.000)

Model performance

R^2	95.20%	94.50%
Adj. R^2	94.00%	93.10%
SEE	0.221	0.217

Note: AMS: Annual maximum series, RFFE: Regional flood frequency estimation, N: Number of sites, SE: standard error, SEE: standard error of estimate; A = catchment area (km²); I_{6_50%} = design rainfall intensity in mm/h for 6-hour duration and 50% AEP.

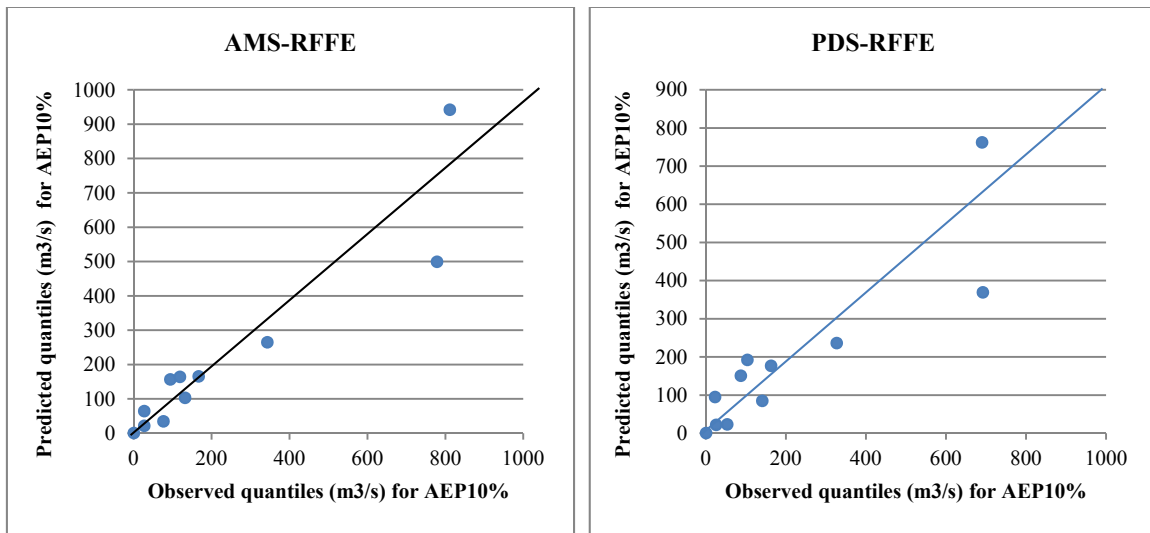


Figure 3. Observed (estimated at-site flood quantiles) vs. predicted flood quantiles for 10% AEP.

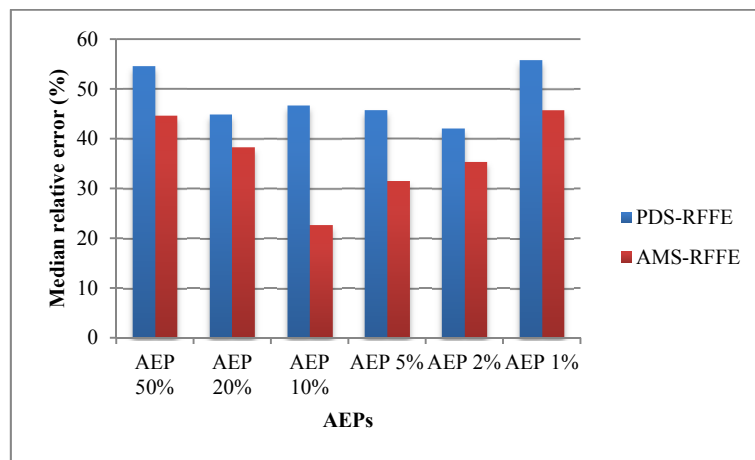


Figure 4. Comparison of median relative error values for the two RFFE models.

5. CONCLUSION

Regional flood estimation models have been developed for the Pilbara arid area in Western Australia using data from eleven gauged catchments. At-site flood frequency analysis is undertaken using the AMS and PDS flood data. The regression equations for the index flood (10% AEP flood, Q_{10}) have R^2 values greater than 90%. It has been found that the median relative error values are in the range of 42% to 56% for the PDS based RFFE model and 23% to 46% for the AMS based RFFE model. These results reveal that the AMS based RFFE model outperforms the PDS based RFFE model. Therefore, the AMS based RFFE model is finally selected to recommend in the upcoming Australian Rainfall and Runoff.

The RFFE technique for the Pilbara region is based on a very small number of gauged catchments spanning a large area. There is a notable variation in catchment conditions over this region. It is therefore likely that the gauges are not fully representative of the wide range of conditions encountered in the region. Hence, the flood estimates in the arid areas given by the RFFE model should be used with caution. Users need to compare local catchment conditions with those at gauged locations and in many cases may need to adjust RFFE model estimates to account for the local catchment conditions.

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