Applicability of Kriging to Regional Flood Estimation Problem in Eastern Australia

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Abstract

Design flood estimation in ungauged catchments is a common problem in hydrology. Regional flood frequency analysis (RFFA) is widely used in design flood estimation at ungauged sites, which attempts to transfer flood characteristics from gauged catchments to ungauged ones. The most commonly adopted RFFA methods in Australia in the past included the Index Flood Method, Quantile Regression Technique and Probabilistic Rational Method; however, the new Australian Rainfall and Runoff (ARR) recommends a Parameter Regression Approach based on Log Pearson Type 3 distribution. This paper presents development of a new RFFA method in Australia based on ordinary kriging. It uses data from 558 gauged catchments from Victoria, New South Wales and Queensland States of Australia. These catchments are small to medium in size, with an upper limit of 1000 km^2. Based on a leave-one-out validation technique, it has been found that the relative error values in design flood estimates by kriging are in the range of 28 to 36%, which are smaller than Australian Rainfall and Runoff (ARR) recommended RFFE Model. However, kriging shows a relatively higher degree of bias than the RFFE Model. The findings of this study will be useful to enhance the RFFE Model in Australia in near future by applying kriging.

***Keywords**:* Floods, ARR, Kriging, RFFE Model, RFFA

1. INTRODUCTION

The new edition of Australian Rainfall and Runoff (ARR) 2016 (Ball et al., 2016) include many recent advances regarding holistic planning, design and operation of flood management issues and involve many alternative approaches in design flood estimation. The development was necessitated to review and evaluate the available design procedures recommended in ARR 1987 (Pilgrim, 1987) as well as update the guidance to provide the best available methods and design data Australia wide under varying conditions. In many design flood problems, for example, culverts and small to medium sized bridges, only the peak flow of the flood hydrograph are the dominant variable of interest; whereas in some design applications such as flood storage design of retarding basins, an estimation of full hydrograph and also other flood characteristics are necessary (Pilgrim, 1987). In regions where adequate streamflow data are available, at-site Flood Frequency Analysis (FFA) can be applied (Stedinger et al., 1993; Kuczera, 1999); however where there is paucity of observed streamflow data, Regional Flood Frequency Analysis (RFFA) technique is recommended for design estimation (Flavell, 2012). Numerous RFFA techniques and procedures have been proposed around the world (Seibert, 1999; Hundecha & Bardossy, 2004; Young, 2006; Sivapalan *et* al., 2013).

The RFFA approach attempts to transfer flood frequency characteristics from a group of homogeneous gauged catchments to the ungauged catchment of interest. There are limited numbers of gauged catchments throughout Australia over an area of about 7.5 million km^2, which limits the development of accurate RFFA techniques in Australia. The RFFA technique referred as 'RFFE Model 2015' is recommended for estimation of design peak discharges at ungauged catchments in Australia in the recent version of ARR (Ball et al., 2016). In the past, the most common RFFA methods in Australia included the 'Probabilistic Rational Method' recommended for general use in Victoria and eastern NSW (ARR 1987); 'Index Flood Method' relied on the assumption of regional homogeneity; and generalised least square based 'Quantile Regression Technique'. The later offered a powerful statistical method which is also popular in the US (Bates, 1994; Griffis & Stedinger, 2007; Hicks et al., 2009; Haddad & Rahman, 2012; Rahman et al., 2015). The performance of RFFA model is largely governed by the quantity and quality of the available data and the capability of the adopted statistical techniques to transfer information from gauged to ungauged sites within the region. It is reported that the relative accuracy of 'RFFE Model 2015' is likely to be within ±50%. Generally, the degree of uncertainty in RFFA technique is typically greater than at-site FFA (Rahman et al. 2012 and 2015).

This paper presents development of a new RFFA method in Australia based on ordinary kriging (Delhomme, 1978; Villeneuve *et* al., 1979); which may be applied as a potential tool for regional analysis of hydrological variables like flood quantiles (Daviau et al., 2000; Grover et al., 2002; Eaton et al., 2002; Chokmani & Ouarda, 2004). Although the range of the kriging method was limited to the field of mining initially, it has been noticeably expanded over the past years in Hydrosciences especially in Europe (Delhomme, 1978; Chokmani & Ouarda, 2004). Generally based on the neighbourhood information, kriging' more specifically ordinary kriging offers the best possible unbiased and optimum prediction of the unknown values. This paper adopts ordinary kriging to estimate flood quantiles using 558 catchments located in eastern Australia. The performance of the new technique is evaluated by applying a leave-one-out (LOO) validation approach (Haddad et al., 2013).

1.1. Data Selection

This paper uses streamflow data from 558 catchments from the States of New South Wales (NSW), Victoria (VIC) and Queensland (QLD). These catchments were also adopted in the development of ARR RFFE Model 2015. An upper limit of catchment size of 1,000 km² was generally adopted. These data were obtained from ARR Revision Project 5 (Rahman et al. 2015).

The selected streams are unregulated since major regulation (e.g. a large dam on the stream) affects the rainfall-runoff relationship significantly by increasing storage effects. Streams with minor regulation, such as small farm dams and diversion weirs, are not excluded because this type of regulation is unlikely to have a significant effect on large floods. The data sets for the selected potential catchments were prepared following a stringent procedure as detailed in (Haddad et al., 2010), gaps in the annual maximum flood series were in-filled as far as could be justified; low floods were censored in FFA (Lamontagne et al., 2013), errors associated with extrapolation of rating curves were investigated and the presence of trends with the data were checked (Rahman et al., 2015; Ishak et al., 2013).

Table 1. Summary of selected catchments from eastern Australia

State	No. of stations	Streamflow record length (years)	Catchment size (km^2)
NSW & Australian Capital Territory	176	20 – 82	1 – 1036
Victoria	186	20 – 60	3 – 997
Queensland	196	20 – 102	7– 963
TOTAL	558	20 – 102	1– 1036

2. METHODS

The RFFA method based on ordinary kriging presented here can be applied as a potential tool for estimating flood quantiles at ungauged sites. Using this powerful geostatistical technique, a spatial correlation model can be adjusted to be used for the estimation of specific quantiles. Amongst the neighbouring catchments, the closest one receives the greater weightage in general, as it is more likely to be similar to the ungauged catchment where flood quantiles needs to be estimated. In essence, the kriging allows predicting design floods at the ungauged sites using flood quantiles from the neighbouring gauged sites (Ouarda et al., 2008).

The kriging considers the spatial structure in the data and the distribution of the parameters along a function named ‘variogram’. The structure function ‘variogram’ typically exhibits the pattern, configuration and intensity of the variable’s spatial autocorrelation (Ouarda et al., 2008). In this study, to overcome the scaling effect, flood quantiles are standardised by the catchment area. A logarithmic transformation of variables is applied to the selected flood quantiles (2, 5, 10, 20, 50 and 100 years return periods). A variogram is developed using R package to identify the nature of spatial correlation. The variance level, usually called the ‘sill’, is reached at a distance, known as the ‘range’. Furthermore, a ‘nugget’ effect is added to the model to identify the level of uncertainty relating to the local estimation, sampling or even localization errors. Thereafter, a predicted (theoretical) model is fitted to the observed (experimental) variogram.

For the performance evaluation of the kriging technique, a cross validation called LOO is adopted where each of the selected gauged catchments is in turn considered as ungauged catchment and the predicted flood quantiles are compared with the observed flood quantiles.

A range of evaluation statistics are calculated to evaluate the performance of the ordinary kriging model: coefficient of determination (R^2) (Equation 1), mean bias (BIAS) (Equation 2), relative mean bias (RBIAS) (Equation 3), mean square error (MSE) (Equation 4), root mean square error (RMSE) (Equation 5), relative mean square error (RRMSE) (Equation 6), Nash-Sutcliffe efficiency (NSE) (Equation 7) and relative error (RE) (Equation 8).

$$R^2 = 1 - \frac{\sum(Q_p - Q_o)^2}{\sum(Q_o - \bar{Q}_o)^2} \quad (1)$$

$$BIAS = \frac{1}{n}\sum(Q_p - Q_o) \quad (2)$$

$$RBIAS(\%) = \frac{1}{n}\sum\left(100 * \left(\frac{Q_p - Q_o}{Q_o}\right)\right) \quad (3)$$

$$MSE = \frac{1}{n}\sum(Q_p - Q_o)^2 \quad (4)$$

$$RMSE = \sqrt{MSE} \quad (5)$$

$$RRMSE = \frac{\sqrt{\frac{1}{n}\sum(Q_p - Q_o)^2}}{\overline{Q_o}} \quad (6)$$

$$NSE = 1 - \frac{\sum(Q_o - Q_p)^2}{\sum(Q_o - \overline{Q_o})^2} \quad (7)$$

$$RE = 100 * \left(\frac{Q_p - Q_o}{Q_o}\right) \quad (8)$$

where,

Q_p = Predicted flood quantile;
Q_o = Observed flood quantile; and
$\bar{Q}_o$ = Average observed flood quantile.

3. RESULTS AND DISCUSSION

Figure 1 shows developed variogram models for the six selected flood quantiles. Table 2 summarises the results, which indicates a decreasing trend of 'sill' and 'range' with the decrease in return period of flood quantiles. The 'range' indicates the distance after which data are no longer significantly correlated. The 'sill' represents the total variance where the empirical variogram appears to level off. Besides, the 'nugget' presented in Table 2 increases with the increase of return periods from 10 to 100 years; however, the trend differs for 5 and 2 year return periods. This indicates that the level of uncertainty increases gradually from 10 year to 100 year return period.

Table 2. Characteristics of developed variogram models

Quantiles	Q_2	Q_5	Q_{10}	Q_{20}	Q_{50}	Q_{100}
range	1.42	5.29	5.90	6.22	6.70	7.05
nugget	0.31	0.27	0.26	0.28	0.34	0.41
psill	0.38	0.47	0.51	0.53	0.56	0.59
sill	0.69	0.74	0.77	0.81	0.90	1.00

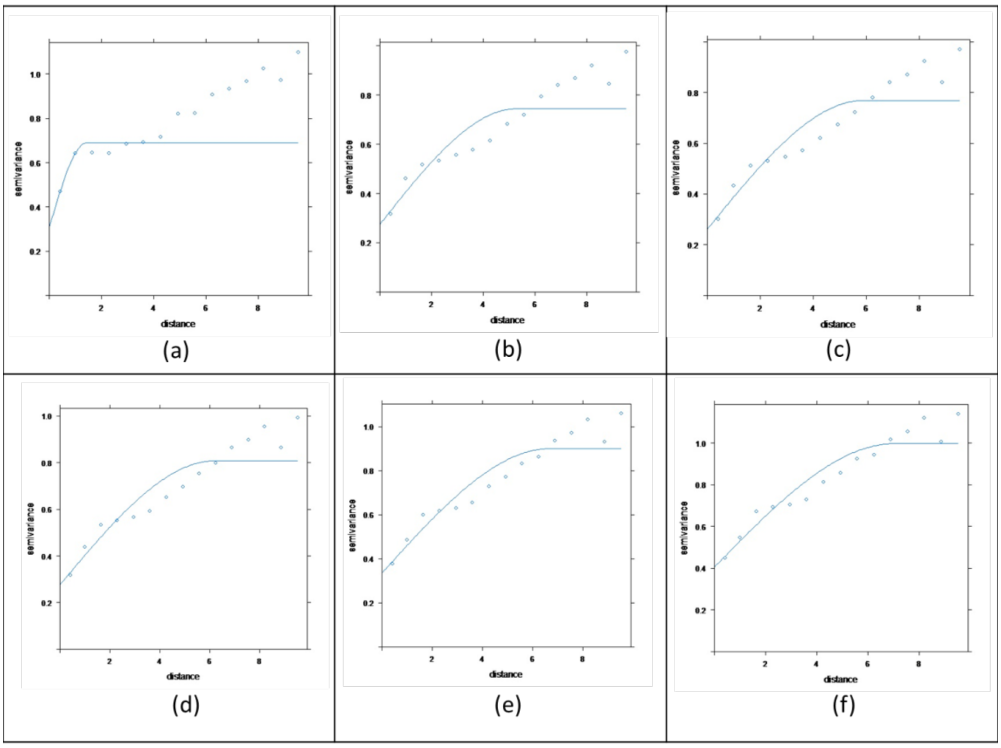

Figure 1. Variogram for the flood quantile models: (a) Q_2 (b) Q_5 (c) Q_{10} (d) Q_{20} (e) Q_{50} and (f) Q_{100}

The predicted (by ordinary kriging) (based on LOO) and observed flood quantiles for the 558 stations are plotted in Figure 2, and the histogram of relative error values for different flood quantiles are presented in Figure 3. These plots show that the predicted and observed flood quantiles match quite well. The performance of ordinary kriging is quite good (Table 3), with the NSE values in the range of 0.6-0.8. The NSE criterion compares the performance of kriging in relation to the observed mean value, where a negative value indicates that the estimation method is worse than using the mean value. On the other hand, the RRMSE value shows that, the least erroneous estimation is achieved for 20 year return period, which is followed by10 year return period, while the RRMSE value is found to be the highest for two year return period.

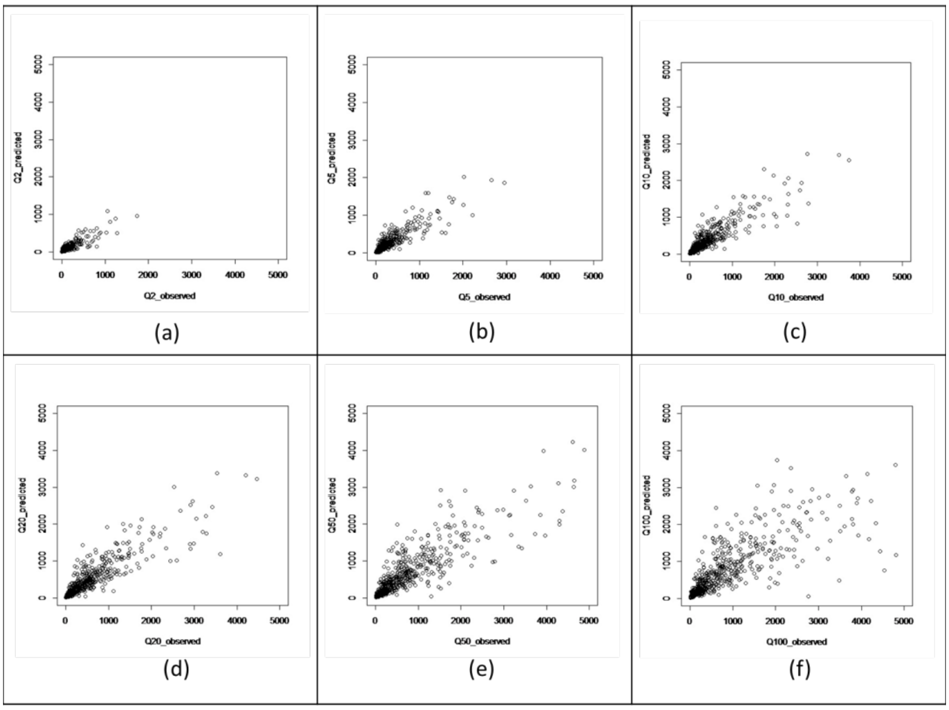

Figure 2. Predicted (by ordinary kriging) vs at-site flood quantiles (a) Q_2 (b) Q_5 (c) Q_{10} (d) Q_{20} (e) Q_{50} and (f) Q_{100}

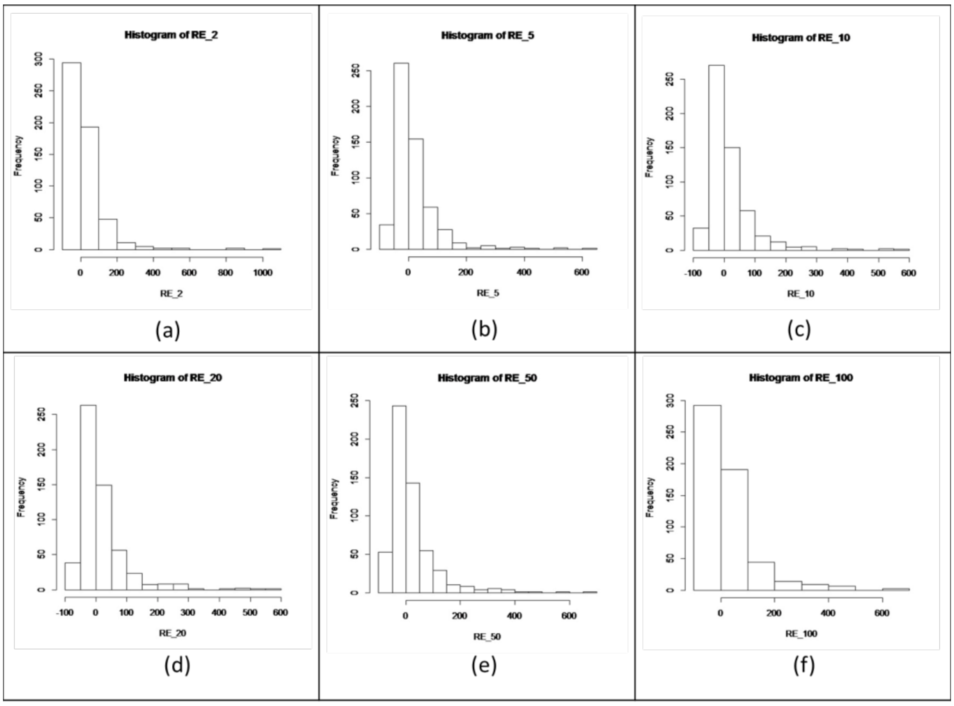

Figure 3. Histogram of relative error values for (a) Q_2 (b) Q_5 (c) Q_{10} (d) Q_{20} (e) Q_{50} and (f) Q_{100}

Table 3. Cross validation statistics from LOO for ordinary kriging

Quantiles	Q_2	Q_5	Q_{10}	Q_{20}	Q_{50}	Q_{100}
Mean_abs_RE	57.15	46.33	44.86	46.79	52.73	58.79

Median_abs_RE	34.20	30.55	28.75	28.41	31.86	35.37
mean (Qpred/Qobs)	1.23	1.16	1.16	1.17	1.20	1.24
median(Qpred/Qobs)	0.97	0.97	0.97	0.95	0.95	0.96
BIAS	-24.60	-31.30	-42.29	-58.29	-95.11	-145.46
RBIAS(%)	23.36	16.06	15.51	16.72	20.38	24.43
MSE($(m^3/sec)^2$)	10030.23	28597.01	54919.76	100666.20	233149.6	494243.4
RMSE(m^3/sec)	100.15	169.11	234.35	317.28	482.86	703.02
R^2	0.71	0.78	0.79	0.77	0.72	0.63
RRMSE	0.85	0.63	0.58	0.58	0.62	0.72
NSE	0.71	0.78	0.79	0.77	0.72	0.63

The negative value for the BIAS as found in the present case (Table 3) shows that the kriging method generally underestimates the observed flood quantiles. Furthermore, the coefficient of determination (R^2) is found to be decreasing generally with the increasing return period as expected. The validation results shown in Table 3 slightly differs this tendency for Q_2 and Q_5 probably due to sampling errors. The median RE values are the smallest for 10 and 20 year return periods and highest for 100 year. Overall, the median RE values are in the range of 28 to 36%, which seems to be an excellent result for Australia.

It should be noted here that LOO is a more rigorous validation technique compared with the split-sample validation where the model is tested on a smaller number of catchments (e.g. 10% of the total catchments). Hence, the RE that is generated by LOO is expected to be higher than if split-sample validation were used. The medians of the absolute relative error values from the LOO validation of the ordinary kriging and ARR RFFE technique are compared in Table 4, which show the ordinary kriging outperforms the ARR RFFE Model. The main conclusion from this analysis is that the quantification of uncertainty in the quantile estimates by the kriging technique is reasonable for the vast majority of the test catchments.

Table 4. Median relative error (RE) from leave-one-out validation of the ordinary kriging and ARR RFFE technique

Quantiles	Q_2	Q_5	Q_{10}	Q_{20}	Q_{50}	Q_{100}
Kriging	34.20	30.55	28.75	28.41	31.86	35.37
RFFE Model 2015	51	49	52	53	57	59

4. CONCLUSION

The study examines development of a new RFFA method in Australia based on ordinary kriging, which may be applied as a potential tool for regional analysis of hydrological variables like flood quantiles at ungauged sites. A large number of catchments (558) located in eastern Australia (NSW, VIC and QLD) ranging from small to medium in size, with an upper limit of 1000 km^2 have been used in the study. The data for this study were obtained from ARR Project 5. For the performance evaluation of kriging technique and compare the result with traditional method, a cross validation approach called leave-one-out (LOO) has been applied. The result has shown that the median relative error values in design flood estimates by kriging are in the range of 28 to 36%, which are smaller than the recommended ARR RFFE Model 2015. However, kriging shows a relatively higher degree of bias, which can be rectified by an interpolated bias correction factor. Overall, the results show the promise of the application of kriging in regional flood estimation in Australia. A detail study is being continued on kriging and future publications will present further development on this.

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