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Developing regional flood frequency models for Victoria, Australia by using Index Flood (IF) approach

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Abstract: The Index Flood (IF) method is a widely used procedure in regional flood frequency analyses (RFFA) to make flood predictions for ungauged catchments. The IF method assumes that a group is hydrologically homogeneous and this homogeneity is exploited to produce quantiles which have been shown to be more reliable than at-site estimates (Cunnane 1988). The IF method has been widely applied in a number of studies and found to be a reliable approach if the groups are hydrologically homogenous. Hence, the RFFA by the IF method is often accomplished in three steps: delineation of homogeneous groups, determination of regional growth curves, and the development of regional prediction models for the IF. The selection of an appropriate regional frequency distribution is of prime importance in RFFA and has been investigated for many decades, but hydrologists still debate the relative merits of different distributions. For instance, Engineers Australia (1987) recommends Log Pearson Type III (LPIII) fitted by the Method of Moments (MOM), LPIII/MOM for Australian catchments. However, many studies (Vogel et al. 1993; Wang 1997; Rahman et al. 1999) have found that the Generalized Extreme Value (GEV) distribution fitted by L moments (GEV/L) method yields more reliable flood quantile estimates than LPIII/MOM.

Although direct statistical analyses of at-site and regional floods have been conducted, no regional growth curves have been derived for general use in Victoria, Australia. The aim of this study was to identify the most appropriate regional flood frequency distribution for Victoria and to conduct RFFA by using the IF method. Hence the study reported in this paper consists of: (1) assessing the suitability of the GEV fitted by L2 moments (GEV/L2) for RFFA for Victoria, Australia; (2) delineation of homogenous groups; (3) development of regional growth curves for the defined groups; (4) development of regional prediction models for the IF and; (5) making predictions for ungauged (test) catchments.

72 catchments were selected and assigned into groups using cluster analysis; homogeneity of each group was also assessed. Regional growth curves for the defined groups were developed and RFFA was carried out by using the Index Flood (IF) method.

A total of 72 unregulated catchments were selected and the extracted Annual Maximum series (AM) of each station was modelled by LPIII/MOM, LN/MOM, GEV/L and GEV/L2 methods. The results indicated GEV/L2 as the most appropriate method for at-site flood frequency analyses in Victoria as the quantiles made by the GEV/L2 exhibited smaller bias and mean square errors than those of the other models. Suitability of GEV/L and GEV/L2 for RFFA was assessed by constructing corresponding moment ratio diagrams. These show that L2 moment ratios of the 72 catchments lie symmetrically around the theoretical GEV curve while the majority of the L moment ratios are scattered below the theoretical GEV curve indicating that GEV/L2 is therefore more appropriate than GEV/L for RFFA in Victoria.

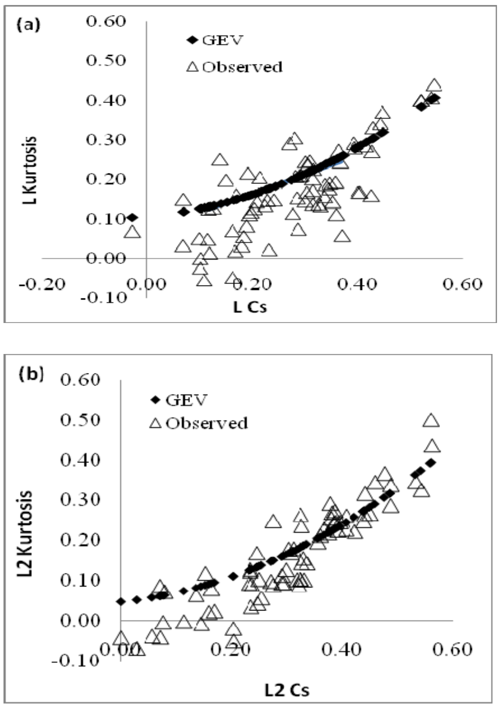

Figure 1. LH moment ratio diagrams: (a) L moment ratio diagram and (b) L2 moment ratio diagram

Keywords: *Regional flood frequency analysis, Victoria, GEV, L2 moments, index flood*

1. INTRODUCTION

Sizing of minor hydraulic structures, such as culverts and bridges, is based on design flood quantiles (Q_T) of medium to high return periods (T). If the length of the available data series is shorter than the T of interest, or when the site of interest is ungauged (no flow data available) obtaining a satisfactory estimate of Q_T is difficult. Regional flood Frequency analysis (RFFA) is one of the approaches that can be used in such situations. The Index Flood (IF) method is a widely used procedure in RFFA: it requires that any group of catchments selected for analysis is hydrologically homogeneous. This homogeneity is exploited to produce quantiles which have been shown to be more reliable than at-site estimates (Cunnane 1988). The method has been widely applied in a number of studies and found to be a reliable approach (Potter & Lettenmaier 1990; Kjeldsen et al. 2002; Portela & Dias 2005; Saf 2008).

The RFFA is often accomplished in three steps: delineation of homogeneous groups, determination of appropriate regional frequency distribution, and development of regional prediction models. The selection of an appropriate regional frequency distribution is of prime importance in flood frequency analysis, and has been investigated for many decades but hydrologists still debate the relative merits of different distributions. In Australia, for example, the LPIII/MOM has been recommended by the Australian Rainfall and Runoff (ARR) (Engineers Australia, 1987). However, many studies (Vogel et al. 1993; Wang 1997; Rahman et al. 1999) have found that the GEV method yields more reliable flood quantile estimates than LPIII.

This paper presents the work undertaken to: (i) investigate the suitability of GEV fitted by two orders of LH moments; $\eta = 0$ (L moments) and $\eta = 2$ (L2 moments) for both at-site and regional flood frequency analyses; (ii) delineate homogenous groups; (iii) derive regional growth curves and; (iv) develop of regional prediction model for the selected IF quantile ($Q_{2.33}$). Finally, the reliability of the ungauged catchment prediction is assessed.

2. STUDY AREA AND DATA

72 Victorian catchments were selected for this study by considering the following criteria: (1) catchment has over 10 years flow data, (2) catchment was not regulated and, (3) catchment was not affected by more than 10% urbanization. The geographical distributions of the selected catchments in Victoria are shown in Figure 2.

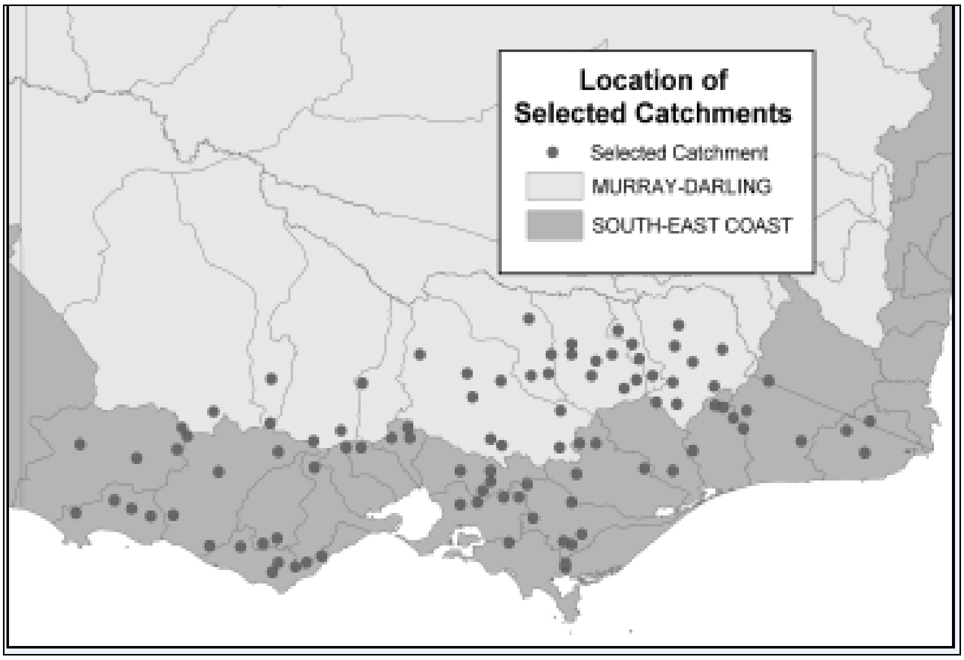

Figure 2. Map of Victoria and the locations of the study catchments

Based on the published literature and the data availability, a total of 8 catchment characteristics were identified as suitable for the regional model development. The selected attributes are tabulated in Table 1.

Table 1: The selected catchment characteristics

Variable	Definition	units	Maximum	Minimum	Mean
AREA	Size of the catchment	km^2	943	6	321
ELEV	Elevation at the catchment centroid	mAHD	1350	30	378
FOREST	Fraction of area covered by forest	-	0.0	1.0	0.6
LENGTH	Main stream length	km	140	4	41
SLOPE	Slope of the central 75% of the mainstream length	-	100	0.75	13.75
SFREQ	Total number of stream junctions divided by catchment area	km^{-2}	2.52	0.12	0.61
SHAPE	Catchment perimeter divided by area	m	1.92	0.17	0.45
RAIN	Mean annual rainfall	mm	1800	550	945

3. METHODOLOGY

RFFA by the IF method was accomplished in the following steps:

Step 1 - At-site flood frequency analysis and selection of the most appropriate flood frequency model- Quantiles of LPIII/MOM and LN/MOM at six selected return periods (T = 2, 5, 10, 20, 50 and 100 years) were computed using the HYDSTRA program, while those of the GEV/L and GEV/L2 were computed according to Wang (1997). The relative performance of each method was assessed using an empirical approach suggested by Rahman et al. (1999). In this method, the deviation (D) between the estimated quantiles (E_G) and the corresponding value from the best fit curve (E_D) was calculated using Equation 1.

$$D = \frac{(E_D - E_G)}{E_G} \tag{1}$$

A small value of D corresponds to a small standard error of estimates. These deviations were then used to evaluate the performance of each distribution in describing the observed data. The reliability of the GEV/L2 estimates over GEV/L estimates was assessed through Monte Carlo simulation. Bias (Equation 2) and MSE (Equation 3) of the GEV flood quantiles of the two methods were computed using 1000 simulated samples of the same size as thosee observed. Relative performance of the GEV/L2 compared to GEV/L was assessed using the Efficiency (ϕ) measure given in Equation 4. Finally, the suitability of the GEV/L2 and GEV/L methods were assessed by constructing and L2 moment ratio diagram and L moment ratio diagram (Figure 1).

$$\text{Bias}(\hat{\theta}) = E[\hat{\theta} - \theta] \tag{2}$$

$$\text{MSE}(\hat{\theta}) = E\left[(\hat{\theta} - \theta)^2\right] = \left[\text{Bias}(\hat{\theta})^2\right] + \text{VAR}(\hat{\theta}) \tag{3}$$

$$\phi = \frac{(\text{MSE})_L}{(\text{MSE})_{L2}} \tag{4}$$

Step 2 - Delineation of homogeneous groups and testing of homogeneity. As noted above, the IF estimates may not be reliable if the group of catchments is not homogeneous. Hosking and Wallis (1997) recommended of use methods that rely on site characteristics only when identifying homogeneous groups, and consequently use at-site characteristics to independently test homogeneity. Hosking and Wallis (1997) further recommended using Ward's method, which is a hierarchical clustering method based on minimizing the Euclidean distance in site characteristics space within each cluster.

The 72 catchments were therefore subject to cluster analysis by Ward's method and homogeneity assessment of the delineated groups by the method proposed by Hosking and Wallis (1997). This is a statistical test based on L moment ratios for testing the heterogeneity of the proposed groups. The test compares the between-site variation in sample L moment ratios with the expected variation for a homogeneous group. The method fits four parameter Kappa distributions to regional average L moment ratios. The estimated Kappa distribution uses to generate 500 homogeneous groups with population parameters equal to regional average sample L moment ratios. The properties of the simulated homogeneous groups were compared to the sample L moment ratios as

$$H_i = \frac{(V_i - \mu_V)}{\sigma_V} \tag{5}$$

where μ_V is the mean of simulated V_i values and σ_V is the standard deviation of simulated V_i values. For the sample and simulated groups V_i is calculated as

$$V_i = \left\{ \frac{\sum_{i=1}^{N} n_i \left(t^i - t^R\right)}{\sum_{i=1}^{N} n_i} \right\} \tag{6}$$

Where N is the number of sites, n_i is the record length at site i, t^i is the sample L moment ratio at site i and t^R is the corresponding regional average sample L moment ratio.

In the study, three measures of H were computed: H_1 (based on L coefficient of variation (L Cv)), H_2 (based on L Cv and L coefficient of skewness (L Cs)) and H_3 (based L Cs and L kurtosis (L Kurt)). If $H_i < 2$, the group can be regarded as 'acceptable homogeneous', if $1 \le H_i < 2$ it is 'possible homogeneous', and if $H_i \ge 2$ it is 'definitely homogeneous' (Hosking and Wallis 1997).

Step 3 - Development of regional dimensionless flood frequency curves. Having identified the homogeneous groups and the most appropriate flood frequency distribution, the next task is to conduct at-site flood frequency analyses. For each of the defined group, average flood quantile, $(Q_T)_{ave}$ at T=2, 5, 10, 20, 50, 100 and T=2.33 were then computed. The regional dimensionless flood quantiles were estimated by dividing $(Q_T)_{ave}$ by the average index flood, $(Q_{2.33})_{ave}$. The regional growth curve for each of the homogeneous groups was obtained by plotting the dimensionless average quantiles $\left[\frac{(Q_T)_{ave}}{(Q_{2.33})_{ave}}\right]$ against T.

Step 4 - Development of regional prediction models for $Q_{2.33}$. A regression relationship between $Q_{2.33}$ and the catchment characteristics was developed by Ordinary Least Squares (OLS) regression using stepwise method for each of the defined groups. As the stepwise method maximizes the predictive ability by selecting only the variable that improves the adjusted R^2, the modelling was started with all selected catchment characteristics (Table 1). The performance of the developed models was assessed using the coefficient of determination (R^2): this coefficient was adjusted to accommodate degree of freedom (adjusted R^2) and Standard Error of Estimate (SES). The modelling was carried out by leaving one catchment aside at a time as a test catchment and the modelling was repeated N times, where N is the number of catchments in the group. The averages of the parameters were taken as the parameters of the regional model.

Step 5 - Model evaluation. Model evaluation was conducted by comparing the predictions against the at-site quantiles as well as the upper and the lower bounds at the 95% confidence intervals.

4. RESULT AND DISCUSSION

The results of the at-site flood frequency analysis showed that the GEV/L2 was the most appropriate method for the majority of selected catchments. It was also found that LPIII/MOM and GEV/L gave comparable results for the majority of catchments, while GEV/L2 described the data better than any the other methods. The results of the deviation D (Equation 1) indicated that D of the GEV/L2 was smaller than that of the LN, LPIII, and GEV/L models for 24 out of 36 cases. The average deviation for the GEV/L2 was 7.46% compared to 37.65% and 13.84% and 9.67% for LN, LPIII, and GEV/L respectively. This indicated that the use of GEV/L2 estimates would result in smaller SEE. This was further confirmed by the results of Monte Carlo simulation studies. Monte Carlo results for station 225213 are presented in Figure 3 to illustrate this.

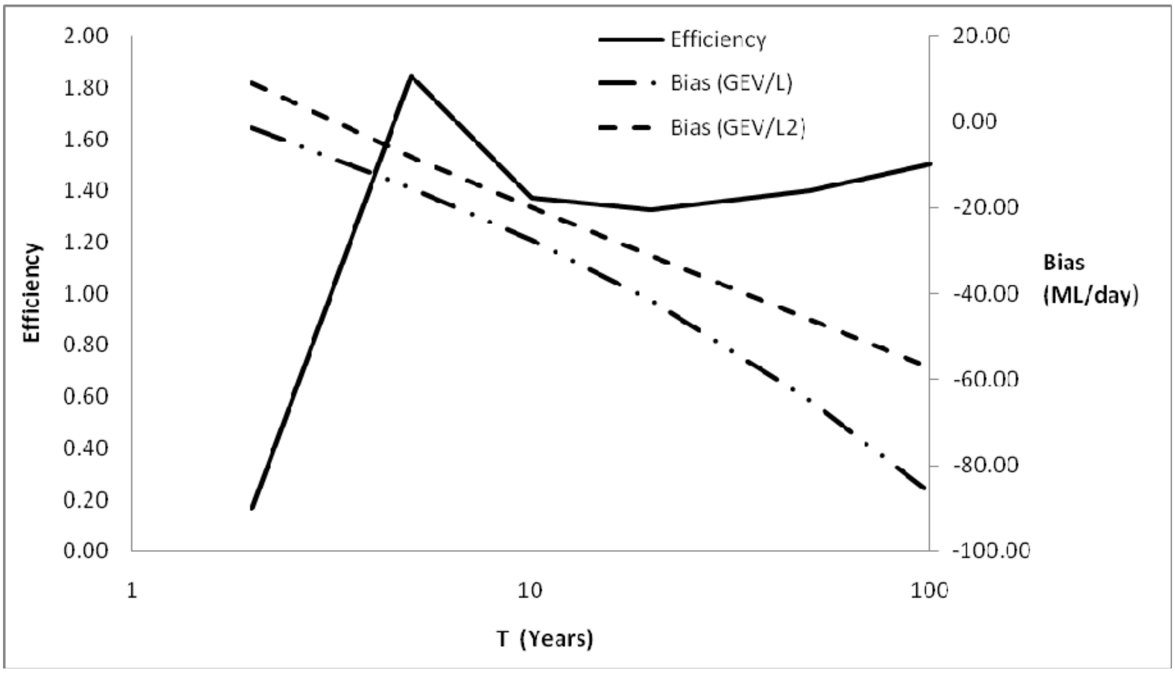

Figure 3. Results of the Monte Carlo Simulation – Sation 225213

It can be seen from Figure 3 that GEV/L2 estimates show smaller bias compared to GEV/L estimates at all selected T values. The efficiency of the GEV/L2 is greater than 1 for medium to higher T values, indicating that GEV/L2 outperforms the GEV/L at medium to high Ts. This is a common observation for majority of catchments. Suitability of GEV/L2 and GEV/L methods for regional flood frequency analyses gauged from the moment ratio diagrams presented in Figure 1. It is clear from Figure 1 that a greater proportion of the catchments in the L moment ratio diagram lie *below* the theoretical GEV curve while those in the L2 moment ratio diagram are evenly scattered above and *below* the GEV curve. Points in the L moments ratio diagram are also more scattered than those in the L2 moments ratio diagram. These observations indicate that the GEV/L2 method is capable of describing the regional data better than GEV/L. Hence, GEV/L2 is selected as the most appropriate method for flood frequency analyses in Victoria.

The catchment characteristics of AREA, ELEV, FOREST, LENGTH, SLOPE, SFREQ, SHAPE and RAIN were used in the cluster analysis. Of the 4 initially indentified groups, three were found to be non-homogeneous (H>2). These four groups were further refined by moving a site or two from one group to another as proposed in Hosking and Wallis (1997). As a result, 5 homogeneous groups were delineated. The H statistics of these five groups are presented in Table 2.

Table 2. The heterogeneity measure of the 5 groups

Group	Number of sites	H_1	H_2	H_3
1	17	1.36	1.03	1.17
2	14	1.32	0.73	1.59
3	18	1.56	1.57	1.35
4	14	1.34	1.59	1.44
5	9	0.87	0.82	-0.48

Figure 4 shows the regional growth curves derived for the five homogeneous groups. It is clear that group 3 has the steepest flood frequency curve indicating greater variability of floods in this area compared to the other groups. Group 5 has the flattest frequency curve indicating least variability. Having developed regional growth curves, the next step was to develop regional prediction models for $Q_{2.33}$ for the defined groups.

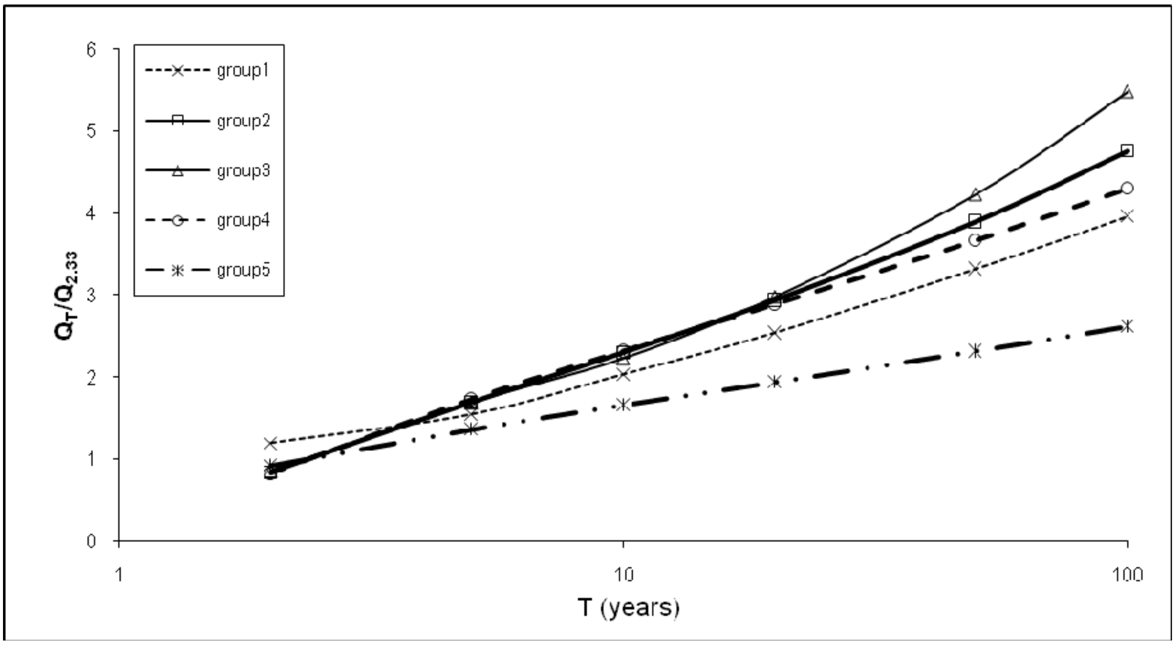

Figure 4. Dimensionless regional flood frequency curves ($Q_T/Q_{2.33}$) for the delineated groups

Table 3 shows the best fitted models for the five group and their performances. It is observed from Table 3 that for four out of the five models, only the AREA was significant. The model efficiencies are not so attractive for two out of the five groups and need further attention in terms of identifying significant catchment characteristics other than AREA and identifying the most suitable transformation to minimize the unexplained variance. Also it is hoped that if the Generalized Least Square (GLS) regression is performed, model efficiencies can be improved.

Table **3**: Model for the five groups

Group	Model	R^2	Adj. R^2	SEE as a % of $(Q_{2.33})_{Ave}$
1	$Q_{2.33} = 561.23 + 8.33(\text{AREA})$	0.80	0.79	30.56
2	$Q_{2.33} = 438.93 + 10.01(\text{AREA})$	0.18	0.11	75.39
3	$Q_{2.33} = -3042.96 + 73.21(\text{LENGTH}) + 1755.55(\text{SFREQ}) + 1.78(\text{RAIN})$	0.74	0.68	53.16
4	$Q_{2.33} = 1388.9 + 3.23(\text{AREA})$	0.19	0.12	72.71
5	$Q_{2.33} = -293.25 + 11.36(\text{AREA})$	0.90	0.88	29.15

The number of time model development was carried out corresponds to the number of catchments in the group by taking one catchment at a time as a test catchment. Hence, the parameters shown in Table 3 are averaged values. Figure 5 compares the predicted $Q_{2.33}$ against the 95% confidence intervals for group 1. Of the 17 test runs undertaken, 14 predictions are within the 95% confidence interval and only 3 are at the upper boundary indicating that model predictions are acceptable. However, there were cases in groups 2 and 4 which gave predicted values outside the confidence intervals: This is expected as the model performances of these two groups were not satisfactory. When predicting Q_T for a test catchment, the corresponding dimensionless value needs to be multiplied by the $Q_{2.33}$ of the group.

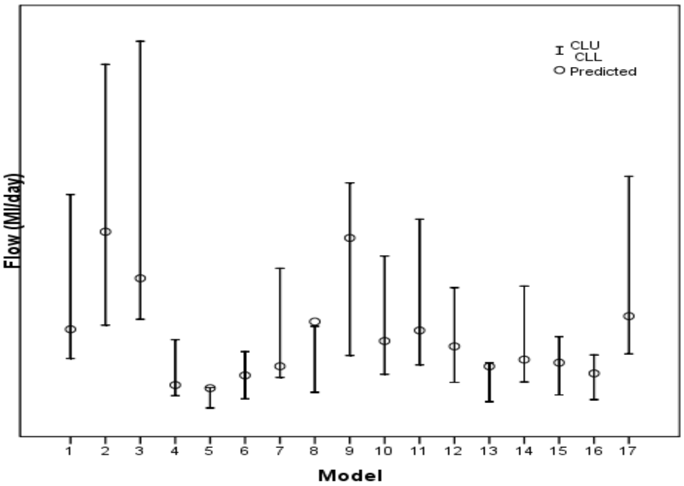

Figure 5. Comparing the predicted $Q_{2.33}$ against the 95% confidence intervals of the group 1

5. CONCLUSIONS

This study has shown the GEV/L2 model as the most appropriate methodology for flood frequency analyses in Victoria, Australia. Regional prediction models for $Q_{2.33}$ (index flood) were developed and regional growth curves for five homogenous groups were derived. The developed prediction models given in Table 2 and the regional growth curves presented in Figure 4 will be valuable tools for making quick predictions of flood quantiles for ungauged stations. It is believed that regional models for groups 2 and 4 can be improved by selecting more appropriate catchment attributes and identifying the most appropriate transformations as well as by using the GLS regression approach for the model development.

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