Rating Curve Uncertainty in Flood Frequency Analysis: A Quantitative Assessment

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Abstract: River discharge is one of the fundamental data in flood frequency analysis. Accuracy of these discharge data is crucial as uncertainty in these data is directly translated into flood quantile estimates which have significant impact in flood risk assessment and engineering design. Generally, these discharge data reported by the gauging authorities are not measured directly, rather estimated through a rating curve which represents a state-discharge relationship at a particular river section. Consequently, this causes uncertainties in the discharge data as the true rating curve is unknown and the established rating curves are generally most likely to be associated with some degrees of errors due to several factors. Despite the fact that rating curve uncertainty can introduce errors in discharge data, it is often disregarded in the flood frequency analysis. This paper examines the impacts of rating curve uncertainty on flood quantiles estimates for a set of New South Wales catchments in Australia, which have been assembled as a part of Australian Rainfall and Runoff Project 5 'Regional Flood Methods'. The results indicate that a higher assumed value of rating curve uncertainty in flood frequency analysis inflates the uncertainty bounds of the estimated flood quantiles (i.e. increases the width of the 90% confidence limits). This is more noticeable for smaller annual exceedance probability floods. Based on results from the 96 catchments examined here, it has been found that the difference in flood quantile estimates for different assumed rating curve uncertainty values do not depend on standard deviation and skew of log-space annual maximum flood series data. It is noted that the rating curve uncertainty issue needs to be recognised in flood frequency analysis as this represents a significant source of uncertainty in flood frequency analysis, which is often ignored in practice.

Keywords: *Rating curve, uncertainty, flood quantiles, flood frequency analysis, ARR, FLIKE.*

1. Introduction

River discharge is one of the fundamental data in flood frequency analysis. These data need to be of high quality to have reliable estimates of design floods. However, in most of the cases these data are not directly measured as continuous direct measurements of discharges are time consuming and expensive (Nihei and Kimizu, 2008). Moreover, in many cases it is infeasible to take the direct measurement of streamflow, in particular during high floods due to practical difficulties, such as high cost of velocity measurement, safety issues during high flow velocities and accessibility of the site during flood event. Generally, a relationship is developed between the discharges and water levels (stage) based on a series of concurrent stage and discharge measurements at a gauging station to estimate the discharges. This stage-discharge relationship is generally designated as rating curve, which provides a means to generate discharge time series (Petersen-Øverleir and Reitan, 2009; Haddad et al., 2010). Various issues on rating curves are presented in details in WMO (2008).

Since the reported discharges are not generally measured directly but estimated from a rating curve, some errors are likely to be associated with the reported discharge data, which consequently influence the results of flood frequency analysis and introduce uncertainty in the estimated flood quantiles. The errors in the discharges derived from a rating curve may be occurred due to several reasons: (i) errors in stage and discharge measurements at the gauging stations used to build the rating curves, (ii) the assumptions regarding a suitable form of stage-discharge relationship and the quality of the fit of the curve, (iii) extrapolation of the curves beyond the maximum gauging points and (iv) changes in the cross section of the river due to vegetation growth or bed movement (McMillan et al., 2010; Jalbert et al., 2011) due to erosion or deposition.

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All these factors introduce uncertainty into discharge estimation through a rating curve. Several studies have investigated the uncertainties present in the river discharge due to rating curve errors, such as Di Baldassarre and Montanari (2009), Di Baldassarre and Claps (2011), Domeneghetti et al. (2012); they concluded that errors in river discharge data due to rating curve errors were significant and could notably influence the results of hydrological and hydraulic studies. An extensive literature review of the methods for estimating uncertainty in the rating curves can be found in Le Coz (2012).

Despite the fact that river discharge data are affected by a significant uncertainty, it is often neglected in the calibration of hydrological models and assumed that these data to be accurate (Morlot et al., 2014; Haque et al., 2014). The calibration results of the models could be notably improved if uncertainty in the river discharge data were considered. Moreover, these uncertainties in river discharge data derived from the rating curves can induce significant uncertainty in flood risk assessment and flood forecasting which have direct impact on the safety of life and property. Since different degrees of extrapolation of the rating curve are required in practice as the range of observed flood levels generally exceed the range of historical "measured" flows. This implies that all the discharges estimated by rating curve are subject to uncertainty particularly during flood events (Kuczera, 1996; Pappenberger et al., 2006; Di Baldassarre and Montanari, 2009). Moreover, as extreme flood discharges are found at the very end of the rating curve, they are likely to be highly affected by this extrapolation uncertainty. The use of these estimated discharges from the extrapolated rating curve in flood frequency analysis may result in inaccurate flood estimates especially for smaller annual exceedance probabilities (AEPs).

Several studies have investigated the uncertainty in the design flood estimates caused by error in the river discharge data derived from a rating curve. For example, Kuczera (1996) showed that uncertainties associated with the extrapolation of the rating curve can vary substantially and can introduce notable uncertainty in design flood estimates. Petersen-Øverleir and Reitan (2009) found that the rating curve imprecision can widen the estimation variability of the flood quantile estimates. Haddad et al. (2010) showed that the rating curve uncertainties have a significant impact on smaller AEP flood quantiles and without taking into account the rating curve uncertainties, the estimated confidence limits are underestimated. Lang et al. (2010) showed that ignoring the rating curve uncertainty can produce biased estimation of flood quantiles. Di Baldassarre et al. (2012) found that the rating curve uncertainty has a significant impact on the uncertainty of design flood estimates. Ozbey et al. (2008) discussed the uncertainty in the flow data reported for 80 sites in Gippsland in relation to Australian Standard 3778.2.3 (Australian Standards International, 2001). Results from this study indicated that the uncertainty in the annual mean flow at most monitoring sites in Gippsland ranges from +/- 5% to +/- 15% in 2005-2006. However, they did not assess the uncertainty of annual maximum (AM) floods in flood frequency analysis, which is expected to be higher.

This paper focuses on the impacts of rating curve uncertainty in flood frequency analysis using a large number of catchments. To our knowledge, no previous study has examined the impacts of rating curve error using a large dataset like this study. The findings of this study will be useful to hydrology practice in Australia and other countries of the world.

2. Study area and data

This study uses data from New South Wales (NSW) State in Australia to assess the impacts of rating curve uncertainty on design flood estimates. A total of 96 catchments, with the best available data were selected to examine the range of possible rating curve extrapolation in practice. These 96 catchments are a subset of the Australian Rainfall and Runoff (ARR) Project 5 Regional flood methods' database. These catchments are unregulated, and are not affected by major urbanisation or any large storage/dam. From these 96 catchments, 12 were selected for in-depth investigation (Table 1). As can be seen from Table 1, these twelve catchments range from 66 km^2 to 900 km^2 and the annual maximum flood record length ranges from 32 years to 60 years. The skew of $\log_e(Q)$, where Q is annual maximum flood series, is presented in the last column, which shows that 8 of these catchments have negative skew, including one having a value very close to zero, and 4 have positive skew values. These different skew values are useful to assess whether the impact of rating curve uncertainty on flood quantile estimates is affected by skew of the flood series for the catchment.

3. Rating curve and rating ratio

A rating curve is generally constructed based on the assumption that a one to one correlation exists between the river discharge and stage, which is generally referred to as the "true rating curve". However, the true rating curve is unknown and the standard method of constructing a rating curve consists of taking field measurements of water stage, h, and river discharge, Q. These measurements help to identify discrete points (Q, h) that are subsequently interpolated through an analytical relationship that generates the rating curve (Figure 1). Then the rating curve extension is needed to get the discharge value for the larger floods, which can introduce systematic uncertainty, either over or under estimation of true river discharge (Figure 1). The rating curve uncertainty is generally unknown but can be expected to increase as the water level rises above the highest measured flow. Potter and Walker (1981) suggested it could be as high as 30% in the extrapolation zone. In the interpolation zone, the uncertainty would be smaller (e.g. 1-5%) where the fitted rating curve is well supported by discharge-stage measurements (Kuczera, 1996; Reis and Stedinger, 2005).

Table 1 Selected 12 catchments from the state of New South Wales in Australia

Station ID	Maximum rating ratio	Average Rating ratio	Catchment area (km^2)	Record length (years)	Period of record	mean	SD	skew
203030	1.25	0.60	332	32	1980-2011	4.736	0.280	-0.607
204037	4.01	0.89	62	40	1972-2011	3.087	1.594	-0.854
204906	2.63	1.06	446	39	1973-2011	5.569	0.924	-0.995
207006	20.73	5.85	363	36	1976-2011	6.493	0.536	-0.159
209001	30.11	11.35	203	34	1946-1979	5.513	0.445	0.083
212008	2.33	0.29	199	60	1952-2011	4.290	0.907	0.262
218005	1.91	0.52	900	47	1965-2011	6.791	0.664	-0.553
219025	2	0.49	717	35	1977-2011	5.155	1.615	-0.263
222016	5.10	2.36	155	35	1976-2010	2.411	0.459	-0.004
410038	5.11	1.47	411	43	1969-2011	4.108	0.441	0.993
416008	8.89	2.84	866	40	1972-2011	5.776	0.387	0.515
419051	47.29	6.18	454	35	1977-2011	3.702	1.570	-0.429

In this study, a "rating ratio" (RR) (Haddad et al., 2010) was used to identify the stations which would have annual maximum flood data associated with a high degree of rating curve extrapolation uncertainty. The RR is estimated by dividing the annual maximum flood series data point for each year (estimated flow Q_E) by the maximum measured flow (Q_M) at that station. The RR can be expressed as:

$$RR = \frac{Q_E}{Q_M} \tag{1}$$

Since the rating curve for a gauging station is usually updated with the availability of new measured flow data, a station may have several rating curves each with a unique Q_M value applicable for a set period of time. Therefore, the appropriate Q_M value applicable for the respective rating curve for a given year was used to estimate the RR value in this study. If the RR value is smaller than 1, the corresponding annual maximum data points may be considered to be free from rating curve extrapolation uncertainty. The annual maximum flood data points are considered to be associated with a higher degree of rating curve uncertainty when the RR values are well above 1. These data points can cause significant uncertainty in flood frequency analysis.

As an example, potential rating curve uncertainty of the annual maximum flood data points for station 201001 in NSW is presented in Figure 2. It can be seen that, 34 out of 54 data points (63% of total data points) have RR values greater than 1 and the maximum RR value is 6.47. The largest measured flow has an approximate AEP of 50%. These data points with RR >> 1 are associated with a higher degree of rating curve uncertainty, which will translate into flood frequency estimates with a higher degree of uncertainty, especially for smaller AEP floods such as 2% and 1% AEPs.

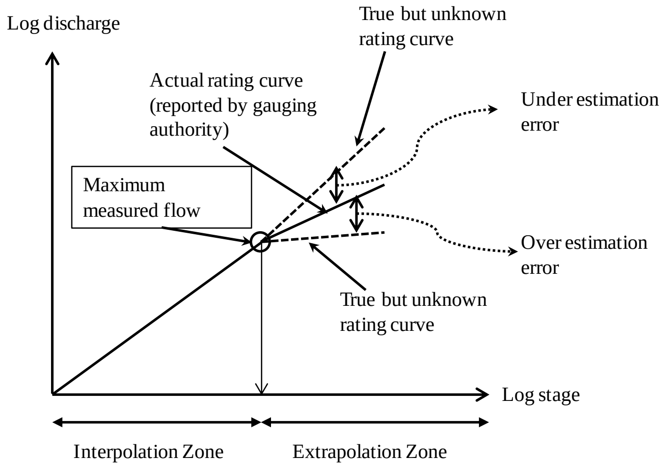

Figure 1 Illustration of rating curve extrapolation uncertainty (Haddad et al., 2010)

As seen in the histogram of rating ratios of annual maximum flood data points for 96 catchments in NSW (Figure 3), 60.5% of the RR values are less than 1 and 39.5% values between 1 and 47.29 (Figure 3). A RR value well above 1 could amplify the uncertainty in flood frequency analysis. However, eliminating all stations with RR value greater than 1 would affect the results in the RFFA as it would reduce the number of stations below the minimum required for a meaningful RFFA.

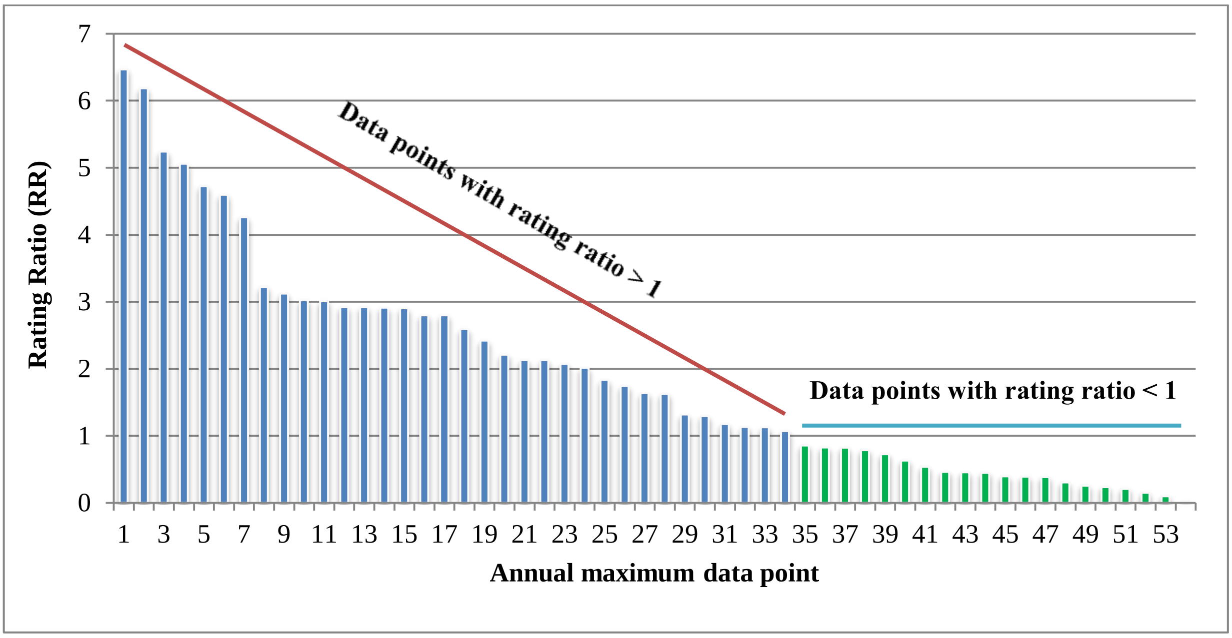

Figure 2 Plot of rating ratios (RR) for station 201001 in the state of New South Wales, Australia

4. Results

In this study, log-log extrapolation of rating curve was explored as this is the most commonly adopted technique to extend the rating curve, among many other techniques. In log-log extrapolation, the uncertainty from the true rating curve increases systematically as the river discharge value increases beyond the range of discharge measurements (Figure 1). Therefore, an extrapolation zone is created as the rating curve is extended. The extrapolation zone is characterized based on the distance from the anchor point and not from the origin. Thus the systematic uncertainty is proportional to the distance from the anchor point (in log space). In this study, the flow that has the RR value just greater than one was used as the "anchor point". The flows with RR value greater than one are expected to be associated with rating curve extrapolation uncertainty. The higher the RR value for a discharge data point, the greater the rating curve uncertainty associated with the data point.

In this study, the FLIKE software, which implements the principles outlined in Kuczera (1999), was adopted to fit the LP3 distribution using the Bayesian parameter fitting procedure to assess the impact of rating curve uncertainty on flood quantile estimates. No prior information was used in the FLIKE with both the "no rating curve" and the "rating curve uncertainty" cases. The results of 12 selected stations are shown in Table 2. In the "no rating curve" uncertainty cases, the uncertainty coefficient of variation (CV) value was considered to be 0% for simplicity. In the "rating curve uncertainty" cases, three scenarios were considered where flows in the extrapolation zone were corrupted by a multiplicative uncertainty assumed to be log-normally distributed with mean one and CV values equal to 10%, 20% and 30%.

The results show that with the increasing CV values, the uncertainty in quantile estimates increases, in some cases reaching over 50% for 2% AEP, which indicates that the rating curve uncertainty has a notable impact on flood quantile estimates. The flood estimates for lower AEPs are found to be more affected by the rating curve uncertainties. Interestingly, there is no notable relationship between the RR values of the stations (see Table 1) and percentage differences in quantile estimates for different CVs, which is somewhat unexpected, and needs further investigation.

Table 2 Impact of rating curve uncertainty on flood quantile estimates based on ARR-FLIKE for the 12 selected catchments in the state of New South Wales, Australia

	2% AEP flood quantile (m^3/s)						
Station	No rating uncertainty (CV = 0%)	Rating uncertainty (CV = 10%)		Rating uncertainty (CV = 20%)		Rating uncertainty (CV = 30%)	
	Expected	Expected	% change from CV = 0%	Expected	% change from CV = 0%	Expected	% change from CV = 0%
203030	171	179	5	190	11	205	20
204037	250	268	7	296	19	330	32
204906	978	1076	10	1209	24	1352	38
207006	1953	2392	22	2538	30	2600	33
209001	645	687	6	753	17	845	31
212008	501	515	3	534	7	560	12
218005	2640	2891	10	3375	28	4036	53
219025	2340	2499	7	2770	18	3094	32
222016	29	31	5	34	15	39	33
410038	176	192	9	227	29	277	57
416008	790	831	5	890	13	967	22
419051	773	806	4	903	17	1014	31

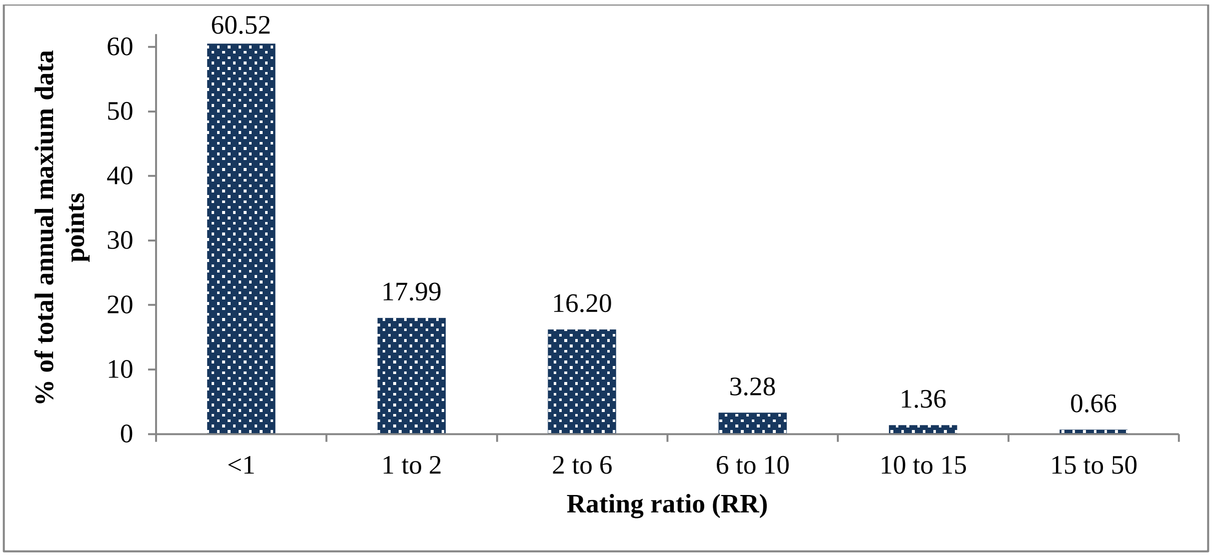

Figure 3 Histogram of rating ratio (RR) of annual maximum flood data points from 96 catchments in the state of New South Wales, Australia

The estimated flood quantiles (expected, 5% and 95% confidence limits) values for different AEP's flood for the site 203030 in NSW are presented in Figures 4(a) and 4(b) considering no rating curve uncertainty (CV = 0%) and CV =20%, respectively. From the figures it can be seen that for the same AEP flood the expected quantiles values are higher in CV =20% than in CV = 0% indicating the presence of uncertainty in the estimated results. This scenario is more significant for the larger flood quantiles (i.e. smaller AEP floods). It can be also seen from the figures that 90% confidence band is wider when CV = 20% is considered as rating curve uncertainty than CV = 0%. This result indicates that uncertainty bound increases in flood frequency analysis when larger errors are associated with a rating curve.

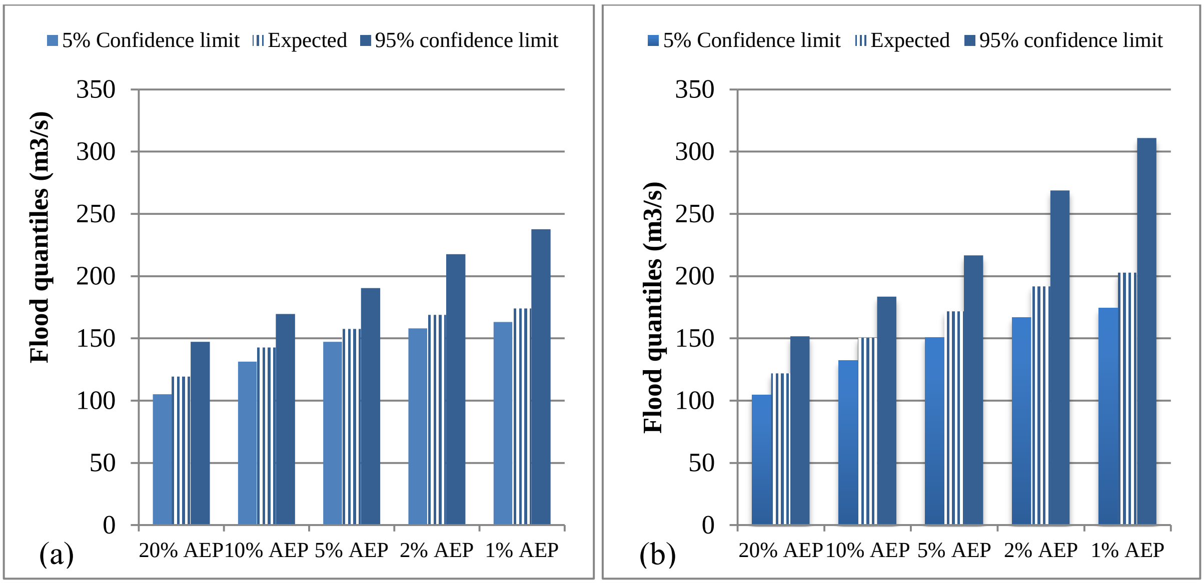

Figure 4(a-b) Estimated flood quantile values for different AEP floods for the site 203030 in the state of New South Wales, Australia; (a) considering no rating curve uncertainty (CV = 0%), (b) considering rating curve uncertainty with CV = 20%

Figure 5 plots the differences in flood quantile estimates (between CV of 0% and CV of 20%) with catchment size; this shows no linkage between the degree of differences in flood quantile estimates for different CVs and catchment area. Figures 6 and 7 show no relationship between differences in flood quantiles due to different CVs and skew and SD, respectively. Figure 8 shows that difference in flood quantiles between no rating curve uncertainty (CV = 0%) and CV = 20% can vary up to 50% for 2% AEP flood. The median difference for different AEPs (between CV of 0% and CV of 20%) based on 96 catchments in NSW are found to be 1%, 2%, 3%, 6%, 9% and 12% for AEPs of 50%, 20%, 10%, 5%, 2% and 1%. These results show that differences in quantile values between CV = 20% and CV = 0% are higher for smaller AEP floods indicating that large floods are likely to be more affected by the rating curve uncertainty.

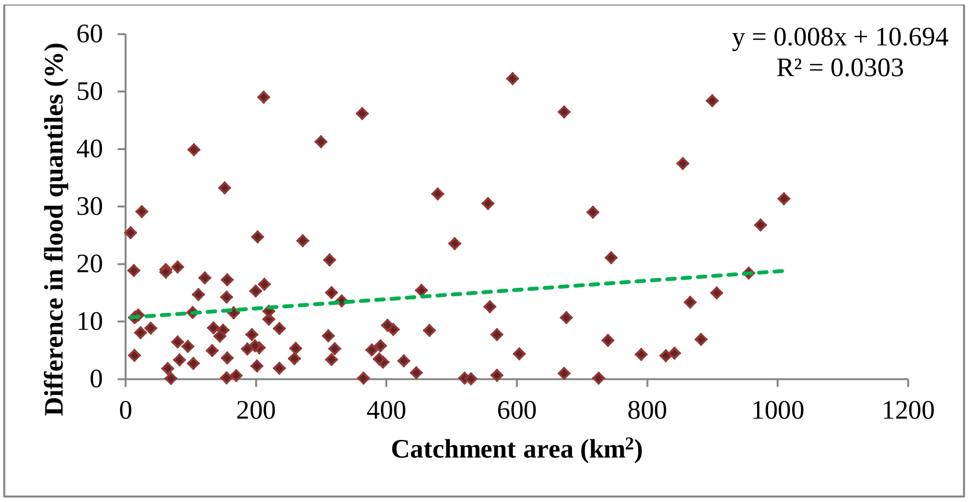

Figure 5 Plot of the catchment size vs. differences in flood quantile estimates between CV of 0% and CV of 20% for 2% AEP flood in the 96 New South Wales catchments (the green dash line represent the probable trend line)

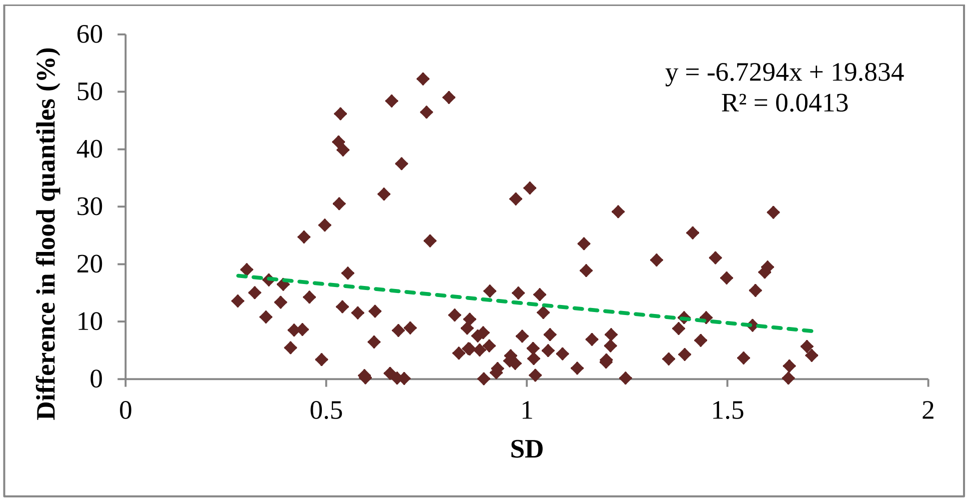

Figure 6 Plot of the SD of annual maximum floods vs. differences in flood quantile estimates between CV of 0% and CV of 20% for 2% AEP flood in the 96 New South Wales catchments (the green dash line represent the probable trend line)

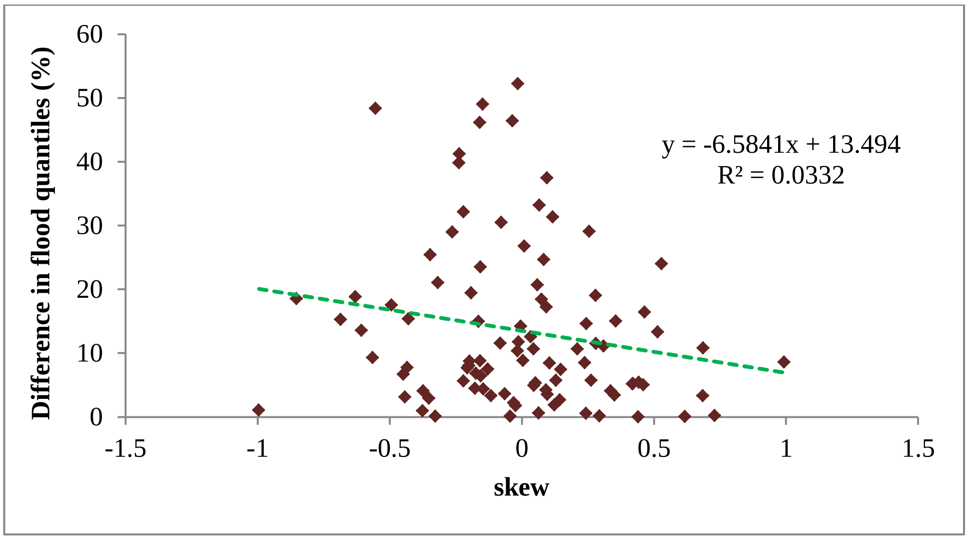

Figure 7 Plot of the skew of annual maximum floods vs. differences in flood quantile estimates between CV of 0% and CV of 20% for 2% AEP flood in the 96 New South Wales catchments (the green dash line represent the probable trend line)

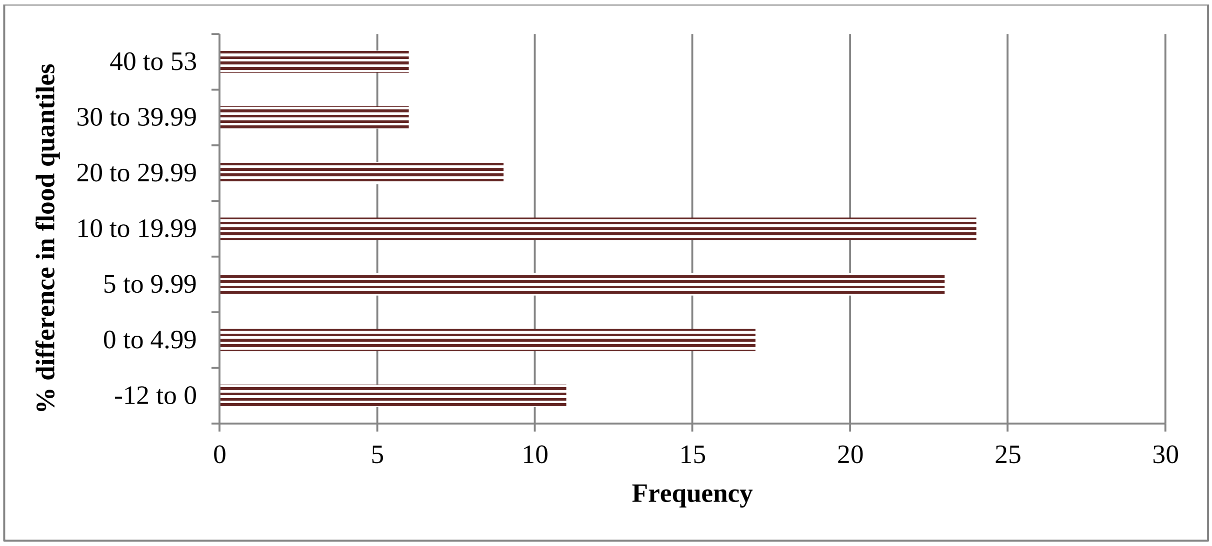

Figure 8 Plot of difference in flood quantiles between CV of 0% and CV of 20% for 2% AEP flood quantiles (96 catchments from NSW)

5. Conclusion

Flood frequency analysis is based on flood data which often consists of river discharge data from the extrapolated zone of the rating curve. These larger flood data are normally subject to considerable uncertainty due to the possible deviation of the constructed rating curve from the true rating curve, which is largely unknown. This study examined the effects of rating curve uncertainty (represented by coefficient of variation (CV)) on flood quantile estimates using data from the state of New South Wales (NSW), Australia. The results show that the rating curve uncertainty can result in notably increased uncertainty in flood quantile estimates. The results indicate that a higher assumed value of rating curve uncertainty (i.e. a higher CV in flood frequency analysis) increases estimated flood quantiles and inflates the uncertainty bounds around the estimated flood quantiles (i.e. increases the width of the 90% confidence limits). This is more noticeable for smaller AEP floods. Based on results from the 96 NSW catchments, no relationship has been found between the difference in flood quantile estimates for different assumed CV values and catchment area, log-space standard deviation (SD), skew of annual maximum flood series data. It is noted that the rating curve uncertainty issue needs to be recognised in flood frequency analysis as this represents a significant source of uncertainty in flood frequency analysis, which is often ignored in hydrologic practice.

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