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EXAMINATION OF POOLED FLOOD FREQUENCY ANALYSIS FOR CANADIAN CATCHMENTS

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Abstract: Floods are known as one of the most damaging forms of natural hazards with devastating influence on people and the environment. Accurately estimating flood frequencies is essential for effective design of flood mitigation systems, reservoir management, and pollution control. Estimation of these frequencies is difficult since extreme events are by definition rare and the length of recorded data is often short. In such situations, extreme flow information from a number of similar sites is combined (pooled) to augment the available at-site information. Pooled flood frequency analysis is a well-known approach used to improve the estimation of extreme flow quantiles at sites with short data records. Identification of pooling groups that will effectively transfer extreme flow information is thus important. This paper aims to explore approaches for obtaining improved flood quantile estimates based on pooled frequency analysis for extreme flow events. This study focuses on the region of influence (ROI) approach among different regionalization techniques to identify homogeneous pooling groups. The ROI is a site focused pooling approach that identifies a potential set of stations for each catchment that constitutes the region for that catchment. Instead of using either catchment characteristics or flood statistics, this study will explore several statistics representing the timing and variability of peak flow events. These flood seasonality measures will be employed in the definition of similarity/dissimilarity between sites. The dissimilarities are defined as a single numeric that represents the separation of two catchments in seasonality space. Different distance metrics can be considered to describe the closeness of each catchment to every other catchment. The discussed pooling techniques were employed for a collection of catchments in the Canadian prairies. The effectiveness of these techniques in identifying extreme flow quantiles was explored for the catchments under study.

1 Introduction

While floods are inevitable natural events, their impact on people and the environment can be reduced by putting mitigation measures in place. Effective mitigation measures require a solid understanding of the frequency of floods. It is crucial to accurately estimate the relationship between extreme flow quantiles and associated recurrence interval to design appropriate infrastructure and plan river engineering works. For these purposes, a sufficiently long streamflow record is required at the site of interest; however, at many hydrometric gauges, the observation period is shorter than is desired. To compensate for the short data record, the trade-off between the spatial and temporal characterization of extreme flows can be effected through the use of regional (pooled) flood frequency analysis (Zrinji and Burn, 1994). In such situations, extreme event information from a collection of sites is combined for the estimation of extreme event quantiles for a site of interest.

Pooled frequency analysis is carried out in a series of steps as follow: data screening; formation of pooling groups; assessment of pooled group homogeneity; revisions to regions; choice of frequency distribution; estimation of pooled growth curve and pooled quantiles.

An important requirement for regional (pooled) flood frequency analysis is the identification of the region or pool of catchments, not necessarily geographically contiguous, that can be considered similar in terms of catchment hydrologic response (Burn, 1997). The defined regions therefore, should be representing a homogenous region with respect to extreme flow characteristics. Research has explored various ways of delineating homogenous regions. Burn (1990) developed the region-of-influence (ROI) approach which is a site focused pooling approach and that avoids the use of fixed regions. This approach allows each catchment to have a potentially unique set of stations that constitute the region for the target site. This approach, and its modifications, has been extensively applied as a regionalization approach in flood frequency analysis (e.g., Tasker et al., 1996; Castellarin et al. 2001; Shu and Ouarda, 2008; Micevski et al. 2015).

Selection of variables to define pairwise similarity (or dissimilarity) among catchments is a necessary step in the ROI approach (Burn et al., 1997). Physiographic characteristics of catchments (such as drainage area, slope, etc.) and flood statistics (such as statistical measures estimated from flow series) are known as two general types of variables (Burn and Goel, 2000). Burn (1997) discussed the difficulties that can occur using these two types of variables and suggested using seasonality statistics of the catchment flood as a similarity measure between sites. In addition, the ROI approach requires the choice of a threshold value that functions as a cut-off point for a dissimilarity measure. Sites with dissimilarity measure greater than the threshold value are excluded from the region of influence for that particular site.

This study is focused on pooled flood frequency analysis of a selection of catchments in Alberta, Canada, and employs the ROI approach for delineation of homogeneous regions. The next section of this paper describes different seasonality measures that have been used as similarity measures between catchments. This is followed by a description of the regionalization strategy in this study. The results of application of these approaches are summarized and discussed next.

2 Seasonality analysis

The timing and regularity of flood events have been introduced as a measure of similarity in the catchment hydrologic response (Bayliss and Jones, 1993; Burn 1997; Cunderlik et al., 2004). Catchments with similarities in the timing and regularity of flood response might be expected to also have similarities in important physiographic and hydrologic response characteristics. Thus, such catchments can be considered as potential members of the same pooling group for pooled flood frequency analysis (Ouarda et al. 2006). Seasonality measures describe the timing and regularity of flood events and can be defined using directional statistics (Mardia, 1972). Circular statistics are the simplest case of directional data.

As per Burn (1997), the date of occurrence of the peak flow for a flood event is defined as a directional statistics by converting the Julian date, where January 1 is the day 1 and December 31 is day 365 (366), of the flood occurrence of the event i to an angular value using:

[1] $\theta_i = (\text{Julian Date})_i \frac{2\pi}{\text{lenyr}}$

where θ_i is the angular value (radians) for the date for event i and lenyr is the number of days in a year. From a sample of n events, the x- and y-coordinates of the mean date can be determined as:

[2] $\bar{x} = \frac{1}{n}\sum_{i=1}^{n}\cos(\theta_i);\ \bar{y} = \frac{1}{n}\sum_{i=1}^{n}\sin(\theta_i)$

where $\bar{x}$ and $\bar{y}$ represent the x- and y-coordinates of the mean event date. The mean event date is then can be defined from:

[3] $\mathrm{MD} = \tan^{-1}\left(\frac{\bar{y}}{\bar{x}}\right)\left(\frac{\text{lenyr}}{2\pi}\right)$

where MD represents the average date of occurrence of the flood event. A measure of the regularity of the n extreme event occurrence, can be determined through:

[4] $\bar{r} = \sqrt{\bar{x}^2 + \bar{y}^2}$

where $\bar{r}$ characterizes the dimensionless spread of the data in a given catchment and range from 0 (low regularity) to 1 (high regularity).

Chen et al. (2013) discussed the importance of information of the flood magnitude in the identification of flood seasonality. They suggest using flood magnitudes (q_i) as weights to take into account their effect in defining timing and regularity of flood events as follows:

[5] $\bar{x}' = \frac{\sum_{i=1}^{n} q_i \cos(\theta_i)}{\sum_{i=1}^{n} q_i}$; $\bar{y}' = \frac{\sum_{i=1}^{n} q_i \sin(\theta_i)}{\sum_{i=1}^{n} q_i}$

Values of MD and $\bar{r}$ can then be estimated using the new defined weighted seasonality measures, $\bar{x}'$and $\bar{y}'$.

3 Similarity measure

The seasonality statistics discussed above can now be employed in the definition of the dissimilarity between catchments. The starting point for regionalization is the selection of a distance metric defining the closeness of each station to every other station (Burn, 1990). This yields a single numerical value that will be used to define the separation of two catchments in seasonality space. Different distance metrics have been introduced in the literature. In this study the Euclidean distance between catchments in the seasonality space was used to define separation between two catchments as follow:

[6] $D_{ij} = \left[\sum_{m=1}^{M} \left(x_m^i - x_m^j\right)\right]^{1/2}$

where D_{ij} is the distance between station i and j and x_m^i is the value of attribute m for station i. Combination of attributes that were used in this study are $\bar{x}$ and $\bar{y}$; MD and $\bar{r}$; and also the weighted modifications of these seasonality measures. The seasonality measures discussed in the previous section were used to define the pairwise closeness of all catchments under study.

4 Pooling scheme

In this analysis, the region of influence (ROI) approach is employed as the basis for the regionalization of catchments. This approach allows each catchment to have a potentially unique set of stations that constitute the region for that catchment (Zrinji and Burn, 1994). The effective identification of a pooling group is governed by two fundamental principles, the homogeneity of the group and its target size (Casterllarin et al., 2001). The collection of catchments should be hydrologically homogeneous so that the extreme flow information can be effectively transferred from sites within the region to the site of interest (Burn, 1997). Hosking and Wallis (1997) demonstrated the homogeneity of a group generally decreases as the group size increases.

The approach taken herein is to use the first 25 stations with minimum pairwise dissimilarities with the target site, defined in the previous section, as a cut-off point for including the station in ROI for the target site. For each site under study four different initial ROIs were constructed using the four types of seasonality measure discussed previously. The resulting collection of catchments is next evaluated using a homogeneity test.

4.1 Assessment of regional homogeneity

The pooling groups resulting from application of the described regionalization approach are subsequently evaluated for hydrologic homogeneity. The aim of regional analysis is to form groups of sites that approximately satisfy the homogeneity condition (Hosking and Wallis, 1997). The homogeneity test proposed by Hosking and Wallis (1993) was used in this analysis to evaluate the homogeneity of each constructed pooling group. For definition and further details refer to Hosking and Wallis (1997).

In this homogeneity test, a statistic (H) based on the weighted variance of the L-coefficient of variation ($\mathrm{L-CV}$) is derived. A region can be considered homogeneous if $\mathrm{H} < 1$, possibly heterogeneous if $1 \leq \mathrm{H} < 2$, and definitely heterogeneous if $\mathrm{H} \geq 2$. Hosking and Wallis (1997) stated that the H-value criteria are useful guidelines and approximate homogeneity is sufficient to ensure that regional frequency analysis is much more accurate than at-site analysis. The goal in this study is to successfully delineate homogeneous ROIs for the catchments under study using different seasonality measures.

4.2 Revisions of regions

The discussed regionalization technique is useful for initial pooling group formation, but it may be determined that these groups are heterogeneous and require revisions. Where the ROI cannot be considered as a homogeneous group, screening of the pooling group and revisions to the group are required.

For the purpose of screening, Hosking and Wallis (1997) proposed a discordancy measure for identifying unusual sites in a region. Discordancy is a measure of how dissimilar a site is from the group as a whole in terms of the sites' L-moments. Critical values for the discordancy statistic and deciding whether a site is discordant are dependent on the number of sites in a region, and can be found in Hosking and Wallis (1997).

In the case of a heterogeneous pooling group, the discordancy measure is used to identify catchments with unusual flood series in comparison with the rest of the pooling group. Catchments with large discordancy values could sequentially leave the pooling group to enhance the homogeneity of the group of sites. Next, the homogeneity of the revised ROI should be re-evaluated. The region revision process continues until the pooling group can be considered homogeneous.

5 Selecting the regional frequency distribution

After identifying a region, the next stage in the specification of a statistical model is the choice of an appropriate regional frequency distribution. There are many families of distribution that might be candidates for fitting to a regional data set. Their suitability as candidates can be evaluated by applying a goodness-of-fit test. In this analysis, the statistical test described by Hosking and Wallis (1997) was used to select the frequency distribution with best fit to the regional data. The selected distribution can be used to estimate the flood quantiles for different return periods for a target site. For further details please refer to Hosking and Wallis (1997).

6 Description of data set and study area

The seasonality measures discussed previously to define region of influence for pooled flood frequency analysis were employed on a collection of hydrometric gauges in Alberta, Canada. Stations with continuous record series, unregulated flow and minimum of 20 years of flow record were initially selected. The annual series of maximum daily flows were extracted for each site.

For the selected sites in the region, trends in the maximum flow magnitude were evaluated using the Mann-Kendall (Kendall, 1975; Mann, 1945) non-parametric test for trend. In this work, the block bootstrap (BBS) (Önöz and Bayazit, 2012) approach was used in conjunction with the trend test. The BBS approach involves resampling data in blocks to estimate the significance of the test statistic from the data sample while reflecting the serial correlation present in the data set. Sites were evaluated for trends in the annual maximum series, and sites exhibiting significant increasing or decreasing trends were removed from the collection of catchments under study. Nonstationary frequency analysis should be considered for these sites.

A total of 60 hydrometric stations passed the data screening and were selected for further analysis. Figure 1 shows the location of these catchments. The catchments in this study experience similar climate conditions. The range of flow record length is from 20 to 92 years with a mean record length of 45years. The catchment drainage areas range from 3 to 132,588 km^2 with an average of 7034 km^2.

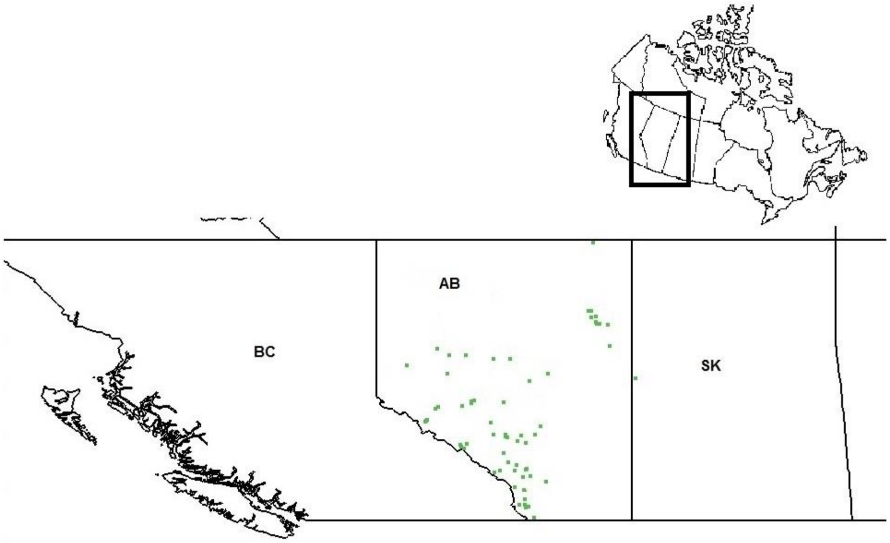

Figure 1: Location of selected gauging stations

7 Results and discussion

The region of influence approach was employed here to identify a potential set of stations for each catchment that constitutes the region for that catchment. Seasonality variables defined in Section 2 were used to define similarity (or dissimilarity) among catchments. The aim in this study is to employ and compare the performance of these different seasonality measures in successfully constructing ROIs for the hydrometric sites under study.

Figure 2 displays the results from calculating the seasonality statistics for the catchments under study. Each catchment is plotted as a point in the space defined by $\bar{x}$ and $\bar{y}$. Figure 2 reveals that the flooding regime for the collection of catchments exhibit a high degree of seasonality as there is a relatively small range in the values for the mean date of occurrence of floods. These stations experience similar climatic conditions and flood events of these catchments mostly arise from spring snowmelt. Due to these natural conditions, the seasonality measures should be an effective means for identifying similarity between catchments.

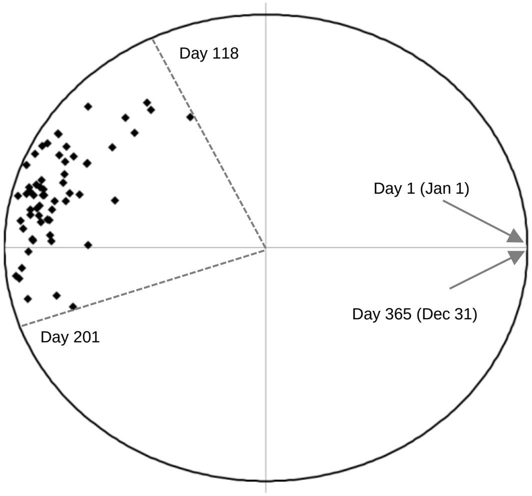

Figure 2: Seasonality space of the gauging stations

7.1 Results of pooling group formation

The seasonality statistics, $\bar{x}$ and $\bar{y}$; MD and $\bar{r}$; and also the weighted modifications of these seasonality measures were employed respectively in the definition of dissimilarity between each pair of catchments using Euclidean distance in the seasonality space. As discussed before, the first 25 stations identified with minimum dissimilarity in each defined seasonality space, were included in the initial ROI for a target site. The resulting collection of catchments was then evaluated for their homogeneity. Revisions were performed where required.

Table 1 summarizes results of the regionalization approach employed in this study for different seasonality measures. This table reveals the number of stations (from total 60 stations) for which the identified ROI was determined as homogeneous, possibly homogeneous, and definitely heterogeneous based on Hosking and Wallis (1997) definition.

Table 1: Summary of homogeneity test for ROIs

Seasonality Statistics	$\mathrm{H} < 1$	$1 \leq \mathrm{H} < 2$	$2 \leq \mathrm{H} < 3$	$H > 3$
$\bar{x}$ & $\bar{y}$	38	10	2	10
MD & $\bar{r}$	42	7	1	10
weighted $\bar{x}$ & weighted $\bar{y}$	42	8	1	9
weighted MD & weighted $\bar{r}$	44	6	1	9

Comparison of the results presented in Table 1 shows that both the weighted seasonality measures, $\bar{x}$ and $\bar{y}$, and also MD and $\bar{r}$ perform better than non-weighted seasonality measure as they were able to successfully construct greater number of homogeneous ROIs. Weighted MD and $\bar{r}$ display slightly better performance, resulting in identifying 44 homogenous ROIs, 6 possibly heterogeneous ROIs, and total of 10 heterogeneous ROIs. It has been noted by Hosking and Wallis (1997) that moderately heterogeneous regions may still offer valuable information concerning quantiles for return periods of rare events.

7.2 Quantile estimation

In the next step, for different combinations of seasonality measures, the identified ROIs and their respective best fitted distribution, were used to the estimate the quantiles of flow for different return periods for sites within the regions. Generalized normal, generalized extreme value, and generalized logistic distribution were regional distributions identified more frequently among others.

At-site flow quantiles were also determined for different return periods, however the at-site analysis should be limited according to the length of flow records at the site, to obtain reliable results. Flood Estimation Handbook (1999) suggested that at-site quantiles can be determined only for return periods where record length is larger than $2T$, where T is the return period of interest. If the record length is less, quantile estimates obtained from regional analysis are more reliable.

7.3 Uncertainty analysis

A measure of uncertainty associated with quantile estimation is essential in this analysis for both at-site and pooled quantiles. This can be estimated through the calculation of confidence intervals (CI) for estimated quantiles. Several approaches have been identified to quantify the uncertainty in either pooled or single site quantile estimates. One approach is the use of resampling or bootstrap to construct confidence intervals.

In this study, the balanced resampling technique introduced by Burn (2003) was used to estimate CIs for the associated at-site quantile estimates. Hosking and Wallis (1997) provided a parametric resampling approach to quantify uncertainty in the estimated pooled quantiles. This parametric approach can reflect the heterogeneity of the pooling and has been reported to provide more realistic estimate of confidence intervals. This approach was employed in this study. Interested reader is referred to Hosking and Wallis (1997) for further information.

The pooled approach to estimate flood quantiles based on using different seasonality measures, was compared with the results of applying single site estimates. The primary basis of comparison was the width of 95% confidence interval. A narrower confidence interval corresponds to more precise estimate and is preferred to an estimate with wider confidence interval (Burn, 2014). Therefore, the ratio of confidence interval width for two estimates were investigated for the case of different ROIs.

Table 2 provides the ratio of width of at-site CI estimated for 6 long record sites over the pooled quantiles. Long recorded sites were used to demonstrate the merits of the pooled approach versus at-site quantile estimates. The results from this table display the successful use of these seasonality measures in constructing effective ROIs for different return periods. The ratios of regional CI to at-site CI are less than 1 for most of the return periods and types of constructed ROIs. Averaging these ratios over different return periods reveals that ROIs constructed using weighted $\bar{x}$ and weighted $\bar{y}$ are most effective among others.

Table 2: Ratios of confidence interval width for the pooled and at-site quantiles

Site	Seasonality Statistics	Return Period								average
		2	5	10	20	30	50	100	500	
05BJ004	$\bar{x}$ & $\bar{y}$	1.06	0.95	0.72	0.57	0.49	0.44	0.39	0.31	0.62
	MD & $\bar{r}$	1.01	0.88	0.65	0.52	0.44	0.40	0.35	0.27	0.57
	weighted $\bar{x}$ & weighted $\bar{y}$	1.01	0.89	0.67	0.52	0.46	0.41	0.36	0.27	0.57
	weighted MD & weighted $\bar{r}$	1.04	0.89	0.67	0.53	0.46	0.41	0.35	0.26	0.58
05CC001	$\bar{x}$ & $\bar{y}$	0.88	0.78	0.78	0.72	0.66	0.62	0.55	0.42	0.68
	MD & $\bar{r}$	0.85	0.72	0.75	0.68	0.62	0.57	0.51	0.41	0.64
	weighted $\bar{x}$ & weighted $\bar{y}$	0.86	0.73	0.74	0.68	0.62	0.58	0.52	0.41	0.64
	weighted MD & weighted $\bar{r}$	0.90	0.88	0.85	0.76	0.68	0.61	0.51	0.36	0.69
05DB002	$\bar{x}$ & $\bar{y}$	0.96	0.90	0.97	0.95	0.93	0.88	0.84	0.78	0.90
	MD & $\bar{r}$	0.96	0.95	1.00	0.94	0.92	0.89	0.85	0.83	0.92
	weighted $\bar{x}$ & weighted $\bar{y}$	0.95	0.86	0.87	0.82	0.79	0.73	0.68	0.61	0.79
	weighted MD & weighted $\bar{r}$	0.86	0.82	0.87	0.92	0.95	0.96	0.94	0.92	0.91
05FA001	$\bar{x}$ & $\bar{y}$	0.79	0.87	0.83	0.74	0.68	0.60	0.54	0.45	0.69
	MD & $\bar{r}$	0.70	0.80	0.77	0.71	0.65	0.59	0.53	0.47	0.65
	weighted $\bar{x}$ & weighted $\bar{y}$	0.66	0.86	0.62	0.77	0.60	0.65	0.56	0.44	0.64
	weighted MD & weighted $\bar{r}$	0.70	0.87	0.79	0.71	0.64	0.55	0.47	0.38	0.64
07AG003	$\bar{x}$ & $\bar{y}$	1.07	0.89	0.69	0.55	0.49	0.43	0.37	0.29	0.60
	MD & $\bar{r}$	1.14	0.99	0.78	0.64	0.56	0.48	0.42	0.33	0.67
	weighted $\bar{x}$ & weighted $\bar{y}$	1.04	0.90	0.71	0.58	0.52	0.45	0.39	0.31	0.61
	weighted MD & weighted $\bar{r}$	1.08	0.95	0.78	0.62	0.56	0.49	0.43	0.35	0.66
07BF002	$\bar{x}$ & $\bar{y}$	0.89	0.91	0.90	0.82	0.75	0.70	0.64	0.62	0.78
	MD & $\bar{r}$	0.87	0.91	0.88	0.80	0.73	0.68	0.63	0.59	0.76
	weighted $\bar{x}$ & weighted $\bar{y}$	0.85	0.87	0.86	0.80	0.73	0.68	0.65	0.63	0.76
	weighted MD & weighted $\bar{r}$	0.85	0.89	0.88	0.82	0.77	0.74	0.70	0.66	0.79

8 Conclusion

This study explored approaches for obtaining improved flood quantile estimates based on pooled frequency analysis for extreme flow events. The region of influence (ROI) approach was employed as a regionalization techniques to identify homogeneous pooling groups. ROI approach requires selection of variables that are used to define the pairwise similarity (or dissimilarity) for the catchments. Geographic catchment characteristics and flood statistics are two common types of attributes used to define inter-site similarities. Following recent research, flood seasonality measures were employed in this analysis in the definition of similarity (or dissimilarity) between sites. Four combinations of seasonality based measures representing timing and regularity of peak flows were used in this study. The seasonality based regionalization was performed on a selection of catchments in the province of Alberta. The performance of these different seasonality based regionalization techniques were evaluated regarding the hydrologic homogeneity of their produced ROIs. It was revealed that ROIs constructed using weighted seasonality measures had greater number of homogeneous pooling groups among all the sites under study. In addition, the pooled approach to estimate flood quantiles based on using different seasonality measures was compared with the results of applying single site estimates. The ratio of width of 95% confidence interval for regional and at-site estimate of flood quantile was the basis of this comparison. The results of these analyses showed that all the seasonality based measures were successful in constructing effective pooling groups. On average for different return periods, the ROIs constructed using weighted coordinates of mean flood date were the most effective regionalization technique among others with the narrowest confidence intervals.

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