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COMPARISON OF SIX EXTREME FLOOD ESTIMATION TECHNIQUES FOR UNGAUGED WATERSHEDS IN COASTAL BRITISH COLUMBIA

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Application/Application
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Abstract
A comparison of six techniques for the estimation of peak flow from ungauged watersheds in coastal British Columbia is carried out. The techniques compared are a new physically-based stochastic-deterministic procedure (Loukas and Quick, 1994a), the British Columbia Ministry of Environment and Parks method, a statistical method based on the Bayes theorem and proposed by Russell (1982), and the well known regional techniques, the Index Flood method, the method of Direct Regression of Quantiles, and the method of Regression of the Distribution Parameters. The techniques are applied to a coastal British Columbia watershed, the Sarita River watershed which is located on the west coast of the Vancouver Island. Estimated the peak instantaneous and daily flows are compared with observed flows. The analysis shows that the stochastic-deterministic procedure, the B.C. Environment method, and the Bayesian method give acceptable results. In particular, the stochastic-deterministic procedure requires very limited information which can be easily obtained from topographical maps and a rainfall atlas. The other two methods require a more extensive knowledge of the hydrology and climate of the area.

Résumé
Six techniques pour l'estimation du pic de débit des lignes de partage des eaux sans système de mesure sur la côte de la Colombie Britannique ont été comparées. Les techniques consistent en une nouvelle procédure stochastique-déterministique basée sur la physique (Loucas and Quick, 1994a), la méthode du ministère des Parcs et de l'Environnement de la Colombie Britannique, une méthode statistique basée sur le théorème de Bayes et proposée par Russell (1982), et les techniques régionales bien connues, la méthode Indice de Crue, la méthode de Régression Directe des Quantiles, et la méthode de Régression des Paramètres de Distribution. Les techniques sont appliquées à la ligne de partage des eaux de la côte de la Colombie Britannique, la ligne de partage des eaux du fleuve Sarita lequel est située sur la côte ouest de l'Ile de Vancouver. Le pic de débits instantanés et quotidiens estimé a été comparé au pic observé. L'analyse a démontré que la procédure stochastique-déterministique, la méthode d'Environnement B.C., et la méthode Bayesienne donnent des résultats acceptables. En particulier, la procédure stochastique-déterministique requiert une information très limitée laquelle peut facilement être tirée des cartes topographiques et d'un atlas sur les précipitations. Les deux autres méthodes nécessitent une connaissance plus approfondie de l'hydrologie et du climat de la région.

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Introduction

Estimation of flood frequency for ungauged watersheds is a difficult problem and over the years various methods have been proposed and tested with varying degree of success. The methods used to estimate the flood frequency for ungauged watersheds can be classified as statistical, simulation, and derived distribution techniques. The statistical methods include the regional techniques and the combination of single site and regional data. The regionalization techniques are very popular and are applied to regions with similar or homogeneous climatic and hydrologic characteristics and they relate the floods to the physiographic and/or climatic characteristics of the watersheds. When there are very limited data for a given watershed, the watershed data can be combined with regional data to estimate the flood frequency with some accuracy. This can be done either analytically (Watt *et al.*, 1989) or numerically using the Bayes' theorem (Russell, 1982).

Another method for estimating flood frequency uses rainfall time series as input to a watershed model which simulates the rainfall-runoff process. The rainfall-runoff models should be calibrated with data from the gauged watersheds of the region and then used for the estimation of floods for the ungauged sites, and the simulation can be either continuous or event-based. The continuous simulation is used when long time-series of rainfall are available or can be statistically generated. The simulated peak flows are then analyzed and the flood frequency is estimated. In the event-based simulation, only certain large events are simulated. In this type of simulation, the return period of the flow is assumed to be the same as the return period of the rainfall producing the flow. This assumption is often criticized and occasionally studied (Reich, 1970; Larson and Reich, 1972; Dickinson *et al.*, 1992).

The derived distribution techniques are based on relatively simple rainfall-runoff models that are used to derive the cumulative distribution function of the floods. These techniques use a model for the rainfall estimation which is usually stochastic, an infiltration model, and a watershed response model. The derivation of the flood frequency can be done either analytically (Hebson and Wood, 1982; Diaz-Granados *et al.*, 1984) or numerically. The oversimplifications needed to derive the flood frequency through an analytical mathematical procedure results in poor performance of the method (Moughamian *et al.*, 1987; Cadavid *et al.*, 1991; Raines and Valdes, 1993). Numerical derivation of the flood frequency has been proven to give a better simulation of flood frequency (Consuegra *et al.*, 1993; Muzik, 1993).

This paper will concentrate on the statistical methods and the methods based on the derived distribution technique. Most of the statistical methods relate the peak flows to the physiographic and meteorological parameters of the watershed so that their application is limited to watersheds that have the same characteristics as the ones used for the development of the regional regression equations. Also, these methods do not account for the variability of the rainfall and runoff processes. On the other hand, the derived distribution techniques consider the variability of the rainfall and runoff processes and so they give a more physically-based estimation of the peak flow. Also, they can be applied to larger geographical areas with minor adjustments because of the implicit or explicit representation of the runoff processes. It is imperative, however, that the various methods are tested by comparing with observed data in order to validate the results.

The objective of this paper is to compare six techniques used for the estimation of flood frequency for ungauged watersheds. For this comparison, regional statistical equations are developed and a new technique which uses the numerical derivation of the flood probability distribution is presented. The study is concentrated on coastal British Columbia and the derivation of the frequency of rainfall-induced floods. The results of the various methods will be compared with observed data from a British Columbia watershed.

The methods used in this study will be briefly presented first, then they will be applied to a coastal British Columbia watershed, the Sarita River watershed, and finally, the results of the various methods will be compared and discussed.

Methods

The methods of flood frequency estimation that will be used in this study are presented in this section. These methods fall into the categories of regional techniques, statistical methods, and methods using the derived distributions. The methods used are the Index Flood method, method of Direct Regression of Quantiles, method of Regression for Distribution Parameters, the B.C. Environment method (regional methods), Russell's Bayesian method (statistical method), and a new flood frequency estimation procedure which is based on the method of derived distributions.

Index Flood Method

The Index Flood method involves the development of a regression equation expressing the "index" flood - usually the mean annual - in terms of independent physiographic and/or climatic variables. Then, the index flood is related to the floods of various return periods for the whole region. It implies that, within a region, all frequency curves can be approximated with the same shape curve, or in other words the regional flood frequency curve is an average over the region, and as a result, a dimensionless regional frequency curve is determined.

When the flood frequency of an ungauged watershed is to be found the index flood is estimated by the regional equation, knowing the characteristics of the area. It is then multiplied with the dimensionless regional frequency curve to give the flood frequency curve for the ungauged watershed.

The physiographic factors used as predictor variables for the index flood are usually the basin area, basin surface storage by lakes and swamps, main channel slope, main channel length, mean basin elevation, drainage density, basin shape factor, and soil and cover type. The climate of the area is of major consideration and it can be represented as a predictor in the regression equation by the mean annual precipitation and mean annual extreme rainfall.

The index flood method is very popular among hydrologists. In Canada, for example, there are twelve studies for the various regions of the country that use the index flood method (Watt *et al.*, 1989).

Method of Direct Regression of Quantiles (DRQ)

Within a hydrologically and climatologically homogeneous region, the floods of various return periods can be assumed to depend on physiographic and climatic characteristics of the individual watersheds. With the DRQ method, the index flood and flood quantiles are related to the characteristics of the watershed. This method is the second most popular regional technique in Canada (Watt *et al.*, 1989).

Method of Regression for Distribution Parameters (RDP)

The RDP method assumes that a standardized flood frequency distribution can be applied over a homogeneous region. It is hypothesized that the parameters of the flood frequency distribution for each individual watershed will change according to the physiographic characteristics. Usually a two parameter probability distribution is assumed to fit the floods of the region. The mean and the standard deviation of the floods for the gauged watersheds are related through regression to physiographic and climatic parameters. Using the predictor equations, it is possible to estimate the probability distribution parameters which are then used to estimate the flood frequency for an ungauged watershed.

B.C. Environment Method

The British Columbia Ministry of Environment and Parks proposed a method for the flood frequency estimation based on the Index Flood method (Reksten, 1987). The whole province was separated into homogeneous subregions, and the mean annual daily flood, Q_{md}, of the watershed in these subregions was plotted against the basin area. No attempt was made to relate the mean annual flood to other physiographic and climatic parameters because these data were not available at the time (Reksten, 1987).

The ratios of the floods for various return periods to the mean annual daily flood, C_t, were calculated for the gauged watersheds of the subregions. Knowing the area of an ungauged watershed, the mean annual daily flood, Q_{md}, can be estimated from graphs and can then be multiplied by the values of C_t to give an estimation of the daily flood for various recurrence intervals.

The B.C. Environment method also estimates the instantaneous flood. In each subregion of British Columbia, the mean ratio of instantaneous to daily flood, I/D, is estimated for the gauged watersheds and plotted against the area of the watersheds, and then the I/D value for a given area multiplied by the daily flood gives the instantaneous flood of the same return period.

The above method averages the response of each watershed, and so the I/D ratio is reduced to only one value, which is questionable since the response of the same watershed can vary significantly with the antecedent conditions.

Russell's Bayesian Method

Russell (1982) proposed a procedure which involves the use of a compound distribution which is a weighted combination of individual probability distributions. The initial values and the weights are assigned to the parameters of the component distributions on the basis of subjective or regional estimates of the mean and the standard deviation of flood peaks. The weights of the component distribution can be updated using the Bayes' theorem in light of any additional measurements or even subjective information such as the largest flood in a number of years, or a flow which was not exceeded in a given number of years. The method requires the low, probable, and high estimates of the mean and the standard deviation. The low value is the one for which there is 90% probability that it will be exceeded, probable is the best estimate and high is the estimate with 90% probability that will not be exceeded. These estimates can be found from regional data for ungauged watersheds and they can also be subjective estimates.

The model developed on the basis of the above procedure estimates the values of the mean and the standard deviation half way between the low and the probable estimates, and the probable and the high estimates. The marginal probabilities assigned for each one of these values are 0.169, 0.206, 0.250, 0.206, and 0.169 going from the low to the high estimates.

The compound distribution is made up of 25 component distributions each specified by a mean and a standard deviation and a weight or marginal probability. The probability of any particular combination of mean and standard deviation is obtained by multiplying the individual probabilities and normalizing to make the sum of all the weights equal to 1.0. The frequency of a given flood is simply the weighted sum of all the component distributions. If further information is available, the weights or marginal probabilities of the component distributions are updated by using the Bayes' theorem. More detailed description of the method can be found in the original paper (Russell, 1982).

Method of Derived Distributions

A brief outline of a stochastic-deterministic procedure for the estimation of the return period of flood runoff which uses the method of derived distributions was given in Loukas and Quick (1994a). The method uses a rainfall simulator to estimate the characteristics of the storm and a simplified watershed model for the simulation of watershed response. Most of the parameters of the procedure are stochastic in nature, so that Monte Carlo simulation is used for the generation of the procedure parameters and the simulation of the peak flow hydrographs.

The rainfall simulator estimates the most important characteristics of the storm and uses the findings of previous research. The storm duration of 24 hours is used because it has been shown through simulation that it is capable of reproducing both the low and the high frequency floods (Loukas and Quick, 1994a). Also, for coastal British Columbia, the most severe storms are long duration frontal storms which last about a day (Loukas and Quick, 1993a).

The depth of the 24-hour extreme rainfall is assumed to follow the Extreme Value type I (EVI) distribution. The parameters of the distribution, the mean and the standard deviation, are estimated from the Rainfall Frequency Atlas for Canada (Hogg and Carr, 1985) or from any other regional information. The values of these parameters need to be adjusted for the effect of the orography increasing the mean by 1.5 times. This is an average value and has been found in an earlier study of the storm rainfall in coastal British Columbia (Loukas and Quick, 1993a). The standard deviation of the 24-hour rainfall is adjusted accordingly.

The storm depth is distributed within the 24-hour period using the cumulative dimensionless hyetographs developed in an earlier study for coastal British Columbia (Loukas and Quick, 1994b). The rainfall percentage at each one of the hourly time steps is generated using a triangular distribution which has been fitted to the observed data. Furthermore, the cumulative storm depth at each hourly time step should be larger than or equal to the storm depth at the previous time step and should range between 0 and 1. This constraint preserves both the randomness of the rainfall depth at each time step and also satisfies the correlation of successive accumulations because dependence is a property of an ordered sample.

The watershed response model used in the procedure has been developed in a previous study (Loukas and Quick, 1993b) and it was shown to give good simulation of the watershed response. The watershed model is an event model which uses a linear reservoir routing technique and simulates the fast runoff with a series of two cascading reservoirs and the slow runoff with one large reservoir. The whole process is infiltration controlled.

Most of the parameters of the model can be estimated from the geomorphology of the watershed and it is assumed that they are not constant but they can be represented using certain statistical distributions. Monte Carlo simulation is used to generate 5000 values of the procedure parameters which are consequently used to simulate the peak flows, representing the variability in the conditions that produce floods. The 5 000 values of the peak flow are then ranked and the flood frequency is estimated. The procedure is capable of simulating, during the same run, the peak daily flood, peak instantaneous flood, and the peak flood volume.

Application

In this section, the application of the various methods to a coastal British Columbia watershed are presented. The study watershed is the Sarita River watershed which is located on the west coast of Vancouver Island and its area is 162 km^2. The majority of the flow is generated by strong frontal systems formed above the North Pacific Ocean. The west coast of Vancouver Island is in the direct path of these frontal systems. As a result, the highest values of unit discharge (*i.e.*, discharge per unit area) in British Columbia have been observed in that region. The results of the various techniques are compared with twelve years of instantaneous peak flow data and thirty seven years of peak daily flow.

The comparative analysis has been developed for rain and therefore is appropriate for coastal British Columbia because 74% of the floods in that area are rain-induced (Melone, 1986). The snowmelt and rain on snow floods have different characteristics and are therefore eliminated from the analysis. Although coastal British Columbia has distinct climatic and physiographic features from the rest of the province, a homogeneity test is applied to eliminate non-conforming stations. The homogeneity test described in Hydrology of Floods in Canada (Watt *et al.*, 1989) has been applied. This homogeneity test has been proposed by Gumbel (1958). It is based on the assumption that the EVI (Gumbel) distribution fits all the regional data and involves the following procedural steps:

- The ratio of the 10-year flood to the mean annual flood is computed for all stations and averaged over the region.
- Each station mean annual flood is multiplied by the regional average ratio to yield a regionally estimated 10-year flood. The return period of this flood is then estimated from the station's frequency curve.
- This estimated return period of each station's flood is plotted against the station length of record. The 95% confidence bands approximated (Kite, 1978) by $y_\varepsilon = 2.25 \pm \frac{6.33}{\sqrt{n}}$, where y_ε is the reduced variable equal to $y_\varepsilon = -\ln\left[-\ln\left(1 - \frac{1}{T_\varepsilon}\right)\right]$, n is the years of station record and T_ε is the estimated return period of the flood. Twenty eight stations are used to test the homogeneity of the instantaneous peak flow records and thirty seven stations are used for the daily peak flows (Table 1). All stations used have passed the test as shown in Figures 1 and 2.

Index Flood, DRQ and RDP Methods

In this study the Index Flood method and the DRQ and RDP methods were used to develop regional equations. The Index Flood method presented in this paper is different from the B.C. Environment method even though they both use the same technique. The Index Flood method of this study includes only the rainfall generated flows of rivers that have no man-made impoundment. Furthermore, the regional equations developed use not only the basin area as a predictor but also other physiographic as well climatic parameters. Also, separate equations have been developed for the instantaneous and daily peak flow.

The physiographic parameters used for the development of the regional equations are basin area, A, main stream length, L, main stream slope, S, mean basin elevation, E, and lake storage, S_t. These physiographic parameters were measured from topographic maps of 1:50 000 scale. The mean annual 24-hour rainfall, P_{24}, is used for the representation of the climatic characteristics and it is estimated from the Rainfall Frequency Atlas for Canada (Hogg and Carr, 1985). The watershed characteristics can be seen in Table 1.

The stepwise multiple regression analysis is conducted as linear analysis using log-transformed data. Only the statistically significant parameters at the 95% level were included in the equations and therefore, for all the equations, only the basin area, A (in km^2), the mean stream slope, S (in m/m), and the mean annual extreme 24-hour storm depth, P_{24} (in mm), are included.

For the index flood method the mean instantaneous flood is given from the equation:

$$Q_{m,in} = 0.011 \bullet A^{0.823} \bullet S^{0.039} \bullet P_{24}1.226 \quad (1)$$

with coefficient of determination, R^2=0.91 and standard error of estimate in percent of the mean of original peak discharges, SEE=9.01%.

The respective equation for the mean daily peak flood is:

$$Q_{m,d} = 0.014 \bullet A^{0.934} \bullet S^{0.089} \bullet P_{24}0.987 \quad (2)$$

with R^2=0.91 and SEE=19.3%.

Data from all the stations are used to develop dimensionless regional frequency curves for instantaneous and daily peak flows. The ratio of the flows for various return periods to the mean annual flood Q_m are calculated using the Extreme Value type I (EVI) distribution. Figures 3 and 4 show the dimensionless frequency curves

Table I: Charactaristics of Coastal British Columbia Watersheds used in the Study

Watershed	Area (km²)	Stream Length (km)	Stream Slope (m/m)	Mean Elevation (m)	Lake Area (km²)	Mean Annual 24-h Storm (mm)	Mean Annual Instant. Flow (m³/s)	Mean Annual Daily Flow (m³/s)
Capilano	172	25.97	0.040	782	-	120	317.8	224.1
Carnation	10.1	7.80	0.085	765	-	135	31.2	13.7
Chapman	64.5	20.65	0.044	680	-	78	80.0	47.5
Hirsch	347	36.47	0.020	820	-	80	350.5	207.1
N. Allouette	37.5	13.00	0.035	478	-	110	76.0	44.3
Oyster	298	37.60	0.022	701	-	60	180.3	145.1
San Juan	580	41.97	0.010	414	-	120	776.4	619.6
Sumas	149	32.91	0.005	414	-	55	25.93	23.3
Zeballos	181	22.00	0.022	725	-	190	552.1	338.5
Exchamiskis	370	47.98	0.005	785	-	80	491.2	354.9
Zymagotitz	376	35.77	0.016	772	-	70	272.8	178.2
Pallant	76.7	15.60	0.012	519	8.63	90	70.3	49.4
Canaka	47.7	15.16	0.045	732	-	90	77.8	41.2
Lit. Wedeena	188	23.33	0.022	855	-	70	192.0	127.1
Mackay	3.63	2.45	0.105	497	-	110	6.95	3.61
Murray	26.2	9.00	0.0095	60	-	55	22.8	10.8
Noons	2.59	5.47	0.131	409	-	85	7.46	4.02
Yakoun	477	62.82	0.0025	351	8.50	75	291.1	270.6
Ucona	185	28.50	0.052	834	4.88	160	394.01	233.9
Stawamus	40.4	13.53	0.032	785	-	140	63.51	37.7
Bings	15.5	5.40	0.045	359	-	60	-	6.93
Browns	86	24.25	0.039	626	-	70	-	77.2
Chemainus	355	55.90	0.0105	644	-	80	-	243.9
Englishman	324	34.40	0.019	828	-	80	-	228.8
Haslam	95.6	16.54	0.036	451	-	60	-	38.6
Koksilah	209	35.80	0.011	493	-	60	-	133.7
Tsable	113	25.30	0.037	681	-	70	-	143.2
Kokish	290	36.20	0.0185	799	-	80	130.9	96.9
Tsitika	360	37.15	0.018	792	-	80	412.0	249.6
Jacobs	12.2	3.50	0.025	483	-	75	17.83	10.96
Mashiter	38.9	12.20	0.084	872	-	100	43.7	22.1
Salloomt	161	22.10	0.030	883	-	100	90.6	62.2
Mamquam	334	30.95	0.036	911	-	110	223.3	152.01
Nusatsum	269	32.00	0.029	897	-	100	151.4	100.4
Kemano	583	30.55	0.018	912	-	85	502.1	323.1
Anderson	27.2	13.50	0.0075	47	-	60	-	10.4
Yorkson	5.96	10.6	0.003	35	-	60	-	2.88
Sarita	162	20.32	0.0175	442	-	190	357.7	313.7

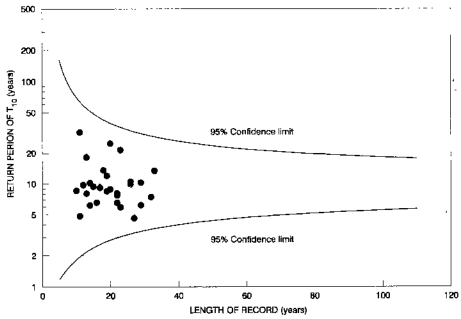

Figure 1. Homogeneity Test for Peak Instantaneous Flow for Coastal British Columbia

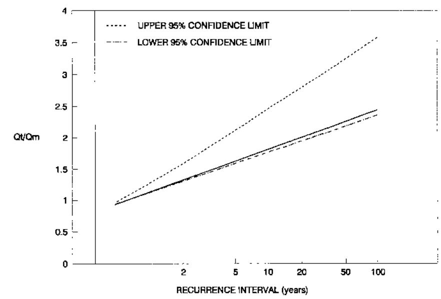

Figure 3. Dimensionless Frequency Curve of Instantaneous Peak Flow for Coastal British Columbia
(Index Flood Method)
(Qt is the flow of t-years and Qm is the mean annual peak flow)

for the instantaneous and daily flows, respectively. Multiplication of the mean annual flood with the dimensionless frequency curves gives the frequency curves for a given watershed.

The regional equations for the floods of the 2, 5, 10, 25, 50, and 100 years recurrence interval are developed for the DQR method. The EVI distribution has been used. The equations for the instantaneous flow are shown in Table 2. The equations

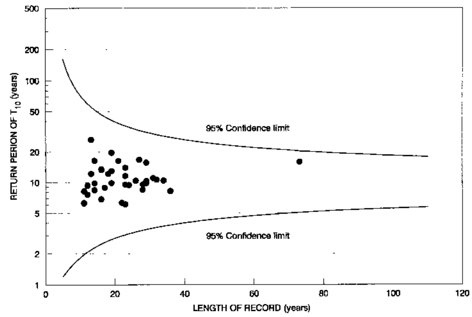

Figure 2. Homogeneity Test for Peak Daily Flow for Coastal British Columbia

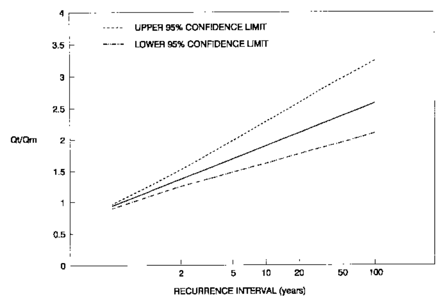

Figure 4. Dimensionless Frequency Curve of Daily Peak Flow for Coastal British Columbia
(Index Flood Method)
(Qt is the flow of t-years and Qm is the mean annual peak flow)

for the daily flow are shown in Table 3.

For the RDP method the regional equations for the mean instantaneous and the mean daily flows are the Equations 1 and 2 developed for the Index Flood method.

The equation for the standard deviation of the instantaneous peak flow for the RDP method is:

$$\sigma Q_m = 0.0156 \bullet A^{0.872} \bullet S^{0.248} \bullet P_{24}1.059 \quad (3)$$

with R^2=0.87 and SEE=12.8%.

Table 2: Regional Equations of Instantaneous Peak Flow for the Method of Direct Regression of Quantiles ($Q_t = K \bullet A^c \bullet S^d \bullet R_m{}^e$)

Return Period T (yrs)	K	c	d	e	R^2	SEE*
100	0.0648	0.861	1.085	0.171	0.90	8.1
50	0.0518	0.856	1.106	0.157	0.90	8.1
25	0.0422	0.853	1.119	0.144	0.90	8.2
10	0.0252	0.841	1.178	0.110	0.90	8.4
5	0.0186	0.835	1.196	0.085	0.91	8.6
2	0.0097	0.819	1.237	0.084	0.90	9.2

Table 3: Regional Equations of Daily Peak Flow for the Method of Direct Regression of Quantiles ($Q_t = K \bullet A^c \bullet S^d \bullet R_m{}^e$)

Return Period T (yrs	K	c	d	e	R^2	SEE*
100	0.0483	0.9442	0.9374	0.112	0.93	8.3
				14		
50	0.0424	0.9439	0.9407	0.1085	0.93	8.4
25	0.0364	0.9434	0.9453	0.1035	0.93	8.5
10	0.0275	0.9369	0.9583	0.0847	0.93	8.7
5	0.0223	0.9413	0.9614	0.0844	0.93	8.8

The equation of the standard deviation of the daily peak flow for the RDP method is:

$$\sigma Q_d = 0.0113 \bullet A^{0.946} \bullet S^{0.146} \bullet P_{24}0.905 \quad (4)$$

with R^2=0.91 and SEE=14.1%.

B.C.Environment Method

The B.C. Environment method (Reksten, 1987) has been applied to the various subregions in which the province of British Columbia has been divided. In this study, the results of the analysis for the Vancouver Island subregion (Chapman *et al.*, 1992) are used.

Two watersheds located in the west coast of the Vancouver Island have similar characteristics to the Sarita River. The Zeballos River and the Ucona River watersheds have similar areas, 181 and 185 km^2, respectively. From the diagrams provided in the B.C. Environment report (Chapman *et al.*, 1992) the mean annual flood is estimated as 300 m^3/s if the Zeballos River is used and 210 m^3/s if the Ucona River is considered.

The ratios of the floods of the various return periods to the mean annual flood are estimated from the results of the analysis of peak daily flows using Log-Pearson type III distribution (Chapman *et al.*, 1992). The values of the ratios, C_t, for the 2-, 5-, 10-, 25-, 50-, 100-year floods are 0.89, 1.28, 1.58, 1.95, 2.28, and 2.55 if the Zeballos River is used and 0.81, 1.34, 1.75, 2.27, 2.65, 3.09 if the Ucona River is used, respectively.

The daily floods of various return periods then can be estimated from the equation:

$$Q_{t,d} = Q_{m,d} \bullet C_t \quad (5)$$

The average ratio of the instantaneous to daily flow, I/D is estimated from the B.C.

Environment report using the Zeballos River as 1.32 and 1.7 when the Ucona River is used. The instantaneous flood can then be found if the daily flow is multiplied by the I/D factor as:

$$Q_{t,in} = Q_{t,d} \bullet I/D \qquad (6)$$

The results for Sarita River watershed are shown in Tables 4 and 5.

Russell's Bayesian Method

In order to use Russell's Bayesian method, it was necessary to determine the low, probable, and high estimates of mean annual flow and its coefficient of variation. Only the watersheds located on the west coast of Vancouver Island (Zeballos, Ucona, Carnation, San Juan in Table 1) are used. The low, probable and high values of the mean annual flood and its coefficient of variation are estimated as the smaller, the average and the larger values of these parameters for the above four watersheds. The estimated low, probable and high values of the mean annual instantaneous flow and its coefficient of variation are: 340 m^3/s, 447 m^3/s, 502 m^3/s and 0.3, 0.5, 0.7, respectively. The estimates for the mean annual daily flood and its coefficient of variation are: 194 m^3/s, 243 m^3/s, 308 m^3/s and 0.35, 0.50, 0.65, respectively. The results for the Sarita River watershed using the Bayesian method are shown into the Tables 4 and 5.

Table 4. Comparison of Estimated Daily Peak Flow (m^3/s) for Various Return Periods Using Various Methods with the Fitted Extreme Value Type I Distribution to the Observed Flows for Sarita River Watershed

	Return Period (yrs)					
	2	5	10	25	50	100
Fitted EVI	275	399	481	584	662	738
Stochastic Deterministic Procedure	315	424	496	591	679	773
Bayesian Method	282	391	463	551	622	690
B.C. Environment Method using Ucona	170	281	368	477	557	649
B.C Environment Method using Zeballos	267	396	474	585	684	765
Index Flood Method	194	271	322	387	435	483
Index Flood Method - 95%	199	294	371	466	533	604
RDP	191	270	321	387	435	483
DRQ	216	296	350	415	463	512

Table 5. **Comparison of Estimated Instantaneous Peak Flow (m^3/s) for Various Return Periods Using Various Methods with the Fitted Extreme Value Type I Distribution to the Observed Flows for Sarita River Watershed**

	Return Period (yrs)					
	2	5	10	25	50	100
Stochastic Deterministic Procedure	470	646	773	946	1100	1256
Bayesian Method	497	688	816	945	1095	1213
B.C. Environment Method using Ucona	289	478	626	811	947	1103
B.C Environment Method using Zeballos	352	523	626	811	947	1103
Index Flood Method	369	505	596	710	795	880
Index Flood Method - 95%	381	593	755	960	1110	1259
RDP	374	484	557	650	718	786
DRQ	372	495	564	641	708	769

Method of Derived Distributions

Finally, for the stochastic-deterministic procedure proposed in this study, the only input data required are the mean annual 24-hour extreme rainfall depth, P_{24}, its standard deviation, and the mean storage factor of the fast runoff, KF_m. The P_{24} and its standard deviation are estimated from the Rainfall Frequency Atlas for Canada (Hogg and Carr, 1985). The KF_m parameter was found by using the equation:

$$t_l = n \bullet KF_m \tag{7}$$

for the Nash linear model of cascading reservoirs, where t_l is the time lag of the watershed, and n is the number of the cascading reservoirs. In this study the parameter n was set to equal to 2 as it has been indicated by other studies (Blazkova, 1992) and previous application of the model (Loukas and Quick, 1993b).

The time lag of the watershed is estimated by the modified Snyder formula:

$$t_l = 0.42 \bullet \left[\frac{L \bullet L_c}{S^{0.5}}\right]^{0.38} \tag{8}$$

where L is the length of the main stream (km), L_c is the distance from the mouth of the watershed to the centroid of the watershed (km), and S is the main stream slope (m/m).

After estimating the parameter values and 5000 Monte Carlo simulations, the flood frequency of the instantaneous peak flow and daily peak flow are estimated for the Sarita River watershed (Tables 4 and 5).

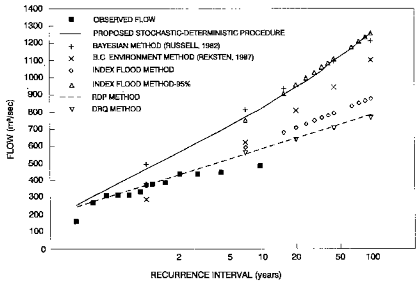

Figure 5. Comparison of the Frequency of the Observed Daily Peak Flow with the Frequency of Simulated Daily Peak Flow using Various Methods for Sarita River Watershed

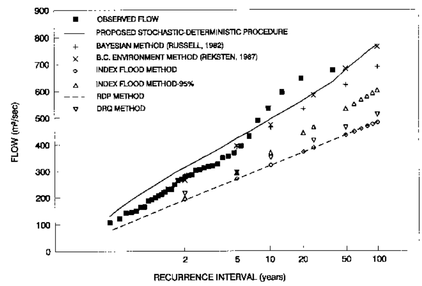

Figure 6. Comparison of the Frequency of the Observed Instantaneous Peak Flow with the Frequency of Simulated Instantaneous Peak Flow using Various Methods for Sarita River Watershed

Results

The results of the analysis of the peak daily flow are compared with the estimates derived from the fitted EVI distribution to the observed data in Table 4 and Figure 5. As can be seen, the estimates of the stochastic-deterministic procedure, the Bayesian method and the B.C. Environment method are closest to the estimates of the fitted EVI distribution. The results by using both the Ucona River and Zeballos River watersheds to estimate the mean annual flood for the B.C. Environment method are included in Table 4. The estimates of the peak daily flow by using the Zeballos River data compare better with the observed flows and the values of the fitted Extreme Value type I distribution (Table 4).

The estimates of the Index Flood method, RDP and DRQ methods are lower than both the observed values and the extrapolated values obtained from the fitted EVI probability distribution.

The comparison for the instantaneous peak flow shows that all the techniques give flows larger than the observed flows (Table 5 and Figure 6). This incompatibility is the result of the small number of years of record. It should be mentioned that the largest daily peak flow of 37 years of record is 677 m^3/s and the largest instantaneous peak flow of 12 years of record is only 486 m^3/s. Examination of the data of the Sarita River showed that the ratio of the instantaneous peak flow to the daily peak flow ranges between 1.11 to 1.55 with a mean of 1.35. Applying these ratios to the largest daily flow on record indicates that the instantaneous peak flow of the same day should have been between 750 to 1050 m^3/s (Fig. 6). If these flows are extrapolated, then the 100-year instantaneous flood should range between 1000 to 1300 m^3/s. As can be seen from Table 5 and Figure 6, only three techniques have estimated flows that are close to these values. These techniques, are the stochastic-deterministic procedure, the Bayesian method, and the B.C. Environment method. In Figure 6 and Table 5 the estimate using the upper 95% confidence level of the regional dimensionless frequency curve (Fig. 3) is also presented. This estimate is within the above range of 1000 to 1300 m^3/s for the 100-year flood. This is not surprising since the west coast of Vancouver Island receives large amounts of rain from the Pacific Ocean storms and so the watersheds located in that area exhibit a response which is higher than the average response of the coastal British Columbia watersheds.

Both the Zeballos River or the Ucona River watersheds were used to estimate the mean annual instantaneous flow for the B.C. Environment method (Table 5). The results showed that the estimates of flows with high return periods are not affected if the data of either watershed is used for the estimation of mean annual instantaneous flow (Table 5).

The estimates of the 100-year instantaneous flood using the other regional techniques are well below the range of 1000 to 1300 m^3/s. This is mainly because the regional equations developed in this study average the watershed response over the coastal region of British Columbia, whereas as it has been mentioned above, the watersheds located on the west coast of the Vancouver Island respond at a much higher rate than the rest of the coastal watersheds.

Summary and Conclusions

This study presented the comparison of several techniques for the estimation of peak flow from ungauged watersheds in coastal British Columbia. The results show that three of the methods, the stochastic-deterministic procedure proposed in this paper, the B.C. Environment regional method (Reksten, 1987), and the Bayesian method (Russell, 1982), give good results which fit the observed flow. The other regional techniques, the Index Flood, RDP, and DRQ methods, failed to give good estimates mainly because they have been developed for the whole coastal British Columbia. Therefore these techniques did not work well when they were applied to a watershed on the west coast of Vancouver Island because the response of the watersheds located in that area is much higher than the response of the other coastal British Columbia watersheds. It would be helpful if regional equations could be developed for the west coast of Vancouver Island but this is not feasible because there are only four watersheds in the area with long enough records for statistical analysis.

The stochastic-deterministic procedure has been proven to be very reliable and it can be applied with very limited data. This procedure requires only the mean annual extreme 24-hour rainfall which, in the absence of data, can be estimated from the Rainfall Frequency Atlas for Canada (Hogg and Carr, 1985), and the time lag of the watershed which can be estimated by using data obtained from a topographical map of the area. This method has been applied to eight more watersheds of the coastal British Columbia and was shown to give good estimates of the flood frequency (Loukas and Quick, 1994a). Furthermore, it is efficient, easy to apply, and estimates both the frequency of the peak instantaneous and daily peak flow in the same analysis.

The Bayesian method gives good results if the initial flow estimates are good and can be used to incorporate new information when it becomes available. The B.C. Environment method also gives good results because it is based on the subdivision of British Columbia into subregions. However, the proposed stochastic-deterministic method has the advantage that the flood flow is directly related to the causative rainfall and watershed characteristics and therefore this method is likely to be the most reliable.

In summary, on the basis of the comparison made in this paper, it has been shown that it is imperative for the hydrologist to know and understand the hydrology of the area and to apply more than one technique for the estimation of peak flow from ungaged watersheds. The methods recommended as appropriate techniques are the proposed stochastic-deterministic procedure, the B.C. Environment method, and the Russell's Bayesian method.

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