ANALYSIS OF HIGHFLOWS IN THE FRASER RIVER CATCHMENT, BRITISH COLUMBIA

By

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B.Sc. (Hons.), M.A.

A Thesis

Submitted to the School of Graduate Studies

in Partial Fulfilment of the Requirements

for the Degree

Doctor of Philosophy

McMaster University

September 1981

HIGHFLOWS IN THE FRASER CATCHMENT

DOCTOR OF PHILOSOPHY (1981)
(Geography)

McMASTER UNIVERSITY
Hamilton, Ontario

TITLE: Analysis of Highflows in the Fraser River Catchment, British Columbia

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NUMBER OF PAGES: xvi, 137

ABSTRACT

Frequency characteristics of highflows in the Fraser River catchment, British Columbia, are modelled in such a way as to permit their prediction for ungauged basins.

Two definitions of highflows, annual flood and partial duration series, are examined. The two series are shown to be stationary and serially independent. The Gumbel distribution is found to describe adequately the observed annual flood data. Following theoretical considerations a nonhomogenous Poisson distribution is used to model the time-dependent behaviour of the number and timing of highflows derived from the partial duration series. Their magnitudes and periods of duration are found to be exponentially distributed.

The 2 year return period annual flood provides the truncation level for the regional analysis. A method of predicting partial series at other levels of interest from this base is proposed and tested. The relationship between the two highflow series is presented and a theoretical distribution for the estimation of annual flood frequencies from partial series is tested across the study area. It compares favourably with the Gumbel distribution as a means of representing the observed annual flood data.

The estimated parameters of the probability distributions employed are entered into a regionalisation procedure that permits the definition of highflow groups. Within each of the derived groups the parametric values are related to basin physiographic

and climatic variables by means of multiple regression equations. The groups are found to be defined by simple, meaningful physical variables which allow the extension of the groups to provide a regional demarcation of the study area. The regression equations are applied to test basins within the Fraser catchment and the results indicate that the method is suitable for the estimation of highflow characteristics in ungauged basins.

ACKNOWLEDGEMENTS

I wish to thank my supervisor Dr. M.K. Woo for his guidance and perseverance throughout the course of this work. We have had our differences but they have been healthy and his concern appreciated. I am grateful for the advice of my supervisory committee: Drs. J. Davies, P.D.M. Macdonald and A. Smith which I frequently called upon. Dr. Smith was particularly encouraging and freely gave of his valuable time at the beginning of the work. Dr. J.J. Drake gladly provided discussion and assistance when necessary. Research funds were provided by grants from the Natural Sciences and Engineering Research Council of Canada and the McMaster University Science and Engineering Research Board.

Of my fellow graduates I would particularly like to thank Morton O'Kelly who always showed an interest in statistical and computing problems; Emil Bóasson for seeking out the satellite mosaic and Peter Steer for the extended loan of his draughting materials. Bob Bignell and Margaret Chan happily gave their expert professional advice whenever requested. Matthew Baxter worked long and hard collecting map data. Diane Dabirian typed the final draft from the manuscript cheerfully and proficiently.

The times of doubt and despondency have been made bearable when shared with Marilyn Baxter. This thesis is a testament to her patience and encouragement.

DEDICATION

This dissertation is dedicated to the memories of Mrs. F. Waylen of Tilshead, Wiltshire, and Mr. F.G. Mundy of Rushall, Wiltshire, England.

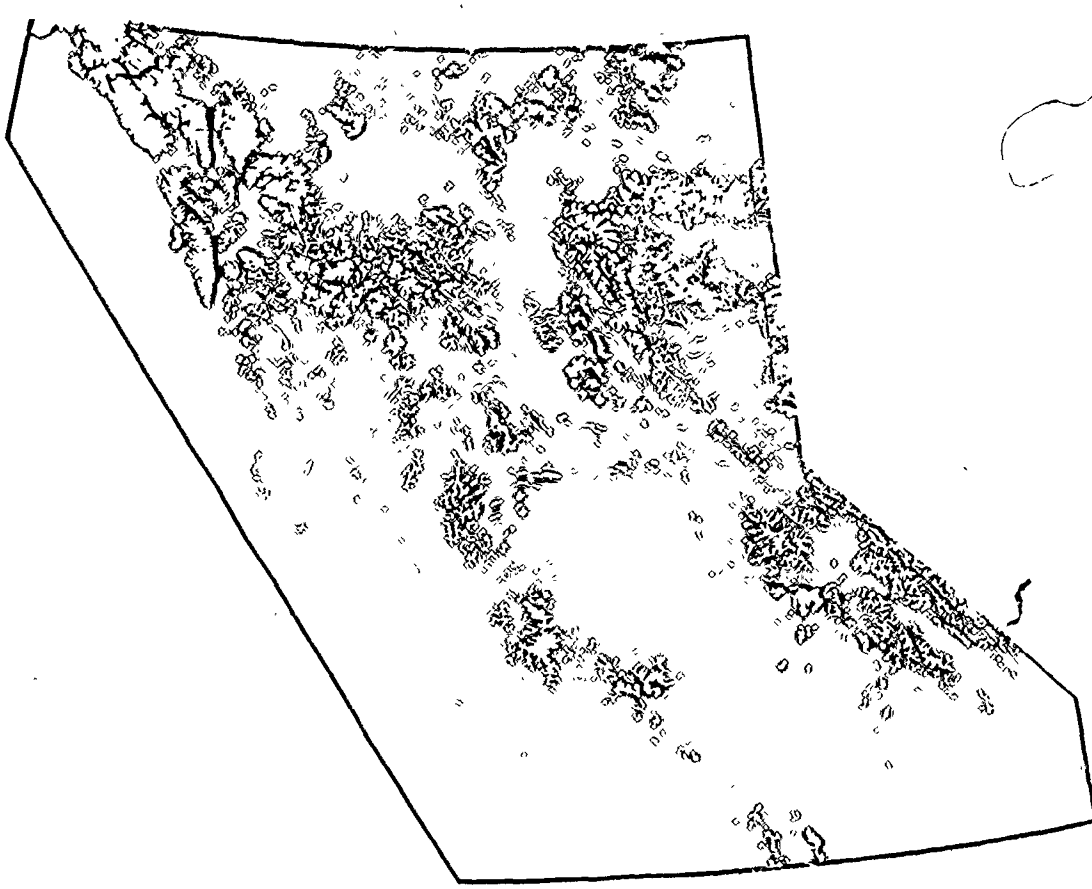
LIST OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

FRONTISPIECE

Satellite image of British Columbia showing the limits of the study area.



LIST OF SYMBOLS

a	regression constants
m	number of exceedances of all sizes per year
n	number of years of record
q_1	75% quartile of annual flood data
q_2	25% quartile of annual flood data
t	time (days)
v	independent variable
x_o	truncation level of partial duration series (m^3s^{-1})
$y(T)$	Gumbel's reduced y variate
A	drainage basin area (km^2)
H	Hurst coefficient
$H(x)$	distribution of peak flows
$M(t)$	largest discharge in the period [0,t]. (m^3s^{-1})
P	critical period between highflows. (days)
P_E	average number of floods greater than a given magnitude
P_M	the probability of the largest flow in a year being of a given magnitude
$\hat{Q}$	estimate of dependent variable
R	maximum range of cumulative departures from the mean
S	sample standard deviation
T	return period (years)
T_k	duration of the k^{th} exceedance (days)
X	magnitude of exceedance (m^3s^{-1})
$\bar{X}$	sample mean
Y_M	random variable in extreme value theory
α } β	parameters of the Gumbel distribution
γ	parameter of the exponential distribution
$\eta(t)$	number of exceedances in the period [0,t]
λ	parameter of the Poisson distribution
$\lambda(t)$	parameter of the nonhomogenous Poisson distribution
μ	population mean

$\xi(s)$	stochastic process
σ	population standard deviation
τ	time of exceedance peak (days)
ϕ	time of upcrossing of the truncation level (days)
χ_t	the largest exceedance in the period [0,t] (m^3s^{-1})

CHAPTER I

INTRODUCTION

Chow (1964, section 25.2.1) defines a flood as any highflow that overtops the natural or artificial banks in any reach of a stream. Floods are therefore a function of local floodplain conditions which effect the relationship between the discharge of water from the reach and the depth of flow. These factors vary spatially and temporally in a given stream and can be effected by human intervention. To avoid such localised complexities this thesis will deal only with highflow discharges. Not all highflows cause flooding at a point. The term flood will not be used unless specifically defined.

1.1 The importance of highflows

Knowledge of the magnitude and frequency of highflows can be applied to a range of human activities, including the design and construction of hydraulic structures, culverts, bridges and dams, the delineation of flood plains and the calculation of flood insurance (Dingman and Platt, 1977; Beard, 1978). Other variables of value in the prevention of flood damage and the development of water resources projects have been analysed using a more recent approach. These variables include the number, timing and duration of highflows. Floods in south-western British Columbia, including parts of the study area, caused an estimated $13 million of damage during December 1980.

Magnitude and frequency characteristics of highflows are central to an understanding of present fluvial landforms and the estimation of rates of sediment transport (Wolman and Miller, 1960; Church, 1980).

1.2 Methods of analysis

The magnitudes of highflows are of prime concern and two major approaches to their analysis have developed. Traditional analysis, exemplified by Gumbel (1958) investigates the characteristics of the largest recorded discharge in a given time period; generally a year. Recently the more practical problem of the frequency with which flows exceed a certain critical level has been studied, notably by Todorovic (1978) and his co-workers. The term flood has connotations of damage and loss in either of the two analyses of highflow this need not necessarily be the case. Langbein (1949), pointed out that the two approaches were not unrelated and Zelenhasic (1970), has provided further evidence of their theoretical links. Despite these works the majority of applied analyses in this field, (eg. Page and McElroy (1981)), remain poorly developed.

1.3 The need for regionalisation

The use of frequency analysis as a means of studying highflows requires that the events be serially independent. Therefore the technique is best applied statistically to extreme events. Practically, such events may be rare and have few realisations during the period of streamflow record. At some sites or areas of interest such data records may not exist. The classification or regionalisation of the results of frequency analyses permits the spatial generalisation of the observed frequency characteristics and identifies underlying common behaviour of stations within a region. This procedure diminishes the importance of aberrations caused by local conditions or the limited sample sizes that may be found at the level of investigation of the individual basin. The exposition of such zones is useful in the planning of water resources projects, while the modelling of regional behaviour facilitates the interpolation of the highflow characteristics in ungauged basins.

1.4 Analysis in the temporal and spatial domains

The analysis of flood frequencies in river basins of all sizes has been carried out extensively in hydrology. Dalrymple's (1960) work exemplifies the approach generally taken and provides a review of the methodology. The procedures have been applied globally. Although the frequency distributions employed have changed, the majority of studies concentrate upon the variability of highflows in the temporal domain. This field has attained a degree of sophistication beyond the initial calculation of empirical exceedance probabilities. The selection and fitting of probability distributions has attracted the attention of statisticians. Extensions of the results to the spatial domain are infrequently encountered, while the difficulty of obtaining reliable flood estimates for ungauged basins persists.

The spatial variation of a single descriptive measure, such as mean flood discharge, has been investigated and related to physical variables (Leith, 1976). Ashkar, El-Jabi and Rousselle (1980) maintain that this approach is relatively unsatisfactory in that it contains little information concerning the temporal domain. This dichotomous situation has been perpetuated through the latest advances in flood frequency analysis.

1.5 Objective

In light of the above observations it is the objective of this thesis to describe the behaviour of highflows in both time and space in such a way as to permit the prediction of the pattern of highflows for ungauged basins. The applicability of a curve fitting technique and an approach leading from the consideration of stochastic processes are tested in the same study area. The stochastic parameters of the models are used to delineate regions of similar highflow characteristics. Empirical relationships are established in each region between readily available physical variables and the stochastic parameters. The allocation of an ungauged basin to its respective region allows the prediction of the stochastic parameters and the return periods of several highflow variables.

1.6 Thesis structure

The thesis is arranged in seven chapters. The analytical methods used in the temporal and spatial domains are reviewed in Chapter II. Chapter III describes the pertinent features of the study area that affect basin hydrology and particularly highflow characteristics. The data used in the thesis are briefly discussed. Chapters IV and V present the results of the analyses and discuss the respective patterns of regionalisation. Regional relationships between the climatic and physiographic variables and the stochastic parameters are established and the prediction schemes tested. Chapter VI combines the two approaches to high-flow analysis in a single theoretically based probability distribution. The results of the analyses in Chapter V are extended and sources of possible error in the formulation of regions discussed. Chapter VII draws conclusions resulting from the preceding chapters.

CHAPTER II

HIGH FLOW ANALYSIS AND REGIONALISATION

2.1 Definitions of Annual Flood and Partial Duration Series

High flows are usually analysed using annual flood series or partial duration series. Annual flood series comprise a sequence of annual floods, defined as the largest instantaneous discharge observed in each year of record. Frequently it is defined using daily mean discharge because of the rarity of instantaneous discharge records. The U.S. Water Resources Council (1976) defines a partial duration series as a series of independent flood peaks; floods are flows greater than a particular base level of interest. An appropriate base level is selected to result in a sequence of independent events. Events are considered independent if they are separated by a period of days, P, defined as

$$P = 5 + \ln.A. \tag{2.1}$$

where A is the drainage basin area (Km^2) (Taesombut and Yevjevich, 1978). The intermediate recession curve between two highflows must also drop below 75% of the flow of the lower of the two enclosing events. In the situation of a multiple peaked event, only the larger observed daily discharge is included in the series. Successive events that are not independent are considered to constitute a multiple peaked exceedance; the duration of the period of flood is taken to be the sum of the periods of the two dependent exceedances.

2.2 Phenomenological considerations

Fig. 2.1 shows a sample of a streamflow record $\xi(s)$, $s \geq 0$. Since streamflow varies with time in a random fashion this may be considered a stochastic process.

Having selected a base level, x_o, only those portions of the sample where $\xi(s) \geq x_o$ are considered highflows. The timing of these exceedances in the period (0,t) defined by the local maxima, may be denoted by

$$\tau_1, \tau_2, \tau_3 \ldots\ldots \tau_k \qquad k = 1, 2, 3 \ldots\ldots \tag{2.2}$$

τ_k is defined as the time of the peak of the k^{th} hydrograph to exceed x_o. Let the number of such exceedances be $\eta(t)$. Then $\eta(t)$ is an integer valued process such that for any time period, t, $t \geq 0$, $\eta(t) = 0, 1, \ldots$. Associated with each of the $\eta(t)$ crossings is a value of the stochastic process at time τ_k; $\xi(\tau_k)$, $k \leq \eta(t)$. The magnitudes of these exceedances form a sequence of random variables

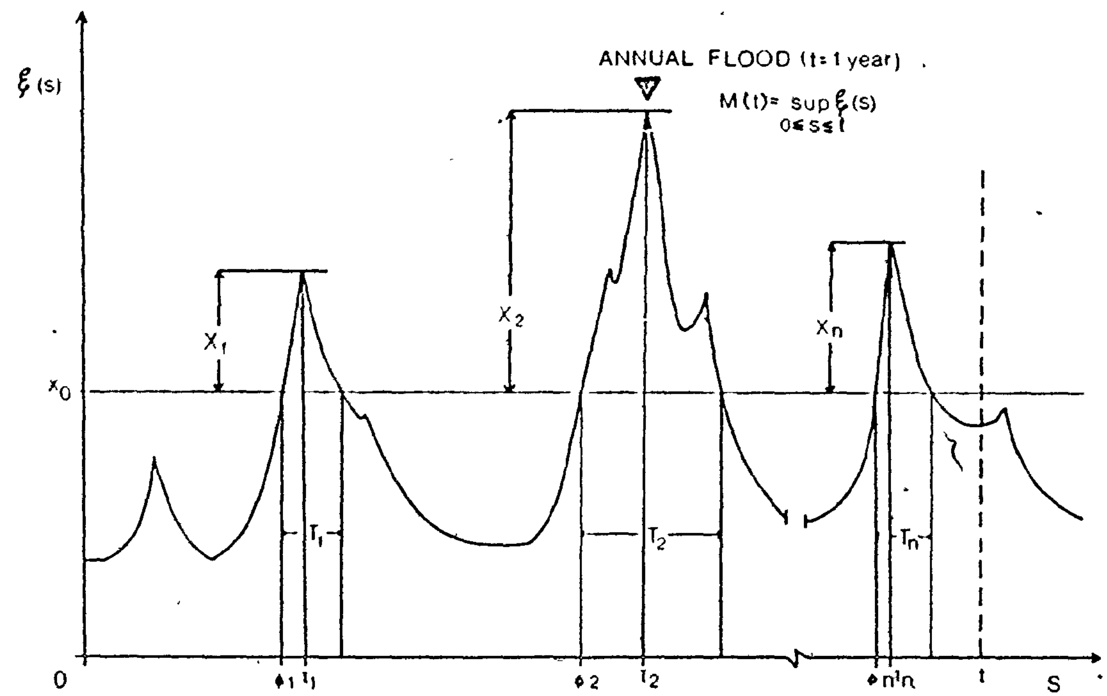
$$X_1, X_2, \ldots X_{\eta(t)} \tag{2.3}$$

where

$$X_k = \xi(\tau_k) - x_o \qquad k = 1, 2, \ldots \tag{2.4}$$

This series is defined as the partial duration series. The largest observed value of X_k in the time period (0,t) is designated $\chi(t)$: i.e.,

$$\chi(t) = \sup_{0 \leq k \leq \eta(t)} X_k \tag{2.5}$$



after Todorovic,1978

Figure 2.1 Sample function of the process $\xi(s)$ and the definition of highflow variables.

The special case where t is equal to one calendar year $\chi(t)$ is not equivalent to an observation of the annual flood series. The maximum value of the process $\xi(s)$ in a year can be denoted by $M(t)$: i.e.

$$M(t) = \sup_{0 \le s \le t} \xi(s) \tag{2.6}$$

To be the supremum, $M(t)$ need not necessarily be greater than the base level, x_o. Annual flood series may be defined as n values of $M(t)$ observed in n years of the process ξ.

Denote the k^{th} upcrossing of x_o of the process $\xi(s)$ by ϕ_k, which is a random variable k = 1, 2, ... The period of time T_k between the k^{th} upcrossing and k^{th} downcrossing of x_o, the duration of the k^{th} exceedance, is the final random variable of interest.

2.3 Literature review

2.3.1 Annual flood series

Annual flood series have been studied extensively (see Dalrymple, 1960; Chow, 1964). The range of approaches used is due to a lack of adequate theoretical basis. Early literature concentrated upon the calculation of observed exceedance probabilities (Jarvis, 1936; Hazen, 1930; Kimball. 1946). Gumbel (1941) applied extreme value theory of Fisher and Tippett (1928) to the problem.

Extreme value theory indicates that if the random variable Y_M is the maximum in a sample of size M, drawn from the same population, providing M is sufficiently large, the distribution of Y_M is one of three forms, depending upon the distribution of the population. The Gumbel distribution, double exponential or Fisher-Tippett extremal type-I distribution (Haan, 1977), is one of the three limiting forms of extreme value distributions. Gumbel (1958) states that streamflow does not meet the mathematical assumptions of extreme value theory.

> 'It must be admitted that the good fit cannot be foreseen from the theory, which is based upon three assumptions: 1) The distribution of daily discharges is of the exponential type. 2) N = 365 is sufficiently large and 3) The daily observations are independent. Assumptions 1) and 2) cannot be checked since the analytical form of the discharge is unknown. The third assumption does not hold and the number of independent observations is obviously less than 365' (p.238)

Later authors (Bobée and Villeneuve, 1975 ; Gupta et al, 1976; Todorovic, 1978; Taesombut and Yevjevich, 1978) have further questioned the theoretical basis of extreme value theory for analysing annual flood series. Daily and monthly streamflow data are neither independent nor identically distributed (Matalas, 1967; Moss and Bryson, 1974). Gumbel's suggestion of replacing the dependent variables by a smaller number of independent ones further violates the assumption concerning sample sizes.

Without its theoretical justification the only basis for using the Gumbel distribution is that it fits the observations in most cases. Hydrologists have employed other distributions, with equal lack of theoretical support. Foster (1924) used the observed skew of annual flood series as an indication that the Pearson type III distribution should be employed. Following the work of Benson (1968) the U.S. Water Resources Council (1976) examined many of the existing techniques and recommended the use of the log-Pearson type III distribution because of its versatility in fitting observed flood series.

Parameter estimation for the log-Pearson distribution requires the skewness of the logarithms of the observed sample. The difficulty in employing distributions that require more than two parameters (Matalas and Wallis, 1973; Bobée, 1975; Houghton, 1978; Boughton, 1980) was foreseen by Slade (1936) when he observed that

> '... skewness is never a truly significant characteristic when the sample from which it is computed has less than 140 items ... and it is quite meaningless to measure them when there are 50 or fewer items' (p. 426)

Since streamflow records seldom cover more than 50 years a surrogate measure of sample skewness has been sought. Hardison (1974), Matalas et al. (1975) and Wallis et al (1977) have looked for regionally averaged measures. A second approach has been to try to interrelate the parametric values of empirically fitted distributions (Landwehr et al, 1979, 1980).

The Natural Environment Research Council of the United Kingdom (1975) carried out investigations similar to those of the U.S. Water Resources Council (1967, 1976). It advocates the use of the Gumbel distribution on the basis of the stability of the parametric estimates compared with those of six other distributions applied to streamflow records in Britain and Ireland.

The use of a single empirically-based distribution and the increased complexity of its application has prompted opposition from engineers and hydrologists. (Dalrymple, 1970; Klemeš 1976). Criticism centres upon the rejection of all other empirically-based models and the concentration of research upon one operational model. Klemeš (1974) points out that, historically, the best operational models need not be physically based and that their success may hinder the development of an understanding of the phenomenon being studied. In response to these trends hydrologists have reconsidered the recent advances in practical terms (eg. Reich and Renard, 1981). Others have attempted to derive the distribution of annual floods by consideration of partial duration series following the work of Todorovic (1970) and Zelenhasic (1970).

2.3.2 Partial duration series

Annual flood series have several practical drawbacks. On occasion the second ranked flood in a particular year, may be larger than the annual flood of another year and yet not be included in the flood analysis. If the probability of a given level of flow is important (as in the design and construction of hydraulic structures) rather than the probability that it is the largest in the year, then this omission might be crucial. The annual floods in arid and semi-arid conditions may not warrant that description in the more common usage of the term flood. Finally, the selection of one flow per year places an unnecessary restriction on an already limited sample.

The advantages of the partial duration series prompted their investigation by hydrologists (Langbein, 1949; Dalrymple, 1960). Initial interest was limited to their empirical relation to annual flood series. Borgman (1963) and Shane and Lynn (1964) modelled the number of highflows, or exceedances of a given truncation level, as a time independent Poisson process. Shane and Lynn (1964) noted that the assumption of time independence was unrealistic. Kirby (1969) defined highflow peaks as successes in a sequence of randomly spaced Bernoulli trials, each representing the occurrence of a hydrograph peak. He showed that when the exceedance level was raised sufficiently high, the observed probability distributions of the number of exceedances approached that of a Poisson process. To completely describe the flood phenomenon the number and magnitude of the exceedances must be considered. This problem has been approached by Todorovic and his co-workers (Todorovic, 1970; Todorovic and Zelenhasic, 1970; Todorovic and Rousselle, 1971; Todorovic and Woolhiser, 1972) and Gupta et al. (1976). Todorovic (1970) investigated the characteristics of sequences of random variables, which were of random length. Todorovic and Zelenhasic (1970) took streamflow partial duration series in an arbitrary but fixed time period to represent such a situation. A time dependent Poisson process models the length of each sequence of observations in a given time period, i.e. the number of exceedances in a year. It was assumed that the magnitude of these exceedances comprised a series of independent and exponentially distributed random variables. No theoretical justification is provided for the latter assumption, although there is a proven empirical fit (Todorovic and Rousselle, 1971).

Good agreement between the proposed models and empirical results has been observed in several U.S. rivers (Todorovic and Woolhiser, 1972; Taesombut and Yevjevich, 1978). The assumptions of independent and identically distributed exceedance magnitudes was relaxed by Todorovic and Rousselle (1971). This allows the characteristics of likely highflows to vary through the year and permits the seasonal model proposed by Gupta et al. (1976) to be replaced by a time dependent stochastic model (North, 1980). The advantages of this approach are that it obviates the necessity of the arbitrary division of the year and increases the sample size for parameter estimation.

2.4 Relationship between partial duration and annual flood series

The works of Langbein (1949) and Chow (1950) remain central to discussions of the relationship between the two highflow series. Chow (1964) presents the argument as follows:

Let P_E be the average number of events per year of a magnitude greater than or equal to x, in a partial duration series. Let m be the average number of exceedances of all magnitudes per year. Thus mn represents the total number of exceedances in the n years of record. Then P_E/m is the probability of an event being equal to x or greater, and $1 - P_E/m$ is the probability of an event being less than x. Thus the probability of an event of magnitude x being the maximum of the m events in a year is $(1 - P_E/m)^m$. This probability approaches e^{-P_E} when P_E is small compared to m. Therefore the probability P_M of the largest flow in a year being equal to, or greater than, x is

$$P_M = 1 - e^{-P_E} \quad \text{.....} \tag{2.7}$$

or

$$P_E = -\ln(1-P_M) \tag{2.8}$$

As P_M and P_E become large they approach one another. Chow (1950) estimated this point to be equivalent to a return period of four or five years.

Zelenhasic (1970) described the above relationship more precisely. The number of exceedances per year were assumed to be Poisson distributed and their magnitudes exponential. Under these assumptions the probability distribution of the largest annual exceedance was found to be 'similar' (Gupta et al., 1976) to the Gumbel distribution. These results explain the Gumbel distribution's applicability and lack of basis in extreme value theory. Cunane (1973) compared estimates of the magnitudes of floods of given return periods using the two highflow series. The partial duration method gave a lower sampling variance when the number of observations was at least 1.65 times larger than that of the annual flood series.

2.5 Regionalising highflows

Benson and Matalas (1967) highlighted two of the major problems of statistical hydrology. Many streamflow records are short and contain sampling errors. These errors are preserved in statistically extended data. Secondly predictions at ungauged locations are impossible because of the lack of historical records for parameter estimation. The aggregation of streamflow records from within an homogenous hydrologic region is therefore a desireable process. It effectively lengthens the 'regional record' of streamflow. Dalrymple (1960) demonstrated that a set of frequency curves of annual flood series can be combined to provide a more reliable frequency estimate than one based on a record of twenty-five years or less. Ungauged basins can be attributed with the characteristics of the region within which they lie.

The above propositions pose two basic problems: How to define regions of similar highflow characteristics and how to predict variations of an individual basin within the group. In the context of highflows analysis has been restricted to annual flood series.

2.5.1 The definition of highflow regions

The Gumbel distribution provides an objective approach to regionalisation via Langbein's regional homogeneity test (Dalrymple, 1960). The 95% confidence limits are drawn up about the 10 year recurrence interval flood as a function of the length of record (see figure 2.2). An average ratio of the 10 year flood to the mean (2.33 year) flood is computed for the entire sample. The product of the ratio and individual basins' mean flood is an estimated 10 year flood. The recorded return period of the flood volume of a corresponding size is plotted on the graph paper, the abcissa being the appropriate length of record. Stations falling within the 95% confidence limits are considered homogenous.

This technique has been widely used by Biswas and Fleming (1966), Coulson (1967), and Collier and Nix (1967). Dalrymple (1960, p. 47) lists regional flood frequency reports in the United States. The use of regression analysis to extend short streamflow records by comparison to longer records induces a dependence in later analyses as all stations possessing short records will tend towards the behaviour of systems gauged for the longest period. The definition of regions is susceptible to changes in the return period taken for the highflow comparison.

2.2.5 Prediction of variability within a region

When the environment is sufficiently homogenous no spatial differentiation is required (Espey and Wimslow, 1974). More commonly multiple regression is used to establish a relationship between the variable of interest and physical variables (Guymon, 1974). Leith (1975, 1976) analysed mean annual floods and Espey and Wimslow (1974) annual floods of a given return period, as independent variables. The multiple regression model is as follows:

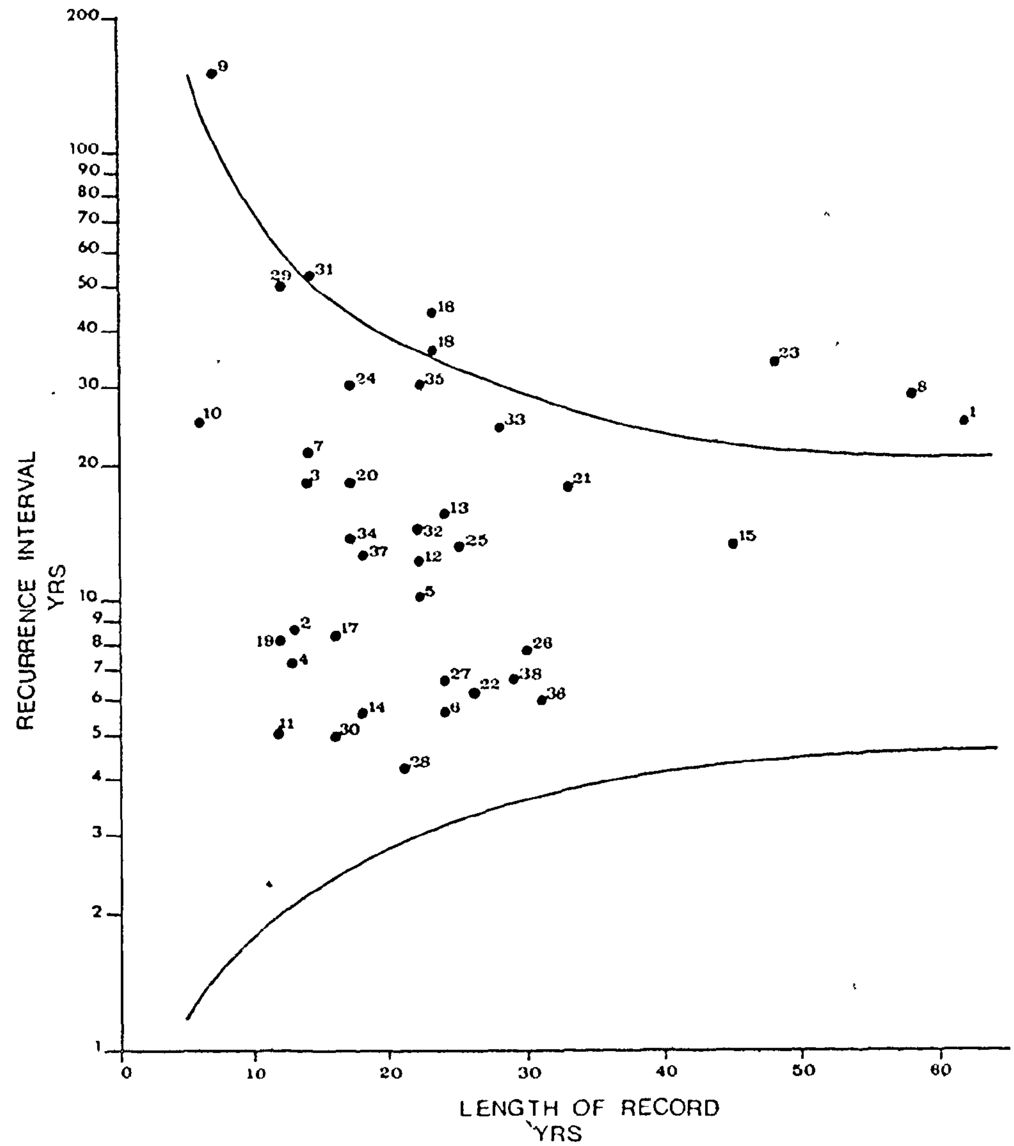


Figure 2.2 Langbein homogeneity test applied to the stations sampled in the analysis of the annual flood series in the Fraser catchment.

$$\hat{Q} = a_o + \sum_{i=1}^{j} a_i v_i \tag{2.9}$$

Where $\hat{Q}$ is the estimate of the variable of interest, the a's are regression constants and coefficients and the v's are the independent variables. The number of variables, j, included in the regression is determined by stepwise regression. Estimates of highflow characteristics may be obtained by substituting basin variables into equation 2.9.

Leith (1975, 1976) grouped sample basins 'a priori' and used the standard errors of the regional regression equations as an indication of the homogeneity of a region.

2.6 Distribution of Annual Flood Series

On the basis of its proven applicability; need for the estimation of only two parameters and potential theoretical basis the Gumbel distribution was selected to model annual flood series. Its probability density function is

$$f(M(t)=x;\alpha,\beta) = \alpha\cdot\exp[-\alpha(x-\beta)-\exp-(\alpha(x-\beta))] \tag{2.10}$$

and its distribution function is

$$F(M(t) \leq x;\alpha,\beta) = \exp[-\exp[-\alpha(x-\beta)]] \tag{2.11}$$

in which α and β are location and scale parameters respectively. Estimates of these parameters by the method of moments are given by Yevjevich (1972) as:

$$\alpha = 1.281/\sigma \tag{2.12}$$

$$\beta = \mu - 0.45\sigma \tag{2.13}$$

and μ and σ are the mean and standard deviation of the distribution respectively. The skewness is a constant of 1.14.

2.7 Distributions of Partial Duration Series variables

The selection of distributions is primarily based upon the theoretical work of Todorovic (1978) and the empirical findings of Taesombut and Yevjevich (1978).

2.7.1 The number of exceedances

Cramer and Leadbetter (1967) indicate that the number of crossings of a given base level, x_o, by a Gaussian process $\xi(s)$ approaches a Poisson process as $x_o \to \infty$. The density function of a Poisson distribution is

$$f(\eta(t)=m;\lambda) = [\exp(-\lambda) \cdot \lambda^m]/m! \tag{2.14}$$

where λ is a parameter > 0 and estimated by.

$$\lambda = \eta(t)/n \tag{2.15}$$

where $\eta(t)$ is the number of crossing in the period of record.

n is the number of years of record.

The mean and variance of the distribution are equal. This is seldom true of streamflow records but Taesombut and Yevjevich (1978) found little significant improvement of goodness of fit when distributions more or less similar to the Poisson were fitted.

To take into account the effect of seasonality the parameter, λ, can be expressed as a function of time (Ross, 1976) and its density function becomes

$$f(\eta(t) = m; \lambda, t) = \exp(-\lambda(t)) \cdot \lambda(t)^m / m! \tag{2.16}$$

where $f(\eta(t) = m)$ is the probability of attaining m events in time t, $t \leq 365$ days. $\lambda(t)$ is the expected number of crossings up to t, and

$$\lambda(t) = \eta(t)/n \tag{2.17}$$

where $\eta(t)$ is the total number of crossings up to time t. Throughout the thesis time, t, will be expressed as Julian days

2.7.2 The timing of exceedances

The nature of the function $\lambda(t)$ is important in the operationalisation of equation (2.16). Todorovic and Woolhiser (1972) and North (1980) express $\lambda(t)$ as a fourier series. Todorovic (1978, p. 348) points out that this is 'a rather cumbersome analytical solution', but could find no better representation.

The cumulative relative frequency of dates of exceedances through the year may also be approximated by the normal distribution, whose probability distribution is given as:

$$F(t\ \mu, \sigma) = \int_{-\infty}^{t} 1/\sqrt{2\pi\sigma}_t \cdot \exp(-(s-\mu_t)^2/2\cdot\sigma_t^2)\,ds \tag{2.18}$$

where μ_t = mean date of exceedance

σ_t = standard deviation of date of exceedance.

In practice the lower bound of the integral is taken to be 0, without much loss of information. The product of F(t) and λ, the observed average number of exceedance per year, defines the function $\lambda(t)$ thus.

$$\lambda(t) = F(t) \cdot \lambda \tag{2.19}$$

There appears to be some physical justification for this method of modelling the timing of events if only one process is responsible for the generation of floods. In this study snowmelt is of particular importance. Snowmelt generally occurs at the same time every year as a result of macro-climatic conditions and astrophysical alignments. Temporal variations are brought about by year to year variations in local meteorological conditions. Statistically these conditions would translate to a long-term mean date of exceedance with a known standard deviation.

2.7.3 The magnitude of exceedances

Empirical evidence supports the application of the exponential distribution to the magnitude of peak floods, $H(x)$.

$$H(x) = P(X_k \leq x) \tag{2.20}$$

for all $k = 1, 2, \ldots$

Zelenhasic (1970) tested both the gamma and exponential distributions. Results (Taesombut and Yevjevich, 1978; Rousselle, 1972) suggest that the exponential distribution, itself a special case of the gamma, be most universally applicable. Its probability density function is

$$f(x,\gamma) = 1/\gamma \cdot \exp(-x/\gamma) \tag{2.21}$$

where the method of moments estimate of γ is

$$\gamma = \mu \tag{2.22}$$

The mean and variance are equal and the probability distribution function is

$$F(x;\beta) = 1 - \exp(1/\gamma \cdot x) \qquad (2.23)$$

2.7.4 The duration of exceedances

Both North (1980) and Todorovic (1978) propose that the methods and techniques of partial duration series analysis could be applied to the duration of exceedances but neither give any indication of distributions that might be used to model their behaviour.

Cramer and Leadbetter (1967) discuss the distribution of lengths of 'upward excursions'. An 'upward excursion' is defined as the interval between an upcrossing of a fixed level by a stochastic process and the following downcrossing. In terms of partial duration series these can clearly be seen to be equivalent to the duration of flooding. They show (p. 274) that the distribution of upward excursions approximates to an exponential distribution as the crossing level grows larger. Equations (2.21) and (2.22) are used in this study to model the distribution of duration of flood.

2.8 <u>Derivation of annual flood series from partial duration series</u>

Applying the principles outlined in section 2.4, Zelenhasic (1970) arrived at the following expression for the distribution of the peak exceedance, χ, of the process $\xi(s)$ in a year

$$F(x) = P(\chi \le x) = P(E_o) + \sum_{k=1}^{\infty} [(H(x))^k \cdot P(E_k)] \qquad (2.24)$$

where $H(x)$ is given by equation (2.23) describing the magnitude of exceedance. $P(E_k)$ is given by equation (2.16) describing the number of exceedances as a Poisson distribution. It is assumed that 1) $X_1, X_2, \ldots X_k$ are independent of η and 2) $X_1, X_2, \ldots X_k$ are mutually independent random events with the common distribution function $H(x)$. By substituting equations (2.16) and (2.23) into (2.24) the distribution of the largest exceedance of the year becomes

$$F(x) = \exp(-\lambda(t)) \sum_{k=1}^{\infty} \lambda(t)^k/k! \cdot (1-\exp(-x/\gamma))^k \tag{2.25}$$

which Zelenhasic (1970) reduces to

$$F(x) = \exp(-\lambda(t)(\exp(-x/\gamma))) \tag{2.26}$$

where $\lambda(t)$ and γ are defined by equations (2.17) and (2.22) respectively.

Following the work of Taesombut and Yevjevich (1978) the estimated annual maximum exceedance, χ, for a given period, T, is expressed by:

$$\chi = \gamma \cdot \ln\lambda + \gamma \cdot y(T) \tag{2.27}$$

where y(T) is Gumbel's reduced y variate

$$y(T) = -\ln[-\ln(1 - 1/T)] \tag{2.28}$$

In order to compare this series of annual peak exceedances and their computed return periods with those of an annual flood series, the discharge of the annual flood estimated from the partial duration series, for a given return period, Q(T)p, becomes

$$Q(T)p = x_o + \gamma\cdot\ln\lambda + \gamma \cdot y(T) \tag{2.29}$$

where x_o is the truncation level selected in the derivation of the partial duration series.

2.9 Regionalisation methodology

Regionalisations are based upon the estimated parameters of the distributions describing the annual flood series and partial duration series. The parameters describe completely the temporal behaviour of highflows at a station. The regionalisation therefore describes both the spatial and temporal variation of highflows across the study area. Discriminant analysis (see Tatsuoka, 1971) is used to provide a statistical distinction between 'a priori' established regions. Discriminant functions are computed which allow the calculation of the probabilities that an individual basin, by virtue of its characterising high flow parameters, belongs to one of the 'a priori' regions. The procedure is repeated iteratively and after each trial, basins are assigned to the region to which it had the highest probability of membership. When all the basins have been correctly assigned the regions, now based upon the parametric values rather than the 'a priori' groupings, can be identified. Details of the method using a program from Nie et al (1975) are provided by Waylen and Woo (1981).

Within each region the parameters of the frequency distributions are related to climatic and physiographic variables using equation (2.9) where the constants and coefficients will vary with each parameter and each region. Predicted highflow parameters of an ungauged basin may be obtained by substituting the values of the relevant climatic and physiographic data into the appropriate regional equations. These parameters in turn may be entered into the probability functions and high flow characteristics at various return periods be estimated.

CHAPTER III

STUDY AREA AND RESEARCH DATA

3.1 Requirements of a study area

A relatively comprehensive network of streamflow gauging stations, representing each of the major contributing areas of the region is necessary. The area of the gauged basins should be similar. These two specifications minimise the spatial interpolation of the findings from the sampled basins and prevent areal biases in the process. Long periods of flow record are desirable. Dalrymple (1960) recommends 25 years of record to estimate the parameters of the Gumbel distribution. Finally the study area should encompass a set of diverse hydrologic environments. This produces a variety of streamflow characteristics, which in turn lend themselves to a clearer exposition of high-flow regions.

The Fraser River catchment, British Columbia, was selected for analysis on the basis of the above requirements.

3.2 The selection of gauging stations

3,2.1 Distribution of sampled stations

Figure 3.1 shows the locations of the 71 gauging stations whose records were selected for study. The study area is defined as the gauging station at Hope (Water Survey of Canada code 08MF005). This station possesses an excellent long streamflow record from 1912 to 1976 (see Appendix A), which combines

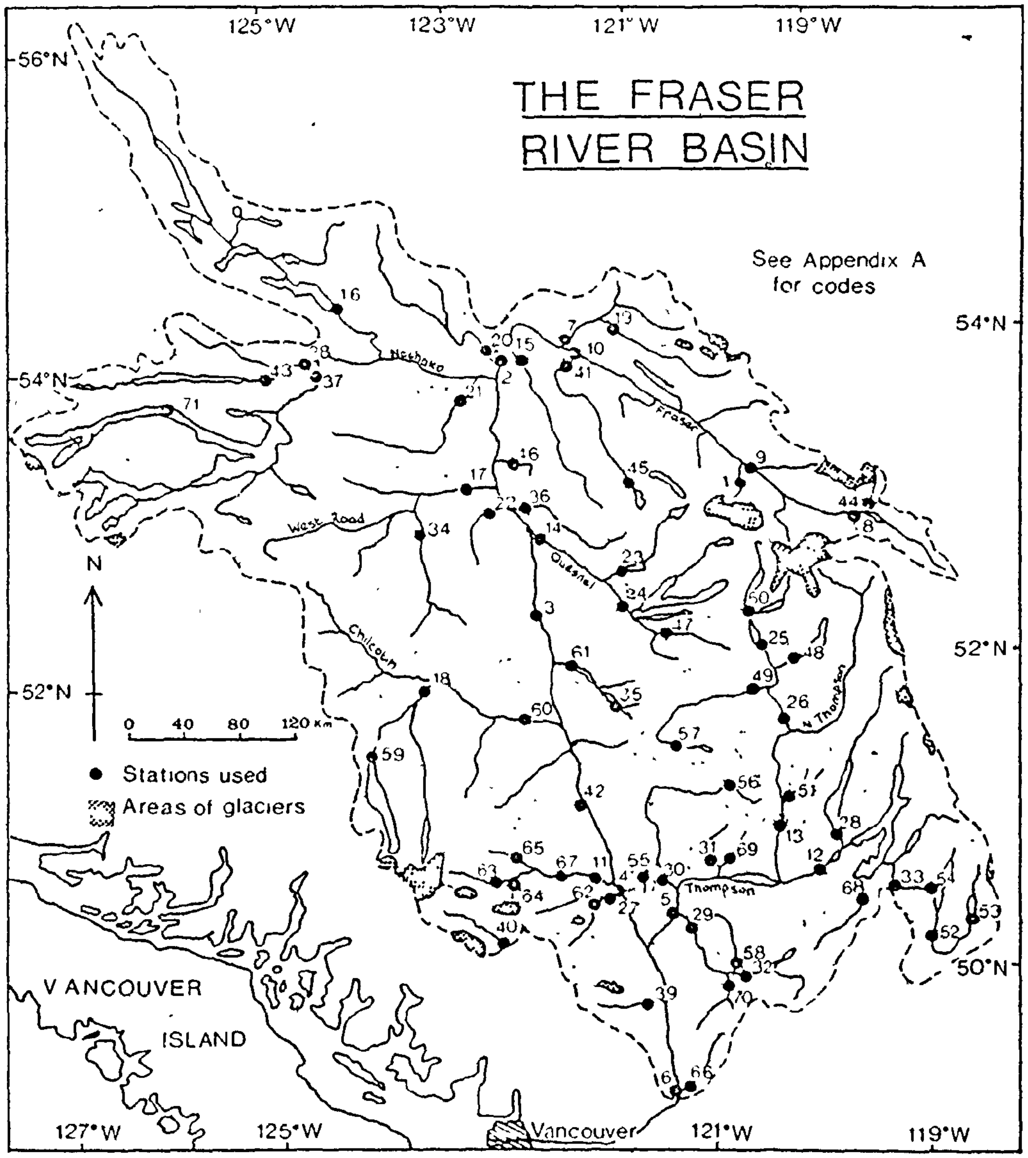


Figure 3.1 The Fraser River Basin showing the location of the sampled basins and streamflow gauges. Areas of glacierisation are shown by the stippled portions.

the contributions of all the Fraser's major tributaries, with the exception of the Lillooet River. Although the Lillooet joins the Fraser below Hope it was included in the regional analysis as the area gauged near Pemberton Meadows (W.S.C. 08MG005) is contiguous to the main study area.

Wherever possible each of the major tributaries has several sampled stations of progressively smaller basin areas. The minimum gauged area was set a $4 \times 10^2 km^2$, which is close to the modal class of gauged basins in British Columbia (Kreuder, 1979). The number of sampled stations in the $2.17 \times 10^5 km^2$ (Water Survey of Canada, 1979) study area, corresponds to a density of one station per $3.00 \times 10^3 km^2$, which is well below the World Meteorological Organisation's (1965) guideline for mountainous terrain of $5.00 \times 10^3 km^2$.

3.2.2 Durations of streamflow records

The periods of recorded streamflow are shown in Appendix A. The requirement of 25 years of record had to be relaxed in some areas, due to the paucity of suitable data. Wherever possible records possessing a common time base have been used. On the Bridge and Nechako systems only data pre-dating flow regulation have been used at affected sample sites. On three rivers the locations of gauging stations have been moved during the period of record. In each case the two records have been considered as one. The movement of sites brought about changes in gauged areas of 9.5%, 2.6% and 0.5% respectively on the North Thompson (W.S.C. 08LB064 and 08LB022), South Thompson (W.S.C.

08LE069 and 08LE031) and Thompson (W.S.C. 08LF051 and 08LF022) Rivers.

3.3 Physiography and Hydrology of the Fraser catchment

3.3.1 General

The study area lies entirely within British Columbia and drains approximately one quarter of the province. In the east the basin is bounded by the Alberta/British Columbia border; to the west by the Coast Mountains. Its North-South extent defined by the 49th and 56th parallels encompasses physically diverse regions collectively termed the Western Cordillera. The review that follows is brief and only discusses those factors that affect the generation and nature of highflows.

3.3.2 Physiography

A comprehensive review of the state of knowledge of the geologic history of this area is provided by Monger and Price (1979). The basin is bounded to the west and southwest by the Coast and Cascade Mountains. An ancient fault, the Fraser Fault, presently occupied by the Fraser Canyon separates the two. Generally the ridge of the Coast Mountains lies to the west of the basin boundary, even so elevations in this area may exceed 3,000 m. The major tributaries draining this area, the Nechako, Chilcotin, Bridge and Lillooet, tend to flow down the mountains' eartern flanks. Only one sampled river, the Coquihalla, flows entirely within the Cascades.

The Rocky Mountains define the northeast limit of the

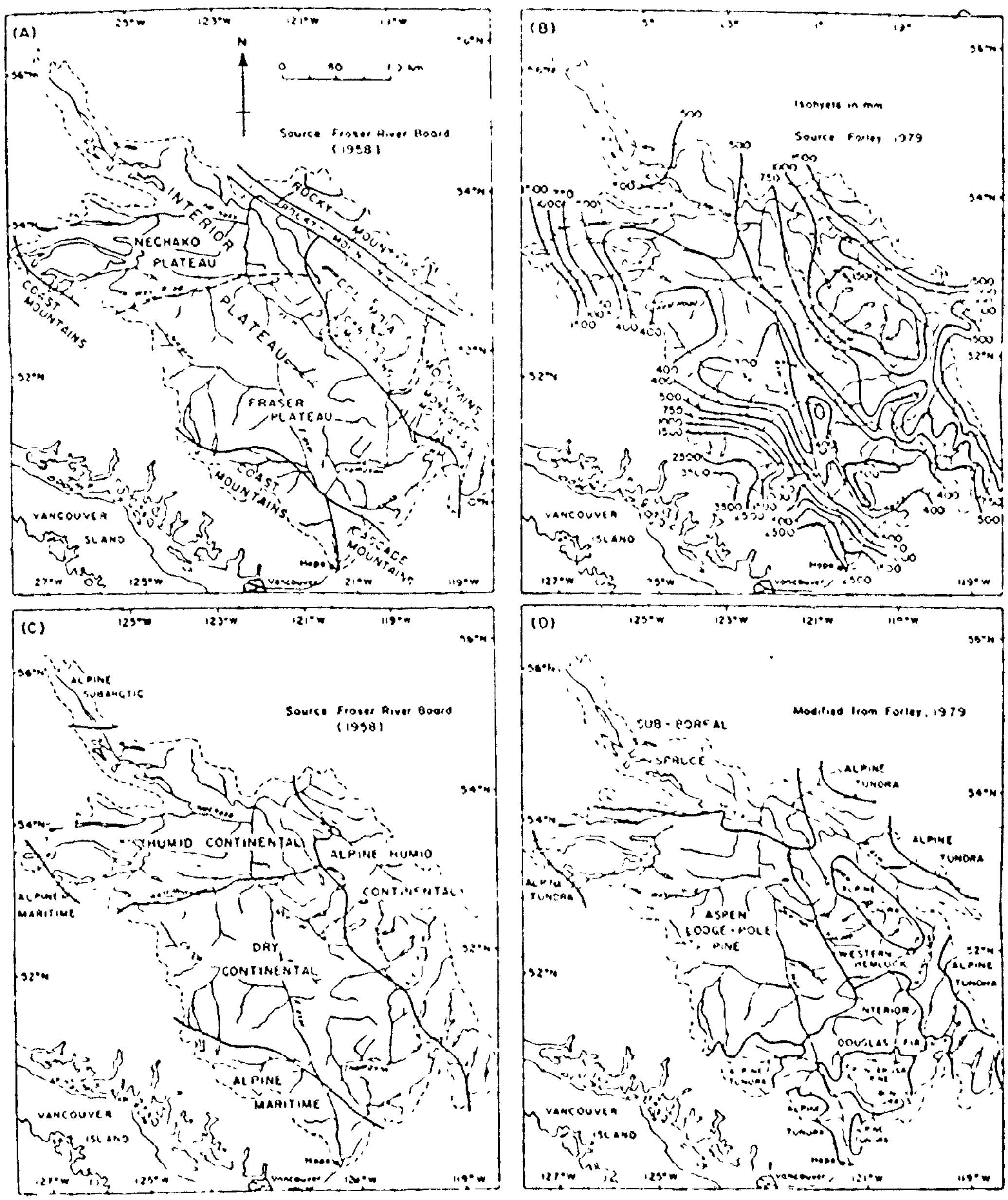


Figure 3.2 The Fraser basin showing (a) physiographic regions, (b) mean annual precipitation, (c) climatic regions, and (d) Biogeoclimatic zones.

basin. Elevations may exceed 3,000 m in this region, where the sampled basins of the McGregor and Moose Rivers are located. The Rocky Mountains are separated from the geologically distinct Columbia Mountains by the Rocky Mountain Trench. The Trench is a long northwest trending valley occupied by the Fraser River for 250 km in its upper course.

The Columbia Mountains are comprised of several physiographic units. Of these the Cariboo and Monashee Mountains lie within the study area. The upper reaches of the North Thompson River divides the two. The eastern extremes of the Columbia Mountains attain similar elevations to those of the Rocky and Coast Mountains, but diminish westward onto the Interior Plateau.

The course of the West Road River and its eastward extension across the Fraser separates the more northerly Nechako Plateau from the Fraser Plateau. Physiographically the division is indistinct. The Nechako Plateau is an area of subdued relief with a regional surface at about 750 m. Occasionally the surface is interrupted by higher land that seldom exceeds 1500 m. The Nechako, Salmon and Stuart Rivers occupy valleys between 20 and 200 m. below the Plateau surface. Elevations of the Plateaux increase towards the South. On the Fraser Plateau local elevation maxima approach 2000 m; 500 m above the regional surface. Local relief is enhanced by the valleys of such rivers as the Nicola and Bonaparte, whose valleys may lie 600 m below the Plateau surface.

3.3.3 Precipitation

Figure 3.3 illustrates the variability of mean monthly precipitation across the basin. The mean annual precipitation across the entire basin estimated by the isohyetal method is 800 mm.

Westerly winds bring high precipitations to the headwaters of the Bridge, Nechako and Lillooet systems. Winter precipitation maxima characterise this 'Alpine Maritime' (Fraser River Board, 1958) precipitation regime. Local precipitation is highly dependent upon relief, thus estimates of 1988 mm.yr^{-1} and 1600 mm yr^{-1} for Tahatsa Lake and Hope (Environment Canada, 1973a) respectively, may be underestimates of local precipitation. Accurate data of such elevation dependency are not available (R. Chilton, B.C. government pers. comm., 1980).

Precipitation on the Interior Plateau declines rapidly in the rainshadow of the Coast Mountains. Mean annual precipitation in the incised valleys of the Fraser Plateau may drop below 300 mm yr^{-1} (Ashcroft, 213 mm yr^{-1}). Such aridity is uncommon on the Nechako Plateau where annual precipitation ranges between 400 and 500 mm. The 'Humid Continental' regime of the north and the 'Dry Continental' of the south have relatively uniform distributions of precipitation throughout the year; summer precipitation arriving as convectional rainfall.

The upper elevations of the Cariboo and Monashee Mountains receive over 1500mm of precipitation annually, with a slight winter maximum. The 'Alpine Humid Continental' regime is highly

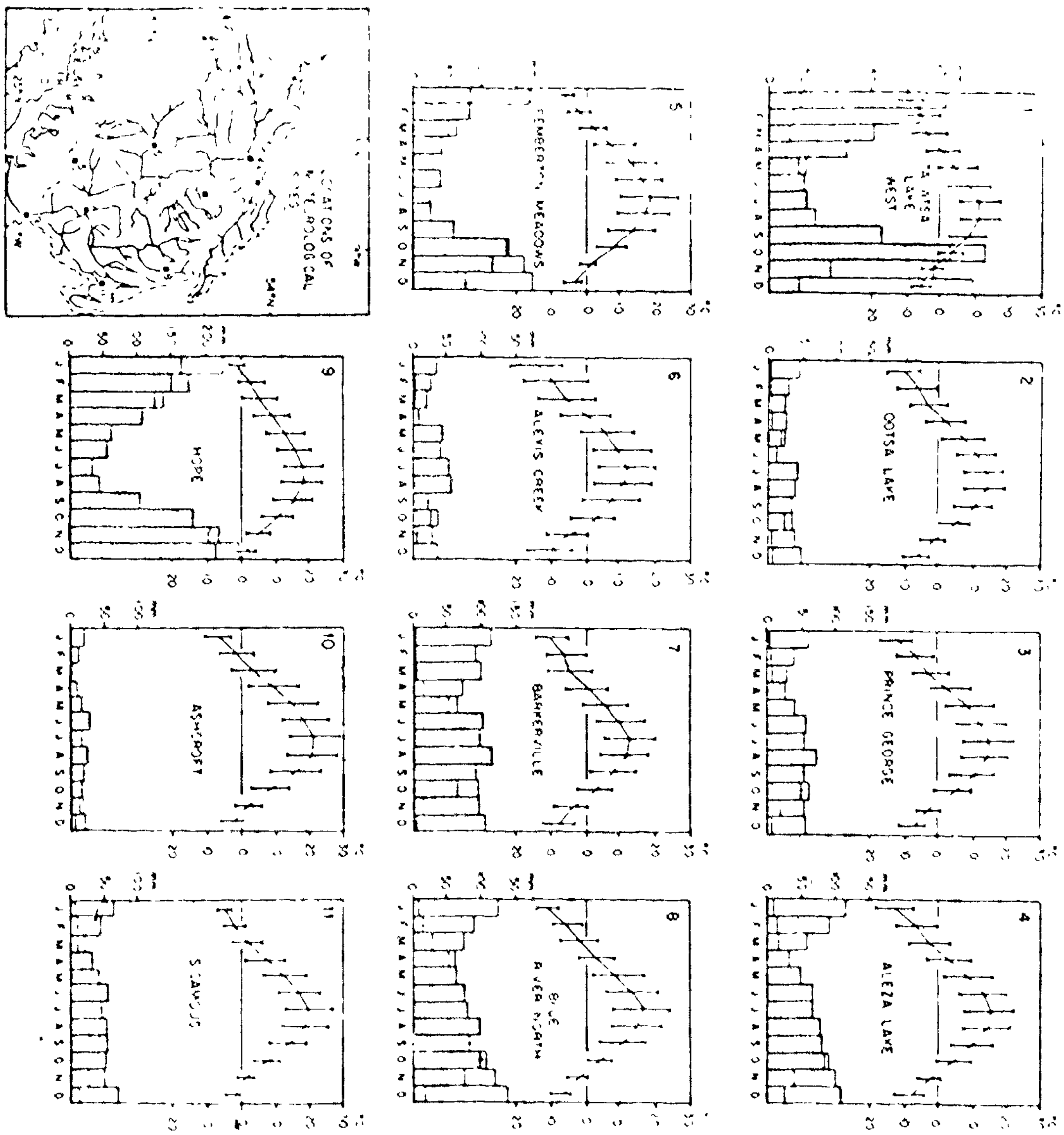


Figure 3.3 Monthly meteorological data for selected stations in the Fraser catchment.

variable locally. There are distinct rainshadow effects in the Rocky Mountain Trench and the Shuswap district. The Rocky Mountains receive equally high precipitation, particularly at higher elevations where the influence of maritime air deflected upward by the Coast Mountains, may be experienced.

3.3.4 Temperature

The temperature characteristics of the area are primarily a function of elevation, latitude and distance from the Pacific. Temporary modification of the pattern is brought about by the type and extent of the air masses occupying the basin. The principal air masses are, Arctic, maritime and continental; Polar maritime and Tropical continental (Kendrew and Kerr, 1956). Polar and Arctic air occupy the basin most of the winter. Extremely low temperatures are experienced when Arctic continental air enters the basin from the east. Pacific air mainly from the south-west, can cause rapid melt and was partially responsible for catastrophic flooding in 1948.

Simple application of the adiabatic lapse rate to the 2500 m of available relief in the basin indicates the local temperature ranges in mountainous areas. The influence of latitude and the distance to the sea can be seen in figure 3.3 (Environment Canada, 1973b). The eastern stations have a range of 5^{oC} more than their western counterparts. At a given latitude it appears that average temperatures remain constant and that the amplitude of monthly temperatures increases as the moderating effect of the ocean diminishes. Table 3.1 shows the meteorological data for the selected stations. It can be seen that the three most southerly stations are on average 5^{oC} warmer than the northern sites.

Table 3.1 Meteorological data for stations in the Fraser catchment

Station	Total Ann. Precip. (mm)	%Snow	Mean Ann. temp. $_{o}$c	range of temp. $_{o}$c
Tahatsa Lake W.	1988	64	1.8	20.6
Ootsa Lake	438	40	3.1	24.0
Prince George	470	36	3.3	26.8
Aleza Lake	931	40	3.0	27.6
Pemberton Meadows	1024	28	7.2	24.5
Alexis Creek	419	40	0.3	25.2
Barkerville	703	49	1.4	22.1
Blue River N.	1127	39	4.1	26.7
Hope	1600	10	9.7	19.1
Ashcroft	213	24	8.7	27.9
Sicamous	604	30	7.9	23.6

Sources, Environment Canada, (1973a, 1973b)

The nature and timing of snowmelt is particularly important in determining streamflow regimes (Pipes et al., 1970). The meteorologic factors combine to produce a pattern of melt that progresses from the low lying areas in the southwest towards the northeast and toward high elevations.

3.3.5 Snow and ice

Three aspects of snow storage should be considered

a) The absolute amount of precipitation that falls as snow

b) The time of the year after which rainfall dominates

c) The frequency of periods of thaw during the time of dominant snow accumulation.

Most of the area experiences a winter precipitation maximum. Snow storage is high as low temperatures correspond to these maxima. Percentages of precipitation in the form of snow vary from 10 to 64 and annual snowfall ranges from 50 mm at Ashcroft to 1170 at Tahtsa Lake. Snowfall dominates the winter months in all but the most southwestern area. Pacific air masses bring frequent rainfall and associated periods of melt to these areas.

Ostrem (1973) investigated the east to west variation of snowlines and glacial feature across the basin. Generally glacierised features appear at lower elevations in the west. Successive deflections of the principal precipitation bearing winds over the Coast, Columbia and Rocky Mountains results in orographic precipitation falling at successively higher elevations. Glaciers occupy less than 1% of the total drainage basin area. They are found in all three principal mountainous areas and have a significant effect upon the streamflow regimes. Fig. 3.1 shows the major areas of glacierisation. Extensive glacial cover is found in the headwaters of the Bridge and Lillooet Rivers. Smaller areas occur in the northern Coast Mountains. Glacierisation in the Cariboo Mountains occurs around the Mounts: Sir Wilfrid Laurier, Sir Sanford and Farnham. Intermittent glacial cover is found along the entire eastern boundary of the basin (Slaymaker, 1972).

3.4 Hydrometeorological regions

Because of its control over hydrologic variables physiography has become the basis of several hydrometeorological divisions of the Fraser basin (see figures 3.2(a) and 3.2(b)). Runoff is the result of the complex interaction of a number of variables in time and space and cannot be easily represented by one alone. Figure 3.2(d) is a modified version of a regionalisation based upon vegetation associations (Farley, 1979). Zones of high elevation, precipitation and snow and ice storage mainly support 'Alpine tundra' vegetation. The 'Western hemlock' zone corresponds closely to the Columbia Mountains of figure 3.2(a) and 'Alpine humid continental' regions (figure 3.2(c)).

The Interior Plateau is divided into distinct regions by vegetation, unlike the poor delineation provided by the physiographic division. The dry deeply dissected southern Plateau is characterised by a ponderossa pine - bunch grass association. The more subdued north supports aspen and lodge pole pine. These divisions reflect the changing environmental conditions across the Interior Plateau. A combination of all the regional divisions with respect to runoff, suggests the regionalisation

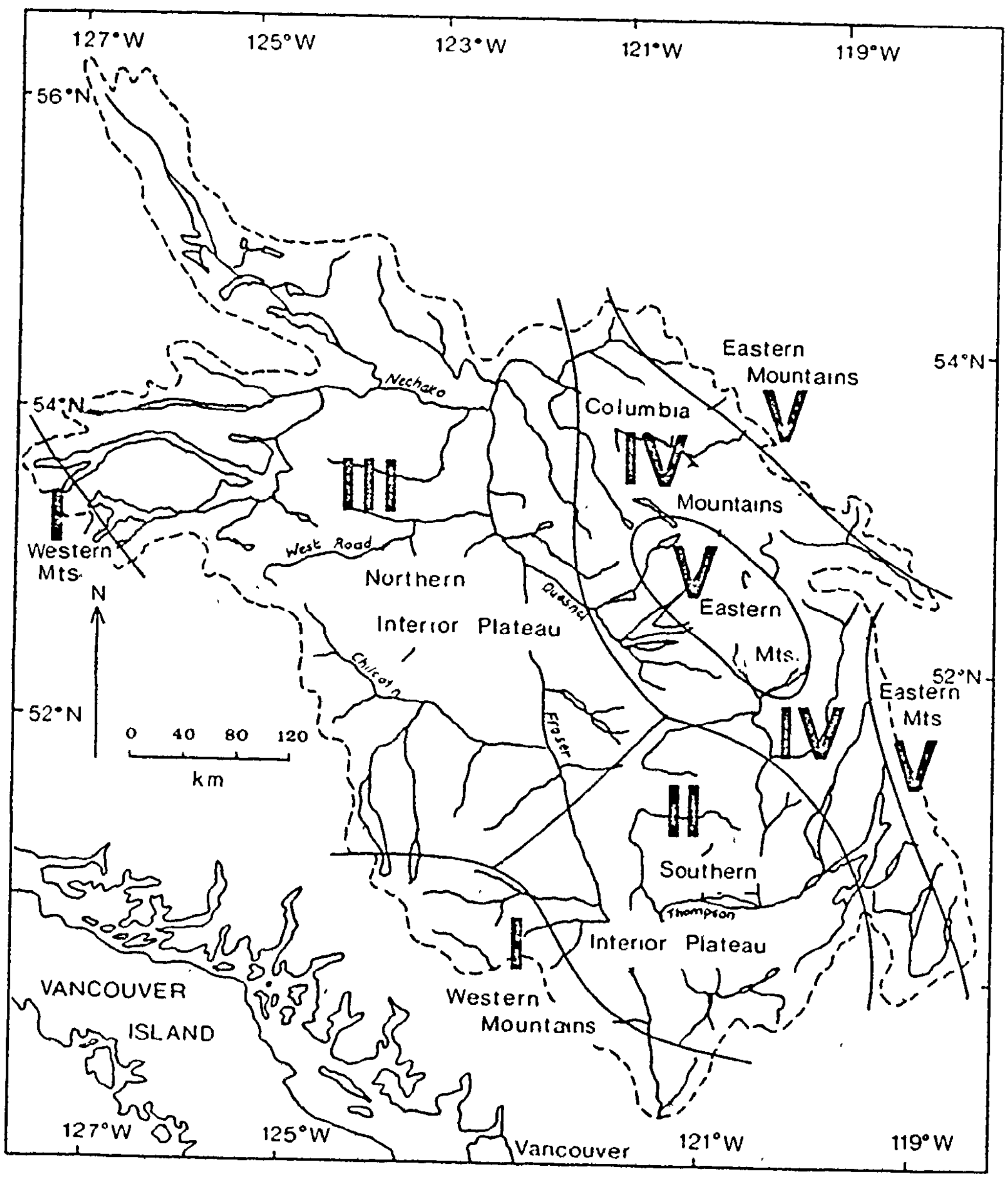


Figure 3.4 Hydrometeorological divisions of the Fraser catchment.

shown in figure 3.4.

3.5 Streamflow regimes

Fig. 3.5 shows mean monthly discharges plus and minus one standard deviation for five samples. Flow characteristics are highly seasonal and are dominated by the release of accumulated snow. The majority of streams are also highly variable in their spring and summer flows from year to year. Winter flow is primarily sustained by baseflow and the depletion of lake storage. Snowmelt causes rapid increases in flow particularly when melt is accompanied by rainfall.

Figure 3.6 illustrates the approximate distribution of the mean and standard deviation of the dates of annual floods. The role of elevation in retarding the date of flood and extending periods of highflows is evident. Local weather conditions, particularly summer convectional rainfall may produce irregularities in the hydrographs. More consistently there is a late fall maximum of precipitation, in mountainous areas this may fall on snow and produce very high flows.

Local and regional variations in the timing and magnitude of hydrologic processes cause marked differences within this generalised regime. The regions of figure 3.4 may be characterised as follows:

I: Western Mountains. This area experiences long periods of highflows sustained during the summer by retreating snowlines and glacial melt. There are marked precipitation maxima during fall and winter.

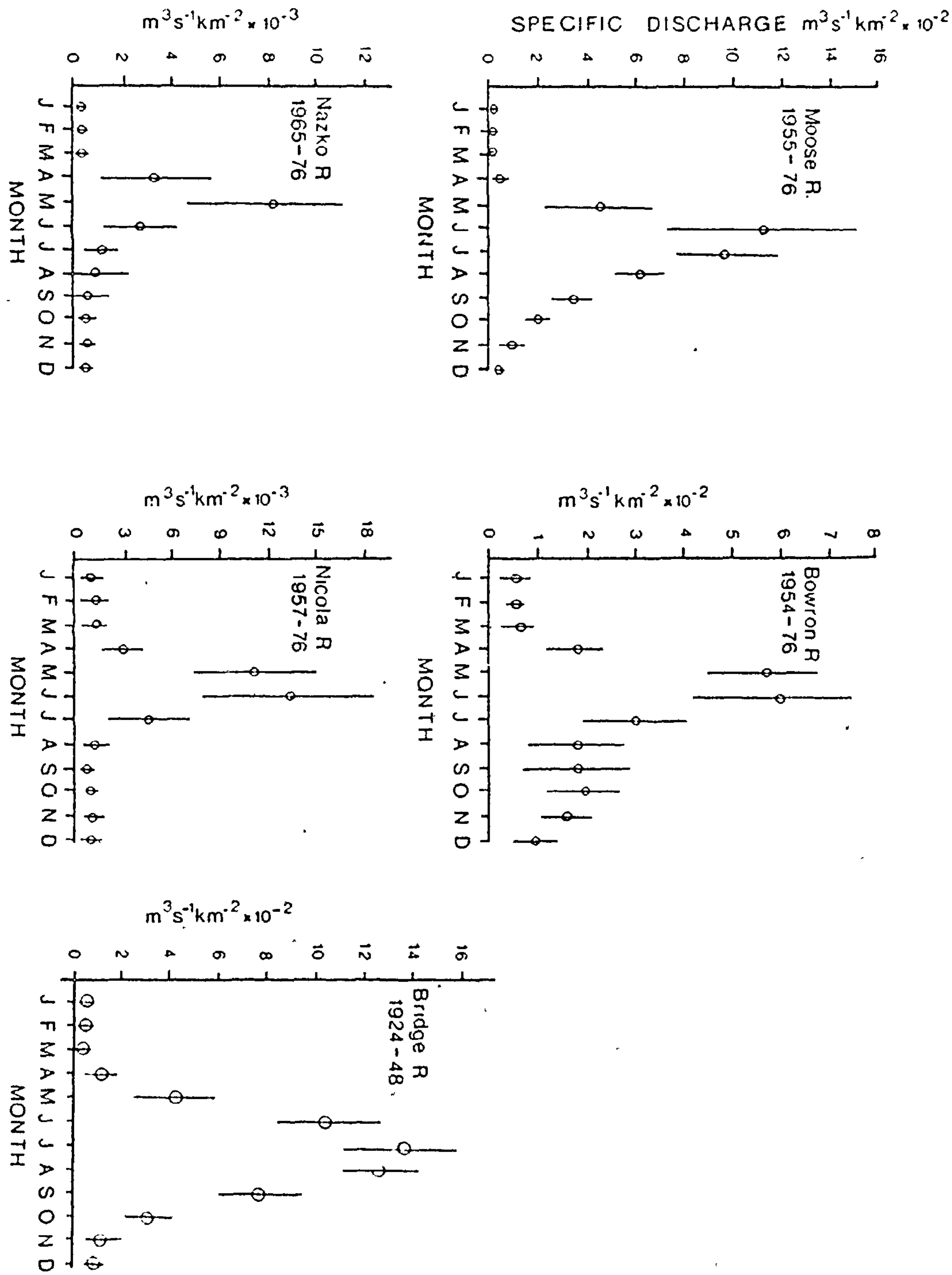


Figure 3.5 Monthly mean discharge plus and minus one standard deviation for sampled basins.

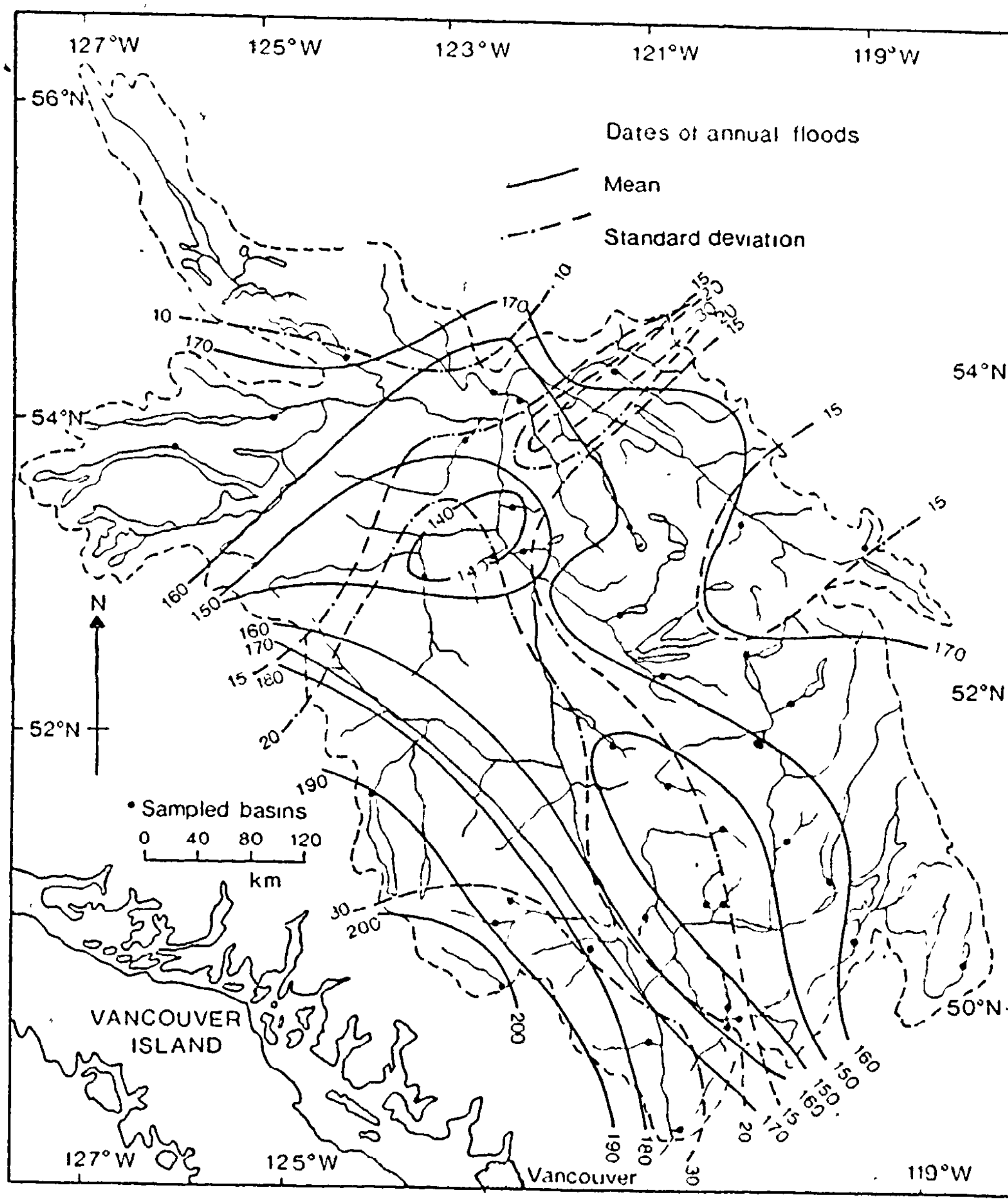


Figure 3.6 Mean and standard deviation of the date of annual floods.

Rain induced melt produces a great variability in winter flows depending upon the proportion of the basin area affected. In the more southerly areas winter is a period of frequent high flows.

II Southern Interior Plateau: The area is relatively low lying and experiences an early snowmelt. The melt period may be extended by the presence of some local available relief. Precipitation is low and evenly distributed throughout the year. Evaporation is high during summer and discharge declines rapidly after snowmelt. Occasional intense summer convectional rain may produce high flows.

III Northern Interior Plateau: The high latitude of the area retards snowmelt although its effect is commonly offset by the general low elevation of the plateau. The plateau rises towards the surrounding mountains and is undissected. Snowmelt tends to occur over a very short period. Flood magnitudes are restricted by the low annual precipitation of the area.

IV Columbia Mountains: Increasing elevations produce increased precipitation and a high proportion of snow storage. Latitude in combination with altitude retards the time of snowmelt. Snow cover is seldom preserved throughout the year.

V Eastern Mountains: At high elevations the Rocky and Columbia Mountains produce streamflow regimes similar to that of the Coast Mountains. Their distance from the warming maritime influence minimises the possibility rain on snow generating flows in the winter months.

Figure 3.7 illustrates the relationship between mean annual flood and drainage basin area for all the sampled basins. The gauging stations on the Fraser River itself are marked independently as are the stations on the Thompson and North and South Thompson Rivers. These stations are not considered to reflect the runoff conditions of their locations. Their large basin areas combine the effects of several hydrologic regions and therefore they have not been allocated to any one group. The remaining stations are distinguished by their geographic locations according to the groups outlined in figure 3.4. At any basin size it can be seen that there are a variety of mean annual flood sizes within the catchment. As a rule mean annual floods are the lowest in the south-central area of the basin and increase towards the peripheries. It can be seen that on the basis of the volume of the mean annual floods the Western and Eastern Mountains are indistinguishable.

The Water Survey of Canada (1972) attempted to differentiate basins ranging in size from 37 km to 18 × 10^3km^2 on the basis of the relationship between drainage basin area and the runoff of the largest recorded flow. They distinguished stations located in the 'Islands and Coast Mountains'; 'Interior Plateau', and 'Interior Mountains' for stations in British Columbia. The distinction between each group is unclear and the basis for differentiation arbitrary.

3.6 Streamflow data

All daily streamflow records of gauging stations, presently

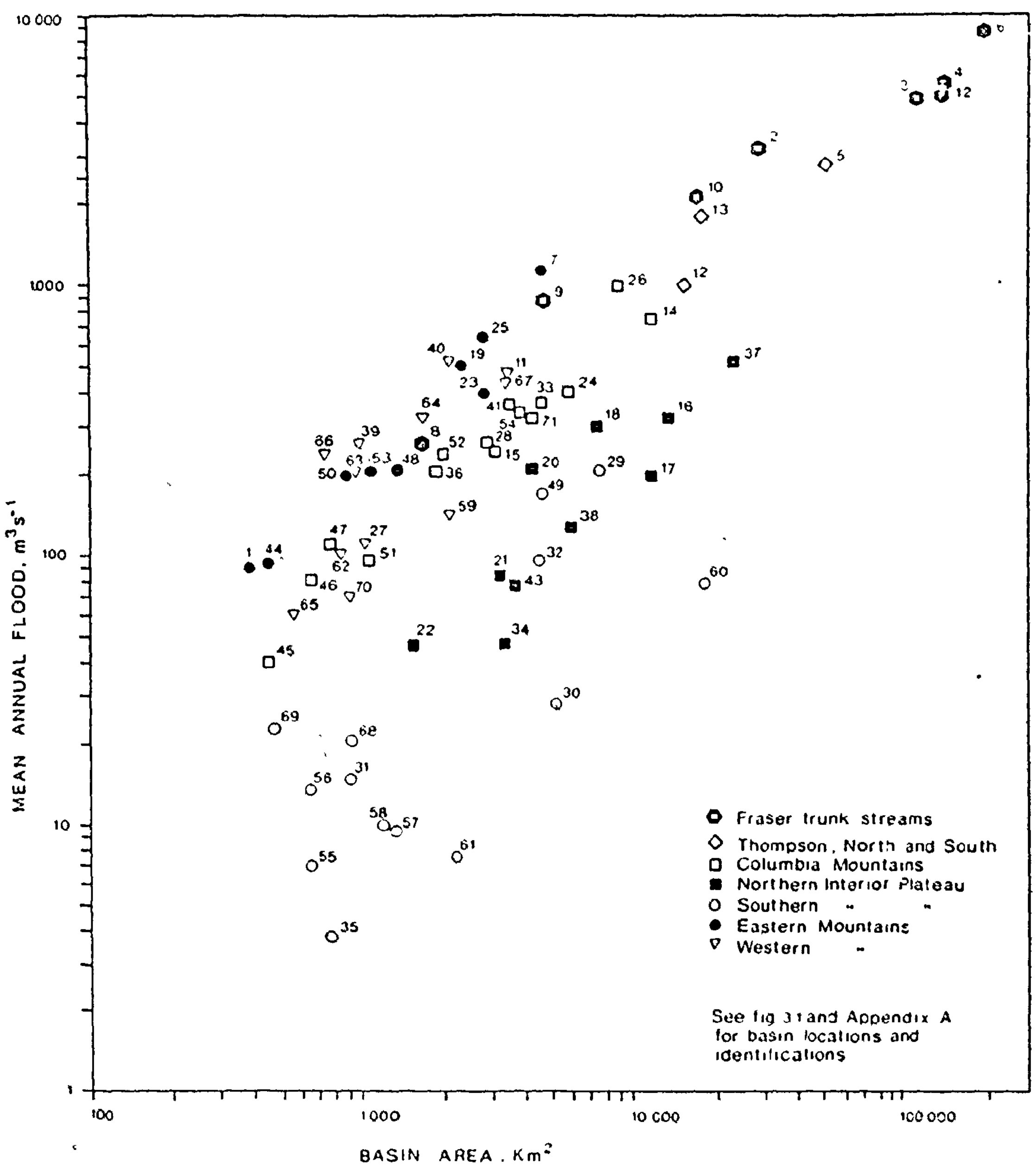


Figure 3.7 The mean annual flood/basin area relationship for the 71 sample basins. The symbols identify the hydrometeorological zone of origin of the basin.

operating, or otherwise, in the Fraser catchment up to and including 1976 were obtained from the Water Survey of Canada. Data collected at 578 stations, constituting 5947 station-years of record, were stored on magnetic tape and accessed by the CYBER 170 at McMaster University Computer Centre.

Daily streamflow were recorded in units of ft^3s^{-1}; these data have been converted to m^3s^{-1}. Frequently a measure of runoff, specific discharge, is referred to; it has units of $m^3s^{-1}km^{-2}$. For individual basins it is obtained by dividing the discharge by drainage basin area.

3.7 Physiographic and Climatic Data

Following the work of Benson and Matalas (1967) and Kreuder (1979) physiographic and climatic data were collected for the sampled basins to establish regional relationships between highflow characteristics and the hydrologic environments. Sources of data were: The Hydrologic Atlas of Canada (1978), Farley (1979), Water Survey of Canada (1979) and the 1,000,000 topographic series of maps. A full compilation of the data is given in Appendix B.

Variables collected included: basin area (A, in km^2); mean annual precipitation (P, in mm); elevation at the centre of the basin (H, in m); distance to the sea (D, in km) average duration of annual snow cover (S, in days); percentage of basin area occupied by glaciers (G) and Lakes (L), and the interquartile range (R, in m).

These variables had been considered important in other

Canadian case studies (Coulson, 1967; Collier and Nix, 1967; and Kreuder, 1979). The precipitation and snow cover data were obtained by the isohyetal method (Gray, 1970). These data are prone to errors of unknown magnitude because of scant climatological records, particularly in mountainous areas of the basin. The physiographic data may be considered accurate because of the readily available large scale maps. Basin areas were taken from Water Survey of Canada (1979) and were used as checks of sums of basin areas above certain elevations in the estimation of hypsometric curves. The interquartile range was calculated as the difference in the elevation above which 25% and 75% of the basin fell. The location of the centre of each basin was estimated by a simple method of moments. The shortest linear distance from the basin centre to a generalised coast, defined as the outer fringe of Vancouver Island and the main land north of the Island, was used as a measure of distance to sea.

CHAPTER IV

ANALYSIS OF ANNUAL FLOOD SERIES

4.1 Introduction

The two previous chapters have considered the frequency of highflows and the spatial variation of those physical processes responsible for their generation. The annual flood series of 38 gauging stations in the Fraser catchment are compiled and their observed highflow behaviours are compared to the Gumbel distribution. The parameters of the Gumbel distribution describe completely the temporal characteristics of the annual flood series. The parameters are estimated easily and can be related to the modal annual flood value and a measure of dispersion. Basin, climatic and physiographic variables can intuitively be linked to the measures. The distribution of parametric values across the basin is considered in the light of these physical variables and their similarity used as the basis of the regionalisation and prediction scheme proposed in Chapter II.

4.2 Sampled stations

The objective of the study is to identify the role of hydrologic environments upon parameters describing flood frequencies. Stations combining the flows of other sampled tributaries would not permit such an identification, due to the coalescing of regional hydrologic characteristics.

A list of the 38 sampled stations is given in Table 4.1 and their locations in Figure 4.1.

Table 4.1 The characteristics of gauging stations sampled for annual flood series analysis

N°	W.S.C. Station N°	River	Gauge Location Lat.	Gauge Location Long.	Area (Km^2)	Years of record	mean m^3s^{-1}	Standard deviation
1	08LD001	Adams R. near Squalix	50°57'	119°39'	2975	62	245.1	49.7
2	08KE016	Baker Crk. at Quesnel	52°59'	122°31'	1574	13	46.6	17.2
3	08KH013	Cariboo R. near Keithley Crk.	52°44'	121°26'	2875	14	391.3	91.7
4	08JC005	Chilako R. near Prince George	53°49'	122°59'	3393	13	81.9	35.0
5	08KE009	Cottonwood R. near Cinema	53°09'	122°28'	1909	22	204.6	66.9
6	08LF027	Deadman R. above Criss Crk.	50°54'	120°28'	490	24	23.3	10.7
7	08KA001	Dore R. near McBride	53°18'	120°15'	404	14	90.0	19.6
8	08MG005	Lillooet R. near Pemberton	50°20'	122°48'	2163	58	517.8	99.7
9	08KB005	McGregor R. at Upper Canyon	54°16'	121°19'	2434	6	511.7	60.7
10	08MF008	Nahalatch R. near Keefers	50°00'	121°37'	1036	6	262.2	125.8
11	08KF001	Nazko R. above Michelle Crk.	52°54'	123°34'	3238	12	48.6	20.4
12	08LG007	Nicola R. near Merritt	50°09'	120°53'	4537	22	97.0	27.6
13	08KC001	Salmon R. near Prince George	54°06'	122°41'	4299	24	226.6	57.2
14	08MC006	San Jose R. near Lac La Hache	51°52'	121°40'	777	22	3.9	2.3
15	08JE001	Stuart R. near Fort St. James	54°25'	124°16'	14555	46	328.9	90.2
16	08KD003	Willow R. near Willow River	54°04'	122°28'	3108	23	241.8	40.1
17	08LF062	Bonaparte R. near Bridge Lake	51°20'	120°48'	666	16	13.9	5.3

18	08KD001	Bowron R. near Wells.	53°16'	121°25'	458	23	38.6	6.8
19	08LA005	Bridge Crk. near 100 Mile House	51°42'	121°10'	1326	13	9.5	3.7
20	08ME005	Bridge R. near Gold Bridge	50°51'	122°50'	1647	16	299.1	56.4
21	08LB020	Barrière R. at the Mouth	51°11'	120°08'	1140	34	96.2	22.7
22	08ME002	Cayoosh Crk. near Lillooet	50°40'	121°58'	878	28	104.6	51.5
23	08MA002	Chilko R. outlet Chilko Lake	51°38'	124°09'	2106	48	140.7	25.3
24	08LA013	Clearwater R. at outlet Hobson L.	52°25'	120°19'	904	17	197.6	37.2
25	08LG010	Coldwater R. at Merritt	50°07'	120°48'	914	24	70.6	19.4
26	08MF003	Coquihalla R. near Hope	49°23'	121°25'	740	30	238.7	96.6
27	08LF007	Criss Crk. near Savona	50°53'	120°58'	490	24	23.3	10.7
28	08LG004	Guichon Crk. near Lower Nicola	50°09'	120°53'	1228	24	9.9	7.6
29	08ME006	Gun Crk. near Minto City	50°54'	122°46'	570	13	61.4	9.7
30	08LF015	Hat Crk. near Cache Creek	50°57'	121°26'	524	16	5.7	3.8
31	08KH010	Horsefly R. above McKinley Creek	52°17'	121°04'	785	14	111.3	17.4
32	08KA008	Moose R. near Red Pass	52°55'	118°48'	458	22	95.7	24.9
33	08LA004	Murtle R. above Dawson Falls	51°59'	120°06'	1378	28	203.4	41.9
34	08KE014	Naver Crk. near Hixon	53°26'	122°35'	658	18	81.5	22.2
35	08JA002	Ootsa R. at Ootsa Lake	53°38'	125°44'	4248	22	328.4	62.0
36	08LE020	Salmon R. at Falkland	50°30'	119°33'	881	31	20.1	10.1
37	08LC018	Shuswap R. at Sugar Lake	50°21'	118°33'	1127	18	211.1	60.2
38	08JB002	Stellako R. at Glenannon	54°01'	125°00'	3600	24	74.9	25.6

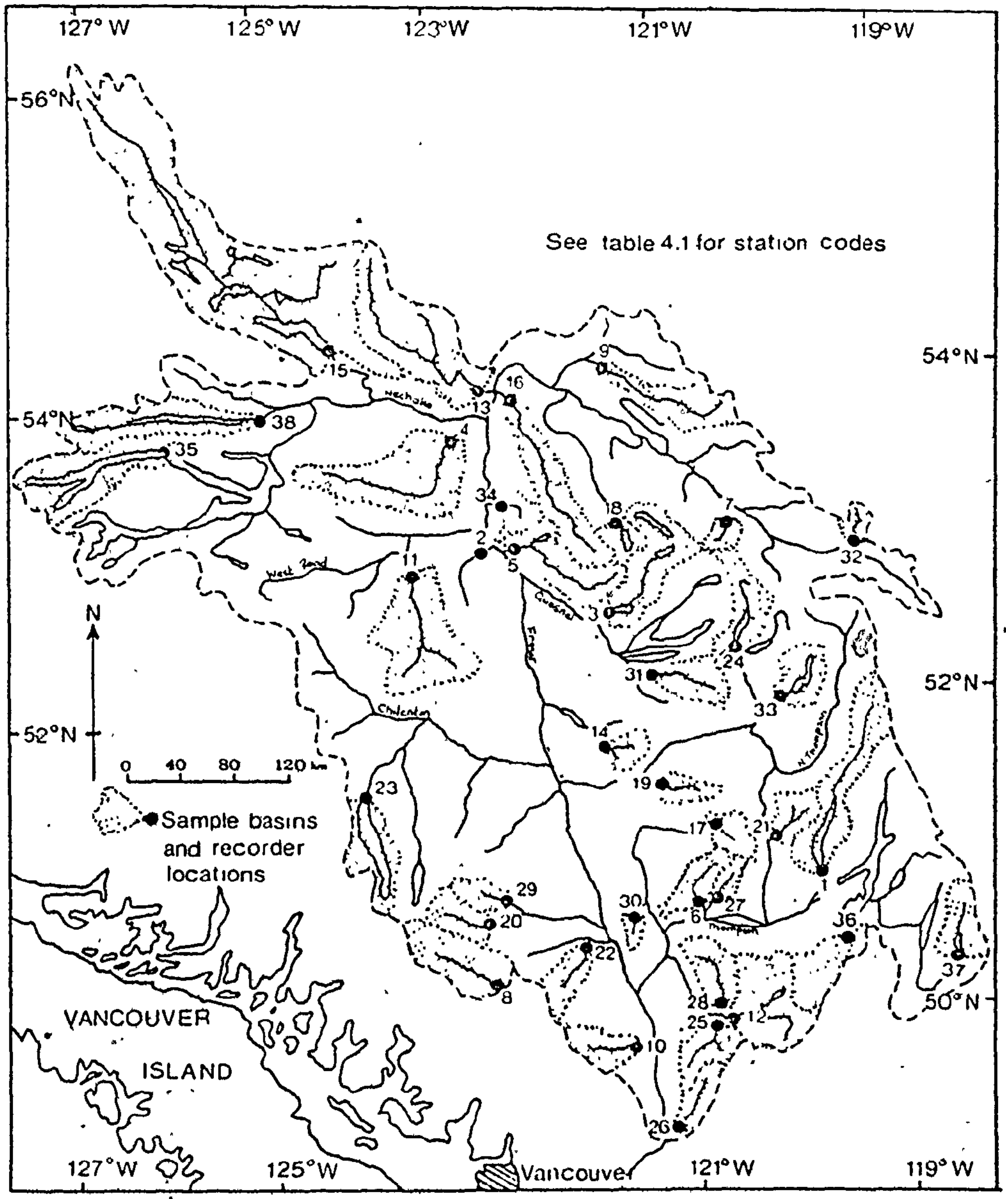


Figure 4.1 The locations of annual flood series sample sites.

4.3 Stationarity of data

The statistical characteristics and resultant regionalisations of both the highflow series are predicated upon the assumptions of their serial independence and stationarity. Serial independence is tested for by the estimation of the sample autocorrelation coefficients. The k^{th} order autocorrelation coefficient is computed as

$$r_k = \frac{\sum_{i=1}^{n-k} Q_i Q_{i+k} - \left[\sum_{i=1}^{n-k} Q_i \cdot \sum_{i=k+1}^{n} Q_i\right]/(n-k)}{\left[\sum_{i=1}^{n-k} Q_i^2 - (\sum_{i=1}^{n-k} Q_i)^2/(n-k)\right]^{0.5} \cdot \left[\sum_{i=k+1}^{n} Q_i^2 - (\sum_{i=k+1}^{n} Q_i^2)/(n-k)\right]^{0.5}} \tag{4.1}$$

where r_k is the estimate of the autocorrelation coefficient at a lag of k periods, n is the sample size and Q_i is the i^{th} observation.

Rescaled range analysis (Hurst, 1951; Mandlebrot and Wallis, 1969) provides a test of long term persistence in a data record. In the relationship

$$R_n/S_n \approx n^H \tag{4.2}$$

R_n is the maximum range for a cumulative departure of individual flows from the mean of n periods and S_n is the sample standard deviation of flows for n periods (Wallis and Matalas, 1970). If H is not significantly different from 0.5 then a lack of long term persistence is implied. Slaymaker (1972) and Church (1980) have identified an apparent long term trend in the behaviour of the mean annual flows of the Fraser River at Hope, which yield a value of H = 0.72.

First order correlation estimates were obtained for the annual flood series in each sampled basin. None of the estimated autocorrelation coefficients were found to be significantly different from zero, suggesting no year to year dependence in highflows. Rescaled range analysis was only applied to the annual flood series of the Fraser River at Hope because the technique gives unreliable results for small sample sizes. The Hurst pox diagram, figure 4.2, shows the results of the analysis of both the annual flood and mean annual flow series. The annual floods yield an H which is not significantly different from 0.5. Klemeš (1974) suggests that long term persistence is positively related to basin storage. In combination with Church's (1980) findings concerning the regional differences in H of mean annual flows it is proposed that if the annual flood series at Hope can be considered to be stationary, then it should also be true of the Fraser's tributaries. Thus the application of frequency analysis is feasible and the comparison of samples having differing data bases is acceptable.

4.4 Distribution of annual floods

All discharges comprising the sampled annual flood series were converted to units of specific discharge and the Gumbel distribution applied as outlined in Chapter II.

The mean and standard deviation were computed for each series and the parameters of the distribution estimated by the method of moments. Lowery and Nash (1970) found this method to be as satisfactory as any other. Applications of equations (2.12)

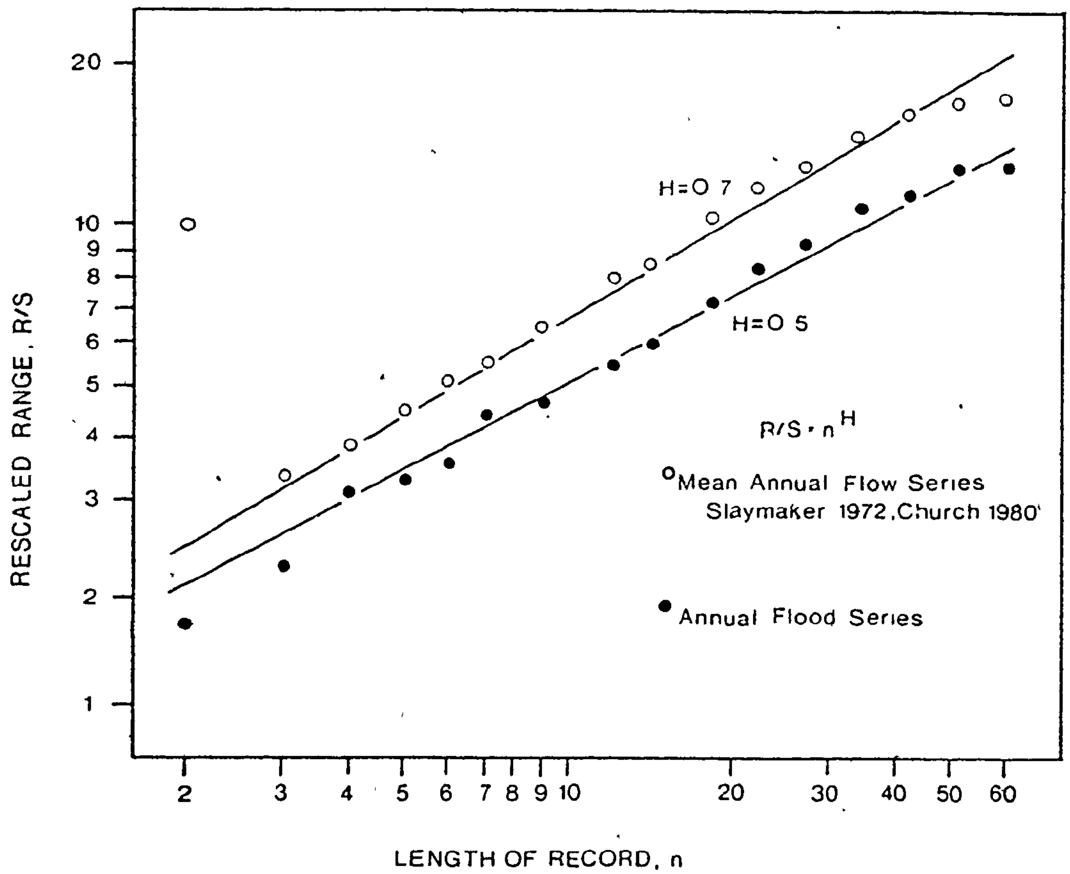


Figure 4.2 Hurst rescaled range analysis of mean annual flows and annual floods of the Fraser River at Hope, 1913-1976.

and (2.13) gave rise to the parameter estimates listed in Table 4.2. Empirical probabilities of flood exceedances were calculated as exceedance probabilities.

$$P(x > x) = \frac{m}{1+n} \tag{4.3}$$

where n is the number of years of record and m is the rank of the flood value, x, in that annual flood series. The largest flood in the period of record is assigned the rank of one. Frequently this probability is expressed as a recurrence interval, T; the reciprocal of the exceedance probability.

Comparison of observed and fitted distributions was carried out using the Kolmogorov-Smirnov test. Haan (1977) warns that in general tests of goodness of fit using the Kolmogorov-Smirnov test are not very powerful in accepting the hypothesis. In hydrology the tails of many observed distributions are particularly important and this is an area where standard goodness of fit statistics are insensitive. Despite its apparent inappropriateness there are at present no better methods. Taesombut and Yevjevich (1978) advocate the use of the chi-squared test on the grounds that the Kolmogorov-Smirnov test is non-parametric. They analysed larger samples ranging from 37 to 180 and used between eight and ten classes. In this way the problem of small samples in each class was lessened. Crutcher (1975) has tabulated critical values of the Kolmogorov-Smirnov statistic that can be applied to tests when parameters are required to specify the theoretical distribution. Using the Kolmogorov-

Table 4.2 Flood statistics and parameter estimates

sample	mean $m^3s^{-1}Km^{-2}$	standard deviation $m^3s^{-1}Km^{-2}$	α	β	Coefficient of variation
1	.0824	.0167	76.808	.0749	.203
2	.0296	.0109	117.144	.0246	.368
3	.1361	.0319	40.144	.1218	.234
4	.0241	.0103	124.259	.0195	.427
5	.1071	.0350	36.561	.0914	.327
6	.0161	.0089	143.223	.0120	.553
7	.2228	.0485	26.431	.2010	.218
8	.2394	.0461	27.783	.2187	.193
9	.2103	.0247	51.891	.1991	.117
10	.2531	.0517	24.777	.2299	.204
11	.0150	.0084	151.701	.0111	.560
12	.0214	.0061	208.686	.0186	.285
13	.0527	.0133	96.286	.0467	.252
14	.0050	.0030	435.383	.0037	.600
15	.0226	.0062	206.365	.0198	.274
16	.0778	.0129	99.704	.7020	.166
17	.0208	.0079	162.068	.0173	.380
18	.0843	.0149	86.219	.0777	.177
19	.0072	.0028	465.972	.0059	.389
20	.1816	.0425	30.137	.1652	.234
21	.0844	.0199	64.509	.0754	.236
22	.1191	.0587	21.837	.0927	.493
23	.0668	.0120	106.366	.0614	.180
24	.2186	.0411	31.187	.2001	.188
25	.0772	.0212	60.370	.0677	.275
26	.3226	.1304	9.821	.2639	.404
27	.0475	.0219	58.412	.0376	.461
28	.0081	.0062	205.557	.0053	.765
29	.1077	.0170	75.209	.1001	.158
30	.0109	.0072	178.302	.0076	.661
31	.1418	.0222	57.674	.1318	.157
32	.2089	.0544	23.538	.1844	.260
33	.1476	.0304	42.129	.1339	.206
34	.1239	.0338	37.934	.1087	.273
35	.0773	.0146	87.755	.0708	.189
36	.0228	.0114	112.064	.0177	.500
37	.1874	.0534	23.974	.1634	.284
38	.0219	.0100	127.938	.0174	.457

Smirnov test none of the sampled streams showed a distribution of annual floods that was significantly different from the Gumbel.

4.5 Variability of parameters within the study area

In equation (2.11), β is a 'location parameter' (Haan, 1977) which is equal to the mode of the observed data (Yevjevich, 1972). Increased values of β generally indicate increased specific discharge values constituting the annual flood series. α is inversely related to the dispersion of the series

$$\alpha = 1/(0.6359(q_2-q_1)) \tag{4.4}$$

where q_2 and q_1 are the 25% and 75% quartiles of the annual flood series. The probability density functions of four sampled basins are shown in figure 4.3a. The effect of the changing values of the parameters can be seen. The four corresponding probability mass functions are drawn in figure 4.3b. The data are plotted on Gumbel's probability paper, on which data following a Gumbel distribution plot as a straight line.

Using the method of moments (equations (2.12) and (2.13)) both α and β are related to the mean and standard deviation of the sample. The coefficient of variation, given as

$$C_v = S/\bar{X} \tag{4.5}$$

where S = the standard deviation of the sample

$\bar{X}$ = sample mean

embodies both of these characteristics as a single statistic. Its distribution across the basin (figure 4.4) resembles that of α and β (figure 4.5).

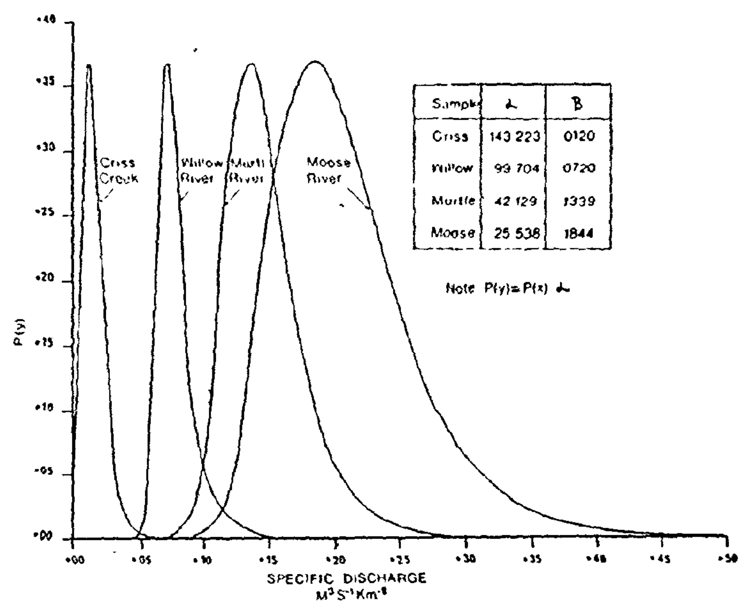


Figure 4.3(a) The Gumbel probability density functions of four sampled records.

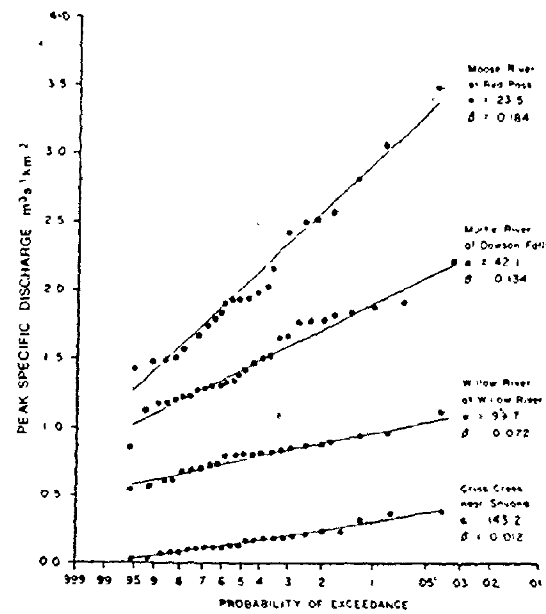


Figure 4.3(b) Corresponding probability plots.

The Coast, Cascade, Columbia and Rocky Mountains are zones of high specific discharge, ranging from 0.100 to 0.200$m^3s^{-1}km^{-2}$, particularly high values of β and considerable annual variability are found at high elevations. The calculated value of α for the Coquihalla River near Hope (W.S.C. 08MF003) is as low as 10.0, generally values are less than 90.0. The coefficient of variation showed that relative to the mean annual flood this variability is low. Many of these streams are glacially fed and thus their sources of springmelt floodwaters are relatively independent of year to year fluctuations in snow storage.

The Interior Plateau is marked by high values of α ranging from 120 to 465 and values of β as low as .0037. Particularly high α values are found at stations gauging basins with a large percentage of lake covered area, such as the Stuart River (W.S.C. 08JE001), Bridge Creek (W.S.C. 08LA005) and Nicola River (W.S.C. 08LG006). The absolute variation in annual floods specific discharges is low due to the low annual precipitation and is further enhanced by the effects of lake storage. The coefficient of variation reveals the difference between the Southern central area of the Interior Plateau and the northern area. In the east, along the flanks of the Columbia and Monashee Mountains there exists a zone of intermediate characteristics. These four zones correspond quite closely to those indicated in figure 3.2 and are physically meaningful in terms of flood characteristics and their physical environment discussed in Chapter II.

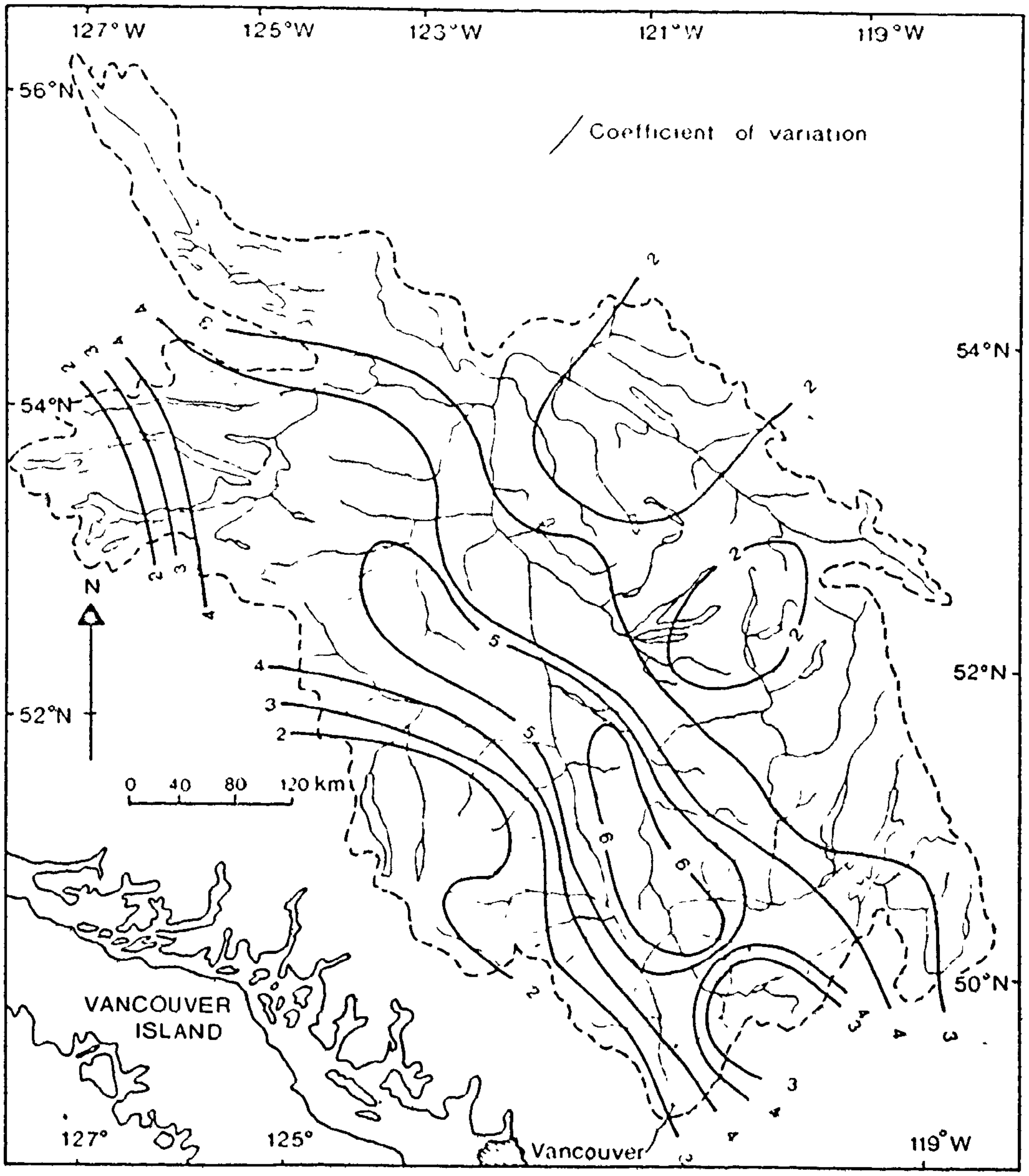


Figure 4.4 The distribution of the coefficient of variation of observed annual flood discharges within the Fraser River Basin.

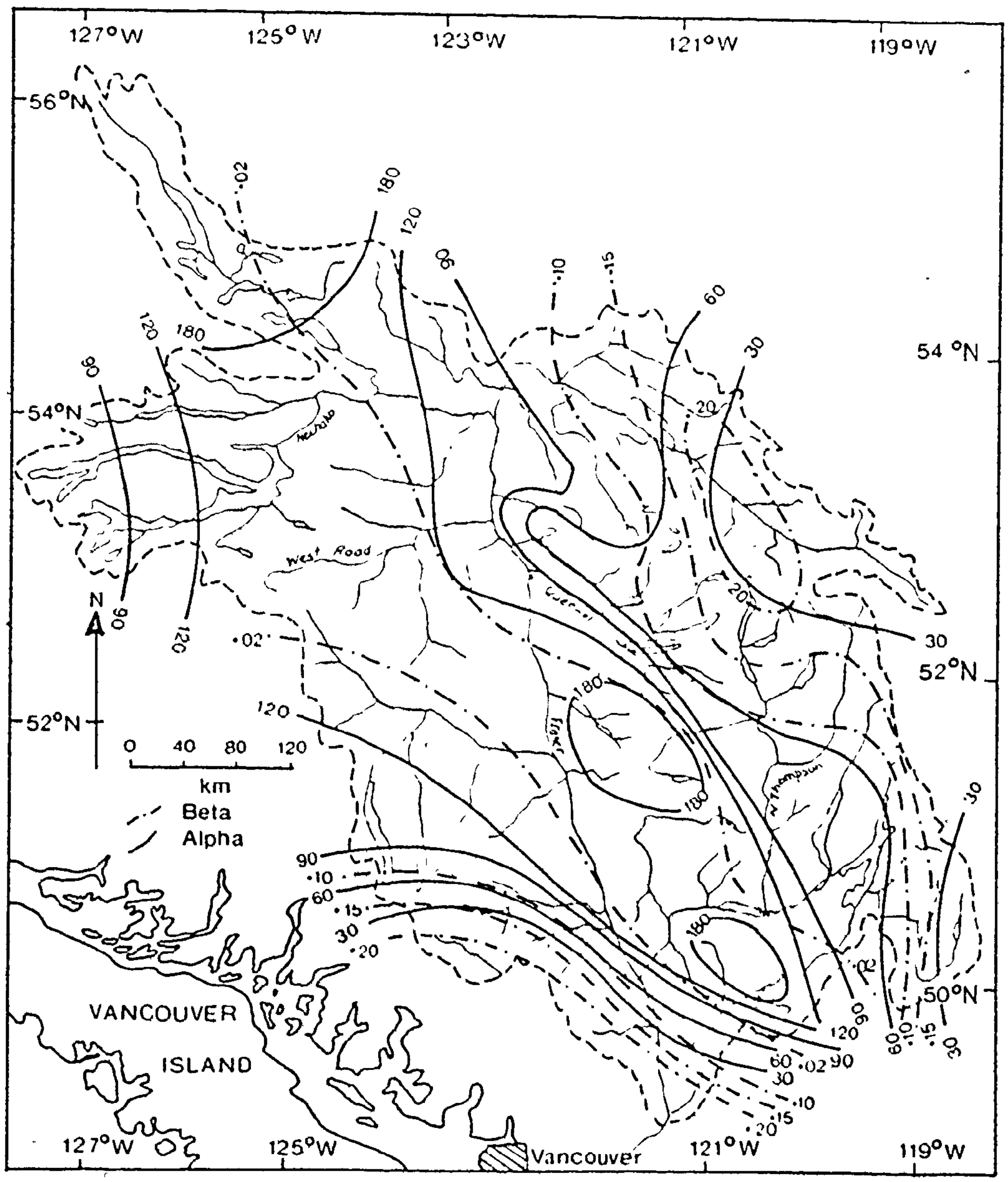


Figure 4.5 The distribution of the estimated Gumbel frequency distribution, parameters, α and β, in the Fraser River Basin.

4.6 Regionalisation

Following the procedure outlined in Chapter II 'a priori' regions were established on the basis of the physiographic characteristics of the study area and the observed variation in the Gumbel parameters. This regionalisation is arbitrary however it is physically meaningful, and successive groupings are achieved statistically. The presentation of frequency distributions as discrete histograms is analogous to this problem of the number of 'a priori' groups . Spiegel (1961) suggests that data should be divided into between five and 20 classes. Steel and Torrie's (1960) method applied to the mean annual flood specific discharge indicates that the maximum number of classes should be 12, as they recommend that the class interval not exceed one fourth of the standard deviation of the data. This figure seems to be particularly high for a sample size of 38 stations. It is primarily due to the large range within the data caused by the Coquihalla River. By excluding this station the maximum number of recommended classes drops to 8. Sturges (1926) suggests that 6 classes be used by the following equation

$$m = 1 + 3.3 \log n \tag{4.6}$$

where m = number of recommended classes

n = number of samples.

Totally objective selections of the numbers of groups therefore approximate to that suggested physically.

The parameters α and β are related to the mean and standard deviation of the annual flood series. To improve the definition between groups the sample statistics were entered into the discriminant analysis. The grouping pattern shown in figure 4.6(a) was derived from the iterative procedure.

This distribution of groupings suggests that they may be extended spatially to divide the catchment into a series of flood regions. This demarcation should be based upon physical considerations. 'A posteriori' investigation reveals that such considerations provided a reasonable approximation to the derived groupings. The 400, 750, and 1500 mm mean annual precipitation isohyets shown in figure 3.2(b) differentiate adequately the discriminant analysis groupings. The success of precipitation as an indicator of regional boundaries is due to the fact that it constitutes the basic input to the majority of flood generating processes. Glacially generated floods do not rely directly on precipitation for their inputs, but the occurence of glaciers in the study area generally corresponds to areas of high precipitation.

The regionalisation procedure did not differentiate between the western and eastern mountain ranges. These areas receive both high precipitation and a high proportion of glacially derived waters. Region II is similar to Region I but has lower relief. This results in a smaller area of glacial coverage. Precipitation is high and the high elevations produce large quantities of snowmelt. Many of the basins in this region such as the Chilko River (W.S.C. 08MA001), Adams River (08LD001), Ootsa River (08JA002) and Cariboo (08KH013) have large areas

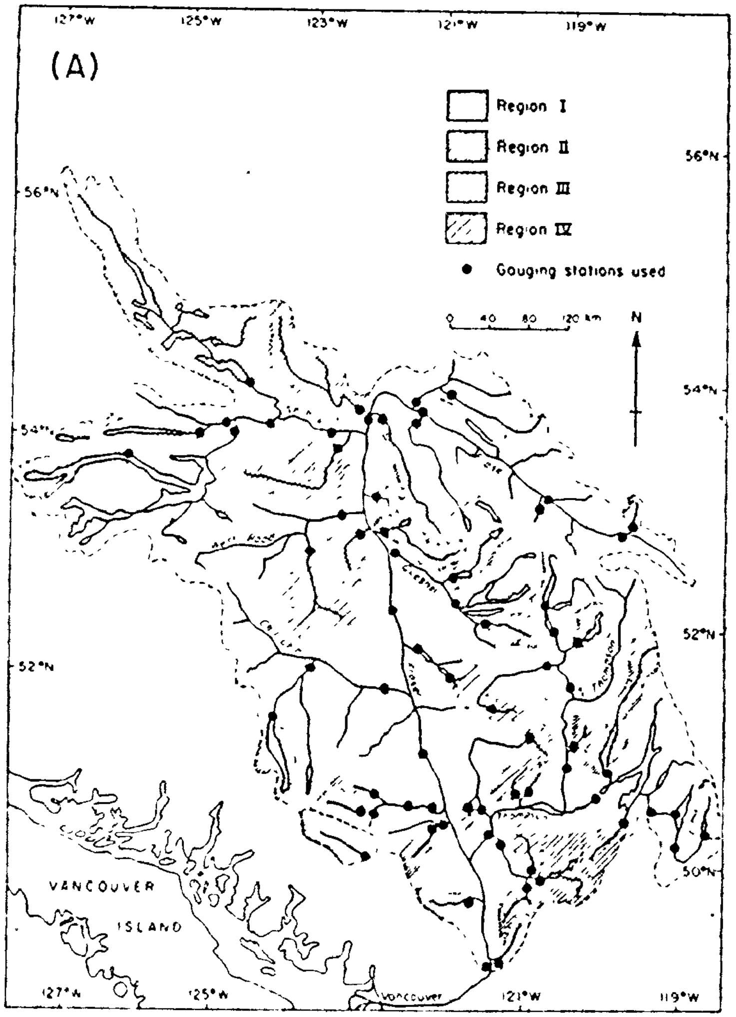


Figure 4.6(a) Locations of four groups of basins defined by discriminant analysis of annual flood characteristics.

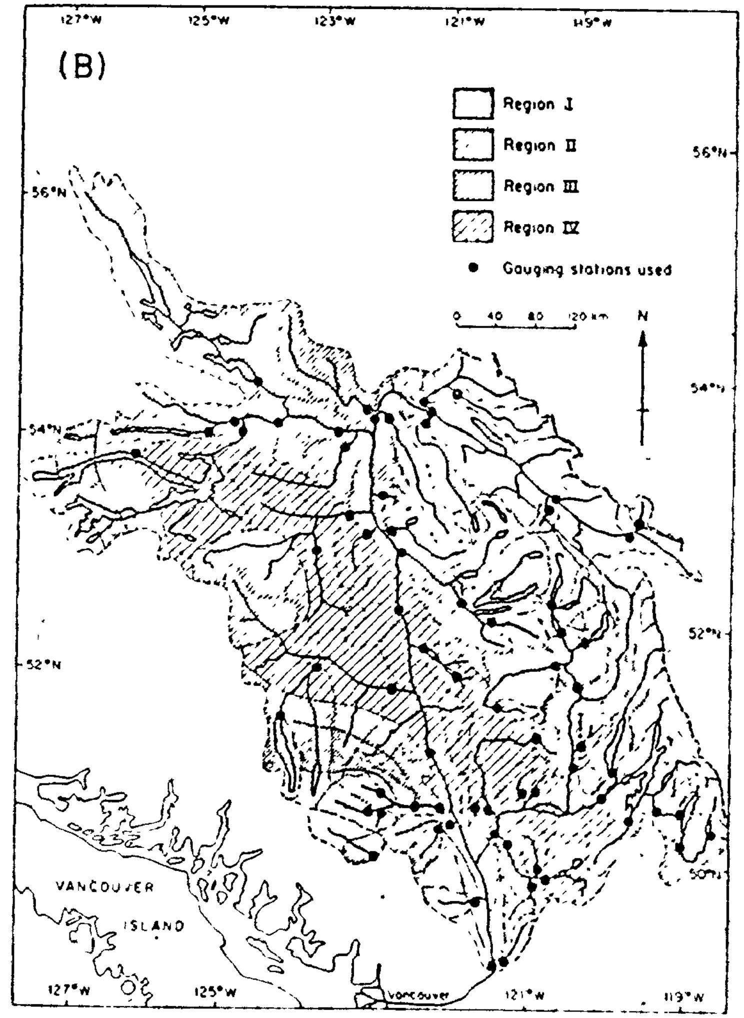


Figure 4.6(b) Boundaries of four annual flood regions as defined by isohyets of annual precipitation.

covered by lakes (see Appendix B) which tend to attenuate flood peaks. Region III occupies the northern Interior Plateau and the areas of higher precipitation around its fringes. Region IV is marked by its increased aridity. In both regions floods are generally the result of snowmelt but their specific discharge is low due to low precipitation.

4.7 Prediction Equations

Estimated mean and standard deviations of the sampled annual flood series from each region are entered into a multiple regression analysis and related to basin physiographic and climatic variables.

Basin elevation and the annual duration of snow cover were excluded by the stepwise regression from all the sets of prediction equations. Other independent variables were selectively omitted for various regions. The number of independent variables included ranged from two to four. A list of the variables retained and the regression constants and coefficients is given in Table 4.3. In all but one case the coefficients of determination exceeded 50 percent.

Basing the prediction equations upon four groupings provided a great improvement over the predictive power derived from one generalised set of equations for the entire basin. The coefficients retained, and their signs, are physically meaningful and support this conclusion. In all cases where basin size is considered to be a significant variable an increase in basin area lowers the contribution of each unit area to flood

Table 4.3 Regression coefficients for the estimation of means and standard deviations for four flood regions in the Fraser catchment, British Columbia.

	Regression Constants	Coefficients of Independent Variables* A	P	D	G	L	R	r^2	No. of Samples
					MEAN				
gion I	0.45	-0.4×10^{-5}			0.3×10^{-2}		-0.32×10^{-3}	0.70	9
gion II	0.27×10^{-2}	-0.1×10^{-4}	0.9×10^{-4}	0.13×10^{-3}				0.64	14
gion III	-0.21	-0.23×10^{-5}	0.37×10^{-3}	0.22×10^{-3}		-0.13×10^{-2}		0.71	9
gion IV	0.19×10^{-1}					-0.88×10^{-3}	-0.21×10^{-4}	0.79	6
					STANDARD DEVIATION				
gion I	0.152	-0.54×10^{-5}			-0.94×10^{-3}		-0.11×10^{-3}	0.53	9
gion II	-0.27×10^{-2}		0.52×10^{-4}		-0.25×10^{-2}	-0.19×10^{-2}		0.62	14
gion III	0.39×10^{-1}	-0.88×10^{-6}	0.80×10^{-4}	0.47×10^{-4}		-0.40×10^{-3}		0.47	9
gion IV	0.11×10^{-1}					-0.65×10^{-3}	-0.97×10^{-5}	0.94	6

See Appendix B for explanation of the symbols flow, and it reduces the variability of flood magnitudes. Increased precipitation produces increases in the two statistics as does glacial coverage. The latter variable is only retained in equations describing Regions I and II. In Region II and III precipitation and distance to the sea become important variables. In the less mountainous regions, III and IV, the area of the basin occupied by lakes reduces both the magnitude and the variability of the flood.

4.8 Test

In order to test the generality of the proposed regionalisation and the predictive power of the regression equations, the predicted annual flood series of four basins in the Fraser catchment were compared to their historical records. One sample station was selected from each of the flood regions. All the stations gauged streams comparable in area to those used in the initial analysis and their records had not previously been used in the derivation of the regions or prediction equations.

The locations of the four test basins are shown in figure 4.7. Table 4.4 summarises the relevant climatic and physiographic basin variables for each basin. These data are collected from the same sources and in an identical fashion to that employed previously. Estimates of the means and standard deviations of each stream are obtained by entering the respective, independent variables, from Table 4.4, and regional coefficients from Table 4.3 into equation (2.9). A comparison of observed and predicted statistics is given in Table 4.4. Estimates of

Table 4.4 Physiographic and climatic data and flood characteristics of four test basins in the Fraser catchment, British Columbia.

		Physiographic & Climatic Variables*					Mean		Standard Deviation	
Basin	Flood Region	A (Km^2)	P (mm)	D (Km)	G (%)	R (m)	Observed	Predicted	Observed	Predicted
Seymour R (LE027)	I	800	1300	500	2.2	760	0.234	0.210	.044	0.062
Raft R (LB017)	II	630	1000	530	0	570	0.185	0.154	.031	0.043
Moffat Crk. (KH019)	III	540	390	480	0	240	0.045	0.042	.017	0.016
Guichon Crk. (LG032)	IV	800	400	310	0	300	0.008	0.011	.003	0.007

* See text for explanation of the symbols.

the Gumbel parameters, α and β, are obtained by substituting the mean and standard deviation into equations (2.12) and (2.13). These in turn are used to calculate the expected return period of any sized annual flow from equation (2.11). Figure 4.7 shows a comparison of the predicted and historical data. The fit can be seen to be satisfactory with all the observed data points falling within the 95% confidence limits of the predicted distribution. Langbein (1949) gives the equation for the confidence limits as

$$\pm \{2.\exp(y)\} \;/\; \sqrt{n} \cdot \sqrt{1/T-1} \qquad (4.7)$$

where: y is Gumbel's reduced y variate given as

$$y = -\ln \{-\ln (1-(1/T))\} \qquad (4.8)$$

T is the recurrence interval

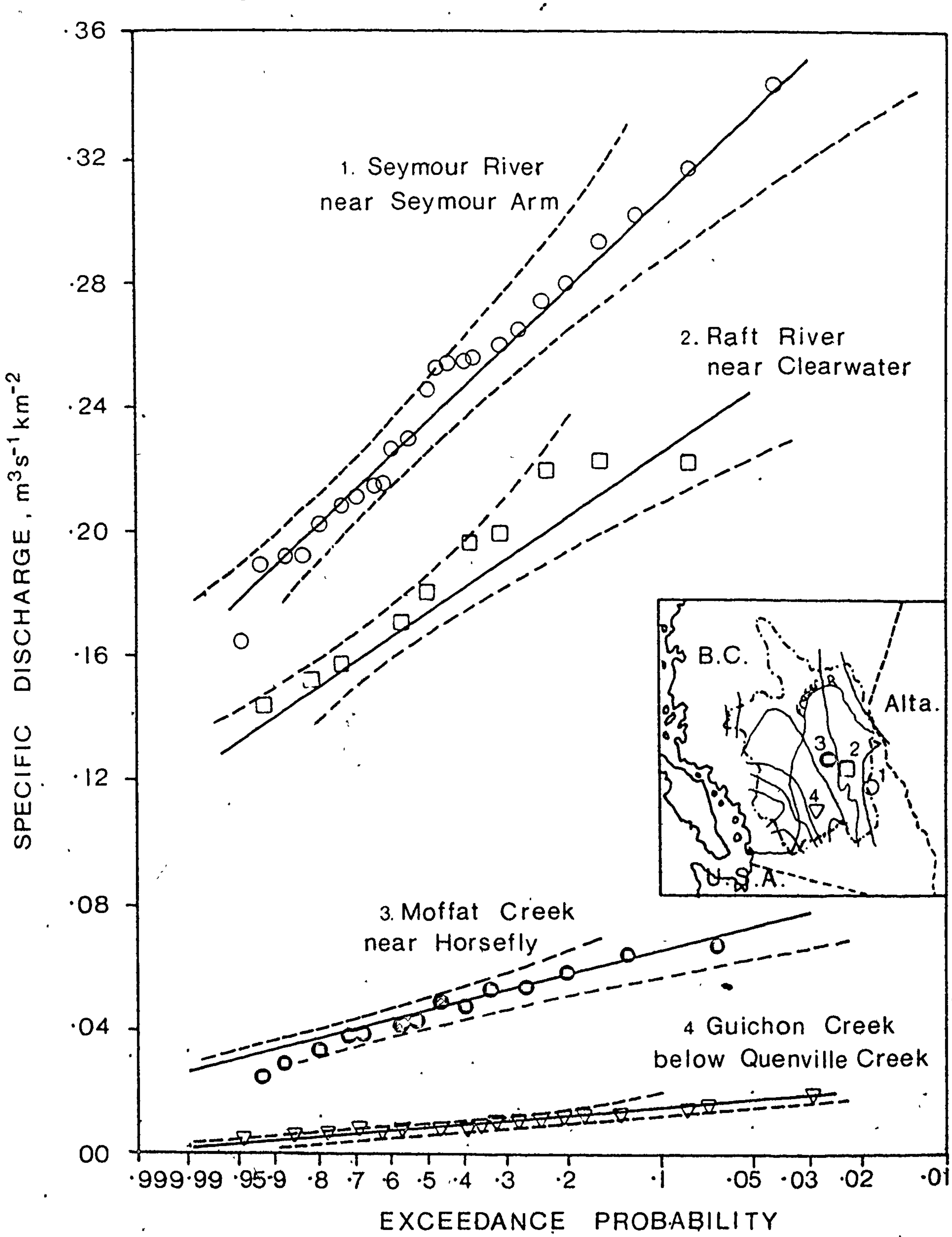
and n is the sample size.

Application of the Kolmogorov-Smirnov test to the two sets of data showed no significant difference between the observed and predicted results.

4.9 Conclusions

In the Fraser catchment the two parameter Gumbel distribution adequately describes the annual flood series of the sampled basins. Using the parameters derived from the annual flood series as independent variables discriminant analysis can be used to divide the complex terrain of the study area into distinct regions. The regions, although based upon flood characteristics, correspond closely to regionalisations based

Figure 4.7 Observed and Predicted distributions of annual floods for four test basins selected in each of the four flood regions shown unset. Dashed lines represent the 95 percent confidence limits.



based upon other physiographic and climatic variables. The strength of this regional correspondence allows the construction of a relationship between flood statistics and physical variables by stepwise regression. The resultant regional equations are physically meaningful and reflect the dominance of differing flood generating processes in each region. The regional equations may be successfully used to predict flood characteristics for basins within each region.

CHAPTER V

ANALYSIS OF PARTIAL DURATION SERIES

5.1 Introduction

The number of floods experienced at a point per year; their time of occurrence during the year; their magnitude above the truncation level and their duration are considered as important variables describing the highflows of a basin. These data are obtained for 35 basins across the study area. The probability distributions outlined in Chapter II are applied to the observed data. Parameters are estimated and Kolmogorov-Smirnov tests used to measure the goodness of fit. Five parameters characterise the temporal variability of the four exceedance variables at each sampled station. These five parameters are entered as the independent variables into the regionalisation procedure using discriminant analysis. The regionalisation is extended to the entire basin. Five sets of regression equations relating the parametric values in each region to physiographic and climatic variables are established.

5.2 Sampled stations

Limited changes to the sample used in the analysis of annual floods were required. Complete annual records of daily discharge are necessary for the analysis of partial duration series. The number of years of suitable data was reduced at several stations. The McGregor (W.S.C. 08KB005) and San Jose (W.S.C. 08MC006) River gauging stations were replaced by stations downstream with more complete records, (W.S.C. 08KB003 and W.S.C. 08MC005, respectively). The Ootsa (W.S.C. 08JA002) and Nahaltach (W.S.C. 08MF008) Rivers have no continuous daily records available. The durations and occurrences of complete years of record are given in Appendix A. The pertinent characteristics of the two new sample basins are given in Table 5.1

Table 5.1 Description of additional sample basins for partial duration series analysis.

W.S.C. Code	River	Location		Area Km^2	Yrs. of record	Mean A. flood m^3s^{-1}	Stand. Dev.
		Lat.	Long.				
08KB003	McGregor at Lower Canyon	54°14'	121°40'	4766	17	1156.3	255.
08MC005	Outlet of Williams Lake	52°07'	123°09'	2240	8	7.5	5.

5.3 Selection of a truncation level

Previous works using partial duration series (Todorovic, 1978; Taesombut and Yevjevich, 1978; North, 1980) have selected a level of truncation on the basis of the statistical characteristics of the resultant series. Rule of thumb criteria are laid out by Dalrymple (1960) and Todorovic (1978) to obtain a relatively large sample of highflows which are independent and possess the statistical characteristics outlined in Chapter II. These studies investigated the applicability of the technique in each basin rather than giving a comparison of results from one basin to another. Spatial comparability is important to,

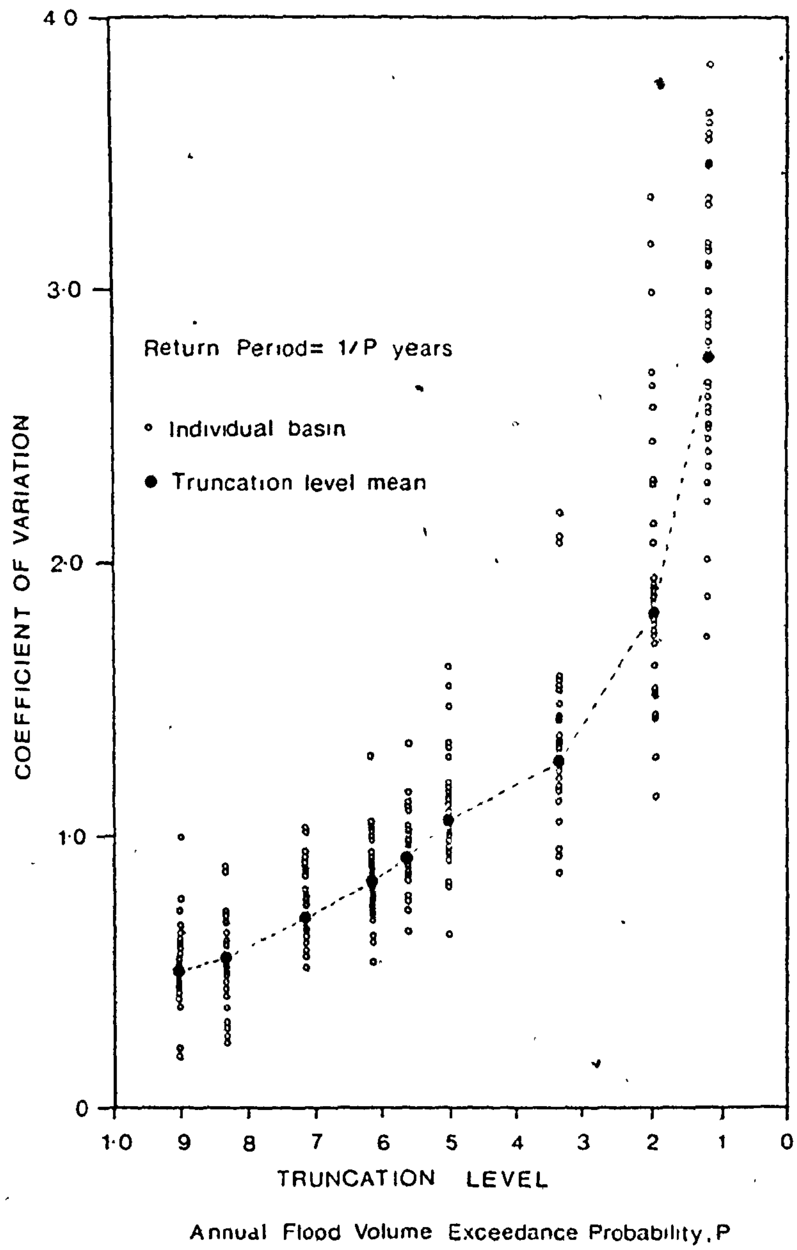


Figure 5.1 The relationship between the coefficient of variation of the number of exceedances per year and changing truncation levels.

this study. The variety of mean annual runoffs experienced across the basin (Waylen and Woo, in press, 1982) indicates that a common specific discharge value as a truncation level is infeasible. Dalrymple (1960) proposed that the 1.15 year annual flood be used. Partial series above discharges corresponding to the annual floods of several return periods have been obtained. Coefficients of variation of the number of crossings per year (see figure 5.1) indicate that at the level recommended by Dalrymple (1960) the process cannot be considered Poisson in the majority of sampled sites as for Poisson distributed variables the coefficient approximates unity.

At the 1.15 year return period truncation level exceedances are not truly independent from year to year. The probability of obtaining no flood is small yet the highly seasonal nature of the flows makes the probability of several crossings low. Figure 5.1 shows the observed values of coefficients of variations for each gauge at the 1.1, 1.2, 1.4, 1.6, 1.8, 2.0, 3.0, 5.0 and 10.0 year return period truncation levels. Most samples approximate to Poisson distributed variables at a truncation level equivalent to the 1.8 or 2.0 year return period annual flood. Application of the Kolmogorov-Smirnov test reveals that the null hypothesis that the observed distribution of the number of exceedances per year is not significantly different from the Poisson cannot be rejected at the 0.20 level for sample sites at truncation levels greater than 1.6 year return period flood. Figure 5.2 illustrates the correspondence between observed

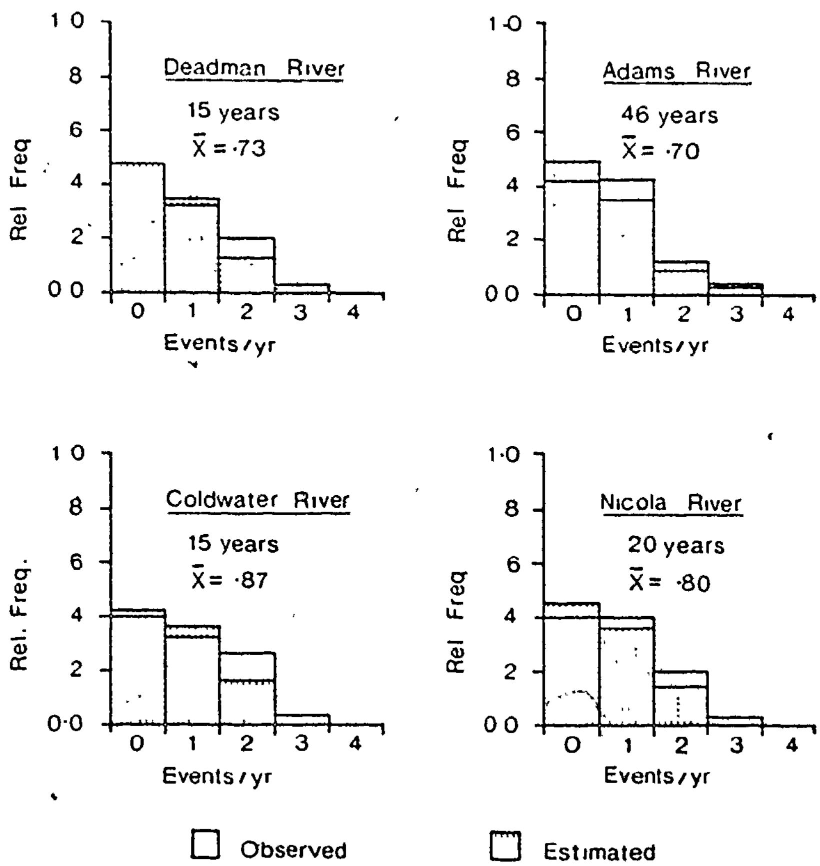


Figure 5.2 Comparison of the observed distributions of the number of exceedances per year and estimated Poisson distributions.

and Poisson distributions for several sample basins.

5.4 Distributions of partial duration series variables

5.4.1 Number and timing

The nonhomogenous Poisson distribution proposed for the modelling of these variables requires knowledge of the function $\lambda(t)$ in equation (2.16). $\lambda(t)$ represents the average number of crossings up to a given time, t, where t is less than or equal to one year. The temporal and spatial variability of $\lambda(t)$ is shown in figure 5.3. North (1980) and Todorovic (1978) refer to these functions as 'intensity curves'. The 'intensity curve' has previously been modelled by a fourier series. This technique provides an excellent geometric fit, but requires the estimation of a large number of coefficients which are not physically meaningful. Standardising the values of $\lambda(t)$ by expressing them as a ratio of λ, the average number of crossings per year, allows each intensity curve to run from zero to one. Multiplication of the standardised intensity function at any time, t, by λ yields $\lambda(t)$. Figure 5.3 suggests that a normal distribution could model the distribution of flood events through the year. Application of the Kolmogorov-Smirnov test showed that in all but two cases the null hypothesis that there was no significant difference between observed distributions and the normal distribution cannot be rejected at the .20 level. The advantages of this technique are that the majority of intensity curves can be characterised by the two parameters of

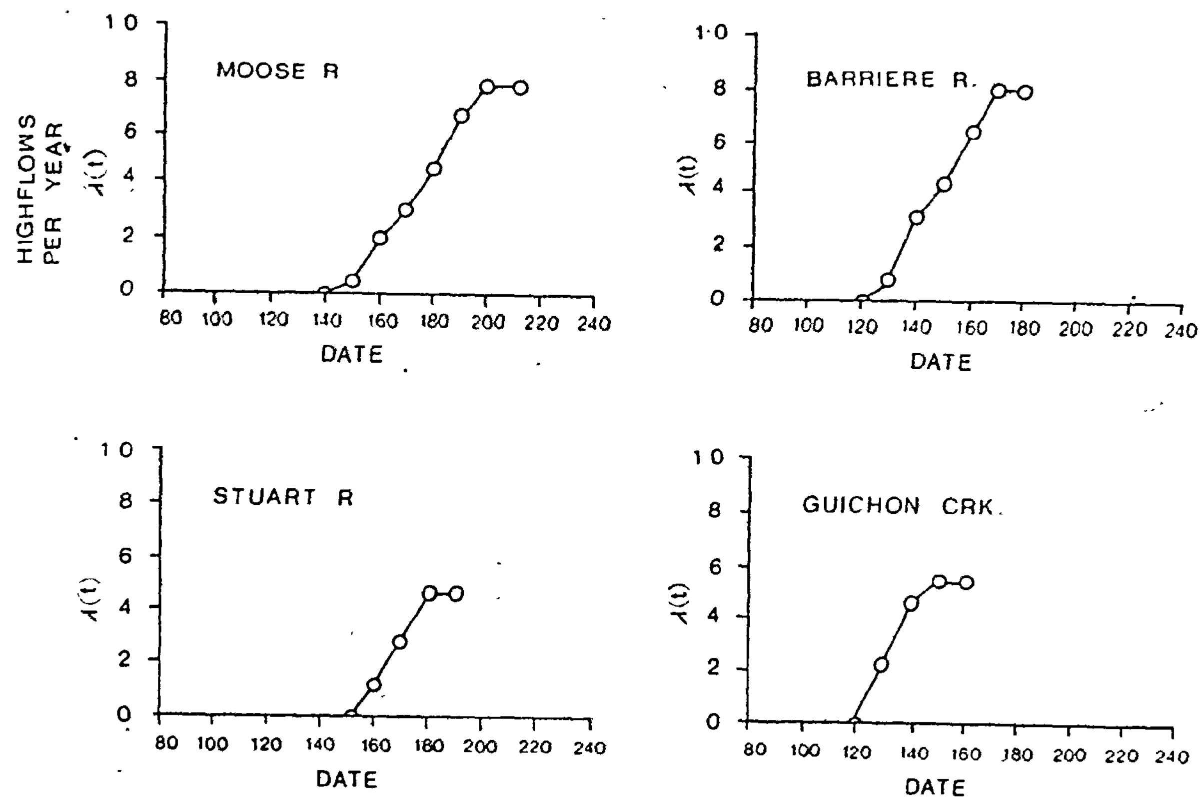


Figure 5.3 'Intensity functions' for four of the sampled basins.

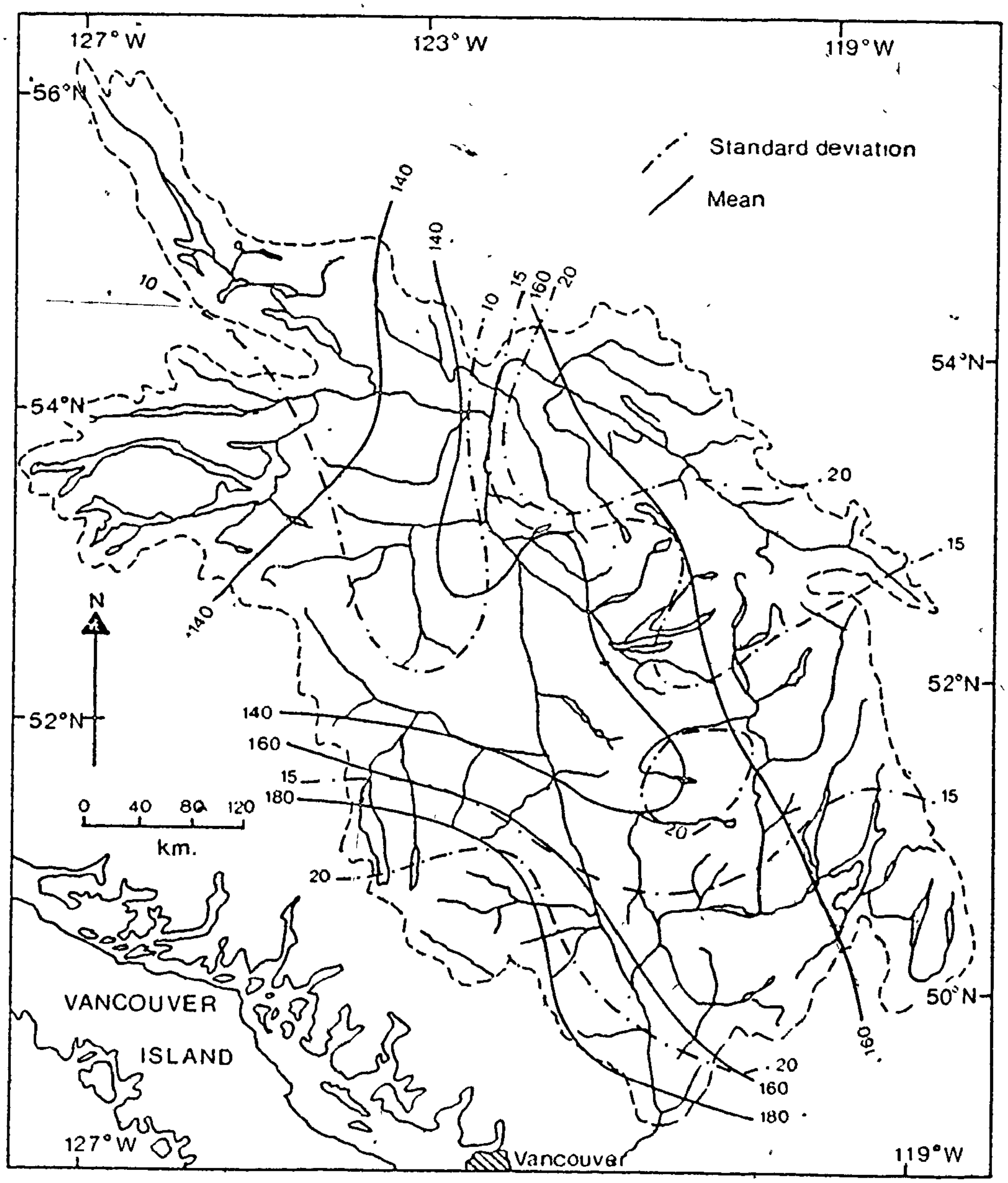


Figure 5.4 Mean and standard deviation of the dates of exceedances across the study area.

the normal distribution and λ, as compared to the ten parameters used by Todorovic (1978). Not only does this parsimony simplify the process of regionalisation but it also provides useful and easily interpreted data concerning the flood characteristics of the basin.

Basins on the low lying Nechako Plateau generally have a lower mean and standard deviation of dates of exceedances (figure 5.4). As elevations increase from this zone the mean date becomes later and the standard deviation increases. The physical reasons for these statistical characteristics have been discussed earlier. It is important to note that the observed pattern is both physically meaningful and similar to that previously observed.

An individual basin's standardised intensity curve may be represented by equation (2.18). The product of this function and λ yields $\lambda(t)$ which can be substituted into equation (2.16). Parzen (1967, p. 147) shows that a sufficient test of the goodness of fit of the nonhomogenous Poisson model is that the observed number and timing of crossings not be sufficiently differently distributed from the Poisson and selected temporal distributions respectively.

The Kolmogorov-Smirnov test has been used to test both of these hypotheses and in all but two cases they cannot be rejected. In figure 5.5 the nonhomogenous Poisson model is applied to the data of a sample basin. The exact number and probability of occurrences of highflows can be modelled.

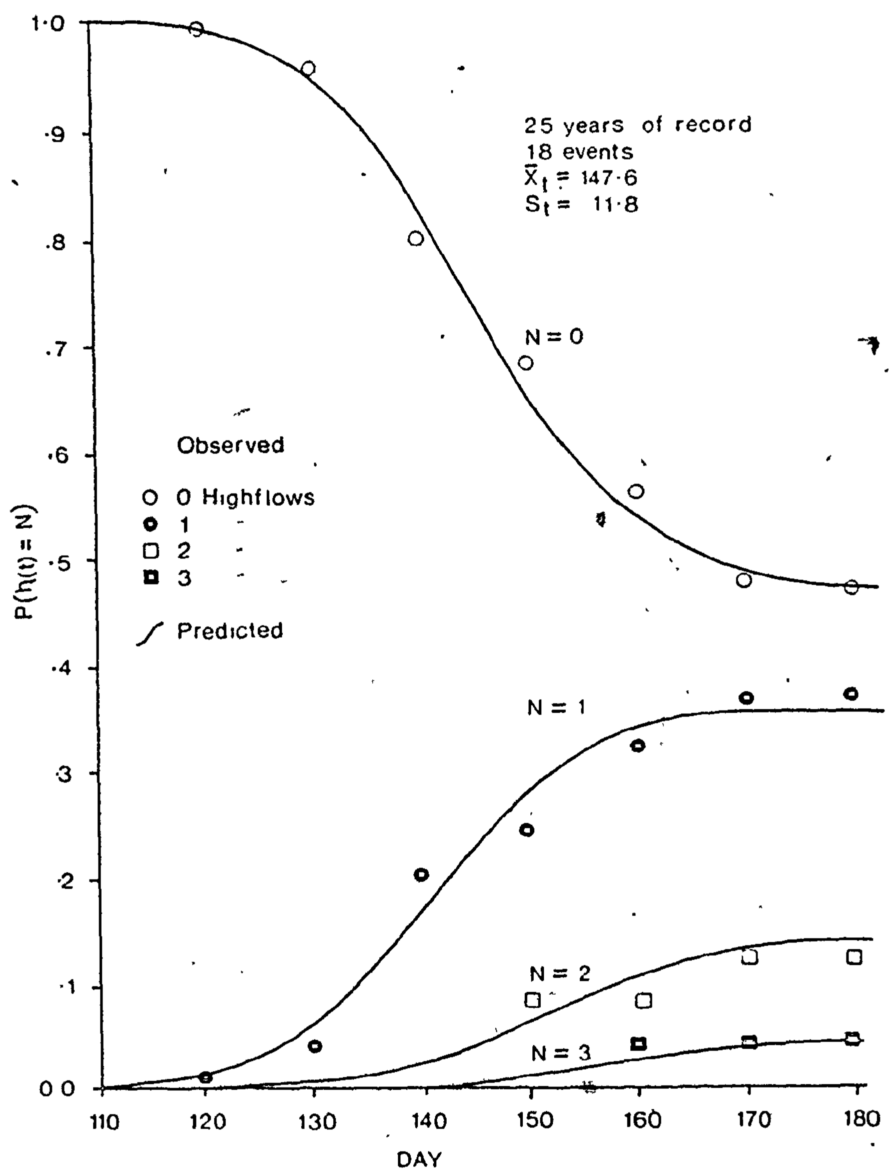


Figure 5.5 The nonhomogenous Poisson model fitted to the number and timing of exceedances on the Barrière River at Barrière.

Table 5.2 lists estimates of all the necessary parameters for each basin.

5.4.2 Magnitude

All highflow discharges are expressed as specific discharges. Maximum daily flows are collected for each period of highflow and compared to estimated exponential distributions. The calculated parameters are listed in Table 5.2. Application of the Kolmogorov-Smirnov test revealed that the null hypothesis that there was no significant difference between the observed and fitted exponential distributions could only be rejected in two cases at the .20 level.

Figure 5.6 reveals the marked influence of elevation upon the parameter γ_m, describing the distribution of the magnitude of peak exceedances. The mountainous areas are evident as areas of high peak specific discharges. The low values of the Interior Plateau resulting from its aridity are often accentuated by the presence of large lakes.

5.4.3 Duration

The frequencies of observed exceedance durations are compared to the exponential distribution and in all but three cases the null hypothesis that the observed distribution does not vary significantly from the fitted exponential distribution could not be rejected at the .20 level. The duration of exceedances at a station is primarily a function of the storage within the basin. Basins possessing a high percentage

Table 5.2 Parameters associated with partial duration series

station	λ	$\overline{X}_{day}$	σ_{day}	γ_D	γ_M
LD001	.70	167	20	14.0	.014
KE016	.54	125	7	8.1	.011
KH013	.58	158	10	13.4	.037
JC005	.27	130	4	14.0	.009
KE009	1.00	134	18	2.9	.018
LF027	.73	143	19	10.2	.007
KA001	1.00	172	14	3.9	.044
MG005*	.79	207	46	2.9	.032
KB003	.69	185	50	3.2	.041
KF001	.42	123	7	10.8	.009
LG007	.80	149	11	8.5	.005
KC001	.71	127	7	9.3	.012
MC005	.88	115	17	22.7	.002
JE001	.59	165	11	50.0	.006
KD003	.45	157	46	4.1	.010
LF062	.81	147	22	21.3	.007
KD001	.80	156	20	6.8	.011
LA005	.71	134	23	26.8	.003
ME005	.48	197	43	3.7	.016
LB020	.72	148	11	5.0	.015
ME002	.93	173	15	6.4	.043
MA002	.50	191	18	16.9	.011
LA013	.44	175	15	7.1	.045
LG010	.87	148	12	4.5	.005
MF003*	.59	232	123	1.6	.107
LF007	.60	150	15	4.1	.023
LG004	.54	134	7	19.9	.008
ME006	.88	161	14	1.9	.009
LF015	.50	156	10	7.4	.007
KH010	.64	154	15	4.8	.018
KA008	.74	172	15	4.4	.057
LA004	.57	164	9	12.4	.029
KE014	.42	150	59	7.4	.007
LE020	.53	146	11	8.7	.009
LC018	.67	167	13	4.9	.045
JB002	.62	149	12	33.9	.009

* Significantly different from the nonhomogenous Poisson model.

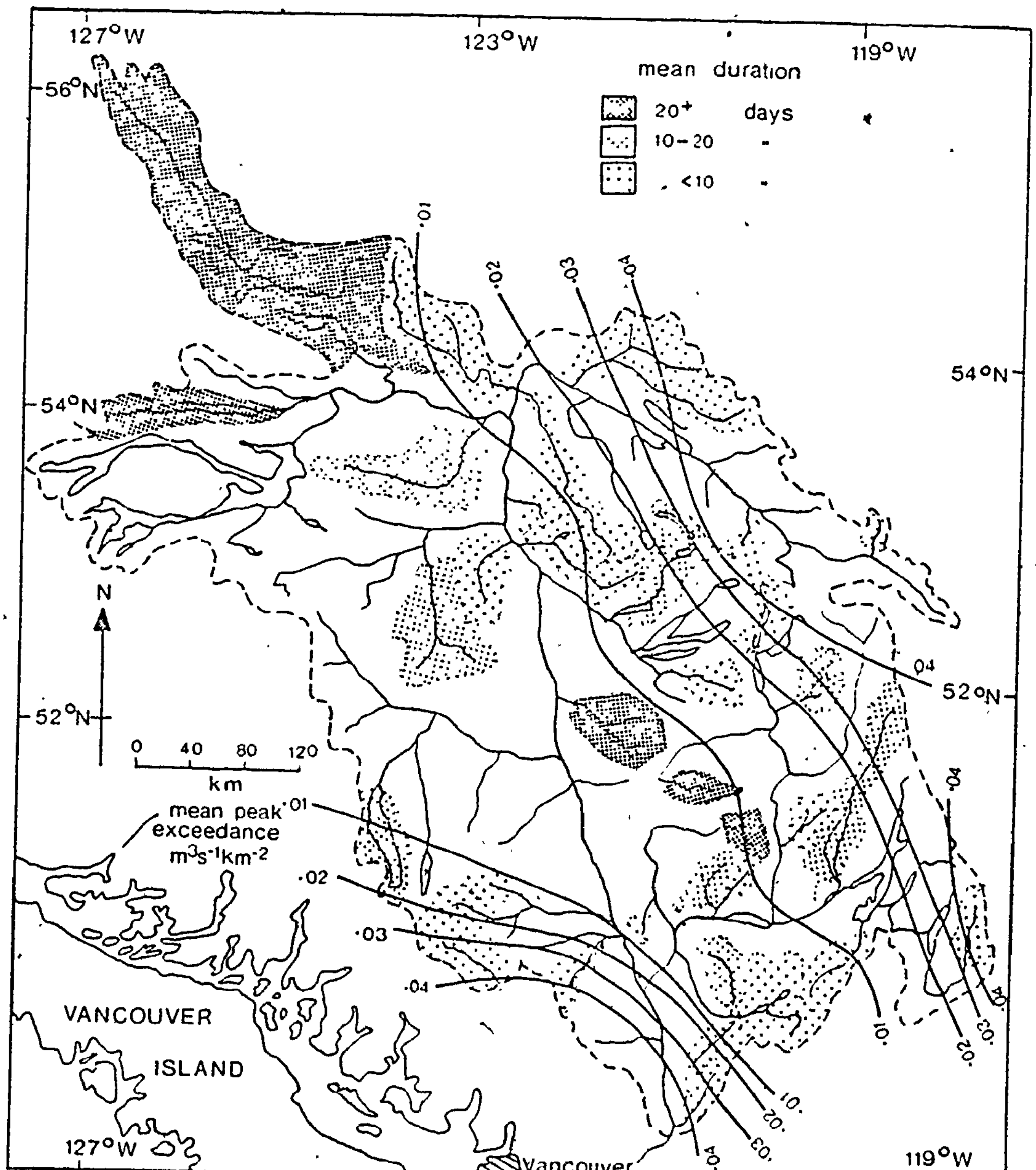


Figure 5.6 Mean peak exceedance specific discharge and duration of exceedances over the study area.

of their areas occupied by lakes show much higher average durations than their surrounding basins with small lake areas (c.f. Stuart River, W.S.C. 08JE001; Stallako River, W.S.C. 08JB002; Outlet of Williams Lake, W.S.C. 08MC005; and Cariboo River, W.S.C. 08KH013). Basins in the mountainous area display relatively short exceedances compared to basins on the Interior Plateau. The greater available relief, distributed snowmelt and the glacial origin of many floods account for these differences.

5.5 Compound model

Highflow characteristics of the Lillooet and Coquihalla Rivers were significantly different from the distributions of the proposed models. Highflows on these two rivers occur at two distinct periods (figure 5.7) during the year. The periods display different exceedance and duration characteristics. The Lilloet experiences spring snowmelt and glacially generated flows from day 140 to 240 with an average exceedance of 56.1 m^3s^{-1} and duration of 3.08 days. A secondary group of exceedances occurs in the late fall, characterised by an average exceedance of 128.4 m^3s^{-1} and a duration of 1.81 days. This group coincides with a local precipitation maximum (see figure 3.3) at a time when snow may be lying in many parts of the basin. Large rainfall events falling on snow produce high exceedances of short duration. A similar temporal division in the Coquihalla data is more noticeable as the basin is unglaciated and therefore sustains no summer highflow after snowmelt. Rain

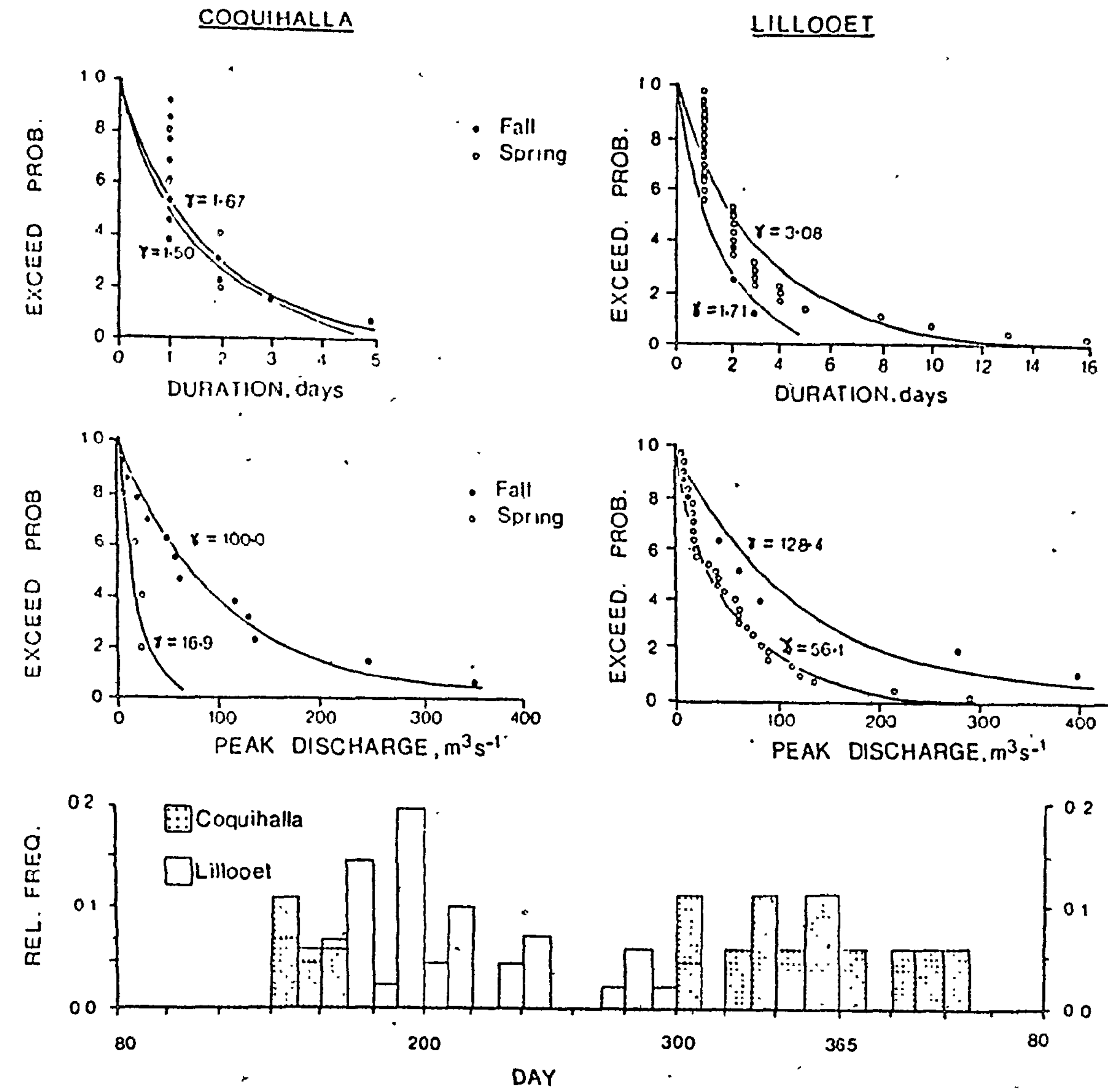


Figure 5.7 Partial duration variables of the Coquihalla and Lillooet Rivers.

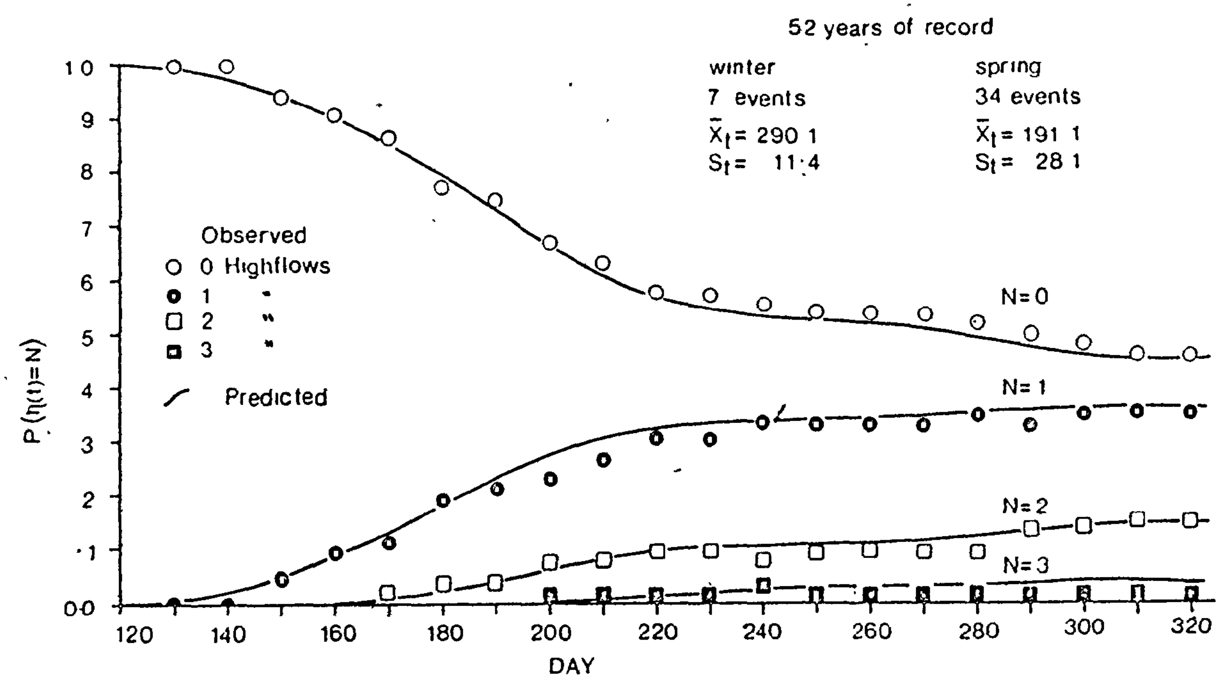


Figure 5.8 The compound nonhomogenous Poisson model fitted to the number and timing of exceedances on the Lillooet River near Pemberton Meadows.

on snow events during the winter are on average shorter and more intense than snowmelt events.

The intensity curves and temporal distribution of highflows can be modelled using the principles previously outlined. Compound normal distributions are used to represent the bimodal character of highflows. Each period of exceedances is modelled separately, the intensity curves obtained and weighted by the average number of exceedances in each period. The intensity curves are then added together and the compounded curve substituted into the nonhomogenous Poisson model. Figure 5.8 indicates the comparability of observed and predicted results.

5.6 Regionalisation

The parameters of the partial duration series suggest strong regional differences in highflows across the study area and similarities between adjacent basins. The value of the regionalisation and regression in predicting annual flood characteristics has been shown in Chapter IV. A similar procedure is followed to allow the prediction of the more comprehensive variables of the partial duration series.

5.6.1 Procedure

The five parameters listed in Table 5.2 were entered into the discriminant analysis. The same number of parameters were used to describe the Coquihalla and Lilloet Rivers although they have been shown to be inadequate in modelling their highflows. The simple descriptive statistics derived are sufficiently different from the remainder of the sampled basins to ensure that having been assigned 'a priori' to a unique group they would not be grouped with any other basins. On the basis of the reasoning of Chapter IV the remaining sampled basins were assigned to one of four groups. Initially groupings were identical to those derived in the analysis of annual floods. Group memberships were reconstituted following each run of the discriminant analysis until no sample had been misallocated.

The final pattern of groupings shown in figure 5.9a resembles that of the annual flood series and the distribution of physical variables. Region I, the high runoff, mountainous region, is well demarcated by the 1500 mm annual isohyet. Descriptive statistics of the group's parametric values listed in Table 5.3 show that highflows tend to be later and larger in this region than in the study area.

The 750 mm isohyet defines region II with the exception of four basins on the southern Interior Plateau. Region III consists of basins on the Interior Plateau which have over 7% of their basin areas occupied by lakes. The effect of lake storage produces a high mean value of the parameter describing the duration of exceedances. The discriminant analysis groups these basins together because of this property. Region IV consists of low lying Interior Plateau basins. They are differentiated from the southern basins by their earlier mean date of highflows. Physically this division can be related

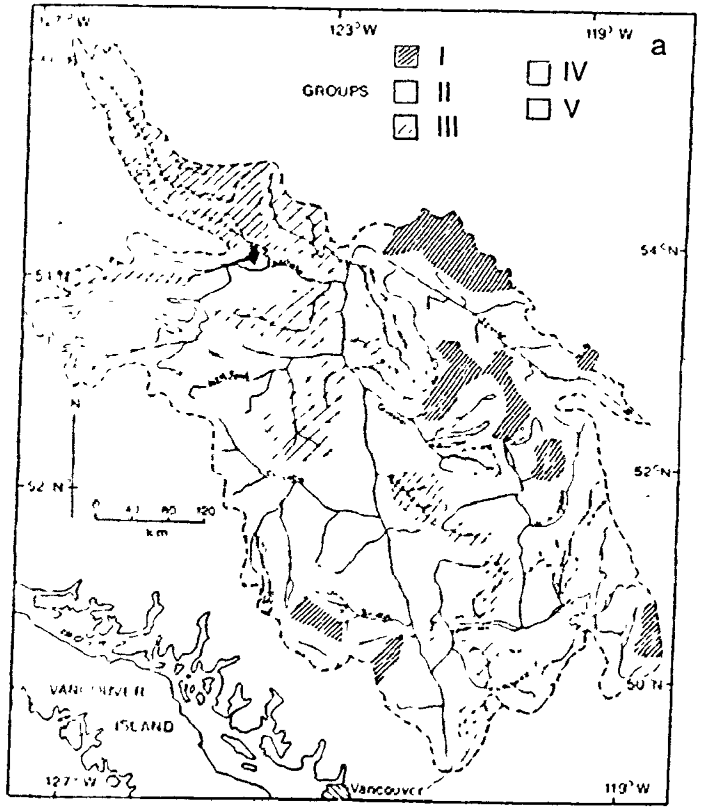


Figure 5.9(a) Groupings of basins on the basis of discriminant analysis applied to partial duration series variables.

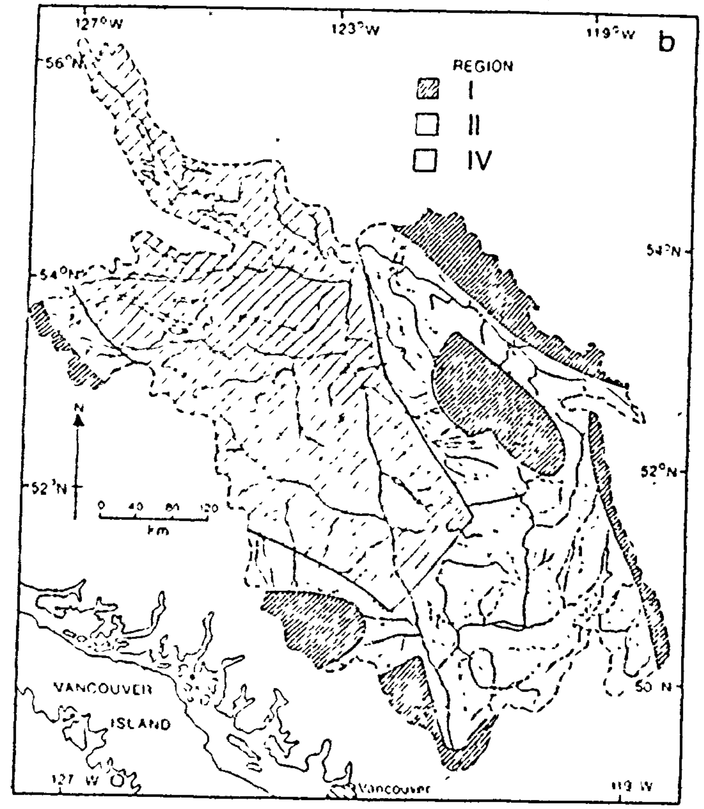


Figure 5.9(b) Extension of groups to provide regional coverage of the study area.

Table 5.3 Regional variation of partial duration series parameters

REGION		I	II	III	IV
Parameter					
Crossings /year	$\overline{X}$	.73	.70	.51	.77
λ	S	.21	.14	.15	.16
mean day	$\overline{X}$	169.7	153.3	131.5	140.7
$\overline{X}_D$	S	6.3	13.5	9.9	17.0
St. dev.	$\overline{X}$	13.7	14.6	7.8	17.2
S_D	S	2.0	3.9	3.7	5.0
mean duration	$\overline{X}$	6.7	8.1	11.0	26.3
γ_D	S	3.5	4.4	5.4	15.5
mean peak exceedance	$\overline{X}$	.0432	.0101	.0120	.0075
γ_M	S	.0066	.0042	.0056	.0058

to the difference of environments of the Nechako and Fraser Plateaux. Rivers on the Fraser Plateau are deeply incised. The range of elevations causes a retardation of the date of high-flows not found on the less dissected Nechako Plateau. These two regions cannot be differentiated on the basis of precipitation. The division between regions II and III in figure 3.4 appears to provide a good boundary.

Figure 5.9b depicts the extension of groups I, II and IV across the study area. Group III classification can only be concluded when knowledge of a basin's lake area is known.

The Lillooet and Coquihalla Rivers can be considered to form a fifth group characterising the highflows in south-west British Columbia. The limited sample size available in this study prevents further investigation.

5.6.2 Prediction equations

Estimated values of the five parameters for each basin constituting a region are entered into a multiple regression analysis as independent variables. Each parameter in turn is regressed against the basins' physiographic and climatic variables. Backwards stepwise linear regression progressively eliminated physical variables from the regression equations. The number of variables included ranges from one to four. A list of the variables and regression coefficients and constants is provided in Table 5.4. In all cases the coefficient of determination exceeds 50%.

The regional equations have greatly improved predictive powers over one generalised set of equations for the entire basin. The various relevant physical variables and their spatial distributions support the statistically based regionalisation. Generally the variables retained and the signs of their coefficients are physically meaningful. Wherever lake coverage is an important variable it reduces the number of highflows per year and leads to a later mean date of occurrence. Glacial coverage is only an important variable in region I and it is positively related to the average peak highflow. Increases in basin area reduce the size of the peak highflows and increase

Table 5.4 Regression constants and coefficients of the regional relationships between partial duration series parameters and basin physiographic and climatic data

Region	Parameter	Intercept	Area	Precip.	Elevation	Distance	Snow	Glacier	Lake	I.Q.	r^2
I	λ	1.60x10					-4.17×10^{-4}		-1.07×10^{-2}		.82
	$\bar{X}_D$	2.10×10^{2}	-9.3×10^{-3}		-1.69×10^{-2}				-1.16		.94
	S_D	2.99×10^{1}	-3.8×10^{-3}		-2.0×10^{-3}					1.14×10^{-2}	.97
	γ_D	2.60	3.7×10^{-3}								.92
	γ_M	3.64×10^{-2}	-7.0×10^{-6}	1.4×10^{-5}				6.7×10^{-5}	8.58×10^{-4}		.99
II	λ	1.06×10^{-1}	6.0×10^{-5}				4.64×10^{-3}		-3.69×10^{-2}		.57
	$\bar{X}_D$	1.25×10^{2}			1.55×10^{-2}				3.62	1.1×10^{-2}	.96
	S_D	1.88				1.31×10^{-2}	5.11×10^{-2}		5.01×10^{-1}		.57
	γ_D	1.42×10^{1}		-1.64×10^{-2}	2.50×10^{-3}				1.43		.79
	γ_M	-1.34×10^{-2}		-3.2×10^{-5}			2.85×10^{-4}			1.1×10^{-5}	.86

Region	Parameter	Intercept	Area	Precip.	Elevation	Distance	Snow	Glacier	Lake	I.Q.	r^2
III	λ	7.72×10^{-1}			1.1×10^{-3}	-2.00×10^{-3}			-2.19×10^{-2}		.96
	$\bar{X}_D$	5.31×10^{1}	1.60×10^{-3}	1.25×10^{-1}					2.78		.90
	S_D	2.31×10^{1}		2.30×10^{-2}	1.37×10^{-2}	-2.04×10^{-1}					.96
	γ_D	9.50×10^{1}	2.1×10^{-3}	-1.05×10^{-1}	-2.83×10^{-2}						.97
	γ_M	-1.72×10^{-2}		4.78×10^{-5}							.54
IV	λ	2.80			-1.49×10^{-3}		-5.53×10^{-3}			-3.9×10^{-4}	.99
	$\bar{X}_D$	2.53×10^{2}		-2.12×10^{-1}		1.16×10^{-1}	-4.53×10^{-1}				.92
	S_D	6.60×10^{1}		-1.11×10^{-1}		4.77×10^{-2}	-1.66×10^{-1}				.91
	γ_D	-8.12×10^{1}		2.43×10^{-1}		-9.22×10^{-2}	9.79×10^{-2}				.85
	γ_M	3.83×10^{-2}	-2.9×10^{-5}	-1.09×10^{-4}		8.52×10^{-5}	2.42×10^{-4}				.99

the average duration of highflows as the result of increased storage within the basin. In region I increased basin area insinuates a greater proportion of the basin at lower elevations. Drake (1974) pointed out the importance of the elevation below which 50% of the basin lies, in determining the hydrologic characteristics of streams in this environment. An increased proportion of lower lying areas produces earlier floods in this region.

5.7 Test

To test the generality of the proposed regionalisation and prediction, the above method was applied to three test basins in the Fraser catchment. The number of potential test locations is severely restricted by the absence of long periods of continuous streamflow records in basins of the necessary size range. The three basins had not previously been used in the derivation of regions and prediction equations.

The locations of the three test basins are shown in figure 4.7. Table 5.5 lists the relevant climatic and physiographic basin variables not previously listed in Table 4.4.

Estimates of the five parameters are obtained by substituting the values of the pertinent variables into the regional regression equations of Table 5.4. A comparison of observed and predicted parameters is provided in Table 5.6. The parameters can be substituted into equations (2.16), (2.18) and (2.21). This allows the prediction of the probabilities of the number, timing, magnitude and duration of highflows exceeding

Table 5.5 Additional basin variable required for the prediction of partial series parameters.

Basin	region	E m.	S days
Seymour R.	I	2000	165
Raft R.	II	1250	165
Moffat Crk.	II	1000	150

the level of the two year return period annual flood, estimated from the predicted annual floods discussed in Chapter IV.

Table 5.6 Predicted and observed parameters of partial series for the test basins

Basin \ Parameter		crossings /year λ	mean day of flood $\bar{X}$ day	Stan. dev. S day	mean exceedance γM	mean duration γD
Seymour R.	observed	1.86	168.0	31.5	.050	2.9
08LE027	predicted	1.52	167.1	25.1	.039	3.2
Raft R.	observed	1.00	145.0	12.0	.026	6.3
08LB017	predicted	0.88	153.5	17.6	.014	2.1
Moffat Crk.	observed	0.80	142.0	15.0	.014	6.4
08KH019	predicted	0.75	152.0	17.0	.019	13.7

Figures 5.10 and 5.11 compare predicted and historical data. Application of the Kolmogorov-Smirnov test showed no significant difference between the observed and predicted results at the .20 level. Comment upon the apparent poor fit in the case of the Raft River (W.S.C. 08LB017) is difficult because of the limited sample size of only four highflows in as many years.

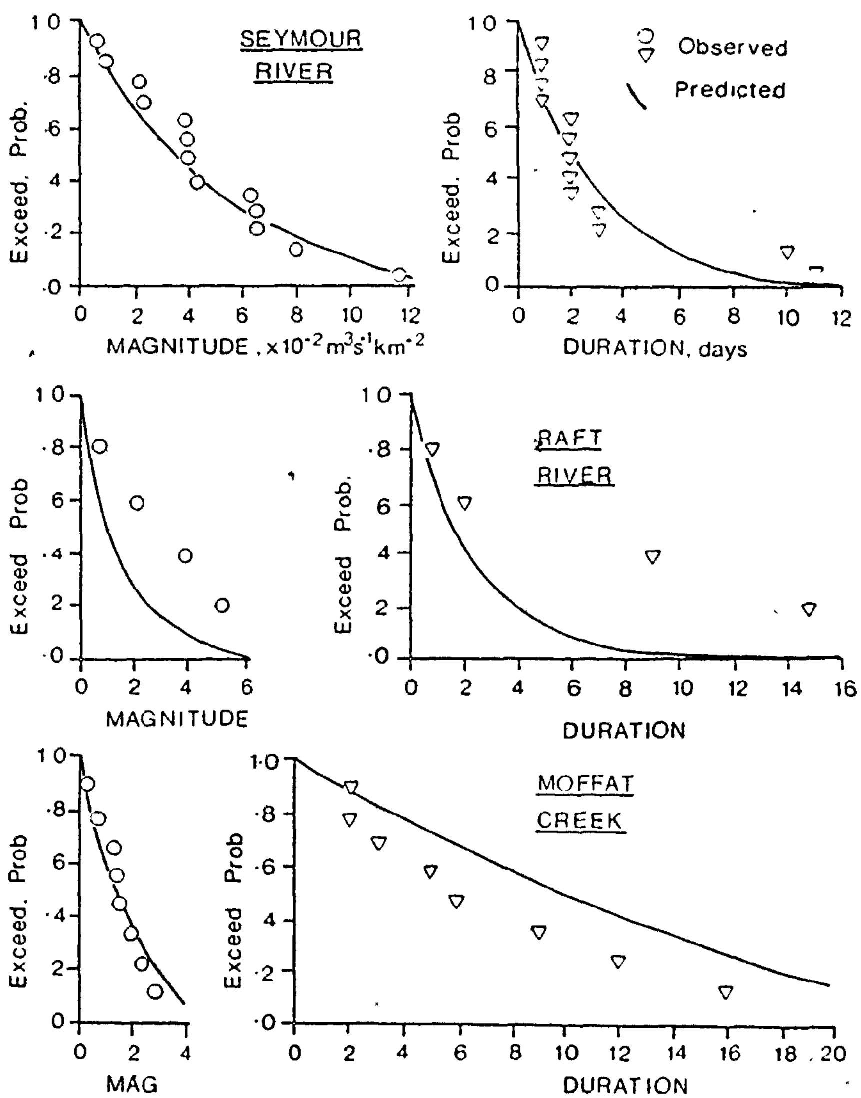


Figure 5.10 Observed and predicted distributions of the magnitudes and durations of exceedances for three test basins.

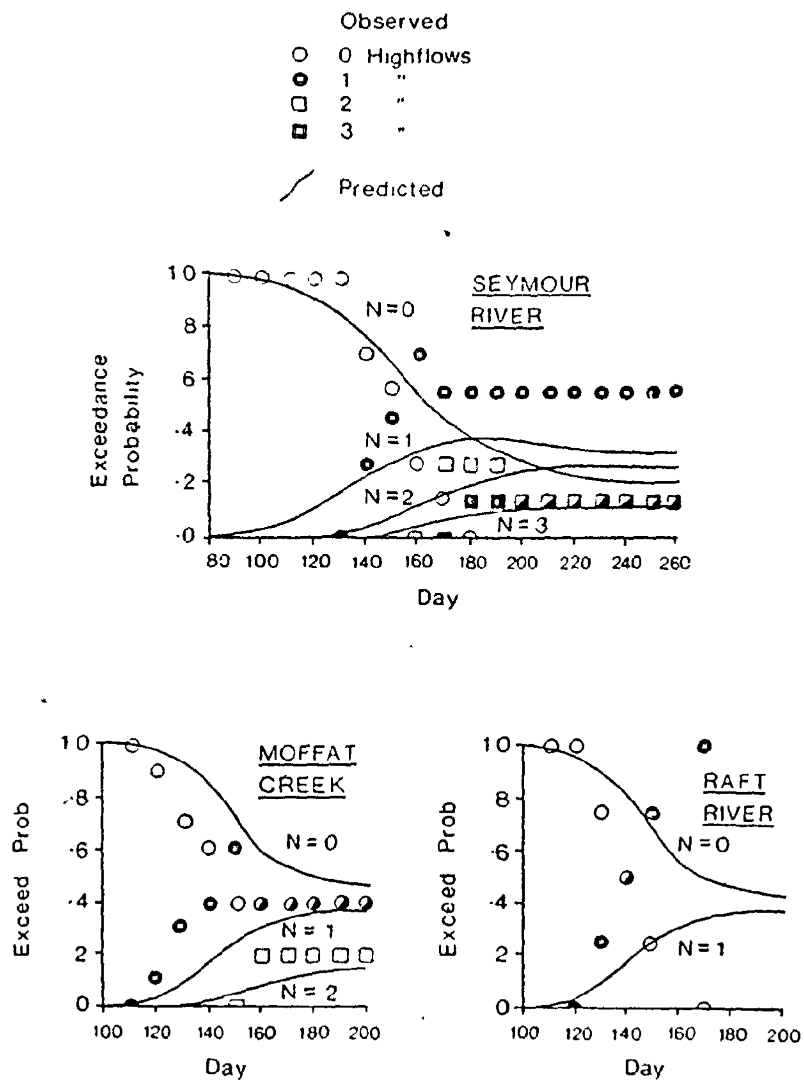


Figure 5.11 Observed and predicted distributions of the number and timing of exceedances for the three test basins.

5.8 Conclusions

The discharge equivalent to the two year return period annual flood constitutes a good common truncation level for the comparison of all the sampled partial duration series. It is a sufficiently low level to ensure a fairly large sample size and high enough to permit the assumption of Poisson distributed exceedances. The proposed probability distributions adequately describe the desired qualities of the partial duration series observed in the study area. The parameters of the distributions can be used as the basis of a flood regionalisation using discriminant analysis. The derived regions correspond closely to the regionalisation of annual floods and of other physical variables. Regional relationships between parametric and basin variables reflect the strength of the regionalisation. The prediction equations are physically meaningful and are indicative of the highflow generating processes in each region. Frequency characteristics of partial duration series can be predicted successfully by means of the regionalisation, prediction equations and probability distributions.

CHAPTER VI

DISCUSSION

6.1 Introduction

The temporal variability of highflows in the Fraser catchment has been satisfactorily modelled using both the annual flood and partial duration series. As indicated previously the two series should be closely related. Zelenhasic's (1970) distribution of annual flood series derived from parameters of the partial duration series is compared to observed annual flood series. The varied physical environments encountered in the study area provide a test of the distribution's general applicability. The approach is useful in that it combines the two types of highflow analyses and has a solid theoretical basis, which is lacking in distributions traditionally used to model annual flood series.

In analysing the spatial variability of the parameters, objectivity was maintained wherever possible. Inevitably during a process of classification or regionalisation subjective decisions have to be made. The importance of these decisions upon the proposed regionalisation and prediction are considered. Principal topics are the selection of the regionalisation procedure; the number of 'a priori' groupings; the extension of the groupings to form continuous regions and the comparison of the two sets of highflow regions.

6.2 Comparison of annual flood and partial duration series

Following the work of Zelenhasic (1970) annual flood series obtained from the observed partial series were compared to recorded annual flood series. Exceedance probabilities of observed magnitudes of annual floods were calculated using equation (4.3). Their expected frequencies, obtained from the partial duration series, were calculated using equation (2.26). The parameters λ and γ_M being the observed average number of exceedances per year and their average magnitude. Figure 6.1 illustrates the estimated probabilities in four sample basins.

The Kolmogorov-Smirnov test showed that in none of the sampled basins with unimodal flood characteristics could the probabilities calculated using the partial series, be considered significantly different from those of the observed annual floods at the .20 level. Although there is no method of comparing relative goodness of fit, visually Zelenhasic's (1970) theoretically based distribution, describes the observed data as well as the Gumbel distribution (see figure 4.3(b)). Zelenhasic's distribution is based upon the assumptions that the magnitudes of exceedances are exponentially distributed and that the number of exceedances in a year follow a Poisson distribution. It has been shown that these assumptions cannot be refuted in the case of the Fraser River catchment. Similar probability distributions have been developed assuming that the magnitudes of exceedances follow a gamma distribution. The gamma is a more flexible distribution, suggesting that a more ubiquitous

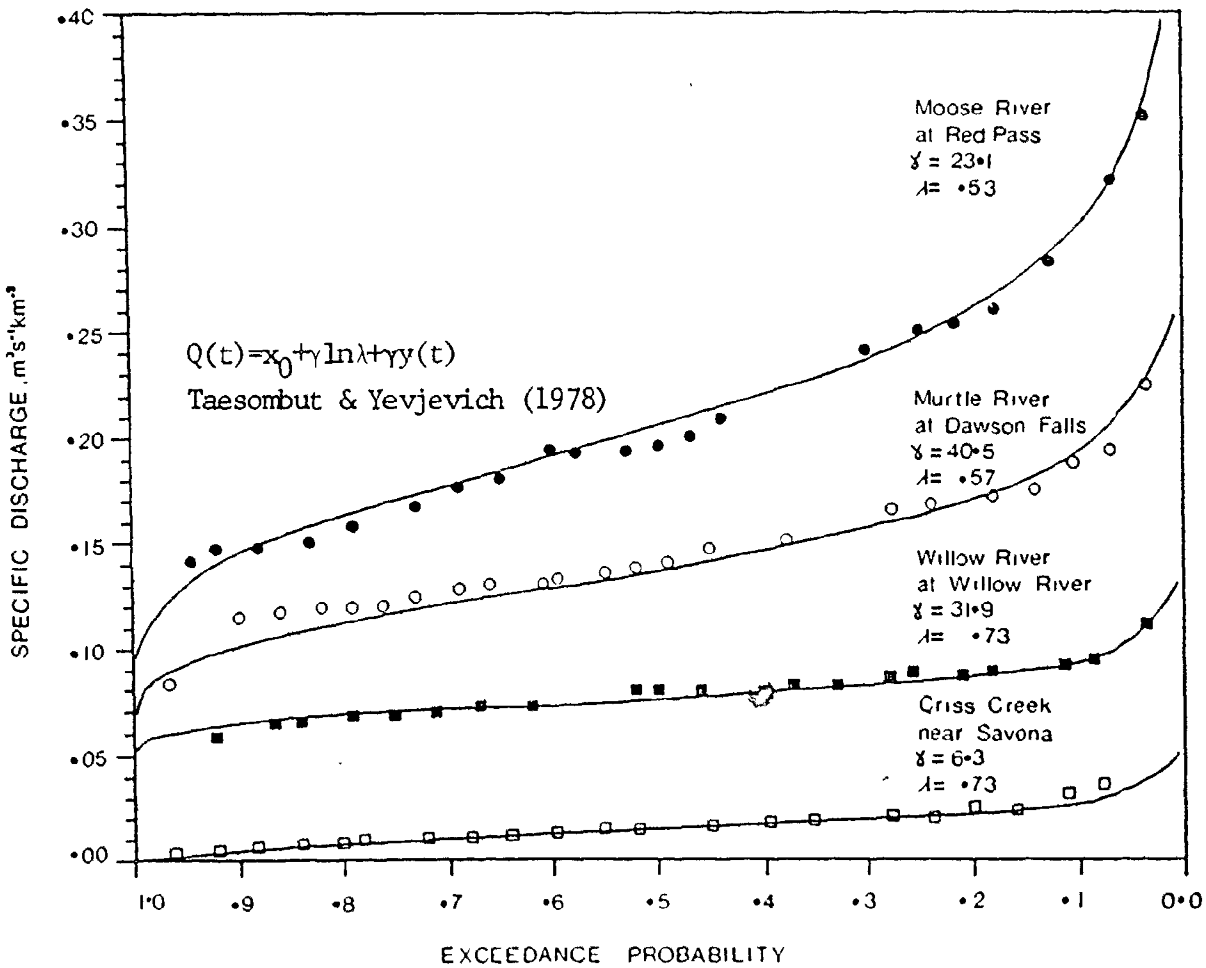


Figure 6.1 Observed and predicted annual flood distributions obtained from the partial duration series of four sampled basins.

application of the partial duration series approach to the derivation of annual flood series distributions is possible.

This correspondence between observed and predicted probabilities has been achieved in spite of the fact that the dominance of snowmelt as a flood generating process in the Fraser catchment limits the number of crossings per year at even the lowest truncation levels. Rarely does the sample size of any partial duration series approach the 1.65 times the number of years of record suggested by Cunnane (1973) as the lower limit at which partial duration series are good predicters of annual flood return periods.

6.3 Extension of results to other truncation levels

The choice of the 2 year return period annual flood as the truncation level yields partial duration series smaller than the annual flood series. Langbein (1949) and Todorovic (1978) have shown how probabilities of flood exceedances derived from the two series approach one another above annual flood return periods of about 4 years. Therefore much of the additional information about highflows, potentially available in partial series is being lost.

Practical knowledge of partial series derived from truncation levels other than that selected here may be required. Obtaining partial series from an infinite set of truncation levels is both expensive and time consuming. Prediction for ungauged basins would require the repetition of the entire regionalisation and regression procedure at each level of interest unless flood characteristics at one level can be related to those at others. The distributions employed in this study allow such a transference of information.

The probability distribution of the magnitudes of exceedances is given as

$$F(X \geq x;\ \gamma_M) = \exp\ (-\gamma_M \cdot x) \tag{6.1}$$

where $\gamma_M = 1.0/\bar{X}$ (6.2)

and $\bar{X}$ is the sample mean.

A graphic example of the probability distribution is shown in figure 6.2a. If the parameter γ_{Mo} is estimated from a sample of N_o observations of exceedances above the truncation level x_o, then the expected proportion of those observations that will be above a new truncation level, $(x_o + \Delta x_1)$, can be expressed as

$$F(X \geq \Delta x_1,\ \gamma_{Mo}) = \exp\ (-\gamma_{Mo} \cdot \Delta x_1) \tag{6.3}$$

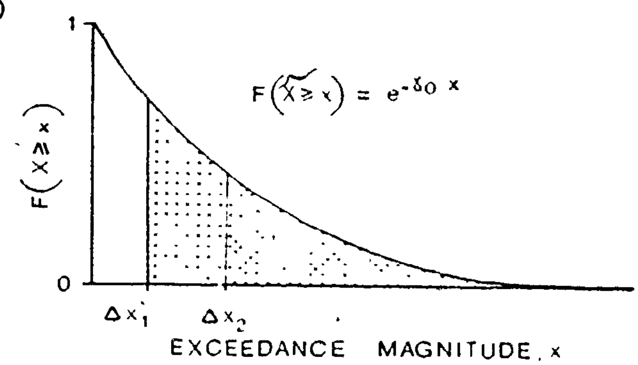
The expected number of exceedances, N_1, at the new truncation level is calculated as

$$N_1 = N_o \cdot F(X \geq \Delta x_1) \tag{6.4}$$

The parameter, λ_1, of the nonhomogenous Poisson model is readily obtainable from equation (6.4) for the truncation level $(x_o + \Delta x_1)$ by the division of, N_1, by the number of years of record in the original sample.

The proposed model of the number and timing of events (see figure 5.5) requires detail of the temporal distribution

(a)



(b)

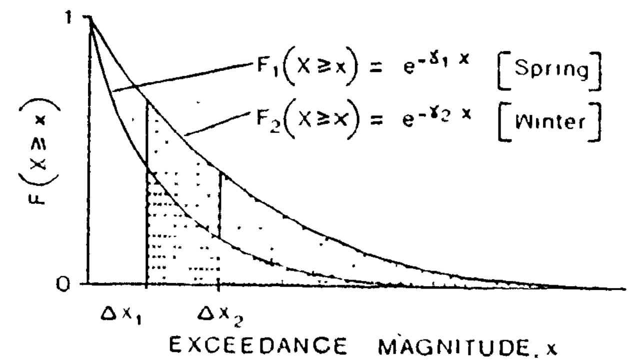


Figure 6.2 The effect upon the expectancy of the number of crossings of raising the truncation level of interest for (a) a single flood generating process (b) the compound case.

Table 6.1 Observed means and standard deviations (in parantheses) of dates of exceedances at several truncation levels.

Truncation level / Sample	1.1*	1.2	1.4	1.6	1.8	2.0	3.0	5.0
Moose R. (KA008)†	174(19)	170(15)	173(15)	172(16)	171(15)	172(15)	173(15)	172(15)
Adams R. (LD001)	164(26)	164(24)	163(22)	167(22)	167(20)	167(20)	167(23)	167(24)
Stellako R. (JB002)	146(31)	142(12)	151(24)	152(18)	150(14)	149(13)	152(77)	150(9)
Cariboo R. (KH013)	159(18)	160(17)	161(16)	157(10)	158(10)	158(10)	161(10)	162(9)
Criss Crk. (LF007)	141(17)	147(16)	147(14)	151(14)	151(14)	150(15)	155(15)	157(15)
Bowron R. (KD001)	152(18)	155(20)	152(18)	154(19)	153(19)	156(19)	162(19)	155(9)
Clearwater R. (LA013)	174(18)	173(14)	173(14)	172(14)	174(14)	175(15)	175(17)	180(13)
Dore Crk. (KA001)	173(18)	174(18)	175(18)	172(14)	171(14)	172(14)	171(16)	171(6)
Salmon R. (KC001)	123(6)	124(6)	126(6)	126(7)	127(7)	127(7)	126(5)	129(7)
Chilko R. (MA001)	193(23)	193(18)	191(17)	193(17)	195(16)	191(18)	188(22)	180(18)
Nicola R. (LG007)	146(13)	146(12)	149(13)	150(13)	148(12)	149(11)	147(12)	148(10)
Horsefly R. (KH010)	160(23)	157(16)	157(15)	155(15)	154(15)	157(15)	153(11)	N/A

† Water Survey of Canada station codes

* Truncation level expressed as return period of annual flood of specific size

of highflows through the year. Table 6.1 indicates that for some basins the mean and standard deviation of the dates of highflows can be considered to remain constant as the truncation level rises. This empirical evidence is supported by a brief consideration of the Gaussian distribution. For Gaussian distributed variables the mean, median and mode are equal. The mean day of highflows should also be the day on which highflows most frequently occur. If highflow exceedances are independent, identically distributed random variables then the higher probability of highflows on the mean day insinuates a greater likelihood of obtaining at least one event of the original sample, N_o, above the truncation level x_o that will exceed the new truncation level, x_1.

A combination of the effects of changing truncation levels upon the number of floods and their times of occurrence allows predictions of the nature of the nonhomogenous Poisson model at any truncation level. Table 6.2 compares parameters predicted from data collected at the 1.2 year return period truncation level and observed parametric values for various truncation levels on the Clearwater River at the outlet of Hobson Lake (W.S.C. 08LA013).

As the truncation level rises the sample size decreases and observed parameter estimates fluctuate. The comparison of predicted and observed highflow characteristics (figure 6.3) shows a fairly good fit for a sample of only 16 years of record. There appears to be a consistent over estimation of the probability

Table 6.2 Observed and predicted numbers and timings of highflows on the Clearwater River. Parameters are predicted from observed parametric values at 1.2 year return period truncation level.

return period years	truncation level m^3s^{-1}	Δx	predicted number $\hat{N}$	observed N	predic. cross./year $\hat{\lambda}$	obser. λ	obser mean $\bar{X}$ day	obser. St.dev. S day
1.2	164.0	-	-	15	-	0.94	173	14
1.4	174.4	10.4	11.6	13	0.73	0.81	173	14
1.6	181.5	17.5	9.7	12	0.61	0.75	173	14
1.8	187.0	23.0	8.5	10	0.53	0.63	174	14
2.0	191.5	27.5	7.6	7	0.48	0.44	175	15
3.0	207.1	43.1	5.2	7	0.32	0.44	175	17
5.0	224.4	60.4	3.4	4	0.21	0.25	180	14
10.0	246.1	82.1	2.0	1	0.12	0.06	163	-

of no floods towards the end of the 'highflow season' at about day 200. It should be borne in mind that one event occurring late in this limited sample size will cause a change in observed relative frequencies of 0.06 and that, by the cumulative nature of the model, will affect all consequent observations.

Equations (6.3) and (6.4) imply that at progressively higher truncation levels the number of highflows and the parameter λ, decline exponentially. This behaviour can be seen in all the sample basins (see figure 6.4). Exponential distributions are also memoryless, that is, any portion of the distribution is itself exponential and described by the same parameter, (Ross, 1976; p. 109). Thus as the truncation level is

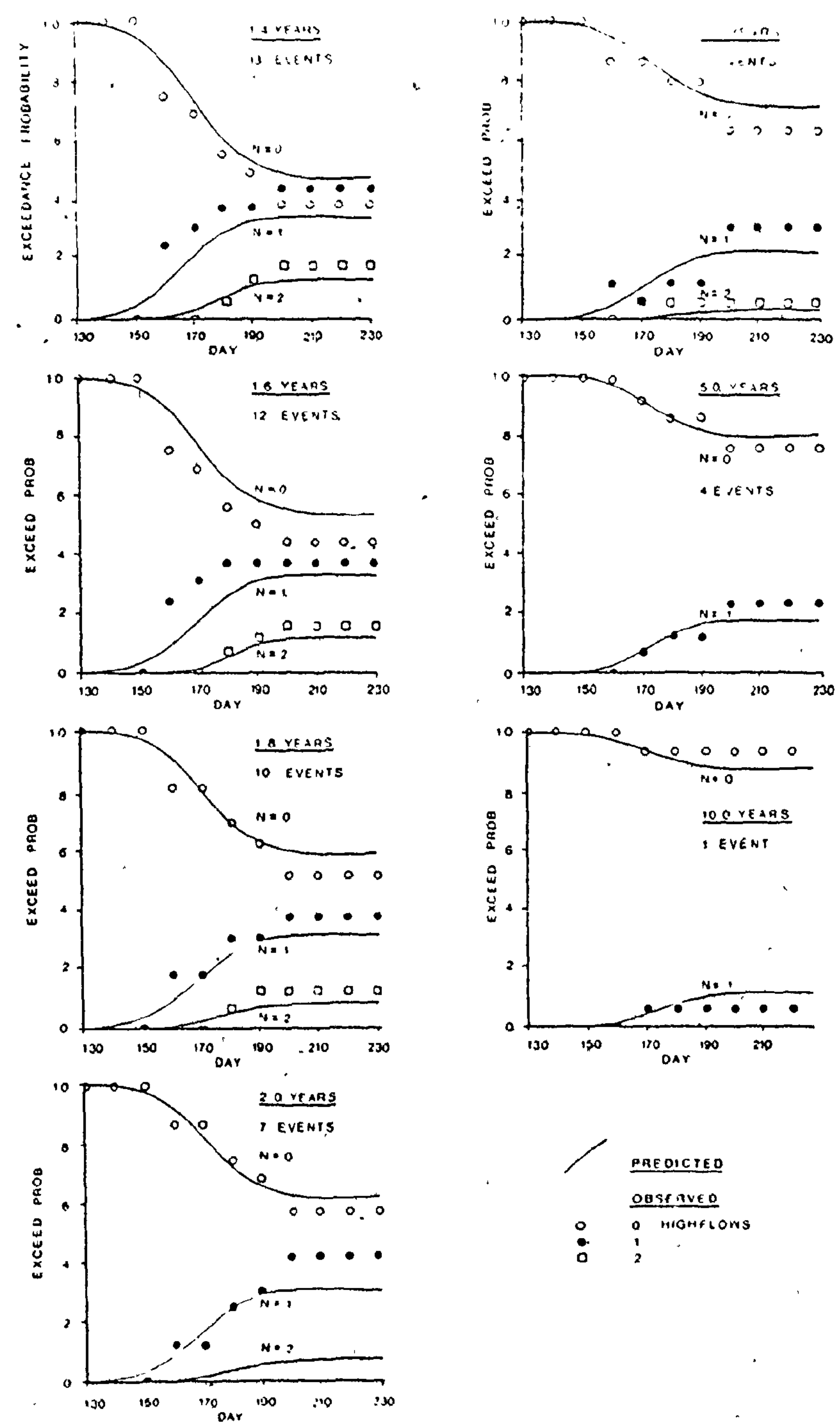


Figure 6.3 Comparison of the observed numbers and timings of exceedances of varying truncation levels to values predicted from the 1.2 year return period truncation level on the Clearwater River (LA013).

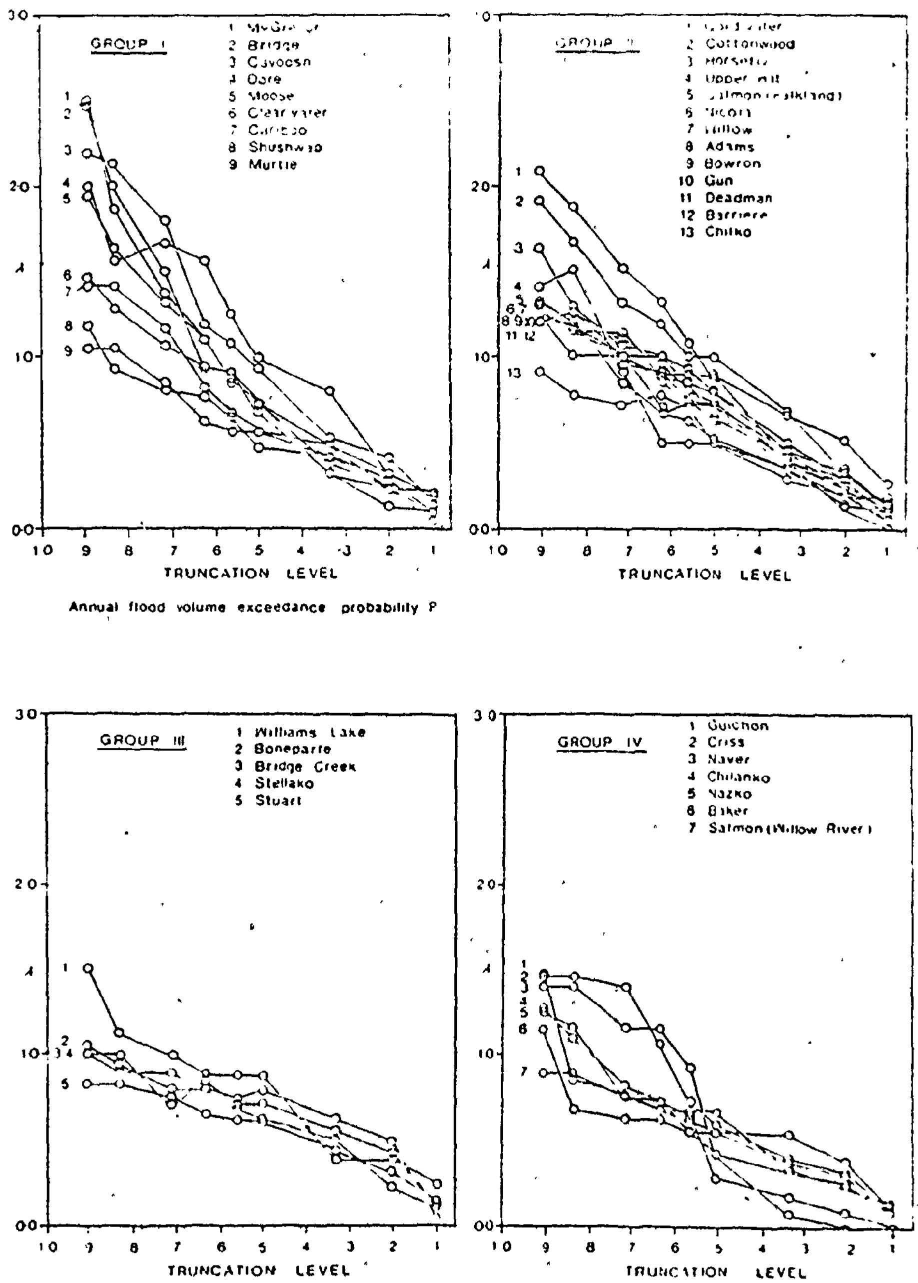


Figure 6.4 Regional variations in the parameter, λ, at varying truncation levels.

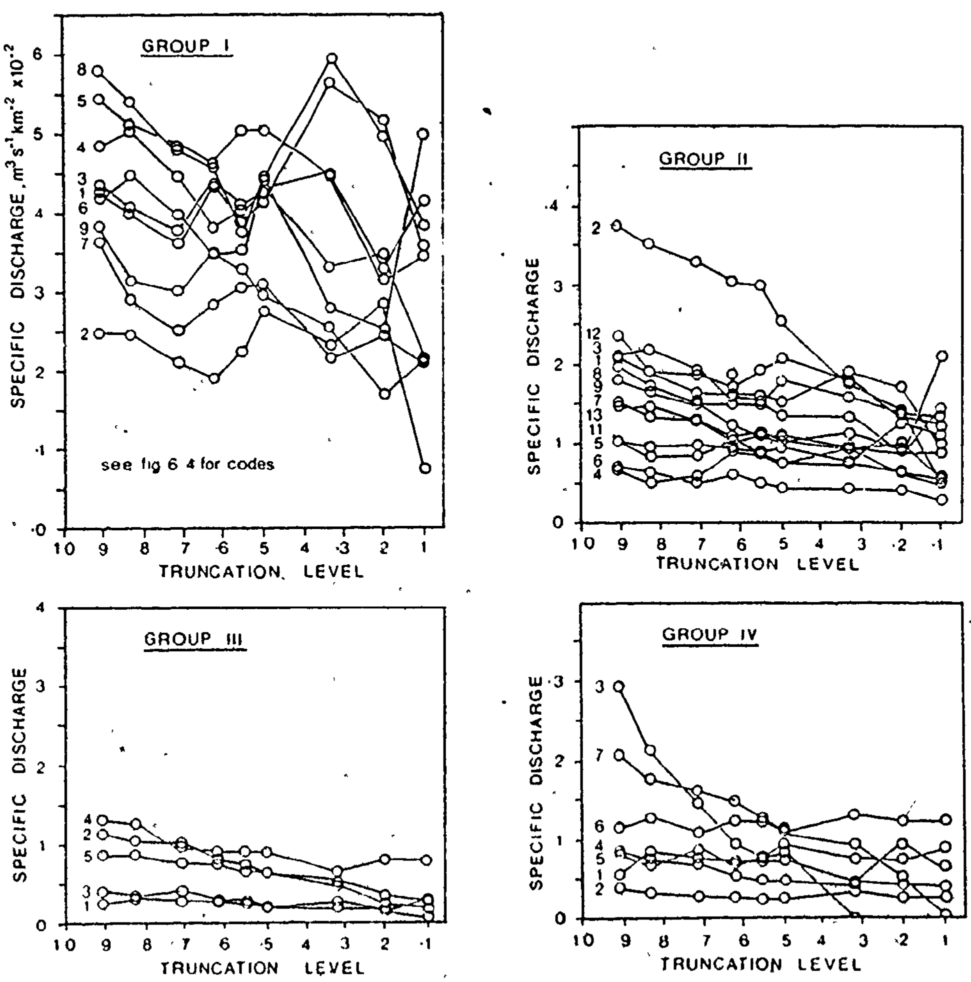


Figure 6.5 Regional variations in the mean peak exceedance at varying truncation levels.

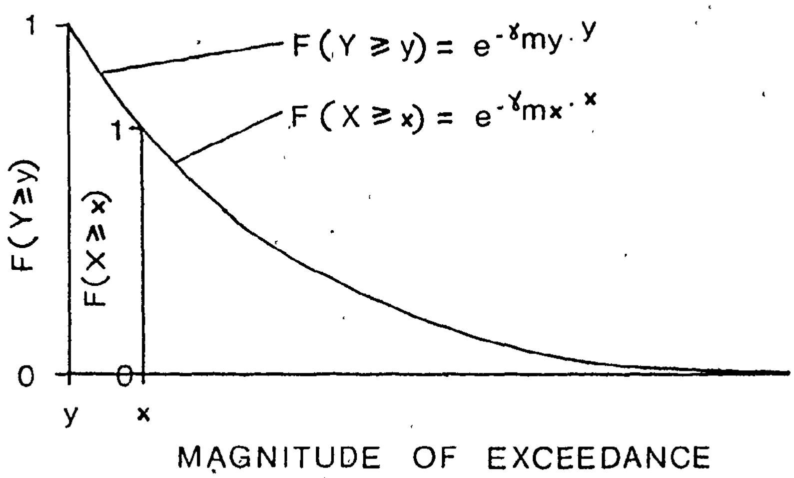


Figure 6.6 Effect upon the expectancy of the number of crossings of reducing the truncation level of interest.

raised the average magnitude of exceedances remains constant. Empirical evidence of this fact is provided by figure 6.5. The limited sample sizes at upper truncation levels produces wide fluctuations in the average exceedance.

6.4 The Compound model

Employing the principles developed for the unimodal situation, predictions of highflow characteristics at upper truncation levels can be obtained for bimodal or multimodal cases. Figure 6.2b shows how the two distinct exceedance populations in the bimodal case can be used to predict the respective numbers of highflows that will occur at higher truncation levels. Equations (6.3) and (6.4) are used in conjunction with the parameters of each period. The results of the method's application to the Coquihalla River at Hope are listed in Table 6.3. At the lower levels of truncation, spring exceedances are almost as frequent as those in winter. On average their magnitude tends to be much smaller than the winter exceedances. Hence, relatively fewer spring exceedances occur at higher truncation levels. At the 3.0 year return period truncation level no exceedances occurred in the observed record during this season. A λ of 0.02, or one highflow every fifty years was predicted.

Consideration of the diminishing relative rates of exceedance has a more ubiquitous application than the two samples selected here as being bimodal. At the 2 year return period truncation level, several streams showed rare isolated exceedances in the late summer and fall. Their relative importance

Table 6.3 Observed and predicted parameters of the partial series of the Coquihalla River using the compound model. Parameters are predicted from the observed parametric values at the 1.4 year return period truncation level.

Return period	truncation level	increase in truncation level	SPRING: Number of crossings		SPRING: crossings per year		SPRING: dates of exceedances		SPRING: mean peak exceed. m^3s^{-1}	WINTER: # of crossing		WINTER: crossings per year		WINTER: dates of exceedances		WINTER: Mean peak exceedances m^3s^{-1}
			obs. N	pred. $\hat{N}$	obs. $\hat{\lambda}$	pred. $\hat{\lambda}$	mean $\overline{X}_{day}$	st. dev. σ_{day}		obs. N	pred. $\hat{N}$	obs. λ	pred. $\hat{\lambda}$	mean $\overline{X}_{day}$	st. dev. σ_{day}	
1.4	178.5	-	14	-	.52	-	151.1	11.8	26.3	18	-	.67	-	353.3	38.2	100.0
1.6	197.0	18.5	7	6.9	.26	.26	151.0	5.6	28.3	14	15.0	.52	.56	350.4	31.5	108.3
1.8	216.9	32.8	5	4.0	.19	.15	153.0	5.0	24.4	12	13.0	.44	.48	349.8	33.2	111.8
2.0	223.1	44.6	4	2.6	.15	.10	152.8	5.5	16.7	12	11.5	.44	.43	352.5	33.3	100.0
3.0	263.6	85.1	0	0.6	.00	.02	-	-	-	8	7.7	.30	.29	332.9	21.3	101.3
5.0	308.6	130.1	0	0.1	.00	.00	-	-	-	5	4.9	.18	.18	330.6	24.7	108.0
10.0	365.2	186.7	0	0.0	.00	.00	-	-	-	2	2.8	.08	.10	325.0	21.0	152.7

was not sufficient to warrant the rejection of the hypothesis of normality in the distribution of highflows. However their influence upon the otherwise excellent predictive abilities of the model is noticeable. These exceedances are physically related to rainfall events. Those occurring in the summer, on the Interior Plateau, may be the result of seasonal convectional activity. The timing of the later highflows and their apparent path across basins affected in the study area suggests an origin in frontal systems crossing the Coast Mountains.

Fiering and Jackson (1971) advocate the use of a uniform temporal distribution and the assigning of low probabilities of occurrence in the case of such 'outliers'. The definition of the time period over which these highflows occurred needs to be physically based due to the small number of observed events. Similar difficulties are encountered in the determination of the frequency characteristics of their magnitude and duration.

6.5 Relevance to the regionalisation procedure

The fact that more diverse physical processes are responsible for exceedances at lower truncation levels suggests that one set of regionalisations may only be used to predict exceedance characteristics in ungauged basins at that particular level of truncation. At the truncation level selected in this study all the major highflow generating processes manifest themselves. Extension of these findings to higher levels of interest is therefore feasible. The procedure can also be used to predict patterns of highflows at lower levels. The extent to which this can be carried out is limited by the necessity of meeting the assumption of Poisson events.

The characteristics of the N_x, crossings at truncation level x are described by the parameter γ_{Mx}. Information concerning the number of exceedances, N_y, of a lower truncation level, y, is required. Equations (6.3) and (6.4) when combined yield

$$N_x = N_y \exp(-\gamma_{My} \cdot (x - y)) \tag{6.5}$$

rewriting (6.5) in terms of N_y

$$N_y = N_x / \exp(-\gamma_{My} \cdot (x - y)) \tag{6.6}$$

It has been shown that γ_{Mx} and γ_{My} will be equal. Therefore given the assumption of exponentially distributed magnitudes of exceedance the selection of a relatively high truncation level as the basis of regionalisation is not a drawback to predictions at lower levels. Implicit in this are the assumptions that events at the lower level of truncation are generated by the same processes and can be considered independent.

6.6 Regionalisation

6.6.1 The problem of 'a priori' groupings

The reasons for the selection of the number and constitution of the groups initially entered into discriminant analyses have been discussed. The introduction of 'a priori' groupings provides a degree of subjectivity in the analysis. The goal of the regionalisation procedure is to sub-divide the sampled basins intó groups with sufficiently similar highflow characteristics to improve the accuracy of the regional regression equations. A division of the study area into many regions leads to small sample sizes within each group and meaningless prediction equations. A third consideration is that all the sampled basins should eventually be classified.

Other grouping procedures were applied to the parameters of the annual flood series. They yielded similar patterns of groupings to those ultimately used. Methods that did not necessitate the 'a priori' designation of the number of groups, such as Ward's grouping procedure, require decisions concerning the point at which grouping should cease. In this study such a point was not obvious. Four groups developed through the analysis although several basins remained ungrouped until late in the procedure. To establish prediction equations these 'outliers' have to be forced into one group or another. When each basin was initially assigned as an individual group and discriminant analysis used to identify those basins that were most alike, a comparable pattern of groupings was obtained. At each stage the two most similar basins are allocated to one group and the analysis repeated.

To avoid entirely the difficulty of grouping, one set of equations for the Fraser catchment were developed using backwards stepwise multiple regression. Their predictive powers were negligible because of the diversity of environments within the study area. Regionalisations consisting of several numbers of groups were also constructed using discriminant analysis. The coefficients of determination of the regional regression equations increased as the number of groups increased. Simultaneously the degrees of freedom associated with each equation decreased. Four 'a priori' groups gave the best significant equations.

6.6.2 Comparison of highflow regions

Both highflow series give rise to groupings which suggest strong regional differences within the study area. The groupings of the sample basins have to be extended across the whole study area. The selected annual isohyets provide excellent boundaries for the annual flood series groupings. The only characteristic being regionalised in this case is the magnitude of the annual floods, hence the correspondence to the annual precipitation. Regionalisation of the partial series is based upon five parameters which characterise several aspects of the series. The nature of the regional boundaries and their extensions reflect the more varied basis of regionalisation and specifically the parameters that make that region distinct from the others.

Region I has particularly high peak exceedances and is therefore well defined by the 1500 mm annual isohyet. The areas of glaciation are also encompassed by this isohyet because of the nature of the relationship between precipitation, elevation and glaciation in the study area. When the magnitude of peak exceedances is an important regional variable the boundaries obtained from the partial series resemble those of the annual floods. The relationship between the magnitudes of highflows of the two series outlined in section 6.2 and a comparison of figures 6.1 and 4.2b show that the parameters λ and γ_M in equation (2.26) have similar effects to those of α and β in equation (2.11). Thus those streams of the northern Interior Plateau, which have simple snowmelt regimes can be differentiated from the higher runoff of region II by the 1000 mm annual isohyet. The number and timing of highflows on the southern Interior Plateau are the variables that cause these basins to be differentiated from those of the northern Plateau. The more southerly basins are grouped to region II by the discriminant analysis. The division is not dependent upon the magnitude of highflows therefore the boundary has no equivalence in the annual flood regionalisation.

Towards this boundary the division of groups is not particularly clear and two basins, Criss Creek (W.S.C. 08LF007) and Guichon Creek (W.S.C. 08LG004) appear to be misallocated. Observed parametric values are compared to those predicted by the regression equations of regions II and IV in Table 6.4. Bearing in mind that the observed parametric values were input to the formulation of the prediction equations for region IV, there are similarities in the predicted parameters, suggesting an indistinct division between the two regions. The sample basins in this part of the study area are small and are generally more contiguous than the remaining sampled basins. It

Table 6.4 Comparison of observed and predicted parameters for stations on Criss Creek and Guichon Creek.

Station \ Parameter		Crossings/ yr. λ	date of exceed. $\bar{X}$ day	St. dev. S day	mean dur. (days) γ_D	mean exceed. γ_M
Criss Crk. LF007	obs.	.60	150	15	4.1	.023
	II	.59	145	14	12.2	.007
	IV	.58	149	15	4.9	.013
Guichon Crk. LG004	obs.	.54	134	7	19.9	.008
	II	.64	151	13	11.5	.007
	IV	.57	133	8	20.1	.004

is an area of rapidly changing physical environments from the eastern flanks of the Coast Mountains; across the highly dissected Fraser Plateau to the Shushwap Mountains. It appears that in this case the scale at which the physiographic and climatic data were collected is not sufficient to identify fully those characteristics that produce differing patterns of highflow in contiguous basins. The basin variables of Criss Creek and Deadman River (W.S.C. 08LF027) are almost identical (see Appendix B) yet the parameters of their highflows are very different. The results indicate that these basins are approaching the lower bound of basin areas that provide accurate predictions as a result of the study.

6.7 Conclusions

Zelenhasic's (1970) distribution adequately describes the annual flood series of the sampled basins in the Fraser catchment. The assumptions underlying its derivation have been supported theoretically and proven empirically. Its similarity to the Gumbel distribution was proposed by Zelenhasic as an explanation for the general use of that distribution despite its lack of theoretical foundation.

The regionalisation procedure employed proved to be as objective as any other and met the requirements of the study. The 'a priori' classifications could be changed by the procedure where statistically necessary. However these regions were physically based and the improved accuracy of predictions within the derived regions numerically justified the selection of the four groups.

The findings of the analysis are not restricted to partial series derived from one truncation level. Parameter estimates of highflow characteristics based upon relatively large sample sizes can be used to estimate those at other truncation levels. Thus the scheme of regionalisation and prediction provides a basis for estimating frequency characteristics of high flows at any desired truncation level in ungauged basins or those possessing short periods of record.

CHAPTER VII

CONCLUSIONS

A traditional approach and recent developments in the stochastic modelling of highflows have been applied to the frequency, timing, magnitude and duration of events in individual basins. The spatial variation of the stochastic parameters provides the basis of a regionalisation of highflows that ultimately enables the prediction of highflow characteristics of ungauged basins in the study area. The procedure has been carried out using only readily available streamflow, physiographic and climatic data. Not only have the stochastic models been tested extensively but they have also been employed as a valuable tool in the planning and development of water resources.

The combination of stochastic and deterministic modelling adopted in determining the temporal and spatial characteristics of highflows, utilises the beneficial aspects of both approaches. The deterministic prediction of highflows at the level of the individual basin requires considerable quantities of current hydrologic data. Obtaining such data for the large, physically diverse and frequently remote basins selected in this thesis, is generally infeasible due to monetary and time constraints. Regardless of the type of approach taken predictions can only be made on the basis of existing information. The stochastic approach requires just streamflow data. The models employed describe adequately the desired qualities of the historical records. Limited and unreliable data are major drawbacks in the estimation of parameters and the development of stochastic models. The type of regionalisation of stochastic parameters used in this study has been shown to diminish the associated error in parameter estimation.

The stochastic models yield at most five parameters describing the temporal characteristics of the highflows within a basin. They serve as convenient inputs to a procedure that aggregates spatially those basins possessing similar temporal characteristics. The resultant pattern of groupings strongly resembles the distribution of physical processes underlying the generation of highflows. A deterministic relationship between simple indicators of these diverse processes and the stochastic parameters in each of the established groups incorporates the role of regional physiographic and climatic controls. The derived expressions allow for parametric variability within the regional framework. This approach accommodates both inter-regional differences in flood generation processes and the highly localised effect of individual basin characteristics intra-regionally, while avoiding the complexities and data requirements of their inclusion in a physically based, deterministic model of highflows.

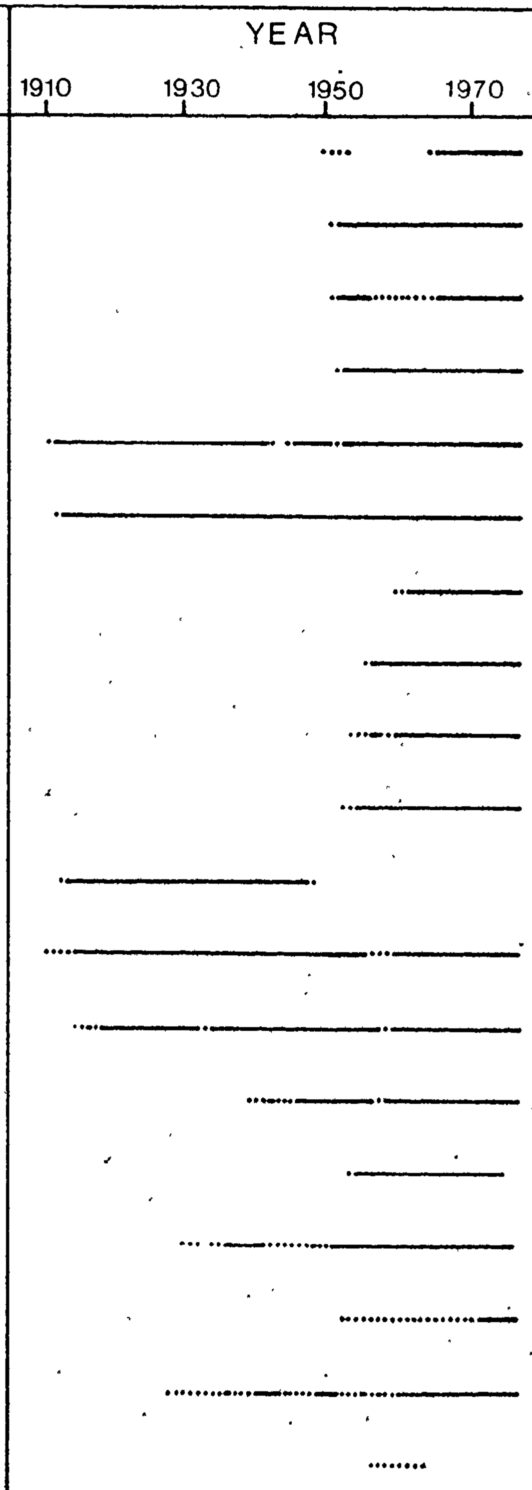
The entire scheme provides a simple and comprehensive technique for the prediction of highflow characteristics in ungauged basins. Input variables are available from maps and government documents. The prediction equations are easily solved and the necessary frequency distributions require, at most, two parameters. The success of the method in an area of complex physical environments and limited data suggests that a more ubiquitous application is feasible with no additional data requirements.

The stochastic models describing the variables of the partial duration series had not previously been widely tested. Neither had the truncation level been selected in such a way as to permit inter-basin comparisons of parametric values. The models have been used successfully in situations of limited streamflow records and in a variety of environments that ranged, in the study area, from glaciated alpine to semi-arid. Similarly it has been shown that the theoretical distribution developed to link annual flood series and recent advances in partial duration series as approaches to highflow analysis, is applicable throughout the study area. No published material had previously analysed the important variable of the duration of highflows. The results suggest that they are exponentially distributed and a theoretical justification is proposed for this observation. The theoretical bases for, and the results of, the analysis of partial duration series give rise to a method of predicting highflow characteristics at truncation levels other than that initially selected. This adds greatly to the value of the regionalisation and prediction procedure as a practical tool.

APPENDIX A.

Lengths of Streamflow Records

CODE	BASIN AND GAUGE LOCATION	comp.	partial
1	Dore R., McBride	10	6
2	Fraser R., Shelley	26	1
3	" " , Marguerite	17	10
4	" " , Texas Crk.	25	1
5	Thompson R., Spences Bridge	62	4
6	Fraser R., Hope	64	1
7	McGregor R., Lower Canyon	16	2
8	Fraser R., Red Pass	21	1
9	" " , McBride	19	5
10	" " , Hansard	23	2
11	Bridge R., Shalalth	34	2
12	South Thompson R., Monte Crk.	59	7
13	North Thompson R., Barrière	57	5
14	Quesnel R., Quesnel	31	7
15	Willow R., Willow R.	22	1
16	Stuart R., Fort St. James	34	13
17	West Road R., Cinema	6	19
18	Chilko R., Redstone	24	26
19	McGregor R., Upper Canyon	0	8



CODE	BASIN AND GAUGE LOCATION	YEAR (1910 1930 1950 1970)	comp.	partial
20	Salmon R., Willow R.		17	7
21	Chilako R., Prince George		11	4
22	Baker Crk., Quesnel		13	1
23	Cariboo R., Keithley Crk.		12	2
24	Quesnel R., Likely		42	11
25	Clearwater R., Clearwater Lake		19	8
26	" " Clearwater Stn.		35	7
27	Seton R., Lillooet		25	10
28	Adams R., Squalix		46	20
29	Nicola R., Spences Bridge		16	14
30	Bonaparte R., Cache Crk.		3	13
31	Deadman R., Criss Crk.		15	10
32	Nicola R., Merritt		20	4
33	Shushwap R., Enderby		36	7
34	Nazko R., Michelle Crk.		12	1
35	San Jose R., Lac La Hache		2	24
36	Cottonwood R., Cinema		12	11
37	Nechako R., Fort Fraser		24	0
38	Nautley Fort Fraser		23	2

CODE	BASIN AND GAUGE LOCATION	YEAR 1910 1930 1950 1970	comp.	partial
39	Nahatlach R., Keefers		4	6
40	Lillooet R., Pemberton Mdws.		51	8
41	Bowron R., Hansard		15	8
42	Fraser R., Big Bar Crk.		12	26
43	Stellako R., Glenannan		26	3
44	Moose R., Red Pass		19	3
45	Bowron R., Wells		15	9
46	Naver Crk., Hixon		12	7
47	Horsefly R., McKinley Crk.		14	3
48	Murtle R., Dawson Falls		21	9
49	Mahood R., Mahood Lake		14	11
50	Clearwater R., Hobson Lake		16	2
51	Barrier R., The Mouth		25	12
52	Shuswap R., Lumby		41	9
53	Shuswap R., Sugar Lake		15	6
54	Shuswap R., Mabel Lake		32	4
55	Hat Crk., Cache Crk.		10	7
56	Bonaparte R., Bridge Lake		16	1
57	Bridge Crk., 100 Mile House		7	11

CODE	BASIN AND GAUGE LOCATION	YEAR (1910 1930 1950 1970)	comp.	partial
58	Guichon Crk., Lower Nicola		13	12
59	Chilko R., Chilko Lake		15	34
60	Chilcotin R., Big Crk.		6	1
61	Williams Lake R., Williams Lake		8	4
62	Cayoosh Crk., Lillooet		15	16
63	Bridge R., Lajoie Falls		21	4
64	Bridge R., Gold Bridge		16	2
65	Gun Crk., Minto City		8	6
66	Coquihalla R., Hope		27	5
67	Bridge R., Tyaughton Crk		11	2
68	Salmon R., Falkland		19	16
69	Criss Crk., Savona		15	11
70	Coldwater R., Merritt		15	10
71	Ootsa R., Ootsa Lake		18	6

APPENDIX B

Physiographic and climatic variables

River[1]		$A(km^2)$	P(mm)	H(m)	D(km)	S(days)	G(%)	L(%)	R(m)
Adams R.	(LD001)	2975	526	1100	586	131	0.3	4.3	800
Baker Crk.	(KE016)	1574	450	800	362	158	0.0	0.8	520
Cariboo R.	(KH013)	2875	782	1250	493	165	3.2	3.5	570
Chilako R.	(JC005)	3393	450	1000	361	165	0.0	3.2	250
Cottonwood R.	(KE009)	1909	642	1000	431	165	0.0	0.0	430
Deadman R.	(LF027)	862	450	1000	382	115	0.0	0.7	200
Dore R.	(KA001)	404	684	2000	546	165	9.7	0.0	910
Lillooet R.	(MG005)	2163	1752	1500	236	151	13.4	0.0	820
McGregor R.	(KB005)	2434	634	1200	566	184	5.1	0.0	740
Nahatlach R.	(MF008)	1036	1132	1250	229	128	1.2	1.2	530
Nazko R.	(KF001)	3238	444	1000	307	155	0.0	0.7	160
Nicola R.	(LG007)	4531	474	1000	307	109	0.0	1.7	250
Salmon R.	(KC001)	4299	481	750	441	165	0.0	2.5	130
San Jose R.	(MC006)	777	447	1000	434	145	0.0	4.3	450
Stuart R.	(JE001)	14555	522	750	388	165	0.0	8.8	310
Willow R.	(KD003)	3108	717	1000	454	165	0.0	1.8	520
Bonaparte R.	(LF062)	666	450	1000	383	116	0.0	11.7	230
Bowron R.	(KD001)	458	800	1000	486	165	0.0	4.1	340
Bridge Crk.	(LA005)	1326	450	1000	432	125	0.0	10.9	140
Bridge R.	(ME005)	1647	1005	1900	271	145	11.2	2.8	870

River[1]		A(km^2)	P(mm)	H(m)	D(km)	S(days)	G(%)	L(%)	R(m)
		Physiographic and climatic variables							
Barrière R.	(LB020)	1140	450	1000	445	120	0.0	1.7	380
Cayoosh Crk.	(ME002)	878	839	1500	275	120	0.0	.9	730
Chilko R.	(MA002)	2106	820	1000	239	145	3.5	11.2	800
Clearwater R.	(LA013)	904	800	1500	538	165	12.5	3.1	790
Coldwater R.	(LG010)	914	502	1000	269	112	0.0	0.0	360
Coquihalla R.	(MF003)	740	1040	1200	218	105	0.0	0.0	500
Criss Crk.	(LF007)	490	450	1000	374	114	0.0	2.0	240
Guichon Crk.	(LG004)	1228	491	1000	317	115	0.0	2.0	260
Gun Crk.	(ME006)	570	806	2000	283	145	6.1	0.0	650
Hat Crk.	(LF015)	524	450	1500	300	115	0.0	0.0	460
Horsefly R.	(KH010)	785	667	1000	488	157	0.0	2.4	600
Moose R.	(KA008)	458	1213	2000	643	205	7.8	0.0	800
Murtle R.	(LA004)	1378	745	1750	527	165	1.0	7.4	520
Naver Crk.	(KE014)	658	654	500	431	165	0.0	0.0	510
Ootsa R.	(JA002)	4248	979	1100	200	159	.9	14.8	600
Salmon R.	(LE020)	880	450	1000	370	105	0.0	0.0	350
Shuswap R.	(LC018)	1127	869	1500	465	125	1.8	4.5	800
Stellako R.	(JB002)	3600	519	500	267	147	.2	6.3	420
McGregor R.	(KB003)	4765	549	1000	564	182	4.0	0.0	650
Williams Lake	(MC005)	2240	425	1000	422	145	0.0	2.0	500

(1) Water Survey of Canada codes in parentheses

BIBLIOGRAPHY

ASHKAR, F., El-Jabi, N. and Rousselle, J., 1980. Hydrologic extreme value model and risk analysis applied to flood plain management. in Modelling Activities Related to Flood Damage Reduction - Proceedings of the technology transfer workshop. Technical Workshop Series No. 2, Inland Waters Directorate, Environment Canada, Ottawa, 473 p.

BEARD, L.R., 1978. Impact of hydrologic uncertainties on flood insurance. J. Hydraulics Div., Amer. Soc. Civil Eng., 104 (HY 11), pp. 1473-1483.

BENSON, M.A., 1968. Uniform flood frequency estimating methods for federal agencies. Water Resources Research, 4(5), pp. 891-908.

BENSON, M.A., and Matalas, N.C., 1967. Synthetic hydrology based on regional statistical parameters. Water Resources Research, 3(4), pp. 931-935.

BISWAS, A.K., and Fleming, G., 1966. Floods in Scotland: Magnitude and frequency. Water and Water Engineering, 17, pp. 246-252.

BOBÉE, B., 1975. The log-Pearson type 3 distribution and its application in hydrology. Water Resources Research, 11(5), pp. 681-689.

BOBÉE, B., and Villeneuve, J.P., 1975. Statistical distributions: Progress and trends in flood frequency analysis. Proc. Canadian Hydrology Symposium - 75., Winnipeg, Manitoba, August, pp. 201-205.

BORGMAN, L.E., 1963. Risk criteria. J. Waterways and Harbours Div., Amer. Soc. Civil Eng., 89(WW4), pp. 1-35.

BOUGHTON, W.C., 1980. A frequency distribution for annual floods. Water Resources Research, 16(2), pp. 347-354.

CHOW, W.T., 1950. Discussion on annual floods and the partial duration flood series, by W.B. Langbein. Trans. Amer. Geophys. Union, 31, pp. 939-941.

CHOW, W.T., 1954. The log probability law and its engineering applications. Proc. Amer. Soc. Civil Eng., 80, pp. 1-25.

CHOW, W.T., 1964. editor in chief Handbook of Applied Hydrology; McGraw-Hill, New York, 1215 p.

CHURCH, M., 1980. Records of recent geomorphological events, in Timescales in Geomorphology. edited by R.A. Cullingford, D.A. Davidson and J. Lewin, Wiley and sons, New York, pp. 13-22.

COLLIER, E.P., and Nix, G.A., 1967. Flood frequency analysis for the New Brunswick-Gaspé region. Tech. Bull. No. 9, Inland Waters Branch, Department of Energy, Mines and Resources, Ottawa, Canada, 20p.

COULSON, A., 1967. Flood frequencies of Nova Scotia streams. Tech. Bull No. 4, Water Resources Branch, Department of Energy, Mines and Resources, Ottawa, Canada, 32p.

CRAMER, H., and Leadbetter, M.R., 1967. Stationary and Related Stochastic Processes. John Wiley, New York, 348 p.

CRUTCHER, H.L., 1975. A note on the possible misuse of the Kolmogorov-Smirnov test. J. of Applied Meteorology, 14, pp. 1600-1603.

CUNNANE, C., 1973. A particular comparison of annual maxima and partial duration methods of flood frequency prediction. J. of Hydrology, 18, pp. 257-271.

DALRYMPLE, T., 1960. Flood frequency analysis. Manual of hydrology: Part 3, Flood flow techniques. U.S. Geol. Surv. Water Supply Paper, 1543-A, 77p.

DALRYMPLE, T., 1970. Comment on 'Uniform flood frequency estimating methods for federal agencies.' by Manuel A. Benson, Water Resources Research, 6(3), p. 998.

DAVIS, D.A., and Coulson, A., 1967. Hydrologic zones in the headwaters of the Saskatchewan River. Technical Bulletin No 6, Inland Waters Branch, Department of Energy, Mines and Resources, Ottawa, Canada, 23 p.

DINGMAN, S.L., and R.H. Platt, 1977. Floodplain zoning. Implications of hydrologic and legal uncertainty. Water Resources Research, 13(3), pp. 518-523.

DRAKE, J.J., 1974. Hydrology and karst solution in the Southern Canadian Rockies. Unpublished Ph.D. thesis, McMaster University, 222 p.

ENVIRONMENT CANADA, 1973(a). Atmospheric Environment, Canadian normals, Vol. 1, Temperature, 1941-1970. Downsview, Ontario, Canada, 181 p.

ENVIRONMENT CANADA, 1973(b). Atmospheric Environment, Canadian normals, Vol. 2, Precipitation, 1941-1970. Downsview, Ontario, Canada, 330 p.

ESPEY, W.H., Jr., and Winslow, D.E., 1974. Urban flood frequency characteristics. J. Hydraulics Div., Amer. Soc. Civil Eng., 100(HY2), pp. 279-295.

FARLEY, A.L., 1979. Atlas of British Columbia; U.B.C. Press, Vancouver, B.C., 171 p.

FIERING, M.B., and Jackson, B.B., 1971. Synthetic Streamflows. Water Resources Monograph 1, American Geophysical Union, Washington, D.C., 98 p.

FISHER, R.A., and Tippett, L.H.C., 1928. Limiting forms of the frequency distribution of the largest or smallest member of a sample. Proc. Cambridge Philosophical Society, Vol. 24, pp. 180-190.

FOSTER, H.A., 1924. Theoretical frequency curves and their applications to engineering. Trans. Amer. Soc. Civil Eng., 87, pp. 142-173.

FRASER RIVER BOARD, 1958. Preliminary Report on Flood Control and Hydroelectric Power in the Fraser River Basin, Victoria, B.C., 171 p.

GRAY, D.M., 1970. editor in chief, Handbook of the Principles of Hydrology; Water Information Centre, Inc., Huntington, New York, 558 p.

GUMBEL, E.J., 1941. The return period of flood flows. Annals of Mathematical Statistics, XII, pp. 163-190.

GUMBEL, E.J., 1958. Statistics of Extremes. Columbia University Press, New York, 375 p.

GUPTA, V.K., Duckstein, L., and Peebles, R.W., 1976. On the joint distribution of the largest flood and its time of occurrence. Water Resources Research, 12(2), pp. 295-304.

GUYMON, G.L., 1974. Regional sediment yield analysis of Alaska streams. J. Hydraulics Div., Amer. Soc. Civil Eng., 100 (HY1), pp. 41-51.

HAAN, C.T., 1977. Statistical Methods in Hydrology. Iowa State University Press, Ames, Iowa, 378 p.

HAAN, C.T., and Allen, D.M., 1972. Comparison of multiple regression and principle component regression for predicting water yields in Kentucky. Water Resources Research, 8(6), pp. 1593-1596.

HARDISON, C.H., 1974. Generalised skew coefficients of annual floods in the United States and their applications. Water Resources Research, 10(4), pp. 745-752.

HAZEN, A., 1930. Flood Flows. John Wiley and sons, New York, 199 p.

HOUGHTON, J.C., 1978. Birth of a parent. The Wakeby distribution for modelling flood flows. Water Resources Research, 14(6), pp. 1111-1115.

HURST, H.E., 1951. Long-term storage capacity of reservoirs. Trans. Amer. Soc. Civil Eng., 116, pp. 770-808.

HYDROLOGIC ATLAS OF CANADA, 1978. Ministry of Supply and Services Canada, Ottawa, Canada, 78 p.

JARVIS, C.S., 1936. Floods in the United States, magnitude and frequency. U.S. Geol. Surv. Water Supply Paper, 771, 497 p.

KENDREW, W.G., and Kerr, D., 1956. The Climate of British Columbia and the Yukon Territory. Edmund Cloutier, Queen's Printer and Controller of Stationary, Ottawa, Canada, 222 p.

KIMBALL, B.F., 1946. Assignment of frequencies to a completely ordered set of sample data. Trans. Amer. Geophys. Union, 27, pp. 843-846.

KIRBY, W., 1969. On the random occurrence of major floods. Water Resources Research, 5(4), pp. 778-784.

KLEMEŠ, V., 1974. The Hurst phenomenon: A puzzle? Water Resources Research, 10(4), pp. 675-688.

KLEMEŠ, V., 1976. Comment on 'Regional skew in search of a parent.' by N.C. Matalas, J.R. Slack and J.R. Wallis. Water Resources Research, 12(6), pp. 1325-1326.

KOOPMAN, R.F., and Wong, S.T., 1973. Comments on 'Comparison of multiple regression and principal components regression for predicting water yields in Kentucky.' by C.T. Haan and David M. Allen. Water Resources Research, 9(5), pp. 1479-1480.

KREUDER, W.L., 1979. Development of hydrometric networks in British Columbia. Water Resources Research, 15(6), pp. 1677-1686.

LANDWEHR, J.M., Matalas, N.C., and Wallis, J.R., 1979. Probability weighted moments compared with some traditional techniques in estimating Gumbel parameters and quantiles. Water Resources Research, 15(6), pp. 1055-1064.

LANDWEHR, J.M., Matalas, N.C., and Wallis, J.R., 1980. Quantile estimation with more or less floodlike distributions. Water Resources Research, 16(3), pp. 547-555.

LANGBEIN, W.B., 1949. Annual floods and the partial duration series. Trans. Amer. Geophys. Union, 30(6), pp. 879-881.

LEITH, R.M., 1975. Streamflow regionalization in British Columbia, No 1. Regression of mean annual floods on physiographic parameters. Report Series No. 40, Inland Waters Directorate, Pacific Region, Water Resources Branch, Vancouver, British Columbia, 42 p.

LEITH, R.M., 1976. Streamflow regionalization in British Columbia, No 2. Regression of mean annual flows on physiographic parameters. Report Series No. 46, Inland Waters Directorate, Pacific Region, Water Resources Branch, Vancouver, British Columbia, 21 p.

LEITH, R.M., 1977. Streamflow regionalization in British Columbia, No 3. Statistics of mean annual flow. Report Series No. 50, Inland Waters Directorate, Pacific and Yukon Region, Water Resources Branch, Vancouver, British Columbia, 40 p.

LOWERY, M.D., and Nash, J.E., 1970. A comparison of methods of fitting the double exponential distribution. J. of Hydrology, 10(3), pp. 259-275.

MANDLEBROT, B.B., and Wallis, J.R., 1969. Some long-run properties of geophysical records. Water Resources Research, 5(2), pp. 321-340.

MATALAS, N.C., 1967. Mathematical assessment of synthetic hydrology. Water Resources Research, 3(4), pp. 937-945.

MATALAS, N.C., and Wallis, J.R., 1973. Eureka! It fits a Pearson type III distribution. Water Resources Research, 9(2), pp. 281-289.

MATALAS, N.C., Slack, J.R., and Wallis, J.R., 1975. Regional skew in search of a parent. Water Resources Research, 11(6), pp. 815-826.

MONGER, J.W.H., and Price, R.A., 1979. Geodynamic evolution of the Canadian Cordillera - progress and problems. Can. J. of Earth Sci., Vol. 16, No 3(2), pp. 770-792.

MOSS, M.E., and Bryson, M.C., 1974. Autocorrelation structure of monthly streamflows. Water Resources Research, 10(4), pp. 737-744.

NATURAL ENVIRONMENT RESEARCH COUNCIL, 1975. Field studies report, Vol. 1: Hydrological Studies. Institute of Hydrology, Wallingford, U.K., 550 p.

NIE, N.H., Hull, C.H., Jenkins, J.G., Steinbrenner, K., and Bent, D.H., 1975. Statistical Package for the Social Sciences. McGraw-Hill, New York, 675 p.

NORTH, M., 1980. Time dependent stochastic model of floods. J. of Hydraulics Div., Amer. Soc. Civil Eng., 106(HY5), pp. 649-665.

OSTREM, G., 1973. The transient snowline and glacier mass balance in southern British Columbia and Alberta, Canada. Geografiska Annaler, Vol. 55A, No. 2, p. 93.

PAGE, K.J., and McElroy, L., 1981. Comparison of annual and partial duration series floods on the Murrumbidgee River. Water Resources Bulletin, 17(2), pp. 286-289.

PARZEN, E., 1967. Stochastic Processes. Holden-Day Inc., San Francisco, 324 p.

PIPES, A., Quick, M.C., and Russell, S.D., 1970. Simulating snowmelt hydrographs for the Fraser River system. Proc. 38th Western Snow Conference, pp. 91-97.

REICH, B.M., and Renard, K.G., 1981. Application of advances in flood frequency analysis. Water Resources Bulletin, 17(1), pp. 67-74.

ROSS, S.M., 1976. Introduction to Probability Models. Academic Press, New York, 272 p.

ROUSSELLE, J., 1972. On some problems of flood analysis. Unpublished Ph.D. dissertation, Colorado State University, Fort Collins, Colorado, 212 p.

SHANE, R.M., and Lynn, W.R., 1964. Mathematical models of flood risk evaluation. J. Hydraulics Div., Amer Soc. Civil Eng., 90(HY6), pp. 1-20.

SLADE, J.J., Jr., 1936. The reliability of statistical methods in the determination of flood frequencies, in Jarvis, C.S., et al. Floods in the United States, magnitude and frequency. U.S. Geological Survey Water-Supply Paper, 771, pp. 421-432.

SLAYMAKER, H.O., 1972. Physiography and hydrology of six river basins, Chapter 3, in Studies in Canadian Geography - British Columbia, editor J.L. Robinson, University of Toronto Press, Toronto, Canada, 139 p.

SPIEGEL, M.R., 1961. Theory and Problems of Statistics. Schaum Publishing Company, New York, 359 p.

STEEL, R.G.D., and Torrie, J.H., 1960. Principles and Procedures of Statistics, McGraw-Hill, New York, 257 p.

STURGES, H.A., 1926. The choice of a class interval. J. Amer. Statistical Assoc., 21, pp. 65-66.

TAESOMBUT, V., and Yevjevich, V., 1978. Use of partial flood series for estimating distribution of maximum annual flood peak. Hydrology Paper No. 97, Colorado State University, Fort Collins, Colorado, 71 p.

TATSUOKA, M.M., 1971. Multivariate Analysis. Wiley, New York, 310 p.

TODOROVIC, P., 1970. On some problems involving random number of random variables. Annals. Math. Stats., 41(3), pp.1059-1063.

TODOROVOC, P., 1978. Stochastic models of floods. Water Resources Research, 14(2), pp. 345-356.

TODOROVIC, P., and Rousselle, J., 1971. Some problems of flood analysis. Water Resources Research, 7(5), pp. 1144-1150.

TODOROVIC, P., and Woolhiser, D.A., 1972. On the time when the extreme flood occurs. Water Resources Research, 8(6), pp. 1433-1438.

TODOROVIC, P., and Zelenhasic, E., 1970. A stochastic model for flood analysis. Water Resources Research, 6(6), pp. 1641-1648.

UNITED STATES WATER RESOURCES COUNCIL, 1967. Hydrology Committee, Guidelines for determining flood flow frequency. Bulletin 15, Washington, D.C.

UNITED STATES WATER RESOURCES COUNCIL, 1976. Hydrology Committee, Guidelines for determining flood flow frequency. Bulletin 17, Washington, D.C.

WALLIS, J.R. and Matalas, N.C., 1970. Small sample properties of H and K - estimators in the Hurst coefficient h. Water Resources Research, 6(6), pp. 1583-1594.

WALLIS, J.R., Matalas, N.C., and Slack, J.R., 1977. Apparent regional skew. Water Resources Research, 13(1), pp. 159-182.

WATER SURVEY OF CANADA, 1972. Magnitudes of Floods in British Columbia. Planning and Studies Section, Water Survey of Canada, Dept. of Environment, Vancouver, B.C., 395 p.

WATER SURVEY OF CANADA, 1979. Surface Water Data; British Columbia. Inland Waters Directorate, Water Resources Branch, Water Survey of Canada, Ottawa, Canada, 338 p.

WAYLEN, P.R. and Woo, M.K., 1981. Regionalization and prediction of annual floods in the Fraser River catchment, British Columbia. Water Resources Bulletin, 17(4), pp. 655-661.

WAYLEN, P.R. AND WOO, M.K., 1982 (in press). Prediction of mean annual flows in the Fraser River catchment, British Columbia. Water Resources Bulletin.

WOLMAN, M.G., and Miller, J.P., 1960. Magnitude and frequency of forces in geomorphic processes. J. of Geology, 68, pp. 54-74.

WORLD METEOROLOGICAL ORGANIZATION, 1965. Guide to Hydrometeorological Practices, Chapter 3, Design of networks. W.M.O. Publ. 168. TP. 82, Geneva, Switzerland.

YEVJEVICH, V., 1972. Probability and Statistics in Hydrology. Water Resources Publications, Fort Collins, Colorado, 294 p.

ZELENHASIC, E., 1970. Theoretical probability distributions for flood peaks. Hydrology Paper No. 42, Colorado State University, Fort Collins, Colorado, 31 p.