REGIONAL FLOOD FREQUENCY ANALYSIS FOR THE ISLAND OF NEWFOUNDLAND, CANADA USING L-MOMENTS

JHAPENDRA POKHREL

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Prepared by

©Jhapendra Pokhrel, B. Eng.

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ABSTRACT

The regional flood frequency analysis (RFFA) for the Island of Newfoundland carried out by the provincial government of Newfoundland and Labrador in 1989 was revisited using the index-flood method based on L-moments. L-moment-based homogeneity tests showed that two of the 1989 regions were possibly redundant. The Water Survey of Canada (WSC) sub regions Y and Z were found to be statistically as well as operationally homogeneous. The conventional goodness-of-fit tests, including the L-moment-based tests were not particularly powerful in discriminating between the fits of generalized extreme value (GEV) and the three-parameter log-normal (LN3) distributions to the regional data from the 1989 regions as well as from the WSC sub regions. However, the robustness evaluation based on Monte Carlo simulation revealed that LN3 was comparatively more robust than the competing GEV distribution. A comparison between the return period flows estimated based on the 1989 regions and those based on the WSC sub regions showed that the estimates based on the WSC sub regions had, in general, equal or better accuracy than the estimates obtained with the 1989 regions. Likewise, the estimates based on the index-flood method using L-moments were found to be more accurate than those based on regression-on-quantile approach of the 1989 study. A similar comparison with the quantile estimates obtained from the more recent RFFA study for the Island of Newfoundland carried out by the provincial government also showed that the index-flood based on L-moment approach produced more accurate estimates than its regression-on-quantile counterpart. The L-moments based LN3 growth factors for the WSC sub regions and nonlinear regional models for index-flood estimation are recommended for carrying out the RFFA on the Island of Newfoundland.

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LIST OF SYMBOLS

$\bar{Q}$	Mean flood
τ	L-CV
μ	Mean
σ	Standard deviation
θ	Distribution's parameter
Φ	Standard normal CDF
α	Significance level
γ	Conventional skewness
ε	Model error
ξ	Location parameter of the distribution
α	Scale parameter of the distribution
Φ^{-1}	Inverse of the standard normal CDF
τ_3	L-skewness (population)
τ_4	L-kurtosis (population)
σ_4	Standard deviation of sample regional L-kurtosis
τ_4^{DIST}	Distribution's L-kurtosis
β_r	Population probability weighted moment
λ_r	Population L-moments
A^*	Modified Anderson-Darling statistics
A^2	Anderson-Darling statistics

B	Bias
B_4	Bias of sample regional L-kurtosis
D_i	Discordancy measure
E	Expected value
F	Non-exceedance probability
F(x)	Cumulative distribution function
H	Heterogeneity measure
h	4th parameter of the kappa distribution
H_0	Null hypothesis
k	Shape parameter of the distribution
K_F	Frequency factor
ln	Natural logarithm
l_r	Sample L-moments
N_{sim}	Number of simulated regions
Q	Flow rate
q	Quantile function
t	Sample L-CV
t_3	Sample L-skewness
t_3^R	Regional average sample L-skewness
t_4	Sample L-kurtosis
t_4^R	Regional average sample L-kurtosis
t^R	Regional average sample L-CV
V	Weighted standard deviation of at-site sample L-CVs
Z^{DIST}	Goodness-of-fit measure of the candidate distribution

LIST OF ACRONYMS

AARB	Average Absolute Relative Bias
ACLS	Area Controlled by Lakes and Swamps
A-D	Anderson-Darling
ARB	Average Relative Bias
CFA	Consolidated Frequency Analysis
CI	Confidence Interval
CV	Coefficient of Variation
DA	Drainage Area
DRD	Drainage Density
GEV	Generalized Extreme Value
GLO	Generalized Logistic
GPA	Generalized Pareto
GREHYS	Groupe de Recherche en Hydrologie Statistique
LAT	Latitude
L-CV	Coefficient of L-variation
LN3	3-parameter Log Normal
LOC	Line of Organic Correlation
LP3	Log-Pearson type III
LSF	Lakes and Swamps Factor
MAR	Mean Annual Runoff
NERC	Natural Environment Research Council

NLLS	Nonlinear Least Squares Regression
OLS	Ordinary Least Squares
PE3	Pearson type III
POT	Peak Over Threshold
PWMs	Probability Weighted Moments
RFFA	Regional Flood Frequency Analysis
RMSE	Root Mean Square Error
ROI	Region of Influence
SHAPE	Watershed Shape Factor
SLP	Slope of Main Channel
TCEV	Two-Component Extreme Value
USGS	United States Geological Survey
USWRC	United States Water Resources Council
WSC	Water Survey of Canada

CHAPTER 1

INTRODUCTION

1.1 General

Engineers are often faced with the problem of estimating flood flow magnitudes for use in the design of hydraulic structures at a water resources project location. Such design often requires that the hydrologists estimate the magnitude and frequency of extreme flood events.

Flood frequency analysis is traditionally based on a probability model that is derived using the data available at a site. However, the historical flow data available at the site of interest are often too short to give reliable estimates of the critical flow (low or high) that might occur during the life of the project. This situation has led engineers or hydrologists to look for alternative ways to augment the limited flow information at the design location by using the data available at neighboring rivers, or from a so called homogeneous hydrologic region. In other words, through the process of regional analysis, the spatial flow information is substituted for temporal records at the target site. This technique would not only improve the estimates at the site with short records, but also provide a basis for flow estimation at ungauged locations. When the interest is in the peak flow estimation, the outcome of the procedure is the flood peaks with associated frequency of exceedence and the exercise is popularly known as regional flood frequency analysis

(RFFA). However, the procedure can, as well, be used for estimating any other flow statistics such as mean flow or low flow.

The general procedure of RFFA involves the following basic steps:

- Collecting the peak flow data at the gauged rivers;
- Screening the data for any transcription errors or any other causes that may make the data unusable for the proposed flood frequency analysis thereby violating certain assumptions regarding the randomness of the data;
- Identifying the homogeneous regions and testing their homogeneity;
- Establishing the regional equations (growth curve or regression relations); and
- Estimating the flow quantile of interest.

The research for estimating the design flow using the regional approach has been documented for the last four decades. The physical processes contributing to the peak flow in a river are complex in nature and hence are difficult to model. The accuracy with which the flow quantile of interest can be estimated through RFFA depends upon the amount of available information about the catchment characteristics and historical flow records. Nonetheless, the methods employed for the analysis also play a significant role. The dominating steps in a typical RFFA are the identification of so called homogenous region and transferring of the regional flow information to the site of interest. Therefore, the methods are updated each time when more information and/or more accurate statistical methods become available for carrying out either or both of these steps.

The earliest, and still a most popular approach suggested for regional estimation is that of USGS (Dalrymple, 1960), which is known as index flood method. This method is in wide use with slight modifications over time. Alternative approaches such as 'regression on quantile' were suggested in the meantime to get around the apparent problems associated with the original index flood method regarding its assumption about the distribution characteristics of the peak flow data over the region. However, the introduction of so called L-moments in statistics and their application in hydrology has firmly re-established the index flood method as a general procedure of flood frequency analysis. The detailed account of the developments in the RFFA techniques is presented in Chapter 2.

1.2 RFFA for the Island of Newfoundland

The history of regional flood estimation in the Island of Newfoundland dates back to 1971 when Poulin (Govt. of Canada) did the first flood frequency analysis based on a short database. However, the Provincial Government (Govt. of Newfoundland and Labrador, 1984, 1989, 1999) updated each of the previous studies trying to improve the estimation of peak flow on the ungauged locations across the Island. Each time, the justification for the update was based solely on the availability of wider hydrometric and physiographic databases: longer records, more gauging stations and wider range of physiographic parameters. However, some of these studies seem to have overlooked the available state-of-the-art RFFA techniques, which the contemporary hydrologists were practicing in other parts of the world. Of particular interest for this Thesis is the 1989 study of the Provincial Government of Newfoundland that divided the Island into four hydrologic regions and suggested several sets of regional regression equations for the estimation of flow at ungauged locations. A more detailed review of the previous RFFA studies for the Island of Newfoundland is given in Section 2.2.

1.3 Objectives of the Thesis

The objectives of this study emanate from a research interest in applying the popular L-moment based index flood approach to the RFFA for the Island of Newfoundland. The L-moments and the RFFA methods based on them were introduced in early 1990 (Hosking, 1990, Hosking and Wallis, 1993). The 1989 RFFA for the Island of Newfoundland was based on 'regression on quantile' approach. By using the latest available data, a comparison between the two approaches can be made; the records were too short in 1988 but are now of sufficient length for frequency analysis. Therefore, this Thesis has the following objectives:

(1) To revisit the 1989 RFFA for the Island of Newfoundland using L-moment based index flood approach applied to the same set of data and physiographic parameters;

(2) To compare the performance of the 1989 regression based estimators and the L-moment based index flood estimators by using the additional 10 years of data since 1988; and

(3) To suggest an appropriate RFFA scheme, based on this study, for use at the gauged or ungauged locations within the Island.

1.4 Scope of the Thesis

The following aspects of the 1989 RFFA are revisited in this Thesis:

(i) Tests on regional homogeneity: L-moment based test is applied to examine the regional homogeneity of the four regions recommended by the 1989 study. The test details are given in Section 3.3.

(ii) Regional estimation of flow quantiles: Regional growth curves, based on the regional distribution, are estimated for each region and a nonlinear regression of mean annual instantaneous flows on the physiographic characteristics of the basins is carried out in order to estimate the index flood at an ungauged location.

The following performance evaluation of the estimators are studied:

(i) Using the database available until 1998, the accuracy of 1989 regional regression estimators is compared with that of their L-moment based index flood counterparts.

(ii) Using the same database as in (i), the accuracy of the L-moment based index flood estimators for 1989 regions and Water Survey of Canada subregions are compared.

Based on the results of performance evaluation and the latest available data, an L-moment based index flood RFFA scheme is suggested for use in the Island of Newfoundland.

1.5 Organization of the Thesis

This Thesis report is organized in five chapters. Chapter 1 covers the introduction of the topic in which the general concept of regional flood frequency analysis and its application in the Island of Newfoundland is briefed. It also outlines the objectives and scope of this study. Chapter 2 is devoted to the review of the existing literature in the regional flood frequency analysis with the particular emphasis on the researches on the regionalization techniques and transfer of the regional information to the site of interest. The adopted stepwise L-moment based flood frequency analysis algorithm is presented at length in Chapter 3. Chapter 4 describes a case study in which the 1989 RFFA of the Provincial Govt. of Newfoundland is revisited following the methodology described in Chapter 3. The results are then compared with the 1989 outcomes and discussed. Summary and conclusions of this study and recommendations for future studies are presented in Chapter 5. Finally, the computer programs used for simulation studies are provided in the Appendices.

CHAPTER 2

LITERATURE REVIEW

Regional flood frequency analysis (RFFA) has been one of the most active areas of research in the field of hydrology for more than four decades. This chapter reviews the developments in this area in general. The earlier reports of the Provincial Govt. of Newfoundland and Labrador on the RFFA for the Island of Newfoundland are also reviewed in order to relate the issue of RFFA to the proposed case study.

2.1 Regional Flood Frequency Analysis: General

The literature on the RFFA has been reviewed under the following subheadings that constitute the general procedure of the analysis:

(i) Screening of data;

(ii) Delineation of homogeneous region;

(iii) Tests of regional homogeneity;

(iv) Selection and estimation of regional frequency distribution;

(v) Estimation of flow magnitude; and

(vi) Assessment of the accuracy of estimated quantiles.

2.1.1 Screening of Data

The frequency analysis of any hydrologic event is based on the assumption that the data are random, independent and homogeneous. The data collected at a site are assumed to follow the same frequency distribution. While the data may be affected by various problems, particularly important in hydrologic data collection are the errors due to incorrect recording, systematic changes in the type or location of the measuring gauge, human-induced regulations or due to any combination of these. As a result, the data may have outliers, trends, serial correlation and/or non-homogeneity thereby reducing the reliability of the subsequent frequency analysis.

Statistical tests for outliers and trends are well established in the literature (Kendall, 1975; Barnett and Lewis, 1994). Computer-based tests for outliers, trends, serial correlation and homogeneity are also currently available (for example, Environment Canada's CFA 3.1). Data from different sites can also be compared using well-known techniques such as double-mass curve or quantile-quantile plots. However, for the purpose of RFFA based on L-moments, Hosking and Wallis (1997) note that the incorrect data values, outliers, trends and non-homogeneity can all be reflected in the L-moments of the sample. They suggest a composite statistic, called discordancy statistic (D_i), that reflects the discordancy between the L-moment ratios of a site and the average L-moment ratios of a group of similar sites. The details on the computation and interpretation of D_i statistics are given in Section 3.3

2.1.2 Delineation of Homogeneous Regions

The delineation of homogeneous regions is a key step in any regional frequency analysis. The aim is to form groups of sites such that their frequency distributions are identical except for the site-specific scale factor. In the literature, it is found that the hydrologically homogeneous groups of the basins are typically formed on one of the following bases.

- Geographically defined regions enclosed by political, administrative or physiographic boundaries;
- Subjective judgment based on site characteristics, time of flood, nature of the distribution, mean annual precipitation, mean annual flood per unit area, etc;
- Objective partitioning based on measured site characteristics;
- Multivariate statistical analysis of the catchment characteristics and/or flood statistics; and
- Other methods

2.1.2.1 Geographical partitioning

Many regional flood studies (Natural Environment Research Council, 1975; Beable and McKercher, 1982) have adopted geographically defined regions enclosed by political, administrative or physiographic boundaries. Likewise, Matalas *et al.* (1975) divided the

United States into only 16 geographical regions while demonstrating the so called 'separation effect' in which they studied the variation of regional skewness. They considered that such regions would be hydrologically homogeneous, but others (Wiltshire, 1986; Acreman and Sinclair, 1986) argued that the hydrological homogeneity could not be guaranteed by the geographical proximity, as the neighboring basins could be physically very different. In the absence of any test for the homogeneity, application of this approach would be arbitrary and subjective; the results would be misleading especially when the regions are very large (Wiltshire, 1986). More recently, Kachroo et al. (2000) used an approach that utilizes a sound judgment about the hydrological responses of the basins based on geographic information and similarity of the statistics of the observed flood data. They delineated geographical regions in Tanzania as well as in other southern African countries, most of which were found to be hydrologically homogeneous at a lower level of confidence.

2.1.2.2 Subjective judgement

Based on the site characteristics, subjective groupings have also been proposed for small regions. The regions thus formed may or may not be geographically contiguous. Govt. of Newfoundland and Labrador (1984) divided the Island of Newfoundland into north and south regions based on the causative factors of flood flows. In the update that followed, specific mean annual peak flow was used to make the subjective division of the Island into four regions (Govt. of Newfoundland and Labrador, 1990). Schaefer (1990), by using the annual precipitation data in Washington state, formed regions with similar mean annual precipitation. Gingras and Adamowski (1993) made use of the differing modes of distribution of maximum stream flow data to form regions in New Brunswick. Likewise, based on flood generating mechanisms, Gingras et al. (1994) formed 9 regions for annual maximum stream flow in Ontario and Quebec. The subjective divisions like these warranted an objective test for homogeneity, however, the use of at-site statistics in subjective partitioning was discouraged because this might affect the validity of test of homogeneity, which is usually based on the at-site data itself (Hosking and Wallis, 1997).

2.1.2.3 Partitioning based on measured basin characteristics

Wiltshire (1985) introduced a method to group the basins based on a single measured partitioning value of one or more basin characteristics. The optimum size of the region would be decided by minimizing, in an iterative fashion, the within-group departures of such statistics as 5-year quantile from that of the group average or the log-likelihood function of the observed flood peaks based on the GEV distribution. Pearson (1991a) applied similar procedure based on the within group variation of sample L-moments (L-CV and L-skewness). Hosking and Wallis (1997) recognized this procedure as an effective 'objective partitioning' provided it was used in conjunction with an efficient homogeneity test scheme such as the heterogeneity measure as defined in Hosking and Wallis (1993). Indeed, Pearson (1991b) successfully applied the Wiltshire's basin grouping procedure using the heterogeneity measure of Hosking and Wallis (1991) to small basins in New Zealand. However, Pearson used the sample L-moments of the annual maximum flood peaks instead of Wiltshire's distribution-based statistics as the partitioning threshold.

2.1.2.4 Multivariate Techniques

The most popular statistical multivariate analysis applied in hydrology is cluster analysis. In this method, a data vector represents the characteristics of a site and the sites are grouped according to the similarity in their respective data vectors. De Coursey (1973) pioneered the use of multivariate analysis in regional estimation. He applied discriminant analysis to flood data from Oklahoma to form groups of basins with similar flood response. Discriminant analysis is an iterative procedure of forming groups or clusters based on the value of the discriminant score, which is a linear combination of peak flows that maximizes the ratio of the between-groups sums of squares to the within-group sums of squares (De Coursey, 1973). White (1975) applied factor analysis to group basins in Pennsylvania. However, he made only qualitative judgments regarding the homogeneity of flood responses. Acreman and Sinclair (1986) applied cluster analysis to the annual maximum flood values from 168 stations in Scotland and formed five regions. Burn (1989) used cluster analysis to form regions for flood frequency analysis in southern Manitoba, Canada. He also included the at-site statistics as the clustering variables. Earlier, Mosley (1981) had used a similar approach to form hydrologic regions for New Zealand. Likewise, Nathan and McMahon (1990) suggested a general procedure of applying cluster analysis to regionalization. They applied the procedure to predict low flow characteristics in a heterogeneous group of 184 catchments in southern Australia and formed five regions. They claimed that their technique was superior to the previously available procedures.

Hosking and Wallis (1997) regard the cluster analysis based on the site characteristics as the most practical method of forming regions from large data sets. They further provide insights into the maximum or minimum size of the regions to be formed by this procedure for use with the index flood method. However, they note that the output of the cluster analysis should not be the final and that a subjective adjustment that improves the physical coherence of the regions as indicated by an objective heterogeneity measure can be useful.

2.1.2.5 Other Methods

Fiorentino et al. (1987) and Gabriele and Arnell (1991) proposed an approach that involved a hierarchy of regions. In this method, relatively larger regions are identified based on constant shape parameters and they are further subdivided into smaller regions over which the dispersion parameter is assumed to be constant. However, this method is likely to create regions with crisp boundaries whereas the aim is usually for a smooth transition between the adjacent regions. Wiltshire (1986c) proposed an approach in which the sites are regarded as having 'fractional membership' in different regions with certain weights. This method is attractive when a smooth transition between the regions is desired. Acreman and Sinclair (1986) used a method in which the fractional membership weights are obtained by a clustering technique. However, Hosking and Wallis (1997) note that these methods suffer from the problem of estimating the fractional membership weights that is usually based on the distribution of site characteristics. As a result, it may be difficult to estimate the accuracy of the final quantile estimates.

Burn (1990) expanded the concept of partial membership of a site to a homogeneous region, to what he called a 'region of influence (ROI)' approach. According to this approach, there is no need to define boundaries between regions; each site can have its own region consisting of the stations that are sufficiently similar to the site of interest. Weighted Euclidean distance in the site characteristics data space is used to measure the station similarity. Burn's method utilizes the inter-site variation of 100-year flood estimated from the at-site statistics in order to define the 'weights' for the site characteristics. Cavadias (1990) based these weights on canonical correlations between the site characteristics and at-site quantile estimates. Zrinji and Burn (1994) extended the ROI approach for ungauged sites. Tasker et al. (1996) compared five models of regional regression approach using 204 gauging stations in Arkansas and concluded that the regional regression based on the region of influence method was the best. Zrinji and Burn (1996) further refined the ROI approach by introducing a hierarchical feature. However, Hosking and Wallis (1997) maintained that there were ambiguities in the ROI procedures and suggested the use of at-site L-CVs rather than the extreme flow events in order to derive the weights of site characteristics in computing the distance measure. Like many others, they argued that the extreme flow quantiles could not be reliably estimated from the at-site data; the use of such statistics in region formation would only make the subsequent regional estimation unreliable.

The recent practice of forming regions by pooling sites using catchment characteristics data has replaced the fixed and contiguous regions with flexible and overlapping groups that are not necessarily geographically contiguous. Reed et al. (1999) presented a terminology review for regional flood frequency analysis and proposed to replace the terms such as regionalization, region and regional growth curve with pooling scheme, pooling group and pooled growth curve respectively.

2.1.3 Tests of regional homogeneity

After a region is formed based on the sites' physical characteristics, they must be tested for hydrological homogeneity so that the information obtained from the region is useful for flood frequency analysis. The hypothesis of homogeneity is based on the assumption that the at-site frequency distributions of the observed data at the sites in the region are the same except for a site-specific scale factor. The test usually involves the study of the similarity of an appropriate statistic obtained from the distribution of observed data. However, the answers to the questions such as which statistic to use, and which distribution to assume for the at-site data, have remained controversial for the last four decades.

2.1.3.1 Dalrymple's Test

The work of Dalrymple (1960) appears to be the first published literature on the RFFA. Dalrymple suggested a procedure for testing the homogeneity of a region for the index flood method based on the study of 10-year flood estimated from the Gumbel frequency curve at each gauging station within the region. The test, which he attributed to W. B. Langbein, provided a confidence interval for the return period assigned to the regional 10-year flood by the at-site statistics obtained from the Gumbel cumulative distribution function.

Benson (1962) was quick to point out that using the Dalrymple's test, the homogeneity could not be achieved at higher return periods and thus the test was not particularly useful. However, Dalrymple's test became very popular among practicing hydrologists and was also recommended in several standard hydrology textbooks (Chow, 1964; Kite, 1977; Singh, 1992). Because the test seldom rejected homogeneity, Wiltshire (1986a) and Hosking (1987) suspected that the test might not be particularly powerful. Moreover, Lu (1991) pointed out that the method lacked theoretical justifications regarding the construction of confidence interval for the T-year floods. Fill and Stedinger (1995) corrected the Dalrymple's original test by incorporating the asymptotic bias and variance of the reduced variate into the confidence interval formula. They also proposed a test statistic for the critical number of sites that could fall outside the confidence interval by sampling variation alone even if the region was practically homogeneous.

2.1.3.2 Wiltshire's Tests

Despite the early concerns about the deficiencies in the Dalrymple's test, no alternative procedures were advocated in the literature until Wiltshire (1986a, b) proposed two approaches based on statistical hypothesis tests. His 'CV-based procedure' involved testing the regional homogeneity based on the coefficient of variation of standardized annual maximum series, whereas the 'distribution-based procedure' made use of the geometry of the cumulative distribution function of the dimensionless regional parent. Using simulation techniques, he concluded that the performance of CV-based test met with no particular success. However, the power of the distribution-based test was satisfactory; its application to 10 geographical regions in UK (NERC, 1975) revealed that most of the regions were heterogeneous (Wiltshire, 1986b).

Unlike Dalrymple who assumed Gumbel distribution as the 'null' distribution at each site, Wiltshire used a non-parametric jack-knife procedure of estimating the at-site distribution in order to evaluate the regional homogeneity.

Acreman and Sinclair (1986) used a slightly different approach based on "likelihood-ratio" tests that compare the fit of the regional and at-site generalized extreme-value distributions fitted to the data by the method of maximum likelihood. If the data came from a different distribution than assumed by the method, then the results of such tests would not be reliable.

2.1.3.3 Tests based on L-moments

L-moments (Hosking, 1990) are the linear combinations of probability weighted moments (PWMs) of Greenwood et al. (1979). The main advantage of L-moments over conventional moments is that they suffer less from the effects of sampling variability. They are more robust to outliers and virtually unbiased for small samples. Therefore, they enable more secure inferences to be made from small samples about an underlying frequency distribution (Hosking, 1990; Hosking and Wallis, 1993). Moreover, they provide an attractive framework for statistical tests on homogeneity based on the sample L-moment ratios.

Chaudhury et al. (1991) proposed a chi-square test for the regional homogeneity that examined the similarity between the at-site distribution and the hypothesized regional distribution. They proposed to use the composite chi-square statistic calculated using the sample L-moment ratios (L-CV and L-skewness) and their correlation structure at all sites in the region and compare it with the critical values of a standard chi-square distribution. Performing a power comparison using Monte Carlo study, they showed that the test based on L-CV and L-skewness was more powerful than the test based on L-CV alone.

The most rigorous L-moment based test of homogeneity is that of Hosking and Wallis (1993). This test compares the variability of the L-moment ratios for the basins in a region with the expected variability obtained from simulation from a collection of basins with same record lengths as their real world counterparts. A heterogeneity measur. is calculated based on the difference between the weighted standard deviation of the sites' L-CVs in the region and the mean of the same statistic obtained from the simulation. Unlike Chowdhury and Stedinger (1991), who fitted GEV distribution to the regional average L-moments, Hosking and Wallis used 4-parameter kappa distribution for their simulation. Details of this test are discussed in Section 3.5

Hosking and Wallis's test has been used as a standard test of homogeneity in recent years (Castellarin, et al., 2001; Burn and Goel, 2000). Earlier, Lu and Stedinger (1992a) and

Fill and Stedinger (1995), through simulation experiments, had found that the tests based on the L-moments were better than the tests proposed by Wiltshire (1986a, b).

2.1.4 Selection and estimation of regional distribution

2.1.4.1 General

After the homogeneity is confirmed of a region, the next step is to select a regional distribution that applies to each site in the region. The candidate distributions are usually evaluated in view of their ability to reproduce the characteristics of the regional flood data sets. For flood frequency analysis purposes, the hydrologists' interest lies in the extreme tails of the distributions. It was recognized (Matalas and Wallis, 1973) that the competing distributions that fit the observed data satisfactorily may differ significantly in their tails. Therefore, the 'robustness' was recognized to be the most important property to look for in a frequency distribution employed for regional or at-site frequency analysis.

The index-flood method of Dalrymple (1960) used a dimensionless average frequency curve. It was abandoned because the coefficient of variation of flood flows was found, in general, to vary inversely with basin drainage area (Benson, 1962). The U. K. Flood Studies Report (1975) recommended an index-flood method employing the GEV distribution for the sites where the record lengths were short. Condie (1979) applied three-parameter log normal (LN3) distribution to regional flood frequency analysis.

Likewise, U. S. Water Resources Council (USWRC, 1981) employed Pearson Type 3 distribution to determine the regional skewness of the log-discharges.

The superior sampling properties of the probability-weighted moments (PWMs) of Greenwood et al. (1979) were exploited in the subsequent research in the area of hydrologic modeling. It was also recognized that the choice of distribution problem was to be looked into in conjunction with the method of parameter and quantile estimation. Kuczera (1982) provided a general framework for identifying a robust and efficient frequency model for at-site or regional analysis. He examined the suitability of log Pearson type III (LP3) and Wakeby distributions as regional distributions with PWM estimation. Based on the limited simulation experiments, he concluded that the LP3 and Wakeby distributions were practical alternatives in the United States under the assumption that the Wakeby parents generated the flood data encountered in the real world.

Rossi et al. (1984) developed a regionalization procedure for two component extreme value distribution, a distribution in which annual floods are assumed to come from two distinct extreme value type-1 distributions.

Hosking et al. (1985) studied the small sample properties of the estimates of the GEV distribution by the method of PWMs and substantiated the potential of GEV distribution for flood frequency analysis. In another study, Hosking and Wallis (1985) made an appraisal of the regional flood frequency procedure in the UK Flood Studies Report (NERC, 1975) and recommended replacing the procedure with GEV/PWM or

WAK/PWM algorithm. Wallis and Wood (1985) tested the regional LP3 quantile estimator as specified by USWRC (1981). They found that with LP3 as the parent, the quantile estimator was less precise than the regional GEV/PWM, or regional WAK/PWM estimators. However, Chowdhury, et al. (1991) found that for certain combinations of L-CV and L-skewness, GEV distribution predicts negative values thereby making its use unreliable in modeling the strictly positive flood phenomena.

The above research basically focused on the robustness and accuracy of the regional distribution in the flood frequency analysis. It was recognized that the distributions with only two parameters yielded accurate quantile estimates if the fitted distribution was same as the population distribution, otherwise the extreme quantiles would be seriously biased. However, by fitting a distribution with three or more parameters, when these could be estimated accurately from the available sample, less biased estimates of quantiles were obtained in the tail of the distribution. As the regional frequency analysis provided an opportunity to augment the size of the sample, it was possible to fit three or more parameter distributions more reliably. Hosking and Wallis (1997, pp. 77) note that the distributions with three to five parameters are appropriate candidates for the regional flood frequency analysis. They also suggest that the final choice of the distribution should be made based on 'goodness-of-fit' tests on the candidate distributions. However, if more than one distribution provided an adequate fit, then the best choice would be the one that provided the most robust and efficient quantile estimates.

2.1.4.2 Goodness-of-fit tests

Several methods are available for testing the goodness-of-fit of a frequency distribution fitted to data from a single sample. Most popular are the Chi-squared, Kolmogorov-Smirnov, Cramer-von-Mises, Anderson-Darling (A-D) and the tests based on moment or L-moment statistics. Among these the A-D test is considered as the most powerful one according to Stephens (1986). Since the test is sensitive to the fit of the distribution to the tails of the data, it is better suited for use with the flood frequency distribution, where the interest lies in fitting the extreme flow data (Klemes, 1987). Chen and Balakrishnan (1995), by modifiying the A-D test statistic and Cramer-von Mises statistic, provided a more attractive general-purpose approximate goodness-of-fit test method applicable for all distributions. Likewise, a modified A-D test based on parameters estimated by the method of L-moments is also available (Lye, 2000). The details are given in Section 3.4

In the regional context, the goodness-of-fit tests based on statistical hypothesis testing have been used as the objective tests for regional distributions. Chowdhury et al. (1991) used combined regional goodness-of-fit statistics for the GEV distribution. They obtained the statistics at each site based on the difference of sample L-CV and L-skewness and their GEV counterparts, weighted by their respective variances. The composite statistic obtained by summing the statistics over all sites in the region would be approximately chi-square distributed if the observations available at each site were from the GEV distribution. Hosking and Wallis (1997) provided an alternative approach that directly involves the regional average L-moments. For a three parameter distribution, the goodness-of-fit is judged by how closely the L-kurtosis of the fitted distribution, corrected for sampling bias, matches its regional average counterpart of the observed data. Pandey et al. (2001) further investigated the effectiveness of this procedure for fitting the distributions using a set of benchmark measures of goodness-of-fit. They showed that for the practical range of L-kurtosis, the sampling bias for sample L-kurtosis was fairly small and the bias correction was not necessary.

Moment ratio diagrams are also used to visually judge the fit of a particular data set to a theoretical distribution. McCuen (1985) has provided the introduction of product moment ratio diagrams. The basic advantage of using moment ratio diagrams is that a single diagram can visually compare the fit of several distributions to a given data set. In the regional context, the position of the regional average dimensionless moments on the diagram would give the closer resemblance of the underlying regional distribution. Hosking (1990) introduced L-moment ratio diagrams. Vogel and Fennessey (1993) concluded that the L-moment diagrams were better than the product moment diagrams in discriminating between the distributions and proposed to replace the product moment diagrams with L-moment diagrams in hydrological investigations. However, the role of L-moment diagrams in identification of underlying distribution is not decisive. Hosking and Wallis (1997) indicate that the L-moment diagrams should be used only in selecting the candidate distributions and more objective tests that reflect the robustness of the distribution should be employed for the final selection. Indeed, Ben-Zvi and Azmon (1997) successfully employed the two-stage procedure for selection of the best fitting regional distribution for 68 hydrometric stations in Israel. They used L-moment diagrams for the preliminary selection of the regional average distribution and the A-D test based on method of moments to confirm the goodness-of-fit of the potential candidates. L-moment diagrams showed that the Generalized Pareto was a strong candidate for the average regional distribution, which was subsequently confirmed by the results of A-D test on the flow data at all the sites in the region.

The recent paper by Peel et al. (2001) also substantiates the fact that L-moment diagrams alone may mislead the distribution selection process.

2.1.5 Estimation of flow magnitude

2.1.5.1 Joint use of at-site and regional data

In the Dalrymple's index-flood method, the observed annual peaks at each site are first standardized by dividing each by their sample mean (the index-flood) and then all the standardized observations from the homogeneous region are used to estimate an average dimensionless frequency curve. Then the quantile for each site is calculated by multiplying the quantile estimate of the regional growth curve by the site's sample mean (the index-flood) of annual records.

The index-flood scheme became very popular among practicing hydrologists. This approach was once the standard U. S. Geological Survey approach for flood quantile estimation (Dalrymple, 1960) and has since been widely used with limited modifications. The modifications have mostly involved the revisiting of the procedures for selection and estimation of the regional frequency distribution along with the use of regional average dimensionless statistics. The distributions considered for regional use included GEV (NERC, 1975; Hosking et al., 1985), Wakeby (Landwehr, et al., 1979) and log-Pearson III (USWRC, 1981). Likewise, the dimensionless statistics used by various researchers included CV and skewness (Nash and Shaw 1965; USWRC, 1976, 1981), at-site order statistics (NERC, 1975; Houghton, 1978), PWMs (Wallis, 1980) and L-moments (Hosking and Wallis, 1993).

The well-known station-year approach is also a variation of the index-flood procedure where the ratios of peak flows to the mean flow at all the stations from a region are pooled together treating them as a single sample for distribution estimation purposes.

Alternative approaches were also explored in the contemporary attempts in pursuit of improved quantile estimates using the regional analysis. Wood and Rodriguez (1975) showed how Bayesian analysis based on at-site and regional hydrological data could be used in inferring probabilities of extreme floods. Kuczera (1982), in his empirical Bayes approach, gave a thorough account of a general framework for combining at-site and regional information in Bayesian analysis in order to find a posterior distribution of the flood magnitude and the associated risk. This approach usually involves extensive numerical methods.

Rossi et al. (1984) used a regional flood frequency procedure in which they fitted a two component extreme value (TCEV) distribution to account for the two distinct flood-generating physical mechanisms. The distribution parameters were estimated by the method of maximum likelihood. In another study using the similar approach, Arnell and Beran (1987) found that the variability of the regional skewness obtained from this approach was comparable with the observed values although the method was not robust.

While the foregoing literature is based on the analysis of annual maximum series, the regional flood estimation based on partial duration series, also known as 'peak over a threshold (POT)' method, has also been used (Rasmussen et al., 1994; El-Jabi et al., 1998). The POT approach is based on the analysis of flood peaks above a specified threshold or base level. The drawback of this method lies in the selection of the threshold, which is usually based on subjective judgment.

2.1.5.2 Using regional data alone

The main goal of regional analysis is to estimate the flow variable at a site where there are no records available. In this situation, the Dalrymple's 'index-flood' at the site of interest is estimated from a regionally calibrated linear or log-linear relationship between the mean floods and physically measurable catchment characteristics (Benson, 1962; NERC, 1975; Stedinger and Tasker, 1985). Nash and Shaw (1966) regressed the at-site means and coefficient of variations of the 57 flood series in Great Britain on their corresponding catchment characteristics. The resulting relation was used to estimate the mean and coefficient of variation at the site of interest, which in turn were used to fit a two-parameter distribution to be used for quantile estimation at that site.

The US Geological Survey (Thomas, 1987; Tasker, 1987) approach was different. They estimated the quantile of interest at every station and regressed these quantiles from a homogeneous region (geographically contiguous) on their respective sets of significant catchment characteristics. The quantiles at the site of interest would be obtained by substituting the catchment characteristics in the respective regional regression relations. This method has been widely used in the U. S. A. and elsewhere as a popularly known 'regression on quantile' method of RFFA. However, this method has been criticized for having to estimate too many sets of parameters and also for the substantial sampling error in the regression relations (Cunnane, 1989).

Despite the criticisms, the regression on quantile method has been adopted as an alternative to the index-flood procedure both for gauged and ungauged locations for two main reasons. First, unlike the index-flood method, it avoids the specification of regional average frequency curve (the growth curve), which was controversial on the part of the assumptions regarding the regional average distribution from a strictly homogeneous region (Benson, 1962). Secondly, the method uses the regression techniques, which are well understood and readily accepted by the hydrologists. However, GREHYS (1996) compared the performances of regression based methods with other currently available alternative methods of regional estimations and concluded that the regression based methods were unreliable for the regions in the provinces of Ontario and Quebec. The accuracy of the estimated flow statistics using this method depends upon the type of regression model (linear or nonlinear) and the parameter estimation method. Pandey and Nguyen (1999) examined the performance of nine different methods of parameter estimation for nonlinear regression methods and concluded that the nonlinear methodology gave more accurate estimates of quantiles from the ungauged sites than the linear or log-linear models.

Because of the better sampling properties of PWMs and their easy-to-interpret linear combination, L-moments, the extent of distribution selection and parameter estimation problem in the index-flood procedure seems to be significantly reduced. Earlier, it was demonstrated that the small sample properties of PWM estimators of parameters and quantiles for the Gumbel distribution (Landwehr et al., 1979) and Generalized Extreme Value distribution (Hosking et al., 1985) were superior than the conventional moments and maximum likelihood estimators. Lettenmaier et al. (1987), by considering various degrees of heterogeneity in the regions, found that the GEV/PWM-based index flood quantile estimators were better than other estimators even if the regions were slightly heterogeneous. Potter and Lettenmaier (1990), in a separate study using the re-sampling method, concluded that the index-flood method based on the GEV distribution estimated by PWMs (GEV/PWM) was the most efficient way of regional estimation. More recently, GREHYS (1996) performed an extensive comparison of various regional estimation procedures and concluded that the GEV/PWM index-flood procedure associated with all regionalization schemes was better for the gauged sites in Ontario and Quebec. Likewise, Mkhandi and Kachroo (2000) found the Pearson type III/PWM as the best estimation procedure for the South African regions.

Hosking and Wallis (1993) provided a general framework for carrying out index-flood based RFFA using L-moments. As the L-moments gain popularity among the frequency analysts, the index-flood method based on L-moments has been accepted as a standard method of regional flood frequency analysis in recent years. The L-moment algorithm suggested by Hosking and Wallis (1997) is summarized in Section 3.4.

2.1.6 Assessment of the accuracy of estimated quantiles

The accuracy of quantiles estimated based on a regional frequency analysis procedure may be affected due to either or any combination of the following reasons.

- Heterogeneity of the regions;
- Wrong choice of the regional distribution; and
- Inadequate data available for parameter estimation.

Traditionally, the magnitude of the uncertainty is achieved by the construction of confidence intervals for estimated parameters and quantiles assuming that all the model assumptions are satisfied. However, it is seldom a case in RFFA based on index-flood procedure that all the assumptions are satisfied and therefore, the confidence interval cannot be relied on in order to infer the accuracy of the estimated quantiles (Hosking and Wallis, 1997, pp. 93). Instead, approaches based on Monte Carlo simulations are considered more reasonable for estimating the accuracy of the estimated quantiles. Hosking and Wallis (1997) provide an algorithm based on Monte Carlo simulation procedure for assessing the accuracy of the estimated quantiles by taking into account the regional heterogeneity, misspecification of distribution and inter-site dependence structure. According to this approach, the summary of the accuracy of estimated quantiles over all of the sites in the region is judged by the regional average relative root mean square error of the estimated quantiles.

Earlier, while comparing the performance of various regional estimation methods, Potter and Lettenmaier (1990) had noted that for data generation, the Monte Carlo methods employ a parent distribution, which may not be a representative of the true flood generating mechanism. They had proposed an alternative approach based on re-sampling from an observed population. However, Hosking and Wallis (1997) suggest the use of a more flexible Kappa distribution if no distribution fits the at-site data well. The details of this procedure are presented in Section 3.5.

2.2 RFFA for the Island of Newfoundland

2.2.1 Government Undertakings

The first flood frequency analysis for the Island of Newfoundland was carried out by Poulin (Government of Canada, 1971). He treated the Island as one region using the data available at seventeen gauging stations. He found that the mean flow in the Newfoundland rivers was the function of drainage area (DA), area controlled by lakes and swamps (ACLS) and slope.

The second study by the provincial government (Government of Newfoundland, 1984) was undertaken on regional basis with the data available in 21 gauging stations. It divided the Island into north and south hydrologic regions based on the maximum daily flow mechanisms; regional regression equations were provided relating the 20 and 100 year flow quantiles to the relevant basin and climate characteristics using the log-transformed variables. The predictor variables for north and south regions were different: for the north the DA, mean annual runoff (MAR) and the latitude (LAT) were significant whereas for the south, the peak flows were the function of DA, MAR, ACLS and slope. Later, Lye and Moore (1991) pointed out some statistical problems associated with the 1984 regression equations that related the instantaneous peak flow with the basin characteristics. First, the use of logarithmically transformed variables in the regression relations introduced bias in the estimation of the quantiles of interest after anti-log transformation, which was unaccounted for in the recommended regression relations. Second, the use of the MAR as a predictor variable was not justified because it could not be estimated at ungauged locations. Moreover, the MAR would be significantly correlated with the drainage area if expressed as volume in cubic meters thereby introducing the problem of multicollinearity. Thirdly, the use of LAT as a predictor variable in only the north region was poorly justified both physically and statistically.

Government of Newfoundland and Labrador (1989) carried out a third and major RFFA for the Island. Records from thirty-nine gauged stations were analyzed with the average record length of 21 years. The short records at 11 stations were extended by relating them with the series at neighboring sites, where the longer records were available for the common base period and the correlation among the peak flows was significant. The relationship was based on the ordinary least square (OLS) regression method. However, this method of record extension is known to reduce the natural variance in the extended series. An attractive alternative for maintaining the variance uses the so-called 'line of organic correlation (LOC)' technique (Hirsch and Gilroy, 1984).

Based on the mean annual peak flow per unit area and the time of occurrence, the Island was divided into four hydrologic regions: A- Avalon and Burin Peninsula; B- central region of the Island; C- Humber valley and northern peninsula; and D- the southwestern region of the island. Region D was formed only with six stations; most of them had record lengths less than 10 years. The homogeneity of the regions was assessed using the test developed by Dalrymple (1960). Regional regression equations relating the flow quantiles with the basin characteristics were then recommended for flow estimation purposes at the ungauged sites. The significant basin characteristics included in the regional relations were DA, lakes and swamps factor (LSF) as a composite measure of the ACLS and the fraction of the basin consisting of the lakes and swamps, drainage density (DRD) and slope (SLP). The MAR, LAT and the watershed shape factor (SHAPE) as the explanatory variables used by the 1984 study were dropped because the MAR could not be accurately estimated and the LAT and SHAPE were found statistically insignificant. However, the regression relations were provided in the log-linear space and no bias corrections were suggested for the quantile estimation that had to be obtained by the anti-log transformation of the log-quantile.

The latest RFFA study (Government of Newfoundland, 1999) analyzed the database available until 1996 from 65 watersheds. Unlike in the 1989 study, the records were not extended at the stations where there were short records. However, for region delineation purposes, it also followed the footsteps of the 1989 study and maintained the four regions, slightly modifying the previous boundaries but without assessing their regional homogeneity. The regions were named northwest (NW), northeast (NE), southeast (SE) and southwest (SW) that approximately corresponded to the 1989 regions, C, B, A and D respectively. As in all of the previous studies, the latest one also suggested the modified regional regression equations for use in the respective regions. The DA was the most significant predictor of the extreme flow quantile as usual. A new variable named as "Lake Attenuation Factor (LAF)" was introduced as a second most significant variable in three of the four regions. The LSF was significant only in the SW region. However, the DRD and SLP were dropped in this study as they did not improve the estimates as measured by the standard error of estimates.

2.2.2 Other Regional Flood Frequency Studies

Some researchers have used the flood data from the Island of Newfoundland for testing one or the other methods of regionalization, especially after the late 1980s when new multivariate techniques became available. Cavadias (1989, 1990) tested the canonical correlation approach using the flood and basin data available from the RFFA study of Govt. of Newfoundland and Labrador (1984). Pilon et al. (1990) used Newfoundland data to test an approach similar to the Dalrymple's test but using L-moments. Based on the study of the variances of L-moments of 1000 replicated hydrometric network, they concluded that all the basins in the Island could be grouped in one region. Likewise, Zrinji and Burn (1994) compared various options of regionalization with the region of influence (ROI) approach using the annual maximum daily flow series in the Island of

Newfoundland. Using the L-moments based homogeneity test of Chowdhury et al. (1991) on the regions formed by the ROI approach, they also concluded that the entire set of gauging stations in the Island formed a 'nearly' homogeneous region. As a result, the comparison of efficiency of various regional estimation methods in the Island was not particularly successful.

Richter (1995), in a thorough study of the relationships of flow and basin variables on the Island of Newfoundland, identified the significant flow and basin variables, which were then analyzed to establish the relationships of the flow measures to basin characteristics in the regional perspectives. By using the mean annual maximum daily flow as a measure, she found that considering the WSC division (Y and Z) for the regional analysis generally improved the estimates at the ungauged sites. She assessed the 1989 regions using the regional regression relationships based on her study and recommended further investigations into the possible improvement in the regional estimation considering alternative regionalization schemes.

2.3 Rationale of the Thesis

From the preceding review of the literature in the developments of the regional analysis techniques, it is apparent that several approaches are available at present. Among the most popular in recent years is the index-flood method based on L-moments. However, all the previous Government undertakings including the most recent one have used the regression-on-flow-variables approach of RFFA in Newfoundland. Different conclusions have been drawn each time concerning the formation of regions and subsequent quantile estimation frameworks. It would be of general interest to see if the same conclusions would be reached by using the more rigorous regionalization technique based on L-moments and the index-flood method of regional estimation. Therefore this thesis proposes to apply the L-moment based index-flood method of RFFA to a case study from the Island of Newfoundland.

The 1989 study of the Provincial Government of Newfoundland and Labrador (Govt. of Newfoundland and Labrador, 1990) has been chosen as the case study for two reasons. First, it is considered to be a major RFFA that divided the Island into four homogeneous regions, which have also been maintained with minor modifications (without testing their hydrological homogeneity) by the most recent study (Govt. of Newfoundland and Labrador, 1999). Secondly, a general comparison can be made between the two methods of regional estimation by using the additional database that is currently available (Environment Canada's HYDAT, CD ROM, 1998). The following Chapter presents the methodology adopted for this purpose.

CHAPTER 3

METHODOLOGY

3.1 General

The methodology for regional flood frequency analysis (RFFA) for the Island of Newfoundland presented here is the index-flood method based on L-moments. The present study is organized in two parts. In the first part, a complete RFFA using the same set of data as of 1989 is independently analyzed using the L-moment algorithm of Hosking and Wallis (1997). However, unlike the 1989 study, this study does not extend the short records for the purpose of frequency analysis for two reasons. First, the L-moments are known to be less biased for short records than are their conventional counterparts and so there is not much to be gained in the frequency analysis by artificially extending the series. Secondly, the extension, which is usually carried out based on the correlation structure between the two sites' data, increases the inter-site dependence. Therefore, with the use of L-moments, the extension of short series for the purposes of at-site or regional frequency analysis is not preferred. In the following Sections, a brief introduction on the L-moments and the index-flood method of RFFA is presented. The step-wise procedure for the RFFA using the L-moment algorithm is then provided in the remainder of the Chapter.

3.2 L-moments

L-moments are intuitively defined as the linear combinations of the order statistics. Hosking (1990) derived them by modifying the probability-weighted moments (PWMs) introduced by Greenwood et al. (1979).

For a random variable X with cumulative distribution function F, the quantities

$$\beta_r = E\{X[F(X)]^r\} \qquad [3.1]$$

represent the probability-weighted moments. The first four L-moments expressed as linear combinations of PWMs are:

$$\lambda_1 = \beta_0 \qquad [3.2a]$$

$$\lambda_2 = 2\beta_1 - \beta_0 \qquad [3.2b]$$

$$\lambda_3 = 6\beta_2 - 6\beta_1 + \beta_0 \qquad [3.2c]$$

$$\lambda_4 = 20\beta_3 - 30\beta_2 + 12\beta_1 - \beta_0 \qquad [3.2d]$$

The first L-moment, λ_1 is a measure of central tendency and is equivalent to the mean of the distribution whereas λ_2 measures the dispersion. Their ratio, λ_2/λ_1, is termed as the L-coefficient of variation, τ, the ratio λ_3/λ_2 is referred to as τ_3 or L- skewness and the ratio λ_4/λ_2 or τ_4 is referred to as L-kurtosis. The L-moments are easy to interpret because they are analogous to the conventional moments; their purpose is to summarize theoretical probability distributions and observed samples. Their popularity for use with the RFFA procedure is growing because they are less biased than the conventional moments and they can better discriminate among the commonly used frequency distributions (Hosking. 1990).

3.3 Stepwise procedure of RFFA

The general procedure of index-flood method of RFFA is as follows.

- Screening of data;
- Delineation of homogeneous region;
- Tests of regional homogeneity;
- Selection and estimation of regional frequency distribution;
- Estimation of flow magnitude; and
- Assessment of the accuracy of estimated quantiles

3.4.1 Data Screening: Discordancy measure

Given a group of N sites. the measure of discordancy (Hosking and Wallis. 1997) for site i is given by

$$D_i = \frac{1}{3} N (u_i - \bar{u})^T A^{-1} (u_i - \bar{u}) \qquad [3.4a]$$

where

$$u_i = \left[t^{(i)} \quad t_3^{(i)} \quad t_4^{(i)}\right]^T \qquad [3.4b]$$

is a vector containing the L-moment ratios for site i. The unweighted group average is given by

$$\bar{u} = \frac{1}{N}\sum_{i=1}^{N} u_i \qquad [3.4c]$$

and the matrix of sums of squares and cross products is defined as

$$A = \sum_{i=1}^{N}(u_i - \bar{u})(u_i - \bar{u})^T \qquad [3.4d]$$

The above procedure can be easily carried out for any number of sites in the proposed region using a simple MACRO written in MATLAB (Appendix A-1). The site i is declared as discordant if the D_i is large. The critical D_i values for use with various sizes of regions are presented in Table 3.1.

The use of D_i measure has been suggested at two stages of RFFA. Initially it is applied to a large group of sites in a large geographical area whereby the sites with gross errors in their data will be flagged as discordant warranting a closer scrutiny for sources of unreliability. When the tentative homogeneous regions are hypothesized on the basis of geography and/or catchment characteristics, the D_i measures are computed for all the sites in the proposed region.

Table 3.1: Critical values for Discordancy measure (after Hosking and Wallis, 1997)

Number of sites	**Critical D_i**	**Number of sites**	**Critical D_i**
5	1.33	10	2.491
6	1.648	11	2.632
7	1.917	12	2.757
8	2.140	13	2.869
9	2.329	14	2.971
		$\langle$15	3

The sites having high D_i values are either removed or moved to a different region depending upon the physical reasons associated with the apparent discordancy.

3.4.2 Delineation of homogeneous regions

As mentioned in Section 2.1.2, it is possible to delineate the hydrologic homogeneous regions using subjective judgment based on site characteristics, time of flood, nature of the distribution, mean annual precipitation, mean annual flood per unit area, etc. Hosking and Wallis (1997) mention that the subjective techniques of region formation are suitable for small-scale studies provided that the resulting regions are objectively tested for heterogeneity.

For the purpose of this study, the subjective delineation adopted by the Government of Newfoundland and Labrador (1984,1989), which used the flood generating mechanisms across the Island, or the distribution of the mean annual flood flow per unit area, as the partitioning criteria, has been maintained. However, following Hosking and Wallis

(1997), the regions thus formed are tested for homogeneity by applying the L-moments based heterogeneity measure discussed in the following Section.

3.4.3 Test of regional homogeneity

After a group of sites is defined based on their physical characteristics, a heterogeneity measure is calculated to assess its hydrological homogeneity. If the region is homogeneous, all sites have the same population L-moment ratios; the difference, if any, is attributed to the sampling variability alone. Thus, the null hypothesis of homogeneity is that the at-site frequency distributions are same except for a site-specific scale factor. The heterogeneity measure used in this study is based on the study of the standard deviations of the site's L-CVs for the reasons mentioned in Section 2.1.3. It is computed as follows.

Suppose that the candidate region has N sites, with i having record length n_i and sample regional average L-moment ratios $t^{(R)}$, $t_3^{(R)}$ and $t_4^{(R)}$ weighted proportionally to the sites' record lengths. The weighted standard deviation of the at-site sample L-CVs is given by

$$V = \left\{ \sum_{i=1}^{N} n_i (t^i - t^R)^2 \Big/ \sum_{i=1}^{N} n_i \right\}^{1/2} \qquad [3.4e]$$

and $t^R = \Sigma n_i \, t^{(i)} / \Sigma n_i$, i = 1 to n

A kappa distribution is then fitted to the regional weighted average L-moment ratios 1, $t^{(R)}$, $t_3^{(R)}$ and $t_4^{(R)}$ using a set of algorithm written in FORTRAN (Hosking, 1996). A large number (1000) of independent and homogeneous Kappa regions are then simulated using a simulation program written in MATLAB (Appendix A-2). If μ_v and σ_v are the mean and standard deviation of the simulated values of V. then the heterogeneity measure (H) is given by

$$H = (V - \mu_v)/\sigma_v \qquad [3.4f]$$

Homogeneity of the proposed region is judged on the basis of the value of H. The region is considered to be acceptably homogeneous if $H < 1$; possibly heterogeneous if $1 \le H < 2$ and definitely heterogeneous if $H \langle 2$.

3.4.4 Selection and estimation of regional distribution

In regional frequency analysis. the aim is to fit a common distribution to the data at all sites in the homogeneous region. However. the chosen distribution may not necessarily fit the data well but it should yield the accurate quantile estimates for each site in the region. Hosking and Wallis (1997) suggest that when several distributions fit the data adequately. the best choice is the one that is most robust. or in other words. gives good quantile estimates even when the future data may come from a slightly different distribution.

In this study. the regional distribution is selected at two stages. First. the candidate distributions are chosen based on the positions of the regionally weighted sample L-moment ratios on the L-moment diagrams. which are the plots of L-skewness vs. L-kurtosis for the candidate distributions. Then the goodness-of-fit is tested using a hierarchy of statistical tests that can better discriminate among the candidate distributions.

Hosking and Wallis (1997)'s L-kurtosis based goodness-of-fit test is first applied to select the candidate three parameter regional distributions and the more powerful A-D test is then applied in order to choose the distribution that is suitable for the majority of the sites in the region.

3.4.4.1 L-moment diagrams

Plots of L-skewness (τ_3) vs. L-kurtosis (τ_4) for commonly used distributions are obtained using their approximate relationships in the form of polynomial approximations as suggested by Hosking and Wallis (1997):

$$\tau_4 = \sum_{k=0}^{k=8} A_k \tau_3^{\,k} \qquad [3.4g]$$

The coefficients A_k for the commonly used distributions are given in Hosking and Wallis (1997).

The sample L-skewness and L-kurtosis of the data at all sites in the region are plotted on the L-moment ratio diagram along with the regionally weighted average L-skewness and L-kurtosis. The position of the plotted points about the candidate distributions in general and that of the regionally weighted average L-moment ratios in particular indicate the most probable candidate distribution for the regional data.

3.4.4.2 Hosking and Wallis Goodness-of-fit test (H-W test)

Hosking and Wallis (1997) suggest a goodness-of-fit test based on the difference between the L-kurtosis of the fitted distribution and the regional average L-kurtosis weighted proportionally to the sites' record lengths and corrected for the sampling bias. The sampling bias is estimated by simulating a large number of kappa regions having the L-moment ratios equal to the regional averages $1,\ t^R,\ t_3,\ t_4$ and the same number of sites and record lengths as their real world counterparts. The L-kurtosis of the fitted distribution is obtained by using the polynomial approximations of L-skewness – L-kurtosis relationships (equation [3.4g]) given by Hosking and Wallis (1997).

The goodness-of-fit measure for the candidate distribution is then given by

$$Z^{DIST} = (\tau_4^{DIST} - t_4^R + B_4) / \sigma_4 \qquad [3.4h]$$

where the bias of t_4^R is

$$B_4 = N_{sim}^{-1} \sum_{m=1}^{N_{sim}} (t_4^m - t_4^R) \qquad [3.4i]$$

and the standard deviation of t_4^R is given by

$$\sigma_4 = \left[(N_{sim} - 1)^{-1} \left\{ \sum_{m=1}^{N_{sim}} (t_4^m - t_4^R)^2 - N_{sim} B_4^2 \right\} \right]^{1/2} \qquad [3.4j]$$

The fit is declared adequate if Z^{DIST} is sufficiently close to zero, a reasonable criterion being $|Z^{DIST}| \leq 1.64$.

Hosking and Wallis (1997) note that the criterion $|Z^{DIST}| \leq 1.64$ is a rough indicator and is not recommended as a formal test. Therefore, to choose the best fitting distribution, the A-D test, a powerful test according to Stephens (1986) and evaluated for use with L-moments (Lye, 2000), is employed. The details of the test procedure are given below.

3.4.4.3 A-D Test based on L-moments

In this test, the null hypothesis, H_0 is that a random sample $X_1, X_2, X_3, \ldots X_n$ has a known continuous distribution with a known form of CDF, F(x) but unknown parameters (θ). The stepwise procedure for testing the hypothesis of goodness-of-fit is presented below.

(i) Estimate the parameters (θ) of the distribution using the sample L-moments at each site. The relationships of sample L-moments and the parameters of the commonly used distributions are provided by Hosking and Wallis (1997).

(ii) Compute the CDF, $u_i = F(x_i : \theta)$ where the x_i's are in ascending order.

(iii) Compute $y_i = \phi^{-1}(u_i)$ where ϕ is the standard normal CDF ϕ^{-1}, its inverse.

(iv) Compute $v_i = \phi[(y_i - m_y)/S_y]$ where m_y and S_y are the sample mean and standard deviation of y_i respectively.

(v) Calculate the A-D statistic using the following equation:

$$A^2 = -n - n^{-1}\Sigma[(2i-1)\ln u_i + (2n+1-2i)\ln(1-u_i)] \qquad [3.4k]$$

(vi) Calculate the modified A-D statistic, A^* as follows.

$$A^* = A^2 (1 + 0.75/n + 2.25/n^2) \qquad [3.41]$$

The null hypothesis, H_o, is rejected at significance level α if A^* exceeds the upper tail significance points of 0.631 and 0.752 for α = 5% and 10% respectively.

In this study, the A-D test is first carried out for the at-site data in all the regions and a preliminary ranking is made among the distributions that pass the test at 5% significance level. The extreme flow data from all the stations within each region are then pooled together and the A-D test is applied to the pooled data considering them as individual samples. The distributions that pass the test at 5% significance level are again ranked and the best fitting regional distribution is selected based on the consistency of the distribution's fit to the at-site as well as the regionally pooled data.

3.4.5 Test of robustness of the candidate distributions

When two or more distributions give acceptable fit to the regional data, the distribution that is most robust is usually employed for the regional flood frequency analysis. A robust distribution should give reasonably accurate estimates even if there are slight deviations in the underlying assumptions such as mis-specification of the distribution or slight heterogeneity in the region. Therefore the robustness of the candidate distribution is measured by comparing the bias and the root mean square (RMSE) of the estimated extreme quantiles

- when the distribution is correctly specified;

- when the distribution is mis-specified.

The bias, B and the RMSE are given by

$$B = E(Q_{Test} - Q_T) \qquad [3.4m]$$

$$RMSE = [E(Q_{Test} - Q_T)^2]^{1/2} \qquad [3.4n]$$

where Q_{Test} is the regionally estimated quantile using the candidate distribution and Q_T is the true quantile at the site of interest. The true quantile is never known in real world and is only estimated by using the underlying probability distribution fitted to the at-site data. Monte Carlo simulation is employed to compute the relative bias and RMSE of the estimated quantiles based on the candidate distributions. The accuracy measures obtained by using the candidate parents are then compared with those obtained by using a 'slightly different' parent. The use of the 'slightly different' parent is to see the effect of wrong choice of the regional distribution.

The simulation procedure is organized in the following steps (Hosking and Wallis, 1997).

- Specify the region in terms of the number of sites and record lengths at each site same as those in the corresponding real world region.

- Calculate the at-site parameters of the underlying frequency distribution based on the sample L-moment ratios.

- Calculate the at-site quantiles of known exceedence probabilities based on the at-site frequency distributions and store them for calculation of the accuracy measures.

- For each of the 1000 repetitions,
  - using the underlying distribution, generate random sample data of the same lengths as those of the sites in the real world region. The inter-site dependence in the annual peak series is not significant in any of the regions and is neglected here.
  - Calculate at-site L-moment ratios and regional average L-moment ratios at all the sites in the simulated region;
  - Fit the candidate distribution;
  - Calculate estimates of the regional growth curve and at-site quantiles; and
  - Calculate the relative bias and RMSE of the estimated quantiles at each site and accumulate them for the purpose of calculating their average over all the simulated regions.
- Calculate the regional average relative bias, regional average absolute relative bias and regional average RMSE of the estimated quantiles over all the sites in the region.

Further details of the application of this procedure are given in Section 4.4.3 of Chapter 4.

3.4.6 Estimation of the flow quantile

The index-flood method of regional estimation is employed here. The key assumption underlying the index-flood method of regional estimation is that the frequency distributions of the flow data at the sites in a homogeneous region are identical apart from a site-specific scaling factor, the index flood. The procedure can as well be applied to any other data than flood.

Let $Q_i(F)$ be the quantile of non-exceedance probability F, and if $\bar{Q}$ be the mean flood (the index-flood) at site i, then their dimensionless ratio, $q(F) = Q_i(F)/\bar{Q}$ is assumed to be constant in the sites that constitute a homogeneous region. The dimensionless ratio is called as the regional quantile of non-exceedance probability, F, or the regional growth curve. Then the quantile estimate at the site of interest is given by

$$Q_i(F) = \bar{Q}.q(F) \qquad [3.4o]$$

3.4.6.1 Estimation of the index-flood

The index-flood, $\bar{Q}$ is estimated by the sample mean if the records are available at site i. At ungauged locations, it is estimated by relating the catchment characteristics to the available mean annual peak floods at the gauged locations within the respective homogeneous region. For this purpose, a non-linear regression between the site characteristics and the index-flood (mean annual flood peaks) of the corresponding sites in the region is carried out. The regression model is usually of the following form:

$$\bar{Q} = \alpha_0 A_1^{\alpha 1} A_2^{\alpha 2} \ldots\ldots A_n^{\alpha n} + \varepsilon_0 \qquad [3.4p]$$

in which $A_1, A_2 \ldots\ldots A_n$ are the site characteristics, $\alpha_0, \alpha_1 \ldots\ldots \alpha_n$ are the model parameters, ε_0 is the additive error term and n is the number of site characteristics.

For this study, the significant site characteristics for the Newfoundland river basins for index-flood estimation are adopted from the 1989 RFFA report of the Govt. of Newfoundland and Labrador (1990). Nonlinear least square regression (NLLS) is carried out using SYSTAT (SPSS Inc., 1998). In NLLS, the squared deviations of the dependent variables from the predicted ones are minimized using Quasi-Newton or Simplex estimation methods. The assumption underlying NLLS is that of homoscadasticity, i.e., the variance of the regression errors is constant.

3.4.6.2 Estimation of the regional growth curve, q(F)

The parameters of the regional growth curve, whose form is usually assumed to be known (the regional distribution), are estimated by pooling the information available at the sites within the homogeneous region. Hosking and Wallis (1997) suggest the following procedure to estimate the parameters of the regional growth curve.

(i) Compute the first four unbiased L-moments and their ratios (L-CV, L-skewness and L-kurtosis) separately at each site in the homogeneous region;

(ii) Obtain the average L-moment ratios weighted proportionally by the record lengths at respective sites;

(iii) Estimate the parameters of the selected regional distribution by the regional average L-moment ratios using the relationships between the L-moments and the parameters of the distribution's as provided by Hosking and Wallis (1997). The L-moments of the distributions are replaced with the regionally weighted average L-moments. l_1, l_2, t^R, t_3 or t_4 as appropriate of the respective regions in order to get the parameters of the selected distribution.

(iv) Plot the quantile function q(F) of the regional frequency distribution estimated in step (iii) versus the Gumbel reduced variate of non-exceedance probability, F, or the return periods as appropriate. The resulting curve is the regional growth curve for the region.

If the closed form of the quantile function is not available (for example, Pearson type III distribution), then tables or approximations must be used. For any mean (μ) and standard deviation (σ), the Pearson III quantile of non-exceedence probability F can be written as follows (Maidment, D. R. 1993).

$$q(F) = \mu + \sigma K_F(\gamma) \qquad [3.4q]$$

where $K_F(\gamma)$ is the frequency factor for quantile of the standard Pearson III variate with non-exceedence probability F, and skew coefficient γ, mean zero, and variance 1. The frequency factors for $0.01 \leq F \leq 0.99$ and $|\gamma| < 2$ are approximated by the Wilson Hilferty transformation:

$$K_F(\gamma) = 2/\gamma(1 + \gamma Z_F/6 - \gamma^2/36)^3 - 2/\gamma \qquad [3.4r]$$

where Z_F is the quantile of the standard normal distribution with non-exceedence probability F.

The quantile of interest at a gauged or ungauged site in the region is then calculated using the equation [3.4o].

3.4.7 Assessment of estimation accuracy

Finally, a statistical assessment is made of the accuracy of the regional growth curve. Monte Carlo simulation is employed for this purpose. The same simulation program used for testing the robustness of the candidate distributions (Section 3.4.5) is used with some modification. The simulated regions match the real world regions in that they have same number of sites and record lengths as their real world counterparts. If the peak-flow data are significantly correlated across the region, the inter-site dependence is also considered in the simulation. Data at each site are generated using the underlying distribution with the parameters estimated from the at-site sample data. The regional average L-moments of the simulated region are then used to estimate the growth curve of the regional distribution for a range of non-exceedence probabilities (F). The growth curves are accumulated over the large number of simulations (N_{sim} = 5000). A plot of the observed growth curves together with the 90% confidence bands for the range of return periods from 2 to 1000 years based on simulation is used to assess the accuracy of the estimated growth curve.

CHAPTER 4

DATA ANALYSIS AND PRESENTATION OF RESULTS

4.1 General

In this Chapter, the 1989 regional flood frequency (RFFA) study (Govt. of Newfoundland and Labrador, 1990) is revisited using the same set of annual maximum instantaneous flow data but using a different method- the L-moment based index-flood method. In an effort to search for a better alternative regionalization scheme for the Island, the Water Survey of Canada (WSC) sub regions are also examined. The results are then assessed using the latest available extreme flow records. More specifically, the analysis is organized in the following steps.

- Abstraction and evaluation of extreme flow data :
- Application of the regional L-moment algorithm of RFFA to the 1989 regions:
- Comparison of the L-moment based index-flood quantile estimators with their regression-on-quantile counterparts for the 1989 regions:
- Evaluation of WSC sub regions Y and Z based on the regional L-moment algorithm:
- Comparison of quantile estimates based on 1989 regions and WSC sub regions; and

- Assessment of the 1989 regions and WSC sub regions using the latest available extreme flow data.

4.2 Extreme flow data

This analysis used the annual maximum (AM) instantaneous flows of Newfoundland Rivers available in the Environment Canada's HYDAT CDROM database. For the purpose of revisiting the 1989 provincial RFFA study, the AM series and the corresponding basin characteristics from the same set of thirty-nine gauging stations as used by the Govt. of Newfoundland and Labrador (1990) were considered. However, in order to assess the results with the latest available data, the extreme flow records that were available in the HYDAT CDROM for the period until 1998 were used. The missing instantaneous values were estimated by relating the available peak flow series with their daily maximum counterparts. The reason for estimating the missing values using the correlation structure of the annual maximum daily flows and the AM series was that the correlation between these two series was always 100 percent. Obviously, it was worth to 'keep' the information about the missing records that is available in terms of the annual maximum daily flows. However for the reasons mentioned in Chapter 3, no data extension was carried out at any station. The record lengths varied from 7 years to 39 years with an average available length of 18 years. The 1989 study had assessed the suitability of the extreme flow records for the RFFA at these stations by using the statistical tests available in Environment Canada's CFA 88 (Govt. of Newfoundland and Labrador, 1990). Therefore, the present analysis made no attempt to assess the quality of these gauging stations. However, for the necessary screening, the L-moments based composite discordancy measure was used as outlined in Section 3.4.1.

Table 4.1 lists the station numbers, names and the summary of extreme flow L-statistics of the gauging stations. All the stations lie in region 02 of the Water Survey of Canada (WSC) regions. The first letter Y or Z in the present notations represents the WSC region, the second letter is sub region and the last digit represents the station number.

Table 4.1. Summary L-statistics of the gauging stations considered in 1989 RFFA study

Station Number	Name of Stations	Years of Record	Mean (l_1) m^3/sec	L-CV (t)	L-skewness (t_3)	L-kurtosis (t_4)
YC1	Torrent River at Bristol's Pool	30	211.0	0.19	0.23	0.14
YD1	Beaver Brook near Roddicton	19	104.0	0.19	0.22	0.20
YD2	Northeast Brook near Roddicton	9	44.4	0.15	0.31	0.23
YF1	Cat Arm River above Great Cat Arm	14	280.2	0.15	0.11	-0.06
YJ1	Harrys River below Highway Bridge	20	322.1	0.21	0.18	0.22
YK2	Lewaseechjeech Brook at Little Grand lake	15	125.3	0.13	0.19	0.02
YK4	Hinds Brook near Grand lake	23	93.7	0.14	0.08	0.01
YK5	Sheffield Brook near Trans Canada Highway	16	84.3	0.14	0.13	0.07
YL1	Upper Humber River near Reidville	39	601.1	0.13	0.20	0.18
YM3	South West Brook near Baie Verte	9	50.4	0.23	0.29	0.19
YN2	Lloyds River below King George IV Lake	8	197.4	0.21	0.32	-0.05
YO6	Peter's River near Botwood	8	57.4	0.33	0.58	0.58
YP1	Shoal Arm Brook near Badger Bay	7	31.0	0.22	0.78	0.67
YQ1	Gander River at Big Chute	39	601.3	0.15	0.07	0.19
YR1	Middle Brook near Gambo	30	29.7	0.16	0.06	0.10

Table 4.1 contd..

Station Number	Name of Stations	Years of Record	Mean (l_1) m^3/sec	L-CV (t)	L-skewness (t_3)	L-kurtosis (t_4)
YR2	Ragged Harbor River near Musgrave Harbor	12	75.7	0.20	0.31	0.16
YR3	Indian Bay Brook near Northwest Arm	8	54.8	0.15	0.13	-0.18
YS1	Terra Nova River at Eight Mile Bridges	31	183.2	0.16	0.17	0.13
YS3	Southwest Brook at Terra Nova National Park	21	13.0	0.13	0.03	0.10
ZA1	Little Barachois Brook Near St. George's	10	118.5	0.23	0.12	0.06
ZA2	Highlands River at Trans Canada Highway	7	71.9	0.29	0.18	0.04
ZA3	Little Codroy River near Doyles	7	159.9	0.21	-0.17	0.12
ZB1	Isle Aux Morts River below Highway Bridge	27	375.8	0.24	0.11	0.03
ZC2	Grandy Brook below Top Pond Brook	7	462.4	0.14	0.28	0.47
ZE1	Salmon River at Long Pond	16	292.2	0.16	-0.01	-0.11
ZF1	Bay Du Nord River at Big Falls	37	218.3	0.23	0.30	0.32
ZG1	Garnish River near Garnish	30	60.4	0.22	0.29	0.19
ZG2	Tides Brook below Freshwater Pond	12	53.8	0.23	0.30	0.45
ZG3	Salmonier River near Lamaline	9	58.1	0.15	0.16	0.30
ZG4	Rattle Brook near Boat Harbor	8	37.1	0.24	0.26	0.36
ZH1	Pipers Hole River at Mother's Brook	36	235.9	0.23	0.10	0.07
ZH2	Come By Chance River near Goobies	18	30.4	0.19	0.06	0.09
ZJ1	Southern Bay River near Southern bay	12	22.9	0.18	0.11	0.22
ZK1	Rocky River near Colinet	39	154.3	0.21	0.20	0.19
ZK2	Northeast River near Placenta	10	86.9	0.33	0.35	0.24
ZL3	Spout Cove Brook near Spout Cove	10	9.2	0.31	0.16	0.06
ZM6	Northeast Pond river at Northeast Pond	19	3.2	0.19	0.15	0.13
ZM9	Seal Cove Brook near Cappahayden	10	26.2	0.10	-0.21	-0.03
ZN1	Northwest Brook at Northwest Pond	23	36.3	0.17	0.10	0.09

4.3 Data screening: discordancy measures

The discordancy statistics (D_i's) were computed for the sites on a group-wise basis in order to see if any site was grossly discordant from the rest of the group. If the D_i statistic for a site is more than the critical value, the data at such site have to be examined for possible problems. For the present analysis with the 1989 regionalization, it was done in the following stages.

- Whole Island as one group to examine the overall gross errors, if any, and
- Each of the 1989 regions to see if any of the sites in each region is discordant from the rest of the group.

In all the cases, the computation was carried out using the MATLAB MACRO *Di_whole.m* (Appendix A-1). The data file *data.mat* is a N x 3 matrix of the L-moment ratios, t, t_3 and t_4 where N is the number of stations in the respective group. The names of gauging stations, record lengths (n), and the D_i values computed at each station with the whole Island as one group and the four 1989 regions are presented in Tables 4.2 and 4.3 respectively.

The D_i values of the stations YO6, YP1 and ZA3 are above the critical value of 3 for this group thereby indicating that they may be regarded as discordant from the rest of the group. It can be observed that the high D_i values are the result of short record lengths at these sites. The high D_i values always warrant a careful scrutiny of the data at the respective stations. However, the values are not particularly far from 3 given the relatively large number of sites (39) in the Island as one group. Therefore, at this stage no gross discrepancies can be identified in these data.

Table 4.2 Discordancy measures: Whole Island as one group

Station Number	n	D_i	Station Number	n	D_i	Station Number	n	D_i
YC1	30	0.10	YQ1	39	0.52	ZG1	30	0.19
YD1	19	0.03	YR1	30	0.23	ZG2	12	1.36
YD2	9	0.76	YR2	12	0.39	ZG3	9	0.76
YF1	14	0.85	YR3	8	2.26	ZG4	8	0.75
YJ1	20	0.13	YS1	31	0.15	ZH1	36	0.42
YK2	15	1.09	YS3	21	0.56	ZH2	18	0.22
YK4	23	0.47	ZA1	10	0.39	ZJ1	12	0.35
YK5	16	0.39	ZA2	7	1.56	ZK1	39	0.04
YL1	39	0.62	ZA3	7	**3.24***	ZK2	10	2.09
YM3	9	0.24	ZB1	27	0.63	ZL3	10	2.12
YN2	8	2.31	ZC2	7	2.00	ZM6	19	0.01
YO6	8	**3.22***	ZE1	16	0.82	ZM9	10	2.18
YP1	7	**4.99***	ZF1	37	0.36	ZN1	23	0.10

*Exceed the critical D_i values for $N \leq 15$

From Table 4.3, it is observed that the stations YO6, YP1 and ZM9 still have high D_is in their respective groups. A close examination of the data at these stations revealed that there was a high outlier at YO6 (Peter's River) recorded in 1983. The YP1 series had the highest positive skewness and ZM9 had negatively skewed data. There were no other discrepancies apparent in the data at these sites.

Table 4.3 D_i statistics for the sites in 1989 regions

Region A				**Region B**			
SN	**Station**	**n**	**Di**	**SN**	**Station**	**n**	**Di**
1	ZG1	30	1.38	1	YN2	8	1.53
2	ZG2	12	1.60	2	YO6	8	**2.78***
3	ZG3	9	0.71	3	YP1	7	**3.29***
4	ZG4	8	1.13	4	YQ1	39	0.63
5	ZH1	36	0.33	5	YR1	30	0.30
6	ZH2	18	0.18	6	YR2	12	0.15
7	ZK1	39	0.23	7	YR3	8	1.24
8	ZK2	10	1.25	8	YS1	31	0.10
9	ZL3	10	1.73	9	YS3	21	0.64
10	ZM6	19	0.31	10	ZE1	16	0.55
11	ZM9	10	**2.40***	11	ZF1	37	0.28
12	ZN1	23	0.75	12	ZJ1	12	0.48
Region C				**Region D**			
1	YC1	30	0.32	1	YJ1	20	0.08
2	YD1	19	0.73	2	ZA1	10	0.64
3	YD2	9	1.40	3	ZA2	7	1.60
4	YF1	14	1.24	4	ZA3	7	1.67
5	YK2	15	1.31	5	ZB1	27	0.60
6	YK4	23	1.02	6	ZC2	7	1.42
7	YK5	16	0.45				
8	YL1	39	1.03				
9	YM3	9	1.50				

*Exceed the critical D_i values

4.4 Testing for regional homogeneity

4.4.1 1989 regions

The following are the four hydrologic regions (Figure 4.1) delineated by the 1989 study.

- Region A: Avalon and Burin Peninsulas;
- Region B: Central region of the Island;

- Region C: Humber Valley and Northern Peninsula; and
- Region D: Southwestern region of the Island.

Based on the L-moment algorithm as outlined in Section 3.4.3, the regional homogeneity of the whole Island as one region and that of each of the above four regions were examined. The weighted regional average L-moment ratios and the weighted standard deviation of the at-site sample L-CVs (V measures) were computed for each region. The results are presented in Table 4.4.

Table 4.4 Weighted regional average L-statistics for 1989 regions

Regions	Mean l_1	L-CV t^R	L-skewness t_3^R	L-kurtosis t_4^R	V
Whole Island	1	0.188	0.169	0.147	0.047
A	1	0.211	0.165	0.158	0.046
B	1	0.180	0.175	0.167	0.042
C	1	0.156	0.188	0.114	0.029
D	1	0.221	0.125	0.132	0.035

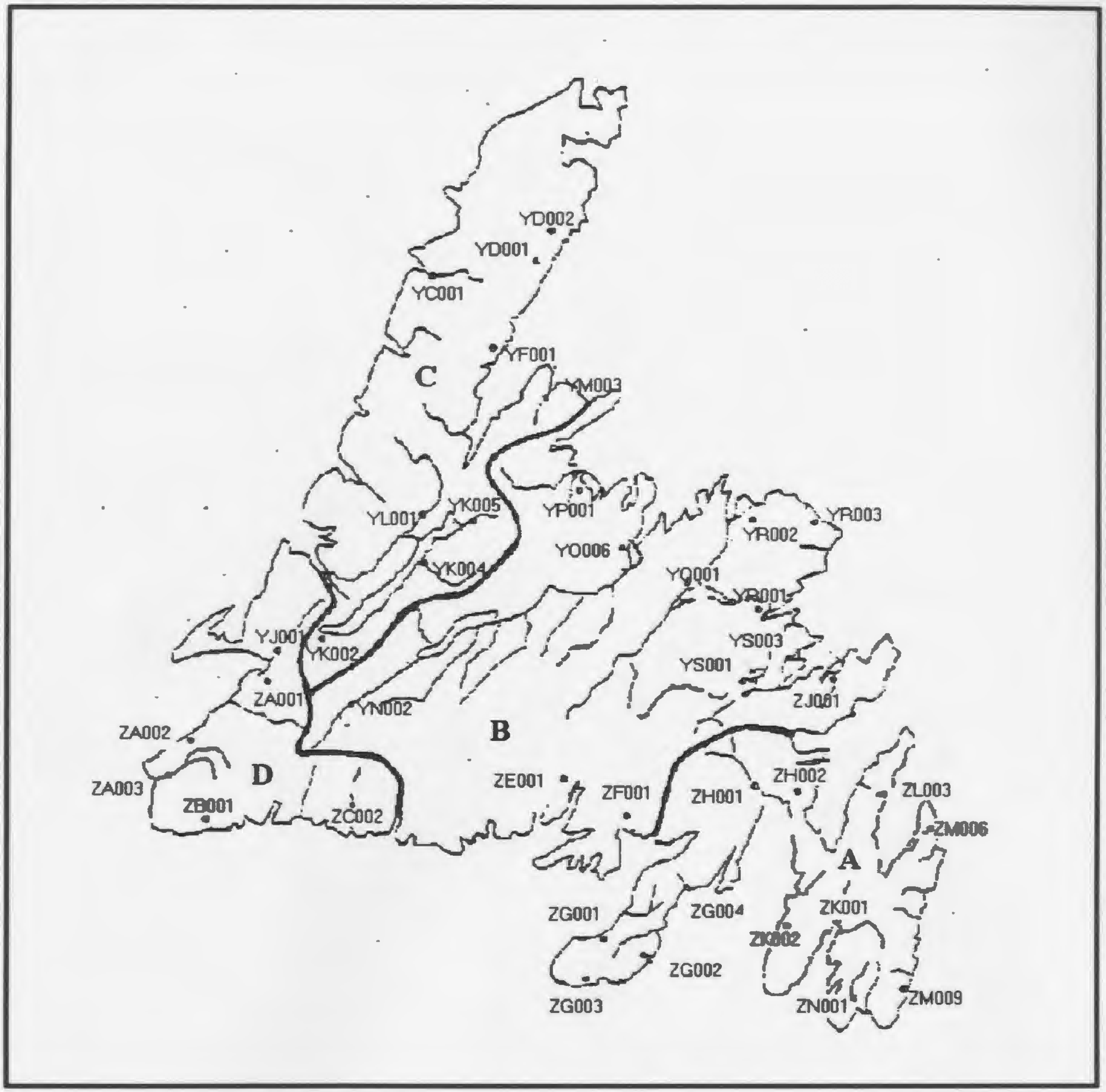


Figure 4.1 The Island of Newfoundland showing 1989 regions

A kappa distribution was then fitted to the regional average L-moments of each region. The parameters were estimated by using the FORTRAN program (Appendix A-2) provided by Hosking (1996).

A large number of kappa regions (1000) were then simulated using a MACRO written in MATLAB (Appendix A-3). Following were the inputs to the simulation MACRO.

- kappa parameters, ξ, α, k and h for the proposed region;
- number of sites in the proposed region (N) and available record length at each site (n); and
- weighted standard deviation of the at-site sample L-CVs (V).

The MACRO executes the following tasks:

- generates 1000 regions from kappa distribution having the same number of sites and record lengths as the proposed region;
- computes the L-CV for each site in the simulated region and the regional average L-CV weighted by the record lengths at each site;
- computes the weighted standard deviation (V_{SIM}) of the at-site sample L-CVs at each of the simulated regions and calculates their mean (μ_v) and standard deviation (σ_v) over all the simulated regions; and
- Calculates the heterogeneity measure, H using equation [3.4f].

The kappa parameters for each region and the computed heterogeneity measures are presented in Table 4.5.

Table 4.5 Kappa parameters and heterogeneity measures for 1989 regions

Regions	No. of sites	Kappa parameters				Heterogeneity Measures, H
		ξ	α	k	h	
Whole Island	39	0.8374	0.2782	0.0125	0.0384	3.83
A	12	0.8468	0.2838	-0.0272	-0.1293	1.46
B	12	0.8786	0.2276	-0.0617	-0.2166	1.55
C	9	0.7794	0.3174	0.1433	0.5172	1.01
D	6	0.8208	0.3457	0.0806	0.0298	-0.45

The heterogeneity measure for the whole Island indicates that the Island as one region is definitely heterogeneous as the H-statistics is greater than the critical value of 2. This could be because of some discordant stations within the data set considered for the analysis. However, the heterogeneity did not reduce by removing the seemingly discordant sites (Table 4.2). It is noted that the H-value is not particularly far from the critical value given the large number of sites (39) in the region hinting that the division of the Island into two might give rise to reasonably homogeneous regions. This possibility is examined later in the following Section by applying the same procedure to the WSC Y and Z regions.

The regions A, B and C are possibly heterogeneous as $1 \leq H \leq 2$. The examination of the discordancy measures for the sites in the region A (Table 4.2) shows that the site ZM9 has the largest D_i measure. With this site removed from the group, the H-statistic was

0.51 indicating that the rest of the group was homogeneous. Likewise, by removing the site YO6 that also has a high D_i measure and the highest L-CV, the H-statistic was –0.18 suggesting that there was less dispersion among the L-CVs in the region than would be expected in a homogeneous region. This also suggests that the sample L-CVs of the sites in the region were correlated and that the information acquired from such region might be redundant. The same was true with the region D as the H value was negative. This region is relatively small with correlated L-moments suggesting that regional analysis might not improve the quantile estimates at gauged or ungauged sites using this region. However, region C was close to being homogeneous with the H value close to 1.

The foregoing indicates that two of the 1989 regions that produced negative heterogeneity measures were possibly redundant. In other words, using the present approach, it may be possible to combine both of these regions with the remaining two to form bigger regions with equal or better regional estimation prospects. The seemingly discordant sites, namely YO6 and ZM9, had too few records to be decidedly flagged as outliers. However, they are peculiar in their regions in that the former has the highest coefficient of L-variation and the latter has the lowest among all 39 sites considered in the analysis. Moreover, the ZM9 series is negatively skewed. The YO6 series was affected by a high outlier recorded in 1983. However, convincing physical reasoning for the anomaly at ZM9 is not available at present. Nonetheless, the ZM9 basin, a small coastal basin located at the eastern tip of Avalon Peninsula, is on the leeward side of the approaching weather systems and is known to remain moist and cold throughout the year. The peak flows recorded over the years at this basin are relatively stable and are characterized by the lowest L-CV. It may be noted that the 1989 study, which had employed CFA88 (Environment Canada, 1985) to test the independence, randomness, homogeneity and trend, did not test the data at YO6 and ZM9 as the record lengths at these sites were less than 10.

In the following Section, the hydrologic homogeneity of the WSC sub regions Y and Z is tested using the L-moments based test. The 1984 RFFA of the provincial Government (Govt. of Newfoundland and Labrador, 1984) had considered the north and south regions approximately separated by the WSC divide for Y and Z sub regions. Likewise, Richter (1995) found that the distribution of specific flood and the average daily maximum flood across the Island of Newfoundland suggested the WSC Y-Z division but did not support the four regions of the 1989 study. It is therefore of interest to see whether the application of the present method of homogeneity testing corroborates the Y-Z division into two hydrologically homogeneous regions for the purpose of instantaneous peak flow estimation.

4.4.2 WSC sub regions

The WSC sub regions Y and Z are shown in Figure 4.2. The weighted regional average L-moment ratios and the weighted standard deviation of the at-site sample L-CVs (V measures) were computed for WSC Y and Z sub region and presented in Table 4.6.

Figure 4.2 The Island of Newfoundland showing the approximate boundary between WSC sub regions Y and Z

Table 4.6. Weighted regional average L-statistics for WSC sub regions Y and Z

WSC sub regions	Mean l_1	L-CV t^R	L-skewness t_3^R	L-kurtosis t_4^R	V
Y	1	0.165	0.180	0.140	0.037
Z	1	0.212	0.160	0.156	0.043

The kappa parameters and the heterogeneity measures. H for the Y and Z sub regions are given in Table 4.7

Table 4.7 Kappa parameters and heterogeneity measures for WSC sub regions

WSC sub regions	No. of sites	Kappa parameters				Heterogeneity Measures. H
		ξ	α	k	h	
Y	19	0.8337	0.2642	0.0375	0.1792	2.23
Z	20	0.8469	0.2874	-0.0192	-0.1266	0.78

The H-values indicate that the sub region Y is definitely heterogeneous and Z is acceptably homogeneous. However. the site YO6. which was discordant in its group due to highest L-CV. could be the potential source of heterogeneity in the sub region Y. Indeed. with YO6 excluded from the group. the H-statistic of the sub region Y was computed at 0.58 thereby demonstrating an acceptable homogeneity of the sub region.

Given the reasonable number of sites in both the regions (18 and 20 in Y and Z respectively). acceptable homogeneity shown by the test indicates both statistical and operational homogeneity of the WSC regions.

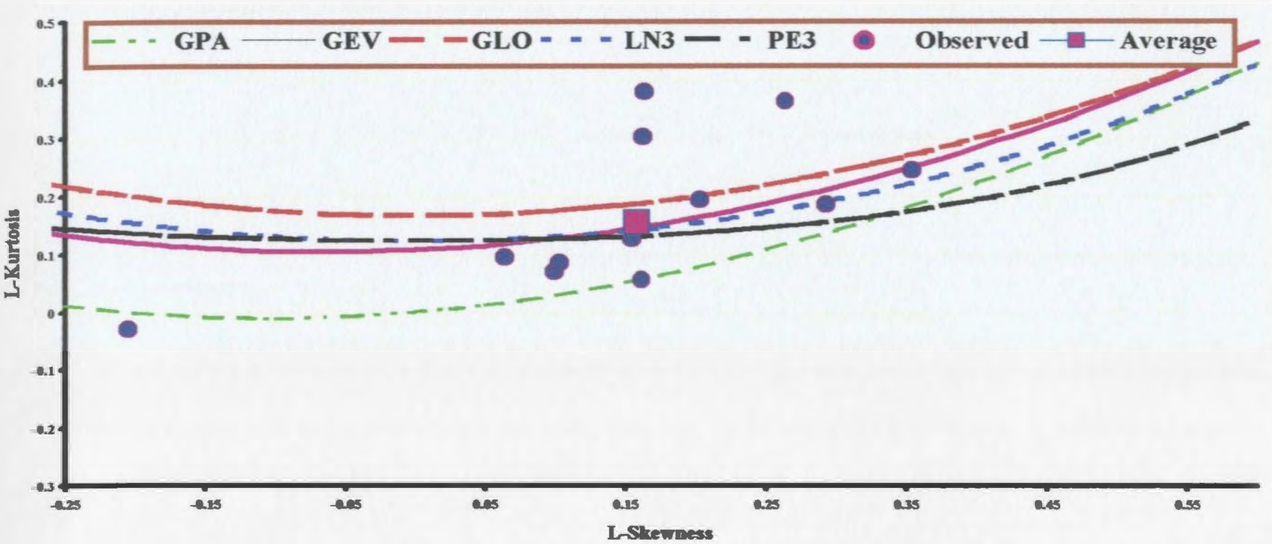
4.5 Selection of regional distribution

In the following sub sections, the results of a step-wise procedure employed for choosing the regional distributions are presented for the 1989 regions and for the WSC sub regions. The L-moment ratio diagrams were used to make a preliminary choice of candidate distributions. The L-kurtosis based goodness-of-fit test was applied to the candidates in order to make a qualitative ranking. The final choice was made based on the rankings provided by the Anderson-Darling test applied to the individual sites' data as well as pooled samples from each region. If more than one distribution qualified through this process, the best regional distribution was recommended based on the robustness criteria discussed later in this Chapter.

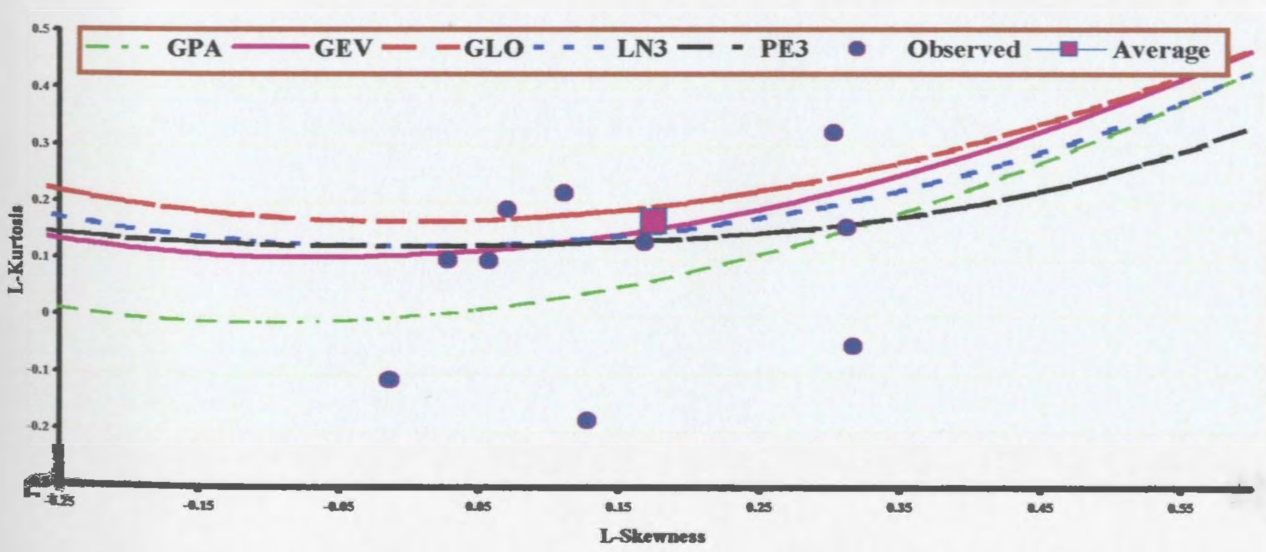
4.5.1 1989 regions

4.5.1.1 Preliminary identification: L-moment diagrams

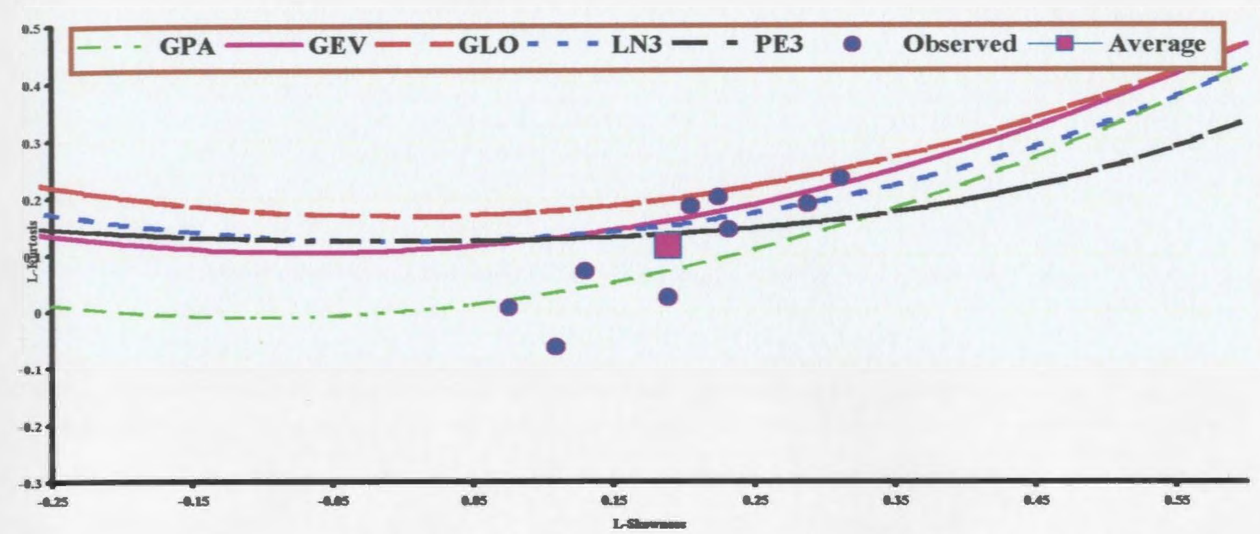
The theoretical plots of L-skewness vs. L-kurtosis for a range of distributions are shown in Figures 4.3a-d. The sample L-moment ratios at the individual sites for the 1989 regions are plotted as points on the diagrams. The regional average L-skewness and L-kurtosis weighted proportionally to the sites' record lengths are also plotted as solid squares on the diagrams.



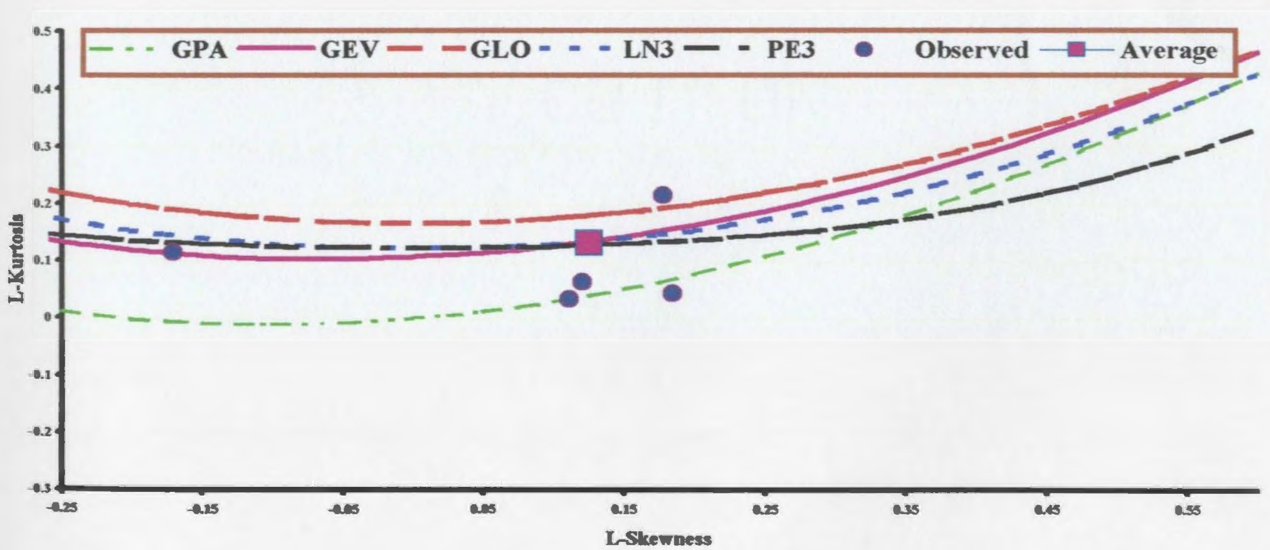
(a) Region A: Avalon and Burin Peninsula



(b) Region B: Central region



(c) Region C: Humber Valley and Northern Peninsula



(d) Region D: Southwestern

Figures 4.3a-d L-moment diagrams for 1989 regions

It is observed that the sites' L-moment ratios in all the regions are scattered around the L-moment diagrams of the most commonly used distributions. The weighted averages, however, fall fairly close to the GEV, LN3 or PE3 in all the regions thereby making these the possible candidate distributions to represent the 1989 regions.

4.5.1.2 L-kurtosis based test

Next, the Hosking and Wallis's L-kurtosis based goodness-of-fit test outlined in Section 3.4.4 was applied to the candidate distributions. This test compares the regionally weighted average L-kurtosis corrected for the sampling bias with that of the candidate distribution having the L-skewness equal to the regional weighted L-skewness of the sample data in the region. A MATLAB program for carrying out this procedure is given in Appendix [A-4].

The bias and standard deviation of the regional L-kurtosis were estimated from the simulated kappa regions (see Table 4.5 for the regional kappa parameters). Table 4.8 presents the kurtosis (τ_4^{DIST}) of the candidate distributions fitted to the regionally weighted average sample L-skewness (τ_3^{R}) and the computed goodness-of-fit measures (Z^{DIST}).

It is observed that based on the L-kurtosis-based goodness-of-fit test, most of the candidate distributions are acceptable for all the four regions as the Z^{DIST} values are within the critical value of 1.64. Exceptions are the GLO for the region C and the GPA for regions A, B and D. However, GEV and LN3 seem to be the most consistent and applicable at all the regions.

Table 4.8 L-kurtosis based goodness-of-fit measures for 1989 regions

Distribution	Region A		Region B		Region C		Region D	
	$t_4^R = 0.1583$ $B_4 = -0.0017$ $\sigma_4 = 0.0291$		$t_4^R = 0.1643$ $B_4 = -0.0027$ $\sigma_4 = 0.0312$		$t_4^R = 0.1139$ $B_4 = 0.0020$ $\sigma_4 = 0.0305$		$t_4^R = 0.1319$ $B_4 = -0.0003$ $\sigma_4 = 0.0512$	
	τ_4^{DIST}	$\lvert Z^{DIST} \rvert$	τ_4^{DIST}	$\lvert Z^{DIST} \rvert$	τ_4^{DIST}	$\lvert Z^{DIST} \rvert$	τ_4^{DIST}	Z^{DIST}
GLO	0.1893	1.01 (IV)	0.192	0.80 (III)	0.196	2.76*	0.180	0.93 (IV)
GEV	0.1483	0.40 (I)	0.152	0.48 (I)	0.158	1.51 (III)	0.134	0.04 (I)
LN3	0.1440	0.55 (II)	0.147	0.64 (II)	0.151	1.28 (II)	0.135	0.05 (II)
PE3	0.1313	0.99 (III)	0.132	1.12 (IV)	0.134	0.72 (I)	0.127	0.10 (III)
GPA	0.0582	3.499*	0.063	3.33*	0.070	1.37 (IV)	0.040	1.80*

* Fails the test as $Z > 1.64$

4.5.1.3 Anderson-Darling (A-D) test

Finally, the fitness of the candidate distributions to the tails of the data at each station was examined using the modified A-D test, which is the most powerful general-purpose approximate goodness-of-fit test. The parameters of the candidate distributions were estimated by the method of L-moments from the at-site data. The modified A-D statistics, A^*s were computed for the GEV, LN3, GLO, PE3 and GPA distributions at all 39 sites. In this method, a distribution is ranked higher if its A^* statistic is smaller than that of the competing candidates. Table 4.9 provides the ranks of the candidate distributions passing the test at 5% significance level. It is observed that the GEV is either best or second best at 27 of the 39 sites, LN3 is so at 21 sites and GLO at 16 sites.

Therefore it can be concluded that GEV is the most consistent distribution for all the sites in all the four regions followed by the LN3 and GLO distributions. PE3 and GPA did not fit most of the sites' data even at 10% significance level. This observation supports the choice of GEV and LN3 distributions by the 1989 study for the at-site frequency analysis within the Island.

Table 4.9 A-D test rankings for the candidate distributions for 1989 regions

Regions	SN	Stations/Distributions	GEV	LN3	GLO	PE3	GPA
Region A	1	ZG1	II	I	III	NA	NA
	2	ZG2	II	III	I	NA	NA
	3	ZG3	II	III	I	NA	NA
	4	ZG4	II	III	I	NA	NA
	5	ZH1	I	II	III	NA	NA
	6	ZH2	III	II	I	NA	NA
	7	ZK1	II	III	I	NA	NA
	8	ZK2	I	III	II	IV	V
	9	ZL3	III	II	IV	V	I
	10	ZM6	II	I	III	V	IV
	11	ZM9	II	III	V	IV	I
	12	ZN1	I	II	III	NA	NA
Region B	1	YN2	III	IV	V	I	II
	2	YO6	II	NA	I	NA	NA
	3	YP1	III	I	II	NA	IV
	4	YQ1	III	II	I	NA	NA
	5	YR1	II	I	III	NA	NA
	6	YR2	I	II	III	NA	NA
	7	YR3	III	IV	I	NA	II
	8	YS1	I	II	III	NA	NA
	9	YS3	I	II	III	NA	NA

Regions	SN	Stations/Distributions	GEV	LN3	GLO	PE3	GPA
	10	ZE1	NA*	NA*	NA	NA	I
	11	ZF1	II	NA	I	NA	NA
	12	ZJ1	III	II	I	NA	NA
Region C	1	YC1	II	I	III	IV	NA
	2	YD1	II	III	I	NA	NA
	3	YD2	III	II	IV	NA	I
	4	YF1	II	I	III	NA	I
	5	YK2	III	II	IV	NA	I
	6	YK4	II	III	NA*	NA	I
	7	YK5	I	II	III	IV	NA
	8	YL1	II	III	I	NA	NA
	9	YM3	II	III	I	NA	IV
Region D	1	YJ1	II	III	I	NA	NA
	2	ZA1	III	II	IV	NA	I
	3	ZA2	II	III	IV	V	I
	4	ZA3	I	II	III	V	IV
	5	ZB1	I	II	III	NA	NA
	6	ZC2	II	III	I	NA	NA

* Passes the test at 10%

Further, in order to test for the regional fit, the data from all the stations in the respective regions were pooled and the A-D test was then applied to the pooled samples at each region. The results are presented in Table 4.10.

It is observed that GEV, LN3 and GLO all gave the acceptable fit to all of the 1989 regions. The ranks show that GEV was best at region A and B, whereas, LN3 and GLO were best at region C and D respectively. However, the GEV was the most consistent distribution as it fitted the data at all sites at 5% significance level (see Table 4.9).

Table 4.10 Modified A-D statistics for candidate distributions for 1989 regions

SN	Region	Record length. ni	Anderson -Darling Statistic. A^*					Best Fit
			GEV	LN3	GLO	PE3	GPA	
1	A	224	0.2271 (I)	0.2422 (II)	0.4686 (III)	7.5217*	NA	GEV
2	B	229	0.5629 (I)	0.6333 (III)	0.6247 (II)	12.9984*	NA	GEV
3	C	174	0.3231 (II)	0.3050 (I)	0.6114 (III)	7.4544*	0.9166	LN3
4	D	78	0.1578 (III)	0.1569 (II)	0.1515 (I)	4.0968*	0.2572	GLO

*Fails the test at reasonable α level NA = Not applicable

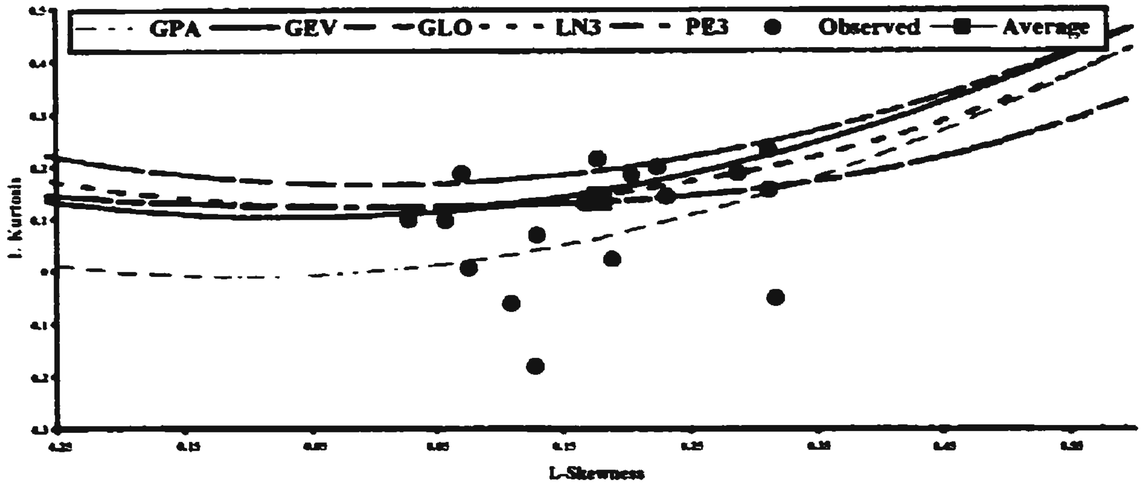
It is interesting to note that the L-moment diagrams and the L-kurtosis based test indicated the suitability of PE3 distribution as a regional distribution for all the regions. However. the A-D test completely ruled out the fit of the PE3 distribution to the regional data.

In regional frequency analysis. a single distribution is recommended as far as possible when the regions are geographically contiguous so that there is a smooth transition across the regional boundaries. Therefore. given its best fit at the regions A and B. and acceptable fit at the other two as shown by the A-D test. the GEV distribution can be reasonably chosen for regional flood frequency analysis at all the 1989 regions. Combining this information with the L-moment diagrams and the L-kurtosis based goodness-of-fit test. the choice of GEV as a regional distribution is also justified for all the regions. However, LN3 is the closest competitor, which is also applicable at all sites and all the regions. Therefore the final choice between GEV and LN3 distributions should be made based on the test for distribution's robustness to estimate the extreme quantiles even when the distribution is slightly mis-specified or the region is slightly heterogeneous. This aspect is dealt with at the end of this Section.

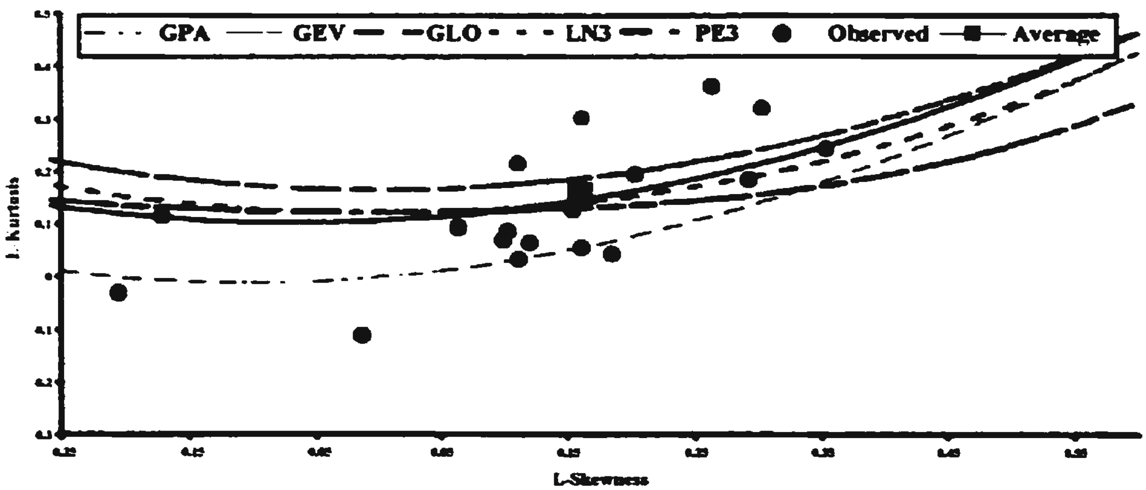
4.5.2 WSC sub regions

It was shown in Section 3 that the WSC sub regions Y and Z are hydrologically homogeneous. Therefore, it was of interest to identify the regional distributions so that a regional frequency analysis could be performed within these regions. The same exploratory test based on L-moment diagrams followed by the statistical L-kurtosis based test for the regional distribution was carried out for both the sub regions. The results of the A-D test performed on the flow data pooled in each region were then used to pick the preferred regional distribution for each of the sub regions.

The L-moment diagrams for the WSC regions Y and Z are given in Figure 4.4a-b. The regionally weighted average L-moment ratios again fall close to the GEV and LN3 distributions, thereby indicating their potential as the regional distributions for the WSC sub regions.



(a)



(b)

Figure 4.4a-b L-moment ratio diagrams for WSC sub regions- Y and Z

Table 4.11 shows the L-kurtosis-based goodness-of-fit statistics, Z^{DIST}'s, computed for the two sub regions Y and Z. It is observed that GEV, LN3 and PE3 provide acceptable fit to the regional data as the Z^{DIST} values are below the critical value of 1.64 whereas the GPA fails the test.

Table 4.11 L-kurtosis based goodness-of-fit measures for WSC regions

Distribution	Sub region Y		Sub region Z	
	$t_4^R = 0.1389$ $B_4 = -0.0018$ $\sigma_4 = 0.0230$		$t_4^R = 0.1597$ $B_4 = -0.0022$ $\sigma_4 = 0.0240$	
	τ_4^{DIST}	$\|Z^{DIST}\|$	τ_4^{DIST}	$\|Z^{DIST}\|$
GLO	0.1933	2.286*	0.1879	1.08
GEV	0.1539	0.574	0.1464	0.64
LN3	0.1477	0.306	0.1427	0.80
PE3	0.1329	0.338	0.1307	1.30
GPA	0.0653	3.277*	0.0557	4.43*

*Fails the test as Z> 1.64

Furthermore, the A-D test was applied to the pooled data from the WSC regions and the results are given in Table 4.12.

Table 4.12 Modified A-D statistics for candidate distributions for the WSC sub regions

SN	Region	Record length, ni	Anderson -Darling Statistic, A^*					Best Fit
			GEV	LN3	GLO	PE3	GPA	
1	WSC Y	358	0.3565 (I)	0.3913 (II)	0.7731*	9.0456*	NA	GEV
2	WSC Z	347	0.1762 (I)	0.1852 (II)	0.3990 (III)	19.6903*	NA	GEV

*Fails the test at 10% significance level NA = Not applicable

It is seen that both the GEV and LN3 distributions pass the test at 5% significance level for these regions. GLO passed the test for sub region Z only. However, based on the ranks, the GEV stood as the best fitting distribution for both Y and Z sub regions. The possibility of PE3 and GPA as being the regional distributions was decisively ruled out by the A-D test, albeit the L-skewness based test indicated their adequacy in fitting the regional data.

The foregoing suggests that either GEV or LN3 could be employed as a regional distribution both for the 1989 regions and WSC sub regions. Therefore, the final choice between the GEV and LN3 as the regional distributions may be based on the robustness criteria as indicated by the differences in the accuracy measures in estimating the extreme quantiles when the parent distributions are slightly different from the assumed ones.

4.5.3 Test for robustness

In the present analysis, two different scenarios were considered in order to study the effect of the "wrong" choice of the regional distribution in estimating the quantiles. The first case involved the choice of GEV when the underlying distribution was LN3 and vice versa. The second scenario involved the choice of GEV or LN3 distribution when the underlying distribution was different from either of these competing candidates. This analysis used GLO as the underlying parent based on the observation that the GLO was the next best fitting distribution after GEV and LN3 as shown by the A-D test applied to the at-site data on the whole Island (see Table 4.9). The study of the accuracy measures under the above two scenarios was organized as follows.

Scenario 1:

(i) GEV chosen as the regional distribution when the true underlying distribution was LN3 (GEV-LN3):

(ii) LN3 chosen as the regional distribution when the true underlying distribution was GEV (LN3-GEV):

Scenario 2:

(i) GEV chosen as the regional distribution when the true underlying distribution was GLO (GEV-GLO):

(iii) LN3 chosen as the regional distribution when the true underlying distribution was GLO (LN3-GLO):

In all the cases under each scenario. the computed accuracy measures were compared with the ideal situation where the choice of the regional distribution was the same as the underlying distribution: GEV-GEV and LN3-LN3.

A MATLAB MACRO employed to carry out the above procedure is provided in Appendix A-5. Tables 4.13a and 4.13b summarize the simulation results for the 1989 regions in scenarios 1 and 2 respectively. The accuracy measures of the estimated quantiles are expressed as percentages. The scenario 1 did not particularly favor one

Table 4.13a. Robustness evaluation for GEV and LN3 distributions for 1989 regions: Scenario 1

	Quantiles	0.9	0.99	0.999	0.9	0.99	0.999	Difference for 100-year event
Region A		GEV-GEV			GEV-LN3			
	ARB	0.69	0.02	0.91	0.21	0.33	1.37	0.31
	AARB	7.16	21.42	35.43	7.69	20.28	30.90	-1.14
	RMSE	1.39	5.37	13.38	1.42	4.90	11.0	-0.47
		LN3-LN3			LN3-GEV			
	ARB	0.81	0.80	2.35	1.67	1.04	2.55	0.24
	AARB	7.92	20.54	31.36	7.19	21.67	36.05	1.13
	RMSE	1.37	4.61	10.21	1.42	5.09	12.57	0.48
Region B		GEV-GEV			GEV-LN3			
	ARB	1.69	-7.28	-10.75	1.64	-7.17	-9.83	0.11
	AARB	5.52	23.18	40.29	2.36	23.27	35.98	0.09
	RMSE	4.25	5.87	13.49	24.45	10.14	11.98	4.27
		LN3-LN3			LN3-GEV			
	ARB	2.18	-6.50	-8.51	3.27	-5.96	-9.18	0.54
	AARB	6.98	23.73	36.79	6.77	22.92	41.03	-0.81
	RMSE	4.94	5.79	10.83	58.98	23.29	14.66	17.5
Region C		GEV-GEV			GEV-LN3			
	ARB	1.03	0.27	0.19	-0.047	0.01	0.80	-0.26
	AARB	4.61	13.65	23.76	4.65	12.86	20.16	-0.79
	RMSE	0.66	2.14	5.63	0.65	2.01	4.67	-0.13
		LN3-LN3			LN3-GEV			
	ARB	-0.69	-2.20	-2.87	-0.045	-2.55	-4.21	-0.35
	AARB	4.43	12.45	19.16	4.46	13.19	22.45	0.74
	RMSE	0.60	1.57	3.20	0.61	1.71	4.14	0.14
Region D		GEV-GEV			GEV-LN3			
	ARB	-0.48	-0.17	0.63	-0.43	-0.82	-1.54	-0.65
	AARB	6.49	12.99	21.11	5.93	11.88	18.20	-1.11
	RMSE	1.56	3.77	9.04	1.50	3.28	7.07	-0.49
		LN3-LN3			LN3-GEV			
	ARB	1.68	2.52	3.61	1.34	2.45	4.55	-0.07
	AARB	6.00	11.31	15.98	6.26	12.04	19.61	0.73
	RMSE	1.50	2.98	6.07	1.62	3.33	7.52	0.35

ARB: Average relative bias
AARB: Average absolute relative bias
RMSE: Relative root mean square error

Table 4.13b. Robustness evaluation for GEV and LN3 distributions for 1989 regions: Scenario 2

	Quantiles	0.9	0.99	0.999	0.9	0.99	0.999	Difference for 100-year event
Region A		GEV-GEV			GEV-GLO			
	ARB	0.69	0.02	0.91	-101.15	-100.65	-100.26	100.67
	AARB	7.16	21.42	35.43	101.15	100.65	100.26	79.23
	RMSE	1.39	5.37	13.38	51.40	50.85	50.46	45.49
		LN3-LN3			LN3-GLO			
	ARB	0.81	0.80	2.35	-101.35	-100.83	-100.44	101.63
	AARB	7.92	20.54	31.36	101.35	100.83	100.44	80.29
	RMSE	1.37	4.61	10.21	51.63	51.03	50.63	46.43
Region B		GEV-GEV			GEV-GLO			
	ARB	1.69	-7.28	-10.75	-102.59	-100.80	-100.41	93.52
	AARB	5.52	23.18	40.29	102.59	100.80	100.41	77.61
	RMSE	4.25	5.87	13.49	58.86	51.04	50.48	45.17
		LN3-LN3			LN3-GLO			
	ARB	2.18	-6.50	-8.51	-103.37	-101.03	-100.56	94.54
	AARB	6.98	23.73	36.79	103.37	101.03	100.56	77.31
	RMSE	4.94	5.79	10.83	56.55	51.18	50.62	45.39
Region C		GEV-GEV			GEV-GLO			
	ARB	1.03	0.27	0.19	-9.89	-23.28	-37.67	23.55
	AARB	4.61	13.65	23.76	9.89	23.28	37.67	9.64
	RMSE	0.66	2.14	5.63	1.00	4.09	9.55	1.95
		LN3-LN3			LN3-GLO			
	ARB	-0.69	-2.20	-2.87	-9.18	-22.60	-36.94	20.41
	AARB	4.43	12.45	19.16	9.18	22.60	36.94	10.16
	RMSE	0.60	1.57	3.20	0.84	3.62	8.66	2.05
Region D		GEV-GEV			GEV-GLO			
	ARB	-0.48	-0.17	0.63	-10.77	-22.64	-34.20	22.47
	AARB	6.49	12.99	21.11	10.77	24.23	38.90	11.24
	RMSE	1.56	3.77	9.04	1.71	5.27	11.31	1.50
		LN3-LN3			LN3-GLO			
	ARB	1.68	2.52	3.61	-8.52	-18.83	-29.25	21.34
	AARB	6.00	11.31	15.98	9.16	22.21	36.89	10.91
	RMSE	1.50	2.98	6.07	1.39	4.10	9.06	1.11

ARB: Average relative bias
AARB: Average absolute relative bias
RMSE: Relative root mean square error

distribution over the other. However at majority of the regions, the bias and the RMSE of the estimated 50 and 100-year quantiles were comparatively less in GEV-LN3 than in LN3-GEV case. Likewise, in scenario 2, there was again a close resemblance between the accuracy measures from the two candidates with the GEV distribution leading in three of the four regions.

Joint evaluation of the simulation results obtained in these two scenarios shows that the GEV is, on an average, more robust than the LN3 distribution for the 1989 regions. In view of the general preference of a common regional distribution, as far as possible, for use in the adjoining regions, the GEV can be chosen as the appropriate distribution for all the 1989 regions. However, based on the average relative bias, the LN3 performs comparatively better than the GEV distribution for the WSC sub regions (Tables 4.14a and 4.14b).

It was of interest to compare the simulation results with the goodness-of-fit test results regarding the choice of the regional frequency distribution. The goodness-of-fit measures consistently established the GEV as the better fitting distribution for the 1989 regions as well as the WSC sub regions (Tables 4.8, 4.9 and 4.10).

Earlier, in an exploratory work, Pokhrel and Lye (2001) had concluded that the GEV distribution was acceptable for all the 1989 regions as well as for both the WSC sub regions. While the robustness evaluation based on the data available for the 1989 study favored the GEV distribution for the 1989 regions, it led to a different choice- LN3 for the WSC sub regions! The general implication is that the goodness-of-fit criteria alone are not sufficient for choosing the appropriate distribution for the purpose of regional flood frequency analysis.

Table 4.14a Robustness evaluation for the GEV and LN3 distributions for WSC sub regions: Scenario 1 (data until 1988)

	Quantiles	0.9	0.99	0.999	0.9	0.99	0.999	Difference for 100-year event
Region WSC Y		GEV-GEV			GEV-LN3			
	ARB	0.75	-6.94	-11.41	-0.15	-6.69	-9.44	0.25
	AARB	5.13	18.52	31.18	5.94	18.52	27.86	0.00
	RMSE	3.25	4.00	8.67	2.27	3.83	7.40	-0.17
		LN3-LN3			LN3-GEV			
	ARB	0.43	-6.71	-9.53	1.63	-6.37	-10.57	0.34
	AARB	6.22	18.48	27.83	5.89	18.33	31.33	-0.15
	RMSE	3.43	3.91	6.98	9.87	5.80	8.51	1.89
Region WSC Z		GEV-GEV			GEV-LN3			
	ARB	0.69	1.39	3.13	0.71	2.10	3.72	0.71
	AARB	6.93	19.55	32.36	7.27	18.50	3.72	-1.05
	RMSE	1.26	4.41	11.02	1.22	3.99	8.93	-0.42
		LN3-LN3			LN3-GEV			
	ARB	1.42	2.88	5.37	1.90	2.97	5.90	0.09
	AARB	7.33	18.71	28.56	7.10	20.10	33.70	1.39
	RMSE	1.24	3.91	8.72	1.25	4.38	11.11	0.47

ARB: Average relative bias
AARB: Average absolute relative bias
RMSE: Relative root mean square error

Table 4.14b Robustness evaluation for the GEV and LN3 distributions for WSC sub regions: Scenario 2 (data until 1988)

	Quantiles	0.9	0.99	0.999	0.9	0.99	0.999	Difference for 100-year event
Region WSC Y		GEV-GEV			GEV-GLO			
	ARB	0.75	-6.94	-11.41	-10.61	-27.97	-43.32	21.02
	AARB	5.13	18.52	31.18	10.61	27.97	43.32	9.45
	RMSE	3.25	4.00	8.67	2.19	6.05	12.70	2.06
		LN3-LN3			LN3-GLO			
	ARB	0.43	-6.71	-9.53	-9.38	-26.35	-41.19	19.64
	AARB	6.22	18.48	27.83	9.39	26.35	41.19	7.87
	RMSE	3.43	3.91	6.98	1.44	5.45	11.81	1.55
Region WSC Z		GEV-GEV			GEV-GLO			
	ARB	0.69	1.39	3.13	-10.92	-22.96	-34.71	24.35
	AARB	6.93	19.55	32.36	12.13	27.28	42.10	7.73
	RMSE	1.26	4.41	11.02	1.50	5.37	11.49	0.96
		LN3-LN3			LN3-GLO			
	ARB	1.42	2.88	5.37	-9.14	-20.22	-30.84	23.10
	AARB	7.33	18.71	28.56	10.70	25.72	40.39	7.01
	RMSE	1.24	3.91	8.72	1.41	4.85	10.51	0.94

ARB: Average relative bias
AARB: Average absolute relative bias
RMSE: Relative root mean square error

4.6 Estimation of regional growth curves

4.6.1 1989 regions

Based on the foregoing, the GEV was selected as the regional distribution for all the 1989 regions. It was then fitted to the regional average L-moments of the sample data from the sites in the respective regions. The parameters were estimated by using the expressions for the distributions' L-moments in terms of its parameters given by Hosking and Wallis (1997). The distribution's L-moments were replaced by the sample regional average L-moments. For a non-excedence probability, F, the GEV quantile function is given by the following equation (Hosking and Wallis, 1997).

$x(F) = \xi + \alpha/k[1 - (-\log F)^k\}]$, $k \neq 0$ [4.6a]

where, ξ, α and k are the location, scale and shape parameters of the GEV distribution.

Table 4.15 contains the regional GEV parameters and the respective quantile functions obtained from the sample data in each of the four regions.

Table 4.15 Regional GEV parameters and the quantile functions for 1989 regions

Regions	k	α	ξ	GEV quantile function $x(F) = \xi + \alpha/k[1 - (-\log F)^k]$
A	0.0082	0.3072	0.8251	$0.8251 + 37.47\,[1 - (-\log F)^{0.0082}]$
B	-0.0075	0.2573	0.8496	$0.8496 - 34.52\,[1 - (-\log F)^{-0.0075}]$
C	-0.0284	0.2189	0.8674	$0.8674 - 7.71\,[1 - (-\log F)^{-0.0284}]$
D	0.0713	0.3389	0.8268	$0.8268 + 4.75\,[1 - (-\log F)^{0.0713}]$

4.6.2 WSC sub regions

The results in the preceding Sections suggest that the LN3 is a reasonably robust regional distribution for the WSC sub regions. Therefore, the regional growth curves were estimated based on the LN3 distribution from the regional average L-moments of the

WSC Y and Z sub regions. For a non-exceedence probability, F, the LN3 quantile function is given by the following equation (Hosking and Wallis, 1997).

$$x(F) = \xi + \alpha/k[1-\exp\{-k\Phi^{-1}(F)\}] \, , \, k \neq 0 \qquad [4.6b]$$

where, ξ, α and k are the location, scale and shape parameters of the GEV distribution. Φ^{-1} is the inverse of the standard normal variate. The regional LN3 parameters and the respective quantile functions are given in Table 4.16.

Table 4.16 Regional LN3 parameters and quantile functions for WSC sub regions

Sub regions	k	α	ξ	LN3 Growth curve $x(F) = \xi + \alpha/k[1-\exp\{-k\Phi^{-1}(F)\}]$	
				F = 0.98 (T = 50 yrs)	F = 0.99 (T = 100 yrs)
Y	-0.3686	0.2771	0.9472	1.798	1.967
Z	-0.3288	0.3593	0.9393	1.993	2.195

4.7 Comparison of quantile estimates

In this Section, the results of comparison between the quantile estimates obtained from at-site frequency analysis and the regional analysis for the 1989 regions and the WSC sub regions, are presented. The differences observed were further compared with their regression-based regional counterparts of the 1989 study.

4.7.1 Region-wise comparison: 1989 regions vs. WSC sub regions

Table 4.17 presents the 50 and 100-year at-site frequency estimates obtained using CFA 3.1 based on the GEV distribution fitted by the method of L-moments. The reason for choosing GEV distribution for use in the CFA 3.1 was that it was the most consistent distribution for the at-site data (see Table 4.9). Also shown in the Table 4.17 are the regional estimates obtained using the 1989 regions and WSC sub regions based on the current approach. It is observed that the average difference between the at-site and regionally estimated quantiles was practically the same for the 1989 regions and WSC sub regions implying that the division of the Island into four regions did not particularly improve the estimated quantiles at the gauged locations. At 50% of the stations, the quantiles were underestimated in both the cases. It may be further noted that the underestimation was by more than 50% at the YO6 and ZM9 basins. Indeed, these stations were found discordant in their respective groups (see Table 4.3). Obviously, the at-site estimates at these stations are not reliable.

One of the examiners of this Thesis suggested that the comparison should only be based on the long record length (30 years or more) stations. These stations have been marked with asterisks. The results (last row of Table 4.17) further strengthen the conclusion reached with the entire data set.

Table 4.17 Comparison of at-site and regional frequency estimates for 1989 regions and WSC sub regions

STNs	N	At-site		Regional (89 regions)		% Difference		Regional (WSC sub regions)		% Difference	
		Q50	Q100	Q50	Q100	dQ50	dQ100	Q50	Q100	DQ50	dQ100
YC1*	30	427.0	483.0	373.5	409.9	12.5	15.1	379.3	415.0	-11.2	-14.1
YD1	19	208.0	234.0	184.0	202.0	11.5	13.7	186.9	204.5	-10.1	-12.6
YD2	9	84.8	95.7	78.6	86.2	7.3	9.9	79.8	87.3	-5.9	-8.8
YF1	14	485.0	521.0	496.1	544.5	-2.3	-4.5	503.8	551.2	3.9	5.8
YJ1	20	655.0	729.0	638.0	694.2	2.6	4.8	579.1	633.6	-11.6	-13.1
YK2	15	195.0	213.0	183.0	200.8	6.2	5.7	185.8	203.3	-4.7	-4.6
YK4	23	151.0	160.0	165.9	182.1	-9.9	-13.8	168.5	184.4	11.6	15.2
YK5	16	140.0	151.0	149.3	163.8	-6.6	-8.5	151.6	165.8	8.3	9.8
YL1*	39	1010.0	1100.0	1064.3	1168.0	-5.4	-6.2	1080.8	1182.4	7.0	7.5
YM3	9	115.0	113.0	89.2	97.9	22.4	13.3	90.6	99.1	-21.2	-12.3
YN2	8	440.0	510.0	370.1	406.9	15.9	20.2	354.9	388.2	-19.3	-23.9
YO6	8	189.0	253.0	107.7	118.4	43.0	53.2	103.2	112.9	-45.4	-55.4
YP1	7	82.2	110.0	58.2	63.9	29.3	41.9	55.8	61.0	-32.2	-44.5
YQ1*	39	1000.0	1070.0	1127.5	1239.7	-12.7	-15.9	1081.1	1182.7	8.1	10.5
YR1*	30	49.1	52.0	55.6	61.1	-13.2	-17.6	53.3	58.3	8.6	12.2
YR2	12	167.0	194.0	142.0	156.1	15.0	19.5	136.2	149.0	-18.5	-23.2
YR3	8	95.3	103.0	102.7	112.9	-7.7	-9.6	98.4	107.7	3.3	4.6
YS1*	31	320.0	347.0	343.6	377.8	-7.4	-8.9	329.4	360.4	3.0	3.9
YS3	21	20.2	21.2	24.4	26.9	-21.0	-26.7	23.4	25.6	16.0	20.9
ZA1	10	246.0	270.0	234.7	255.4	4.6	5.4	236.2	260.2	-4.0	-3.6
ZA2	7	177.0	201.0	142.4	154.9	19.6	22.9	143.3	157.8	-19.1	-21.5
ZA3	7	278.0	289.0	316.6	344.6	-13.9	-19.2	318.6	350.9	14.6	21.4
ZB1	27	777.0	850.0	744.3	809.9	4.2	4.7	748.9	824.8	-3.6	-3.0
ZC2	7	834.0	918.0	915.9	996.6	-9.8	-8.6	921.6	1015.0	10.5	10.6
ZE1	16	473.0	492.0	547.9	602.4	-15.8	-22.4	582.3	641.4	23.1	30.4
ZF1	37	509.0	601.0	409.3	450.0	19.6	25.1	435.0	479.1	-14.5	-20.3
ZG1*	30	138.0	162.0	121.0	133.5	12.3	17.6	120.3	132.5	-12.8	-18.2
ZG2	12	125.0	147.0	107.9	119.0	13.7	19.0	107.2	118.1	-14.2	-19.7
ZG3	9	104.0	113.0	116.4	128.4	-11.9	-13.7	115.7	127.5	11.3	12.8
ZG4	8	86.1	99.1	74.4	82.1	13.6	17.2	74.0	81.5	-14.1	17.8

Table 4.17 Contd..

STNs	N	At-site		Regional (89 regions)		% Difference		Regional (WSC sub regions)		% Difference	
		Q50	Q100	Q50	Q100	dQ50	dQ100	Q50	Q100	DQ50	dQ100
ZH1*	36	475.0	516.0	473.0	521.9	0.4	-1.1	470.2	517.8	-1.0	-0.4
ZH2	18	55.7	59.6	61.0	67.3	-9.4	-12.9	60.6	66.7	8.8	12.0
ZJ1	12	42.9	46.5	42.9	47.1	0.1	-1.4	45.6	50.2	6.2	7.9
ZK1*	39	317.0	356.0	309.3	341.3	2.4	4.1	307.5	338.7	-3.0	-4.9
ZK2	10	256.0	314.0	174.1	192.1	32.0	38.8	173.1	190.6	-32.4	39.3
ZL3	10	23.1	26.2	18.4	20.3	20.4	22.6	18.3	20.1	-20.9	-23.2
ZM6	19	6.3	6.9	6.4	7.1	-2.7	-2.9	6.4	7.0	2.1	2.1
ZM9	10	35.7	36.3	52.5	58.0	-47.2	-59.7	52.2	57.5	46.3	58.5
ZN1	23	63.6	68.3	72.8	80.3	-14.4	-17.5	72.3	79.6	13.7	16.6
Average absolute %difference (all stations)						**13.3**	**16.6**			**13.5**	**16.6**
Average absolute %difference (long record stations)						**9.01**	**11.63**			**7.28**	**9.5**

*Long record length stations

4.7.2 L-moment-based index-flood vs. regression on quantiles of 1989 study

Table 4.18 shows the comparison between the differences in the at-site and regional quantile estimates observed in the 1989 regression-based approach (Govt. of Newfoundland and Labrador. 1990) and the same obtained with the present approach using the same set of data. The sites YO6 and ZM9 were removed for the comparison. Likewise. the estimates at YR3 were also excluded from the comparison as the 1989 study had neglected the site for the so-called 'anomalous behavior' of its T-year quantiles.

Table 4.18 Comparison of % age differences in quantile estimates obtained from 1989 regression based approach and the current approach

SN	Station	1989 Approach		Current Approach	
		dQ50	dQ100	dQ50	dQ100
1	YC1*	0.30	0.50	11.2	14.1
2	YD1	-18.90	-17.80	10.1	12.6
3	YD2	10.80	10.60	5.9	8.8
4	YF1	-39.70	-35.50	-3.9	-5.8
5	YJ1	14.80	11.70	11.6	13.1
6	YK2	-16.80	-17.20	4.7	4.6
7	YK4	5.40	5.30	-11.6	-15.2
8	YK5	16.90	15.70	-8.3	-9.8
9	YL1*	3.00	2.70	-7.0	-7.5
10	YM3	5.50	4.80	21.2	12.3
11	YN2	-20.50	-22.70	19.3	23.9
12	YP1	-0.80	2.70	32.2	44.5
13	YQ1*	-6.70	-3.50	-8.1	-10.5
14	YR1*	4.10	0.20	-8.6	-12.2
15	YR2	4.70	1.60	18.5	23.2
16	YS1*	26.20	20.90	-3.0	-3.9
17	YS3	-18.50	-19.20	-16.0	-20.9
18	ZA1	40.40	37.70	4.0	3.6
19	ZA2	42.50	37.50	19.1	21.5
20	ZA3	-13.40	-8.70	-14.6	-21.4
21	ZB1	-44.40	-44.10	3.6	3.0
22	ZC2	-2.70	-1.20	-10.5	-10.6
23	ZE1	0.90	4.00	-23.1	-30.4
24	ZF1*	-11.60	-12.80	14.5	20.3
25	ZG1*	2.40	-2.10	12.8	18.2
26	ZG2	34.80	36.20	14.2	19.7
27	ZG3	-0.30	1.90	-11.3	-12.8
28	ZG4	-6.80	-4.40	14.1	17.8
29	ZH1*	17.60	21.00	1.0	-0.4
30	ZH2	10.70	7.90	-8.8	-12.0
31	ZJ1	19.20	21.20	-6.2	-7.9
32	ZK1*	7.00	6.60	3.0	4.9
33	ZK2	-34.00	-35.60	32.4	39.3

Table 4.18 contd..

SN	Station	1989 Approach		Current Approach	
		dQ50	dQ100	dQ50	dQ100
34	ZL3	-11.40	-11.70	20.9	23.2
35	ZM6	43.20	42.70	-2.1	-2.1
36	ZN1	-22.80	-22.30	-13.7	-16.6
Absolute Average (all stations)		**16.10**	**15.34**	**11.0**	**13.5**
Absolute Average (long record stations)		**12.33**	**11.44**	**7.28**	**9.5**

*Long record length stations

It is observed that the differences at majority of the stations are less from the current approach than from the 1989 regression approach. The overall averages are also less in the recent approach than in the previous one. It may be noted that the sites used for this comparison were the gauged sites that were used in developing the regional equations and therefore did not necessarily represent the behavior of the estimated quantiles at the ungauged locations. An independent set of stations was not available for carrying out such comparison with the data available for the 1989 study. However, in the assessment that follows, thirteen independent sites with the average record length of 12 years were available for comparing the performance of 1989 regions and WSC sub regions based on the latest available data.

4.8 Assessment using the latest available data

Finally, the above results were assessed using the longer records of observed flows until 1998 (currently available) at the same set of thirty-nine stations. The record lengths at these stations varied from 16 to 49 years. The basic L-statistics of the data at 39 stations available until 1998 is presented in Table 4.19.

The same step-wise methodology of L-moment-based RFFA was applied to the 1989 regions as well as WSC sub regions. The aim was to examine if the longer records also substantiated the results obtained with the data used in the 1989 study. Furthermore, the additional 13 gauged stations that are now available for an independent comparison of the quantile estimates provide the basis for an independent evaluation of estimating ability of the regression-on-quantile approach of RFFA and the L-moments based index-flood procedure. This Section provides the summary of the results obtained at each step and also highlights the observed differences, wherever appropriate.

Table 4.19 Summary L-statistics of the gauging stations (data until 1998)

Station Number	Name of Stations	Years of Record	Mean (l_1) m^3/sec	L-CV (t)	L-skewness (t_3)	L-kurtosis (t_4)
YC1	Torrent River at Bristol's Pool	40	198.2	0.19	0.21	0.19
YD1	Beaver Brook near Roddicton	19	103.9	0.19	0.22	0.20
YD2	Northeast Brook near Roddicton	19	40.9	0.16	0.15	0.17
YF1	Cat Arm River above Great Cat Arm	14	280.2	0.15	0.11	-0.06
YJ1	Harrys River below Highway Bridge	30	332.4	0.20	0.18	0.18
YK2	Lewaseechjeech Brook at Little Grand lake	25	126.5	0.14	0.15	0.02
YK4	Hinds Brook near Grand lake	23	93.7	0.14	0.08	0.01
YK5	Sheffield Brook near Trans Canada Highway	26	76.3	0.16	0.04	0.14
YL1	Upper Humber River near Reidville	49	598.9	0.14	0.18	0.13
YM3	South West Brook near Baie Verte	18	41.3	0.26	0.19	0.19
YN2	Lloyds River below King George IV Lake	18	196.6	0.23	0.25	0.14
YO6	Peter's River near Botwood	18	50.7	0.23	0.47	0.44
YP1	Shoal Arm Brook near Badger Bay	16	24.8	0.23	0.27	0.47
YQ1	Gander River at Big Chute	16	603.2	0.15	0.05	0.17
YR1	Middle Brook near Gambo	40	29.6	0.17	0.10	0.09
YR2	Ragged Harbor River near Musgrave Harbor	21	70.3	0.17	0.33	0.20
YR3	Indian Bay Brook near Northwest Arm	18	58.7	0.16	0.00	-0.10
YS1	Terra Nova River at Eight Mile Bridges	31	183.2	0.16	0.17	0.13
YS3	Southwest Brook at Terra Nova National Park	31	13.8	0.18	0.18	0.17
ZA1	Little Barachois Brook Near St. George's	18	121.8	0.22	0.10	0.05
ZA2	Highlands River at Trans Canada Highway	17	61.3	0.29	0.32	0.12
ZA3	Little Codroy River near Doyles	16	167.2	0.24	0.15	0.12
ZB1	Isle Aux Morts River below Highway Bridge	37	388.5	0.26	0.19	0.06
ZC2	Grandy Brook below Top Pond Brook	17	394.5	0.19	0.09	0.11
ZE1	Salmon River at Long Pond	16	292.2	0.16	-0.01	-0.11
ZF1	Bay Du Nord River at Big Falls	47	216.4	0.21	0.28	0.29

Table 4.19 Contd..

Station Number	Name of Stations	Years of Record	Mean (l_1) m^3/sec	L-CV (t)	L-skewness (t_3)	L-kurtosis (t_4)
ZG1	Garnish River near Garnish	40	62.8	0.24	0.35	0.24
ZG2	Tides Brook below Freshwater Pond	20	50.6	0.23	0.23	0.26
ZG3	Salmonier River near Lamaline	19	63.4	0.22	0.03	-0.02
ZG4	Rattle Brook near Boat Harbor	18	40.4	0.26	0.19	0.23
ZH1	Pipers Hole River at Mother's Brook	46	240.4	0.23	0.07	0.05
ZH2	Come By Chance River near Goobies	28	31.9	0.23	0.08	0.12
ZJ1	Southern Bay River near Southern bay	22	23.1	0.20	0.19	0.25
ZK1	Rocky River near Colinet	49	154.8	0.21	0.16	0.13
ZK2	Northeast River near Placenta	20	74.4	0.31	0.24	0.24
ZL3	Spout Cove Brook near Spout Cove	19	8.83	0.26	0.15	0.12
ZM6	Northeast Pond river at Northeast Pond	29	3.4	0.20	0.17	0.08
ZM9	Seal Cove Brook near Cappahayden	20	27.5	0.11	0.20	0.28
ZN1	Northwest Brook at Northwest Pond	30	38.6	0.16	0.04	0.05

4.8.1 Discordancy statistics and heterogeneity measures

4.8.1.1 Whole Island as one region

For the whole Island as one group, only the stations YO6 and YP1 had the Di values more than the critical for N > 15. However, the heterogeneity measure, H computed for the whole Island (H = 3.9) suggested that the Island as one region was definitely heterogeneous. Removal of the discordant sites, too did not improve the homogeneity.

4.8.1.2 1989 regions

In region A, the station ZM9 had the highest D_i value of 2.8 rendering the region to be possibly heterogeneous. However, with ZM9 excluded, the heterogeneity measure was computed at 0.82, which indicated that the rest of the group was acceptably homogeneous. The ZM9 basin was again singled out as the coefficient of variation at this basin was least among the sites in the whole Island. The possible reasons for this anomaly were discussed in the preceding Sections.

Region B had negative heterogeneity measure (H = - 0.47) indicating a significant correlation among the sites' L-moments. This region has seen a change in its homogeneity status over the last ten years; the H-value changed from 1.55 in 1988 to -0.47 in 1998. As discussed earlier, the negative H-measure implies that the region is redundant and offers a potential for encompassing more basins to form a larger homogeneous region.

Region C was rendered possibly heterogeneous due to the basin YM3, which had highest L-CV in the group with a D_i of 2.22. This basin might have been better in region D since the others in region D also have high L-CV. With this basin excluded from the group, the H statistic was computed at 0.52 indicating the homogeneity of the region at an acceptable level.

Region D was found homogeneous with H-value of 0.59. This region has also undergone a change in the state of homogeneity over the years; the 1989 H-value of –0.45

has changed to 0.59. These changes in the states of homogeneity are not particularly surprising because the statistics are better stabilized as more data become available.

4.8.1.3 WSC sub regions

The same stations YM3 and ZM9 made the WSC sub regions Y and Z possibly heterogeneous with the H-values of 1.80 and 1.85 respectively. However. without including these basins in their respective groups. the sub regions were acceptably homogeneous with the heterogeneity measures computed at 0.91 and 0.74 for Y and Z respectively.

4.8.2 Choice of regional distribution

4.8.2.1 1989 regions

Following the same rigorous procedure applied to the data available for the 1989 study. the goodness-of-fits of the candidate distributions were examined. The results were similar to those obtained with the 1989 data and therefore are not reported here. LN3 and GEV continued to be the competing distributions for the four regions of the 1989 study. The robustness evaluation under the Scenario 1 (Section 4.4.3) was not particularly useful in ranking the two competing distributions. Interestingly. unlike the previous results. which indicated practically similar degree of robustness of GEV and LN3 distributions under the Scenario 2 (Table 4.13b), the longer data are found to have more power in discriminating between the two candidates- LN3 was consistently. though marginally.

more robust than the GEV. Table 4.20 provides the simulation results under the Scenario 2 for the 1989 regions.

Table 4.20 Robustness evaluation for regional distributions for 1989 regions under Scenario 2 (data until 1998)

	Quantiles	0.9	0.99	0.999	0.9	0.99	0.999	Difference for 100-year event
Region A		**GEV-GEV**			**GEV-GLO**			
	ARB	-0.32	-0.53	0.20	-11.54	-24.45	-37.63	23.92
	AARB	5.56	15.26	24.60	12.61	24.80	37.63	9.54
	RMSE	0.83	2.56	5.83	1.30	4.63	9.70	2.08
		LN3-LN3			LN3-GLO			
	ARB	0.62	1.00	1.94	-10.11	-22.11	-34.30	23.10
	AARB	5.69	14.58	21.55	11.44	23.28	34.41	8.70
	RMSE	0.80	2.21	4.24	1.08	3.94	8.32	1.73
Region B		**GEV-GEV**			**GEV-GLO**			
	ARB	1.71	1.88	4.02	-10.20	-22.99	-35.52	24.86
	AARB	4.26	19.16	35.70	10.20	23.49	37.16	4.34
	RMSE	0.67	3.39	10.67	0.98	4.64	10.70	1.25
		LN3-LN3			LN3-GLO			
	ARB	1.00	0.63	2.07	-9.67	-22.57	-35.02	23.21
	AARB	4.74	17.41	28.86	9.67	23.21	36.88	5.80
	RMSE	0.61	2.60	6.52	0.93	4.36	10.06	1.76
Region C		**GEV-GEV**			**GEV-GLO**			
	ARB	-0.76	-1.02	-0.50	-10.23	-22.43	-35.60	21.41
	AARB	4.56	10.86	16.43	10.23	22.43	35.60	11.57
	RMSE	0.49	1.43	3.27	0.90	3.52	8.04	2.09
		LN3-LN3			**LN3-GLO**			
	ARB	-0.32	-0.35	0.07	-9.05	-20.66	-33.15	20.31
	AARB	4.84	10.51	14.82	9.05	20.66	33.15	10.15
	RMSE	0.47	1.17	2.19	0.76	3.00	6.94	1.84

Table 4.20Contd..

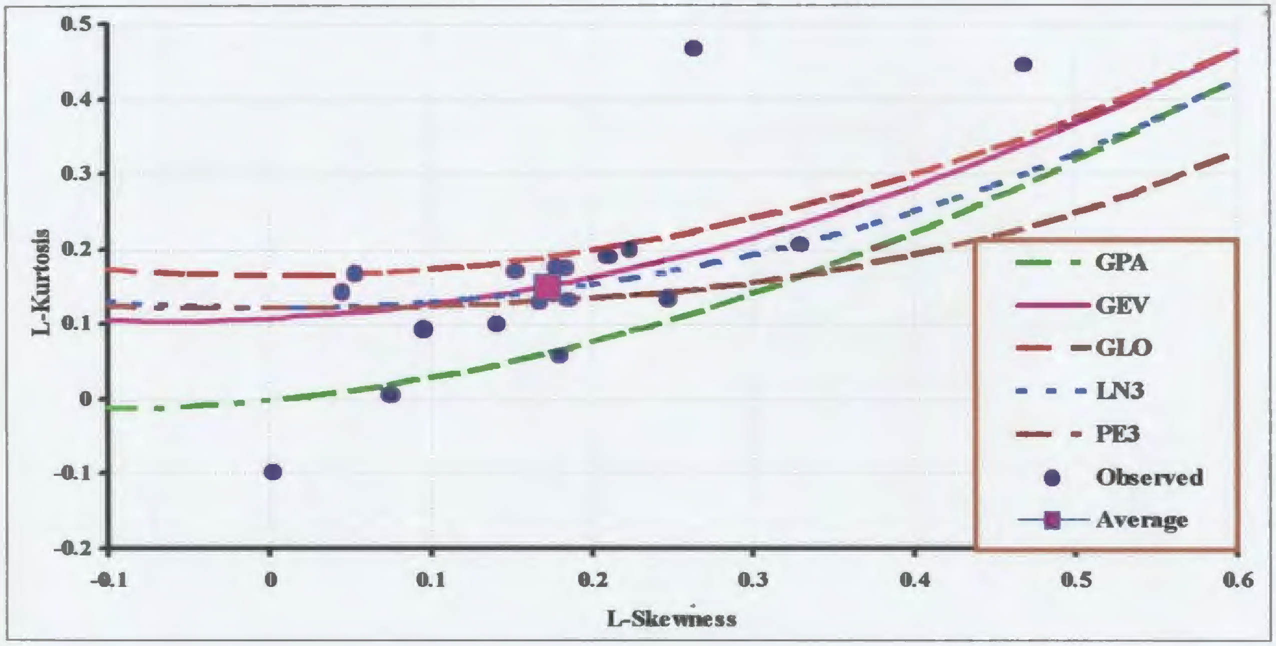
	Quantiles	0.9	0.99	0.999	0.9	0.99	0.999	Difference for 100-year event
Region D		GEV-GEV			GEV-GLO			
	ARB	1.55	3.11	6.38	-14.04	-26.68	-38.62	29.80
	AARB	4.12	14.36	24.74	14.04	26.68	38.90	12.32
	RMSE	1.08	3.29	8.26	1.55	5.07	10.78	1.78
		LN3-LN3			LN3-GLO			
	ARB	0.64	1.27	2.77	-11.71	-23.05	-33.88	24.32
	AARB	4.73	12.88	19.58	11.71	23.05	36.74	10.17
	RMSE	0.91	2.25	4.41	1.19	3.93	8.73	1.68

ARB: Average relative bias
AARB: Average absolute relative bias
RMSE: Relative root mean square error

4.8.2.2 WSC sub regions

The preliminary tests based on L-moment diagrams showed that the LN3 and GEV are the strong candidate distributions for the two sub regions Y and Z (Figures 4.5a-b). The L-kurtosis-based goodness-of-fit test was also employed in order to rank the candidate distributions. The results are provided in Table 4.21.

The results indicate that the GEV and LN3 continue to be the competing distributions for the Y and Z sub regions because the Z^{DIST} values are well below the critical of 1.64. Therefore, it is customary to base the final choice on the robustness criteria using Monte Carlo simulation. The simulation was designed following the same procedure as explained in Section 4.4.3. As in the case of 1989 regions, the results under the Scenario 1 were not particularly useful. The results under the Scenario 2 (Table 4.22), however, confirmed that the LN3 was more robust than the GEV for the WSC regions as well. It may be recalled that for the WSC sub regions, the data available for the 1989 study also established the LN3 to be more robust than its closest rival- the GEV distribution.



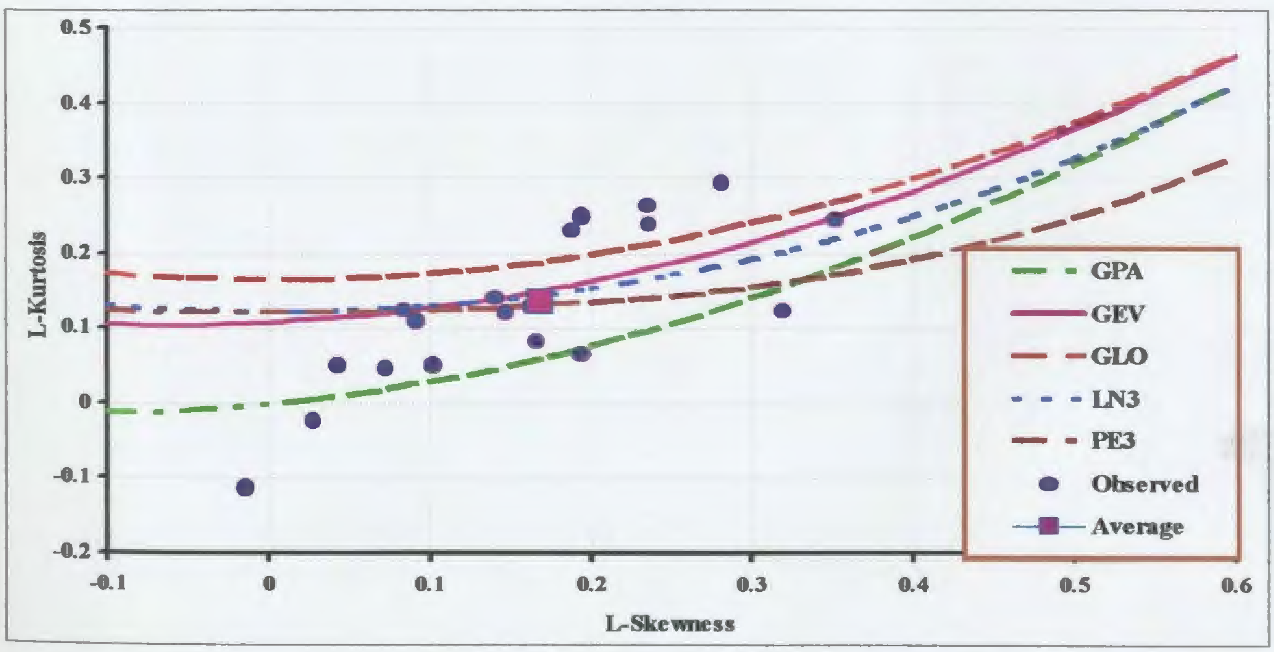


Figure 4.5a-b L-moment diagrams for WSC sub regions (top) Y and (bottom) Z (data until 1998)

Table 4.21 L-kurtosis based goodness-of-fit measures for WSC regions (data until 1998)

Distribution	Sub region Y $t_4^R = 0.1475$, $B_4 = -0.00051$, $\sigma_4 = 0.0196$		Rank	Sub region Z $t_4^R = 0.1403$, $B_4 = 0.00028$, $\sigma_4 = 0.0177$		Rank
	τ_4^{DIST}	$\lvert Z^{DIST}\rvert$		τ_4^{DIST}	$\lvert Z^{DIST}\rvert$	
GLO	0.1915	2.5086*	III	0.1906	2.2097*	III
GEV	0.1514	0.4647	II	0.1502	0.0723	I
LN3	0.1460	0.1902	I	0.1452	0.3549	II
GPA	0.0621	4.0904*	IV	0.0606	5.1357*	IV

*Fail the test as $\lvert Z^{DIST}\rvert > 1.64$

Table 4.22 Robustness evaluation for regional distributions for WSC sub regions under Scenario 2 (data available until 1998)

	Quantiles	0.9	0.99	0.999	0.9	0.99	0.999	Difference for 100-year event
Region WSC Y		GEV-GEV			GEV-GLO			
	ARB	0.09	-1.35	-1.53	-10.65	-24.20	-38.01	22.85
	AARB	4.47	15.30	25.71	10.65	24.20	38.01	8.89
	RMSE	0.54	2.10	5.56	1.03	4.24	9.58	2.14
		LN3-LN3			LN3-GLO			
	ARB	0.14	-1.11	-1.15	-9.60	-22.78	-35.98	21.67
	AARB	4.85	14.38	21.97	9.60	22.78	35.98	8.40
	RMSE	0.51	1.78	3.85	0.83	3.82	8.77	2.04
Region WSC Z		GEV-GEV			GEV-GLO			
	ARB	0.69	1.84	4.04	-11.35	-23.85	-36.73	25.69
	AARB	5.14	15.88	26.79	12.06	24.89	37.71	9.01
	RMSE	0.76	2.67	6.71	1.19	4.41	9.47	1.74
		LN3-LN3			LN3-GLO			
	ARB	0.84	1.80	3.44	-10.18	-22.14	-34.21	23.94
	AARB	5.47	14.80	22.57	11.27	23.95	35.84	9.15
	RMSE	0.75	2.28	4.70	1.06	3.99	8.58	1.71

ARB: Average relative bias
AARB: Average absolute relative bias
RMSE: Relative root mean square error

4.8.3 Comparison of the quantile estimates: 1989 regions vs WSC sub regions

In this Section. the regional quantile functions for the 1989 regions as well as the WSC sub regions based on the observed data are provided (Table 4.23). An evaluation of the regional estimation abilities of these regions is also presented. The evaluation involved comparing the observed percentage differences between the at-site and the regionally estimated quantiles based on the 1989 regions with those obtained based on the WSC sub regions. The comparison was carried out at two stages- first at the gauging stations used in the analysis and then at 13 independent test stations.

Table 4.23 Regional LN3 parameters and quantile functions for 1989 regions and WSC sub regions (data until 1998)

Sub regions	k	α	ξ	LN3 Growth curve $x(F) = \xi + \alpha/k\,[1-\exp\{-k\Phi^{-1}(F)\}]$	
				F = 0.98 (T = 50 yrs)	F = 0.99 (T = 100 yrs)
A	-0.3284	0.3752	0.9367	2.03	2.24
B	-0.3995	0.3120	0.9351	1.93	2.13
C	-0.3169	0.2916	0.9526	1.79	1.95
D	-0.3623	0.3894	0.9271	2.11	2.35
WSC Y	-0.3599	0.2933	0.9455	1.84	2.01
WSC Z	-0.3494	0.3738	0.9327	2.05	2.27

4.8.3.1 Gauged basins

Table 4.24 provides the 50 and 100-year at-site GEV frequency estimates obtained using Environment Canada's CFA 3.1 and their regionally estimated counterparts for the 1989 regions and the WSC sub regions. The reason for using GEV distribution for at-site estimation was that, as with the previous data set, the GEV gave adequate fit at all individual stations and best fit at majority of them. Also shown in the Table are the percentage differences between the two sets of estimates based on the 1989 division and the WSC sub division. It is observed that the average percentage differences for the 100-year flood estimates at the gauged basins are not significantly different in the two schemes. Again, the implication is that the use of WSC sub regions is enough for practical purposes for the regional estimation at the gauged basins in the Island.

Table 4.24 Comparison of at-site and regional frequency estimates for 1989 and WSC sub regions (data until 1998)

STNs	Mean	At-site		Regional (89)				Regional (WSC)			
		Q50	Q100	Q50	Q100	%dQ 50	%dQ 100	Q50	Q100	%dQ 50	%dQ 100
YC1	198.2	396.0	444.0	355.6	387.4	10.2	12.7	364.2	399.1	8.0	10.1
YD1	103.9	208.0	234.0	186.5	203.2	10.4	13.2	191.0	209.3	8.2	10.6
YD2	40.9	72.5	78.9	73.4	79.9	-1.2	-1.3	75.1	82.3	-3.6	-4.3
YF1	265.4	485.0	521.0	476.1	518.8	1.8	0.4	487.7	534.4	-0.5	-2.6
YJ1	332.4	663.0	736.0	702.7	780.7	-6.0	-6.1	610.6	669.1	7.9	9.1
YK2	126.5	205.0	223.0	197.5	215.2	3.7	3.5	232.4	254.7	-13.4	-14.2
YK4	93.7	152.0	160.0	168.1	183.2	-10.6	-14.5	172.2	188.7	-13.3	-17.9
YK5	76.3	131.0	141.0	136.9	149.2	-4.5	-5.8	140.3	153.7	-7.1	-9.0
YL1	598.9	954.0	1020.0	1074.3	1170.5	-12.6	-14.8	1100.3	1205.7	-15.3	-18.2
YM3	41.3	97.0	110.0	74.1	80.8	23.6	26.6	75.9	83.2	21.7	24.4
YN2	196.6	442.0	509.0	379.1	419.3	14.2	17.6	361.2	395.8	18.3	22.2
YO6	50.7	131.0	167.0	97.8	108.1	25.4	35.3	93.1	102.1	28.9	38.9
YP1	24.9	57.1	66.1	48.0	53.1	15.9	19.7	45.8	50.1	19.9	24.1
YQ1	603.2	992.0	1050.0	1163.2	1286.3	-17.3	-22.5	1108.3	1214.5	-11.7	-15.7
YR1	29.6	51.6	55.2	57.1	63.2	-10.7	-14.5	54.4	59.6	-5.5	-8.1
YR2	70.3	145.0	170.0	135.5	149.9	6.5	11.8	129.1	141.5	10.9	16.8
YR3	58.7	95.2	99.8	113.1	125.1	-18.8	-25.4	107.8	118.1	-13.2	-18.4
YS1	183.2	342.0	383.0	353.3	390.7	-3.3	-2.0	336.6	368.9	1.6	3.7

Table 4.24 Contd..

STN	Mean	At-site		Regional (89)				Regional (WSC)			
		Q50	Q100	Q50	Q100	%dQ 50	%dQ 100	Q50	Q100	%dQ 50	%dQ 100
YS3	13.8	26.4	29.3	26.6	29.4	-0.6	-0.3	25.3	27.7	4.1	5.3
ZA1	121.8	243.0	264.0	257.5	286.1	-6.0	-8.4	250.0	276.7	-2.9	-4.8
ZA2	61.3	165.0	199.0	129.7	144.1	21.4	27.6	125.9	139.3	23.7	30.0
ZA3	167.2	358.0	398.0	353.4	392.7	1.3	1.3	343.2	379.7	4.1	4.6
ZB1	388.5	896.0	1020.0	821.3	912.5	8.3	10.5	797.4	882.3	11.0	13.5
ZC2	394.5	735.0	793.0	834.1	926.8	-13.5	-16.9	809.9	896.1	-10.2	-13.0
ZE1	292.2	473.0	492.0	563.4	623.0	-19.1	-26.6	599.8	663.6	-26.8	-34.9
ZF1	216.4	479.0	557.0	417.3	461.4	12.9	17.2	444.2	491.5	7.3	11.8
ZG1	62.8	180.0	188.0	127.6	140.7	29.1	25.2	128.8	142.6	28.4	24.2
ZG2	50.6	113.0	130.0	102.9	113.5	8.9	12.7	103.9	115.0	8.0	11.5
ZG3	63.4	120.0	128.0	128.9	142.2	-7.4	-11.1	130.2	144.1	-8.5	-12.5
ZG4	40.4	94.5	107.0	82.1	90.5	13.1	15.4	82.9	91.7	12.3	14.3
ZH1	240.4	470.0	505.0	488.5	538.8	-3.9	-6.7	493.4	545.9	-5.0	-8.1
ZH2	31.9	63.3	68.5	64.8	71.5	-2.4	-4.4	65.5	72.5	-3.5	-5.8
ZJ1	23.1	47.3	52.9	44.5	49.2	6.0	7.0	47.3	52.4	-0.1	1.0
ZK1	154.8	315.0	350.0	314.7	347.1	0.1	0.8	317.9	351.7	-0.9	-0.5
ZK2	74.4	199.0	232.0	151.2	166.8	24.0	28.1	152.7	169.0	23.2	27.2
ZL3	9.1	20.0	22.2	18.5	20.4	7.4	8.0	18.7	20.7	6.5	6.8
ZM6	3.4	6.7	7.4	6.8	7.5	-1.6	-1.2	6.9	7.6	-2.6	-2.6
ZM9	27.5	43.7	47.3	56.0	61.7	-28.0	-30.5	56.5	62.5	-29.3	-32.2
ZN1	38.6	64.1	67.7	78.5	86.6	-22.5	-27.9	79.3	87.7	-23.7	-29.6
		Absolute Average				**11.1**	**13.7**			**11.6**	**14.4**

4.8.3.2 Ungauged basins

Furthermore, the regional estimation accuracy of the two regionalization schemes, 1989 regions and the WSC sub regions, were compared using a set of independent test stations. For the purpose of this comparison, thirteen gauged stations with an average record length of 12 years were available. These stations represented all of the four 1989 regions and were not used in developing the regional equations or homogeneity assessment. They represented independent test stations or ungauged locations for the purpose of testing the estimating ability of the regional quantile functions obtained from the present approach. The results are provided in Table 4.25.

Table 4.25 Comparison of at-site and regional frequency estimates for 1989 and WSC regions at test stations (data until 1998)

STN	Rec. length	Mean	At-site		Regional (1989)				Regional (WSC)			
			Q50	Q100	Q50	Q100	%dQ 50	%dQ 100	Q50	Q100	%dQ 50	%dQ 100
YA1	25	33.2	67.4	76.7	59.5	64.8	11.8	15.5	60.9	66.7	9.6	13.0
YD2	17	40.3	73.1	80.2	72.3	78.8	1.0	1.7	74.1	81.2	-1.4	-1.2
YG1	10	302.7	543	586.0	543	591.6	0.0	-1.0	556.1	609.4	-2.4	-4.0
YH1	12	6.0	17.5	22.4	10.7	11.6	39.0	48.1	10.9	12.0	37.5	46.5
YJ3	11	30.0	46.4	47.9	63.5	70.6	-36.9	-47.3	55.2	60.5	-18.9	-26.3
YO8	7	240.4	454	495.0	463.6	512.7	-2.1	-3.6	441.7	484.0	2.7	2.2
YQ4	9	656.3	1190	1260.0	1265.5	1399.5	-6.3	-11.1	1205.8	1321.3	-1.3	-4.9
YQ5	6	36.3	63.1	66.3	70.0	77.4	-10.9	-16.7	66.7	73.1	-5.7	10.2
YS5	13	228.5	389	403.0	440.6	487.2	-13.3	-20.9	419.8	460.0	-7.9	-14.1
ZK4	15	100.3	226	264.0	203.8	224.7	9.8	14.9	205.8	227.7	8.9	13.8
ZM16	15	12.4	25.2	27.8	25.1	27.7	0.4	0.4	25.4	28.0	-0.6	-0.9
ZN2	8	9.6	23.1	25.7	19.5	21.5	15.7	16.4	19.7	21.8	14.9	15.3
ZL4	13	16.6	37.9	43.1	33.7	37.2	11.0	13.7	34.1	37.7	10.1	12.5
						Absolute average	**12.2**	**16.3**			**9.4**	**12.7**

It can be observed that the absolute average percentage differences between the at-site frequency estimates and their regional counterparts in case of the WSC sub regions are less than the respective differences obtained in case of the 1989 regions. This observation in conjunction with the results obtained with the data until 1988 supports the preference of the WSC sub regions over the 1989 regions for the regional flood frequency analysis for the Island of Newfoundland.

4.8.4 Evaluation of RFFA methods

Like the 1989 study, the most recent RFFA by the provincial government of Newfoundland and Labrador (Govt. of Newfoundland and Labrador 1999) also adopted the regression-on-quantile approach with slightly modified boundaries of 1989 regions using the data available until 1996. In this Section, the results of comparison between the quantile estimates of the 1999 study and the present study at a set of common stations across the Island are presented. In order to facilitate a fair comparison, the same length of data as used in the 1999 study at the 39 stations were considered. The WSC sub regions were employed for the regional estimation. The regional growth factors for 50 and 100-year flood magnitudes were then estimated for each sub region and are presented in Table 4.26.

Table 4.26 Regional LN3 parameters and quantile functions for WSC sub regions (data until 1996)

Sub regions	k	α	ξ	LN3 Growth curve $x(F) = \xi + \alpha/k\,[1-\exp\{-k\Phi^{-1}(F)\}]$	
				F = 0.98 (T = 50 yrs)	F = 0.99 (T = 100 yrs)
WSC Y	-0.3655	0.2977	0.9437	1.85	2.04
WSC Z	-0.3828	0.3569	0.9291	2.04	2.27

The test basins were divided into two groups. The first group included the 39 basins used in the present analysis and the second group had the newly available basins used as the test or ungauged basins previously given in Table 4.25. However, for the 1999 study. both of these groups represented the gauged sites as the data available at these basins until 1996 were used to formulate the regression equations. The results are provided in Table 4.27 and 4.28. The at-site frequency estimates presented in Column 4 and the percentage differences between the at-site frequency estimates and their regression-based regional counterparts at the respective stations presented in the last Column were taken from the RFFA report of the Govt. of Newfoundland and Labrador (1999).

In both the gauged and test basins. the differences between the at-site and regional estimates from the L-moment based index-flood methods are considerably less than those between the same estimates obtained by the regression-on-quantiles approach.

Table 4.27 Comparison of at-site and regional frequency estimates at gauged stations (data until 1996)

STN	Rec. Length	Index flood (Mean)	At-site		L-moments based index-flood (current)				Regression on quantiles (1999)	
					Regional		%dQ50	%dQ100	%dQ50	%dQ 100
			Q50	Q100	Q50	Q100				
YC1	38	200.5	395	439	370.9	409.0	-6.50	-7.33	-8.4	-8.6
YD1	19	103.9	204	228	192.3	212.1	-6.08	-7.50	4.8	4.3
YD2	17	40.6	76.6	85.4	75.2	82.9	-1.86	-3.02	-13.9	-16.1
YF1	14	280.2	552	627	518.4	571.6	-6.48	-9.69	10.4	9.1
YJ1	28	336.9	634	698	623.3	687.3	-1.72	-1.56	-7.9	-10.2
YK2	23	127.2	238	267	235.3	259.5	-1.15	-2.89	-8.6	-10.3
YK4	21	92.9	136	145	171.8	189.4	20.84	23.44	16.2	21.1
YK5	24	76.1	133	145	140.7	155.1	5.47	6.51	-4.4	-4.4
YL1	47	601.6	948	1010	1112.9	1227.2	14.82	17.70	153.6	170.1
YM3	17	42.3	90.8	100	78.3	86.3	-15.96	-15.87	-27	-27.5

Table 4.27 Contd..

STN	Rec. Length	Index flood (Mean)	At-site		L-moments based index-flood (current)				Regression on quantiles (1999)	
					Regional		%dQ50	%dQ100	%dQ50	%dQ100
			Q50	Q100	Q50	Q100				
YN2	16	195.7	NA	NA	362.0	399.2	NA	NA	NA	NA
YO6	16	51.4	76.1	82.3	95.0	104.8	19.89	21.47	41.9	42.7
YP1	15	24.4	30.1	30.8	45.1	49.7	33.26	38.03	15.5	22.9
YQ1	15	600.4	1020	1100	1110.7	1224.7	8.17	10.18	-37.4	-37.7
YR1	38	29.6	47.5	50.8	54.8	60.4	13.32	15.89	-3	-2.7
YR2	20	70.8	151	180	130.9	144.4	-15.36	-24.65	20.6	10.2
YR3	16	58.2	84.1	86	107.6	118.6	21.84	27.49	47.8	55.8
YS1	31	183.2	292	323	339.0	373.8	13.86	13.59	13.1	10.6
YS3	29	14.0	26.8	29.9	25.9	28.5	-3.47	-4.91	20.8	18.7
ZA1	18	121.8	234	254	248.5	276.5	5.84	8.14	13.3	12
ZA2	15	63.4	NA	NA	129.4	144.0	NA	NA	NA	NA
ZA3	15	161.2	344	384	328.9	366.0	-4.59	-4.92	-31.7	-31.9
ZB1	35	384.4	947	1090	784.1	872.5	-20.78	-24.93	-45	-46.2
ZC2	15	383.8	790	886	783.0	871.2	-0.89	-1.70	89.9	97
ZE1	16	292.2	443	464	596.1	663.3	25.68	30.05	-31.8	-26.6
ZF1	45	215.0	497	564	438.7	488.1	-13.29	-15.55	-7.3	-15.4
ZG1	38	60.0	116	129	122.3	136.1	5.15	5.22	19.9	19.2
ZG2	20	50.6	107	120	103.3	114.9	-3.58	-4.44	-6.3	-7.4
ZG3	17	61.7	138	157	125.9	140.1	-9.61	-12.06	-13.2	-15.9
ZG4	17	37.1	77.4	85.5	75.7	84.2	-2.25	-1.54	-35.5	-35.6
ZH1	44	240.1	452	483	489.8	545.0	7.72	11.38	13.9	16.8
ZH2	26	32.5	64.3	69.4	66.2	73.7	2.87	5.83	5.4	7.4
ZJ1	20	23.5	47.1	52.7	47.9	53.3	1.67	1.13	-13.4	-15.6
ZK1	47	157.9	329	370	322.2	358.5	-2.11	-3.21	-5.8	-7.9
ZK2	18	79.8	195	225	162.8	181.2	-19.78	-24.17	-1	-3.2
ZL3	18	9.1	19.6	21.7	18.6	20.7	-5.38	-4.83	-17.7	-17
ZM6	27	3.4	7.25	8.14	6.9	7.6	-5.07	-7.11	11.8	9.8
ZM9	18	27.3	32.6	33.1	55.6	61.9	41.37	46.53	66.7	81.4
ZN1	30	38.6	63	66.8	78.8	87.7	20.05	23.83	-8.5	-4.7
						Absolute average	**10.73**	**12.85**	**24.1**	**25.8**

NA: At-site frequency estimates not available in 1999 study

Table 4.28 Comparison of at-site and regional frequency estimates at test stations (data until 1996)

STN	Rec. Length	Index flood (Mean)	At-site		L-moments based index-flood (current)				Regression on quantiles (1999)	
					Regional		%dQ50	%dQ100	%dQ50	%dQ100
			Q50	Q100	Q50	Q100				
YA1	25	33.15	69.1	79.2	61.3	67.3	-12.72	-17.68	9	2.9
YD2	16	40.0	76.6	85.4	74.0	81.2	-3.51	-5.17	-13.9	-16.1
YG1	9	311.7	493	520	576.6	632.8	14.50	17.83	97	111.8
YH1	11	5.7	7.89	8.43	10.5	11.6	24.86	27.33	9.5	9.4
YJ3	11	30.0	41.7	42.5	55.5	60.9	24.86	30.21	85.3	95.9
YO8	6	238.7	466	522	441.6	484.6	-5.53	-7.72	-24	-26.1
YQ4	8	634.4	1240	1330	1173.6	1287.8	-5.66	-3.28	-40.2	-39.5
YQ5	5	36.1	64.4	66	66.8	73.3	3.59	9.96	-7.7	-1.5
YS5	12	223.33	359	368	413.2	453.4	13.12	18.84	39.9	47.6
ZK4	14	103.15	249	294	210.4	233.1	-18.35	-26.13	-24.2	-28.1
ZM16	14	12.8	24.4	26.4	26.1	28.9	6.51	8.65	4.8	6.8
ZN2	7	9.8	21.4	24.4	20.0	22.1	-7.00	-10.41	-5.7	-9.7
ZL4	12	17.5	35.3	38.8	35.7	39.6	1.12	2.02	24.7	24.9
						Absolute average	**10.87**	**14.25**	**29.68**	**32.33**

4.8.5 Assessment of the accuracy of regional growth curves

From the results presented in the preceding Sections, it can be concluded that the preferred regionalization scheme for the Island of Newfoundland is the L-moment based index-flood method. The suggested scheme, therefore, consists of the WSC sub regions Y and Z with the three-parameter log-normal (LN3) as the regional distribution for both the regions. This sub Section provides a statistical assessment of the accuracy of the regional growth curves estimated for the sub regions. Monte Carlo simulation (Hosking and Wallis, 1997) was employed for this purpose. The program used for testing the robustness (Section 4.4.3) was used with some modification (Appendix A-6). The simulated regions matched the real world regions Y and Z in that they had same number of sites and record lengths as their real world counterparts. Inter-site dependence was neglected as the peak flow data were not significantly correlated across the region (results are not reported here). Data at each site were generated using LN3 distribution with the parameters estimated from the at-site sample data. The regional average L-moments of the simulated region were then used to estimate the LN3 growth curve for a range of non-exceedence probabilities (F). The growth curves were accumulated over the large number of simulations (N_{sim} = 1000).

The 90% confidence intervals based on simulation for 2, 10, 20, 50, 100 and 200-year return period flows for WSC Y and Z sub regions are provided in Table 4.29a and 4.29b respectively. Likewise, the observed growth curves together with the 90% confidence bands for the range of return periods from 2 to 1000 years for WSC Y and Z sub regions are shown in Figure 4.6.

Table 4.29a. Return period growth factors with 90% confidence intervals for WSC Y sub region (data until 1998)

Return Period (Yrs)	Annual Exceedence Probability (AEP)	Reduced Gumbel Variate	Observed Growth Factor	Lower 90% Confidence Level	Upper 90% Confidence Level
2	0.5	0.37	0.94	0.92	0.97
10	0.1	2.25	1.42	1.38	1.50
20	0.05	2.97	1.60	1.54	1.70
50	0.02	3.90	1.84	1.74	1.98
100	0.01	4.60	2.01	1.89	2.20
200	0.005	5.30	2.19	2.04	2.43

Table 4.29b. Return period growth factors with 90% confidence intervals for WSC Z sub region (data until 1998)

Return Period (Yrs)	Annual Exceedence Probability (AEP)	Reduced Gumbel Variate	Observed Growth Factor	Lower 90% Confidence Level	Upper 90% Confidence Level
2	0.5	0.37	0.93	0.90	0.97
10	0.1	2.25	1.54	1.47	1.60
20	0.05	2.97	1.76	1.67	1.85
50	0.02	3.90	2.05	1.91	2.18
100	0.01	4.60	2.27	2.09	2.43
200	0.005	5.30	2.49	2.26	2.70

It can be observed that the 90% confidence intervals for both the sub regions are not particularly wide even for high return periods thereby indicating an acceptable accuracy of the estimated growth curves. It is interesting to note that the LN3 growth curves are almost straight lines indicating that the underlying distribution is very close to GEV.

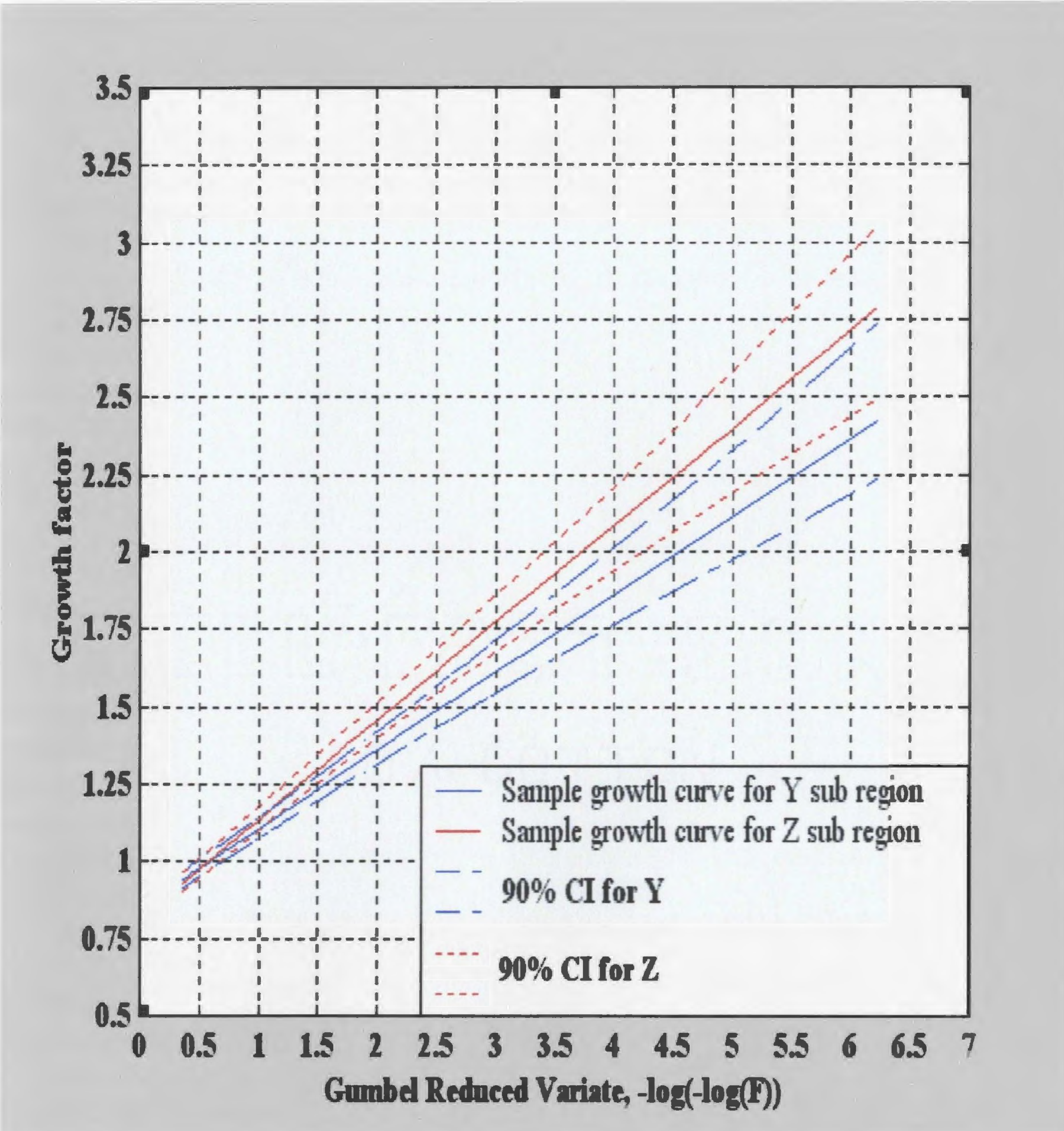


Figure 4. 6 Regional LN3 growth curve for WSC sub regions Y (top) and Z (bottom) with 90% confidence interval (data until 1998)

4.9 Estimation of the index flood

In order to estimate the return period flow at a gauged or ungauged location using index-flood based RFFA procedure. the index-flood at the location of interest is required. Without loss of generality. this analysis used mean annual instantaneous flood at the basin outlet as the index flood. In this Section, a systematic development of non-linear regression equations relating the index flood with the influential physiographic characteristics of the basins is presented.

4.9.1 Abstraction of physiographic data

The latest available extreme flow data at 19 gauging stations in the sub region Y and 20 gauging stations in the sub region Y were used for estimating the mean flood. The significant physiographic variables related to the mean flood at these basins were extracted from the RFFA report of the 1989 study (Govt. of Newfoundland and Labrador. 1990). The physiographic parameters used in this analysis include the drainage area (DA). lakes and swamps factor (LSF) and the drainage density (DRD) and were chosen based on the significance of each parameter in the regional regression equations of the 1989 RFFA study. The details on these variables can be found in the RFFA report of the 1989 study (Govt. of Newfoundland and Labrador, 1990). The mean annual instantaneous flow at the gauging stations and the corresponding physiographic variables are presented in Tables 4.30.

4.9.2 Nonlinear regression analysis

Nonlinear regression of the mean annual instantaneous flows ($\bar{Q}$) on the basin characteristics was carried out using SYSTAT (SPSS Inc., 1998). The regression was carried out on the regional basis based on least square estimation using Gauss-Newton method. The regression outputs showing the coefficients with 95% confidence intervals and the corresponding p-values for sub regions Y and Z are presented in Figure 4.7

The regression equations are of the form:

$$\bar{Q} = DA^{a1}\, LSF^{a2}\, DRD^{a3} + \text{error} \qquad [4.9]$$

For the sub region Y, only the drainage area (DA) and the drainage density (DRD) are significant with the model R^2 of 87%, whereas for the sub region Z, the DA, lakes and swamps factor (LSF) and the DRD are significant with the model R^2 of 96%.

The regression diagnostics for the homoscedasticity and normality of the residuals for the sub regions Y and Z are presented in Figures 4.8a and 4.8b respectively. It is seen that the errors are independent and normally distributed thereby showing the acceptable quality of the regression coefficients.

Table 4.30 Mean annual instantaneous flows and the significant physiographic variables considered in regression analysis (data until 1998).

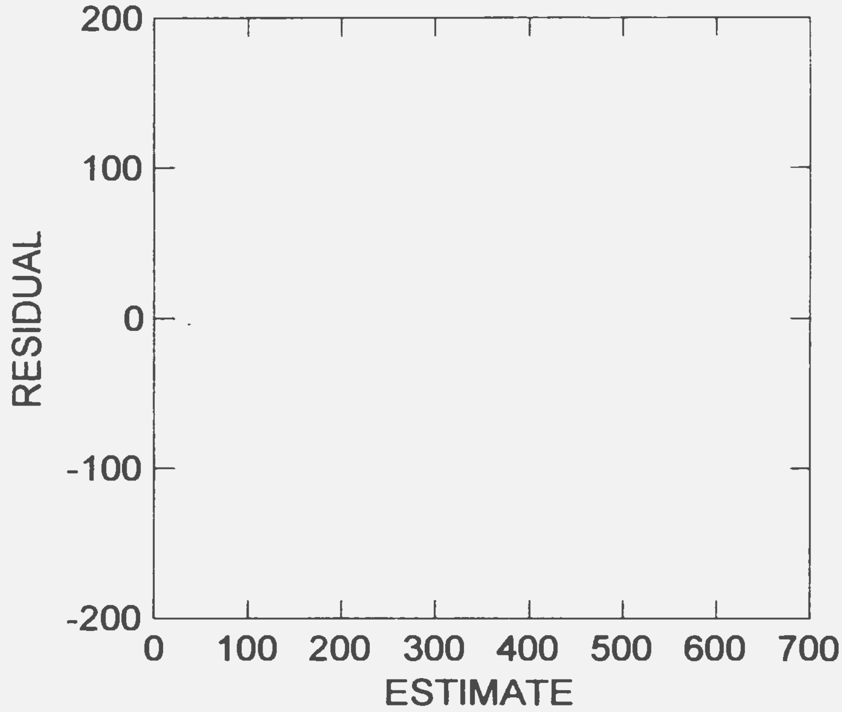
Basins	Mean Q (m^3/sec)	DA (km^2)	LSF	DRD (km^{-1})
YC1	193.57	624.00	1.91	0.78
YD1	103.95	237.00	1.68	0.34
YD2	40.35	200.00	1.91	0.93
YF1	280.21	611.00	1.94	0.58
YJ1	326.39	640.00	1.67	1.12
YK2	108.37	470.00	1.92	0.63
YK4	94.13	529.00	1.77	0.64
YK5	76.35	391.00	1.85	0.19
YL1	597.80	2110.00	1.68	0.79
YM3	43.41	93.20	1.49	0.68
YN2	196.62	469.00	1.91	1.37
YO6	50.70	177.00	1.89	0.80
YP1	25.68	63.80	1.72	0.88
YQ1	603.24	4400.00	1.82	0.45
YR1	29.37	275.00	1.86	0.26
YR2	67.38	399.00	1.79	0.74
YR3	60.17	554.00	1.80	0.68
YS1	182.70	1290.00	1.76	0.73
YS3	13.64	36.70	1.92	0.64
ZA1	124.0	343.0	1.781	1.04
ZA2	70.7	72.0	1.395	1.15
ZA3	156.7	139.0	1.46	1.46
ZB1	388.5	205.0	0.72	0.72
ZC2	403.6	230.0	0.96	0.96
ZE1	292.2	2640.0	1.92	0.36
ZF1	217.2	1170.0	1.838	0.61
ZG1	63.1	205.0	1.909	0.55
ZG2	50.0	166.0	1.852	1.35
ZG3	64.6	115.0	1.852	1.55
ZG4	42.4	42.7	1.837	1.62
ZH1	234.5	764.0	1.564	0.71
ZH2	31.5	43.3	1.868	1.11
ZJ1	34.8	67.4	1.774	1.24
ZK1	152.2	301.0	1.472	1.01
ZK2	74.4	89.6	1.639	1.11
ZL3	9.1	10.8	1.955	1.01
ZM6	3.4	3.6	1.895	1.01
ZM9	27.5	53.6	1.93	1.13
ZN1	38.8	53.3	1.935	1.09

```
Dependent variable is QBAR


     Source    Sum-of-Squares    df  Mean-Square
 Regression      9.97766E+05      2  4.98883E+05
   Residual      71255.52089     17   4191.50123

      Total      1.06902E+06     19
Mean corrected   5.65173E+05     18

        Raw  R-square (1-Residual/Total)          =      0.93335
Mean corrected R-square (1-Residual/Corrected)  =      0.87392
           R(observed vs predicted) square       =      0.87411

                                   Wald Confidence Interval
Parameter Estimate     A.S.E.   Param/ASE  Lower < 95%> Upper  p-value
 A1         0.84341    0.01500  56.20869   0.81175    0.87506   0.0000
 A3         0.83932    0.20965   4.00349   0.39700    1.28163   0.001
```

$\bar{Q} = DA^{0.84}\,DRD^{0.84}$	[For Y]
$\bar{Q} = DA^{1.06}\,LSF^{-2.35}\,DRD^{1.3}$	[For Z]

```
Dependent variable is QBAR

     Source    Sum-of-Squares    df  Mean-Square
 Regression      5.79001E+05      3  1.93000E+05
   Residual      13013.09570     17    765.47622

      Total      5.92014E+05     20
Mean corrected   2.84692E+05     19

        Raw  R-square (1-Residual/Total)          =      0.97802
Mean corrected R-square (1-Residual/Corrected)  =      0.95429
           R(observed vs predicted) square       =      0.95869

                                    Wald Confidence Interval
Parameter    Estimate  A.S.E. Param/ASE  Lower< 95%>Upper   p-value
 A1          1.06787  0.00931 114.69532  1.04823  1.08751   0.0000
 A2         -2.34470  0.09906 -23.66923 -2.55370 -2.13570   0.0000
 A3          1.29936  0.12407  10.47290  1.03760  1.56112   0.0000
```

Figure 4.7 Nonlinear regression output of the WSC Y (top) and Z (bottom) sub regions. Also shown in the middle are the regression relations for the sub regions.



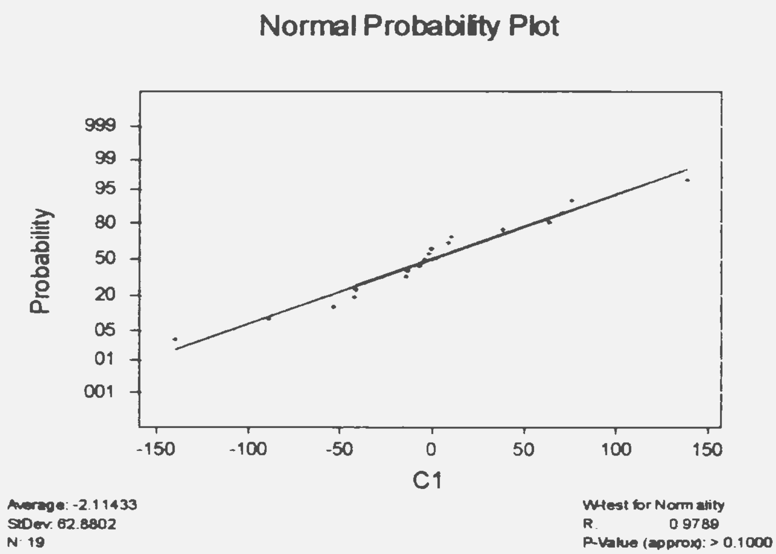
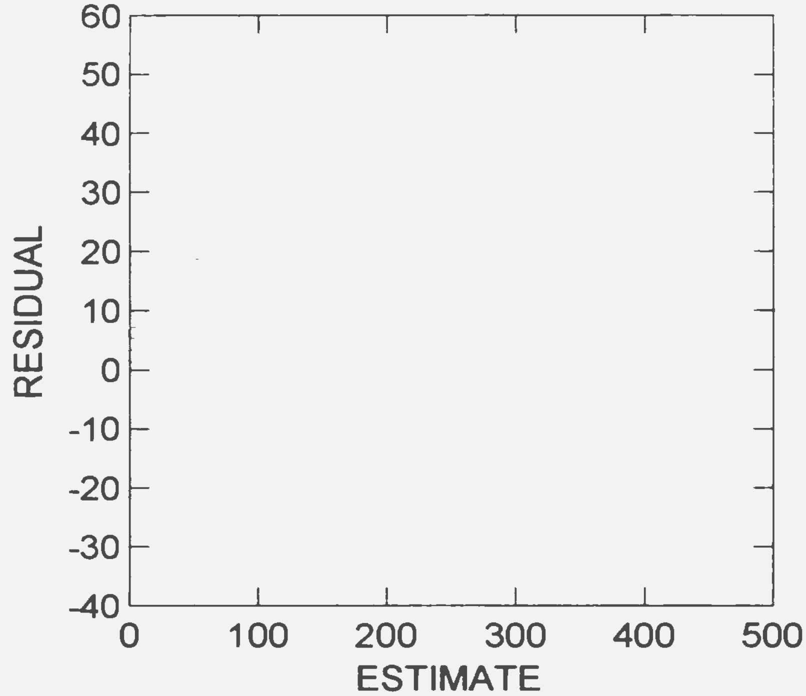


Figure 4.8a Residual plot (top) and normality plot (bottom) for the regression residuals in sub region Y



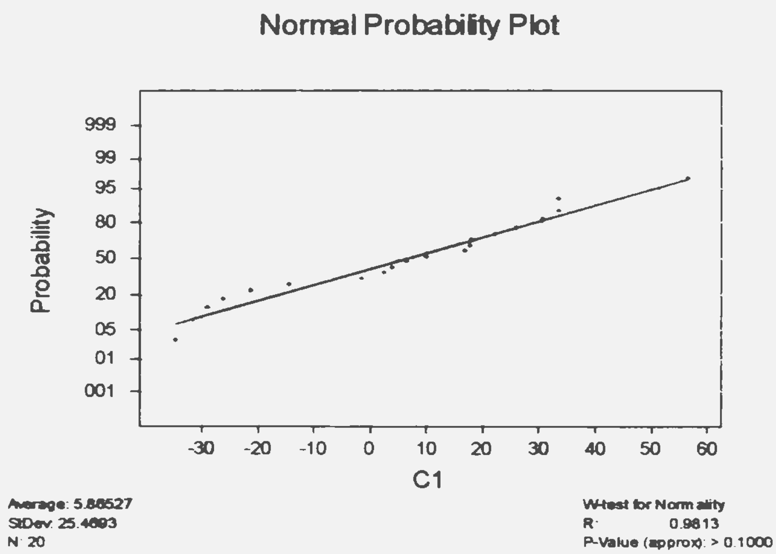


Figure 4.8b Residual plot (top) and normality plot (bottom) for the regression residuals in sub region Z

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 General

The objective of this Thesis was to revisit the 1989 regional flood frequency analysis (RFFA) carried out by the provincial government of Newfoundland and Labrador in 1989 using a latest available approach called index-flood method based on L-moments. Due to the better statistical properties of L-moments for the relatively small samples commonly encountered in hydrological studies, the use of L-moments in flood frequency analysis has gained popularity in recent years.

The 1989 study was particularly important for motivating this Thesis for two reasons. First, a general comparison of the RFFA approaches- regression on quantile method used by 1989 study and the more recent L-moments based index-flood method could be made by comparing the accuracy of the estimated quantiles by using the latest available data. Secondly, the delineation of homogeneous regions for regional flood frequency analysis has long remained a controversial topic due to the simplified assumptions of hydrological homogeneity of the regions, which usually represent complex physical phenomena. A truly homogeneous hydrologic region may not exist and the observed state of homogeneity of a region tends to change either as more data or newer methods become available. Therefore, it was of interest to compare the performance of the 1989 regions with other possible delineation schemes- for example, the WSC sub division using the longer data sets and the method of L-moments. However, other multivariate techniques might result in different regionalization schemes for the Island; these were out of the scope of this Thesis.

Using a rigorous procedure based on the L-moments, the hydrological homogeneity of the 1989 regions and that of the WSC sub regions was tested. The regional distributions for use in the quantile estimation with the index-flood method for the 1989 regions as well as the WSC sub regions were chosen based on a hierarchy of the conventional goodness-of-fit measures. The final choice of the regional distribution was made based on the extensive study of the robustness criteria by performing Monte Carlo simulations. Regional growth curves were estimated for use in the WSC Y and Z sub regions; the accuracy measures were also reported in order to assess the confidence associated with the regional estimation. A comparison was made between the accuracy of the quantile estimates obtained from the 1989 study and the current study- independently with regard to the regionalization schemes as well to the estimation techniques. The quantile estimates obtained based on the present approach were further compared with those obtained based on the recent RFFA for the Island of Newfoundland (Govt. of Newfoundland and Labrador, 1999) at common locations.

Finally, nonlinear regression equations were developed for the purpose of the estimation of the index flood at ungauged locations. In order to derive the relationships between the mean annual instantaneous flow and the basin characteristics, the physiographic variables identified by the 1989 RFFA of the provincial government of the Newfoundland and Labrador were used on the basis of their significance in the regression equations.

5.2 Conclusions

1. The method of L-moments allows one to objectively test the homogeneity of the regions. The discordancy measures based on the L-moment ratios of the observed sample data facilitate the homogeneity test by singling out the discordant sites in the region.

2. Excluding the discordant basins- basin ZM9 (Seal Cove) from region A and basin YO6 (Peter's River) from region B of the 1989 regions, the former was found to be homogeneous, whereas the latter was possibly redundant as indicated by the negative heterogeneity measure. Region D was also found to be possibly redundant.

3. The Water Survey of Canada sub regions Y and Z were found to be hydrologically homogeneous. The Peter's River record was affected by a high outlier recorded in 1983 and was discordant in the sub region Y. The Seal Cove in the sub region Z had the lowest L-CV and the difference between the at-site and regional quantile estimate was the highest at this basin. Indeed, the climatic conditions in this area are known to be different from the neighboring gauged basins. Due care is required while using the regional analysis in this area.

4. The state of hydrological homogeneity and the choice of regional distribution change as more data become available.

5. The conventional goodness-of-fit tests, including the Anderson-Darling test, indicated that the generalized extreme value (GEV) distribution was better than the log-normal (LN3) for the majority of the 1989 regions and the WSC regions although the discrimination between the two was not particularly apparent with the 1989 data. However, an extensive study of robustness criteria based on Monte Carlo simulation and the latest available data revealed that the LN3 is slightly more robust than the GEV distribution for the 1989 as well as the WSC sub regions.

6. The regional estimation using the index-flood method based on L-moments with the WSC sub regions was found to have equal or better accuracy of quantile estimates than the similar estimation with the 1989 regions. This finding further substantiated the possible redundancy of some of the 1989 regions.

7. The regional estimation using the index-flood method based on L-moments produced, in general, more accurate quantile estimates than the 1989 regression on quantile approach at the gauged sites on the Island. The accuracy was assessed by comparing the at-site and regional estimates based on the two schemes.

8. At the test basins, the present regional estimation scheme based on L-moments with the data available until 1996 produced significantly more accurate quantile estimates than the regression on quantiles approach used by the most recent RFFA study by the Government of Newfoundland and Labrador (1999).

9. The simulated 90% confidence bands obtained for the regional growth curves for the WSC sub regions Y and Z were not particularly too wide thereby indicating a

reasonable accuracy of the regional flood estimation by index-flood method based on L-moments on the Island of Newfoundland.

5.3 Recommendations

1. For the regional estimation of the T-year peak flows at the gauged or ungauged locations on the Island of Newfoundland, the following general model is recommended.

$$Q_T = \bar{Q}\, q_T \qquad [5.1]$$

where, $\bar{Q}$ is estimated by using equation [5.2] or [5.3], and q_T is obtained from Tables 5.1 or 5.2 for the sub regions Y or Z as appropriate.

Table 5.1 T-year growth factors for WSC sub region Y

SN	Return Period, Yrs (T)	Observed Growth Factor (q_T)	Lower 90% Confidence Level	Upper 90% Confidence Level
1	2	0.94	0.92	0.97
2	10	1.42	1.38	1.50
3	20	1.60	1.54	1.70
4	50	1.84	1.74	1.98
5	100	2.01	1.89	2.20
6	200	2.19	2.04	2.43

Table 5.2 T-year growth factors for WSC sub region Z

SN	Return Period. Yrs	Observed Growth Factor	Lower 90% Confidence Level	Upper 90% Confidence Level
1	2	0.93	0.90	0.97
2	10	1.54	1.47	1.60
3	20	1.76	1.67	1.85
4	50	2.05	1.91	2.18
5	100	2.27	2.09	2.43
6	200	2.49	2.26	2.70

2. For index flood ($\bar{Q}$) estimation at the ungauged (or gauged with too few records) locations in the WSC sub regions, the following models are recommended.

$$\bar{Q} = DA^{0.84}\, DRD^{0.84} \quad \text{[For Y]} \qquad [5.2]$$

$$\bar{Q} = DA^{1.06}\, LSF^{-2.35}\, DRD^{1.3} \quad \text{[For Z]} \qquad [5.3]$$

where DA, DRD and LSF represent the drainage area (km^2), drainage density (km^{-1}) and Lakes and Swamps Factor, respectively.

5.4 Limitations of the Thesis and insights for future research

This Thesis did not attempt to suggest the best regionalization scheme for the Island of Newfoundland. A comparison was made, using the L-moment based index-flood estimation technique, of the performance of the regions that were already delineated by previous studies based on physiographic characteristics of the Island. The limitation of this type of partitioning is that the regional estimation at the basins located across the regional boundaries becomes problematic- the regional boundaries themselves are crisp and there is always a strong judgment required as to which region the site of interest is to be assigned to.

The region delineation for regional flood frequency analysis is one of the most actively researched areas at present. More recently, methods based on multivariate techniques, such as canonical correlation technique and region of influence approach are being used in Canada and elsewhere in the world. These techniques avoid the use of geographical boundaries between the regions and hence allow for a smooth transition of the regional estimation from one basin to the other. The island is actually quite small and regardless of the increase in years of record, there is doubt that further regionalization would improve estimates any further. However, it would be of interest to examine the applicability of these innovative techniques for regional flood estimation on the Island of Newfoundland.

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APPENDICES

A-1

```
%File: Di_whole.m
%This macro computes the discordancy measures of the individual
%sites in the group
clear;
load data.mat -ascii; %File: data.mat contains the l-moment
%ratios (t, t3, t4) of the sites in the group
n=input('Enter the number of sites in the group: ');
ubar=[0;0;0];
for i=1:n,
   ubar=ubar+1/n*data(i,1:3)';
end
A=zeros(3);
for i=1:n,
   A=A+(data(i,1:3)'-ubar)*(data(i,1:3)'-ubar)';
end
for i=1:n,
   Di(i)=1/3*n*(data(i,1:3)'-ubar)'*inv(A)*(data(i,1:3)'-ubar);
end
disp('==========================');
disp('The Di Statistics follows');
disp('==========================');
Di'
```

```
% File: Hetero.m
clear;
load region.mat -ascii; % vector containing the no of records at
each %site in this region
V=input('Enter the weighted sd of sample LCVs for the region: ');
ns=input('Enter the no of sites in this region: ');
nrg=input('Enter the no of regions to be simulated: ');
eps=input('Enter the location parameter of kappa distribution:');
alpha=input('Enter the scale parameter of kappa distribution: ');
k=input('Enter the shape parameter of kappa distribution: ');
h=input('Enter the 4th parameter of kappa distribution: ');
disp ('Simulating.....please wait');
disp ('  ');

for k1=1:nrg,
for k2=1:ns,
   nrec=region(k2);
y=0;
for i=1:nrec,
y(i)=eps+alpha/k*(1-((1-(rand)^h)/h)^k);
end
x=sort(y);
x1=0;
for j=1:nrec,
   x1(j)=x(j)*(j-1);
end
x2=sum(x1)/(nrec*(nrec-1));
x3=2*x2-mean(x);
x4(k2)=x3/mean(x);
end
for k3=1:ns,
   x5(k3)=x4(k3)*region(k3);
end
x6=sum(x5)/sum(region);
for l=1:ns,
   x7(l)=region(l)*((x4(l)-x6)^2)/sum(region);
end
x8(k1)=sqrt(sum(x7));
end
H=(V-mean(x8))/std(x8);

disp ('Results');
disp ('================================');
disp ('  ');
```

```
if and(lt(H,1),ge(H,0))
    disp('The region is homogeneous');
    disp ('  ');
   elseif H < 0
      disp('The L-moments are correlated');
      disp ('  ');
   elseif and(ge(H,1),lt(H,2))
      disp('The region is possibly heterogeneous');
      disp ('  ');
   else
      disp('The region is definitely heterogeneous!');
      disp ('  ');
end
fprintf('The heterogeneity measure, H= %6.2f\n',H);
```

```
c============================================================ pelkap.for
c*  j. r. m. hosking august 1996
c  parameter estimation via l-moments for the kappa distribution
c  parameters of routine:
c  xmom *input* array of length 4, contains the l-moments lambda-
c 1, lambda-2, tau-3, tau-4.
c  para   *output* array of length 4. on exit, contains the
c parameters in the order xi, alpha, k, h.
c ifail  *output* fail flag. on exit, it is set as follows.
c                    0  successful exit
c                    1  l-moments invalid
c                    2  (tau-3, tau-4) lies above the generalized-
c logistic line (suggests that l-moments are not consistent
c with any kappa distribution with h.gt.-1)
c                    3  iteration failed to converge
c                    4  unable to make progress from current point
c in iteration
c                    5  iteration encountered numerical
c difficulties - overflow would have been likely to occur
c                    6  iteration for h and k converged, but
c overflow would have occurred when calculating xi and alpha
c n.b.  parameters are sometimes not uniquely defined by the
c first 4 l-moments. in such cases the routine returns the
c solution for which the h parameter is largest. other routines
c used: dlgama,digamd the shape parameters k and h are estimated
c using newton-raphson iteration on the relationship between
c (tau-3,tau-4) and (k,h).
c  the convergence criterion is that tau-3 and tau-4 calculated
c from the estimated values of k and h should differ by less than
c 'eps' from the values supplied in array xmom.

      implicit double precision (a-h,o-z)
      double precision xmom(4),para(4)
      data  zero/0d0/, half/0.5d0/,one/1d0/,two/2d0/,three/3d0/,
     four/4d0/
      data five/5d0/,six/6d0/,twelve/12d0/,twenty/20d0/,
     thirty/30d0/
      data p725/0.725d0/,p8/0.8d0/
c eps,maxit control the test for convergence of n-r iteration
c maxsr is the max. no. of steplength reductions per iteration
c   hstart is the starting value for h
c   big is used to initialize the criterion function
c   oflexp is such that dexp(oflexp) just does not cause overflow
c   oflgam is such that dexp(dlgama(oflgam)) just does not cause
c   overflow
```

```
      data eps/1d-/,maxit/20/,maxsr/10/,hstart/1.001d0/,big/10d0/
      data oflexp/170d0/,oflgam/53d0/
      read(*,*)xmom(1),xmom(2),xmom(3),xmom(4)
      t3=xmom(3)
      t4=xmom(4)
      do 10 i=1,4
   10 para(i)=zero
c         test for feasibility
      if(xmom(2).le.zero)ifail=1
      if(dabs(t3).ge.one.or.dabs(t4).ge.one)ifail=1
      if(t4.le.(five*t3*t3-one)/four)ifail=1
      if(t4.ge.(five*t3*t3+one)/six )ifail=2
c         set starting values for n-r iteration:
c         g is chosen to give the correct value of tau-3 on the
c         assumption that h=1 (i.e. a generalized pareto fit) -
c         but h is actually set to 1.001 to avoid numerical
c         difficulties which can sometimes arise when h=1 exactly
      g=(one-three*t3)/(one+t3)
      h=hstart
      z=g+h*p725
      xdist=big
c         start of newton-raphson iteration
      do 100 it=1,maxit
c      reduce steplength until we are nearer to the required
c      values of tau-3 and tau-4 than we were at the previous step
      do 40 i=1,maxsr
c         - calculate current tau-3 and tau-4
c           notation:
c           u. ratios of gamma functions which occur in the pwm's
c           beta-sub-r
c       alam. - l-moments (apart from a location and scale shift)
c       tau.  - l-moment ratios
c
      if(g.gt.oflgam)ifail=5
      if(h.gt.zero)goto 20
      u1=dexp(dlgama(   -one/h-g)-dlgama(   -one/h+one))
      u2=dexp(dlgama(   -two/h-g)-dlgama(   -two/h+one))
      u3=dexp(dlgama(-three/h-g)-dlgama(-three/h+one))
      u4=dexp(dlgama( -four/h-g)-dlgama( -four/h+one))
      goto 30
   20 u1=dexp(dlgama(   one/h)-dlgama(   one/h+one+g))
      u2=dexp(dlgama(   two/h)-dlgama(   two/h+one+g))
      u3=dexp(dlgama(three/h)-dlgama(three/h+one+g))
      u4=dexp(dlgama( four/h)-dlgama( four/h+one+g))
   30 continue
      alam2=u1-two*u2
      alam3=-u1+six*u2-six*u3
      alam4=u1-twelve*u2+thirty*u3-twenty*u4
      if(alam2.eq.zero)ifail=5
```

```
      tau3=alam3/alam2
      tau4=alam4/alam2
      e1=tau3-t3
      e2=tau4-t4
c
c         - if nearer than before, exit this loop
dist=dmax1(dabs(e1),dabs(e2))
      if(dist.lt.xdist)goto 50
c         - otherwise, halve the steplength and try again
del1=half*del1
      del2=half*del2
      g=xg-del1
      h=xh-del2
   40 continue
c         too many steplength reductions
ifail=4
c         test for convergence
50 continue
      if(dist.lt.eps)goto 110
c         not converged: calculate next step
c         notation:
c         u1g  - derivative of u1 w.r.t. g
c         dl2g - derivative of alam2 w.r.t. g
c  d..  - matrix of derivatives of tau-3 and tau-4 w.r.t. g and h
c         h..  - inverse of derivative matrix
c         del. - steplength
      xg=g
      xh=h
      xz=z
      xdist=dist
      rhh=one/(h*h)
      if(h.gt.zero)goto 60
      u1g=-u1*digamd(  -one/h-g)
      u2g=-u2*digamd(  -two/h-g)
      u3g=-u3*digamd(-three/h-g)
      u4g=-u4*digamd( -four/h-g)
      u1h=       rhh*(-u1g-u1*digamd(  -one/h+one))
      u2h=  two*rhh*(-u2g-u2*digamd(  -two/h+one))
      u3h=three*rhh*(-u3g-u3*digamd(-three/h+one))
      u4h= four*rhh*(-u4g-u4*digamd( -four/h+one))
      goto 70
   60 u1g=-u1*digamd(  one/h+one+g)
      u2g=-u2*digamd(  two/h+one+g)
      u3g=-u3*digamd(three/h+one+g)
      u4g=-u4*digamd( four/h+one+g)
      u1h=       rhh*(-u1g-u1*digamd(  one/h))
      u2h=  two*rhh*(-u2g-u2*digamd(  two/h))
      u3h=three*rhh*(-u3g-u3*digamd(three/h))
      u4h= four*rhh*(-u4g-u4*digamd( four/h))
```

```
   70 continue
      dl2g=u1g-two*u2g
      dl2h=u1h-two*u2h
      dl3g=-u1g+six*u2g-six*u3g
      dl3h=-u1h+six*u2h-six*u3h
      dl4g=u1g-twelve*u2g+thirty*u3g-twenty*u4g
      dl4h=u1h-twelve*u2h+thirty*u3h-twenty*u4h
      d11=(dl3g-tau3*dl2g)/alam2
      d12=(dl3h-tau3*dl2h)/alam2
      d21=(dl4g-tau4*dl2g)/alam2
      d22=(dl4h-tau4*dl2h)/alam2
      det=d11*d22-d12*d21
      h11= d22/det
      h12=-d12/det
      h21=-d21/det
      h22= d11/det
      del1=e1*h11+e2*h12
      del2=e1*h21+e2*h22
c     take next n-r step
      g=xg-del1
      h=xh-del2
      z=g+h*p725
c     reduce step if g and h are outside the parameter space
      factor=one
      if(g.le.-one)factor=p8*(xg+one)/del1
      if(h.le.-one)factor=dmin1(factor,p8*(xh+one)/del2)
      if(z.le.-one)factor=dmin1(factor,p8*(xz+one)/(xz-z))
      if(h.le.zero.and.g*h.le.-one)
     *  factor=dmin1(factor,p8*(xg*xh+one)/(xg*xh-g*h))
      if(factor.eq.one)goto 80
      del1=del1*factor
      del2=del2*factor
      g=xg-del1
      h=xh-del2
      z=g+h*p725
   80 continue
c end of newton-raphson iteration
  100 continue
c     not converged
      ifail=3
c     converged
  110 ifail=0
      para(4)=h
      para(3)=g
      temp=dlgama(one+g)
      if(temp.gt.oflexp)ifail=6
      gam=dexp(temp)
      temp=(one+g)*dlog(dabs(h))
      if(temp.gt.oflexp)ifail=6
```

```
      hh=dexp(temp)
      para(2)=xmom(2)*g*hh/(alam2*gam)
      para(1)=xmom(1)-para(2)/g*(one-gam*u1/hh)
      write(*,*)ifail,para(1),para(2),para(3),para(4)
end
c=================================================== digamd.for
      double precision function digamd(x)
c digamma function (euler's psi function) - the first derivative
c of log(gamma(x))based on algorithm as103, appl. statist. (1976)
c vol.25 no.3
      implicit double precision (a-h,o-z)
      data zero/0d0/,half/0.5d0/,one/1d0/
      data small/1d-9/,crit/13d0/
c   c1...c7 are the coeffts of the asymptotic expansion of digamd
c   d1 is  -(euler's constant)
data c1,c2,c3,c4,c5,c6,c7,d1/
     *  0.83333 33333 33333 333d-1,  -0.83333 33333 33333 333d-2,
     *  0.39682 53968 25396 825d-2,  -0.41666 66666 66666 666d-2,
     *  0.75757 57575 75757 575d-2,  -0.21092 79609 27960 928d-1,
     *  0.83333 33333 33333 333d-1,  -0.57721 56649 01532 861d 0/
      digamd=zero
      if(x.le.zero)goto 1000
c    use small-x approximation if x.le.small
     if(x.gt.small)goto 10
      digamd=d1-one/x
      return
c     reduce to digamd(x+n) where x+n.ge.crit
   10 y=x
   20 if(y.ge.crit)goto 30
      digamd=digamd-one/y
      y=y+one
      goto 20
c     use asymptotic expansion if y.ge.crit
30    digamd=digamd+dlog(y)-half/y
      y=one/(y*y)
      sum=((((((c7*y+c6)*y+c5)*y+c4)*y+c3)*y+c2)*y+c1)*y
      digamd=digamd-sum
      return
1000  write(6,7000)x
      return
7000  format(' *** error *** routine digamd :',
     *  ' argument out of range :',d24.16)
      end
c=================================================== dlgama.for
      double precision function dlgama(x)
c  logarithm of gamma function
c  based on algorithm acm291, commun. assoc. comput. mach. (1966)
      implicit double precision (a-h,o-z)
      data small,crit,big,toobig/1d-7,13d0,1d9,2d36/
```

```
c  c0 is 0.5*log(2*pi)
c  c1...c7 are the coeffts of the asymptotic expansion of dlgama
data c0,c1,c2,c3,c4,c5,c6,c7/
     *   0.91893 85332 04672 742d 0,  0.83333 33333 33333 333d-1,
     *  -0.27777 77777 77777 778d-2,  0.79365 07936 50793 651d-3,
     *  -0.59523 80952 38095 238d-3,  0.84175 08417 50841 751d-3,
     *  -0.19175 26917 52691 753d-2,  0.64102 56410 25641 026d-2/
c    s1 is -(euler's constant), s2 is pi**2/12
      data s1/-0.57721 56649 01532 861d 0/
      data s2/ 0.82246 70334 24113 218d 0/
      data zero/0d0/,half/0.5d0/,one/1d0/,two/2d0/
      dlgama=zero
      if(x.le.zero)goto 1000
      if(x.gt.toobig)goto 1000
c     use small-x approximation if x is near 0, 1 or 2
      if(dabs(x-two).gt.small)goto 10
      dlgama=dlog(x-one)
      xx=x-two
      goto 20
   10 if(dabs(x-one).gt.small)goto 30
      xx=x-one
   20 dlgama=dlgama+xx*(s1+xx*s2)
      return
   30 if(x.gt.small)goto 40
      dlgama=-dlog(x)+s1*x
      return
c     reduce to dlgama(x+n) where x+n.ge.crit
40    sum1=zero
      y=x
      if(y.ge.crit)goto 60
      z=one
   50 z=z*y
      y=y+one
      if(y.lt.crit)goto 50
      sum1=sum1-dlog(z)
c     use asymptotic expansion if y.ge.crit
   60 sum1=sum1+(y-half)*dlog(y)-y+c0
      sum2=zero
      if(y.ge.big)goto 70
      z=one/(y*y)
      sum2=((((((c7*z+c6)*z+c5)*z+c4)*z+c3)*z+c2)*z+c1)/y
   70 dlgama=sum1+sum2
      return
1000  write(6,7000)x
      return
7000  format(' *** error *** routine dlgama :',
     *  ' argument out of range :',d24.16)
      end
```

```
%file: gof.m; This program computes the bias and standard
%deviation of the sample regional L-kurtosis
clear;
load region.mat -ascii;
ns=input('Enter the no of sites in this region: ');
eps=input('Enter the location parameter of kappa distribution:');
alpha=input('Enter the scale parameter of kappa distribution: ');
k=input('Enter the shape parameter of kappa distribution: ');
h=input('Enter the 4th parameter of kappa distribution: ');
t4R=input('Enter the sample L-kurtosis for this region: ');
Nsim=input('Enter the number of regions to be simulated: ');

disp ('Simulating.....please wait');
disp ('  ');

for m=1:Nsim,
   for n=1:ns,
   nrec=region(n);
   y=0;
      for i=1:nrec,
      y(i)=eps+alpha/k*(1-((1-(rand)^h)/h)^k);
      end
   x=sort(y);
   b0=mean(x);
   x1=0;
   x2=0;
   x3=0;
      for j=1:nrec,
      x1(j)=x(j)*(j-1);
      x2(j)=x(j)*(j-1)*(j-2);
      x3(j)=x(j)*(j-1)*(j-2)*(j-3);
      end
   b1=sum(x1)/(nrec*(nrec-1));
   b2=sum(x2)/(nrec*(nrec-1)*(nrec-2));
   b3=sum(x3)/(nrec*(nrec-1)*(nrec-2)*(nrec-3));
   l1=b0;
   l2=2*b1-b0;
   l3=6*b2-6*b1+b0;
   l4=20*b3-30*b2+12*b1-b0;
   t(n)=l2/l1;
   t3(n)=l3/l2;
   t4(n)=l4/l2;
   end
   for i=1:n,
   t4r(i)=region(i)*t4(i)/sum(region);
```

```
    end
    T4(m)=sum(t4r);
end
%Calculate the bias of t4R
for m=1:Nsim,
    b4(m)=(T4(m)-t4R)/Nsim;
    b5(m)=(T4(m)-t4R)^2;
end
B4=sum(b4); %Bias of t4R
B5=sum(b5);
sigma4=sqrt((B5-Nsim*B4^2)/(Nsim-1));%Std. deviation of t4R
disp ('============================');
fprintf('The Bias of t4R, B4= %8.4f\n',B4);
fprintf('The Std. dev of t4R, Sigma4= %8.4f\n',sigma4);
```

```
%Test for Robustness of GEV distribution when the underlying
%distribution is LN3;

clear;
load regionX.mat -ascii;%contains the sites' record lengths in
%the region
sum_nrec=sum(region);
ns=input('Enter no. of sites in the region: ');
Nsim=input('Desired no. of simulated regions : ');
disp ('Region X');
%The parameters of the underlying distribution (LN3) follow;
%there are 6 sites in this region
kp=[-0.3678  -0.2099 -0.6692 -0.3021 -0.4022 -0.1876];
alphap=[0.3332  0.3800  0.4200  0.4034  0.4274  0.3333];
epsp=[0.9366 0.9597  0.8425  0.9377  0.9105  0.9684];
indxfld=[332.35 121.81  61.34 167.17  388.46  394.54];
F=[0.9;0.99;0.999];% The cumulative probabilities corresponding
to 10, 100 and 1000 yr- return periods

xF=zeros(ns,length(F));
%Estimate the true quantiles based on the underlying distribution
%at each site
for i=1:ns
   for j=1:length(F)
       xF(i,j)=epsp(i)+alphap(i)/kp(i)*(1-exp(-
kp(i)*norminv(F(j))));
       qT(i,j)=1*xF(i,j);
   end
end

%Beginning of the regional simulation based on the underlying
%distribution

xF_SIM=zeros(ns,length(F));
XF_SIM=zeros(ns,length(F));
bias=zeros(ns,length(F));
Bias=zeros(ns,length(F));
BIAS=zeros(ns,length(F));
BIAS_SIM=zeros(ns,length(F));
relSE=zeros(ns,length(F));
relMSE=zeros(ns,length(F));
RELRMSE=zeros(ns,length(F));
RELMSE=zeros(ns,length(F));
```

```
for m=1:Nsim,
   for i=1:ns,
       nrec=regionX(i);
      y=0;
         for i1=1:nrec
         y(i1)=epsp(i)+alphap(i)/kp(i)*(1-exp(-
kp(i)*norminv(rand)));
         end
      x=sort(y);
      b0=mean(x);
      indxfld(i)=b0;
      x1=0; x2=0;   x3=0; x4=0;
         for j=1:nrec,
            x1(j)=x(j)*(j-1);
            x2(j)=x(j)*(j-1)*(j-2);
            x3(j)=x(j)*(j-1)*(j-2)*(j-3);
            x4(j)=x(j)*(j-1)*(j-2)*(j-3)*(j-4);
         end
      b1=sum(x1)/(nrec*(nrec-1));
      b2=sum(x2)/(nrec*(nrec-1)*(nrec-2));
      b3=sum(x3)/(nrec*(nrec-1)*(nrec-2)*(nrec-3));
      b4=sum(x4)/(nrec*(nrec-1)*(nrec-2)*(nrec-3)*(nrec-4));
      l1(i)=b0;
      l2(i)=2*b1-b0;
      l3(i)=6*b2-6*b1+b0;
      l4(i)=20*b3-30*b2+12*b1-b0;
      l5(i)=70*b4-140*b3+90*b2-20*b1+b0;
      t(i)=l2(i)/l1(i);
      t3(i)=l3(i)/l2(i);
      t4(i)=l4(i)/l2(i);
   end

   for i=1:ns,
        l1r(i)=regionX(i)*l1(i)/sum_nrec;
        l2r(i)=regionX(i)*l2(i)/sum_nrec;
         l3r(i)=regionX(i)*l3(i)/sum_nrec;
        l4r(i)=regionX(i)*l4(i)/sum_nrec;
        tr(i)=regionX(i)*t(i)/sum_nrec;
        t3r(i)=regionX(i)*t3(i)/sum_nrec;
       t4r(i)=regionX(i)*t4(i)/sum_nrec;
   end

   %regional average L-moments of the simulated series
   L1=sum(l1r);
   L2=sum(l2r);
   L3=sum(l3r);
   L4=sum(l4r);
   L5=sum(l4r);
   T=sum(tr);
```

```
   T3=sum(t3r);
   T4=sum(t4r);

  %regional GEV parameters (distribution under test)
   C=2/(3+T3)-log(2)/log(3);
   K=7.8590*C+2.9554*C^2;
   ALPHA=L2*K/(1-2^-K)*gamma(1+K);
   EPS=L1-ALPHA*(1-gamma(1+K))/K;


   %Quantile estimation and computation of accuracy measures
   X_F=zeros(ns,length(F));Bias=zeros(ns,length(F));

   for i=1:ns
  XF=zeros(ns,length(F));bias=zeros(ns,length(F));relSE=zeros(ns
,length(F));
      for j=1:length(F)
            XF(i,j)=EPS+ALPHA/K*(1-(-log(F(j)))^K);
            QT=indxfld(i)*XF(i,j);
            bias(i,j)=(QT-qT(i,j))/qT(i,j)*100;
            relSE(i,j)=((QT-qT(i,j))/qT(i,j)).^2;
      end

       X_F=X_F+XF;
       Bias=Bias+bias;
       relMSE=relMSE+relSE;
   end

   XF_SIM=XF_SIM+1/Nsim*X_F;
   BIAS_SIM=BIAS_SIM+1/Nsim*Bias;
   RELMSE_SIM=RELMSE+1/Nsim*relMSE;
end
   disp ('==========================');

AV_BIAS=mean(BIAS_SIM);AAV_BIAS=mean(abs(BIAS_SIM));
AV_RELRMSE=(mean(RELMSE_SIM)).^1/2*100;
AV_XF=mean(XF_SIM);

disp('robustness of GEV when LN3 is the parent');
disp('non-exceedence prob, absolute bias and RMSE follow in the
columns in the order as shown:');
disp(' ');
disp('====================================');
[F';AV_BIAS;AAV_BIAS;AV_RELRMSE]
```

```
%Program for computing the superimposed LN3 growth curves for WSC
sub regions Y and Z

clear;
load WSCY.mat -ascii;
sum_nrec=sum(WSCY);
ns=19;%input('Enter no. of sites in the region: ');
Nsim=1000;%input('Desired no. of simulated regions : ');
disp ('Region WSC Y');

%LN3 parameters (sample, sub region Y)
kp=[-0.4339   -0.4645 -0.3142 -0.3719 -0.3678 -0.3161 -0.1542 -
0.0920  -0.3814 -0.5140 -1.0149 -0.5479 -0.1092 -0.1956 -0.6923
   -0.0049 -0.3460 -0.3973 -0.3789];
alphap=[0.3146   0.2998   0.2658   0.2431   0.3332   0.2344   0.2439
   0.2888   0.2303   0.3604   0.2664   0.3602   0.2719   0.2947
   0.2530   0.2752   0.2761   0.4382   0.3038];
epsp=[0.9284  0.9265   0.9572   0.9532   0.9366   0.9620   0.9811
   0.9867   0.9544   0.9010   0.8232   0.8935   0.9851   0.9709
   0.9010   0.9993   0.9508   0.9094   0.9403];

F=[0.5:.01:0.99 .991:.001:.998];
XF_sample=zeros(1,length(F));
k=-0.3599;alpha=0.2933;eps=0.9455; %WSC Y

for j=1:length(F)
     XF_sample(j)=eps+alpha/k*(1-exp(-k*norminv(F(j))));
end

u_L=zeros(length(F),1);%lower 95% conf.interval
u_U=zeros(length(F),1);
XF=zeros(Nsim,length(F));

% Beginning of the regional simulation

for m=1:Nsim,
   for i=1:ns,
       nrec=WSCY(i);

   y=0;
       for i1=1:nrec
        y(i1)=epsp(i)+alphap(i)/kp(i)*(1-exp(-
kp(i)*norminv(rand)));
       end
   x=sort(y);
```

```
   b0=mean(x);
   indxfld(i)=b0;
   x1=0;
   x2=0;
   x3=0;
   x4=0;
      for j=1:nrec,
      x1(j)=x(j)*(j-1);
      x2(j)=x(j)*(j-1)*(j-2);
       x3(j)=x(j)*(j-1)*(j-2)*(j-3);
       x4(j)=x(j)*(j-1)*(j-2)*(j-3)*(j-4);
      end
   b1=sum(x1)/(nrec*(nrec-1));
   b2=sum(x2)/(nrec*(nrec-1)*(nrec-2));
   b3=sum(x3)/(nrec*(nrec-1)*(nrec-2)*(nrec-3));
   b4=sum(x4)/(nrec*(nrec-1)*(nrec-2)*(nrec-3)*(nrec-4));
   l1(i)=b0;
   l2(i)=2*b1-b0;
   l3(i)=6*b2-6*b1+b0;
   l4(i)=20*b3-30*b2+12*b1-b0;
   l5(i)=70*b4-140*b3+90*b2-20*b1+b0;
   t(i)=l2(i)/l1(i);
   t3(i)=l3(i)/l2(i);
   t4(i)=l4(i)/l2(i);
   end

   for i=1:ns,
       l1r(i)=WSCY(i)*l1(i)/sum_nrec;
       l2r(i)=WSCY(i)*l2(i)/sum_nrec;
       l3r(i)=WSCY(i)*l3(i)/sum_nrec;
       l4r(i)=WSCY(i)*l4(i)/sum_nrec;
       tr(i)=WSCY(i)*t(i)/sum_nrec;
       t3r(i)=WSCY(i)*t3(i)/sum_nrec;
       t4r(i)=WSCY(i)*t4(i)/sum_nrec;
   end
%regional average L-moments of the simulated series
   L1=sum(l1r);
   L2=sum(l2r);
   L3=sum(l3r);
   L4=sum(l4r);
   L5=sum(l4r);
   T=sum(tr);
   T3=sum(t3r);
   T4=sum(t4r);

%regional LN3 parameters and growth curve (distribution under
test)
   e0=2.0466534;e1=-3.6544371;e2=1.8396733;e3=-.20360244;f1=-
2.0182173;
```

```
   f2=1.2420401;f3=-.21741801;
   K=-
T3*(e0+e1*T3^2+e2*T3^4+e3*T3^6)/(1+f1*T3^2+f2*T3^4+f3*T3^6);
   ALPHA=L2*K*exp(-K^2/2)/(1-2*normcdf(-K/sqrt(2)));
   EPS=L1-ALPHA/K*(1-exp(K^2/2));

%Quantile estimation
   for j=1:length(F)
      XF(m,j)=EPS+ALPHA/K*(1-exp(-K*norminv(F(j))));
   end

end
disp ('==========================');

%Plot of regional growth curve
for i=1:length(F)
   gum_var(i)=-log(-log(F(i))); %Gumbel reduced variate for
plotting growth curves
end

%95% Confidence interval computation and plotting of regional
growth curve

XF=sort(XF);
index_L=round(0.05*Nsim);
index_U=round(0.95*Nsim);

for j=1:length(F)
  u_L(j)=XF(index_L,j);
  u_U(j)=XF(index_U,j);
end
disp('Gumbel_Var Sample_growth curve for sub region Y:');
disp(' Growth Factor   Lower_5%  Upper_5%')
table=[gum_var(1) XF_sample(1) u_L(1) u_U(1);gum_var(41)
XF_sample(41) u_L(41) u_U(41);
   gum_var(46) XF_sample(46) u_L(46) u_U(46);gum_var(49)
XF_sample(49) u_L(49) u_U(49);
   gum_var(50) XF_sample(50) u_L(50) u_U(50);gum_var(55)
XF_sample(55) u_L(55) u_U(55)]

disp('===================================');

%===========================================================

load WSCZ.mat -ascii;
sum_nrec=sum(WSCZ);
ns=20;%input('Enter no. of sites in the region: ');

disp ('Region WSC Z');
```

```
%LN3 parameters (sample, sub region Z)
kp=[-0.2099  -0.6692 -0.3021 -0.4022 -0.1876 0.0284  -0.5864 -
0.7418  -0.4870 -0.0575 -0.3885 -0.1480 -0.1731 -0.4003 -0.3350
   -0.4895 -0.2888 -0.3425 -0.4093 -0.0880];
alphap=[0.3800  0.4200  0.4034  0.4274  0.3333  0.2784  0.3254
   0.3428  0.3664  0.3883  0.4394  0.4018  0.3985  0.3389
   0.3630  0.5008  0.4288  0.3440  0.1811  0.2850];
epsp=[0.9597  0.8425  0.9377  0.9105  0.9684  1.0040  0.8959
   0.8536  0.9053  0.9888  0.9114  0.9701  0.9652  0.9294
   0.9374  0.8698  0.9368  0.9393  0.9613  0.9874];

XF_sample1=zeros(1,length(F));
k=-0.3494;alpha=0.3738;eps=0.9327;%WSC Z

for j=1:length(F)
      XF_sample1(j)=eps+alpha/k*(1-exp(-k*norminv(F(j))));
end

u_L1=zeros(length(F),1);%lower 95% conf.interval
u_U1=zeros(length(F),1);
XF1=zeros(Nsim,length(F));

% Beginning of the regional simulation

for m=1:Nsim,
   for i=1:ns,
       nrec=WSCZ(i);

   y=0;
      for i1=1:nrec
       y(i1)=epsp(i)+alphap(i)/kp(i)*(1-exp(-
kp(i)*norminv(rand)));
      end
   x=sort(y);
   b0=mean(x);
    indxfld(i)=b0;
    x1=0;
   x2=0;
    x3=0;
    x4=0;
      for j=1:nrec,
      x1(j)=x(j)*(j-1);
      x2(j)=x(j)*(j-1)*(j-2);
       x3(j)=x(j)*(j-1)*(j-2)*(j-3);
       x4(j)=x(j)*(j-1)*(j-2)*(j-3)*(j-4);
      end
   b1=sum(x1)/(nrec*(nrec-1));
   b2=sum(x2)/(nrec*(nrec-1)*(nrec-2));
    b3=sum(x3)/(nrec*(nrec-1)*(nrec-2)*(nrec-3));
```

```
    b4=sum(x4)/(nrec*(nrec-1)*(nrec-2)*(nrec-3)*(nrec-4));
    l1(i)=b0;
    l2(i)=2*b1-b0;
    l3(i)=6*b2-6*b1+b0;
    l4(i)=20*b3-30*b2+12*b1-b0;
    l5(i)=70*b4-140*b3+90*b2-20*b1+b0;
    t(i)=l2(i)/l1(i);
    t3(i)=l3(i)/l2(i);
    t4(i)=l4(i)/l2(i);
    end

    for i=1:ns,

l1r(i)=WSCZ(i)*l1(i)/sum_nrec;l2r(i)=WSCZ(i)*l2(i)/sum_nrec;

l3r(i)=WSCZ(i)*l3(i)/sum_nrec;l4r(i)=WSCZ(i)*l4(i)/sum_nrec;
        tr(i)=WSCZ(i)*t(i)/sum_nrec; t3r(i)=WSCZ(i)*t3(i)/sum_nrec;
        t4r(i)=WSCZ(i)*t4(i)/sum_nrec;
    end

%regional average L-moments of the simulated series
    L1=sum(l1r);
    L2=sum(l2r);
    L3=sum(l3r);
    L4=sum(l4r);
    L5=sum(l4r);
    T=sum(tr);
    T3=sum(t3r);
    T4=sum(t4r);

%regional LN3 parameters and growth curve (distribution under
test)
    K=-
T3*(e0+e1*T3^2+e2*T3^4+e3*T3^6)/(1+f1*T3^2+f2*T3^4+f3*T3^6);
    ALPHA=L2*K*exp(-K^2/2)/(1-2*normcdf(-K/sqrt(2)));
    EPS=L1-ALPHA/K*(1-exp(K^2/2));

%Quantile estimation
    for j=1:length(F)
        XF1(m,j)=EPS+ALPHA/K*(1-exp(-K*norminv(F(j))));
    end

end

disp ('==============================');

disp ('See plot for regional growth curve');

%95% Confidence interval computation and plotting of regional
```

```
growth curve

XF1=sort(XF1);

for j=1:length(F)
  u_L1(j)=XF1(index_L,j);
  u_U1(j)=XF1(index_U,j);
end

disp('Gumbel_Var Sample_growth curve for sub region Z:');
disp(' Growth Factor   Lower_5%  Upper_5%')

table1=[gum_var(1) XF_sample1(1) u_L1(1) u_U1(1);
   gum_var(41) XF_sample1(41) u_L1(41) u_U1(41);
   gum_var(46) XF_sample1(46) u_L1(46) u_U1(46);
   gum_var(49) XF_sample1(49) u_L1(49) u_U1(49);
   gum_var(50) XF_sample1(50) u_L1(50) u_U1(50);
   gum_var(55) XF_sample1(55) u_L1(55) u_U1(55)]

disp('===================================');

plot(gum_var,XF_sample,'b');
hold on;
plot(gum_var,XF_sample1,'r');
plot(gum_var,u_L,'b:');
plot(gum_var,u_U,'b:');
plot(gum_var,u_L1,'r:');
plot(gum_var,u_U1,'r:');
hold off;
xlabel('Gumbel Reduced Variate, -log(-log(F))');
ylabel('Growth factor');
Title('90% Confidence Bands for Sample LN3 Growth Curves')
```