Flood Frequency Analyses for New Brunswick Rivers

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A flood frequency analysis was carried out in the present study to determine the characteristics of high flow events in New Brunswick. High flow events are a key component in river engineering, for the design and risk assessment of various projects. For many practical situations, at-site historical flood data are available, such that extreme flood events can be estimated (or predicted) with reasonable accuracy. However, for many other situations (e.g., ungauged basins) flood estimates are required at locations where no historical data are available. When this arises, regional flood frequency analysis may be considered as a viable means to approximate at-site flood characteristics by exploiting the information available at neighbouring sites.

In the past, some studies have been dedicated to the analysis of floods across the Province of New Brunswick (e.g. Environment Canada and New Brunswick Department of Municipal Affairs and Environment, 1987). Since new data are available, the goal of the present study was to update those flood frequency analyses previously analysed. As such, results presented in this document will better reflect our current state of knowledge regarding the high flow regimes throughout the province.

Single stations analyses were carried out for 56 hydrometric stations located in the New Brunswick watershed and one station in Nova Scotia. A regional flood frequency analysis was also carried out using both regression equations and the index flood approach. In general, the results of the present study are consistent with those from early studies, although it can be seen that updating the flood information resulted, for many stations, in an improvement of flood estimates.

RÉSUMÉ

Aucoin, F., D. Caissie, N. El-Jabi and N. Turkkan. 2011. Flood frequency analyses for New Brunswick rivers. Can. Tech. Rep. Fish. Aquat. Sci. 2920: xi + 77p.

Dans la présente étude, une analyse fréquentielle des crues a été réalisée en vue de déterminer les caractéristiques d'événements de crues au Nouveau-Brunswick. Dans le cadre de projets en ingénierie fluviale, l’étude des débits de crues constitue un élément clé, autant du point de vue de la conception que de celui de l'évaluation du risque. Pour de nombreuses situations pratiques, des données historiques de débits sont disponibles au niveau des sites d’intérêt, de sorte que les débits extrêmes peuvent être estimés (ou prédits) avec précision raisonnable. Cependant, dans beaucoup d'autres scénarios (p. ex., bassins non jaugés), l’on souhaite faire l’estimation des crues où aucune information n’est disponible. Lorsque ce problème se pose, l’analyse régionale fréquentielle constitue une alternative viable, laquelle suggère que l’estimation des caractéristiques des crues au niveau du site d'intérêt soit basée sur l’information disponible au niveau des sites jaugés voisins.

Dans le passé, quelques études ont été consacrées à l’analyse fréquentielle des crues pour la province du Nouveau-Brunswick (par exemple, Environment Canada and New Brunswick Department of Municipal Affairs and Environment, 1987). Puisque de nouvelles données sont maintenant disponibles, l'objectif de la présente étude était de mettre à jour l’analyse fréquentielle des crues. Les résultats présentés dans ce document visent donc à mieux refléter l’état actuel des connaissances à propos du régime des débits de crues au niveau de la province.

Dans cette étude, des analyses ont été réalisées pour 56 stations hydrométriques situées dans la province. En plus des 56 stations analysées, une analyse régionale fréquentielle des crues a été effectuée en utilisant des équations de régression et l'approche d’indice de crues. En général, les résultats ici présentés sont compatibles avec ceux des études précédentes. Cependant, il est possible d’observer que l'actualisation de l’information concernant les crues a entraîné, pour de nombreuses stations à travers la province, de nettes améliorations en ce qui concerne l'estimation des crues.

1.0 Introduction

The understanding of floods plays a key role in many hydrological studies, especially in the design of hydraulics structures such as dams, culverts, bridges and others. The estimation of floods is also important in the evaluation of flood risk, particularly in areas in close proximity of flood plains. Extreme hydrological events are not only important in the design of water resource projects but also for fish habitat and in the management of fisheries resources. In New Brunswick there have been a number of studies dealing with floods and regional flood frequency analyses. For instance, a study was carried out by Montreal Engineering Co. Ltd, (1969), where high flows were estimated for many stations across the Maritime Provinces. Another study dealing with high flows in New Brunswick was carried out by Acres Consulting Services Ltd. (1977). That study corresponded to one of the most extensive analysis of floods within the province: it included a flood frequency analysis for each station, regional floods equations, and flood risk maps for a number of communities within the province. A flood study in NB was also carried out in 1987 (Environment Canada and New Brunswick Department of Municipal Affairs and Environment, 1987). The latter study depicted regional equations as well as envelope curves for the estimation of floods. More recently, a study by Caissie and Robichaud (2009) looked at many aspects of the flow regime within the Maritime Provinces including mean flow, flow duration, as well as high and low flows. The present document focuses on updating information related to floods in the province of New Brunswick. Here, both single station analyses and regional flood equations are presented.

Arguably, there are two main approaches when it comes to flood estimation. The first, often referred to as the *block maxima* approach (BM), consists in modeling only the most extreme observation of each year, i.e., the *annual maxima*. Due to its simplicity, the latter corresponds to the most commonly encountered method in practice. The BM approach can get around the high correlation of daily discharge time series by considering only the highest observed value each year. As such, these annual maxima will approximately behave as realizations of independent random variables. Then, under the assumption of the data being stationary through time, simple frequency distribution functions can be fitted to the maxima in order to yield estimates of the frequency of events.

Although the BM approach is simpler to apply, it has the disadvantage of being somewhat “wasteful” in data, especially in situations that deal with short data series (e.g., less than 20 years). A way around this problem is to use the “threshold models” approach, also commonly referred to as *peak over threshold* (POT) method. The POT method considers only observations that fall above a specific threshold, a level that is selected to reflect only extremes events (e.g., floods). The POT approach allows for more observations (or data) and is especially valuable for shorter time series. The main difficulty in implementing the method lies in the selection of the threshold level: if the level is set too high, only few observations will be retained for further analysis; if the level is set too low, the retained observations will tend to be serially correlated, thus violating the independence assumption.

Some theoretical arguments suggest the exclusive use of certain distributions when dealing with extreme data. For this reason, both the BM and POT approaches remain the object of extensive research in the statistical literature. For example, without knowing the “parent distribution” of the raw data, it can be shown that, under certain conditions, extreme data will converge to some explicitly known *limiting distributions.* For the BM approach, the limiting distribution can be shown to belong to the *generalized extreme value* (GEV) family of distributions, whereas, for the POT approach, the limiting distribution can be shown to belong to the *generalized Pareto* (GP) family of distributions (Coles, 2001; Salvadori *et al.*, 2007).

All previous flood studies for New Brunswick have used the annual maxima (BM) approach. Since the goal of the present study was to update this information, the BM approach was used. More precisely, the study focused on flood characteristics at 56 hydrometric stations across the province, and the analyzed flow characteristics included the single station frequency analyses and regional flood analyses (regression equations and index flood) to calculate floods for ungauged basins.

2.0 Material and Methods

2.1 Data and Study Region

The hydrological analysis was carried out using historical data from 56 hydrometric stations of which 53 are located in New Brunswick. In order to enhance the quality of the regional frequency analysis, three stations located outside the province of New Brunswick were also included: two stations located in Quebec and one station located in Nova Scotia. All data used in this study were collected from the HYDAT database up to 2005 (Environment Canada, 2007) and the Environment Canada web site for 2006-2008. Data extracted included extreme values, i.e., annual maximum daily discharges and instantaneous discharge. The 56 stations are plotted on a map of New Brunswick (Figure 1) and some of their relevant characteristics are presented in Table 1. Similar to previous studies (e.g., Environment Canada and New Brunswick Department of Municipal Affairs and Environment, 1987) some stations are affected by flow regulation and identified by (Reg) in Table 1. However, these stations were nevertheless included in the analysis as it was felt that the degree of regulation would not impact much on the regional flood frequency equations. The number of years of record varies between 11 and 92 with a mean value of 39 years. The smallest drainage basin corresponds to Narrows Mountain Brook at 3.89 km^2 whereas the largest river corresponds to the Saint John River below Mactaquac at 39900 km^2. Moreover, a summary of the physiographic and climatic characteristics for the selected hydrometric stations is provided in Table 2 (data coming from, Environment Canada and New Brunswick Department of Municipal Affairs and Environment, 1987).

2.2 Single Station Flood Frequency Analysis

A frequency analysis was carried for each station to estimate floods of different recurrence intervals. The maximum daily discharge by year was extracted from the HYDAT database and fitted to two distributions, namely the 3-parameter lognormal (LN3) and the generalized extreme value (GEV) distributions. The main motivation for considering LN3 stemmed from the fact that it was previously used with good success to describe floods in New Brunswick (Environment Canada and New Brunswick Department of Municipal Affairs and Environment, 1987). However, although the LN3 has been extensively used for describing extreme events in the past, the GEV distribution has gained in popularity over the years due to its theoretical properties. The extreme value theory suggests that distribution of extreme events, such as *annual daily discharge maxima* (under certain conditions, asymptotically), will most likely converge in probability toward a distribution belonging to the family of GEV distributions (Coles, 2001).

2.2.1 Probability Density Functions

The probability density function (PDF) of LN3 is given by:

$$f(x) = \frac{1}{\sqrt{2\pi}\sigma(x-\lambda)} \exp\left\{\frac{-\left[\ln(x-\lambda)-\mu\right]^2}{2\sigma^2}\right\} \tag{1}$$

defined for $\lambda < x < \infty$; and where $\mu \in R$ is the shape parameter, $\sigma > 0$ is the scale parameter, and $\lambda \in R$ is the threshold parameter. In hydrology, the cumulative distribution function (CDF) is most often used to represent flows of different recurrence intervals. For LN3, the CDF is given by:

$$F(x) = \int_{\lambda}^{x} \frac{1}{\sqrt{2\pi}\sigma(t-\lambda)} \exp\left\{-\frac{[\ln(t-\lambda)-\mu]^2}{2\sigma^2}\right\} dt \tag{2}$$

with parameters defined in equation (1).

For GEV, the PDF is given by:

$$f(x) = \frac{1}{\sigma'}\left[1+\xi\left(\frac{x-\mu'}{\sigma'}\right)\right]^{-(1/\xi+1)} \exp\left\{-\left[1+\xi\left(\frac{x-\mu'}{\sigma'}\right)\right]^{-1/\xi}\right\} \tag{3}$$

defined for $1+\xi(x-\mu')/\sigma' > 0$; and where $\sigma' > 0$ is the scale parameter, $\mu' \in R$ is the location parameter, and $\xi \in R$ is the shape parameter. The CDF for the GEV is given by the following equation:

$$F(x) = \exp\left\{-\left[1+\xi\left(\frac{x-\mu'}{\sigma'}\right)\right]^{-1/\xi}\right\} \tag{4}$$

with parameters defined in equation (3). Note that, for simplicity, x, $f(x)$, and $F(x)$ are used here for both LN3 and GEV; however they are different for each distribution.

2.2.2 Parameter Estimation

The method of maximum likelihood was used for estimating the parameters for both LN3 and GEV. More formally, let $\vec{x} = (x_1, x_2, ..., x_n)'$ denote a vector of n observations, whose PDF is believed to be $f(x_i \mid \theta)$, for $i = 1, 2, ..., n$, and where θ corresponds to a vector of unknown parameters. For example, θ would correspond to $\theta = (\xi, \sigma', \mu')'$ for the GEV distribution. Under the assumption that $\vec{x}$ corresponds to a realization of the random vector $\vec{X} = (X_1, X_2, ..., X_n)$, where the X_i's are independent and identically distributed, the likelihood function can be defined as the joint probability function of the n observations conditionally on the unknown vector of parameters; that is

$$L(\theta \mid \vec{x}) = \prod_{i=1}^{n} f(x_i \mid \theta) = f(x_1 \mid \theta) * f(x_2 \mid \theta) * ... * f(x_n \mid \theta) \qquad (5)$$

The method of maximum likelihood consists in finding the value of θ for which (5) is at a maximum, or, equivalently, in finding θ for which the log-likelihood function (LL) is at a maximum.

$$LL(\theta \mid \vec{x}) = \ln \prod_{i=1}^{n} f(x_i \mid \theta) = \sum_{i=1}^{n} \ln f(x_i \mid \theta) \qquad (6)$$

In other words, the idea consists in finding the parameter values $\hat{\theta}$ that are the most likely for the observed sample $\vec{x}$ under the chosen distribution function. Note that some optimization algorithms will only allow the search of minima. When this is the case, minimizing the negative-log-likelihood function (NLL) will be equivalent to maximizing the LL. The estimation of unknown parameters using this method almost always requires the use of iterative procedures. In the present study, the statistical freeware R (2009) was used for all computations pertaining to parameter estimation.

2.2.3 Goodness-of-Fit and Model Selection

Usually, once the unknown parameters have been estimated for distinct distributions, there is an interest in 1) assessing the quality of the fitted models, as well as 2) determining which model fits the data best using selected criteria. As such, three diagnostic tools were used, namely, the quantile-quantile plot or (Q-Q plot), the NLL value, and the Anderson-Darling (AD) statistic (Anderson and Darling, 1952).

2.2.3.1 Q-Q Plot

The Q-Q plot is a visual assessment tool that plots the sorted observations (that represent the maximum annual daily discharges) against their respective cumulative frequencies. The cumulative frequency, denoted here by h, was plotted graphically using the Weibull plotting position formula (Chow *et al.*, 1988):

$$h = \frac{m}{n+1} \tag{7}$$

where m refers to the rank of the annual maximum daily discharge in increasing order, and n is the number of years of record. Given h, the position on the x axis was determined using the Gumbel reduced variable Y:

$$Y = -\ln\left(-\ln\left(h\right)\right) \tag{8}$$

The above transformation is usually used for plotting flood data due to the logarithmic nature of such events. This type of a plotting transformation is referred to as plotting data on a Gumbel paper. The fitted lines for several distribution functions can also be plotted in order to discriminate between the relative performances of each model. When both distributions fit the data reasonably well, descriptive criteria (as described below) can be used to discriminate between distributions.

2.2.3.2 Negative Log-likelihood Value

The NLL value, which corresponds to the value at which the negative-log-likelihood function is minimized, can be used as a means for discriminating between distributions. For example, the distribution that yields the smallest NLL value will be regarded, based on this criterion, as the most probable (or “likely to be”) for the observed sample.

2.2.3.3 Anderson-Darling Statistic

In addition to the NLL value and the visual Q-Q plot, the AD statistic was also used as a means of discriminating between the fitted distributions. The AD statistic can be found under several different forms across the statistical literature, and only the most popular form is described here. Let $\bar{Z} = (Z_1, Z_2, ..., Z_n)$ denote a random vector defined such that $Z_i = Z_{(i)}$, where $X_{(1)} \leq X_{(2)} \leq ... \leq X_{(n)}$ are the order statistics for the random vector $\bar{X}$, whose notation was presented previously. The AD statistic, often referred to as A^2, can thus be defined as:

$$A^2 = -n - \sum_{i=1}^{n} \frac{2i-1}{n} \left[\ln F(Z_i) - \ln \left\{ 1 - F(Z_{n+1-i}) \right\} \right] \tag{9}$$

In this case, the notation $\hat{F}(Z_i)$ is used instead of $F(Z_i)$, since the latter is not fully specified (the parameters must be estimated).

An important feature of the AD version presented in equation (9) is that it gives more weight to the observations in the tails of the distribution than to those in the center of the distribution. Incidentally, inferences for values located in the tails are usually of interest when fitting distribution function (e.g., high flood events). Furthermore, the reference distribution of A^2 can be studied (using either simulations or asymptotic results), and p-values can be calculated, i.e., $\Pr[A^2 \le a^2]$, where a^2 is a realization of A^2. Generally a smaller A^2 represents a better fit; however, without knowing the reference distribution of A^2, it is usually difficult to have a definition of a “small” value (since the reference distribution will be different for varying assumptions, parametric model, parameter values, the sample size, etc.). That said, AD may also be put to good use when considered as a “relative” measure of the goodness-of-fit between different distributions. More information pertaining to the AD statistic can be found in D’Agostino and Stephens (1986).

2.2.4 Recurrence Intervals

The relation between the CDF, i.e., $F(x)$, and the recurrence interval (*T,* in years) used in flood hydrology, is given by the equation:

$$F(x) = 1 - \frac{1}{T} \tag{10}$$

where *T*-year flood denoted by QD-*T*, such that $\text{QD-}T = 1/[1 - F(x)]$. For example, in the present study, the following values of T were considered: $T = 2, 10, 20, 50, 100$ years.

2.3 Regional Regression Equations

Characteristics of floods differ from one drainage basin to another and results of single station analysis are only applicable to the specific gauged streams or those streams near hydrometric stations. As many water resource projects are undertaken for ungauged basins, there is a requirement for the development of regional equations. In a previous study (Environment Canada and New Brunswick Department of Municipal Affairs and Environment, 1987) the province was divided into 5 different regions. This tends to limit the applicability of regional equations in terms of sample size and drainage size for each region. As such, the present study considers the province as one region.

The main idea behind regional regression analysis is to establish a relationship between floods and physiographic parameters describing the basin. With the discharge as the dependent variable and the physiographic factors as independent variable(s) (in this case the area of the drainage basin and precipitation), linear regressions of the following types can be entertained:

$$Q_T = a\,(DA)^{b1} \qquad \text{or} \qquad Q_T = a\,(DA)^{b1}(MAP)^{b2} \tag{11}$$

where *a, b1,* and *b2* are regression parameters; *DA* and *MAP* are used in reference to the “drainage area” (in km²) and the “mean annual precipitation” (in mm), respectively; and Q_T denotes the T-year flood (in m³/s). At this point, it should be noted that no difference will be made between regression parameters, their estimators and their estimated values, such that the lower-cases *a, b1,* and *b2* shall be used ex-changeably to refer to any of those quantities. It should also be noted here that two regression models are presented in equation (11): the first one only considers *DA* as predictor, while the second uses both *DA* and *MAP*. Later in this report, estimated regional regression equations will be given for both cases.

Parameters for both regression models shown in equation (11) were calculated using the statistical freeware R (2009). However, in order to fit the regression, Q_T, *DA*, and *MAP* must first be transformed to the natural logarithmic scale. Once the variables were log transformed, the model was fitted to yield the following parameter estimates: *a*, b1,* and *b2*. Note that *a** needs to be exponentiated to obtain *a*; that is $a = \exp\{a^*\}$ in equation (11).

Often a major concern when fitting a regression model is the possibility that there may by "outliers" that exert undue influences on the final fit. For example, it could be suspected that some larger basins might greatly influence the regression fit if included in the model (this might result in a final model that does not well describe the smaller basins). In this study, simple regression diagnostics based on the "leverage effect" (see, Kutner *et al.*, 2005) were employed for the purpose of detecting such unwanted effects.

2.4 Index Flood Method

The *index-flood* method was originally proposed by Dalrymple (1960) and has since then been extensively used in flood hydrology. The main reason for its success lies in its great simplicity of implementation, as well as in its flexibility to be modified or extended. In fact, the *index-flood* method has undergone many reformulations through the years. In this study, two versions of the method are briefly described.

2.4.1 Averaging Approach

The first version of the *index-flood* method presented here corresponds to that originally proposed by Dalrymple (1960), and is referred to here as the *averaging approach*. The main idea behind this approach is to express the estimated floods (from distinct sites) using what is called the *index of floods (*or simply *index).* The latter permits the estimation of higher return floods using data from lower return floods (e.g., estimation of 100-year flood from data on the 2-year flood) and can be described as follows:

1. Single station analyses are carried out using appropriate frequency distributions and the recurrence intervals of interest are estimated for each site.

2. Dimensionless flood indices are calculated for each site by dividing the estimated flows of different recurrence intervals by a scaling factor. For example, common choices of scaling factors are the mean annual flood (MAFL), estimated from the sample; and the 2-year flood (QD2), estimated from the fitted distribution.

3. For a recurrence interval T, the average of indices is estimated for all sites and this value corresponds to the *regional index* for that specific recurrence interval.

This version of the *index-flood* method has the property of giving equal weights to all stations considered regardless of the number of observations available at each site. Depending on the situation, this property could be regarded as either an advantage or a drawback. For instance, longer record lengths are generally available for large basins, although, for most design projects, interest lies in mid-size basins with record lengths often substantially shorter. In some instances, it may be important not to give too much weight on large basins in comparison to mid-size basins (with less data) when calculating the regional index. In the application of the *index-flood* method, it is assumed that all stations are somewhat similar; that is, they are part of a *homogeneous region*. In the present study, the plausibility of the assumption of a *homogeneous region* was assessed based on spatial inspection of the indices, as will be discussed further in the “Results and Discussion” section.

2.4.2 Pooling Approach

A second *index-flood* method presented here is based on the pooling of observations from all sites when calculating the index (Hosking and Wallis, 1997; Salvadori *et al.*, 2007). This approach makes the following assumptions (Hosking and Wallis, 1997):

1. Observations at any given site are identically distributed.

2. Observations at any given site are serially independent.

3. Observations at different sites are independent.

4. Frequency distributions at different sites are identical apart from a scale factor.

5. The “true” frequency distribution function is correctly identified.

Assumptions 1 to 2 were already stated in the present study and are generally reasonably made in most situations. Assumption 3 rarely holds in practice, but early studies (e.g., Matalas and Benson, 1961; Stedinger, 1983) have shown that, when ignoring between-site dependence, the variability associated with the estimates is underestimated; however, the estimates themselves remain unbiased. Thus, if only point estimates are of interest, then this assumption can be relaxed. Assumption 4 is somewhat equivalent to saying that all sites considered come from a same homogeneous region. With the pooling approach *index-method*, it is actually possible to test the validity of assumption 4 using classical statistical hypotheses tests (such tests results will be presented in the “Results and Discussion” section). Finally, assumption 5 simply means that the fitted frequency distribution is regarded as the “true distribution” from which the observations are assumed to have been generated (in this case, the GEV distribution).

The pooling approach version of the *index-flood* method can therefore be described as follows:

1. A flood index is estimated for each station. Usually, the index is estimated from the sample (e.g. sample mean or median), although more sophisticated indices can be used (e.g. QD2 obtained from prior analysis).

2. All observations are *normalized* by dividing them with the estimated index.

3. The *normalized* data from all stations are then pooled together to form a new sample (i.e., a regional sample).

4. A frequency distribution is fitted to the regional sample and the resulting parameter estimates correspond to the *regional parameters*. These parameters can then be used to obtain regional recurrence interval estimates for gauged and ungauged stations.

The above method is more formally expressed using mathematical notation. That said, let ψ_i denote the index for station i, for $i = 1, 2, ..., k$ and where k is the total number of sites. Let also X_{ij} denote the j^{th} random variable that comes from site i, for $j = 1, 2, ..., n_i$, and where n_i is the number of available observations at site i. Finally, let $I_{ij} = X_{ij} / \psi_i$ denote a random variable distributed according to a regional GEV distribution; $I_{ij} \overset{iid}{\sim} GEV(\xi_\psi, \sigma_\psi', \mu_\psi')$ for all ij's, where *iid* stands for "independent and identically distributed", and where ξ_ψ, σ_ψ', and μ_ψ' are the *regional parameters* (note: here GEV could be replaced by any other distribution). Thus, for an index ψ, a regional estimate of the recurrence interval $\hat{Q}_T$ is given by $\hat{Q}_T = \hat{F}_{GEV}^{-1}(1-1/T)*\psi$, where $\hat{F}_{GEV}^{-1}$ is the inverse CDF of $GEV(\hat{\xi}_\psi, \hat{\sigma}_\psi', \hat{\mu}_\psi')$, the estimated regional GEV distribution. If ψ is taken to be one of the ψ_i's, then $\hat{Q}_T$ corresponds to an *T*-year flood at-site (i) estimate and may be re-written as $\hat{Q}_{i,T}$.

The main difference between the pooling approach and the averaging approach lies in the relative importance of each station in determining the regional estimates. While the averaging approach gives equal weights to all stations, the pooling approach gives more importance to stations with more data. If assumption 4 can be shown to be reasonable for a given application, then pooling of all observations could be expected to provide better results.

2.5 Daily to Instantaneous Flows

All analyses so far pertained to the mean daily discharge (or annual maximum daily discharge). However, for many practical applications, there is an interest in the design of structures using instantaneous peak flows (or annual maximum instantaneous daily discharge). The flood frequency analyses could easily have been carried out using instantaneous flows rather than daily flows; however, past studies have relied on ratios between instantaneous flows to daily flow. The present study will also calculate instantaneous flows based on daily flows. Previous studies have dealt with this problem by constructing *envelope curves*, which are based on observed (maximum) ratios of the instantaneous peak flow to mean flow in relationship with the basins' drainage size.

3.0 Results and Discussion

3.1 Single Station Flood Frequency Analyses

For LN3 and GEV, respectively, results of the 56 single station high flow frequency analyses are provided in Table 3 and Table 4, for recurrence intervals of 2, 10, 20, 50 and 100 years. For the Saint John River (Mactaquac), which has a drainage area of 39900 km^2, the 2-year flood was estimated to be 5809 m^3/s using LN3. This corresponds to the highest estimated 2-year flood in New Brunswick. Conversely, the lowest estimated 2-year flood (LN3) was 1.09 m^3/s, and was observed at Narrows Mountain Brook, which has a drainage area of 3.89 km^2. Using the GEV distribution, the 2-year flood was estimated at 5840 m^3/s and 1.08 m^3/s; being quite similar to those obtained using LN3. Notably greater differences among distributions were noted at higher recurrence intervals. For all 56 stations, the maximum likelihood parameter estimates, as well as their corresponding NLL values and AD statistics, are presented in Table 5 (LN3) and Table 6 (GEV).

The NLL criterion favored the LN3 approximately 52% of the time; however, from a practical point of view, NLL values were almost identical for both distributions. Similar NLL values for the two distributions suggest that they are almost equally likely under the observed data. From the single station Q-Q plots (Appendix A) it is clear that, for the majority of the single analysis, both the LN3 and GEV fitted the data almost exactly the same (especially in the central portion of the plot). In fact, when discrepancies existed, they were mostly located in the tails, level at which the AD statistic is more sensitive than the NNL. As an example, the Q-Q plot for the station 01AL004 located along Narrows Mountain Brook is presented (Figure 2; see also Figure A.10b, Appendix A). For the upper right portion of this plot (at high recurrence intervals), it is evident that GEV adjusts better to the observational data than LN3.

Results of the AD statistics favor GEV over LN3 approximately 64% of the time. The relation between the AD for both the GEV and LN3 is illustrated in Figure 3. Many of the data points are below the line (representing equal values) which suggests a better regional fit for GEV. Moreover, of the 64% identified above, 44% corresponds to cases where a difference greater than 10% was observed. Although these results have no statistical bases, they are an indication of a potential overall superiority of GEV over LN3. In the case of the Narrows Mountain Brook (for station 01AL004, Figure 2), the AD values for the GEV and LN3 (Table 6 and Table 5) were 0.170 and 0.215, respectively. These results show the impact of a single data point (highest observed flood) on the overall AD values, as GEV and LN3 were almost identical for all other data points.

Thus, based on the AD and the Q-Q plots, it was observed that both LN3 and GEV yielded reasonable estimates for most stations; with GEV performing slight better in some cases. As such, discharges as a function of the different recurrence intervals are available for both the GEV and the LN3 distributions (Table 3 and 4). Based on these results, the regional high flow frequency analysis (presented in the next sub-section) was carried out and corresponding regression equations were calculated using the GEV.

3.2 Regional Flood Frequency Analyses

3.2.1 Regression Method

In order to estimate high flows for ungauged basins, regional regression equations for the relation between estimated high flows and basin sizes and precipitation were developed using five recurrence intervals estimated for the GEV distribution (QD2, QD10, QD20, QD50, and QD100). For these five regional regression equations (see equation 11), the estimated coefficients are presented in Table 7, along with their corresponding coefficients of determination (R^2). For the regression models with only the drainage area as a predictor, R^2 varied between 0.964 and 0.985. In fact, the coefficient of determination can be observed to increase for decreasing recurrence intervals. It should be noted that the R^2 values are those obtained from the regression of transformed (natural logarithmic) variables. It should also be noted that these regression equations were developed for a specific range of basin sizes and should not be applied outside those ranges (ranges are provided in Table 7). Results from Table 7 also suggest that including the precipitation as a predictor only slightly improves the R^2. The relationship between the 100-year floods (estimated from GEV distribution) and the drainage areas is illustrated in Figure 4 (note: the latter corresponds to the regression model with only the drainage area as a predictor). Although this figure presents the regression equation for the GEV only, data points for both the GEV and LN3 were presented. This figure also shows the fitted regression line from the previous flood report (Environment Canada and New Brunswick Department of Municipal Affairs and Environment, 1987) and it can be observed that both regression lines are almost identical. The fits for the other recurrence intervals are presented in Appendix B. Finally, estimated coefficients for a regional regression model with the mean annual flood (MAFL) as the dependent variable is also presented in Table 7. The MAFL values will be use in the index-flood method.

As described previously ("Material and Methods" section), it was deemed necessary to assess whether or not there existed extreme data points that could exert undue influences on the regression equations. Regression diagnostics based on the "leverage effect" showed that no such points existed, and, therefore, the regression equations are expected to correspond to good approximations of floods for the province of New Brunswick. Moreover, it was possible by visual inspection of Figure 4, to conclude that no particular data point was pulling the regression line unduly.

3.2.2 Index Flood Method

Regional flood indices calculated for both *index-flood* approaches (described in section 2.4.1 and 2.4.2) and for the recurrence periods 2, 10, 20, 50, and 100 years. A concern when using the *index-flood* method is whether the stations are part of the same homogeneous region. For the *averaging approach,* homogeneity was assessed based on at-site index in relation to their positions within the province. No spatial patterns could be identified, and it was thus concluded that the index could be applied on a province-wide basis. However, it is well known that at-site index value can be a function of drainage size: larger indices tend to be observed for smaller basins and *vice-versa.*

A homogeneity assessment was carried out for the *pooling approach*. The method explicitly assumes that observations come from a same theoretical distribution. This can be tested statistically using classical hypotheses testing. Therefore, a classical test derived from an extension of the Shapiro-Wilk statistic (e.g. Ashkar *et al.*, 1997) was used to assess the plausibility of this assumption (in this case the GEV). A significance level was fixed at $\alpha = 0.10$ and 56 independent tests were carried out (this is only possible under the assumption of between-site independence). Stations that yielded a p-value smaller than $\alpha = 0.10$ were rejected (i.e., fitted GEV distribution regarded as inconsistent with the actual data). In this study, 9 of 56 tests were rejected.

These 9 “critical” stations corresponded to: 01AD002 (14700 km^2), 01AF002 (21900 km^2), 01AJ001 (34200 km^2), 01AL004 (3.89 km^2), 01AM001 (557 km^2), 01AQ001 (239 km^2), 01BP001 (1340 km^2), 01BR001 (177 km^2), and 01DL001 (63.2 km^2).

From the 9 “critical” stations, it was noted that three stations were among the four largest basins. This suggests that these large basins might not be directly comparable with other stations and these large rivers had an index of flood less than 2.0. As such, the index method might provide poor estimates for large basins and large basins might unduly pull down the regional estimates. For this reason, the statistical test was conducted a second time, leaving out the four largest basins. That time, 5 stations of 52 were rejected, but the probability of rejecting 5 (or more) out of 52 tests solely at random was determined to be of approximately 0.55. Nonetheless, it seems worthwhile to point out the five stations that were rejected for this second test: 01AL004 (3.89 km^2), 01AQ001 (239 km^2), 01BP001 (1340 km^2), 01BR001 (177 km^2), and 01DL001 (63.2 km^2). These stations, with the exception of 01BR001, showed an index of flood (QD100/QD2) greater than 4.0 and many stations corresponded to somewhat small basins. Although without statistical bases, this might be regarded as an indication that the results obtained from the index flood method should be used cautiously, especially for both large and small basins.

The results of the index flood methods are presented in Table 8. The two versions of the method were carried out using both the MAFL (sample mean) and the estimated at-site QD2 (theoretical median). For both the *averaging and pooling* approaches, the indices obtained using MAFL as normalizing factor were systematically lower (8% to 10%) than those calculated using QD2. For consistency, although the test results are only strictly valid for the indices from the pooling approach, all indices were calculated leaving out large rivers (i.e., stations 01AK004, 01AJ001, 01AF002, and 01AD002). Indices ranged between 1.64 (QD10) to 2.70 (QD100) for the averaging approach and 1.65 (QD10) to 2.62 (QD100) for the pooling approach. Indices using the MAFL as the normalizing factor showed consistent but slightly lower value. Similarly, Table 8 presents the results of the flood index for only the four largest basins. As expected, the indices for that analysis are systematically lower than those of other stations in New Brunswick.

As mentioned previously, results of the index of floods show that caution should be exercised when using the regional indices for very large basins or very small basin because their flood behaviour could be slightly different. This is true for both the averaging and the polling approaches. Results presented in Table 8 can be used to calculate flows for different recurrence intervals at ungauged basins provided that low return floods are known (e.g. QD2 or MAFL), both of which can be obtained by regression (Table 7).

3.4 Instantaneous Flows and Envelope Curves

The 56 single station frequency analyses, as well as the regional analyses were carried out using the daily flows (annual maximum daily discharge). However, as mentioned previously, for design and risk management purposes, some knowledge about the instantaneous peak flows (annual maximum instantaneous discharge) is often required. In this study, envelope curves were thus constructed to this end; that is, as a means of converting the information acquired for daily mean flow so they can be used in terms of instantaneous peak flow.

Here, the (maximum) ratio of the instantaneous peak flow to mean flow (QP/QD) was considered, and its relationship with the drainage area was studied. For each station and each year, the ratio QP/QD was computed, and both the mean and maximum QP/QD ratio was retained (Table 9). In total, ratios were available for 54 of the 56 stations. Mean QP/QD ratios varied between 1.01 and 1.90 and higher ratios generally showed a higher variability (e.g., QP/QD = 1.90 and Cv = 32.4%). Maximum recorded QP/QD ratios were also reported in Table 9, with values ranging from 1.05 (St. Francis R.) to 3.35 (Hayden Brook). Figure 5 shows a scatter plot of these values plotted against their corresponding drainage area (km^2), from which the following main observations can be made:

- for stations with drainage areas less than 200 km^2, the ratio QP/QD does not exceed 3.5;

- for stations with drainage areas ranging from 200 to 800 km^2, the ratio QP/QD does not exceed 2.5;

- and for stations with drainage areas greater than 800 km^2, the ratio QP/QD does not exceed 2 (however, note that Aroostook River (6060 km^2) has a maximum QP/QD value of 2.0; Figure 5).

Based on these results, envelope curves of instantaneous flow can be developed for the different recurrence intervals. Of particular interest is the envelope curve for the estimated 100-year flood. The latter is shown in Figure 6. The envelope curve in the present study (represented by the dashed lines) was obtained by multiplying QD100 by the appropriate QP/QD factors presented in Figure 5. Also shown in this figure is the highest instantaneous daily discharge recorded for each station. As can be observed, most of the stations fall below the envelope curve with the exception of a few. For instance, three stations were identified with flows close to or higher than the envelope curve. Those stations correspond to the Point Wolfe River (130 km^2 and Q_{max} = 258 m^3/s in 1999), the Northwest Oromocto River at Tracy (557 km^2 and Q_{max} = 776 m^3/s in 1970) and the Renous River at McGraw Brook (611 km^2 and Q_{max} = 697 m^3/s in 1970). From those three stations, only the Northwest Oromocto River would have exceeded the present study envelope curve. In addition, the envelope curves from two previous studies (Environment Canada and New Brunswick Department of Municipal Affairs and Environment, 1987; Montreal Engineering Co. Ltd, 1969) are also presented; study of 1969 (blue) and study of 1987 (red).

For comparison purposes, the regional equations of previous reports were (Montreal Engineering Co. Ltd, 1969):

$$Q = 250\ A^{3/4} \tag{12a}$$

$$\mathrm{Q} = 3.47\ \mathrm{A}^{3/4} \qquad \text{(SI units)} \tag{12b}$$

$$Q = 500\ A^{3/4} \tag{13a}$$

$$\mathrm{Q} = 6.94\ \mathrm{A}^{3/4} \qquad \text{(SI units)} \tag{13b}$$

where Q is in cubic feet per second (cfs) and A is in square miles (mile^2) in equation 12a and 13a. The same equations are given in SI units (12b and 13b) where Q is in m^3/s and A in km^2. The equation from Environment Canada and New Brunswick Department of Municipal Affairs and Environment (1987) was:

$$Q = 6.18\ A^{0.73} \tag{14}$$

where Q is in m^3/s and A in km^2.

The envelope curve suggested by (Montreal Engineering Co. Ltd, 1969; equation 12) was exceeded for many stations, which casts some doubts upon the current use of such equation. However, the second envelope curve provided (equation 13) was very similar to the results suggested in the present study. On the other hand, the envelope curve suggested in the 1987 study was only exceeded for three stations. Finally, the envelope curve in the present study, which was build from longer data series, can be seen to be slightly more conservative than that from the 1987 study, being exceeded only once, and closely approached on two instances. Although this new envelope curve is expected to provide users with reliable flood estimates for most basins, it is essential to carry out flood estimates based on best available information at the time of the study as well as exercising good judgement of the level of risk associated with flood damage.

For points that lie somewhat close to the curve, particular attention is needed and more conservative multiplicative factors can be used. In fact, it is for the user to decide which multiplicative factor should be used for any given situation. Moreover, the physical characteristics of the basin of interest should always be taken into consideration when carrying out flood frequency estimates as well as other potential flood estimation techniques (e.g., probable maximum flood, etc.).

4.0 Summary and Conclusions

Flood frequency estimation remains an important topic for design purposes in New Brunswick. Flood data constitute the main source of information for this analysis. As such, the present study aimed at revisiting regional flood frequency estimates, as more data are now available, and at comparing them with those of previous studies. To carry out the analysis, 56 stations were analyzed. *Maximum daily discharges* (m^3/s) for each year were analyzed using both the generalized extreme value (GEV) and the 3-parameter lognormal (LN3) distribution functions.

Goodness-of-fit assessments (e.g., Anderson-Darling statistic, AD) suggested the GEV model to be the overall most appropriate distribution function. These findings were also strengthened by extreme value theory, which suggests that the annual maxima (such as flood data) be modeled as realizations of random variables distributed according to a member of the *generalized extreme value* (GEV) family of distributions. Based on such considerations, the GEV was therefore subsequently used in developing regional regression equations. Regional regression equations allowed the estimation of at-site floods as a function of drainage area (or drainage area and precipitation) for various recurrence intervals (i.e., 2, 10, 20, 50 and 100). In all cases, the fitted regression models were consistent with the calculated T-year flood events, such that they could be applied to predict floods for ungauged basins (within their range of application).

In addition to regional regression equations, the regionalization of floods was carried out based on two versions of the *index flood* method. Classical hypotheses testing and the index of flood results suggested that large and small basins should be treated with caution, as there indices could be statistically different. As such, the index of floods was divided in two homogenous groups of stations (i.e. one group with only the four largest stations, and the rest of the stations). For design purposes, interest often lies in estimating the instantaneous daily peak discharge rather than the daily mean flow. Therefore, as both the single station and regional regression equations were derived for daily flows, envelope curves of instantaneous flows were developed based on 54 hydrometric sites. The relation between the ratio QP/QD-max and drainage area suggested the use of three factors of QP/QD-max (2, 2.5 and 3.5) that varied in accordance with the drainage area.

5.0 Acknowledgements

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Table 1. Analysed hydrometric stations for the flood frequency analysis

Station number	Station Name	Drainage Area (km^2)	Acutal Period of Record used	Number of years
01AD002	Saint John River at Fort Kent	14700	1927-2007	79
01AD003	Saint Francis River at outlet of Glasier Lake	1350	1952-2008	57
01AF002	Saint John River at Grand Falls (Reg)	21900	1931-2007	77
01AF003	Green River near Rivière-Verte (Reg)	1150	1963-79,1981-1993	30
01AG002	Limestone River at Four Falls	199	1968-1993	26
01AG003	Aroostook River near Tinker (Reg)	6060	1975-2007	33
01AH005	Mamozekel River near Campbell River	230	1973-1990	18
01AJ001	Saint John River near East Florenceville (Reg)	34200	1952-1994	43
01AJ003	Meduxnekeag River near Belleville	1210	1968-2007	40
01AJ004	Big Presque Isle Stream at Tracey Mills	484	1968-2007	40
01AJ010	Becaguimec Stream at Coldstream	350	1974-2007	34
01AJ011	Cold Stream at Coldstream	156	1974-1993	20
01AK001	Shogomoc Stream near Trans Canada Highway	234	1919-40,1944-2007	86
01AK004	Saint John River below Mactaquac (Reg)	39900	1967-1994	28
01AK005	Middle Branch Nashwaaksis Stream near Royal Road	26.9	1966-1993	28
01AK007	Nackawic River near Temperance Vale	240	1968-2007	40
01AK008	Eel River near Scott Siding	531	1974-1993	20
01AL002	Nashwaak River at Durham Bridge	1450	1962-2007	46
01AL003	Hayden Brook near Narrows Mountain	6.48	1971-1993	23
01AL004	Narrows Mountain Brook near Narrows Mountain	3.89	1972-2003	32
01AM001	North Branch Oromocto River at Tracy	557	1963-2007	45
01AN001	Castaway Brook near Castaway	34.4	1972-81,1983-1993	21
01AN002	Salmon River at Castaway	1050	1974-2007	34
01AP002	Canaan River at East Canaan	668	1926-40,1963-2008	61
01AP004	Kennebecasis River at Apohaqui	1100	1962-2008	47
01AP006	Nerepis River near Fowlers Corner	293	1976-1993	18
01AQ001	Lepreau River at Lepreau	239	1917-2008	92
01AQ002	Magaguadavic River at Elmcroft (Reg)	1420	1917-32,1943-2007	81
01AR006	Dennis Stream near St. Stephen	115	1967-2008	42
01AR008	Bocabec River above Tide	43	1967-1979	13
01BC001	Restigouche River below Kedgwick River	3160	1963-2007	45
01BE001	Upsalquitch River at Upsalquitch	2270	1919-32,1944-2007	78
01BJ001	Tetagouche River near West Bathurst	363	1923-33,1952-1994	54
01BJ003	Jacquet River near Durham Centre	510	1965-2007	43
01BJ004	Eel River near Eel River Crossing	88.6	1968-1983	16
01BJ007	Restgouche River above Rafting Ground Brook	7740	1969-2007	39
01BK004	Nepisiquit River near Pabineau Falls (Reg)	2090	1958-1974	17
01BL001	Bass River at Bass River	175	1966-1990	25
01BL002	Rivière Caraquet at Burnsville	173	1970-2007	38
01BL003	Big Tracadie River at Murphy Bridge Crossing	383	1971-2007	37
01BO001	Southwest Miramichi River at Blackville	5050	1919-32,1962-2007	60
01BO002	Renous River at McGraw Brook	611	1966-1994	29
01BO003	Barnaby River below Semiwagan River	484	1973-1994	22
01BP001	Little Southwest Miramichi River at Lyttleton	1340	1952-2007	56
01BQ001	Northwest Miramichi River at Trout Brook	948	1962-2007	46
01BR001	Kouchibouguac River near Vautour	177	1931-32,1970-1994	27
01BS001	Coal Branch River at Beersville	166	1964-2008	45
01BU002	Petitcodiac River near Petitcodiac	391	1962-2008	47
01BU003	Turtle Creek at Turtle Creek	129	1963-2008	46
01BU004	Palmer's Creek near Dorchester	34.2	1967-1985	19
01BV005	Ratcliffe Brook below Otter Lake	29.3	1961-1971	11
01BV006	Point Wolfe River at Fundy National Park	130	1964-2008	45
01BV007	Upper Salmon River at Alma	181	1968-1978	11
01BD002	Matapedia Amont de la Rivière Assemetquagan, QC	2770	1970-92,1995,1997	25
01DL001	Kelley River (Mill Creek) at Eight Mile Ford, NS	63.2	1970-96,1999-2007	36
01BF001	Rivière Nouvelle au Pont, QC	1140	1965-1997	33

Table 2. Summary of physiographic and climatic characteristics for selected hydrometric stations (data from report by Environment Canada and New Brunswick Department of Municipal Affairs and Environment, 1987)

Station	Percentage of lakes+swamps (%)	Mean annual precipitation (mm)	Average water content of snow cover on March 31 (mm)
Saint John River (Fort Kent)	5.71	997	231
St Francis River	2.81	1060	224
Saint John River (Grand Falls)	4.90	1010	231
Green River	1.21	1070	252
Limestone River	9.78	975	159
Aroostook River	5.83	934	190
Mamozekel River	0.04	1030	198
Saint John River (East Florenceville)	4.97	1010	217
Meduxnekeag River	5.61	958	157
Big Presque Isle Stream	3.70	925	140
Becaguimec Stream	0.77	1130	126
Cold Stream	0.08	1100	129
Shogomoc Stream	11.9	1120	147
Saint John River (Mactaquac)	5.33	1010	205
Middle Branch Nashwaaksis Stream	2.16	1220	145
Nackawic River	5.11	1060	129
Eel River (Scott Siding)	13.3	1070	142
Nashwaak River	1.39	1210	167
Hayden Brook	0.56	1230	190
Narrows Mountain Brook	0.61	1230	190
North Branch Oromocto River	15.1	1150	117
Castaway Brook	6.60	1180	130
Salmon River	6.41	1130	146
Canaan River	3.57	1040	137
Kennebecasis River	0.72	1190	108
Nerepis River	1.28	1140	110
Lepreau River	10.2	1240	101
Magaguadavic River	7.39	1175	126
Dennis Stream	8.37	1160	110
Bocabec River	6.44	1180	85
Restigouche River (Kedgwick)	0.73	1140	240
Upsalquitch River	0.63	1080	232
Tetagouche River	2.24	988	235
Jacquet River	2.00	1050	235
Eel River (Eel River Crossing)	0.68	1100	216
Restigouche River (Rafting Ground)	0.77	1120	224
Nepisiquit River	2.35	1010	241
Bass River	8.11	1010	209
Rivière Caraquet	10.4	1130	194
Big Tracadie River	2.34	1090	204
Southwest Miramichi River	3.52	1090	177
Renous River	6.22	1180	199
Barnaby River	10.7	1080	170
Little Southwest Miramichi River	5.06	1180	222
Northwest Miramichi River	3.96	1130	213
Kouchibouguac River	11.7	1050	161
Coal Branch River	5.23	1070	150
Petitcodiac River	0.76	1030	124
Turtle Creek	0.31	1310	125
Palmer's Creek	0.15	1210	98
Ratcliffe Brook	3.14	1410	108
Point Wolfe River	1.05	1390	140
Upper Salmon River	0.54	1380	144
Rivère Matapedia, QC	2.54	1040	265
Kelley River, NS	4.29	1250	100
Rivière Nouvelle, QC	0.17	1060	228

Table 3. Results of single station flood frequency analyses using the 3 Parameter Lognormal (LN3) distribution

	Daily discharge				
Station	**QD2 (m^3/s)**	**QD10 (m^3/s)**	**QD20 (m^3/s)**	**QD50 (m^3/s)**	**QD100 (m^3/s)**
Saint John River (Fort Kent)	2303	3265	3582	3965	4237
St Francis River	197	315	359	416	458
Saint John River (Grand Falls)	3194	4663	5136	5701	6099
Green River	219	348	392	447	486
Limestone River	33.6	49.1	55.4	63.7	70.1
Aroostook River	936	1342	1481	1653	1777
Mamozekel River	39.9	65.7	76.0	89.8	100
Saint John River (East Florenceville)	4761	7239	7989	8861	9459
Meduxnekeag River	236	380	435	506	559
Big Presque Isle Stream	92.1	158	187	228	262
Becaguimec Stream	79.4	136	160	191	216
Cold Stream	34.1	63.0	75.7	93.3	107
Shogomoc Stream	36.5	57.5	65.4	75.6	83.3
Saint John River (Mactaquac)	5809	8877	10126	11802	13106
Middle Branch Nashwaaksis Stream	6.12	10.9	13.2	16.4	19.1
Nackawic River	51.4	84.1	97.6	116	130
Eel River (Scott Siding)	70.3	99.1	108	119	127
Nashwaak River	320	555	650	778	877
Hayden Brook	1.93	3.93	4.81	6.02	6.99
Narrows Mountain Brook	1.09	1.99	2.47	3.23	3.89
North Branch Oromocto River	120	216	262	330	387
Castaway Brook	8.44	12.9	14.5	16.6	18.1
Salmon River	197	258	277	298	313
Canaan River	144	207	228	253	271
Kennebecasis River	228	400	475	579	662
Nerepis River	83.3	124	139	159	174
Lepreau River	61.6	124	156	207	251
Magaguadavic River	220	352	405	476	531
Dennis Stream	24.1	38.9	44.8	52.6	58.7
Bocabec River	11.3	21.6	26.0	31.9	36.6
Restigouche River (Kedgwick)	573	871	976	1109	1206
Upsalquitch River	341	534	604	693	759
Tetagouche River	72.9	116	132	154	170
Jacquet River	111	162	180	203	219
Eel River (Eel River Crossing)	25.7	42.2	50.5	63.2	74.0
Restigouche River (Rafting Ground)	1331	2113	2434	2866	3203
Nepisiquit River	344	625	744	908	1039
Bass River	39.1	66.9	79.8	98.3	114
Rivière Caraquet	31.7	56.0	65.7	78.7	88.8
Big Tracadie River	61.9	96.8	110	128	141
Southwest Miramichi River	841	1315	1493	1724	1897
Renous River	131	228	273	336	388
Barnaby River	94.8	155	181	216	244
Little Southwest Miramichi River	222	424	526	678	808
Northwest Miramichi River	180	312	367	442	500
Kouchibouguac River	34.3	55.5	65.8	81.1	94.0
Coal Branch River	44.9	67.0	74.5	83.7	90.3
Petitcodiac River	87.0	137	156	179	197
Turtle Creek	37.1	64.4	75.7	90.8	103
Palmer's Creek	12.4	21.6	25.2	29.9	33.6
Ratcliffe Brook	12.3	25.1	30.7	38.7	45.2
Point Wolfe River	59.7	102	120	144	163
Upper Salmon River	82.3	138	161	193	219
Rivère Matapedia, QC	438	631	699	783	845
Kelley River, NS	17.3	30.7	37.8	48.8	58.3
Rivière Nouvelle, QC	258	384	428	483	523

Table 4. Results of single station flood frequency analyses using the Generalized Extreme Value (GEV) distribution

	Daily discharge				
Station	**QD2 (m^3/s)**	**QD10 (m^3/s)**	**QD20 (m^3/s)**	**QD50 (m^3/s)**	**QD100 (m^3/s)**
Saint John River (Fort Kent)	2313	3254	3542	3867	4080
St Francis River	196	315	361	422	467
Saint John River (Grand Falls)	3196	4666	5115	5623	5954
Green River	219	349	394	448	486
Limestone River	33.5	48.9	55.4	64.4	71.6
Aroostook River	945	1328	1447	1582	1671
Mamozekel River	40.0	65.2	75.4	89.3	100
Saint John River (East Florenceville)	4745	7269	7982	8747	9223
Meduxnekeag River	236	378	433	505	559
Big Presque Isle Stream	92.1	156	187	232	272
Becaguimec Stream	79.6	135	158	190	216
Cold Stream	34.1	62.3	75.5	95	111
Shogomoc Stream	36.4	57.7	66.2	77.4	86.1
Saint John River (Mactaquac)	5840	8775	9964	11562	12804
Middle Branch Nashwaaksis Stream	6.09	10.8	13.3	17.2	20.8
Nackawic River	51.0	83.7	98.5	120	138
Eel River (Scott Siding)	70.5	98.9	107	116	122
Nashwaak River	320	551	650	787	897
Hayden Brook	1.94	3.88	4.78	6.09	7.20
Narrows Mountain Brook	1.08	1.96	2.53	3.56	4.64
North Branch Oromocto River	120	213	262	342	417
Castaway Brook	8.44	12.9	14.6	16.6	18.1
Salmon River	198	258	275	292	302
Canaan River	144	208	228	252	267
Kennebecasis River	229	396	472	583	675
Nerepis River	83.3	124	139	160	176
Lepreau River	61.1	121	159	225	293
Magaguadavic River	219	351	409	491	558
Dennis Stream	24.0	38.8	45.0	53.7	60.7
Bocabec River	11.3	21.4	26.0	32.8	38.4
Restigouche River (Kedgwick)	572	874	985	1123	1223
Upsalquitch River	340	532	601	688	750
Tetagouche River	72.8	116	132	155	172
Jacquet River	111	163	181	204	221
Eel River (Eel River Crossing)	26.0	41.5	49.8	63.1	75.5
Restigouche River (Rafting Ground)	1331	2098	2428	2888	3260
Nepisiquit River	349	611	719	866	981
Bass River	39.2	66.0	79.4	100	119
Rivière Caraquet	31.6	55.8	66.2	80.8	92.6
Big Tracadie River	61.7	96.8	111	130	145
Southwest Miramichi River	838	1318	1509	1762	1956
Renous River	132	225	271	339	399
Barnaby River	95.1	153	179	215	244
Little Southwest Miramichi River	221	418	531	724	913
Northwest Miramichi River	179	310	369	454	524
Kouchibouguac River	34.8	54.2	63.7	78.0	90.5
Coal Branch River	45.0	66.8	74.0	82.3	88.0
Petitcodiac River	86.7	138	158	184	204
Turtle Creek	37.0	64.0	75.9	92.8	107
Palmer's Creek	12.4	21.4	25.0	29.9	33.7
Ratcliffe Brook	12.3	24.6	30.3	38.6	45.5
Point Wolfe River	60.3	100	117	141	159
Upper Salmon River	82.4	136	160	194	222
Rivère Matapedia, QC	437	638	711	802	869
Kelley River, NS	17.2	30.4	38.6	53.4	68.6
Rivière Nouvelle, QC	259	383	425	474	507

Table 5. Parameters for the 3 parameter lognormal distribution (single station analysis), the Anderson-Darling (AD) statistic and the negative log-likelyhood (NNL) value

Station	Shape	Scale	Threshold	AD	NLL
Saint John River (Fort Kent)	8.19	0.184	-1305	0.338	625.6
St Francis River	5.39	0.337	-22.90	0.189	326.2
Saint John River (Grand Falls)	8.80	0.156	-3446	0.232	643.8
Green River	5.85	0.244	-129.1	0.318	175.9
Limestone River	3.03	0.437	12.88	0.161	94.16
Aroostook River	7.04	0.237	-207	0.223	231.7
Mamozekel River	3.54	0.436	5.410	0.372	74.32
Saint John River (East Florenceville)	10.02	0.0815	-17749	0.190	384.4
Meduxnekeag River	5.49	0.364	-6.088	0.426	235.9
Big Presque Isle Stream	4.11	0.573	31.40	0.366	198.7
Becaguimec Stream	4.21	0.477	12.18	0.319	166.2
Cold Stream	3.35	0.548	5.661	0.200	83.30
Shogomoc Stream	3.58	0.358	0.6118	0.296	341.7
Saint John River (Mactaquac)	8.26	0.455	1937	0.162	249.0
Middle Branch Nashwaaksis Stream	1.34	0.635	2.294	0.333	64.57
Nackawic River	3.65	0.481	13.09	0.638	173.3
Eel River (Scott Siding)	4.99	0.139	-77.12	0.305	88.84
Nashwaak River	5.70	0.452	20.88	0.237	291.0
Hayden Brook	0.68	0.545	-0.05081	0.445	34.40
Narrows Mountain Brook	-0.76	0.835	0.6218	0.215	15.36
North Branch Oromocto River	4.22	0.684	52.33	0.336	236.8
Castaway Brook	2.25	0.301	-1.080	0.233	51.88
Salmon River	6.43	0.0736	-426.2	0.304	178.3
Canaan River	5.53	0.175	-107.9	0.272	317.5
Kennebecasis River	5.14	0.543	57.46	0.219	279.7
Nerepis River	4.23	0.360	14.38	0.307	83.33
Lepreau River	3.54	0.803	27.10	0.410	436.1
Magaguadavic River	5.16	0.439	45.34	0.517	466.5
Dennis Stream	3.00	0.431	4.072	0.163	150.2
Bocabec River	2.41	0.509	0.1653	0.233	41.04
Restigouche River (Kedgwick)	6.54	0.280	-117.7	0.322	300.7
Upsalquitch River	6.01	0.302	-68.63	0.280	486.5
Tetagouche River	4.24	0.376	3.532	0.190	252.7
Jacquet River	4.77	0.280	-6.382	0.154	211.3
Eel River (Eel River Crossing)	2.31	0.754	15.59	0.370	55.19
Restigouche River (Rafting Ground)	6.86	0.466	375.2	0.243	293.2
Nepisiquit River	5.70	0.515	43.76	0.273	109.8
Bass River	3.11	0.629	16.67	0.177	101.6
Rivière Caraquet	3.47	0.439	-0.3835	0.301	154.5
Big Tracadie River	4.01	0.382	6.634	0.212	165.3
Southwest Miramichi River	6.71	0.356	20.15	0.578	425.7
Renous River	4.41	0.609	49.31	0.348	154.6
Barnaby River	4.16	0.516	30.50	0.266	108.2
Little Southwest Miramichi River	4.86	0.738	93.82	0.380	334.3
Northwest Miramichi River	5.05	0.481	24.16	0.350	263.8
Kouchibouguac River	2.68	0.699	19.64	0.519	101.1
Coal Branch River	4.22	0.220	-22.98	0.469	185.5
Petitcodiac River	4.60	0.319	-12.60	0.533	229.3
Turtle Creek	3.50	0.470	4.082	0.147	191.4
Palmer's Creek	2.57	0.415	-0.5980	0.212	59.01
Ratcliffe Brook	2.48	0.569	0.3231	0.197	36.68
Point Wolfe River	3.85	0.502	12.94	0.415	205.9
Upper Salmon River	4.12	0.503	21.07	0.265	53.32
Rivère Matapedia, QC	6.18	0.263	-42.79	0.582	156.5
Kelley River, NS	1.99	0.811	10.03	0.300	115.2
Rivière Nouvelle, QC	5.80	0.254	-70.98	0.399	192.9

Table 6. Parameters for the Generalized Extreme Value distribution function (single station analysis), the Anderson Darling (AD) statistic and the negative log-likelyhood (NLL) value

Station	Loc	Scale	Shape	AD	NLL
Saint John River (Fort Kent)	2092	620	-0.168	0.311	625.4
St Francis River	173	62.7	0.008	0.171	326.1
Saint John River (Grand Falls)	2853	967	-0.167	0.230	643.6
Green River	192	76.3	-0.079	0.323	175.9
Limestone River	30.8	7.37	0.079	0.143	94.13
Aroostook River	856	250	-0.159	0.235	231.6
Mamozekel River	35.4	12.5	0.051	0.370	74.40
Saint John River (East Florenceville)	4115	1791	-0.228	0.203	384.3
Meduxnekeag River	209	74.6	0.008	0.416	235.9
Big Presque Isle Stream	81.9	26.9	0.175	0.315	198.8
Becaguimec Stream	69.9	26.2	0.082	0.355	166.4
Cold Stream	29.5	12.2	0.156	0.192	83.40
Shogomoc Stream	32.4	10.8	0.031	0.304	341.6
Saint John River (Mactaquac)	5298	1468	0.045	0.176	249.2
Middle Branch Nashwaaksis Stream	5.39	1.82	0.244	0.335	64.88
Nackawic River	45.6	14.5	0.133	0.619	173.4
Eel River (Scott Siding)	63.7	19.5	-0.202	0.318	88.75
Nashwaak River	279	110	0.085	0.213	291.1
Hayden Brook	1.62	0.85	0.148	0.397	34.33
Narrows Mountain Brook	0.98	0.264	0.416	0.170	15.51
North Branch Oromocto River	107	34.1	0.269	0.282	236.7
Castaway Brook	7.53	2.5	-0.037	0.235	51.90
Salmon River	182	44.7	-0.259	0.318	178.1
Canaan River	129	40.8	-0.142	0.260	317.4
Kennebecasis River	201	73.5	0.139	0.216	280.0
Nerepis River	75.6	21.0	0.016	0.301	83.32
Lepreau River	53.6	18.9	0.385	0.255	435.9
Magaguadavic River	196	61.2	0.105	0.405	465.5
Dennis Stream	21.4	7.00	0.084	0.126	150.0
Bocabec River	9.62	4.45	0.141	0.199	40.95
Restigouche River (Kedgwick)	510	169	-0.038	0.319	300.6
Upsalquitch River	301	108	-0.043	0.298	486.5
Tetagouche River	64.8	21.9	0.027	0.181	252.7
Jacquet River	101	29.0	-0.047	0.154	211.3
Eel River (Eel River Crossing)	23.7	5.77	0.264	0.408	55.70
Restigouche River (Rafting Ground)	1196	361	0.092	0.218	293.3
Nepisiquit River	302	128	0.061	0.316	110.0
Bass River	35.1	10.7	0.212	0.159	101.8
Rivière Caraquet	27.3	11.3	0.094	0.242	154.2
Big Tracadie River	55.2	17.6	0.045	0.212	165.3
Southwest Miramichi River	748	245	0.030	0.532	425.4
Renous River	117	38.5	0.189	0.337	154.8
Barnaby River	85.1	26.7	0.108	0.291	108.5
Little Southwest Miramichi River	195	67.1	0.327	0.313	334.4
Northwest Miramichi River	157	59.1	0.125	0.290	263.6
Kouchibouguac River	31.7	8.04	0.188	0.611	101.9
Coal Branch River	40.1	13.6	-0.121	0.478	185.4
Petitcodiac River	76.8	27.2	0.007	0.513	229.0
Turtle Creek	32.3	12.4	0.110	0.138	191.5
Palmer's Creek	10.8	4.48	0.045	0.220	59.07
Ratcliffe Brook	10.3	5.38	0.145	0.212	36.83
Point Wolfe River	53.2	19.3	0.075	0.389	206.3
Upper Salmon River	73.1	24.7	0.112	0.266	53.40
Rivère Matapedia, QC	397	112	-0.037	0.594	156.4
Kelley River, NS	15.6	4.08	0.393	0.266	115.5
Rivière Nouvelle, QC	232	76	-0.105	0.379	192.9

Table 7. Regional regression coefficient estimates and R^2 (GEV distribution)

	a	***b1***	***b2***	**R^{2*}**
MAFL**	0.463476	0.884	*	0.984
	4.2645E-06	0.926	1.617	0.990
QD2 (m^3/s)	0.394690	0.897	*	0.985
	1.1131E-05	0.935	1.460	0.990
QD10 (m^3/s)	0.753188	0.871	*	0.981
	1.3152E-06	0.919	1.848	0.988
QD20 (m^3/s)	0.950031	0.857	*	0.977
	5.5022E-07	0.910	2.002	0.987
QD50 (m^3/s)	1.273837	0.839	*	0.971
	1.7180E-07	0.896	2.205	0.983
QD100 (m^3/s)	1.580312	0.824	*	0.964
	7.0216E-08	0.886	2.360	0.978

* The R^2 was obtained from the log-transformed regression equations.

** Represents the Mean Annual Flood (MAFL), to be used in conjuction with the index-flood method.

Range of application of regression equations:
Drainage area = 3.89 km^2 to 39900 km^2
Mean Annual Precipitation = 925 mm to 1410 mm

Table 8. Regional flood indices using the index of flow method in New Brunswick (values in parentheses represents the coefficient of variations (Cv,%)

	QD2	QD10	QD20	QD50	QD100
	Averaging Approach (excluding 4 largest basins)				
MAFL	0.92 (4.2%)	1.50 (5.6%)	1.76 (9.3%)	2.13 (15.3%)	2.45 (20.7%)
QD2	1.00 (n/a)	1.64 (9.3%)	1.93 (13.5%)	2.35 (19.8%)	2.70 (25.4%)
	Averaging Approach (4 largest basins only)				
MAFL	0.97 (2.0%)	1.43 (3.8%)	1.58 (4.1%)	1.75 (5.6%)	1.87 (7.6%)
QD2	1.00 (n/a)	1.47 (3.7%)	1.62 (4.9%)	1.80 (7.2%)	1.93 (9.4%)
	Pooling Approach (excluding 4 largest basins)				
MAFL	0.92	1.51	1.76	2.10	2.36
QD2	1.00	1.65	1.93	2.31	2.62
	Pooling Approach (4 largest basins only)				
MAFL	0.98	1.43	1.56	1.71	1.81
QD2	1.00	1.46	1.60	1.75	1.85

Table 9. Results of mean and maximum QP/QD ratio and associated variability (Cv, %) for analysed hydrometric stations

Station	QP/QD Mean Ratio	QP/QD Cv (%)	Maximum Recorded QP/QD Ratio
Saint John River (Fort Kent)	1.04	7.11	1.48
St Francis River	1.01	0.90	1.05
Saint John River (Grand Falls)	1.07	11.9	1.78
Green River	1.07	5.00	1.20
Limestone River	1.21	16.9	2.08
Aroostook River	1.14	20.2	2.01
Mamozekel River	1.18	9.80	1.45
Saint John River (East Florenceville)	1.07	7.03	1.25
Meduxnekeag River	1.13	8.97	1.52
Big Presque Isle Stream	1.14	8.43	1.37
Becaguimec Stream	1.18	9.00	1.41
Cold Stream	1.33	17.8	2.05
Shogomoc Stream	1.03	2.06	1.09
Saint John River (Mactaquac)	1.07	4.16	1.19
Middle Branch Nashwaaksis Stream	1.45	27.8	2.61
Nackawic River	1.14	7.21	1.31
Eel River (Scott Siding)	1.02	1.92	1.07
Nashwaak River	1.19	11.0	1.51
Hayden Brook	1.90	32.4	3.35
Narrows Mountain Brook	1.63	26.0	2.70
North Branch Oromocto River	1.23	12.0	1.70
Castaway Brook	1.29	11.9	1.71
Salmon River	1.14	6.70	1.35
Canaan River	1.19	12.6	1.83
Kennebecasis River	1.19	10.2	1.54
Nerepis River	1.48	19.3	2.10
Lepreau River	1.20	10.0	1.65
Magaguadavic River	1.08	7.71	1.41
Dennis Stream	1.25	16.7	1.82
Bocabec River	1.30	12.8	1.56
Restigouche River (Kedgwick)	1.05	4.04	1.18
Upsalquitch River	1.06	3.55	1.16
Tetagouche River	1.14	8.98	1.47
Jacquet River	1.17	8.62	1.43
Eel River (Eel River Crossing)	1.14	6.51	1.29
Restigouche River (Rafting Ground)	1.05	4.57	1.24
Nepisiquit River	1.08	6.43	1.25
Bass River	1.17	9.14	1.42
Rivière Caraquet	1.17	9.33	1.54
Big Tracadie River	1.07	4.66	1.28
Southwest Miramichi River	1.14	13.9	1.68
Renous River	1.22	20.6	2.18
Barnaby River	1.11	7.30	1.32
Little Southwest Miramichi River	1.11	6.78	1.35
Northwest Miramichi River	1.14	10.0	1.61
Kouchibouguac River	1.19	8.99	1.52
Coal Branch River	1.34	16.8	2.02
Petitcodiac River	1.28	18.9	2.12
Turtle Creek	1.42	18.7	2.11
Palmer's Creek	1.78	21.4	2.53
Ratcliffe Brook	1.33	7.76	1.49
Point Wolfe River	1.84	26.0	2.99
Upper Salmon River	1.86	22.7	2.42
Rivère Matapedia, QC	N/A	N/A	N/A
Kelley River, NS	1.48	22.4	2.17
Rivière Nouvelle, QC	N/A	N/A	N/A

Note: QP/QD represents the ratio between the instantaneous and daily flow

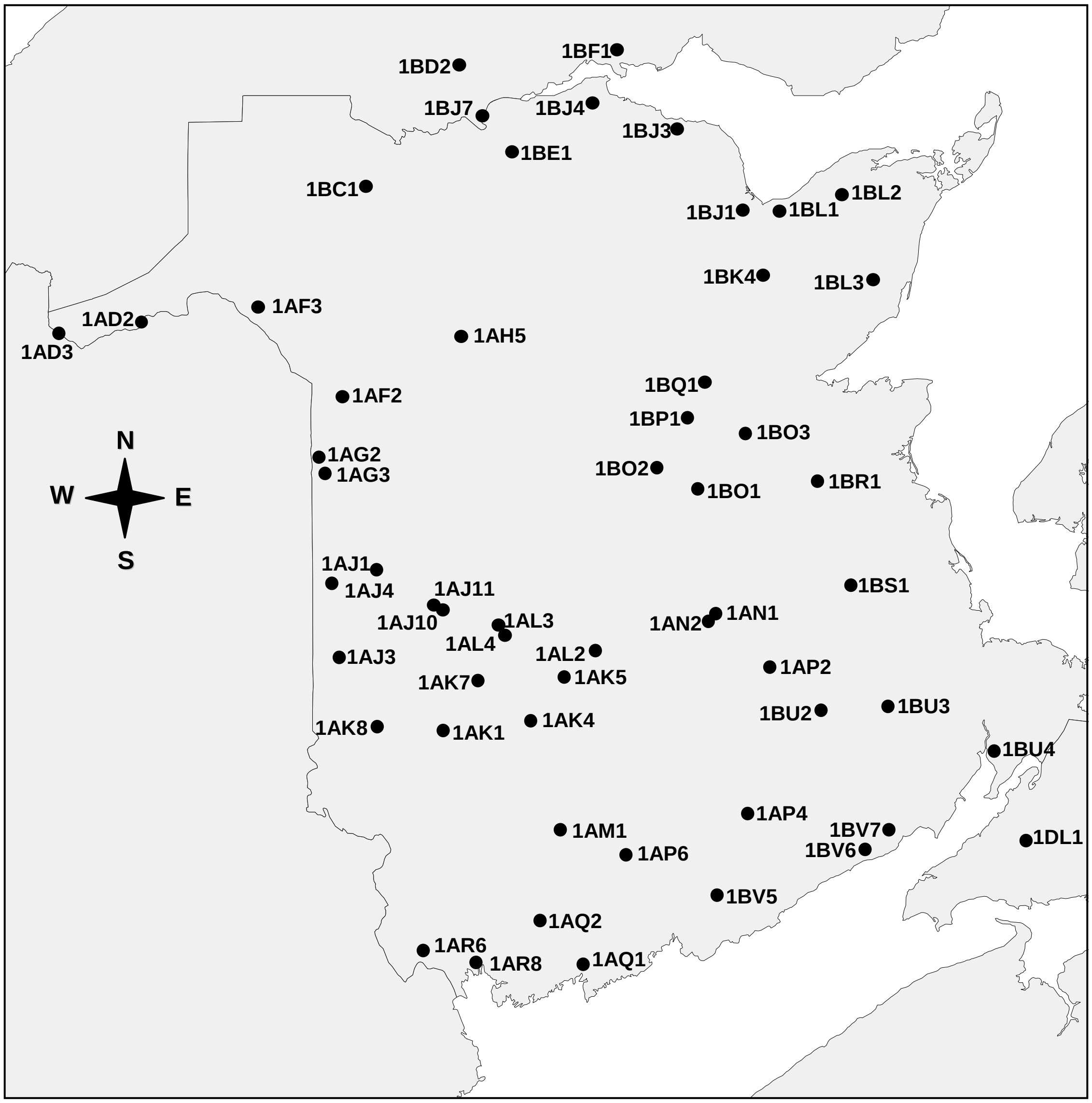


Figure 1. Location of selected hydrometric stations (56 stations).

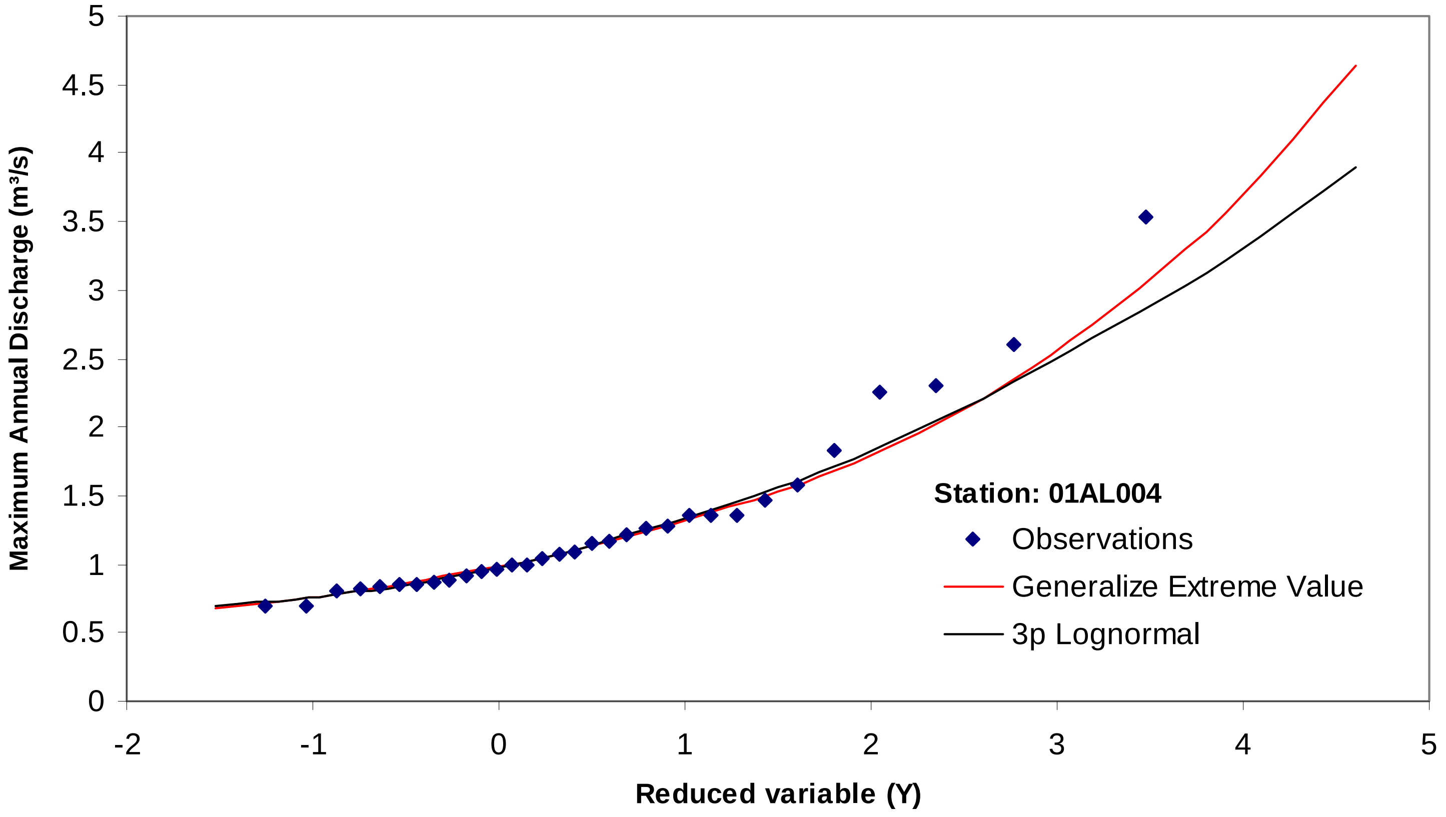


Figure 2. Flood frequency analysis for Narrows Mountain Brook (NB), station 01AL004

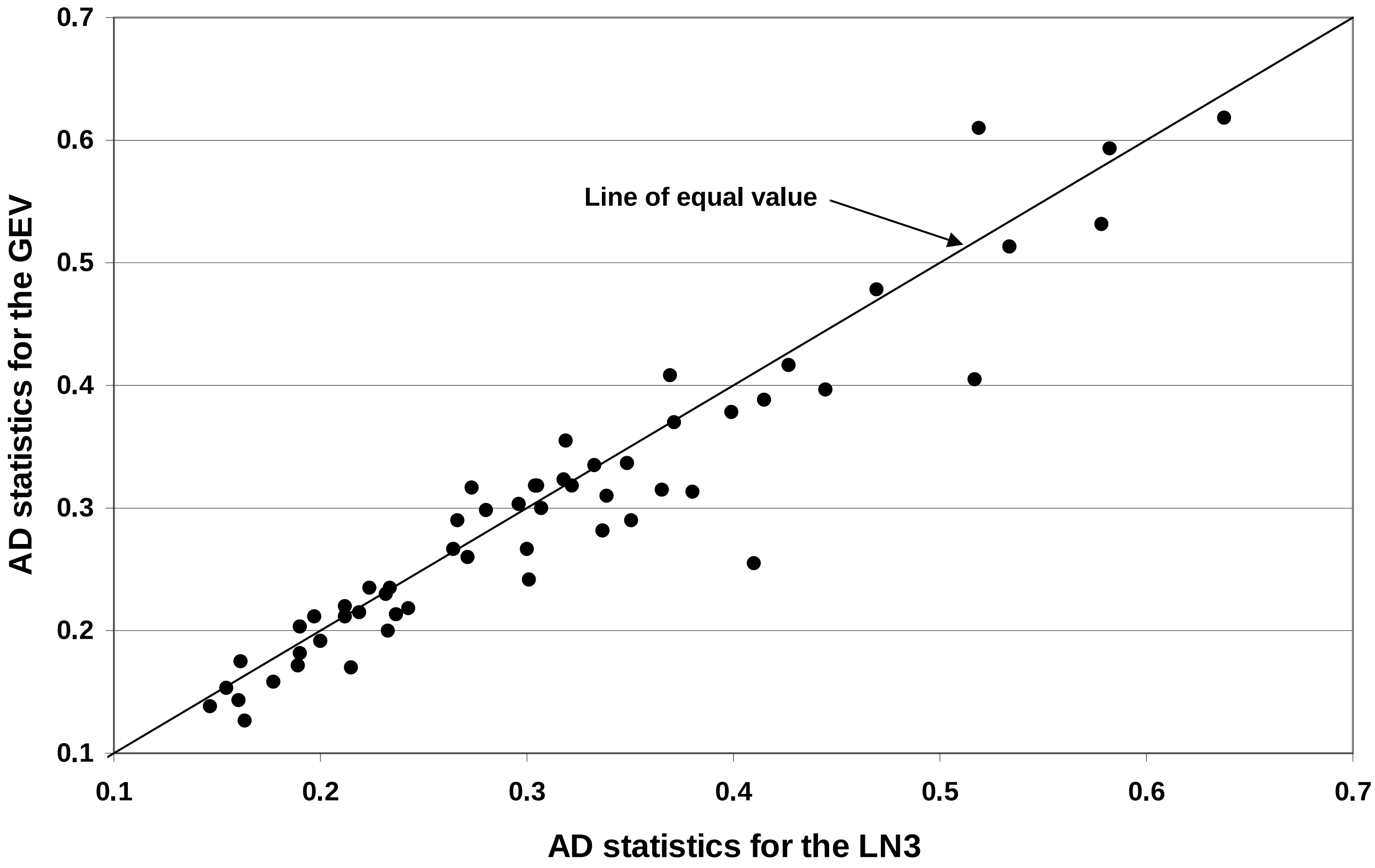


Figure 3. Relation between the Anderson-Darling (AD) statistics obtained from the 3-parameter Lognormal (LN3) and Generalized Extreme Value (GEV) distributions

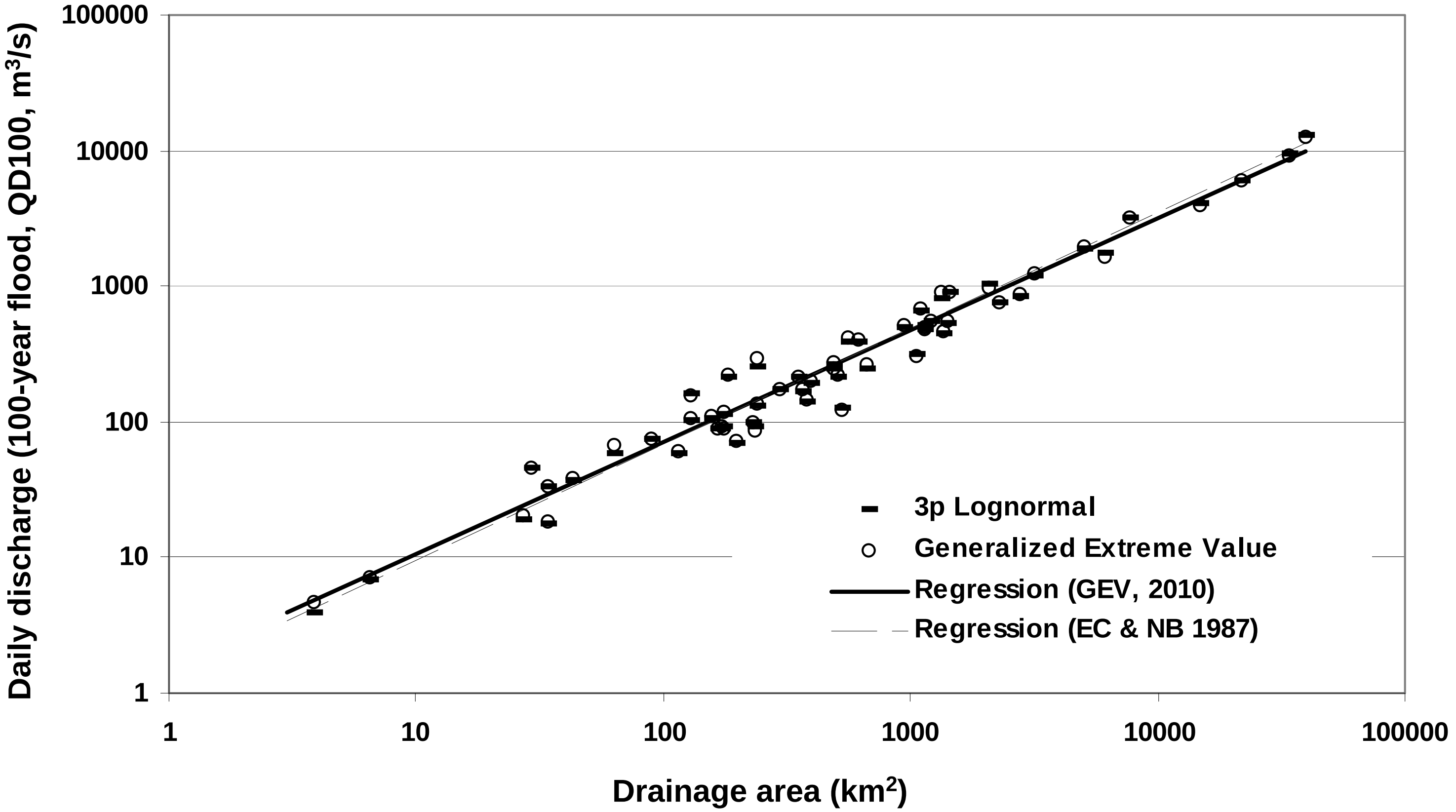


Figure 4. Estimated 100-year flood (daily discharge) as a function of drainage area (km^2) for all 56 hydrometric stations (GEV and LN3). Regional regression line for both the present study (QD100 = 1.58 A$^{0.842}$) and the EC & NB study (1987; QD100= 1.33 A$^{0.855}$) are presented.

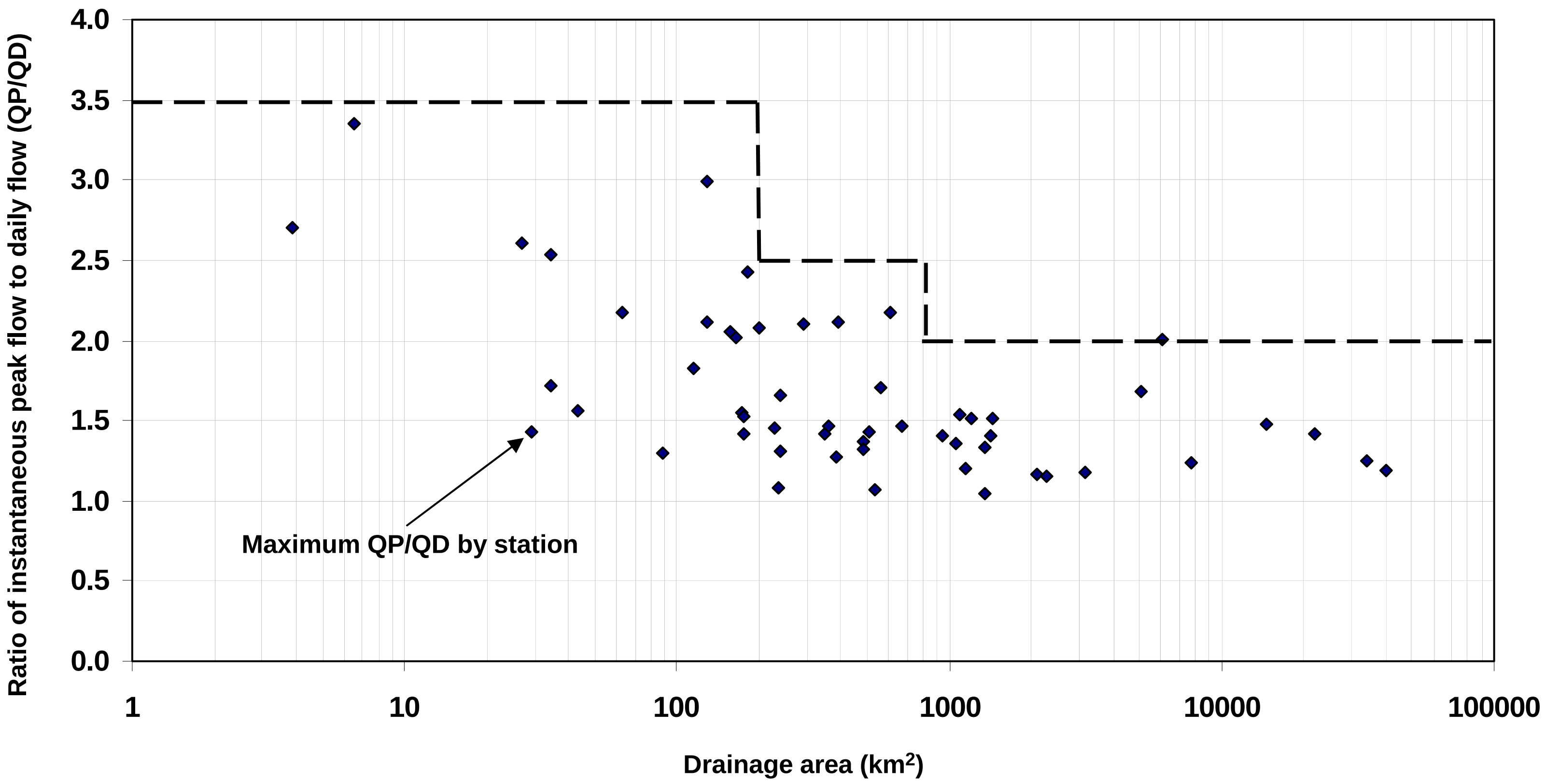


Figure 5. Ratio of instantaneous peak flow to daily flow (QP/QD) for the 54 analysed hydrometric stations (see Table 9 for more details).

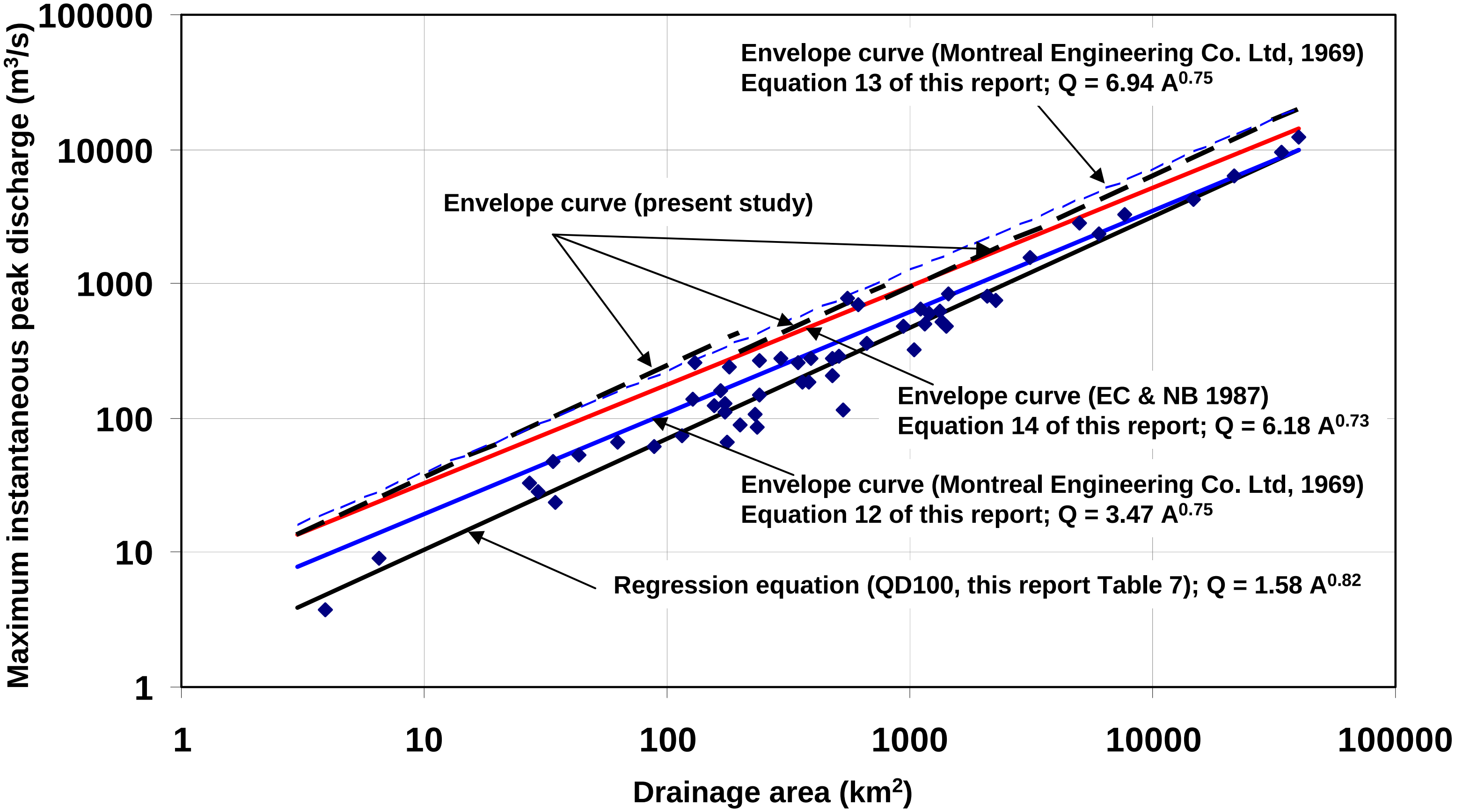


Figure 6. Envelope curve of the present study for instantaneous flows (m^3/s) in relation to those of previous studies. Data points represent the maximum instantaneous discharge (highest recorded flow) for each station in NB.

Appendix A

Single Station Flood Frequency Analyses

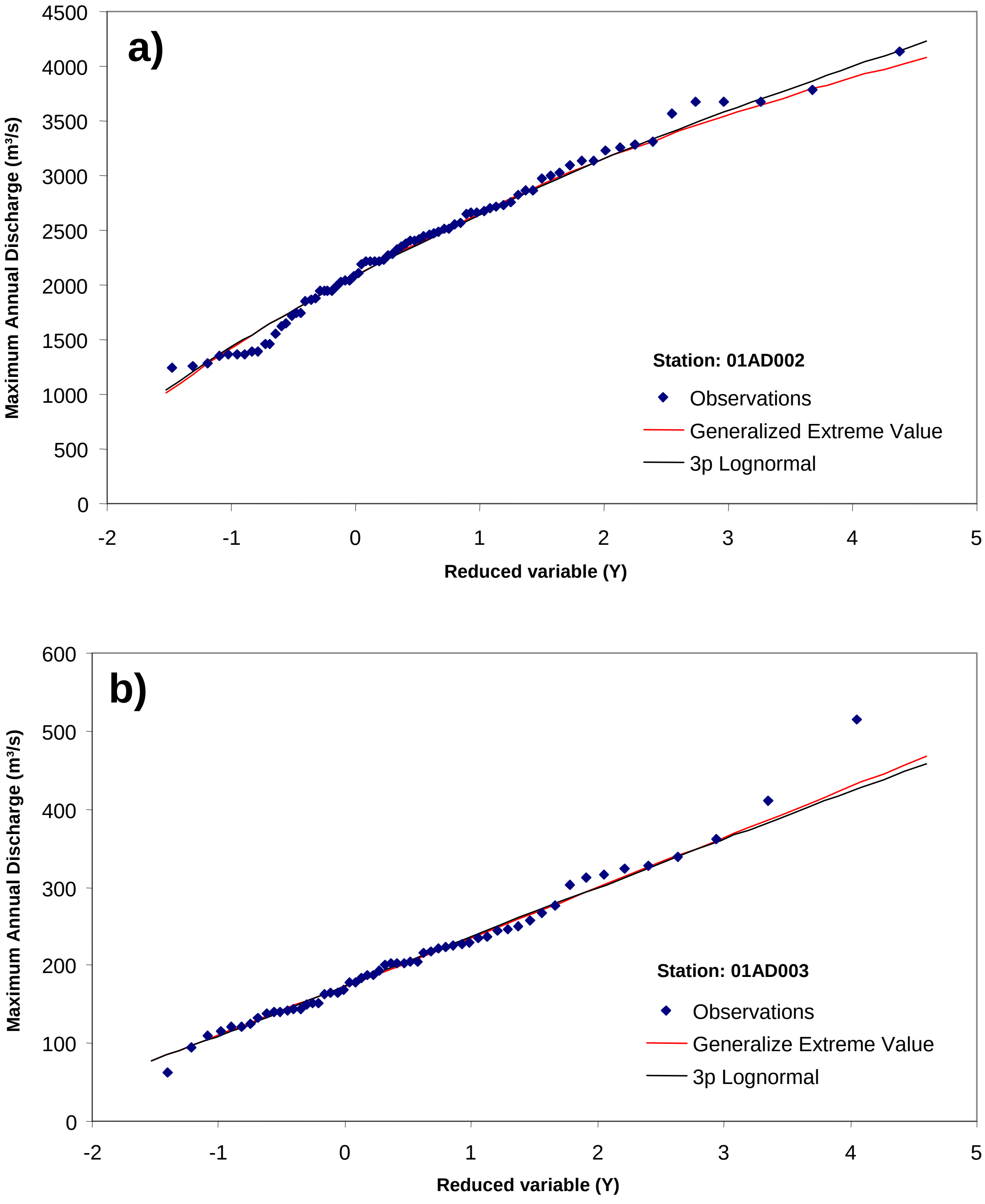


Figure A.1 Flood frequency analysis for a) Saint John River at Fort Kent and b) St Francis River

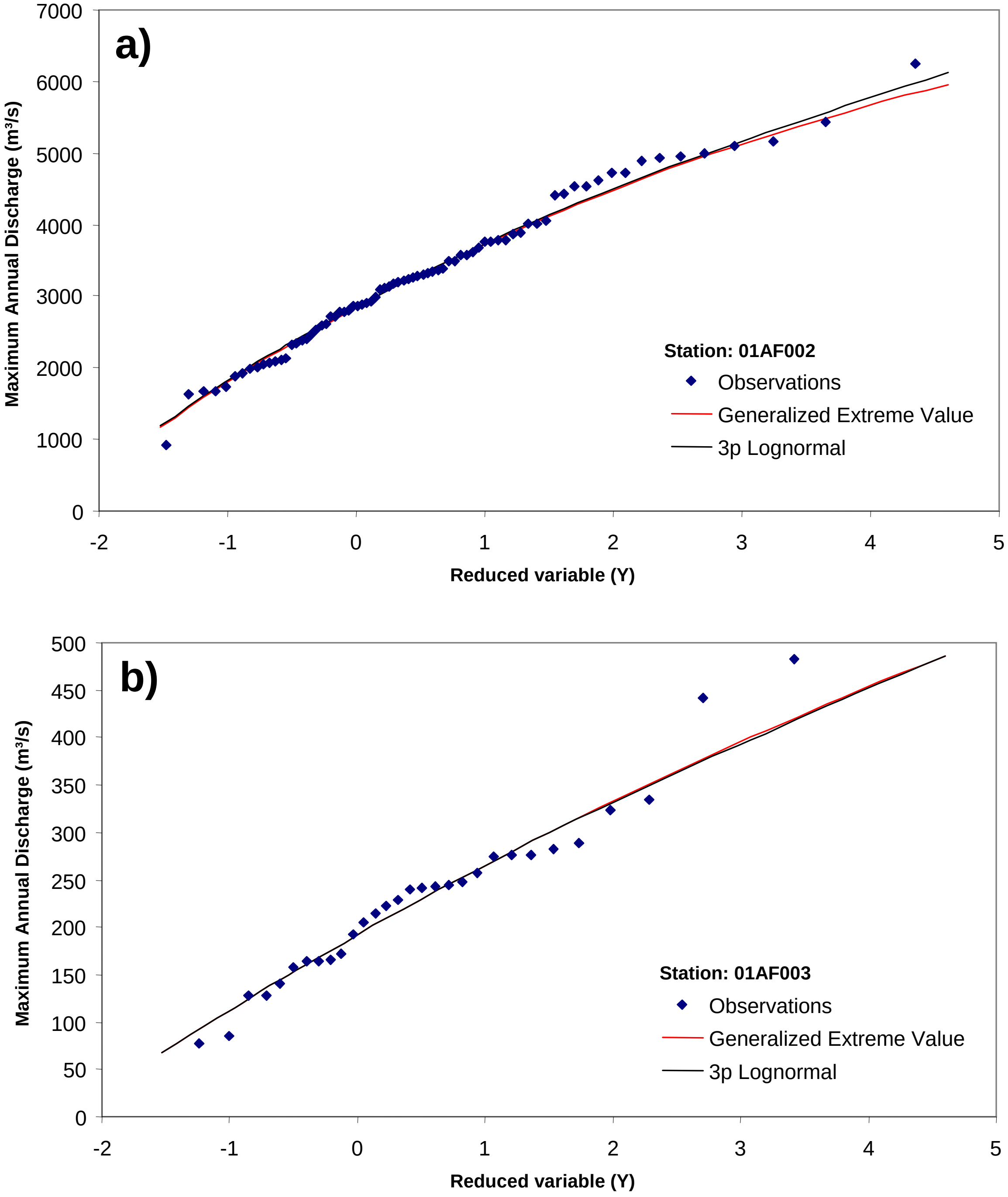
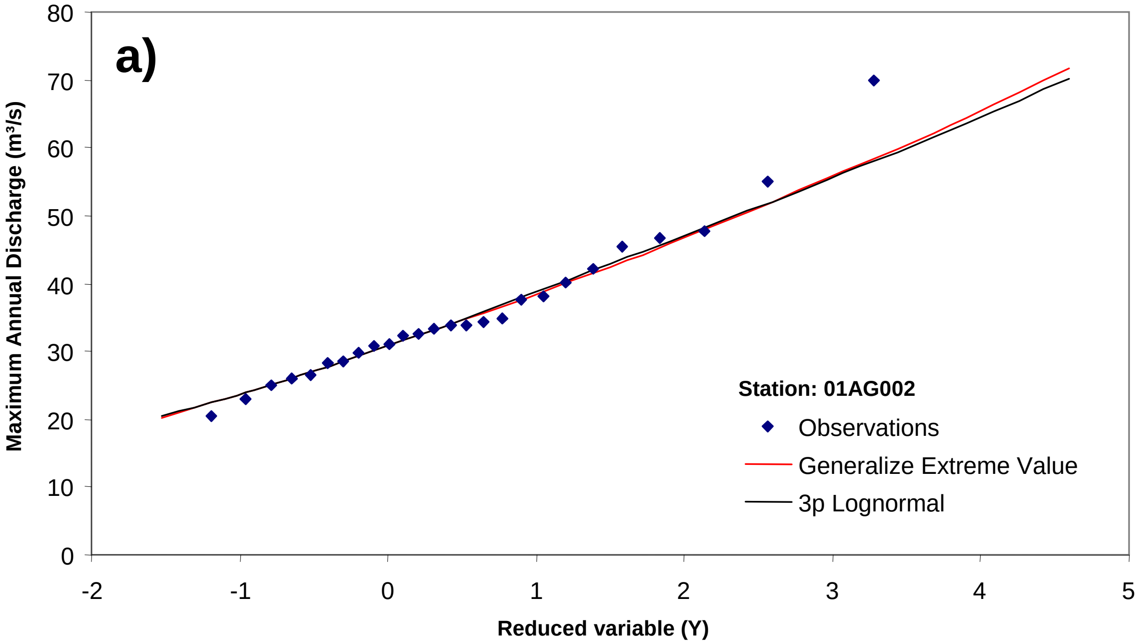


Figure A.2 Flood frequency analysis for a) Saint John River at Grand Falls and b) Green River



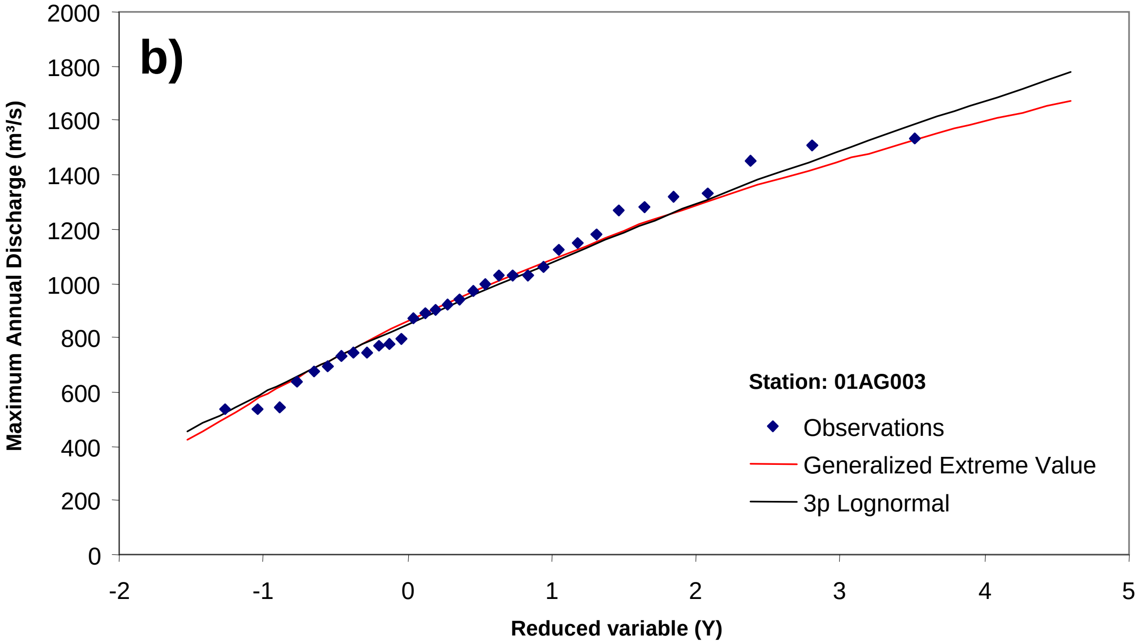
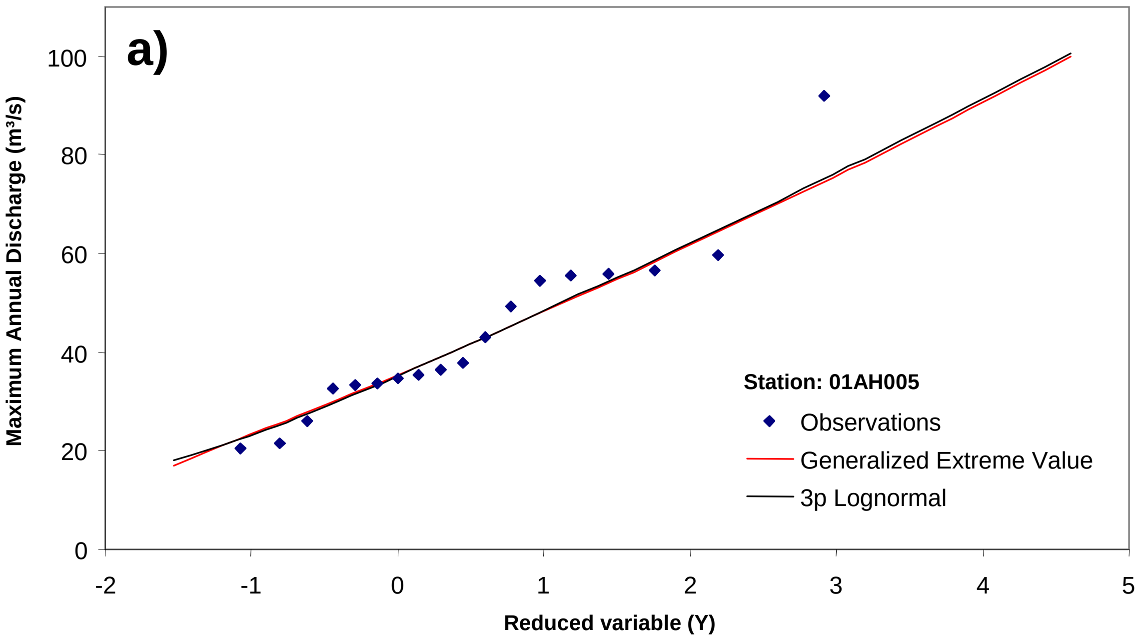


Figure A.3 Flood frequency analysis for a) Limestone River and b) Aroostook River



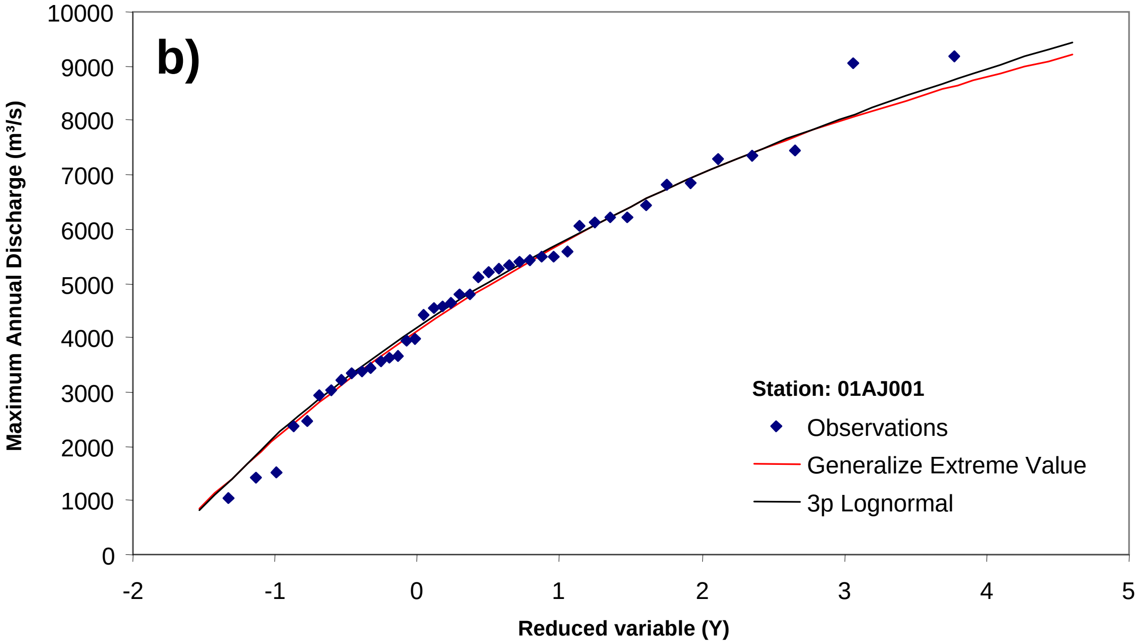
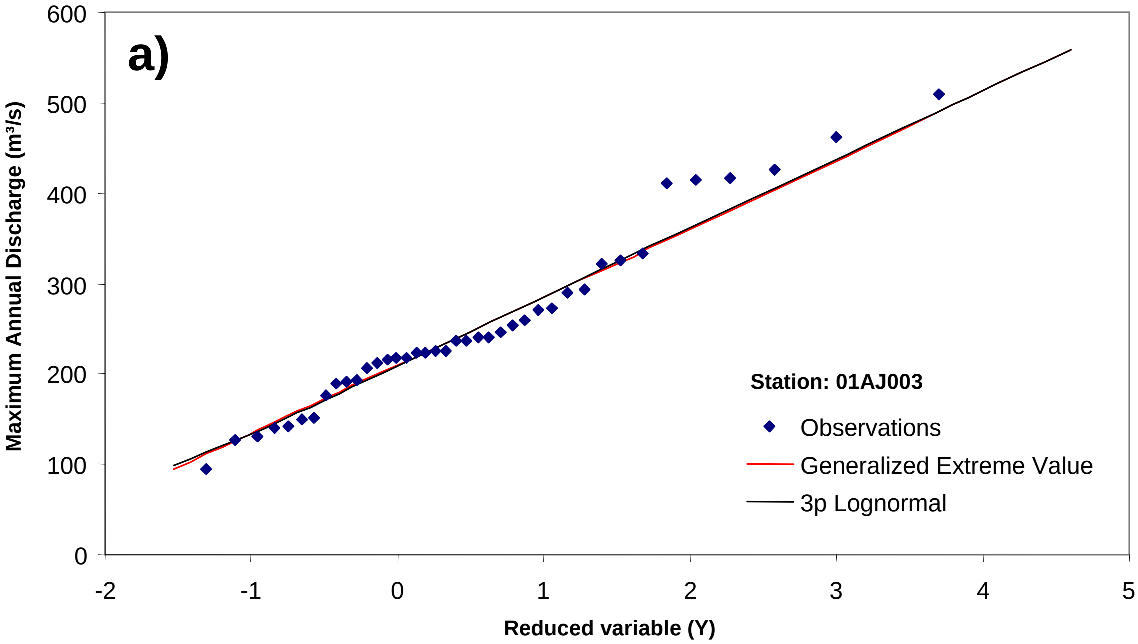


Figure A.4 Flood frequency analysis for a) Mamozekel River and b) Saint John River near East Florenceville



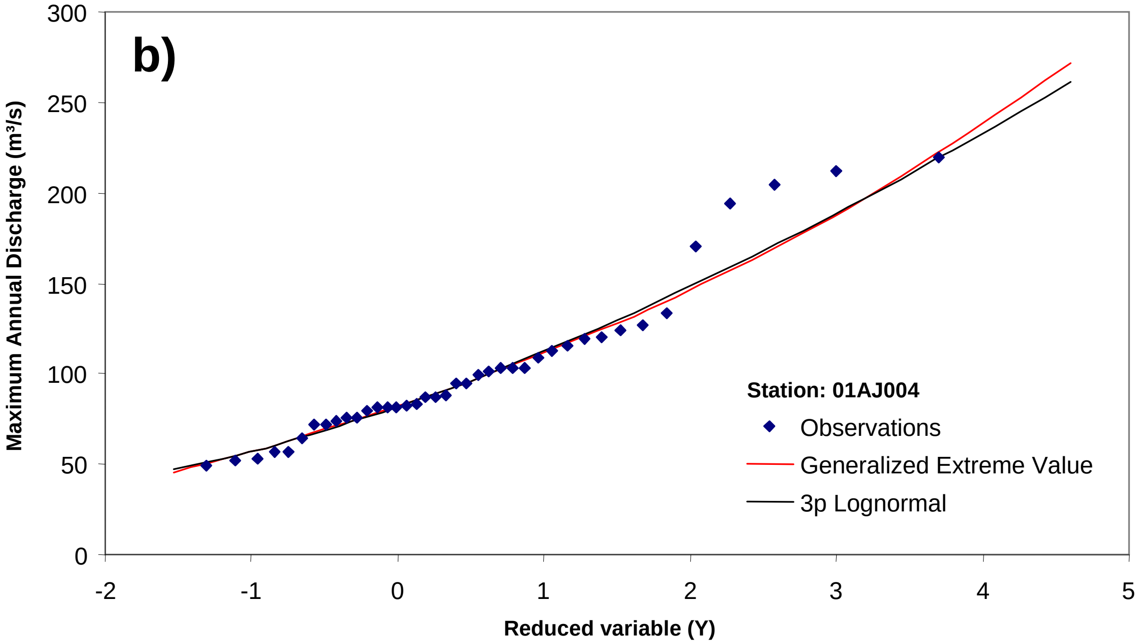


Figure A.5 Flood frequency analysis for a) Meduxnekeag River and b) Big Presque Isle Stream

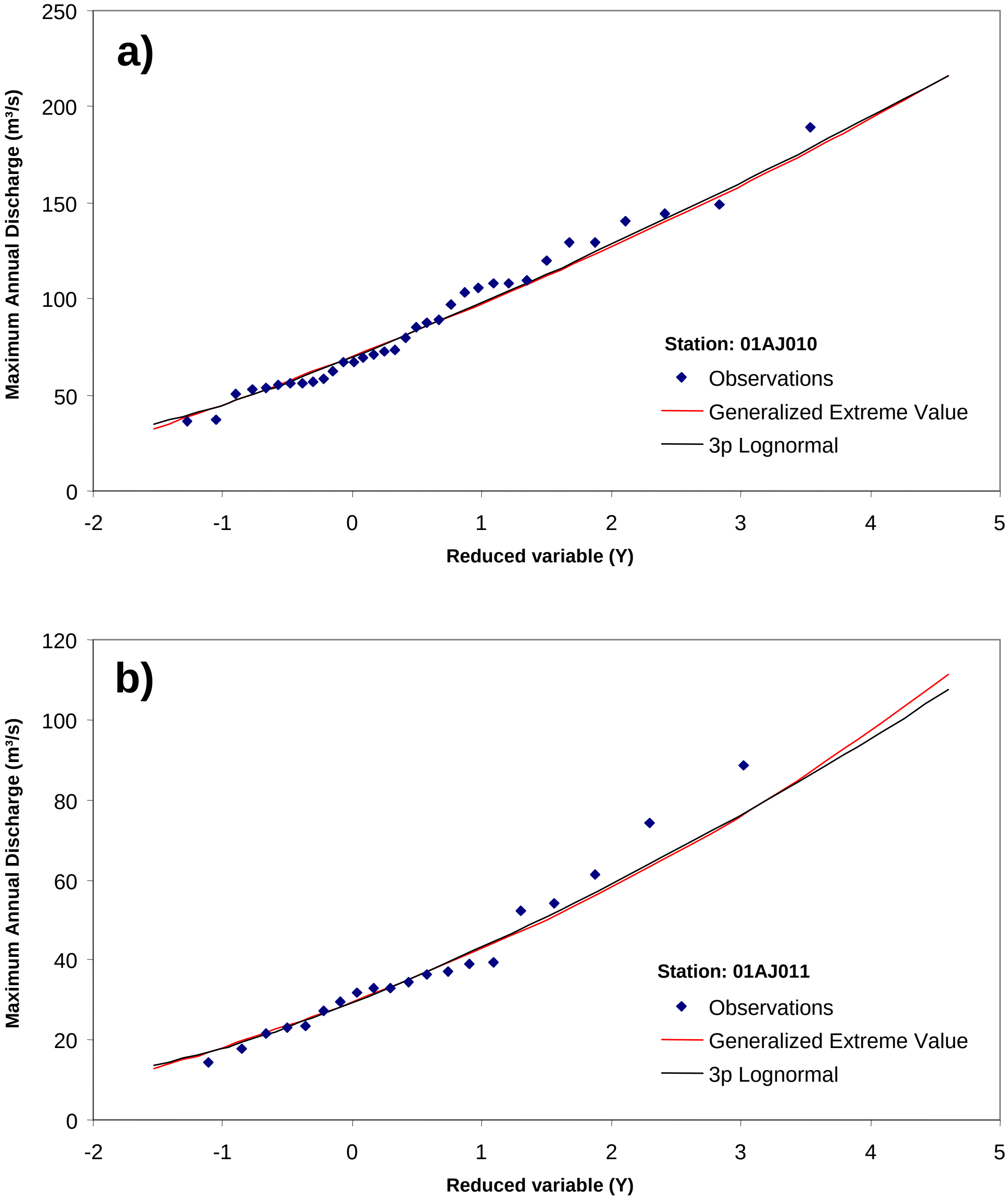
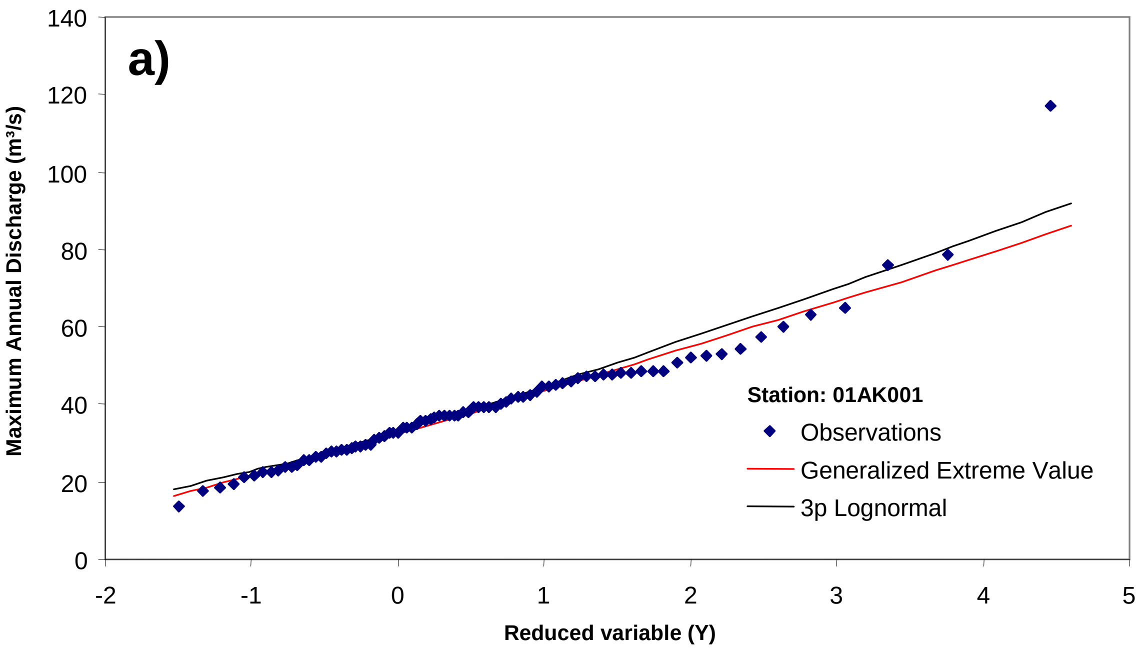


Figure A.6 Flood frequency analysis for a) Becaguimec Stream and b) Cold Stream



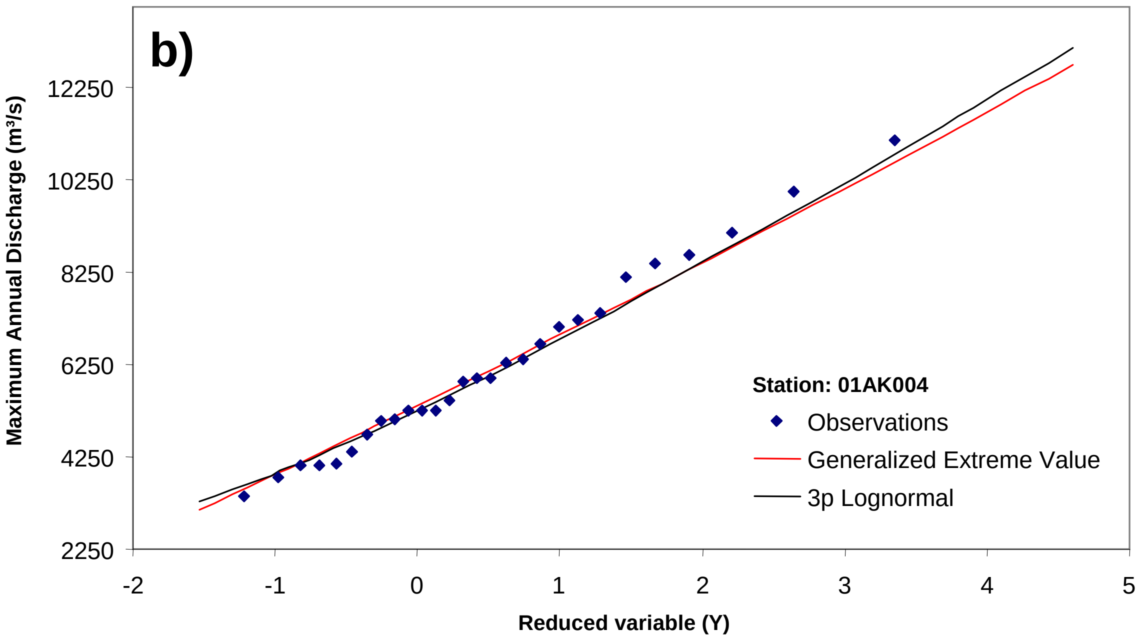


Figure A.7 Flood frequency analysis for a) Shogomoc Stream and b) Saint John River below Mactaquac

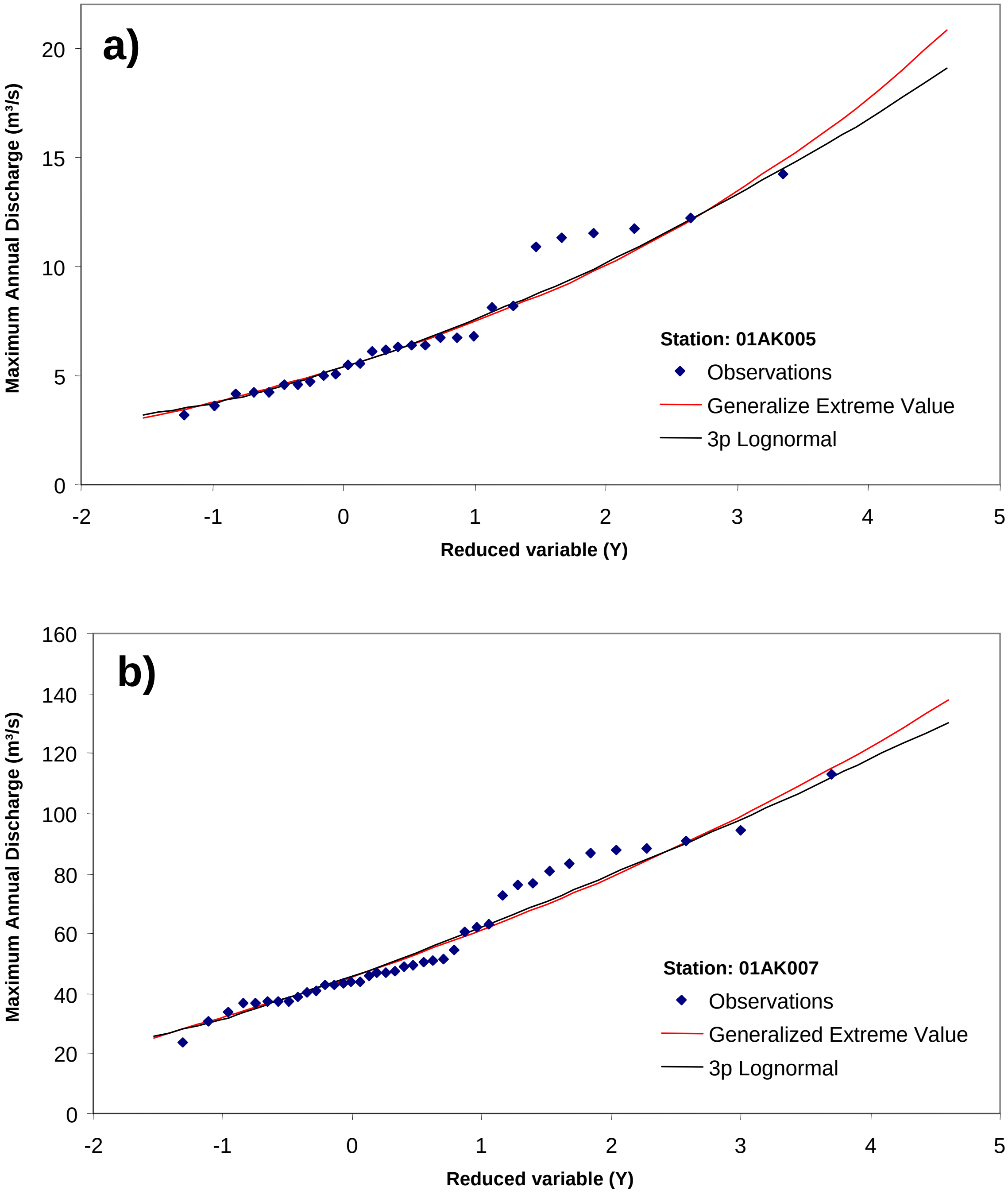
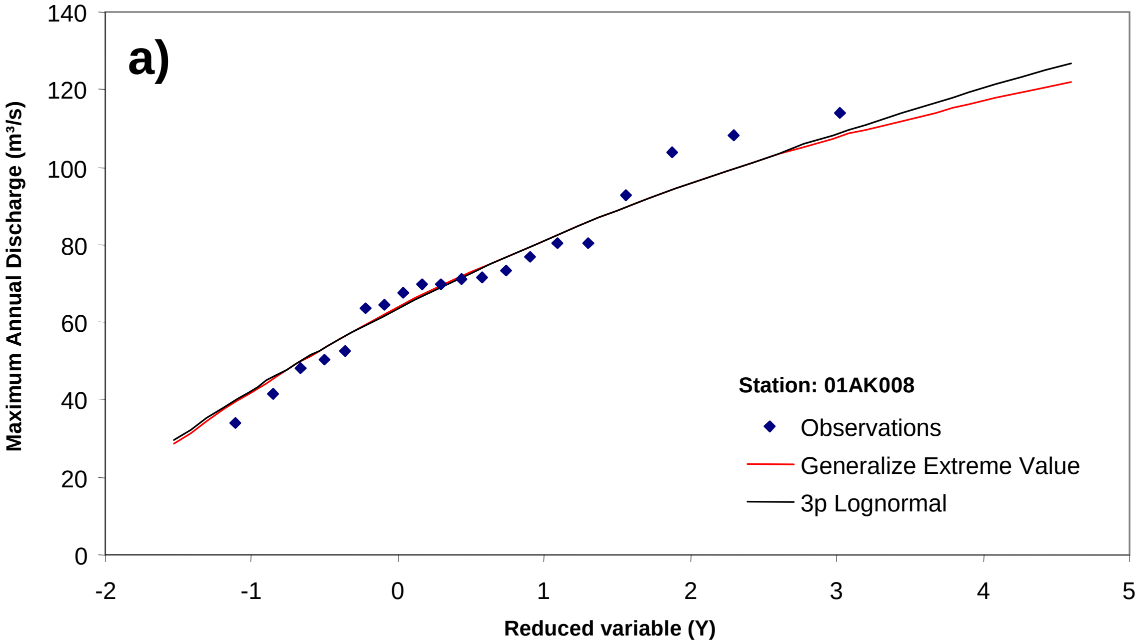


Figure A.8 Flood frequency analysis for a) Middle Branch Nashwaaksis Stream and b) Nackawic River



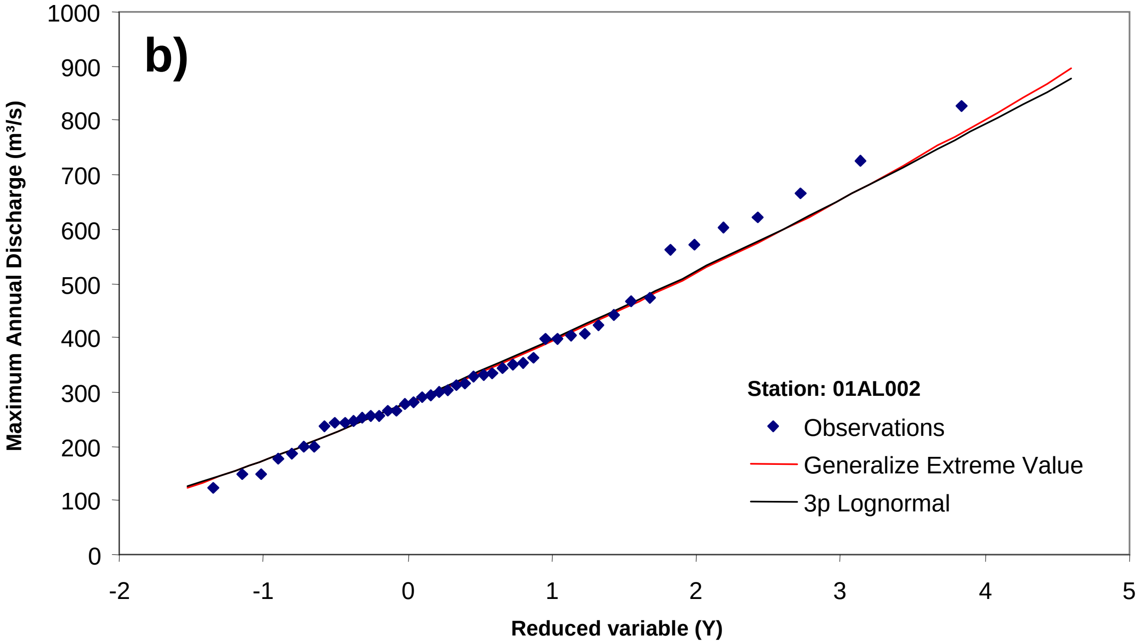
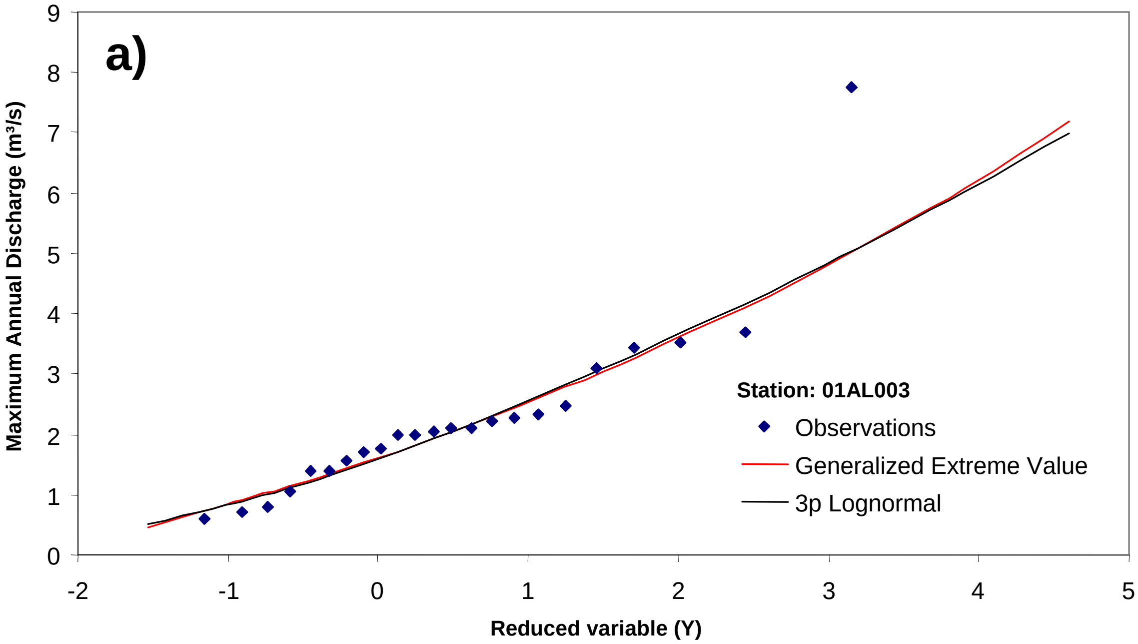


Figure A.9 Flood frequency analysis for a) Eel River and b) Nashwaak River



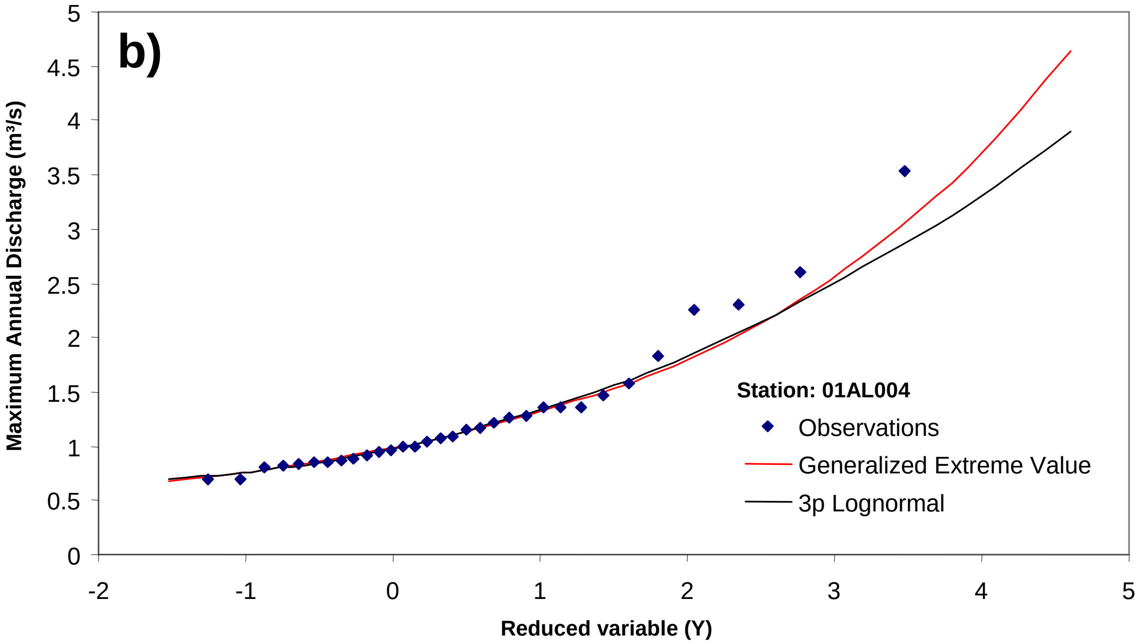


Figure A.10 Flood frequency analysis for a) Hayden Brook and b) Narrows Mountain Brook

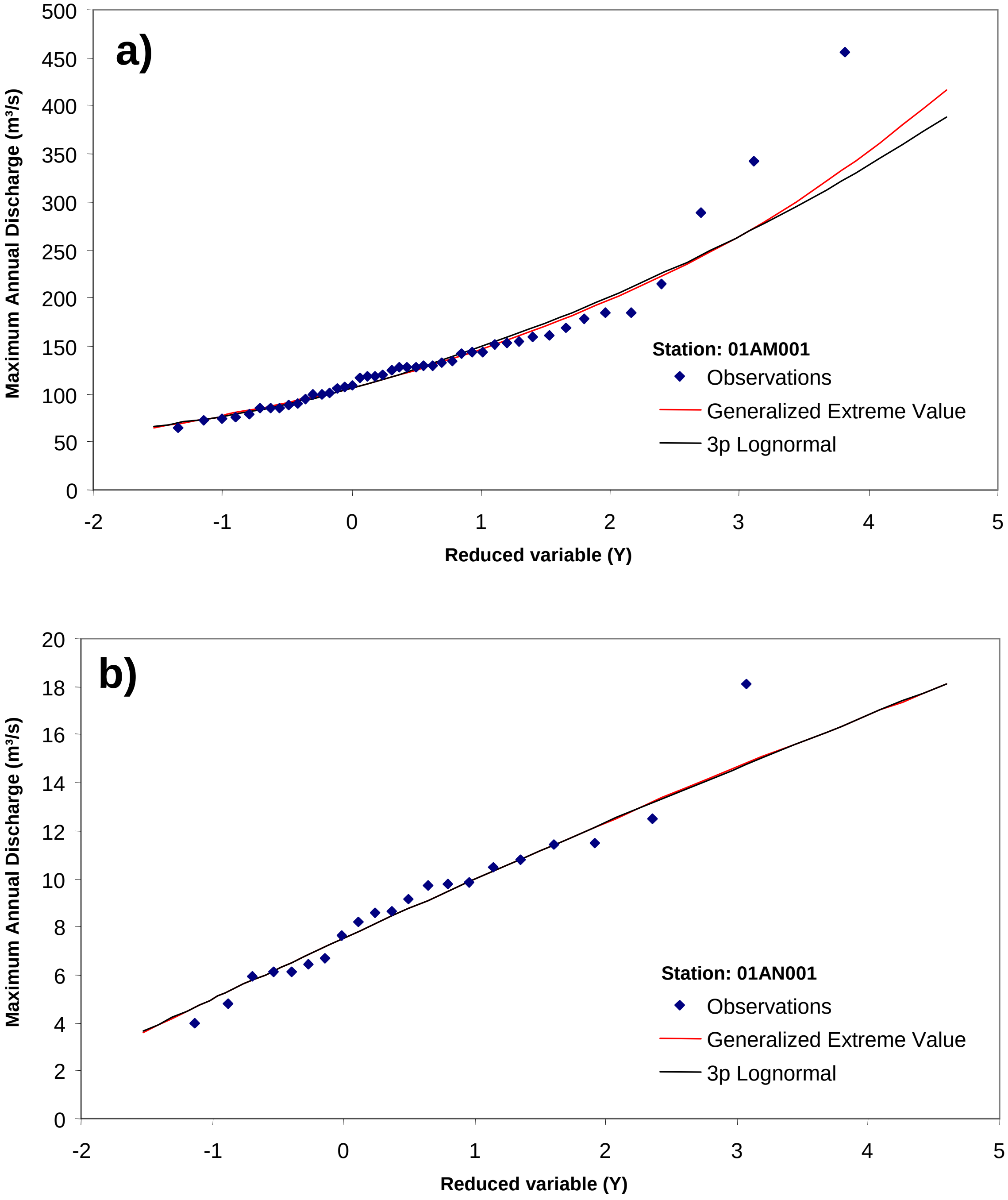


Figure A.11 Flood frequency analysis for a) North Branch Oromocto River and b) Castaway Brook

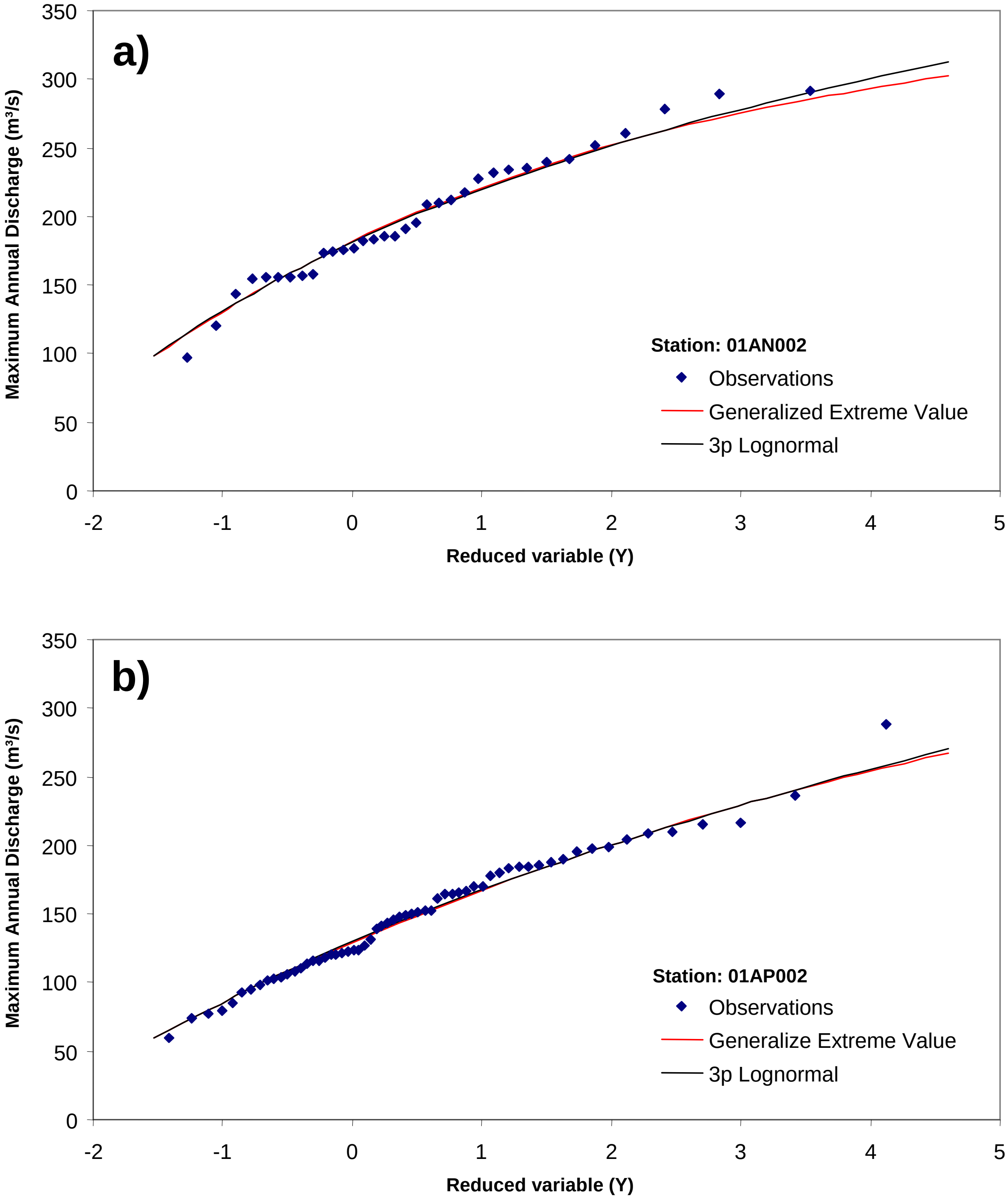


Figure A.12 Flood frequency analysis for a) Salmon River and b) Canaan River

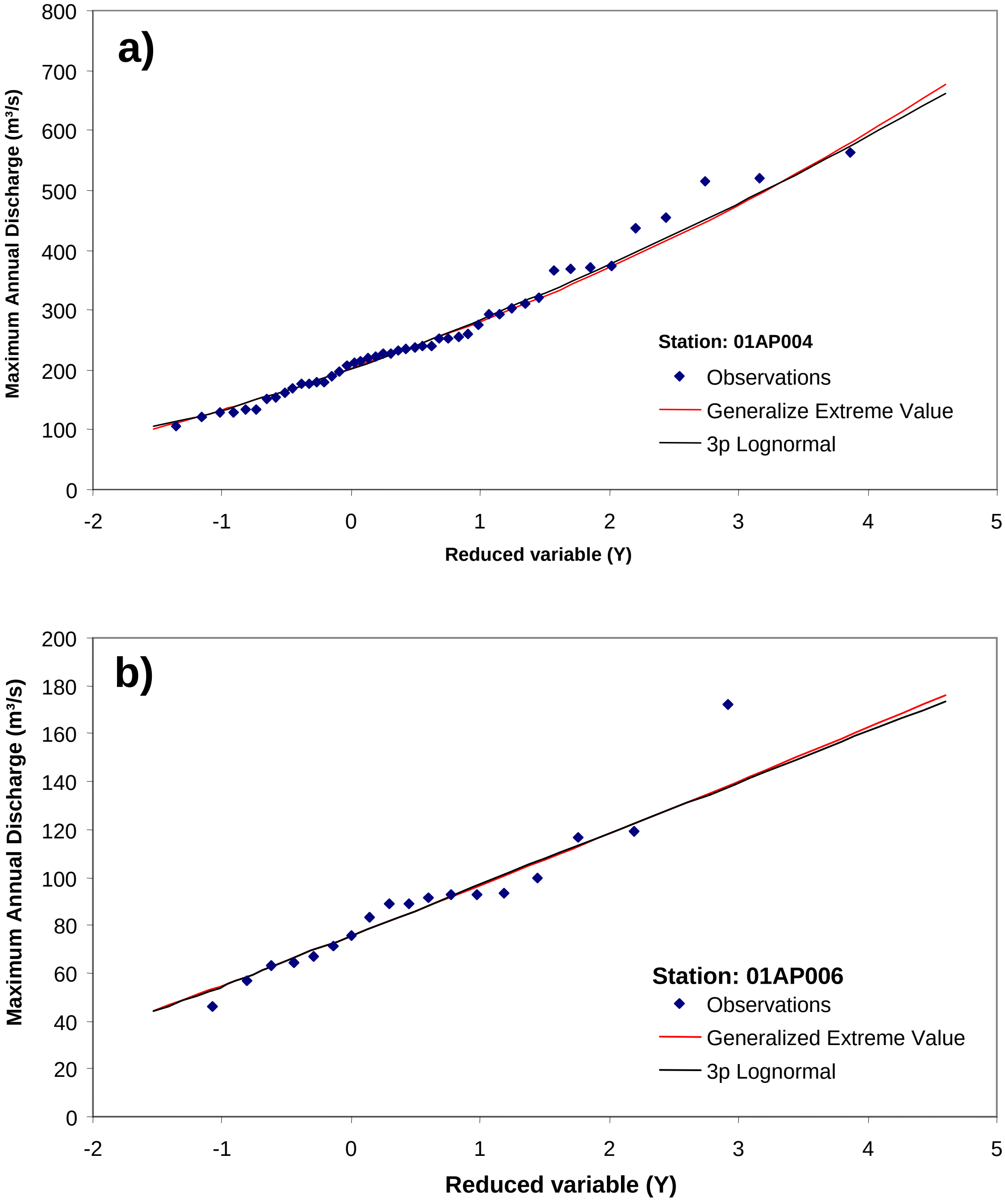


Figure A.13 Flood frequency analysis for a) Kennebecasis River and b) Nerepis River

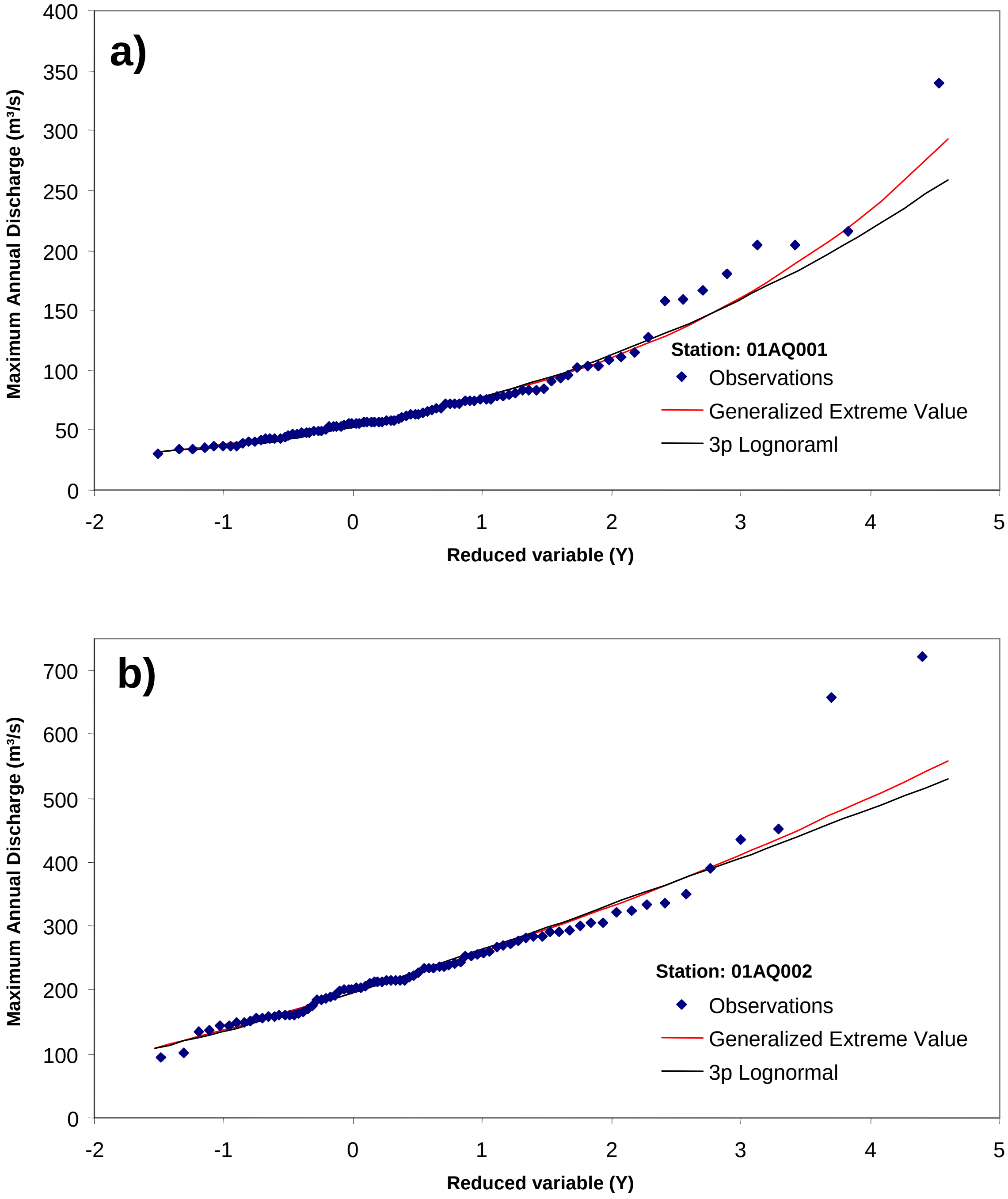


Figure A.14 Flood frequency analysis for a) Lepreau River and b) Magaguadavic River

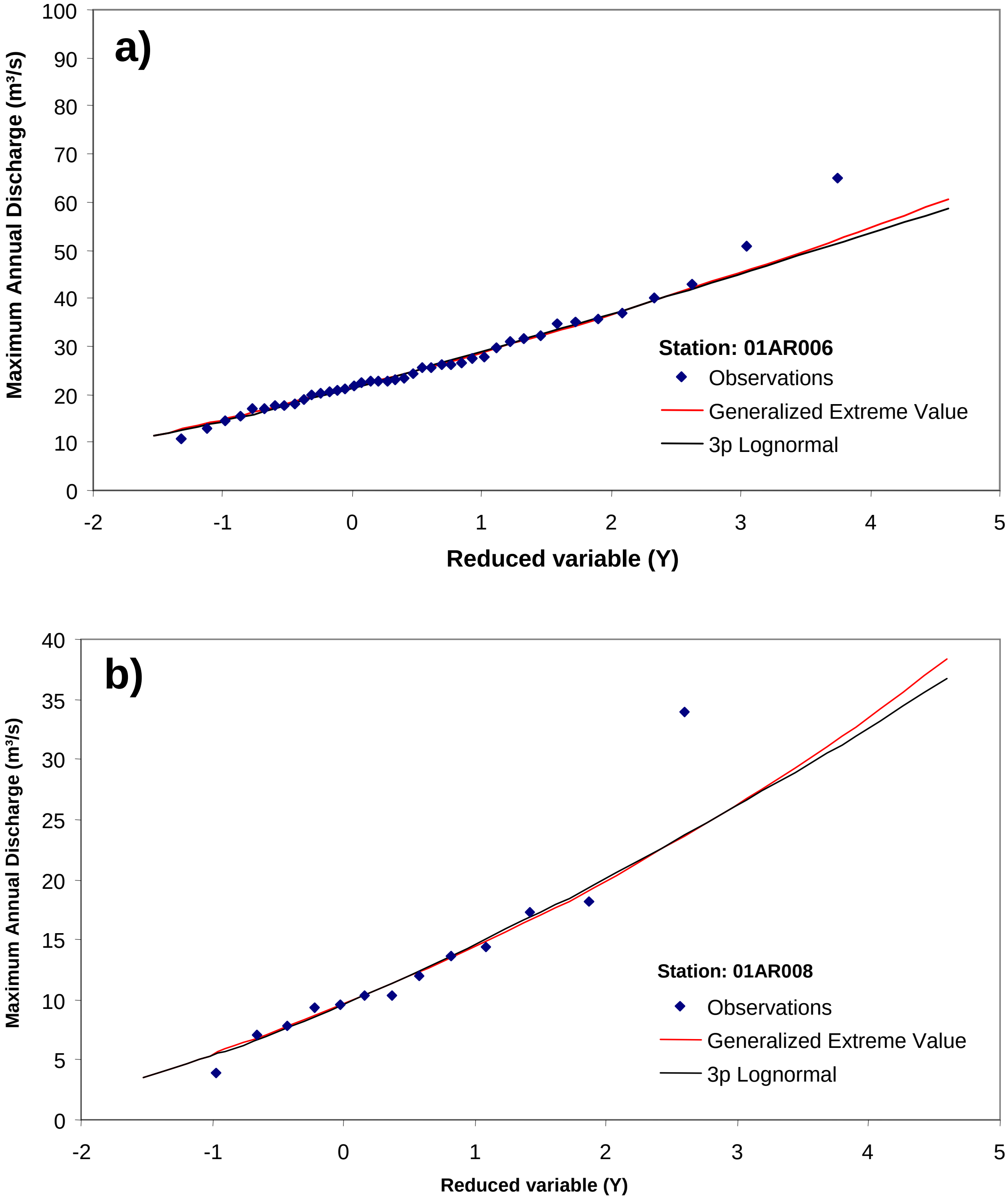
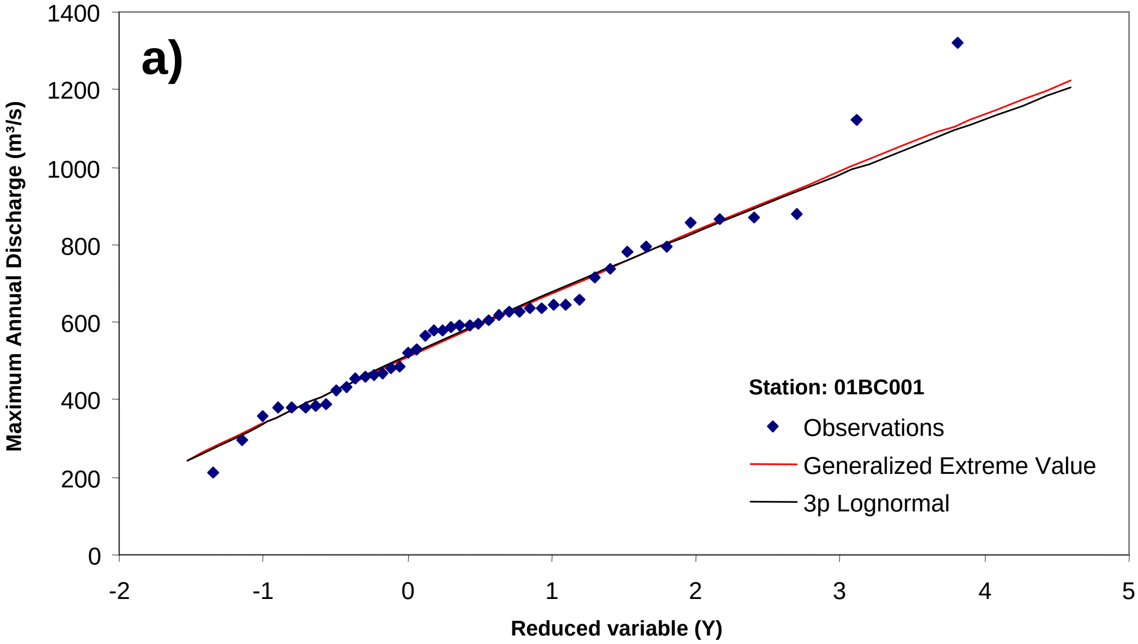


Figure A.15 Flood frequency analysis for a) Dennis Stream and b) Bocabec River



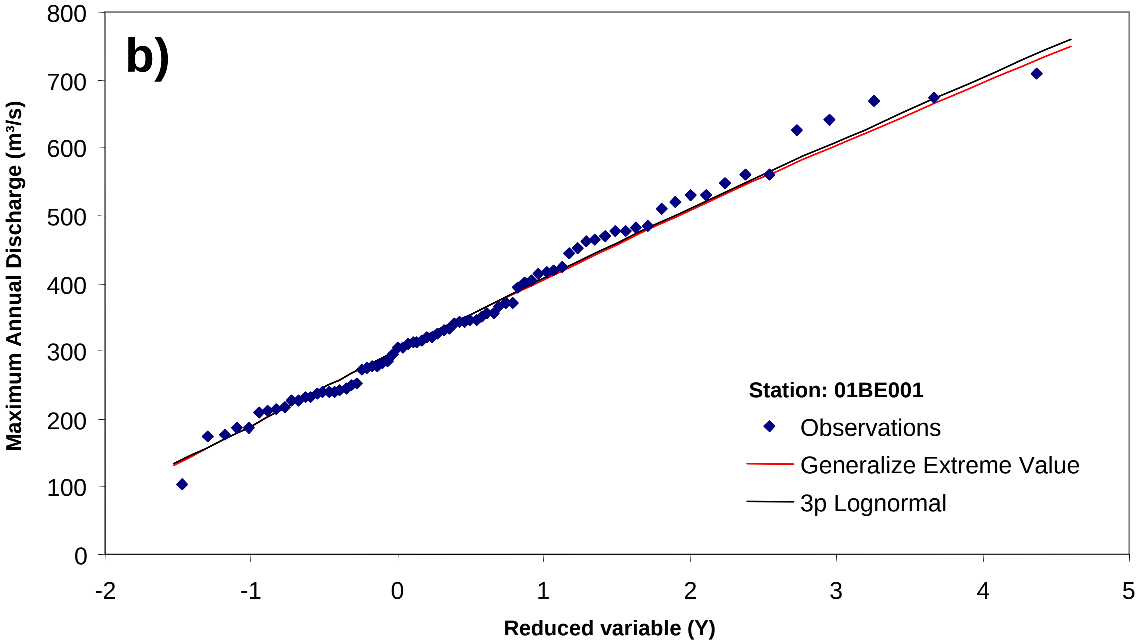


Figure A.16 Flood frequency analysis for a) Restigouche River and b) Upsalquitch River

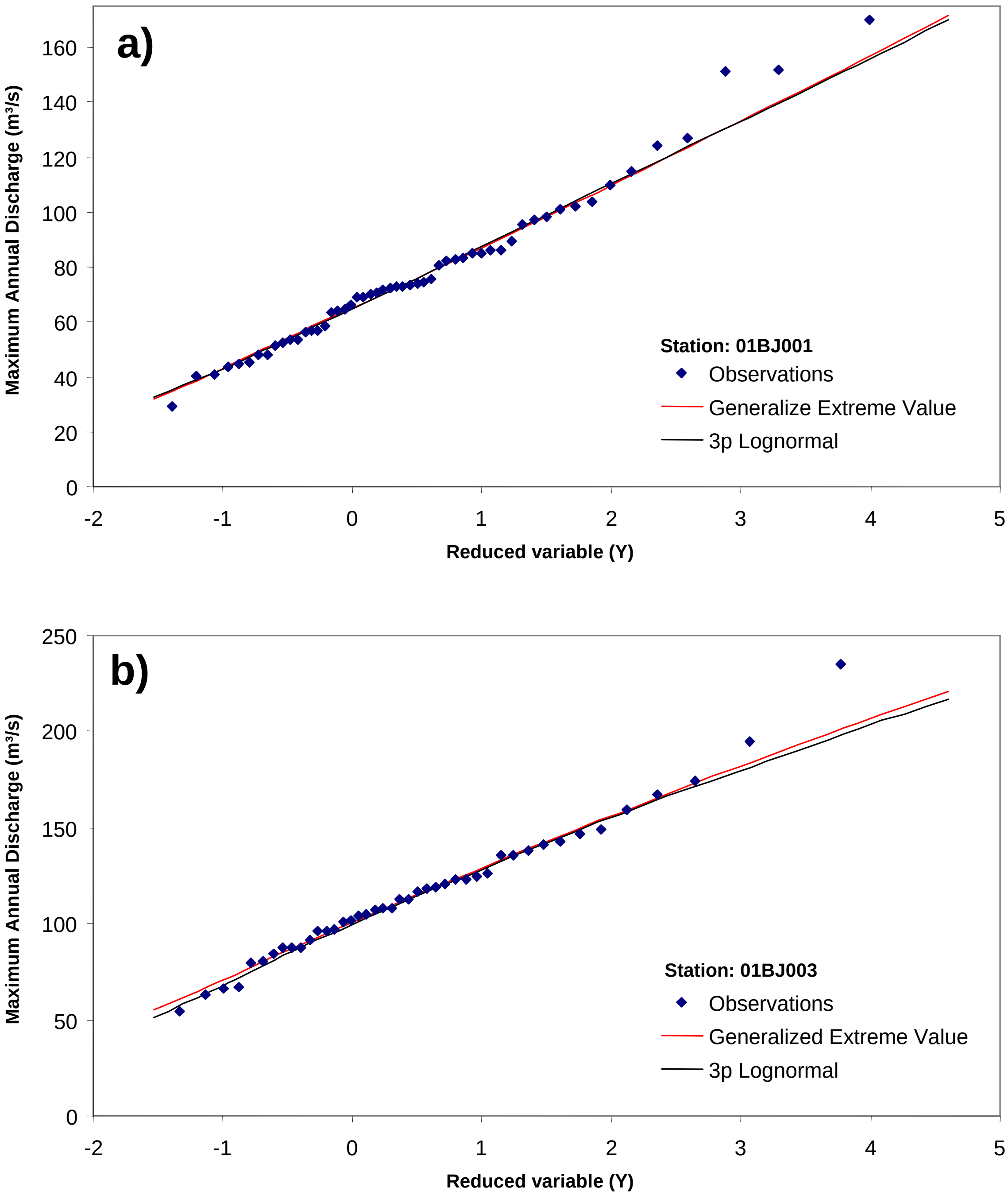
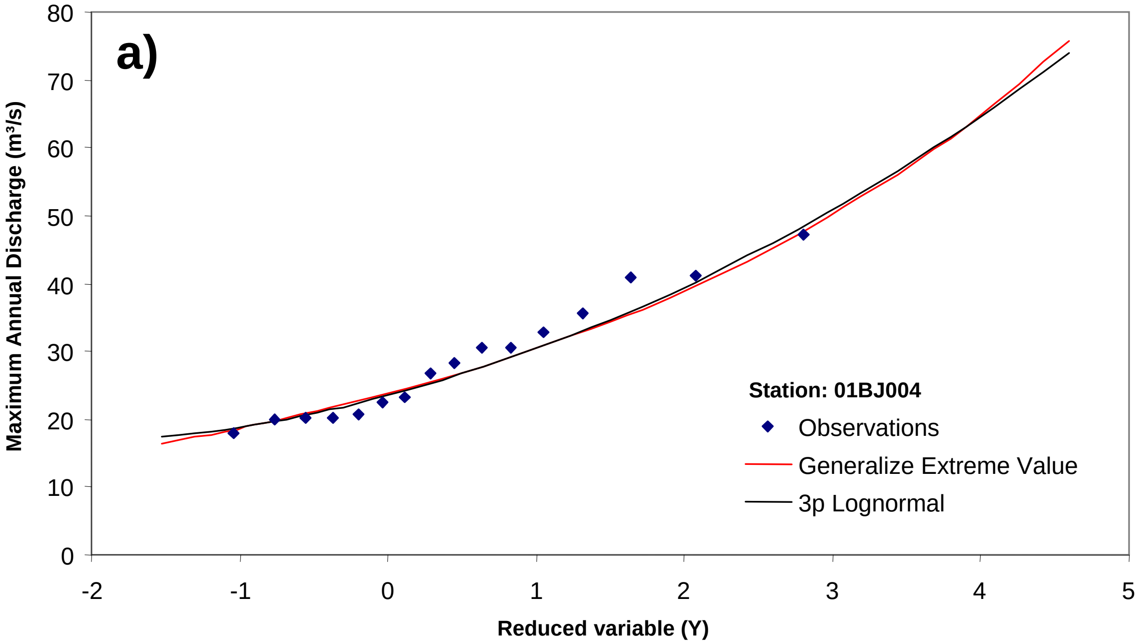


Figure A.17 Flood frequency analysis for a) Tetagouche River and b) Jacquet River



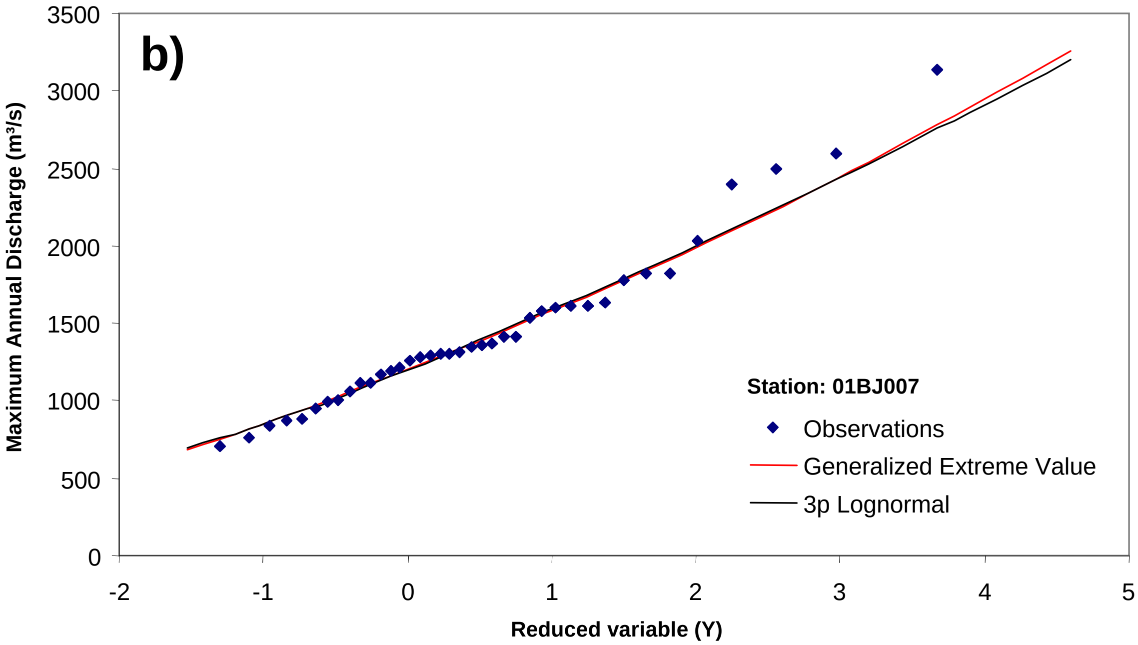
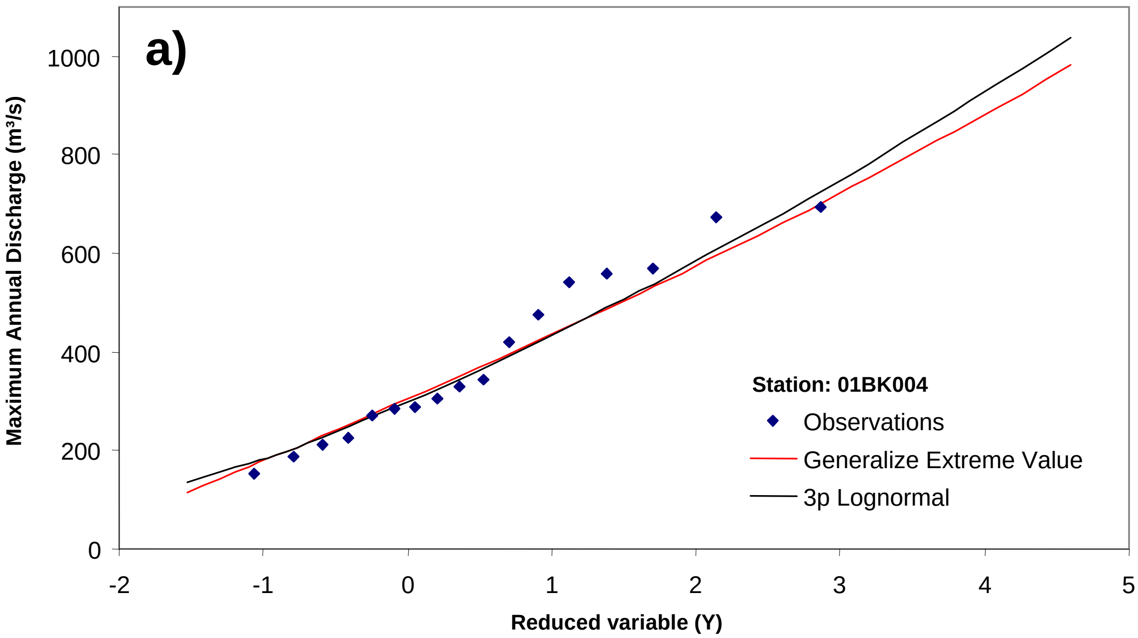


Figure A.18 Flood frequency analysis for a) Eel River and b) Restigouche River



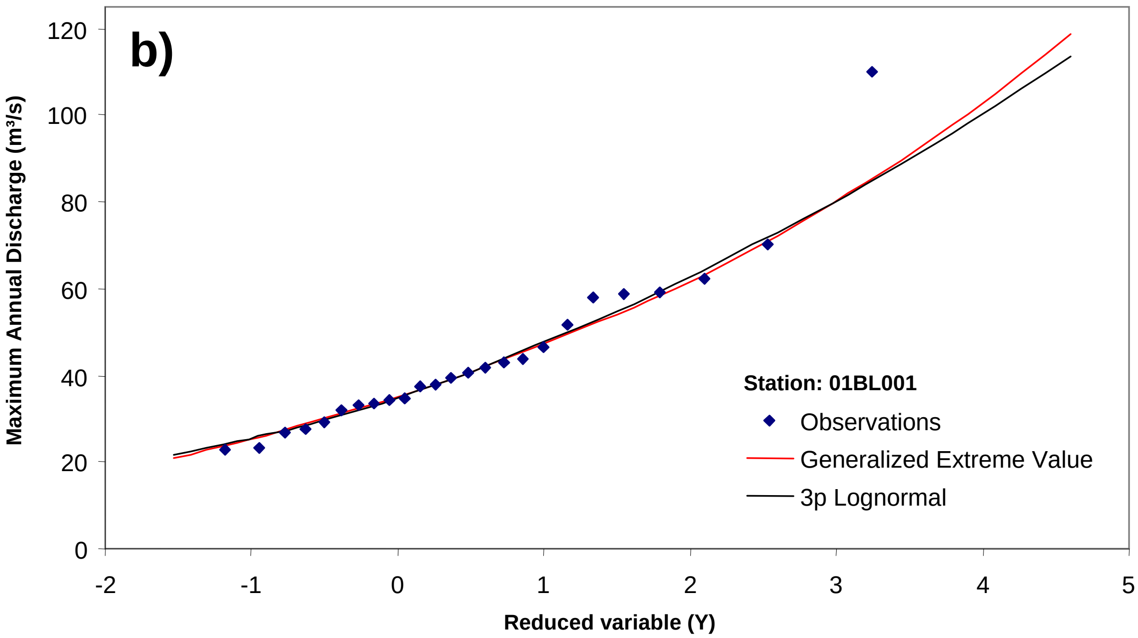
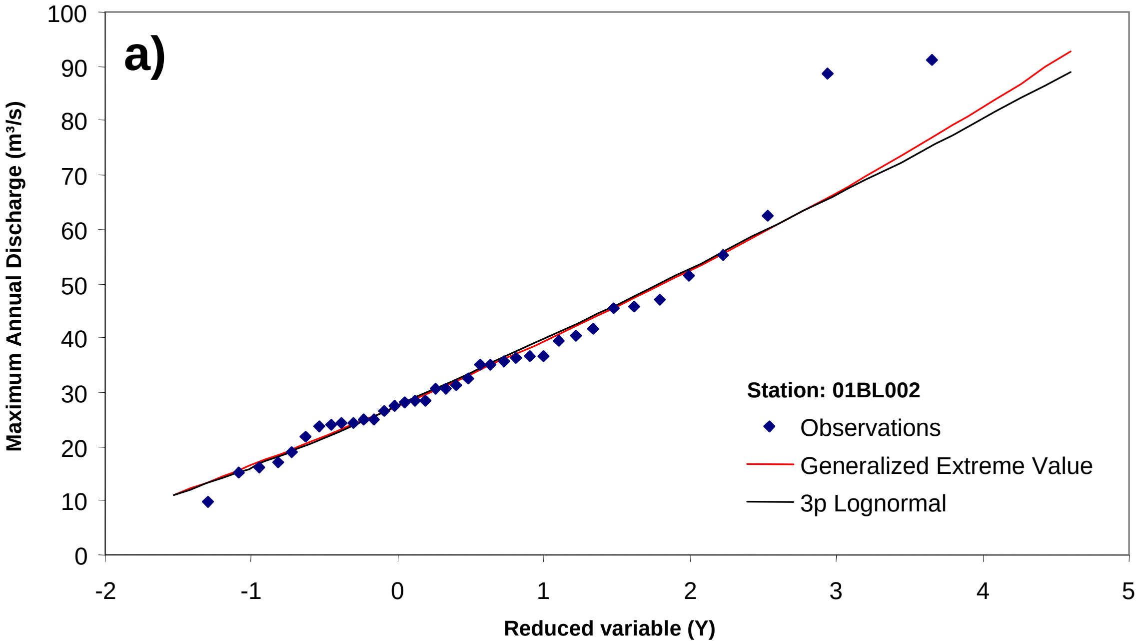


Figure A.19 Flood frequency analysis for a) Nepisiquit River and b) Bass River



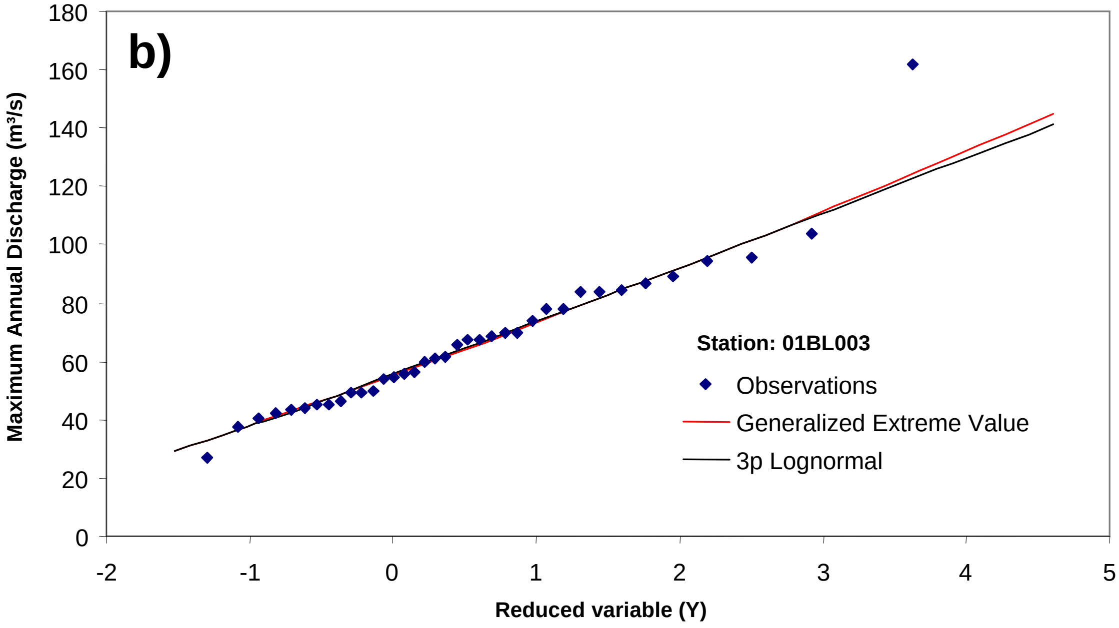


Figure A.20 Flood frequency analysis for a) Rivière Caraquet and b) Big Tracadie River

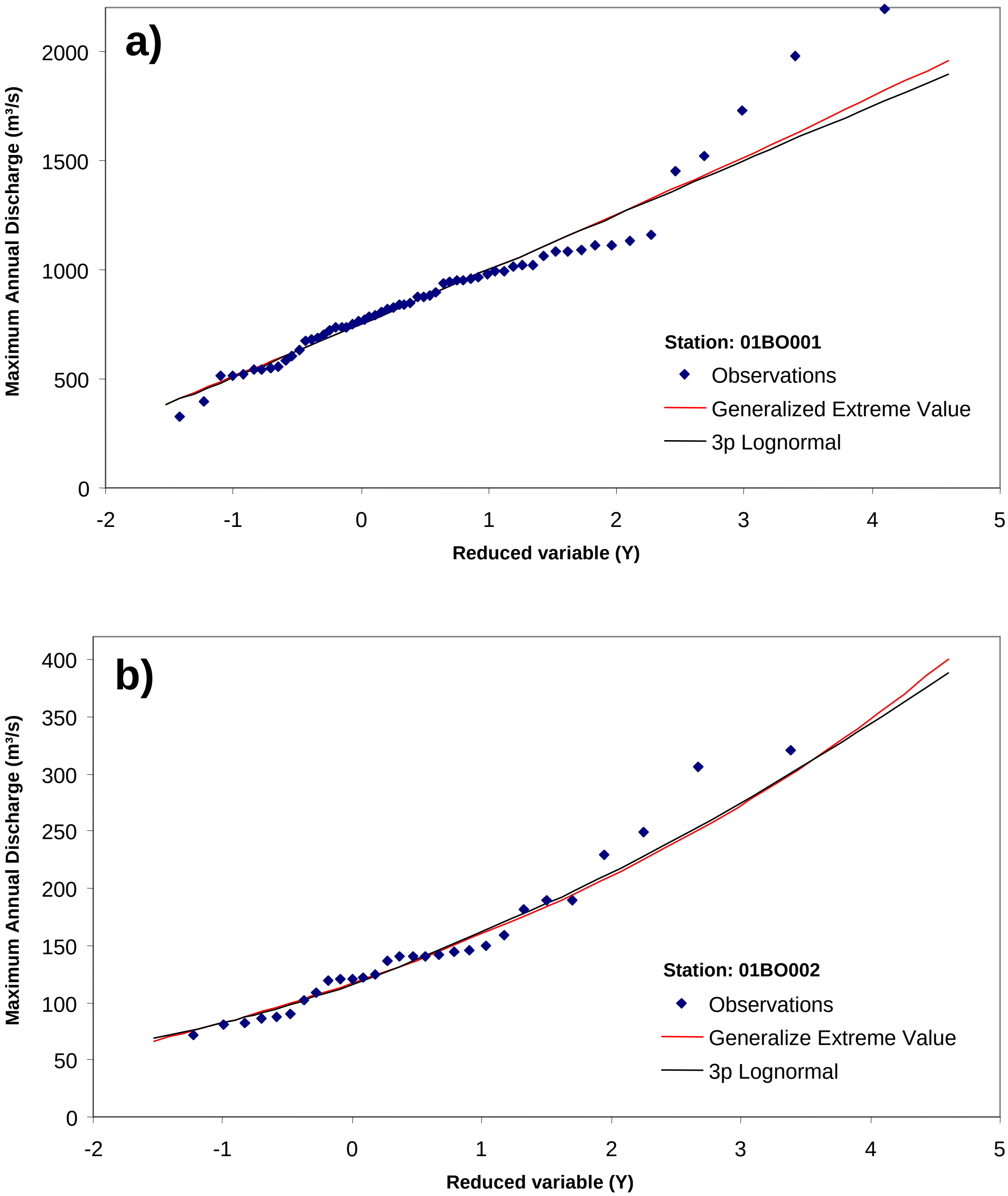


Figure A.21 Flood frequency analysis for a) Southwest Miramichi River and b) Renous River

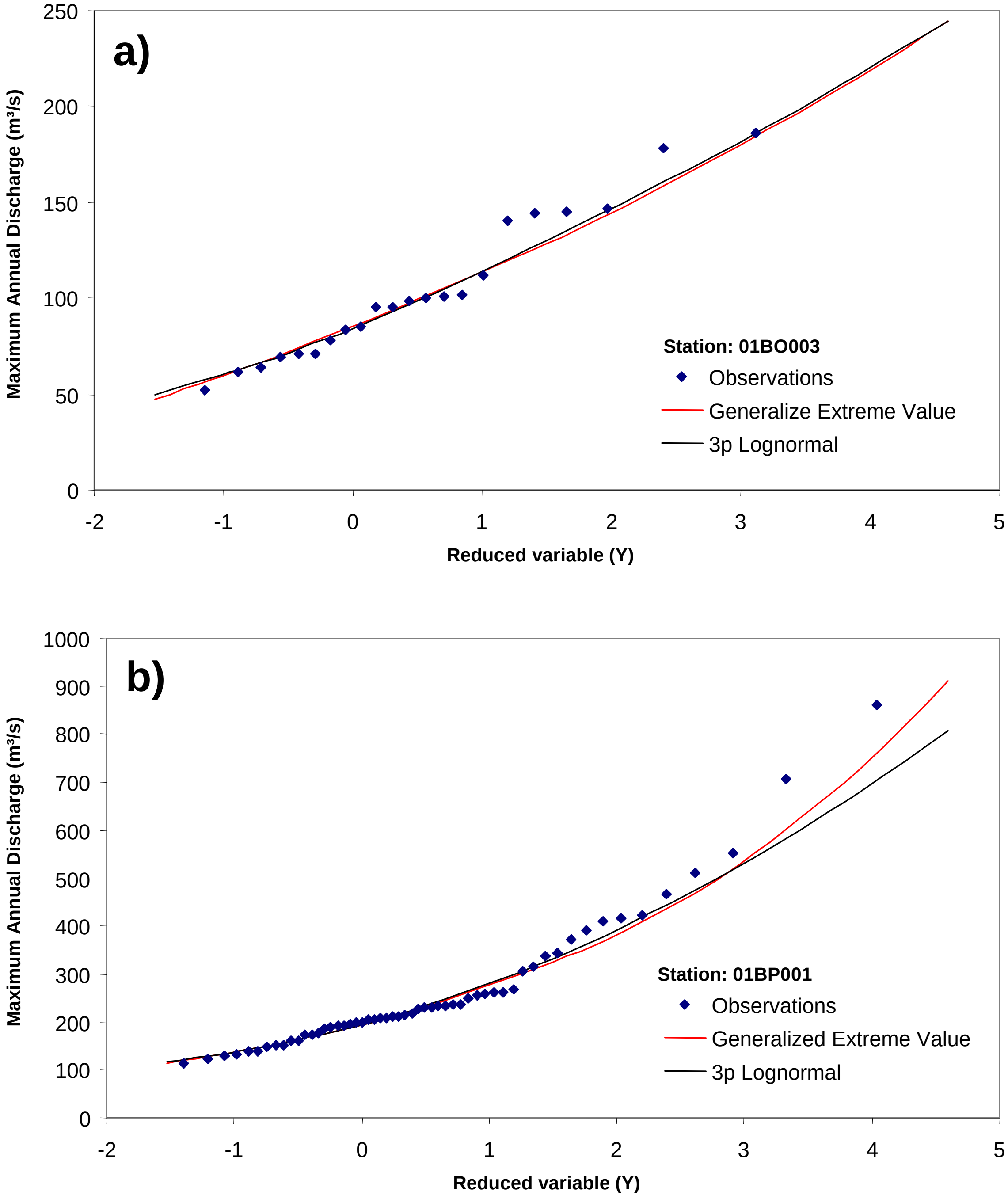
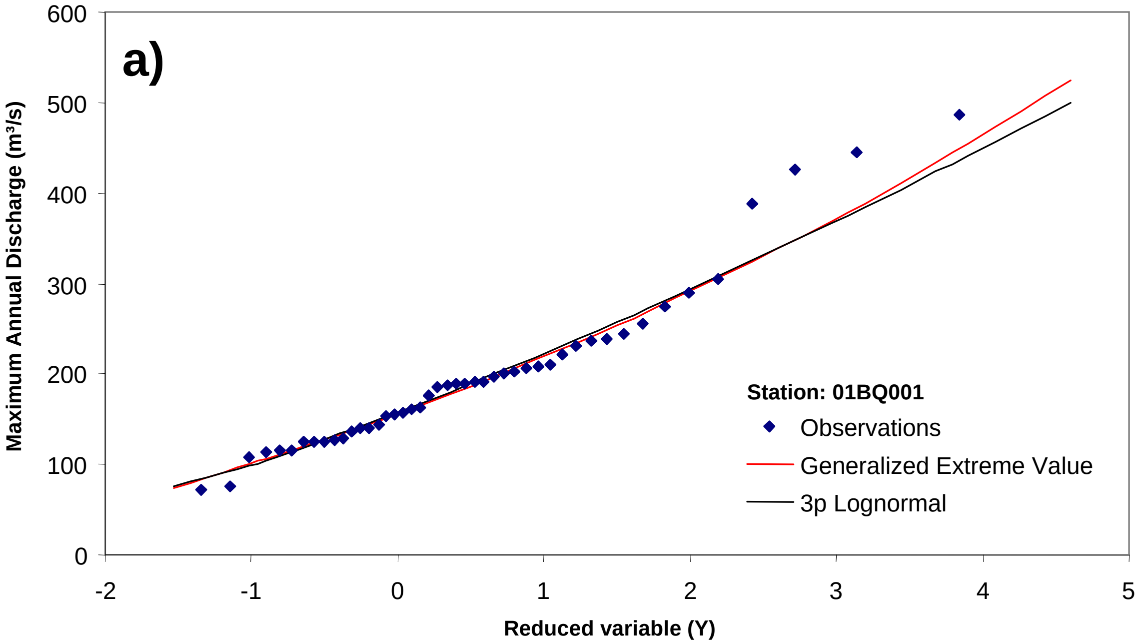


Figure A.22 Flood frequency analysis for a) Barnaby River and b) Little Southwest Miramichi River



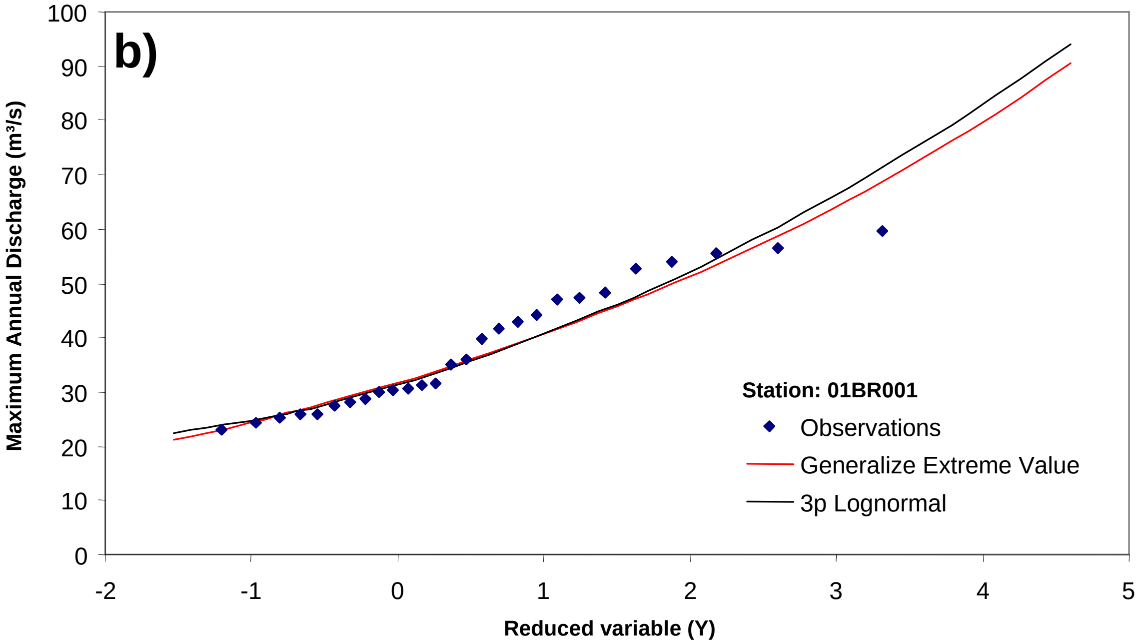
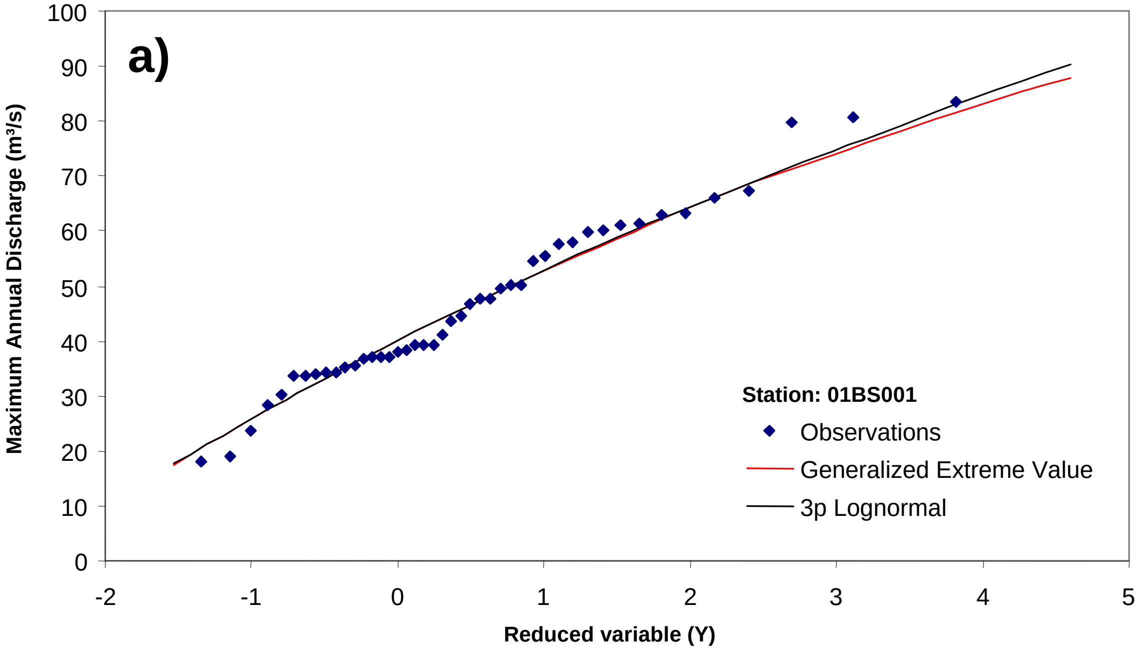


Figure A.23 Flood frequency analysis for a) Northwest Miramichi River and b) Kouchibouguac River



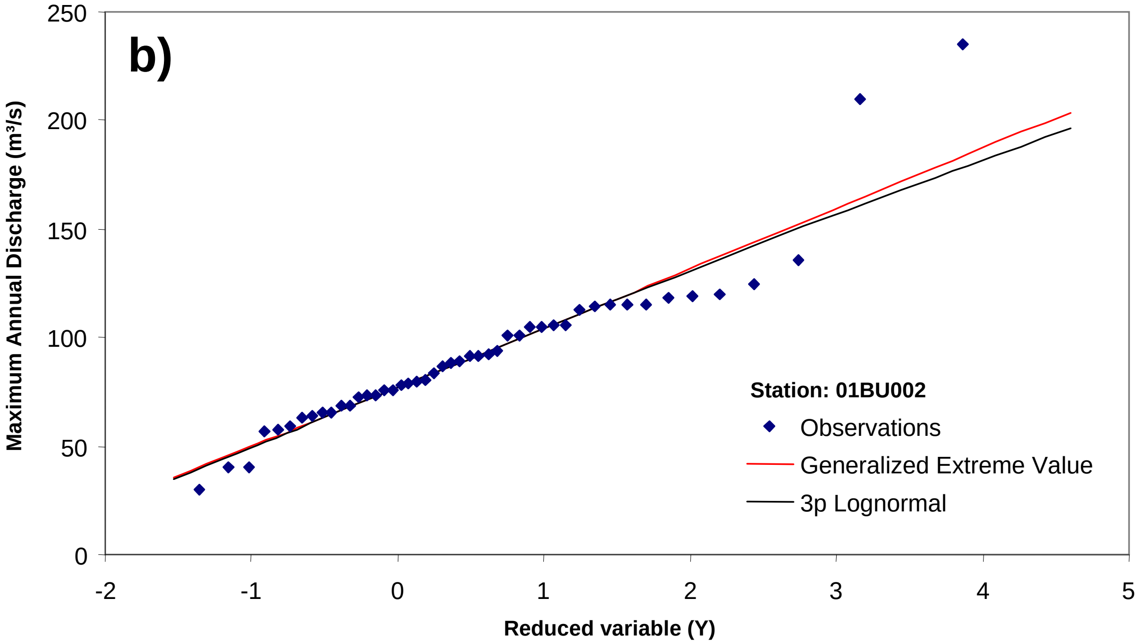
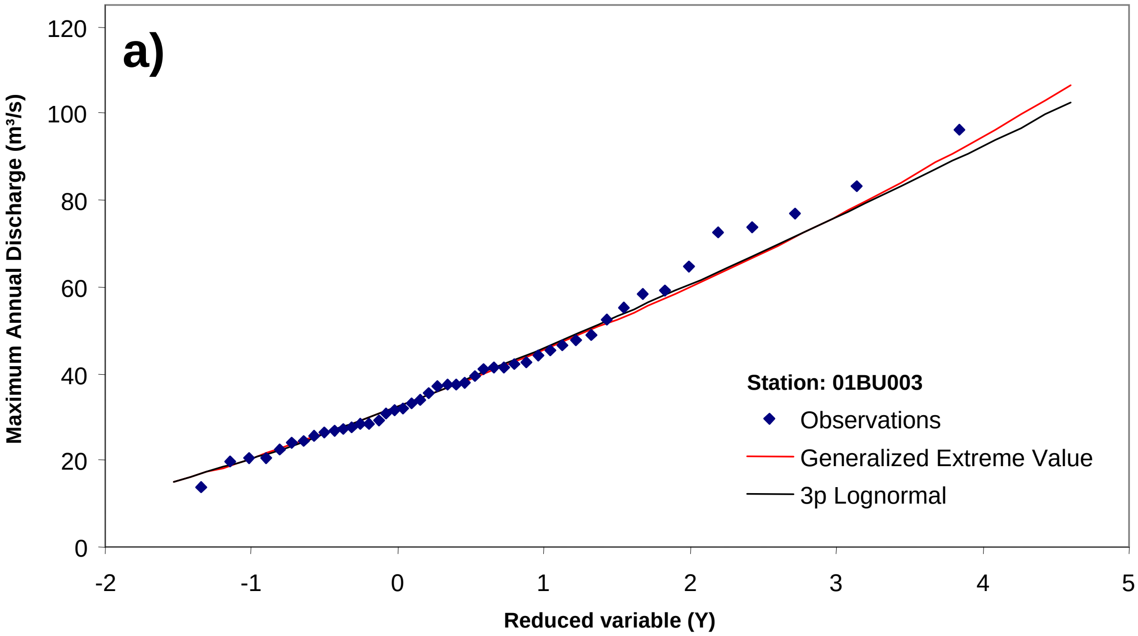


Figure A.24 Flood frequency analysis for a) Coal Branch River and b) Petitcodiac River



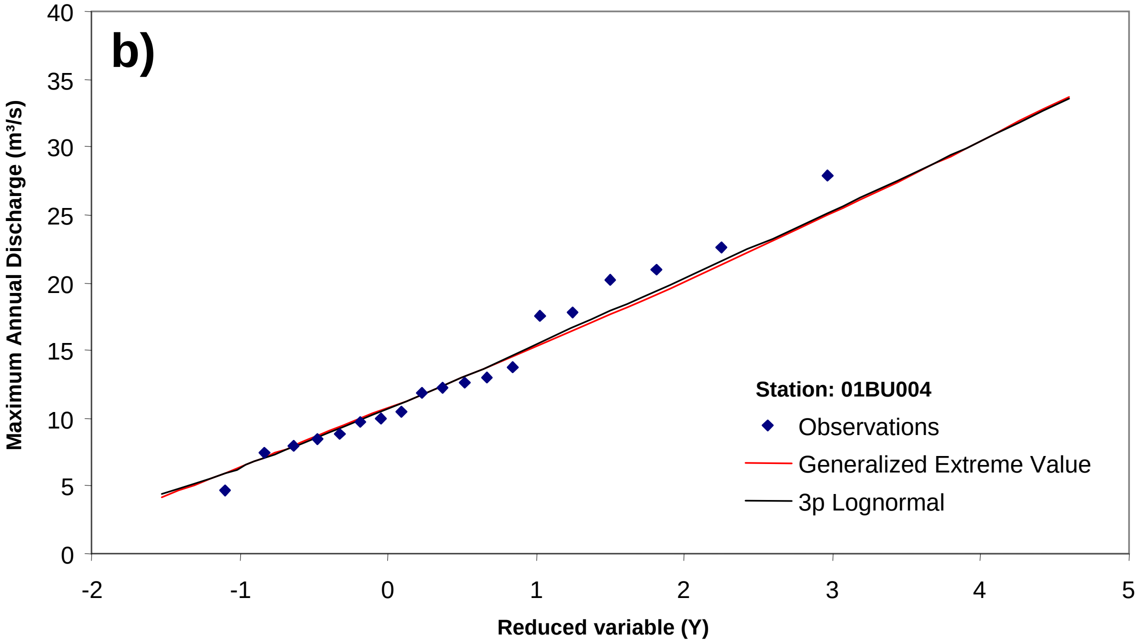
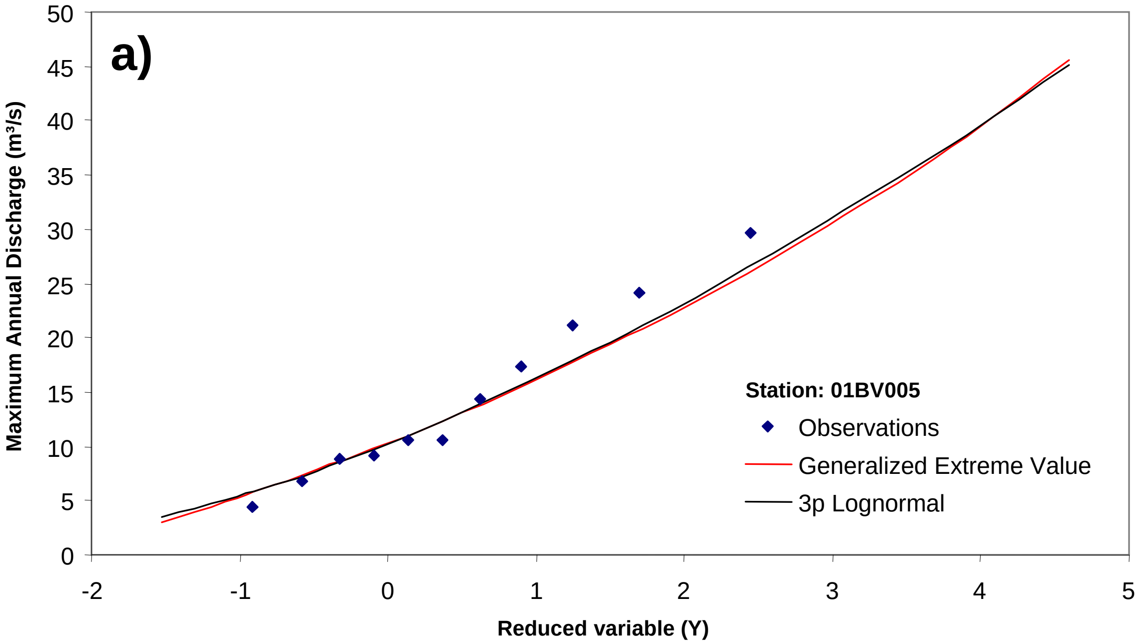


Figure A.25 Flood frequency analysis for a) Turtle Creek and b) Palmer's Creek



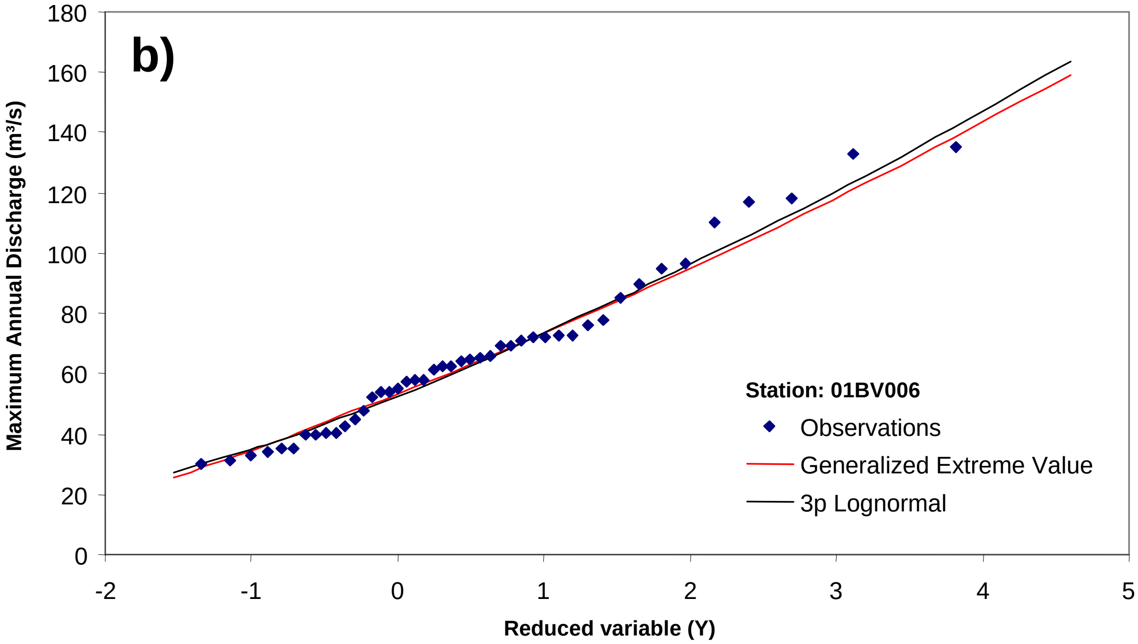
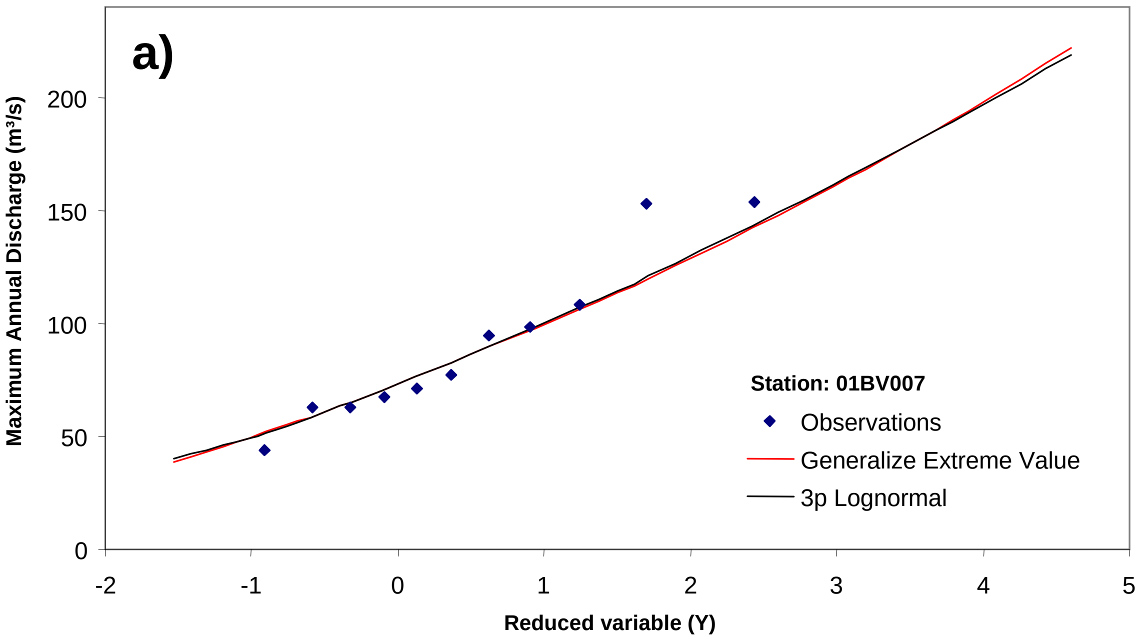


Figure A.26 Flood frequency analysis for a) Ratcliffe Brook and b) Point Wolfe River



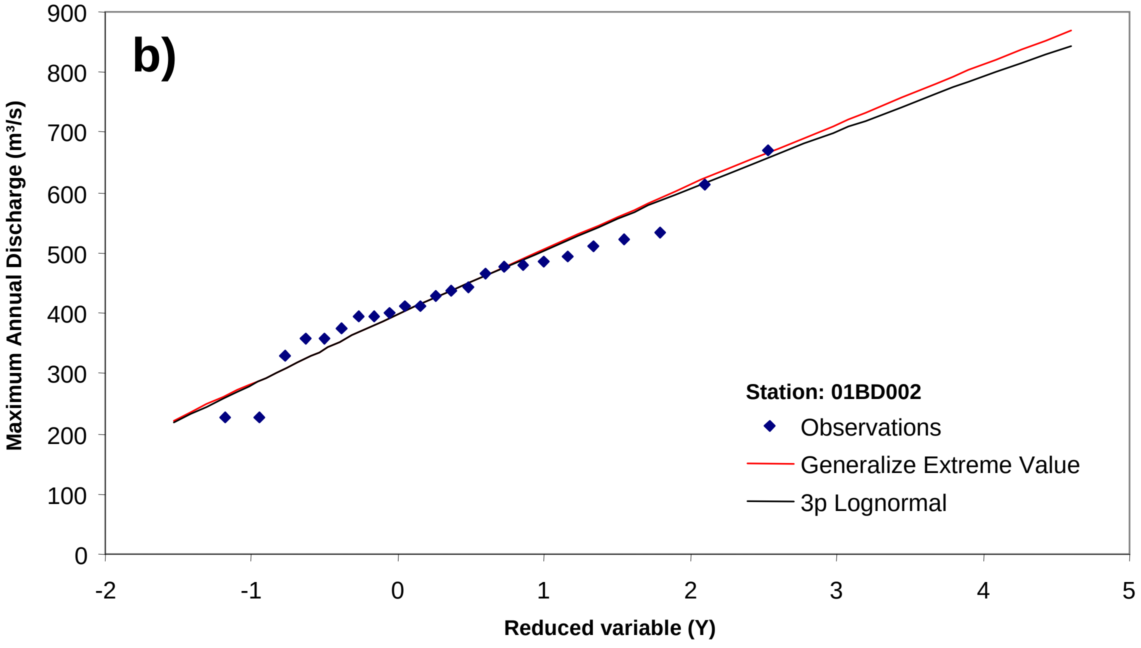
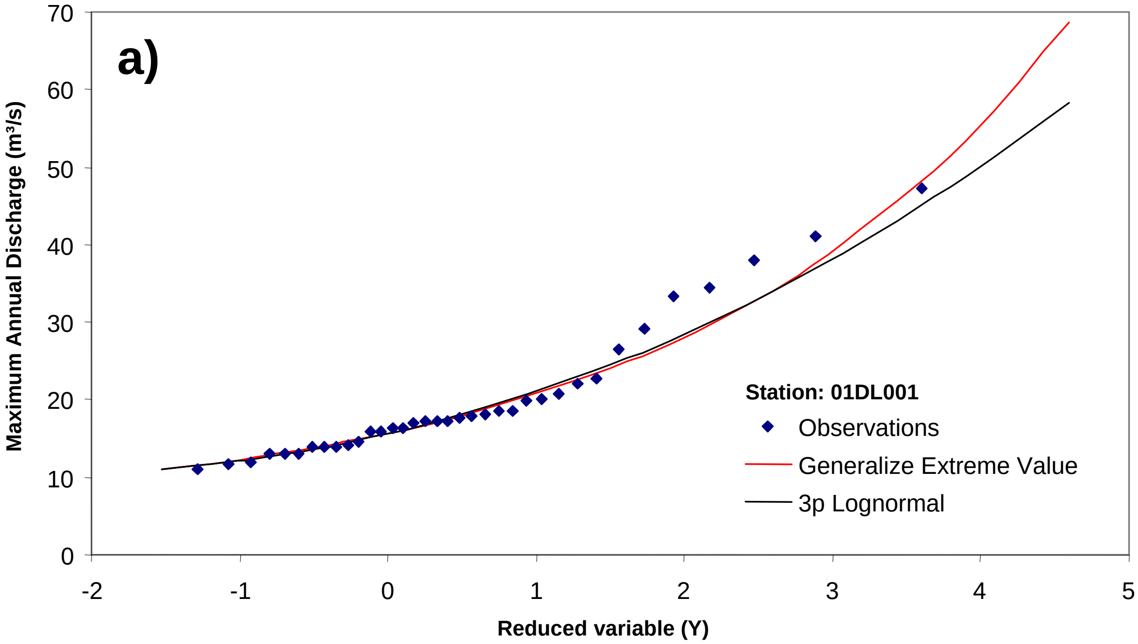


Figure A.27 Flood frequency analysis for a) Upper Salmon River and b) Rivière Matapedia, QC



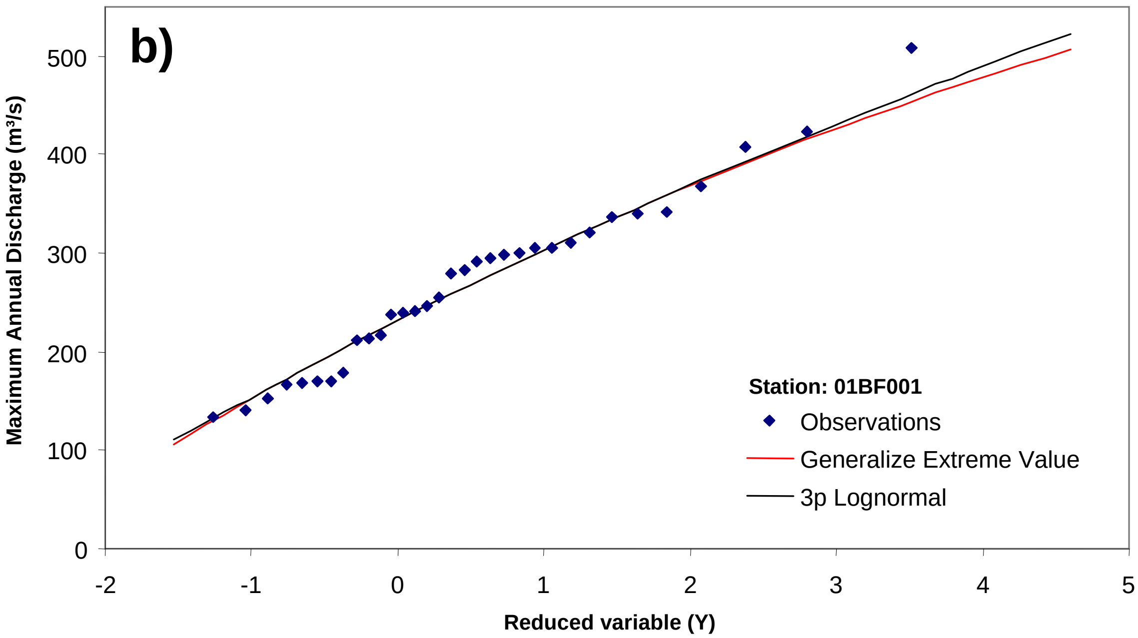


Figure A.28 Flood frequency analysis for a) Kelley River, NS and b) Rivière Nouvelle au Pont, QC

Appendix B

Regional Flood Frequency Analyses

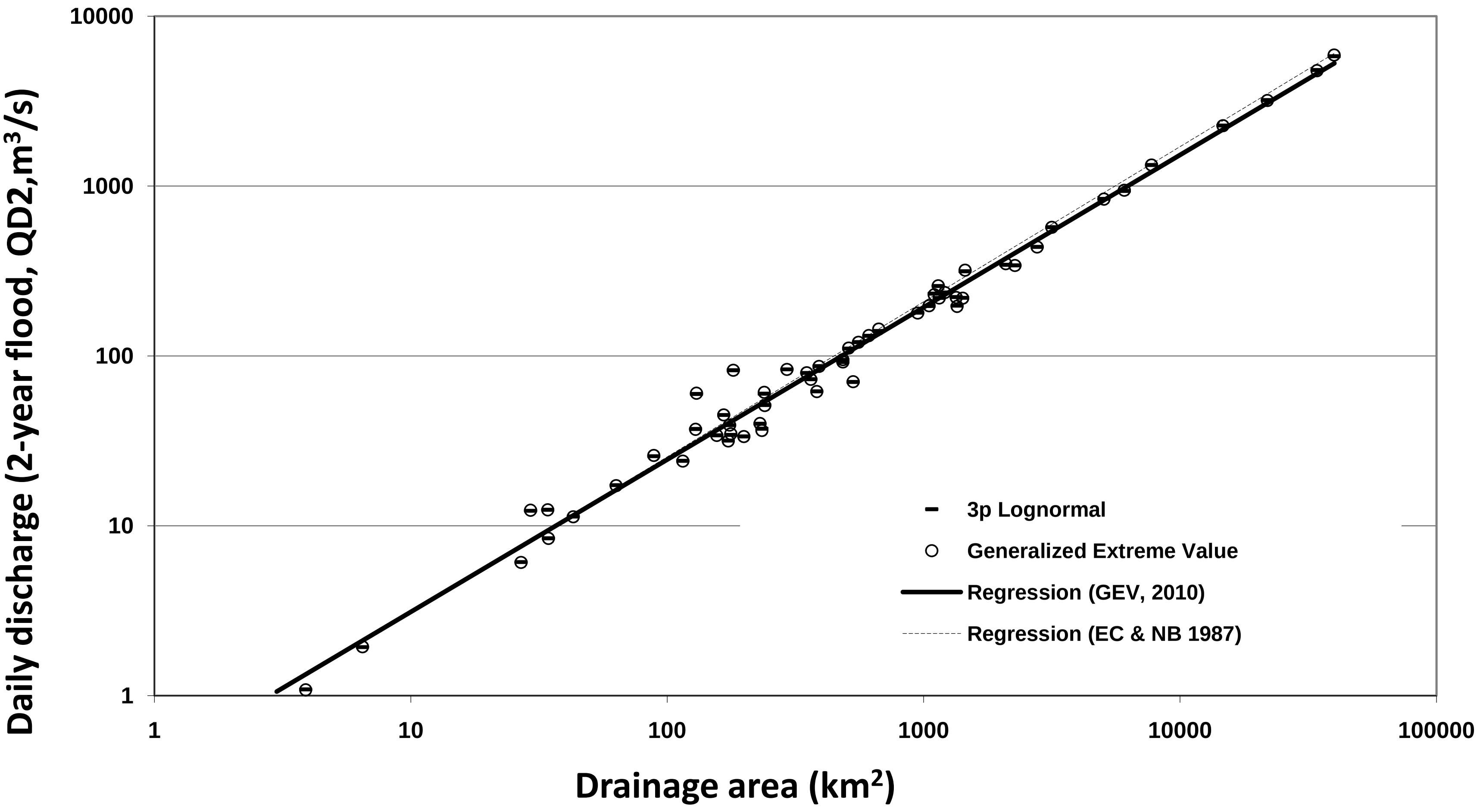


Figure B.1 Estimated 2-year flood (daily discharge) as a function of drainage area (km^2) for all 56 hydrometric stations (GEV and LN3). Regional regression line for both the present study and the EC & NB study (1987) are presented.

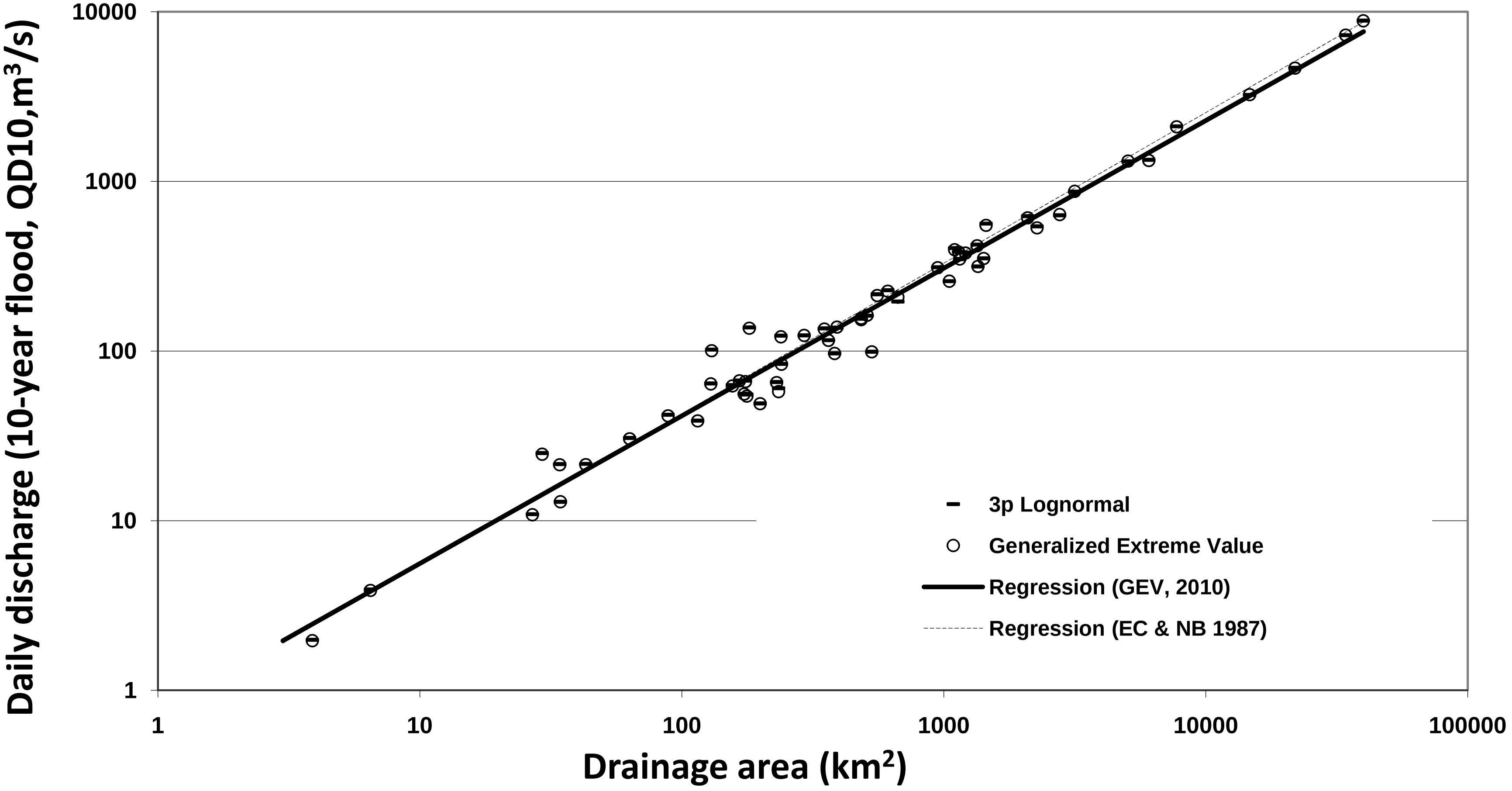


Figure B.2 Estimated 10-year flood (daily discharge) as a function of drainage area (km^2) for all 56 hydrometric stations (GEV and LN3). Regional regression line for both the present study and the EC & NB study (1987) are presented.

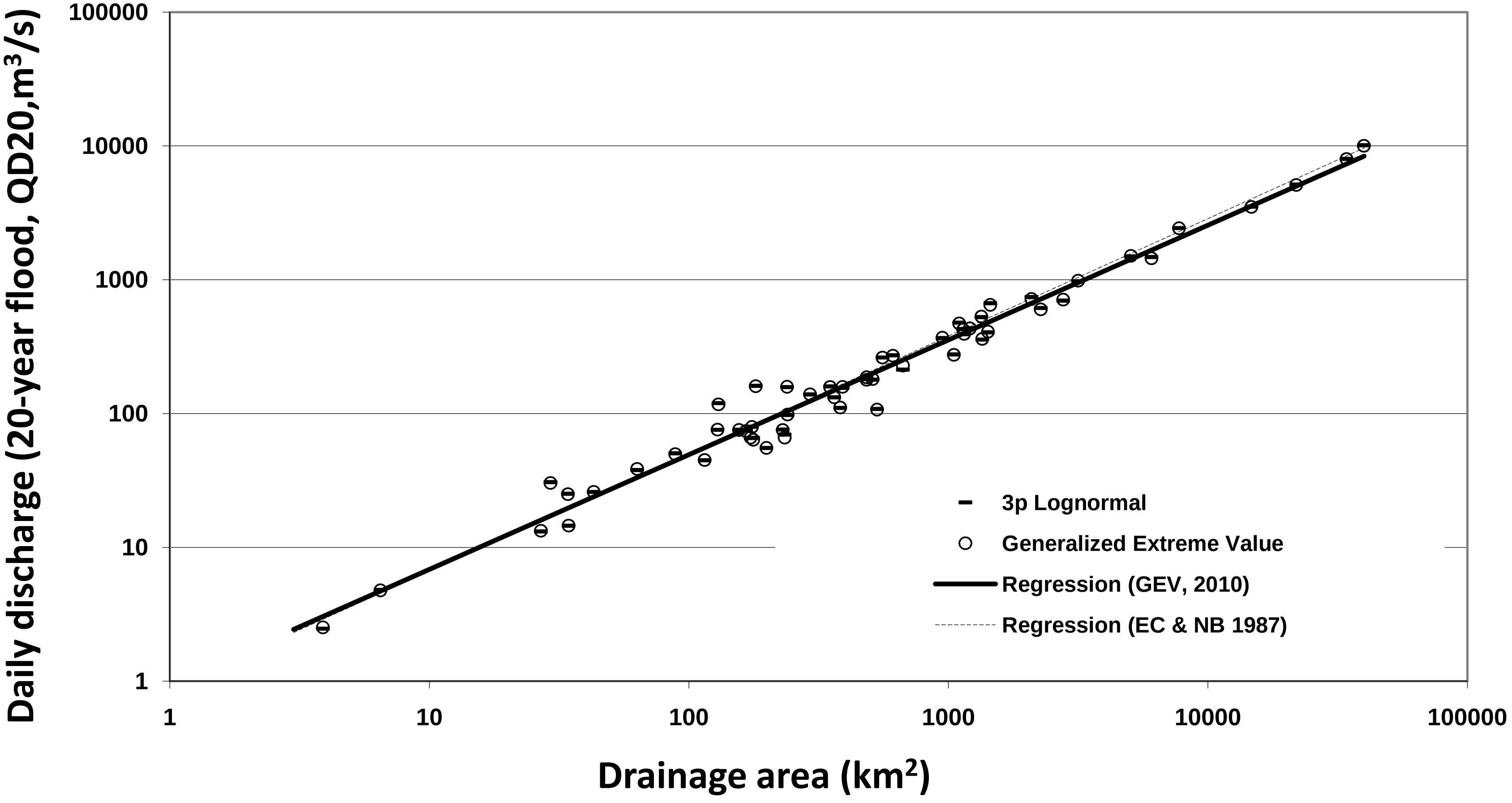


Figure B.3 Estimated 20-year flood (daily discharge) as a function of drainage area (km²) for all 56 hydrometric stations (GEV and LN3). Regional regression line for both the present study and the EC & NB study (1987) are presented.

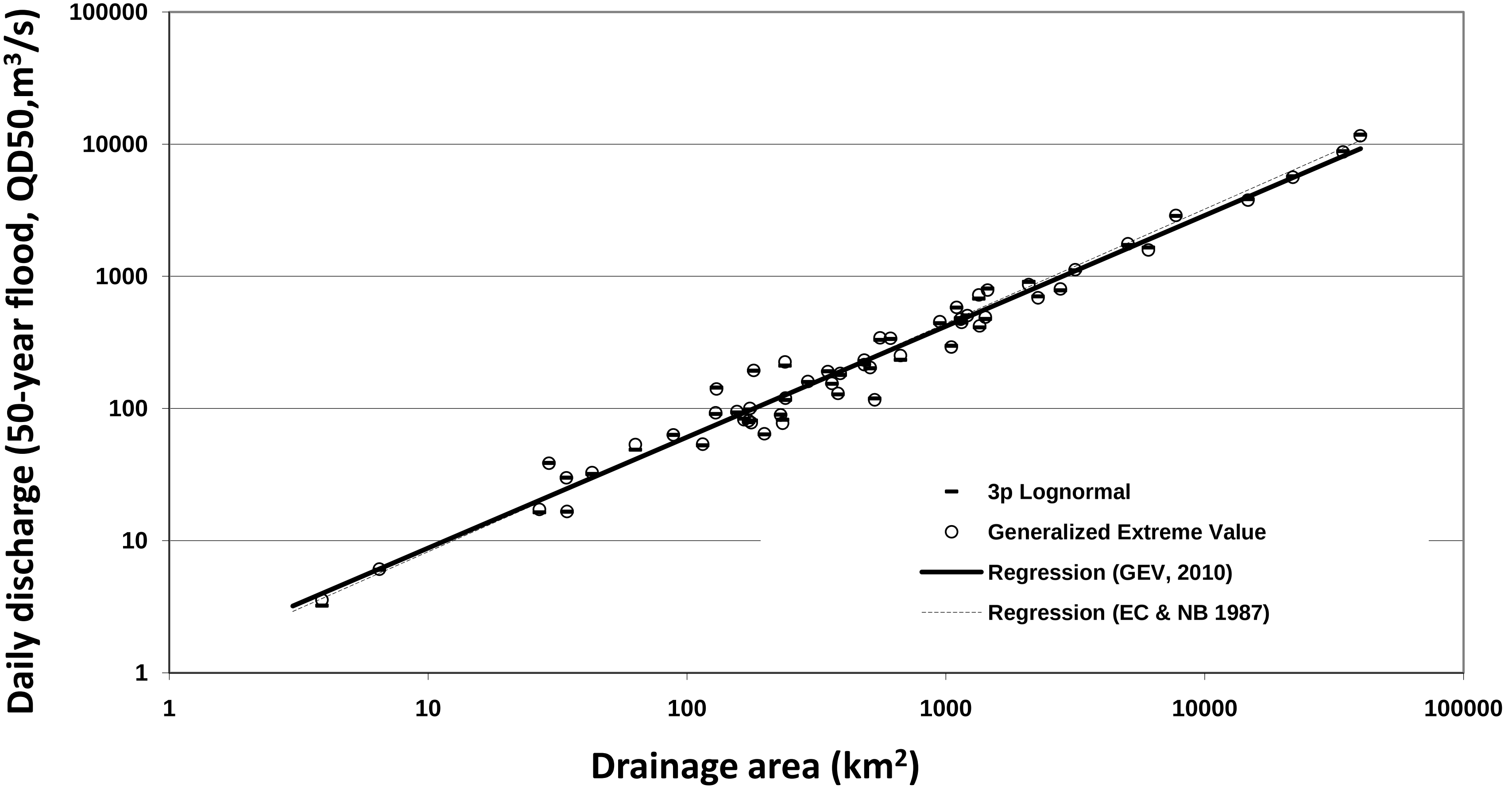


Figure B.4 Estimated 50-year flood (daily discharge) as a function of drainage area (km^2) for all 56 hydrometric stations (GEV and LN3). Regional regression line for both the present study and the EC & NB study (1987) are presented.