Analyses of design floods for small drainage basins in New Brunswick

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Analyses of design floods for small drainage basins in New Brunswick

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

Caissie, D., Goguen, G., El-Jabi, N. 2021. Analyses of design floods for small drainage basins in New Brunswick. Can. Tech. Rep. Fish. Aquat. Sci. 3443: vii + 25 p.

Flood frequency plays a key role in the design of hydraulic structures as well as in the management of fisheries and aquatic resources. There are two main approaches used to carry out flood frequency analyses, namely the annual maximum series (AMS) approach and the partial duration series approach (or peak over threshold, POT approach). In this study, both approaches were used to analyse instantaneous design floods for small basins (less than 35 km^2) in New Brunswick (NB). Results showed that very few stations are available to analyse small basin floods in NB. In fact, only 9 stations were available to carry out the analysis where 4 stations are active and 5 stations are discontinued. Results showed that both approaches (AMS and POT) were very good in fitting flood data for small basins. Results also showed that the currently used NB Watercourse and Wetland Alteration (WAWA) equation most likely underestimates 100-year instantaneous floods when compared to values calculated in the present study. Design floods calculated from other regional flood equations in NB (i.e., from the literature) do envelop observed data for small basins analysed in this study.

RÉSUMÉ

Caissie, D., Goguen, G., El-Jabi, N. 2021. Analyses of design floods for small drainage basins in New Brunswick. Can. Tech. Rep. Fish. Aquat. Sci. 3443: vii + 25 p.

La fréquence des crues joue un rôle important dans la conception des ouvrages hydrauliques ainsi que dans la gestion des pêches et des ressources aquatiques. Il existe deux approches utilisées pour effectuer les analyses de fréquence des crues, à savoir l'approche de la série annuelle maximale (AMS) et l'approche de la série de durée partielle (ou pic au-dessus du seuil, approche POT). Dans cette étude, les deux approches ont été utilisées pour analyser les débits de conception instantanés pour les petits bassins (moins de 35 km^2) au Nouveau-Brunswick (NB). Les résultats ont montré que très peu de stations sont disponibles pour analyser les débits de crues de petits bassins au NB. En fait, 9 stations étaient disponibles pour effectuer l'analyse alors que 4 stations sont toujours actives (5 stations ont été abandonnées). Les résultats ont montré que les deux approches (AMS et POT) étaient très bonnes pour ajuster les données de la fréquence des crues pour les petits bassins versants. Les résultats ont également montré que l'équation de modification d'un cours d'eau et d'une terre humide (*Watercourse and Wetland Alteration* ou *WAWA*) du NB actuellement utilisée dans la province sous-estime très probablement les débits instantanés d'une période de récurrence de 100 ans par rapport aux valeurs calculées dans la présente étude. Les crues de conception calculées avec d'autres équations régionales au Nouveau-Brunswick (provenant de la littérature) enveloppent les données observées des petits bassins de cette étude.

1. INTRODUCTION

Floods have often been associated with some of the most damaging natural hydrological phenomena. Notably, floods play a key role in many hydrological studies such as the design of hydraulic structures, the operation of reservoirs as well as in flood forecasting. Extreme hydrological events are not only important in the design of hydraulic structures (culverts, dams, bridges, etc.) but also in the management of fisheries and aquatic resources, as floods can impact fish populations (Elwood and Waters, 1969; Milner et al., 2013).

Historically, two main approaches have been used for flood analysis, namely the annual maximum series (AMS) and the partial duration series approach, also known as the peak over threshold approach (POT). The AMS approach consists of analysing extreme events during a specific time interval (e.g., maximum discharge for each year or annual maxima). The AMS approach has been the classic approach to flood analyses in most studies, because of its simplicity. For instance, under the assumption that annual floods are from stationary and independent time series, frequency distribution functions are simply fitted to flood data and discharges of different recurrence intervals are calculated. Many distributions have been used to fit annual flood data (such as the Gumbel, log-Person Type III, lognormal, etc.; Chow et al., 1988). Although the AMS approach is simple in application, it has the disadvantage of considering only one flood per year. When considering only one flood per year, it has been observed that the annual flood during some years are relatively small compared to secondary floods of other years. Therefore, the AMS approach considers some questionable flood data while disregarding other important flood information. To overcome these limitations, the POT approach has been used. The POT approach consists of analyzing all discharge data above a specific threshold or truncation level that is selected to reflect only flood data. Flows above the truncation level are considered flood exceedances. As the POT approach considers flows above a certain truncation level, then flood characteristics (magnitude, duration and volume) can also be analyzed (Bačová-Mitková and Onderka, 2010). Another advantage of the POT approach is that it has a strong theoretical background based on the extreme value theory (Todorovic, 1970; Zelenhasic, 1970). With this approach, the distribution of the largest flood peaks within a time interval (e.g., year) as well as the number of occurrences of floods (or flood count) are considered in the analysis.

In the application of the POT approach, the first step is to select a truncation level. Studies have shown that truncation levels should most likely be set between 1 and 2 floods per year on average (Cunnane, 1973; Taesombut and Yevjevich, 1978; Cunnane, 1979; Ashkar and Rousselle, 1983b; Bačová-Mitková and Onderka, 2010; Ben-Zvi, 2016). Based on these observations, we will consider two fixed truncation levels in the present study, namely truncation levels corresponding to 1 and 1.5 floods per year on average. Selecting multiple truncation levels at fixed flood counts has the following advantages: i) simplifying the POT approach by imposing specific truncation levels, ii) comparing results from different truncation levels to determine which level provides a better fit of the flood data, and iii) providing a range of flood quantile estimates to compare both AMS and POT approaches.

Some theoretical arguments suggest that certain distributions should be favored when dealing with extreme data (as they tend to converge to some limiting distributions). For the AMS 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). In the present study, the GEV distribution will be used to analyze flood data for the AMS approach and GP distributions will be used for flood exceedances for the POT approach.

In New Brunswick, there have been a number of studies that have dealt with floods and regional flood frequency analyses in the past. For instance, Montreal Engineering Co. Ltd. (1969) carried out a flood frequency analysis, and estimated high flows for many stations across the Maritime provinces. Another study was carried out by Acres Consulting Services Ltd. (1977) where high flows were estimated across the province. The latter study was one of the most comprehensive analyses of floods within the province; it included single station flood frequency analyses, regional flood equations, and flood risk maps for a number of communities. Another flood study was carried out for New Brunswick rivers in 1987 (Environment Canada and New Brunswick Department of Municipal Affairs and Environment, 1987) which consisted of both single and regional flood frequency analyses. More recently, a study was carried out by Aucoin et al. (2011) where more data were available (an additional 25 years of data) to update both single station analysis and regional flood equations. The above studies addressed flood frequency and regional flood estimates for the province of New Brunswick; however, no studies were carried out to specifically address floods for small drainage basins. Therefore, the present study will focus on flood estimation for small rivers, notably basins less than 35 km^2. This analysis is important in the design of small hydraulic structures such as dams, culverts, etc. It is important to note that the design flood represents the instantaneous peak discharge particular to a project or hydraulic structure. As such, the design flood (instantaneous discharge) is the maximum discharge flowing through a hydraulic structure without damage or failure to the structure.

The analysis will be carried out using data from hydrometric stations across the province where data are available for both daily discharge and peak flows (instantaneous discharge). Most hydraulic structures, such as culverts, are designed for a 100-year flood event (e.g., Nova Scotia, 2015; US Department of Agriculture, 2008; US Department of Transportation, 2012); however, lower return floods are sometime accepted on secondary roads or temporary stream crossing (e.g., British Columbia, 2019). For the purpose of the present study, we will determine the design floods for hydraulic structures of small basins by using the 100-year instantaneous discharge. However, floods for other recurrence intervals will also be presented, as these discharges are sometimes used if the damage of a structure or risk of failure is not as important.

The analysis in this study is designed so that it meets the following specific objectives: 1) to estimate design floods for 9 small drainage basins in New Brunswick using the AMS and POT approaches, 2) to compare results from both approaches, particularly, for discharge with higher recurrence intervals (100-year floods), 3) to use the 100-year daily flood value to calculate the instantaneous 100-year design floods for the purpose of designing hydraulic structures, and 4) to examine how the newly determined design floods for small basins in New Brunswick compare with previous flood predictions presented in previous studies.

2. MATERIALS AND METHODS

2.1 Study area

The hydrologic analysis was carried out using historical data from 9 hydrometric stations located in New Brunswick (drainage area less than 35 km^2; Table 1). All data used in this study were collected from the Historical Hydrometric Data at the following site (https://wateroffice.ec.gc.ca/mainmenu/historical_data_index_e.html). Extracted data included extreme values, i.e., annual maximum daily discharges, daily discharge, as well as peak flows (instantaneous discharge). Station IDs and the location of each station are presented in Figure 1. The smallest watercourse is the Narrows Mountain Brook with a drainage area of 3.89 km^2 whereas the largest basins are Palmers Brook (34.2 km^2) and Castaway Stream (34.4 km^2), which are very similar in size. The mean annual flow varied between 0.10 m^3/s (Middle Branch Nashwaaksis - Sandwith`s Farm and Narrow Mountain Brook) and 1.00 m^3/s (Ratcliffe Brook). The maximum instantaneous flow varied between 2.14 m^3/s and 29.7 m^3/s. The sample size for the different watercourses varied between 11 years for the Ratcliffe Brook and 51 years for the Middle Branch Nashwaaksis stream at Sandwith`s Farm. The overall mean sample size was 27 years (all stations). It is worth noting that 5 out of 9 stations are discontinued (only 4 stations are currently active).

2.2 Annual maximum series approach

For the analysis of the annual maximum series (AMS) approach, the generalized extreme value (GEV) distribution was used. The cumulative distribution of the GEV is given by (Aucoin et al., 2011),

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

where σ is the scale parameter, μ is the location parameter and ε is the shape parameter. If we isolate x from equation (1), we have,

$$x = \frac{\sigma}{\varepsilon}[(-\ln(F(x)))^{-\varepsilon} - 1] + \mu \tag{2}$$

where x represent the discharge for different values of $F(x)$.

In hydrology, $F(x)$ is also expressed as,

$$F(x) = 1 - \frac{1}{T} \qquad (3)$$

where T represents the recurrence interval in years, such that a 2-year flood has a $F(x) = 0.5$ and a 100-year flood has a $F(x) = 0.99$. Therefore, the estimation of discharge for different recurrence intervals using the GEV distribution, Q_{T_GEV}, is given by,

$$Q_{T\_GEV} = \frac{\sigma}{\varepsilon}\left[\left(-\ln\left(1 - \frac{1}{T}\right)\right)^{-\varepsilon} - 1\right] + \mu \qquad (4)$$

2.3 Peak Over Threshold (POT) approach

The POT approach consists in analyzing two distinctive properties of floods, namely the number of occurrences of floods and the characteristics of floods (magnitude, duration and volume). Figure 2 illustrates a discharge hydrograph with associated POT events which describe flood exceedances above the truncation level (Q_b). Every event above the truncation level is associated with a flood exceedance, ξ (magnitude), a flood duration (*Dur*) and a flood volume (*Vol*) (grey area; Figure 2). The distribution of the number of exceedances η(t) in a time interval $(0,t]$ has been analyzed (e.g., Todorovic and Zelenhasic, 1970; Todorovic and Woolhiser, 1972) and is generally observed to follow a Poisson distribution (Ashkar and Rousselle, 1983a). In the present study, the Poisson distribution will also be used to model the occurrence of events, as it has been shown to work well in previous studies (Caissie and El-Jabi, 1991). The time interval $(0,t]$ for the analysis of floods is generally taken as the year, unless studies are carried out on a seasonal basis.

When the number of exceedances follow a Poisson distribution, the equation is given by,

$$P(n) = e^{-\lambda}\,\frac{\lambda^n}{n!} \qquad (5)$$

where n represents the number of events (exceedances) in a particular time interval $(0,t]$ and λ represents the parameter of Poisson distribution. The Poisson distribution parameter, λ, is equal to the mean number of events in the time interval and is calculated by the following equation,

$$E(n) = \lambda \tag{6}$$

where $E(n)$ represents the expected value or the mean number of events.

In equation (5), $P(0)$ represents the probability of having no event in the time interval whereas $P(n)$ represents the probability of having n events. One important property of the Poisson distribution is that the mean and the variance are equal, therefore the variance is given by,

$$var(n) = E(n) = \lambda \tag{7}$$

The ratio of equation (6) and (7), also called the dispersion index, has been used in the past to identify a Poisson process, as this ratio gives a value of 1 when the number of occurrences of flood exceedances are Poisson distributed.

2.4 Distribution of the magnitude of flood exceedances

Following the fit for the distribution of the number of floods, the distribution of the flood exceedances (ξ) as well as the distribution of the maximum exceedances are also fitted. The distribution of the maximum or annual exceedances (where $(0,t]$ is one year) is given by the following cumulative distribution function, $F(x)$ (Todorovic and Zelenhasic, 1970; Zelenhasic, 1970),

$$F(x) = \sum_{n=0}^{\infty} (H(x)^n P(n)) \tag{8}$$

where $H(x)$ is the cumulative distribution function of the flood exceedances (e.g., exponential, generalized Pareto or other distributions) and where $P(n)$ represents the distribution of the number of occurrences of floods as described above. In equation (8) there is no restriction on the distribution of the number of occurrences of floods; however, if the number of occurrences of floods is a Poisson process, then substituting equation (5) into (8) further simplifies equation (8) to the following equation,

$$F(x) = e^{-\lambda(1-H(x))} \tag{9}$$

where $H(x)$ represents the distribution of flood exceedances. One simple distribution of $H(x)$, which has been widely used in flood analysis in the past, is the exponential distribution (e.g., Todorovic and Zelenhasic, 1970; Todorivic and Rousselle, 1971; Caissie and El-Jabi, 1991); however, in this study, we used the generalized Pareto (GP) distribution (Ribatet et al., 2007) as it has more flexibility to fit flood data (being a two-parameter distribution). The GP distribution is given by the following equation,

$$H(x) = 1 - \left[1 + k'\frac{x}{\alpha'}\right]^{-\frac{1}{k'}} \tag{10}$$

where α' is the scale parameter, k' is the shape parameter and x represents the flood exceedance (which differs from the x in equation (2) of the AMS approach). By substituting equation (10) in equation (9), the distribution of annual maximum exceedances (i.e., equation 9) becomes,

$$F(x) = e^{-\lambda\left[1+k'\frac{x}{\alpha'}\right]^{-\frac{1}{k'}}} \tag{11}$$

We can extract x from equation (11), giving,

$$x = \frac{\alpha'}{k'}\left(\left[\frac{-\ln(F(x))}{\lambda}\right]^{-k'} - 1\right) \tag{12}$$

where x represents the flood exceedances for different recurrence intervals for the POT model (when using the GP distribution). By adding the truncation level (Q_b) and substituting $F(x)$ in equation (12) by equation (3), the equation to calculate discharges for different recurrence intervals is obtained, and is given by,

$$Q_{T\_GP} = \frac{\alpha'}{k'}\left(\left[\frac{-\ln(1-\frac{1}{T})}{\lambda}\right]^{-k'} - 1\right) + Q_b \qquad (13)$$

where Q_{T_GP} represents different flood discharges as a function of the recurrence interval for the generalized Pareto distribution.

In the present study, results of fitted flood data for both the AMS and POT approaches will be calculated and compared to make the final decision on the discharges for different recurrence intervals.

2.5 Design floods

The above frequency analysis was carried out using mean daily discharges and, as such, the calculated discharges for different recurrence intervals are given as daily values. However, the design floods of hydraulic structures require the use of instantaneous discharge rather than the daily flow. The design flood can be calculated by studying the ratio between instantaneous and daily discharge of hydrographs. The instantaneous flow can be very different than the daily discharge, especially for small basins which are generally more responsive (than larger rivers). In these cases, the instantaneous to daily flow ratios can sometimes reach factors as high as 3 (Aucoin et al., 2011). In the present study, high recurrence flows are of greater interest, and as such, we looked at ratios of instantaneous to daily flows among the highest observed discharges at each station. The objective of using high observed discharge (data from the 5 highest recorded discharges) was to eliminate any potential high ratios resulting from low return floods (e.g., 2-year event). This approach was used to prevent the calculation of floods which would result in overdesigned structures at high return floods. The design floods were then compared to different regional equations provided in the literature.

Results and Discussion

3.1 Single station flood frequency analysis

Results of the flood frequency analysis are presented in Table 2. For the AMS approach, the GEV distribution was used (labeled as AMS-GEV) whereas the GP distribution was used for the POT approach. For the POT approach, the truncation level was set at two different flood counts, i.e., a flood count of 1 and 1.5. Truncation levels corresponding to 1 and 1.5 floods per year on average, labeled POT1 and POT1.5 respectively (Table 2). Notably, each flood count represents a different truncation level. A detailed example is presented using the Middle Branch Nashwaaksis River (at Royal Road), i.e., the first station in Table 2. The POT1 truncation level was selected at 5.54 m^3/s for this station whereas the POT1.5 truncation level was slightly lower at 5.09 m^3/s. Flood discharges (daily mean) of 6.09 m^3/s (T = 2 years) and 20.8 m^3/s (T = 100 years) were calculated using the GEV distribution. For the POT approach, the 2-year floods were 6.31 m^3/s (POT1) and 6.23 m^3/s (POT1.5) whereas the 100-year floods were 18.1 m^3/s (POT1) and 23.5 m^3/s (POT1.5). Also presented in Table 2 are the mean flood value (mean of the three methods) as well as the coefficient of variation (Cv; expressed in percentage). For the Middle Branch Nashwaaksis River (at Royal Road), the mean discharge varied between 6.21 m^3/s (T = 2 years) and 20.8 m^3/s whereas the variability (Cv) was between 1.8% (2-year) and 13.1% (100-year; Table 2).

Results for other stations are also presented in Table 2. Results showed that low return floods (2-year; mean value) were generally between 1.06 m^3/s (Middle Branch Nashwaaksis – Sandwith`s Farm) and 13.0 $m^3/s$ (Palmers Brook). The 100-year flood (mean value of methods) varied between 2.18 $m^3/s$ (Middle Branch Nashwaaksis - Sandwith`s Farm) and 57.5 m^3/s (Ratcliffe Brook). Results showed similarities among floods of different approaches (AMS and POT), as previous studies have shown that these approaches are complementary when using the GEV and GP distributions (Aucoin et al. 2011). The variability among methods was low for low return floods (Cv between 0.3% and 6.1%) and higher at the 100-year event (Cv between 1.4% and 25.9%), which is expected in flood frequency analyses. The variability among methods for 100-year floods was generally low for most stations (Cv less than 10%); however, the Middle Branch Nashwaaksis (at Royal Road; Cv = 13.1%) and Ratcliffe Brook (Cv = 25.9%) showed values higher than 10% (Table 2). The sample size could be a factor for Ratcliffe Brook with only 11 years of data; however, Middle Branch Nashwaaksis (at Royal Road) had 28 years of data, which was comparable to the sample size of other stations.

Figure 3 shows the fitted distributions for all studied stations. Figure 3a shows the fit of the distributions for the Middle Branch Nashwaaksis (at Royal Road). The 100-year discharge was calculated at 18.1 m^3/s (POT1), 20.8 m^3/s (GEV) and 23.5 m^3/s (POT1.5). A relatively good fit was observed for all distribution although differences were noted at high return floods (sample size was 28 years of data). The highest 100-year flood (among the three methods) was generally selected in the present study for each station, unless data points would suggest that this value was too high. Therefore, for this station, a 100-year flood value of 23.5 m^3/s (POT1.5) was retained for subsequent analyses, i.e., to estimate the design flood and to compare this value with regional equations. Results for the Middle Branch Nashwaaksis River (at Sandwith's Farm) showed 100-year discharges of 2.14 m^3/s (AMS), 2.09 m^3/s (POT 1) and 2.31 m^3/s (POT 1.5) (Figure 3b; Table 2). This station has the longest time series with 51 years of data. Given the fact that the highest observed discharges were slightly above the fitted lines, a 100-years flow of 2.31 m^3/s (highest value among methods) was retained for subsequent regional analyses. Hayden Brook (Figure 3c) also showed a relatively good fit with 23 years of data. The highest observed discharge was at 7.76 m^3/s (observed in 1973) and was relatively higher than other observed discharges. This highest recorded flow also deviated the most from the fitted distributions. As such, the 100-year flood value of 8.28 m^3/s (POT1.5, highest values) was selected for this station. Narrows Mountain Brook had 46 years of data and a good fit was observed for this station for all distributions which showed similar results (Figure 3d). A 100-year flood value of 4.74 m^3/s (AMS-GEV; highest value) was selected for this station. For the Castaway Stream, the 100-year discharge was estimated at 19.8 m^3/s (highest value; POT1.5; Figure 3e), although most distributions showed similar discharge values. Catamaran Brook was the only station with a clear downward curvature for high return floods (with the POT approach), most likely due to the two highest flows having the same value (13 m^3/s). The 100-year flood for Catamaran Brook was selected at 16 m^3/s (highest value; AMS-GEV; Figure 3f). The 100-year flood for Palmers Brook was selected at 34.0 m^3/s (highest value; POT1.5; Figure 3g) whereas the 100-year flood for the Holmes Brook was selected at 5.48 m^3/s (highest value; Figure 3h). For these last two stations, all distributions provided similar results. The greatest difference among fitted distributions in the 100-year flood was observed for Ratcliffe

Brook (45.5 m^3/s to 74.2 m^3/s; Figure 3i), presumably due to a lower sample size at this station. For this station a mid-value 100-year flow was selected at 52.9 m^3/s (POT1), recognizing that the small sample size for this station (11 years of data) most likely contributed to these larger differences (Cv = 26%; Table 2). In fact, Ratcliffe Brook showed the highest uncertainty (highest Cv) for the estimation of the 100-year event compared to all other stations (Table 2).

3.2 Design floods

Table 3 presents different instantaneous to daily discharge ratios for all studied basins. Here, the instantaneous to daily flow ratios were selected for the 5 highest observed discharge at each site (which generally represents flows between a 10-year and a 50-year recurrence interval). For example, the five highest observed (measured) discharges for the Middle Branch Nashwaaksis Brook (Royal Road) were 11.3 m^3/s, 11.5 m^3/s, 11.7 m^3/s, 12.2 m^3/s and 14.2 m^3/s (Figure 3a) with corresponding ratios of 1.34, 2.18, 1.15, 2.61 and 2.29 respectively. These observed flows were all higher than the 10-year flood (Q_{10} = 10.8 m^3/s; Table 2). For this station the instantaneous to daily flow ratio of 2.61 was selected (maximum value of the 5 highest floods; Table 3). This discharge was observed December 12, 1993 with an instantaneous flow of 31.8 m^3/s and a daily mean value of 12.2 m^3/s (i.e., higher than a 10-year event). The maximum ratio for the remaining data (excluding the 5 highest discharge) at Middle Branch Nashwaaksis Brook (Royal Road) was 2.06, and reported in parentheses in Table 3.

Results for other stations showed ratios between 1.37 (Ratcliffe Brook) and 2.67 (Hayden Brook) with a mean value of 2.08 (5 highest discharges for all stations). These results show that small basins in NB generally have instantaneous flow about twice that of daily values, but can reach 2.7 (as was the case for Hayden Brook). Peak discharge was generally observed in December and April for these small basins, likely due to a combination of rain and snowmelt floods. For each station, the instantaneous to daily flow ratios were used to calculate the 100-year instantaneous discharge (design flood) calculated from the daily value of the flood frequency analyses (Table 2; see text above). In the case of the Middle Branch Nashwaaksis Brook (Royal Road) the 100-year daily discharge retained for the regional analysis was 23.5 m^3/s (see Table 2 and text above). With a ratio of 2.61, the instantaneous flow was calculated at 61.3 m^3/s (Table 3). The same approach was used to calculate the design flood (instantaneous discharge) for all stations using data from

Table 2 and Table 3. The results are presented in the last column of Table 3. The mean ratio for the small basin in NB for the 5 highest observed discharge was calculated at 2.08, meaning that small basin instantaneous discharge is generally twice the daily mean value. Instantaneous flows for small basins in New Brunswick varied between 4.62 m^3/s (Middle Branch Nashwaaksis - Sandwith`s Farm) and 72.4 m^3/s (Ratcliffe Brook). Table 3 also presents instantaneous to daily discharge ratios for lower return floods (i.e., remaining data when excluding the 5 highest discharge). The remaining discharge time series generally represented floods with a recurrence interval less 20 years. Results show that low return floods have a slightly higher ratio between 1.47 to 3.57 with a mean value of 2.55 (Table 3, value in parentheses).

3.3 Regional flood frequency characteristics

The design floods (instantaneous 100-year flow; last column of Table 3) for small basins in New Brunswick calculated in this study are plotted in Figure 4. This figure shows two clusters of basins, i.e., 4 basins less than 7 km^2 and 5 basins greater than 27 km^2. Among the smallest drainage basins, a greater variability in flood values was observed (4.62 m^3/s - 22.1 m^3/s) whereas the larger basins showed discharge between 29.4 m^3/s and 72.4 m^3/s. This figure shows that flood information is missing for drainage basins between 7 and 27 km^2 within the province. If future data were to be collected, this range of basin sizes would be important in order to fill this gap. Also, basins are predominately in the southern part of the province, and more data should fill the gap for basins reflecting the northern part of the province (Figure 1).

Different regional equations are plotted in relation to small basin flood values (Figure 4). In the New Brunswick Watercourse and Wetland Alteration Certification Manual, the design equation of $Q_p = 1.39\ A$ is presented for small basins; however, the equation $Q_p = 1.64\ A$ is most often used to be more conservative and to accommodate for climate change (pers. comm., Kyle Werner, National Defence / Government of Canada, Fredericton, NB). This equation will be referred to as the NB WAWA equation (i.e., $Q_p = 1.64\ A$). As shown in Figure 4, the NB WAWA equation most likely underestimates design floods of hydraulic structures for small basins in New Brunswick, as 5/9 stations showed flood values higher than this equation. As for the other regional equations, they envelope the small basin flood values in the province. For example, the study by Environment Canada and New Brunswick Department of Municipal Affairs and Environment,

(1987) would capture all flood values, including the Ratcliffe Brook (highest discharge among basins greater than 10 km^2) and Hayden Brook (highest discharge among basins less than 10 km^2). Ratcliffe Brook showed a flood discharge of 72.7 m^3/s (regional equation) compared to 72.4 m^3/s (current flood frequency analysis; Table 3). The regional equation developed by Aucoin et al. (2011) also envelops all the flood data including both Ratcliffe Brook and Hayden Brook. The equation by Aucoin et al. (2011) seems a bit more conservative for flood design of basin larger than 10 km^2 (having a slightly higher slope), and being slightly more distant to larger basins flood values. Although the equation developed by Environment Canada and New Brunswick Department of Municipal Affairs and Environment, (1987) envelops all the data points of the present study, the milder slope of this equation could potentially not envelope all data points for basins larger than 35 km^2 (beyond observed data points; Figure 3). This is however beyond the scope of the present study.

2. CONCLUSIONS

This study presents a flood frequency analysis to provide data related to floods for small drainage basins in New Brunswick. Two flood frequency approaches were used for the analysis, namely the annual maximum series (AMS) approach and the peak over threshold (POT) approach. These two approaches are complimentary in flood frequency analyses although they approach the flood phenomenon differently. Using both the AMS and POT, two different distributions were used, i.e., the generalized extreme value (GEV) distribution for the AMS approach and the generalized Pareto (GP) distribution for the POT approach. In the POT approach, two truncation levels were used for the flood frequency analysis, namely at a flood count of 1 and 1.5 (mean number of floods per year on average). Results with both AMS and POT showed good agreement between observed data and predicted floods from the frequency analysis. Design floods were selected for each station based on the 100-year events (other recurrence intervals were also presented) and instantaneous to daily discharge ratios were calculated. Design floods were compared to regional equations provided in the literature.

This study revealed that very few stations are available to conduct flood analysis in small basins of New Brunswick. In fact, only 9 stations were available for drainage basin less than 35 km^2. Of these 9 stations, 4 stations are still active while 5 stations have been discontinued. The stations are clustered into two groups based on their drainage area (4-7 km^2 and 27-35 km^2). Flow information is missing for the rest of stations falling in between the two clusters. Most of the study stations are in the southern part of the province. The most northern station was Catamaran Brook, which is in the middle section of the province. Presently, no data are available in the northern part of the province for small basins, where these basins would be influenced by snowmelt dominated floods. Results showed that the currently used NB WAWA equation mostly like underestimates 100-year design floods (instantaneous discharge) while other established regional equations (e.g., Environment Canada and New Brunswick Department of Municipal Affairs and Environment, 1987; Aucoin et al. 2011) do envelop observed data for small basins and therefore adequately cover calculated design floods for the 9 studied stations.

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Table 1. Analysed hydrometric stations in New Brunswick

River	Station ID	Latitude	Longitude	Drainage Area (km^2)	Mean Annual Flow (m^3/s)	Maximum Instantaneous Flow (m^3/s)	Period of record	Years of record	State of station
Middle Branch Nashwaaksis (Royal Road)	01AK005	46° 02' 06"	66° 42' 05"	26.9	0.54	14.2	1966-1993	28	Discontinued
Middle Branch Nashwaaksis (Sandwith`s Farm)	01AK006	46° 04' 58"	66° 43' 58"	5.70	0.10	2.14	1967-2017	51	Active
Hayden Brook	01AL003	46° 17' 56"	67° 02' 13"	6.48	0.18	7.76	1971-1993	23	Discontinued
Narrows Mountain Brook	01AL004	46° 16' 37"	67° 01' 17"	3.89	0.10	3.54	1972-2017	46	Active
Castaway Stream	01AN001	46° 17' 54"	65° 42' 43"	34.4	0.87	18.1	1972-1981; 1983-1993	21	Discontinued
Catamaran Brook	01BP002	46° 51' 23"	46° 51' 23"	28.7	0.65	13.0	1990-2017	28	Active
Palmers Brook	01BU004	45° 53' 14"	64° 30' 59"	34.2	0.94	27.9	1967-1984	18	Discontinued
Holmes Brook	01BU009	45° 53' 16"	65° 08' 48"	6.20	0.12	5.22	1996-2016	21	Active
Ratcliffe Brook	01BV005	45° 22' 04"	65° 48' 42"	29.3	1.00	29.7	1961-1971	11	Discontinued

Table 2. Results of flood frequency analysis using both the annual maximum series (AMS) and peak over threshold (POT) approaches for small drainage basins in New Brunswick. Discharges for different recurrence intervals are mean daily values

		Truncation Level (m^3/s)		Recurrence interval (years) 2	5	10	20	50	100
Middle Branch Nashwaaksis at Royal Road	AMS-GEV			6.09	8.68	10.8	13.3	17.2	20.8
	POT1	5.54		6.31	8.90	10.8	12.8	15.7	18.1
	POT1.5	5.09		6.23	8.63	10.9	13.7	18.6	23.5
			Mean	6.21	8.74	10.8	13.3	17.2	20.8
			Cv (%)	1.8	1.6	0.2	3.1	8.4	13.1
Middle Branch Nashwaaksis at Sandwith`s Farm	AMS-GEV			1.05	1.35	1.54	1.73	1.97	2.14
	POT1	0.97		1.08	1.39	1.57	1.74	1.95	2.09
	POT1.5	0.89		1.07	1.35	1.55	1.76	2.06	2.31
			Mean	1.06	1.36	1.56	1.75	1.99	2.18
			Cv (%)	1.2	1.6	1.0	1.0	3.2	5.2
Hayden Brook	AMS-GEV			1.94	3.04	3.88	4.78	6.09	7.20
	POT1	1.70		1.96	2.96	3.80	4.79	6.37	7.85
	POT1.5	1.43		1.94	2.94	3.81	4.86	6.60	8.28
			Mean	1.95	2.98	3.83	4.81	6.36	7.77
			Cv (%)	0.7	1.9	1.1	0.9	4.1	7.0
Narrows Mountain Brook	AMS-GEV			1.19	1.69	2.16	2.74	3.74	4.74
	POT1	1.06		1.19	1.68	2.10	2.59	3.38	4.11
	POT1.5	0.96		1.18	1.65	2.10	2.65	3.62	4.60
			Mean	1.19	1.68	2.12	2.66	3.58	4.48
			Cv (%)	0.3	1.2	1.8	2.9	5.2	7.3
Castaway Stream	AMS-GEV			8.44	11.2	12.9	14.6	16.6	18.1
	POT1	8.30		8.83	10.8	12.4	14.3	17.2	19.8
	POT1.5	6.50		8.73	11.6	13.2	14.7	16.4	17.5
			Mean	8.67	11.2	12.9	14.5	16.7	18.5
			Cv (%)	2.4	3.4	3.2	1.5	2.4	6.3
Catamaran Brook	AMS-GEV			6.95	9.49	11.1	12.7	14.7	16.2
	POT1	6.65		7.81	10.4	11.5	12.3	13.1	13.4
	POT1.5	5.65		7.67	10.1	11.4	12.5	13.7	14.4
			Mean	7.48	10.0	11.4	12.5	13.8	14.7
			Cv (%)	6.1	4.7	1.9	1.4	6.0	9.5
Palmers Brook	AMS-GEV			12.8	18.2	21.7	25.1	29.5	32.8
	POT1	11.2		13.2	18.7	21.9	24.7	27.9	30.0
	POT1.5	9.50		12.9	18.2	21.8	25.4	30.3	34.0
			Mean	13.0	18.4	21.8	25.1	29.2	32.3
			Cv (%)	1.4	1.7	0.5	1.5	4.2	6.4
Holmes Brook	AMS-GEV			1.38	2.17	2.80	3.50	4.55	5.48
	POT1	1.25		1.47	2.24	2.85	3.50	4.49	5.34
	POT1.5	1.02		1.47	2.24	2.84	3.50	4.50	5.36
			Mean	1.44	2.22	2.83	3.50	4.51	5.39
			Cv (%)	3.4	1.8	0.9	0.1	0.8	1.4
Ratcliffe Brook	AMS-GEV			12.3	19.3	24.6	30.3	38.6	45.5
	POT1	10.4		12.0	18.3	23.9	30.6	41.9	52.9
	POT1.5	9.1		11.7	17.9	24.6	34.0	52.7	74.2
			Mean	12.0	18.5	24.4	31.6	44.4	57.5
			Cv (%)	2.6	3.9	1.8	6.5	16.7	25.9

AMS-GEV = Annual Maximum Series - Generalized Extreme Value distribution

POT1 and POT1.5 = Peak Over Threshold approach using the Generalized Pareto distibution with a flood count of 1 and 1.5 respectively

Table 3. High flow characteristics for daily and instantaneous discharge ratios for small streams in New Brunswick and date of occurrence of flood events

River	Daily vs. instantaneous discharge[a]					Instantaneous[c] 100-year flow
	Year	Date	Daily discharge (m^3/s)	Instantaneous discharge (m^3/s)	Ratio[b]	
Middle Branch Nashwaaksis (Royal Road)	1993	12-Dec	12.2	31.8	2.61 (2.06)	61.3
Middle Branch Nashwaaksis (Sandwith`s Farm)	1973	29-Apr	2.14	4.28	2.00 (3.02)	4.62
Hayden Brook	1983	18-Apr	3.43	9.15	2.67 (3.35)	22.1
Narrows Mountain Brook	2010	14-Dec	2.34	5.87	2.51 (3.57)	11.9
Castaway Stream	1991	22-Apr	11.5	17.1	1.49 (1.47)	29.4
Catamaran Brook	2010	14-Dec	13.0	29.6	2.28 (2.98)	36.8
Palmers Brook	1969	23-Dec	21.0	43.6	2.08 (2.53)	70.7
Holmes Brook	2014	16-Apr	5.22	9.00	1.72 (2.44)	9.44
Ratcliffe Brook	1964	27-Dec	21.1	28.9	1.37 (1.49)	72.4
				Mean =	2.08 (2.55)	

[a.] Data taken from the 5 highest observed discharge of the time series

[b.] Maximum ratio from the 5 highest observed floods. Values in parentheses are the maximum ratios for remaining data, i.e., excluding the 5 highest discharge

[c.] The 100-year instantanous discharge was calculated from the selected 100-year daily flood in Table 2 (see text for details)

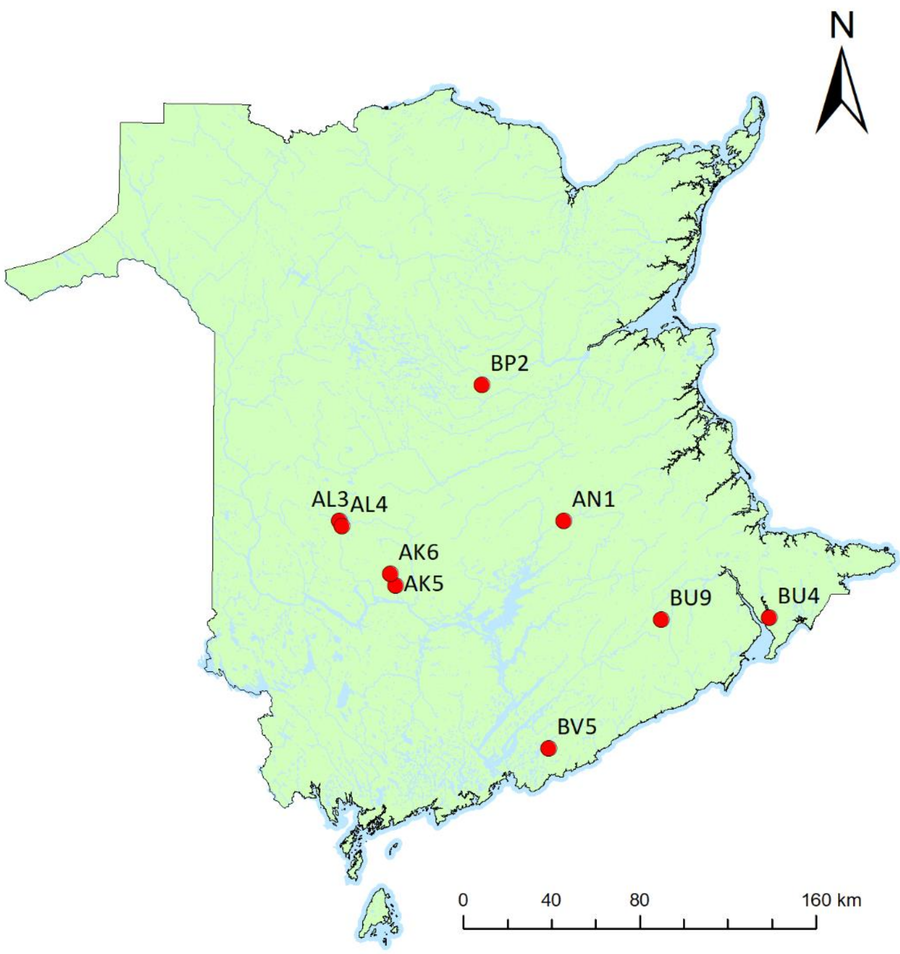

Figure 1. Map showing the location of the studied small drainage basins in New Brunswick (station IDs have been shortened, e.g., BP2 = 01BP002)

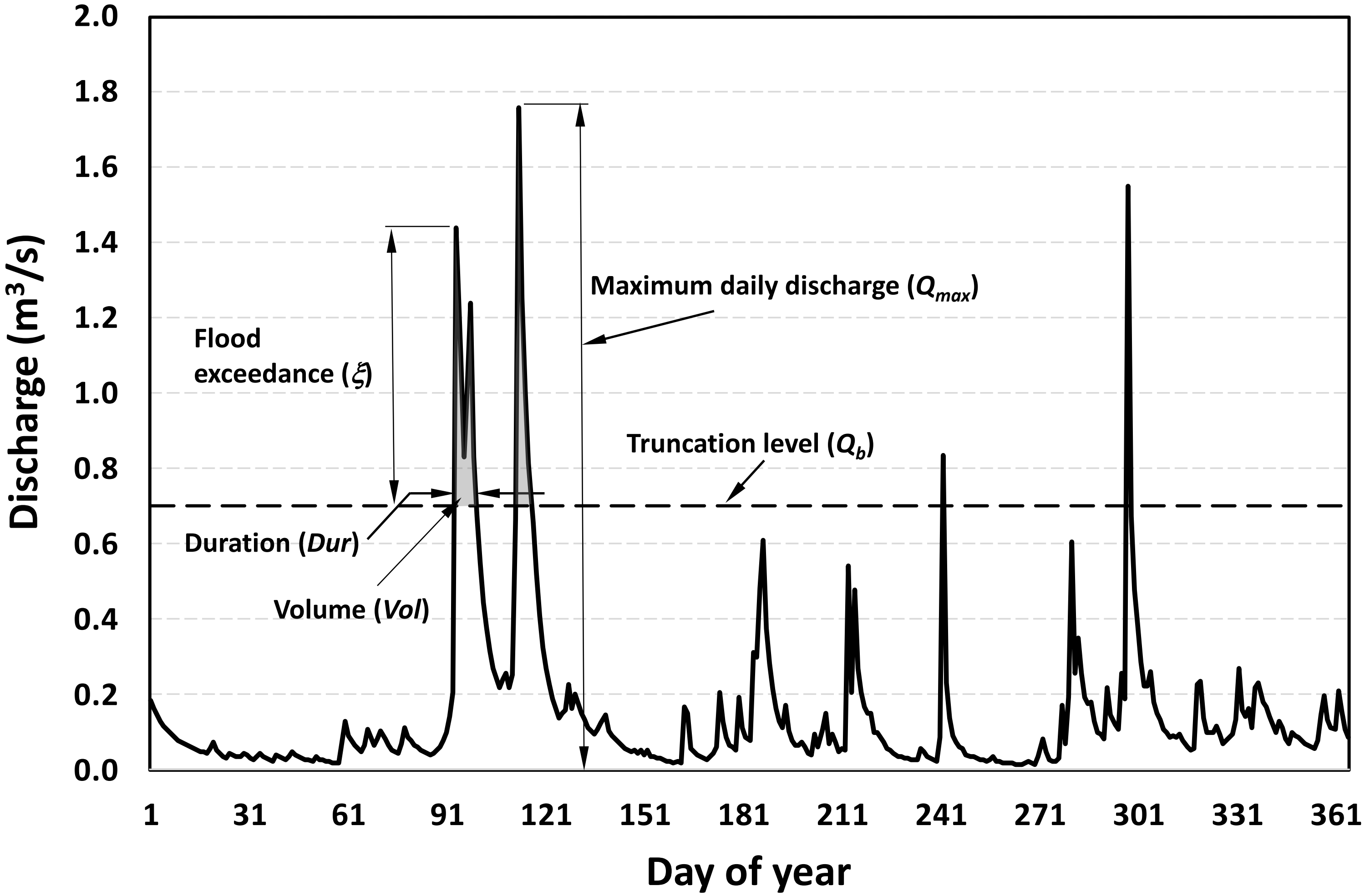

Figure 2. Discharge hydrograph with corresponding flood characteristics above the truncation level (exceedance, duration and volume) when using the Peak Over Threshold (POT) approach

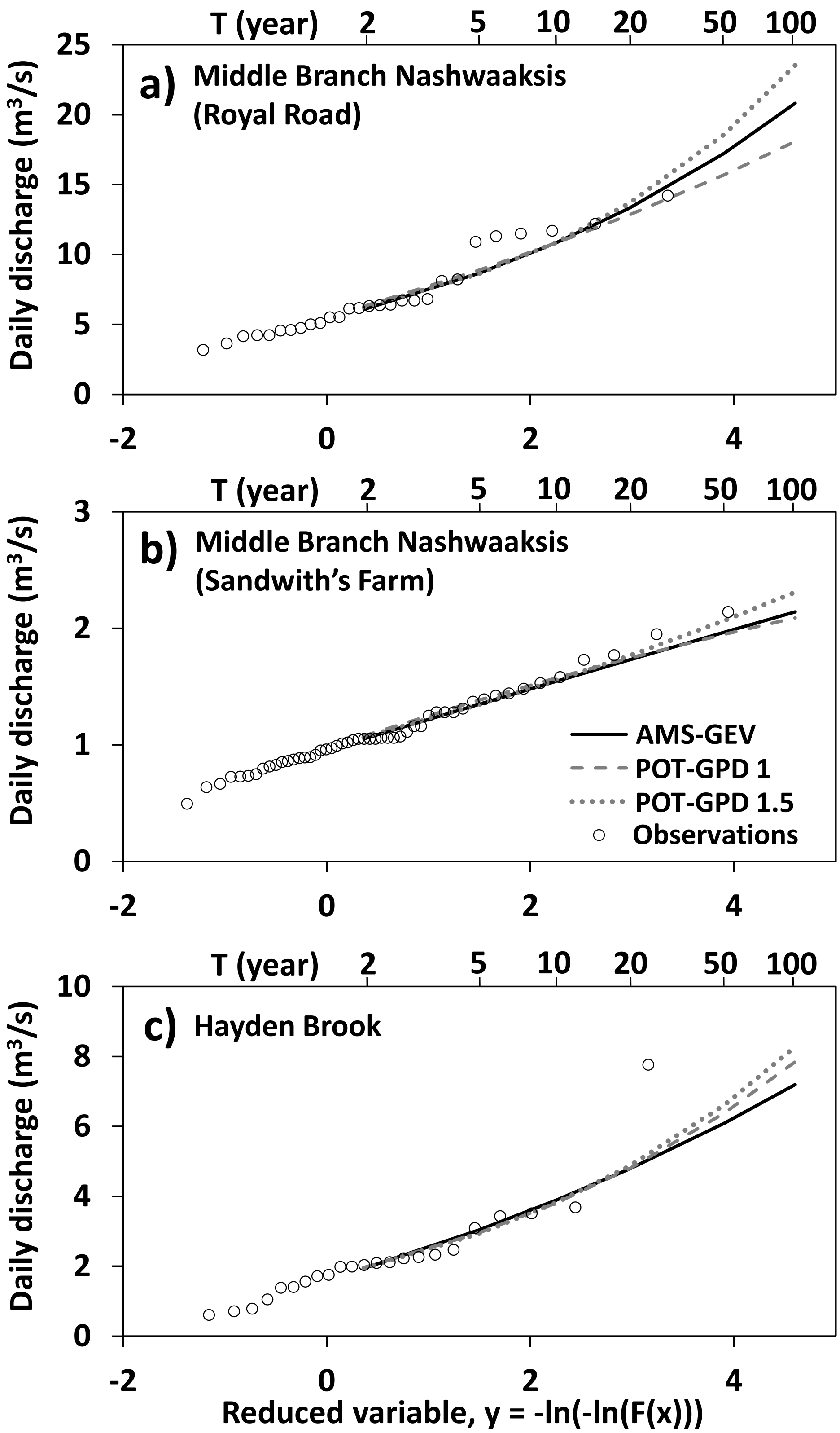

Figure 3. Flood observations and frequency distribution fit

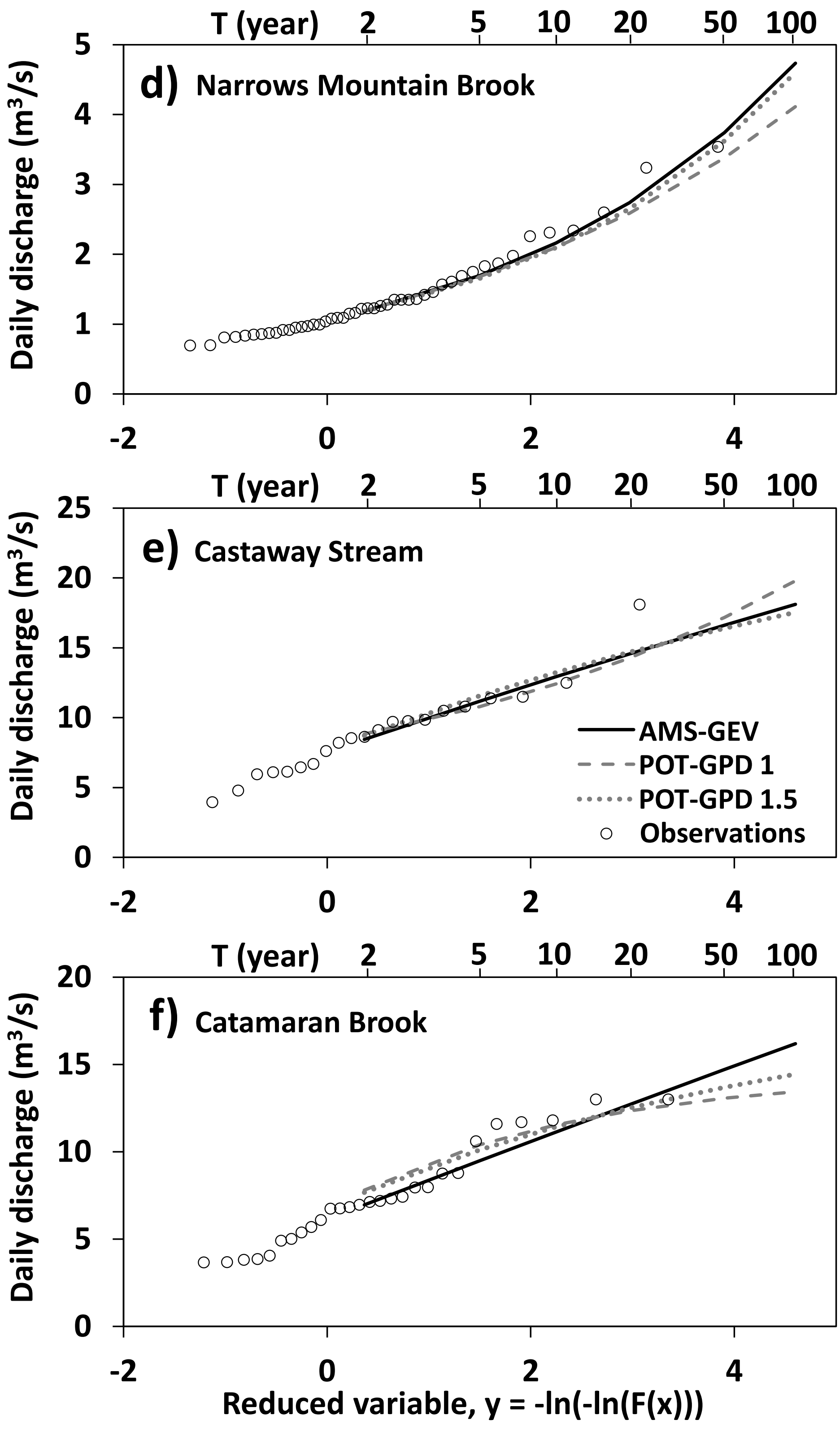

Figure 3. Flood observations and frequency distribution fit (continued)

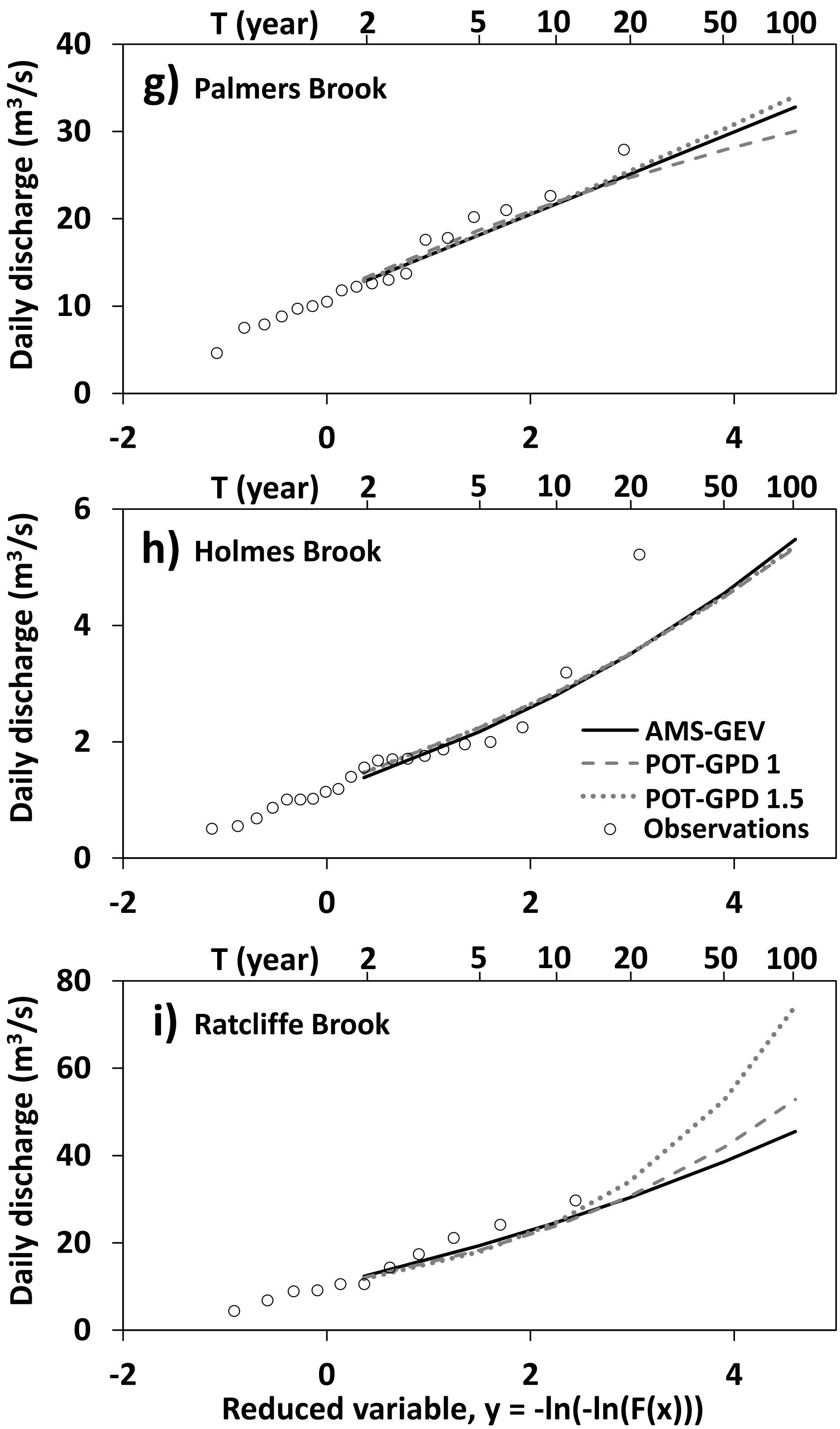

Figure 3. Flood observations and frequency distribution fit (continued)

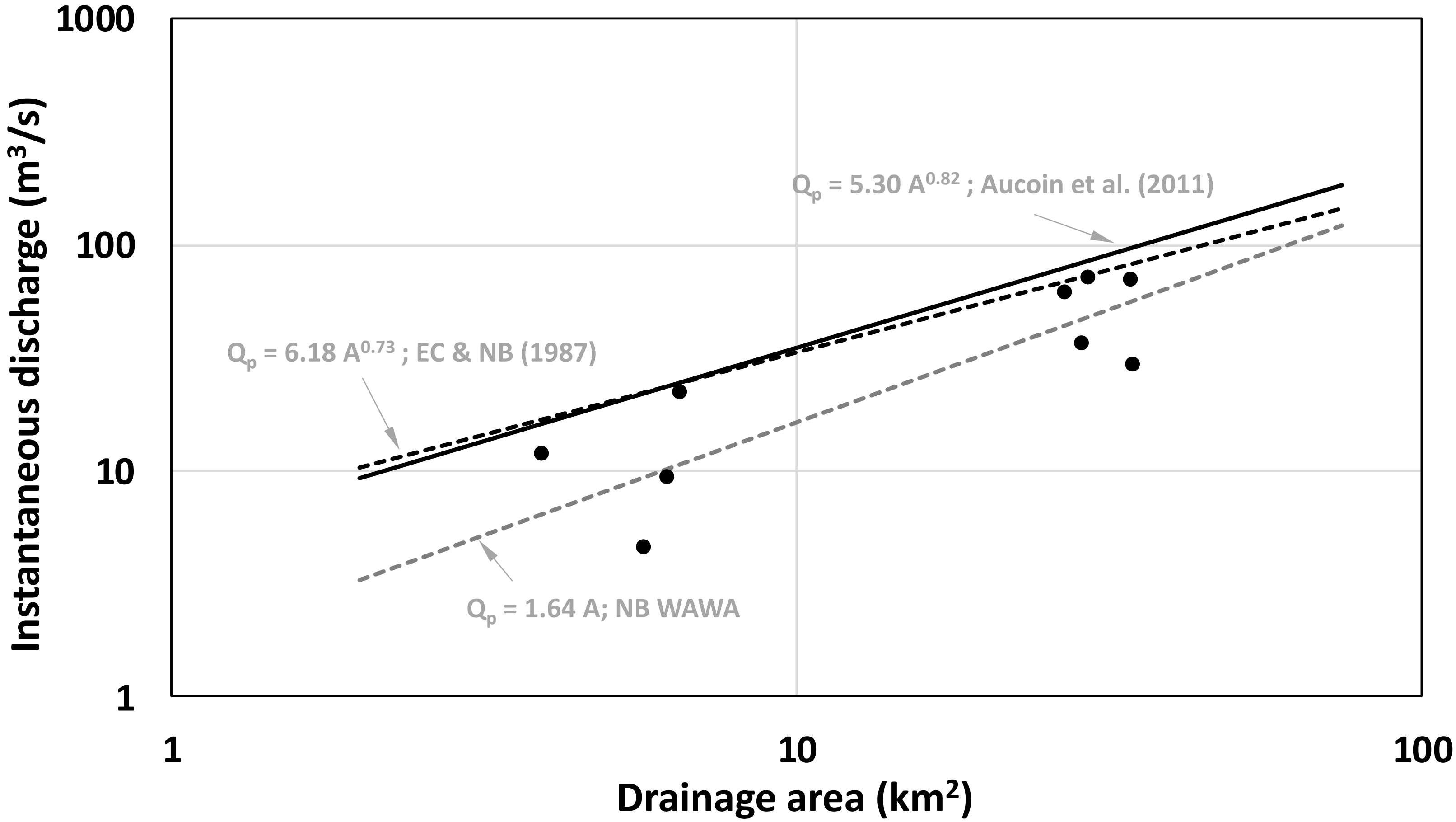

Figure 4. Design floods (100-year instantaneous discharge) for small basins in New Brunswick in relation to the NB WAWA equation and regional flood frequency equations (EC & NB Dept. Env. 1987; Aucoin et al. 2011)