Low flow estimation for New Brunswick rivers

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Low flow estimation for New Brunswick rivers

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Caissie, D., L. LeBlanc, J. Bourgeois, N. El-Jabi and N. Turkkan. 2011. Low flow estimation for New Brunswick rivers. Can. Tech. Rep. Fish. Aquat. Sci. 2918: x + 46p.

The present study has the objective of updating the 1990 low flow estimation guidelines for the province of New Brunswick. To carry out the analysis, 38 hydrometric stations were selected and single station low flow frequency analyses were carried out. Similar to previous studies, the annual minimum flow was used and these data were fitted to a 3 parameter Weibull distribution function. Low flows for each station were calculated for 1, 7 and 14-day durations and for recurrence intervals of 2, 10, 20 and 50 years. Following the single station frequency analysis, a regional low flow study was carried out in order to estimate low flow for ungauged basins. This analysis consisted of calculating regression equations between low flows and hydroclimatique variables. The regression analysis showed very good results with over 90% of the variability of low flows explained by drainage area and the mean annual precipitation. A comparison of low flows from the current study to those of the previous low flow studies revealed very consistent results (within 5%). However, the present study has more years of low flow data and should therefore have less uncertainties associated with the estimates.

RÉSUMÉ

Caissie, D., L. LeBlanc, J. Bourgeois, N. El-Jabi and N. Turkkan. 2011. Low flow estimation for New Brunswick rivers. Can. Tech. Rep. Fish. Aquat. Sci. 2918: x + 46p.

La présente étude a pour objectif de mettre à jour l'étude de 1990 sur les lignes directrices pour l'estimation des débits faibles de la province du Nouveau-Brunswick. Pour effectuer cette analyse, 38 stations hydrométriques ont été sélectionnées et la fréquence du débit faible a été calculée pour chaque station. Parallèlement aux études antérieures, le débit minimum annuel a été utilisé et les données ont été ajustées à une fonction de répartition de Weibull à 3 paramètres. Les débits faibles pour chaque station ont été calculés pour une durée de 1, 7 et 14 jours et pour des périodes de récurrence de 2, 10, 20 et 50 années. Suite à l'analyse de fréquence de chaque station hydrométrique, une étude régionale des étiages a été réalisée afin d'estimer les débits faibles pour les bassins non jaugés. Cette analyse consiste à calculer des équations de régression entre les débits faibles et variables hydroclimatiques. L'analyse de régression a montré de très bons résultats avec plus de 90% de la variabilité des débits faibles expliquée par la superficie des bassins versants et les précipitations annuelles moyennes. Une comparaison des débits d'étiage de la présente étude à ceux des études précédentes a révélé des résultats très cohérents (moins de 5%). Toutefois, la présente étude comporte plus d'années d'observations des débits faibles et devrait donc avoir moins d'incertitudes associées aux estimations.

1.0 INTRODUCTION

River low flows have always been an important parameter in hydrological studies. Low flow conditions are mainly driven by local climate, underlying geology, soils, topography, vegetation, as well as by lakes and swamps (Smakhtin, 2001; Burn et al., 2008). Anthropogenic impacts can also influence low flow conditions such as irrigation, water withdrawals and climate change among others (Lins and Slack, 1999; Hisdal et al. 2001). These conditions and factors all needs to be considered during the planning, design, construction and the maintenance of different hydraulic structures and water resource systems. River low flows can also impact fish habitat and instream water toxicity by reducing the dilution capacity and increasing water temperatures (Nemerow 1985). For example, low flows can affect fish movement and increase fish stress and mortality due to high water temperatures (Magoulick and Kobza, 2003; Lund et al., 2002).

The present study will focus on estimating low flows in the province of New Brunswick (NB) with the objective of updating results from previous studies (e.g., Environment Canada and New Brunswick Department of the Environment, 1990; Hébert et al., 2003; Savoie et al., 2004; Benyahya et al., 2009). The low flow estimation guideline of 1990 was carried out using 38 hydrometric stations across the province and the same stations will be analysed in the present study. Similar to this previous study, the annual minimum flow (AMF) was used. The low flow frequency analysis consists of fitting the AMFs to a distribution function and calculating the discharge for different frequencies. The study was carried out for each analysed station (single station analysis) and low flow frequencies were calculated for 1-day, 7-day and 14-day durations and for different recurrence intervals (e.g., 2-year, 10-year, 20-year and 50-year). Following the single station analysis, a regression analysis was carried out in order to estimate low flows for ungauged basins.

Previous studies have also used the AMF approach and calculated regional regression equations for low flows in New Brunswick. For example, Hébert et al. (2003) studied 31 hydrometric stations in NB and calculated low flows for 1-day, 7-day and 14-day durations and for different recurrence intervals (between 2 and 50 years). Another low flow study was carried in 2003 where the Deficit Below Threshold (DBT) approach was used (Savoie et al., 2004). This approach consists of analysing low flows below a specific threshold to better described low flows in terms of magnitude, timing, duration and volume deficit (El-Jabi et al., 1997). With the DBT approach it is possible to relate duration of low flows as well as the volume deficit associated with different magnitude of low flow events. A more recent study by Benyahya et al., (2009) compared results of the AMF and DBT approaches. Their study concluded that both approaches provided similar results provided that the generalized Pareto distribution was used for the DBT approach. In the present study, the AMF approach will be used to make the study consistent with previous regional low flow studies in NB (e.g., Environment Canada and New Brunswick Department of the Environment, 1990; Hébert et al., 2003). Also, regression equations were analysed by considering the whole province as one hydrological region.

The objective of the present study is to update the results of previous low flow studies in NB. As such, the specific objectives are: (i) to carry out a single station frequency analysis using 38 hydrometric stations within the province, (ii) to compare low flows among different rivers, (iii) to calculate provincial regression equations in order to estimate low flows at ungauged basins and (iv) to compare results with those of previous studies.

2.0 MATERIALS AND METHODS

2.1 Source of data and study region

Hydrometric data used in the present study were obtained from the Environment Canada's database (HYDAT). In order to have reliable low flow estimates, stations with at least 15 years of data were selected for the study. In total, 38 hydrometric stations were selected and one station was located outside of New Brunswick (Figure 1). This station (01DL001, Kelley River at Eight Mile Ford) is located in Nova Scotia near the New Brunswick border.

The average drainage area of all stations was 1090 km^2 with a median of 387 km^2. The station description (river name and station ID), drainage area, period of record, number of years of record and the minimum recorded daily flow are all listed in Table 1. The location of each hydrometric station is shown in Figure 1. Table 2 show the physiographic and climatic parameters associated with each stations. Data from this table were taken from the report by Environment Canada and New Brunswick Department of the Environment (1990).

2.2 Low flow frequency analysis

Daily low flows of each studied stations were extracted from HYDAT. From these data, the minimum annual discharge was calculated for a 1-day, 7-day and 14-day duration. The water year used was from May 1 to April 30 to be consistent with the study by Environment Canada and New Brunswick Department of the Environment (1990). Many statistical distributions can be used to represent low flows (Kite, 2004). However, the Type III Extremal distribution (or the 3 parameter Weibull) is the most often used distribution for low flows and was chosen for fitting the annual minimum discharge in the present study. The 3 parameter Weibull cumulative distribution function (*cdf*) is given by the equation:

[1] $$F(x) = 1 - e^{-((x-t)/\eta)^{\beta}}; x \geq t$$

where *x* represents discharge, t is a threshold parameter, $\eta > 0$ is a scale parameter, and β is a shape parameter.

Many methods have been used for the estimation of the distribution's parameters, and two commonly used methods are the method of moments and maximum likelihood method. The maximum likelihood method was selected for this study because it is considered a better estimator. The parameters were calculated using the Minitab software (Minitab® 15.1.30.0).

With the distribution's parameters and the *cdf*, the low flow estimates Q_T were then calculated for different recurrence intervals, *T* (2-year, 10-year, 20-year and 50-year). The 3 parameter Weibull quantiles Q_T are obtained from:

[2] $$Q_T = \eta\left(-ln(1 - F(x))^{1/\beta}\right) + t$$

where the relation between *F(x)* and recurrence interval, *T*, is given by:

[3] $$F(x) = \frac{1}{T}$$

The Minitab software also calculates the Anderson-Darling (AD) statistics and corresponding p-values. The Anderson-Darling statistics is a measure of goodness of fit of a specified distribution. Smaller AD values represent a better fit of the data to the given distribution. The chosen significance level for the p-value in the present study was 0.05. The p-values lower than 0.05 means that the low flows do not follow the selected distribution as well.

2.3 Provincial low flow frequency analysis

It is well known that physiographic and climatic characteristics vary across the province of New Brunswick. The division of the province into low flow regions was done by Environment Canada and New Brunswick Department of the Environment (1990). They divided the province into three regions, i.e., the north and south region, where the south region was further subdivided into large (> 400 km^2) and small (< 400 km^2) basins. However, after comparing low flows from different parts of the province, both spatially and by drainage basin size results were almost identical. Therefore, the selection of different regions in the present study could not be justified. In addition, it should be pointed out that the division of the province into different regions can impose severe limitations on the use of regression equations (e.g., smaller range of applicability of equations). As such, the province will be considered as one region, thus simplifying the application of regression equations for a wider range of drainage basins.

In the present study, the adjusted R^2 was used to determine the best fit of regression equations. The adjusted R^2 is a modified version of the coefficient of determination (R^2) where it penalizes the addition of variables. As such, the adjusted R^2 better reflects the impact of having more predictor variables for the fit. The root mean square error (RMSE) is another criterion for evaluating the fit of a regression equation, and it informs on the errors of the fitted model. The RMSE will also be used in this study to compare the different performance of regional regression models.

The 1-day, 7-day and 14-day low flow for 2, 10, 20 and 50-year return periods were used in the formulation of the regression equations. Single and multiple variables regression equations for New Brunswick were calculated within the Excel™ software and R freeware. Many physiographic and climatic parameters were tested in the formulation (e.g., drainage area, area of lakes and swamps, percentage of lakes and swamps, mean annual precipitation, basin perimeter, mean annual runoff, latitude and longitude). The regression equations with the best adjusted R^2 value and correspondingly good RMSE were selected for the low flow estimations. Also, simpler equations with relatively similar adjusted R^2 and RMSE values were chosen over more complex equations.

Among the physiographic and climatic characteristics, drainage area and mean annual precipitation were the only variables retained for the low flow regression equations. Other physiographic and climatic parameters did not significantly improve the fit and they were not as practical in the application of the regression equations. For this reason, the basin perimeter, latitude, areas of lakes and swamps, longitude, mean annual runoff and average content of snow cover were not retained in the regression analysis. It should nevertheless be noted that these parameters, in some instance, could be very important in local low flow processes.

3.0 RESULTS AND DISCUSSION

The daily low flow data from each hydrometric station were used to calculate the minimal annual discharge for durations of 1-day, 7-day and 14-day for recurrence intervals of 2-year, 10-year, 20-year and 50-year. The results for this low flow analysis are presented in Table 3 (1-day), Table 5 (7-day) and Table 7 (14-day).

The 3 parameter Weibull distribution parameters, Anderson-Darling statistics and p-values are presented in Tables 4 (1-day), 6 (7-day) and 8 (14-day). In general, results showed that the 3 parameter Weibull probability distribution function generally fitted the data well. However, some rivers showed p-values under the significance level of 0.05, which means a poorer fit of the data. In particular, Canaan R. (01AP002; 1-day, 7-day and 14-day), Petitcodiac R. (01BU002; 1-day), Tetagouche R. (01BJ001; 1-day), Palmers Creek (01BU004; 7-day, 14-day) and Upsalquitch R. (01BE001; 7-day, 14-day) showed low p-values. These stations also showed correspondingly higher AD values ranging from 0.762 to 1.69. A graphic representation of the fitted low flows for the 1-day, 7-day and 14-day daily minimum annual discharge is presented for all 38 rivers in Appendix A. It can be observed from the fitted distribution that even when the p-values were less than 0.05, the fitted distribution was nevertheless very good, especially for low flow values. In many cases, the poorer performance of the Weibull distribution was due to differences at the higher discharges (e.g., flows for reduced variable less than 0; see Appendix A, Figure A11 for both Upsalquitch R. and Tetagouche R.). Prior to the regional regression analysis, a comparison between low flows of the current study to those of the previous by Environment Canada and New Brunswick Department of the Environment (1990) was carried out. This analysis was carried out for 1-day, 7-day and 14-day low flows and similar low flows were observed between these two studies. Results of this analysis for the 14-day duration of different recurrence intervals were presented in Figure 2. It can be observed that, in most cases, low flows predicted in the 1990 report were very close to those of the present study. This is particularly true for flows greater than 0.5 m^3/s as most of the difference was noted at the very low flow values ($< 0.5\ m^3/s$). In general, current low flow estimates were within 5% on average to those calculated in the previous study. Therefore, results of the present study, although having more data and correspondingly lower uncertainties associated with the low flow estimates, showed very consistent low flows with previously calculated values. This means that both regional equations established in the 1990 report and those of the present study (see below) will provide similar low flow estimates.

Following the single station analysis, single and multiple variable regression equations were developed for the province. Equations were developed for the 2-year, 10-year, 20-year and 50-year. Unlike the study by Environment Canada and New Brunswick Department of the Environment (1990), which divided the province into three regions, the present study used the whole province as one homogenous region. The drainage area and mean annual precipitation were the only two variables selected for the regression equations. This is in contrast with the above previous study, which used many different variables in their development of regression equations. Including more variables did not significantly improve the fit of regional low flows, i.e., explaining more of the variability. Therefore, simpler equations were favoured over complex equations. Both log transformed data and square root transformed data were tested for the regional regression equations. The square root transformed data were selected because they slightly outperformed the log transformed data.

The multiple variable provincial regression equation is given by:

[4] $$LF_{TD} = (c\sqrt{DA} + d\sqrt{MAP} + k)^2$$

where LF_{TD} is the low flow for a recurrence interval *T* and a duration *D*, *DA* is the drainage area (km^2), *MAP* is the mean annual precipitation of the basin (mm), *c* and *d* are the regression coefficients and *k* is the regression constant. In the present study, two sets of equations were provided, i.e., equation [4] and equations using drainage area only as the explanatory variable (equation [5] below).

[5] $$LF_{TD} = (c\sqrt{DA} + k)^2$$

where parameters are the same as in equation [4].

The regression equations showed very good results with over 90% of the variability of low flows explained by the fit (Table 9). The lowest adjusted R^2 value (for all return periods and durations) was 0.890 and the highest was 0.952. The root mean square error (RMSE) ranged between 0.925 m^3/s and 2.012 m^3/s. The root mean square error informs on the performance of the model (lower value, better performance). It is calculated using the following equation:

[6] $$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(O_i - P_i)^2}{N}}$$

where O_i represents the observed values, P_i represents the predicted values and N the number of observations.

When considering only the drainage as the explanatory variable, the regression results showed R^2 between 0.890 and 0.945 and RMSE between 0.977 m^3/s and 2.012 m^3/s (Table 9). These values were similar to those obtained by the multiple regression equations (drainage area and mean annual precipitation). The RMSEs were generally higher for 14-day low flows than for 1-day low flows; however, RMSEs were generally lower for higher recurrence intervals (50-year) compared to lower recurrence intervals (2-year). When comparing RMSEs, the improvement in using a multiple variable equation was in the order of 0.08 m^3/s (2-year) to 0.05 m^3/s (50-year). Consequently, the use of only drainage area for the estimation of low flows provides equally good results although adding the mean annual precipitation will slightly improve the estimation. Figure 3 displays the results of a regression analysis for all NB stations for a 1-day low flow with a 2-year and 20-year recurrence interval (equation with drainage area only). Figure 3a shows more variability in low flow estimates for smaller drainage basins, particularly for basins less than 700 km^2. Figure 3b (20-year) shows even more variability and in this case for basins less than 1000 km^2. Similar results were also observed for the multiple regression analysis where low flows showed more variability for smaller drainage basin, i.e., at lower flows in this figure of observed vs. predicted flows (Figure 4).

These results show that regional low flow estimates are more reliable for lower return values (2-year) than higher return low flows (20-years). Also, a significant variability in low flow processes is observed in New Brunswick for smaller drainage basins and this is particularly noticeable at higher return low flows (20 and 50-years). Therefore, under these circumstances caution should be exercised when calculating low flows for ungauged basins. This relatively high variability in low flows is most likely due to the different processes that are involved during low flows regimes, as shown in Burn et al. (2008). Among these processes, the presence of lakes and swamps, aquifer storage and connectivity, type of soil and topography are important in New Brunswick.

4.0 SUMMARY AND CONCLUSIONS

River hydrology plays a key role in many water resource studies (e.g., design of hydraulic structures, water withdrawal project, etc.) and low flows are particularly important in many of these studies. Therefore, the objective of the present study was to update low flow estimates in New Brunswick using the same hydrometric stations and distribution function (3 parameter Weibull) as in the study by Environment Canada and New Brunswick Department of the Environment (1990). Results showed that low flows of the present study, although carried out with more data, were nevertheless consistent with those of this previous study. In fact, low flow of this and previous studies were within 5% of each other (on average). This means that results of this study produced similar regional regression equations as those of previous studies. Because of the similarities among low flows, the equations developed in this study as well as those of previous studies should provide similar low flow estimates. Regional regression equations developed in this study showed that over 90% of the variability can be explained using drainage area. The mean annual precipitation was also used as a secondary explanatory variable; however the adjusted R^2 were not very different. Results of the present study also showed that low flows were quite variable for drainage basin less that 700 km^2. This higher variability of low flows is due to the many different processes that influence low flow, as pointed out in recent studies (Burn et al. 2008). This variability should be taken into consideration when estimating low flows for ungauged basins. In conclusion, such regional low flow characterization will help both water resource and fisheries managers to better deal with water issues (e.g., water availability and instream flow requirements) in New Brunswick. However, calculations should be carried out with care and caution for the design and/or evaluation of projects because good judgement is always an essential component in any hydrological analyses.

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Table 1. Selected hydrometric stations in New Brunswick.

Station ID	River name	Drainage area (km^2)	Period of record	N	Minimum flow (m^3/s)[α]
01AD002	St. John River at Fort Kent	14700	1927-2007	81	14.4
01AD003	St. Francis River at Outlet of Glasier Lake	1350	1952-2007	56	1.69
01AG002	Limestone Stream at Four Falls	199	1968-1993	26	0.142
01AJ003	Meduxkeneag River near Belleville	1210	1968-2007	40	0.459
01AJ004	Big Presque Isle Stream at Tracey Mills	484	1968-2007	40	0.178
01AJ010	Becaguimec Stream at Coldstream	350	1974-2007	34	0.145
01AJ011	Cold Stream at Coldstream	156	1974-1993	20	0.057
01AK001	Shogomoc Stream near Trans Canada Hwy	234	1919-40,1944-2005	84	0.048
01AK007	Nackawic Stream near Temperance Vale	240	1968-2007	40	0.016
01AK008	Eel River near Scott Siding	531	1974-1993	20	0.116
01AL002	Nashwaak River at Durham Bridge	1450	1962-2007	46	2.16
01AL003	Hayden Brook near Narrows Mountain	6.48	1971-1993	23	0.013
01AM001	North Branch Oromocto River at Tracy	557	1963-2007	45	0.004
01AN001	Castaway Stream near Castaway	34.4	1972-1993	22	0.033
01AN002	Salmon River at Castaway	1050	1974-2007	34	1.12
01AP002	Canaan River at East Canaan	668	1926-40,1963-2005	58	0.057
01AP004	Kennebecasis River at Apohaqui	1100	1962-2007	46	1.01
01AP006	Nerepis River near Fowlers Corner	293	1976-1993	18	0.02
01AQ001	Lepreau River at Lepreau	239	1919-2005	87	0.028
01BC001	Restigouche River below Kedgwick River	3160	1963-2007	45	5.41
01BE001	Upsalquitch River at Upsalquitch	2270	1919-32,1944-2005	76	2.24
01BJ001	Tetagouche River near West Bathurst	363	1923-32,1952-1994	53	0.322
01BJ003	Jacquet River near Durham Center	510	1965-2007	43	0.5
01BL001	Bass River at Bass River	175	1966-1990	25	0.012
01BL002	Riviere Caraquet at Burnsville	173	1970-2007	38	0.345
01BL003	Big Tracadie River at Murchy Bridge Crossing	383	1971-2007	37	0.793
01BO001	Southwest Miramichi River at Blackville	5050	1919-32,1962-2005	58	9.34
01BO002	Renous River at McGraw Brook	611	1966-1994	29	0.677
01BO003	Barnaby River below Semiwagan River	484	1973-1994	22	0.272
01BP001	Little Southwest Miramichi River at Lyttleton	1340	1952-2007	56	1.7
01BQ001	Northwest Miramichi River at Trout Brook	948	1962-2007	46	1.42
01BR001	Kouchibouguac River near Vautour	177	1970-1994	25	0.184
01BS001	Coal Branch River at Beersville	166	1965-2007	43	0.065
01BU002	Peticodiac River near Petitcodiac	391	1962-2007	46	0.102
01BU003	Turtle Creek at Turtle Creek	129	1963-2007	45	0.143
01BU004	Palmers Creek near Dorchester	34.2	1967-1985	19	0.014
01BV006	Point Wolfe River at Fundy National Park	130	1964-2007	44	0.108
01DL001	Kelley River at Eight Mile Ford	63.2	1970-97,1999-2007	36	0.028

Note: N is the Number of years of data

[α] minimum flow represents the minimum recorded daily flow during all years of observations

Table 2. Physiographic and climatic variables for selected hydrometric stations. Data taken from Environment Canada and New Brunswick Department of the Environment (1990).

Stations	DA (km^2)	AL&S (km^2)	%L&S (%)	MAP (mm)	SNOW (water in mm)	P (km)	MAR (mm)	LAT (°)	LONG (°)
01AD002	14700	839	5.71	997	231	1183	592	47.2569	68.5931
01AD003	1350	37.9	2.81	1058	224	259	593	47.2069	68.9569
01AG002	199	19.5	9.78	975	159	77.3	593	46.8283	67.7431
01AJ003	1210	67.8	5.61	958	157	234	670	46.2161	67.7283
01AJ004	484	17.6	3.7	925	140	138	643	46.4378	67.7447
01AJ010	350	2.68	0.77	1131	126	106	685	46.3408	67.4661
01AJ011	156	0.12	0.077	1098	129	72	653	46.3422	67.4692
01AK001	234	28.0	11.9	1115	147	100	675	45.9450	67.3222
01AK007	240	12.3	5.11	1057	129	83.8	673	46.0492	67.2403
01AK008	531	70.4	13.3	1069	142	168	635	45.9367	67.5469
01AL002	1450	20.1	1.39	1213	167	237	772	46.1258	66.6122
01AL003	6.48	0.036	0.56	1225	190	11.1	910	46.2989	67.0369
01AM001	557	84.3	15.1	1153	117	135	685	45.6736	66.6828
01AN001	34.4	2.27	6.6	1175	130	27	840	46.2983	65.7119
01AN002	1050	67.3	6.41	1133	146	165	709	46.2911	65.7233
01AP002	668	23.8	3.57	1040	137	153	628	46.0719	65.3667
01AP004	1100	7.93	0.72	1189	108	199	728	45.7019	65.6013
01AP006	293	3.74	1.28	1142	110	82.1	725	45.5022	66.3206
01AQ001	239	24.2	10.2	1236	101	114	976	45.2033	66.4667
01BC001	3160	23.0	0.73	1142	240	431	668	47.6667	67.4842
01BE001	2270	14.1	0.63	1085	232	306	574	47.8317	66.8817
01BJ001	363	8.16	2.24	988	235	148	674	47.6558	65.6936
01BJ003	510	10.2	2	1053	235	152	655	47.8978	66.0297
01BL001	175	14.2	8.11	1013	209	78.8	575	47.6500	65.5778
01BL002	173	18	10.4	1125	194	56.0	685	47.7056	65.155
01BL003	383	8.96	2.34	1094	204	92.2	699	47.4350	65.1069
01BO001	5050	178	3.52	1095	177	611	731	46.7361	65.8267
01BO002	611	38	6.22	1182	199	143	764	46.8214	66.1147
01BO003	484	51.6	10.7	1075	170	104	650	46.8860	65.5956
01BP001	1340	67.8	5.06	1184	222	259	772	46.9358	65.9072
01BQ001	948	37.6	3.96	1130	213	201	772	47.0947	65.8372
01BR001	177	20.8	11.7	1050	161	66.4	682	46.7433	65.2047
01BS001	166	8.67	5.23	1072	150	73.5	712	46.4436	65.0653
01BU002	391	2.99	0.76	1029	124	155	652	45.9436	65.1703
01BU003	129	0.4	0.31	1311	125	57.3	892	45.9581	64.8789
01BU004	34.2	0.05	0.15	1213	98	28.2	861	45.8872	64.5164
01BV006	130	1.36	1.05	1390	140	72.3	1278	45.5589	65.0172
01DL001	63.2	2.71	4.29	1250	50	39.8	983	45.5861	64.4514

Note: DA = Drainage area; AL&S = Area of lakes and swamps; %L&S = Percentage of lakes and swamps; MAP = Mean annual precipitation; P = Perimeter; MAR = Mean annual runoff; LAT = Latitude; LONG = Longitude.

Table 3. One-day low flow (m^3/s) for different recurrence intervals for New Brunswick rivers.

Station	2-year	10-year	20-year	50-year
01AD002	32.4	19.6	17.5	15.9
01AD003	3.55	2.21	1.99	1.81
01AG002	0.455	0.262	0.213	0.163
01AJ003	1.19	0.564	0.496	0.454
01AJ004	0.795	0.339	0.268	0.213
01AJ010	0.462	0.251	0.204	0.160
01AJ011	0.218	0.101	0.0808	0.0651
01AK001	0.278	0.0984	0.0754	0.0596
01AK007	0.0600	0.021	0.018	0.016
01AK008	0.614	0.227	0.172	0.132
01AL002	3.88	2.69	2.47	2.29
01AL003	0.0219	0.0158	0.0146	0.0136
01AM001	0.333	0.0438	0.0178	0.0030
01AN001	0.0767	0.0433	0.0385	0.0350
01AN002	1.84	1.24	1.16	1.11
01AP002	0.436	0.158	0.116	0.0852
01AP004	2.53	1.51	1.31	1.13
01AP006	0.218	0.0736	0.0441	0.0180
01AQ001	0.389	0.104	0.0692	0.0456
01BC001	9.70	6.82	6.24	5.75
01BE001	5.81	3.55	3.10	2.72
01BJ001	0.711	0.415	0.375	0.346
01BJ003	1.02	0.662	0.592	0.531
01BL001	0.0960	0.0349	0.0241	0.0153
01BL002	0.690	0.463	0.417	0.377
01BL003	1.57	1.05	0.954	0.870
01BO001	18.8	12.6	11.3	10.2
01BO002	1.34	0.787	0.711	0.657
01BO003	0.580	0.345	0.309	0.282
01BP001	5.21	3.15	2.68	2.24
01BQ001	2.69	1.83	1.67	1.53
01BR001	0.429	0.258	0.222	0.189
01BS001	0.206	0.110	0.0918	0.0767
01BU002	0.385	0.175	0.144	0.122
01BU003	0.311	0.206	0.184	0.164
01BU004	0.0403	0.0156	0.0138	0.0130
01BV006	0.310	0.152	0.132	0.118
01DL001	0.0719	0.0386	0.0336	0.0298

Table 4. Parameters of the Weibull distribution and statistical test values for the 1-day low flow in New Brunswick.

Station	Shape	Scale	Threshold	Anderson-Darling	P-value
01AD002	1.614	23.24	13.85	0.555	0.159
01AD003	1.684	2.461	1.565	0.376	0.435
01AG002	3.337	0.4995	0.00752	0.211	> 0.500
01AJ003	1.116	1.07	0.4213	0.651	0.094
01AJ004	1.556	0.8217	0.1458	0.263	> 0.500
01AJ010	2.545	0.4639	0.05984	0.248	> 0.500
01AJ011	1.685	0.2161	0.04373	0.258	> 0.500
01AK001	1.284	0.3097	0.04477	0.362	0.461
01AK007	0.9484	0.06689	0.0146	0.256	> 0.500
01AK008	1.408	0.6804	0.08971	0.524	0.193
01AL002	1.843	2.268	2.019	0.458	0.278
01AL003	2.038	0.01215	0.01177	0.496	0.222
01AM001	0.9866	0.4917	-0.006437	0.234	> 0.500
01AN001	1.426	0.0589	0.03115	0.191	> 0.500
01AN002	1.257	1.037	1.062	0.211	> 0.500
01AP002	1.472	0.4951	0.05022	1.458	< 0.005
01AP004	2.046	2.038	0.8282	0.198	> 0.500
01AP006	2.168	0.2947	-0.03074	0.314	> 0.500
01AQ001	1.238	0.4903	0.02467	0.45	0.292
01BC001	2.069	5.767	4.872	0.175	> 0.500
01BE001	2.048	4.507	2.045	0.677	0.081
01BJ001	1.366	0.5171	0.3159	0.762	0.049
01BJ003	2.061	0.7055	0.425	0.437	0.315
01BL001	1.78	0.1149	0.002487	0.273	> 0.500
01BL002	2.113	0.4585	0.305	0.199	> 0.500
01BL003	1.964	1.017	0.7301	0.371	0.444
01BO001	2.146	12.65	8.141	0.279	> 0.500
01BO002	1.353	0.9687	0.6033	0.323	> 0.500
01BO003	1.515	0.4205	0.2495	0.227	> 0.500
01BP001	2.584	4.59	1.228	0.523	0.157
01BQ001	1.884	1.666	1.323	0.492	0.228
01BR001	2.287	0.357	0.1244	0.381	0.408
01BS001	1.916	0.1857	0.05244	0.471	0.251
01BU002	1.457	0.3719	0.09597	1.053	0.01
01BU003	2.279	0.218	0.1251	0.389	0.393
01BU004	0.8598	0.04258	0.0125	0.636	0.1
01BV006	1.276	0.2735	0.1052	0.455	0.282
01DL001	1.506	0.05945	0.0253	0.383	0.421

Table 5. Seven-day low flow (m^3/s) for different recurrence intervals for New Brunswick rivers.

Station	2-year	10-year	20-year	50-year
01AD002	34.4	20.6	18.2	16.4
01AD003	3.72	2.34	2.10	1.91
01AG002	0.503	0.299	0.244	0.188
01AJ003	1.42	0.684	0.604	0.553
01AJ004	0.973	0.426	0.328	0.247
01AJ010	0.542	0.317	0.269	0.227
01AJ011	0.268	0.126	0.09997	0.0782
01AK001	0.311	0.116	0.0913	0.0745
01AK007	0.0879	0.0288	0.0229	0.0194
01AK008	0.751	0.300	0.228	0.171
01AL002	4.32	2.90	2.64	2.42
01AL003	0.0241	0.0175	0.0163	0.0153
01AM001	0.402	0.0570	0.0238	0.0043
01AN001	0.0853	0.0488	0.0431	0.0387
01AN002	1.99	1.31	1.21	1.15
01AP002	0.519	0.170	0.121	0.0866
01AP004	2.72	1.63	1.44	1.29
01AP006	0.269	0.0879	0.0562	0.0305
01AQ001	0.474	0.136	0.0920	0.0620
01BC001	10.1	7.19	6.66	6.21
01BE001	6.20	3.80	3.31	2.89
01BJ001	0.749	0.469	0.436	0.415
01BJ003	1.07	0.706	0.633	0.569
01BL001	0.115	0.0439	0.0306	0.0193
01BL002	0.727	0.494	0.450	0.412
01BL003	1.64	1.07	0.970	0.883
01BO001	19.8	13.5	12.4	11.5
01BO002	1.58	0.927	0.830	0.758
01BO003	0.672	0.393	0.346	0.309
01BP001	5.59	3.47	3.01	2.57
01BQ001	2.89	1.94	1.78	1.65
01BR001	0.466	0.291	0.256	0.226
01BS001	0.234	0.126	0.108	0.0931
01BU002	0.431	0.224	0.198	0.179
01BU003	0.341	0.226	0.204	0.185
01BU004	0.0607	0.0209	0.0172	0.0151
01BV006	0.367	0.177	0.152	0.136
01DL001	0.0812	0.0430	0.0383	0.0352

Table 6. Parameters of the Weibull distribution and statistical test values for the 7-day low flow in New Brunswick.

Station	Shape	Scale	Threshold	Anderson-Darling	P-value
01AD002	1.683	25.62	13.84	0.421	0.348
01AD003	1.694	2.553	1.659	0.331	> 0.500
01AG002	3.647	0.5614	-0.004245	0.268	> 0.500
01AJ003	1.129	1.248	0.5139	0.623	0.109
01AJ004	1.81	1.036	0.1269	0.337	> 0.500
01AJ010	2.277	0.4691	0.1422	0.264	> 0.500
01AJ011	1.863	0.2719	0.04476	0.246	> 0.500
01AK001	1.27	0.3361	0.05889	0.338	> 0.500
01AK007	1.055	0.1005	0.01688	0.251	> 0.500
01AK008	1.6	0.8184	0.09996	0.321	> 0.500
01AL002	1.85	2.71	2.094	0.507	0.212
01AL003	1.905	0.01264	0.01365	0.215	> 0.500
01AM001	1.029	0.5872	-0.008942	0.169	> 0.500
01AN001	1.556	0.06565	0.03339	0.132	> 0.500
01AN002	1.33	1.195	1.085	0.262	> 0.500
01AP002	1.373	0.6112	0.05093	1.559	< 0.005
01AP004	1.748	2.037	1.067	0.241	> 0.500
01AP006	1.755	0.3395	-0.006263	0.327	> 0.500
01AQ001	1.29	0.5846	0.03358	0.662	0.089
01BC001	1.902	5.559	5.492	0.295	> 0.500
01BE001	2.119	4.862	2.115	0.833	0.031
01BJ001	1.175	0.4799	0.398	0.442	0.308
01BJ003	2.074	0.7377	0.4564	0.197	> 0.500
01BL001	1.919	0.1376	0.001304	0.272	> 0.500
01BL002	1.949	0.4543	0.3508	0.173	> 0.500
01BL003	1.884	1.08	0.7471	0.439	0.313
01BO001	1.809	11.82	10.12	0.326	> 0.500
01BO002	1.46	1.165	0.6777	0.308	> 0.500
01BO003	1.66	0.5136	0.2604	0.277	> 0.500
01BP001	2.462	4.592	1.632	0.687	0.062
01BQ001	1.716	1.761	1.466	0.541	0.174
01BR001	2.103	0.3517	0.1708	0.318	> 0.500
01BS001	1.716	0.1996	0.07259	0.448	0.296
01BU002	1.296	0.3584	0.1613	0.597	0.127
01BU003	1.965	0.224	0.1547	0.193	> 0.500
01BU004	1.004	0.06767	0.01369	0.902	0.023
01BV006	1.281	0.3283	0.1201	0.427	0.337
01DL001	1.232	0.06571	0.03239	0.251	> 0.500

Table 7. Fourteen-day low flow (m^3/s) for different recurrence intervals for New Brunswick rivers.

Station	2-year	10-year	20-year	50-year
01AD002	37.3	21.8	19.1	16.9
01AD003	3.91	2.46	2.21	2.01
01AG002	0.550	0.334	0.276	0.216
01AJ003	1.71	0.803	0.687	0.608
01AJ004	1.11	0.490	0.374	0.274
01AJ010	0.638	0.379	0.323	0.272
01AJ011	0.318	0.153	0.124	0.0998
01AK001	0.335	0.132	0.109	0.0947
01AK007	0.116	0.0341	0.0255	0.0202
01AK008	0.856	0.346	0.266	0.205
01AL002	4.81	3.23	2.92	2.66
01AL003	0.0260	0.0189	0.0179	0.0172
01AM001	0.473	0.0697	0.0337	0.0134
01AN001	0.0972	0.0560	0.0491	0.0437
01AN002	2.15	1.39	1.29	1.21
01AP002	0.597	0.179	0.127	0.0926
01AP004	2.97	1.77	1.57	1.42
01AP006	0.329	0.109	0.0731	0.0445
01AQ001	0.552	0.163	0.115	0.0831
01BC001	10.5	7.39	6.82	6.36
01BE001	6.55	3.99	3.47	3.00
01BJ001	0.807	0.490	0.452	0.427
01BJ003	1.14	0.735	0.656	0.587
01BL001	0.136	0.0510	0.0352	0.0220
01BL002	0.763	0.530	0.493	0.463
01BL003	1.71	1.11	0.999	0.907
01BO001	21.3	14.4	13.2	12.2
01BO002	1.82	1.03	0.922	0.842
01BO003	0.731	0.433	0.385	0.349
01BP001	5.99	3.77	3.30	2.87
01BQ001	3.11	2.07	1.90	1.77
01BR001	0.474	0.311	0.290	0.275
01BS001	0.260	0.139	0.121	0.107
01BU002	0.492	0.266	0.239	0.220
01BU003	0.357	0.243	0.225	0.211
01BU004	0.0792	0.0234	0.0191	0.0169
01BV006	0.417	0.213	0.188	0.172
01DL001	0.0971	0.0473	0.0415	0.0378

Table 8. Parameters of the Weibull distribution and statistical test values for the 14-day low flow in New Brunswick.

Station	Shape	Scale	Threshold	Anderson-Darling	P-value
01AD002	1.764	29.03	13.71	0.436	0.319
01AD003	1.742	2.704	1.721	0.314	> 0.500
01AG002	3.722	0.6019	0.004794	0.206	> 0.500
01AJ003	1.269	1.574	0.5353	0.447	0.299
01AJ004	1.95	1.198	0.1125	0.358	0.468
01AJ010	2.371	0.5504	0.1661	0.204	> 0.500
01AJ011	1.795	0.3112	0.06445	0.215	> 0.500
01AK001	1.154	0.3467	0.08295	0.272	> 0.500
01AK007	1.096	0.1398	0.01619	0.275	> 0.500
01AK008	1.551	0.9182	0.1307	0.274	> 0.500
01AL002	2.006	3.12	2.212	0.598	0.126
01AL003	1.378	0.01237	0.01647	0.187	> 0.500
01AM001	0.9791	0.6874	0.0006429	0.19	> 0.500
01AN001	1.664	0.07577	0.03641	0.229	> 0.500
01AN002	1.327	1.328	1.144	0.192	> 0.500
01AP002	1.235	0.7202	0.06207	1.688	< 0.005
01AP004	1.633	2.202	1.215	0.139	> 0.500
01AP006	1.643	0.4017	0.007179	0.331	> 0.500
01AQ001	1.239	0.6686	0.05444	0.485	0.236
01BC001	1.806	5.976	5.669	0.406	0.377
01BE001	2.163	5.221	2.144	0.811	0.035
01BJ001	1.217	0.5428	0.4049	0.437	0.318
01BJ003	2.05	0.805	0.4668	0.194	> 0.500
01BL001	1.889	0.1635	0.001282	0.329	> 0.500
01BL002	1.611	0.4232	0.4256	0.264	> 0.500
01BL003	1.878	1.149	0.7631	0.482	0.239
01BO001	1.76	12.9	10.83	0.196	> 0.500
01BO002	1.395	1.379	0.7583	0.157	> 0.500
01BO003	1.581	0.5397	0.303	0.223	> 0.500
01BP001	2.324	4.676	1.997	0.642	0.085
01BQ001	1.598	1.902	1.6	0.474	0.247
01BR001	1.309	0.2826	0.2603	0.653	0.093
01BS001	1.524	0.2168	0.08979	0.51	0.208
01BU002	1.222	0.3883	0.2044	0.281	> 0.500
01BU003	1.582	0.2065	0.1937	0.19	> 0.500
01BU004	0.8893	0.0958	0.01573	1.115	0.007
01BV006	1.23	0.3495	0.1571	0.309	> 0.500
01DL001	1.172	0.08528	0.03476	0.147	> 0.500

Table 9. Regional regression equations for the New Brunswick region.

Return period	Duration	c	d	k	Adjusted R^2	RMSE(m^3/s)
2-year	1-day	0.05369	0.07562	-2.735	0.943	1.438
	7-day	0.05499	0.07570	-2.715	0.948	1.606
	14-day	0.05691	0.07698	-2.750	0.952	1.961
10-year	1-day	0.04337	0.07191	-2.623	0.915	1.118
	7-day	0.04435	0.07096	-2.572	0.916	1.216
	14-day	0.04552	0.07311	-2.636	0.918	1.370
20-year	1-day	0.04126	0.07057	-2.582	0.909	1.022
	7-day	0.04221	0.07029	-2.555	0.907	1.110
	14-day	0.04314	0.07341	-2.646	0.908	1.224
50-year	1-day	0.03945	0.06875	-2.527	0.909	0.925
	7-day	0.04039	0.06977	-2.543	0.904	1.105
	14-day	0.04107	0.07420	-2.673	0.903	1.185
2-year	1-day	0.05234	-	-0.17761	0.936	1.517
	7-day	0.05364	-	-0.15524	0.941	1.673
	14-day	0.05553	-	-0.14700	0.945	2.012
10-year	1-day	0.04208	-	-0.19093	0.905	1.179
	7-day	0.04308	-	-0.17284	0.907	1.270
	14-day	0.04422	-	-0.16320	0.909	1.417
20-year	1-day	0.04000	-	-0.19561	0.899	1.078
	7-day	0.04095	-	-0.17768	0.898	1.160
	14-day	0.04183	-	-0.16374	0.898	1.270
50-year	1-day	0.03822	-	-0.20204	0.896	0.977
	7-day	0.03914	-	-0.18369	0.891	1.158
	14-day	0.03975	-	-0.16370	0.890	1.244

Regression equation:a) $LF = (c \sqrt{DA} + d \sqrt{MAP} + k)^2$; b) $LF = (c \sqrt{DA} + k)^2$; LF = Low flow; DA = Drainage area; MAP = Mean annual precipitation.

<u>NOTE</u>:
Range of independant variables used in regression equations:

$6 \text{ km}^2 < DA < 14700 \text{ km}^2$
$925 \text{ mm} < MAP < 1390 \text{ mm}$

Number of stations in region: 38

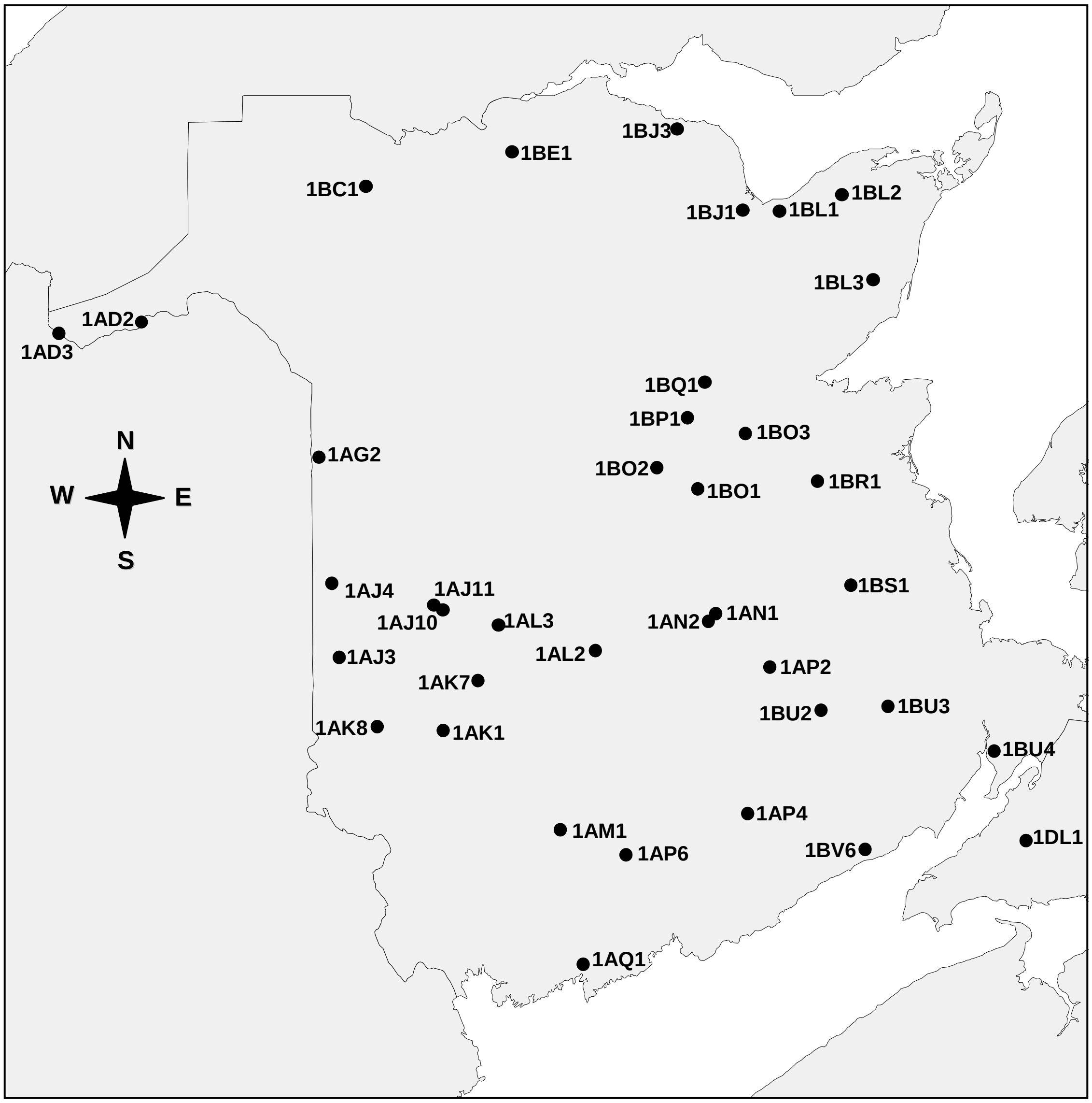


Figure 1. Location of selected hydrometric stations in New Brunswick for the low flow analysis (38 stations).

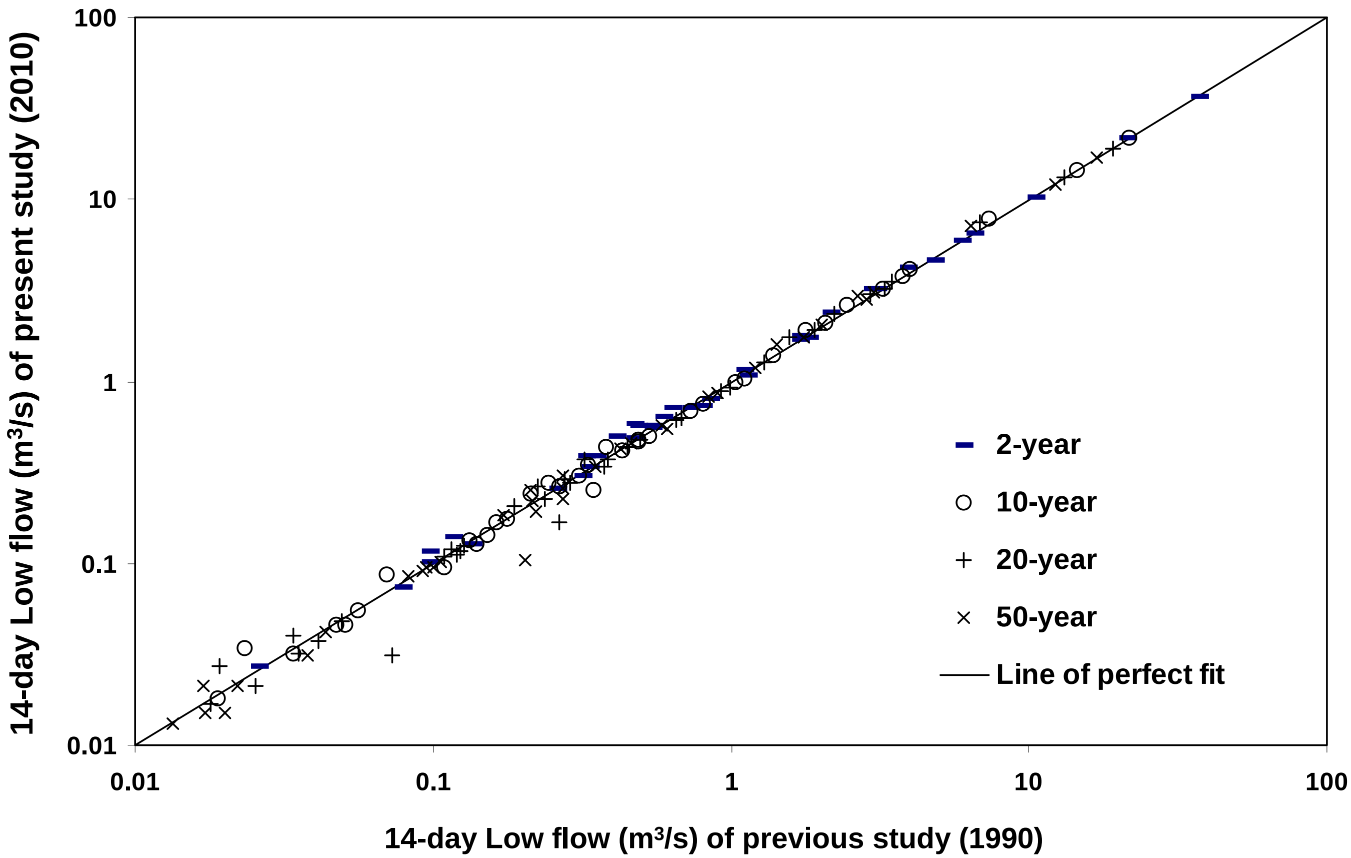
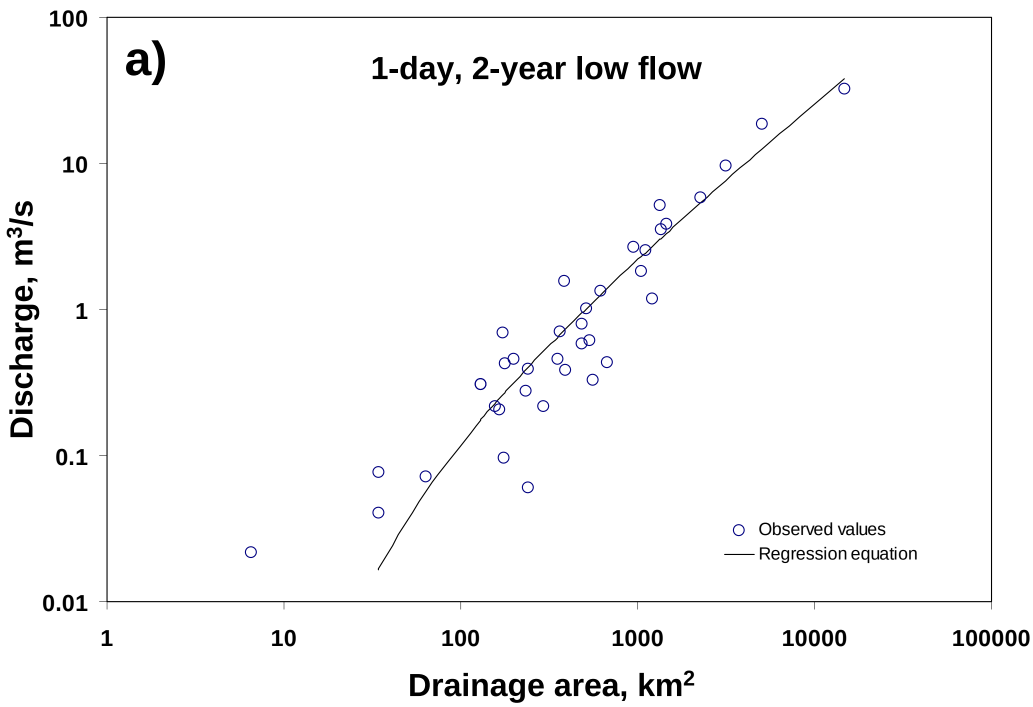


Figure 2. Comparison of low flows (14-day) from the current study with those of previous study (Environment Canada and the Provinces of New Brunswick, 1990). Line of perfect fit indicates the same flow for both studies.



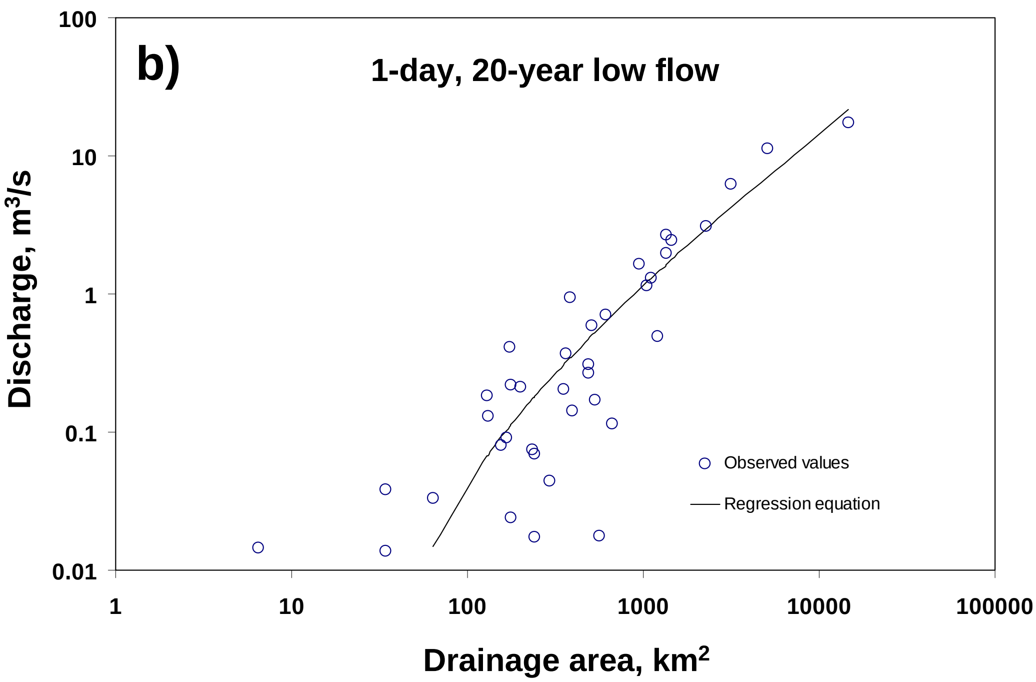


Figure 3. Results of the regression analysis in NB for the 1-day low flow; a) 2-year recurrence interval and b) 20-year recurrence interval

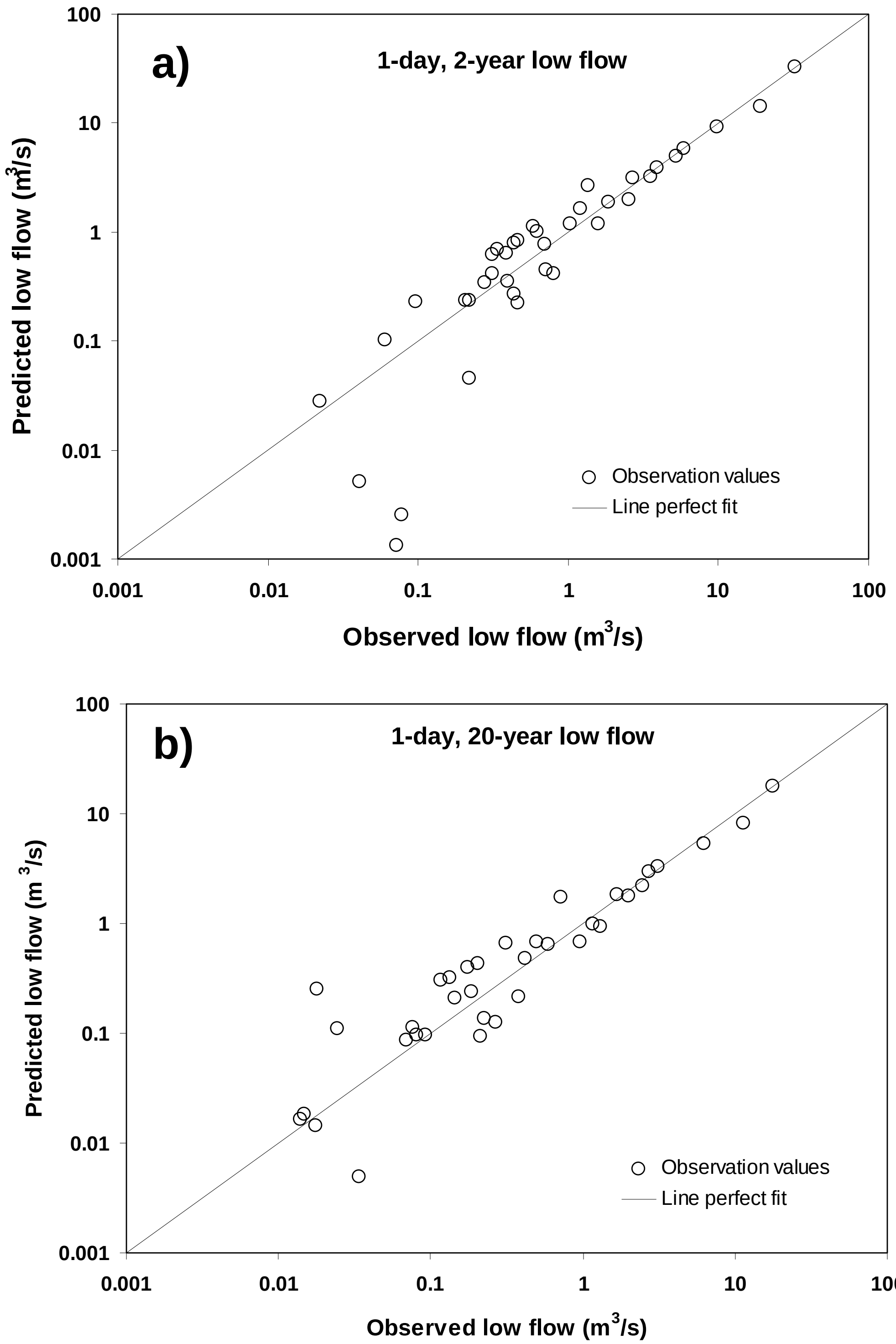
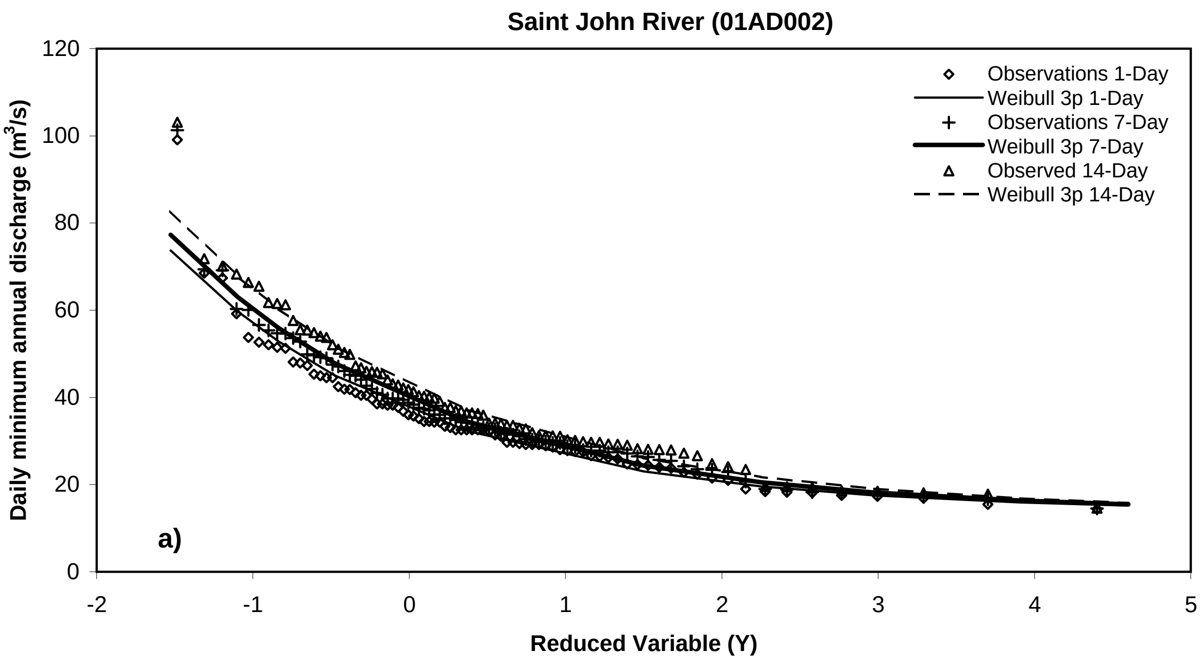


Figure 4. Predicted vs. observed 1-day low flow in NB using multiple regression analysis; a) 2-year low flow; b) 20-year low flow.

Appendix A

Single Station Low Flow Analysis



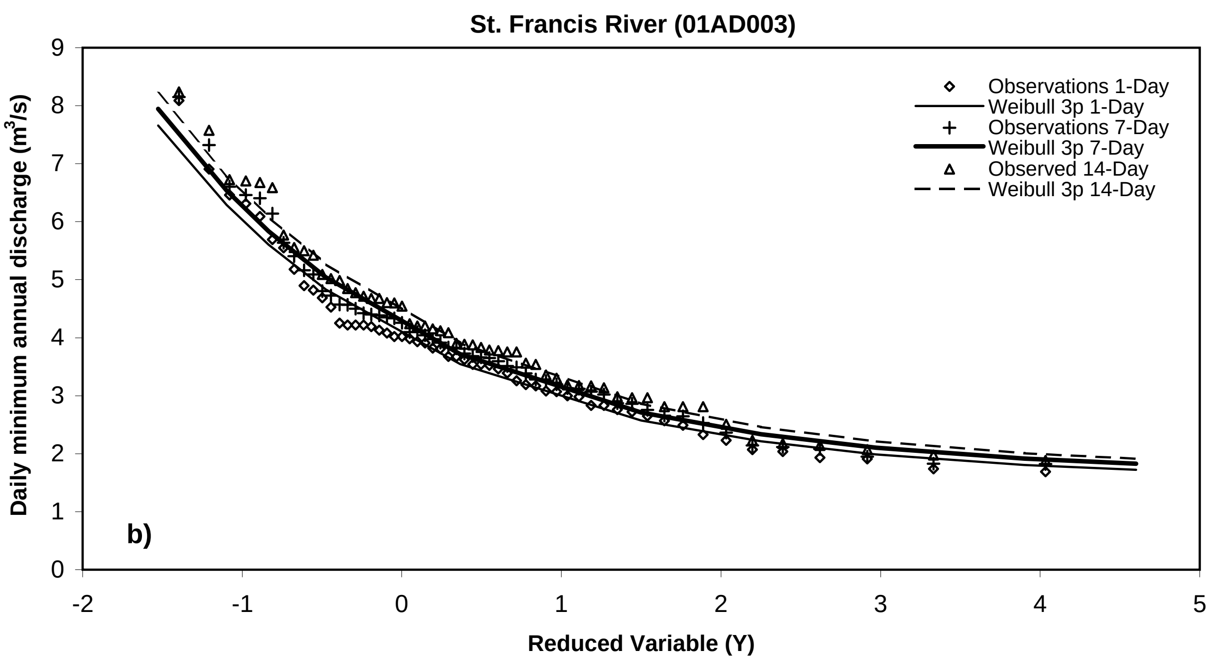
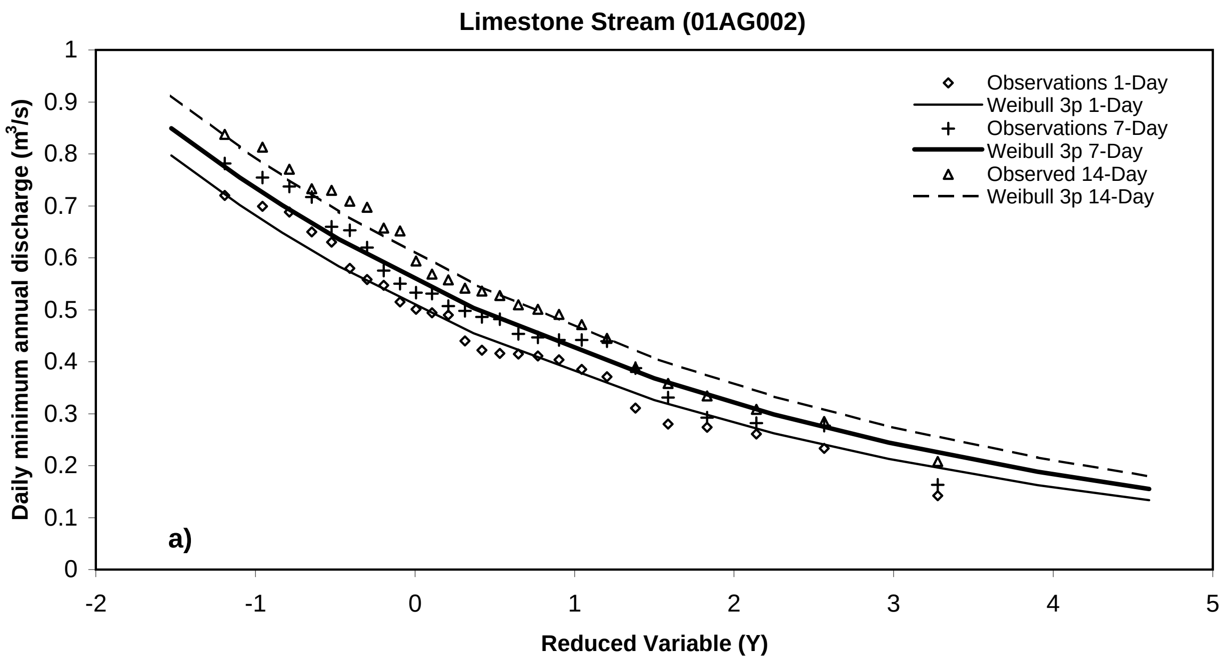


Figure A1. Fitted minimum annual discharge using the 3 parameter Weibull distribution; a) Saint John River, b) St. Francis River



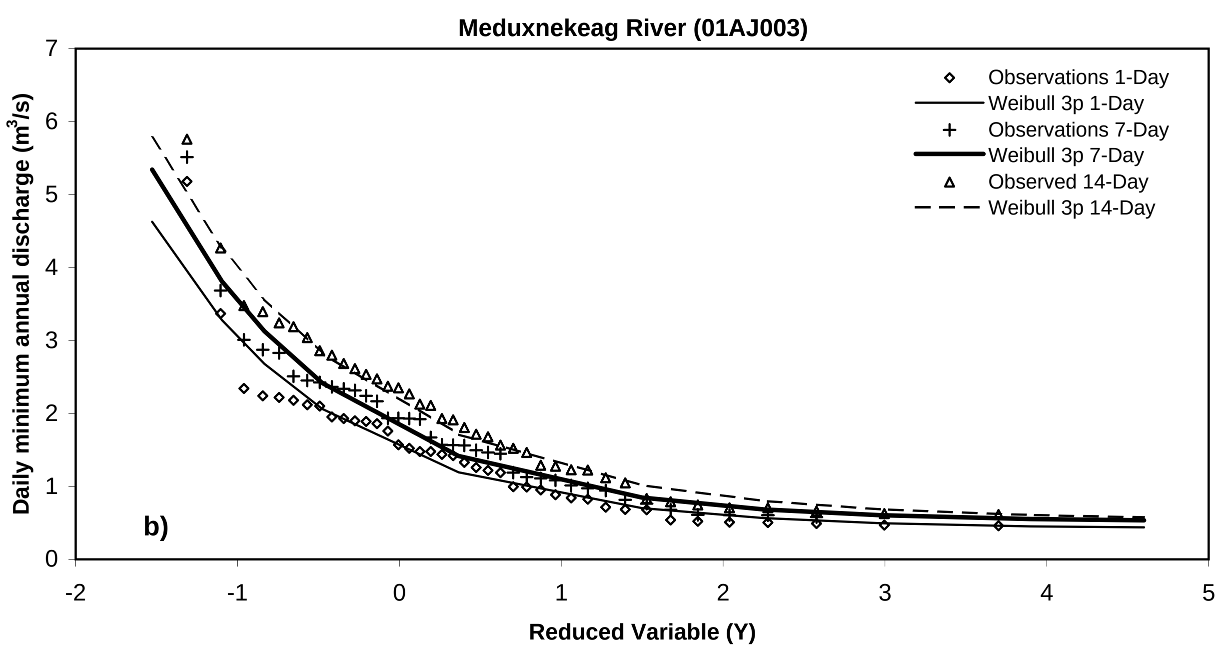
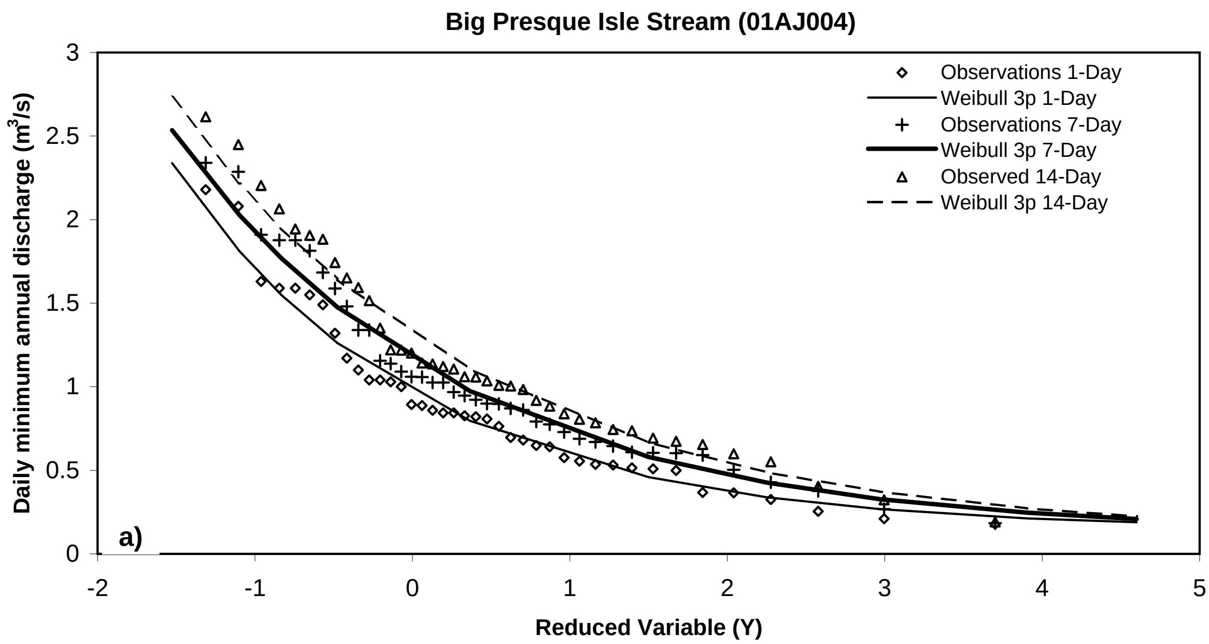


Figure A2. Fitted minimum annual discharge using the 3 parameter Weibull distribution; a) Limestone Stream, b) Meduxnekeag River



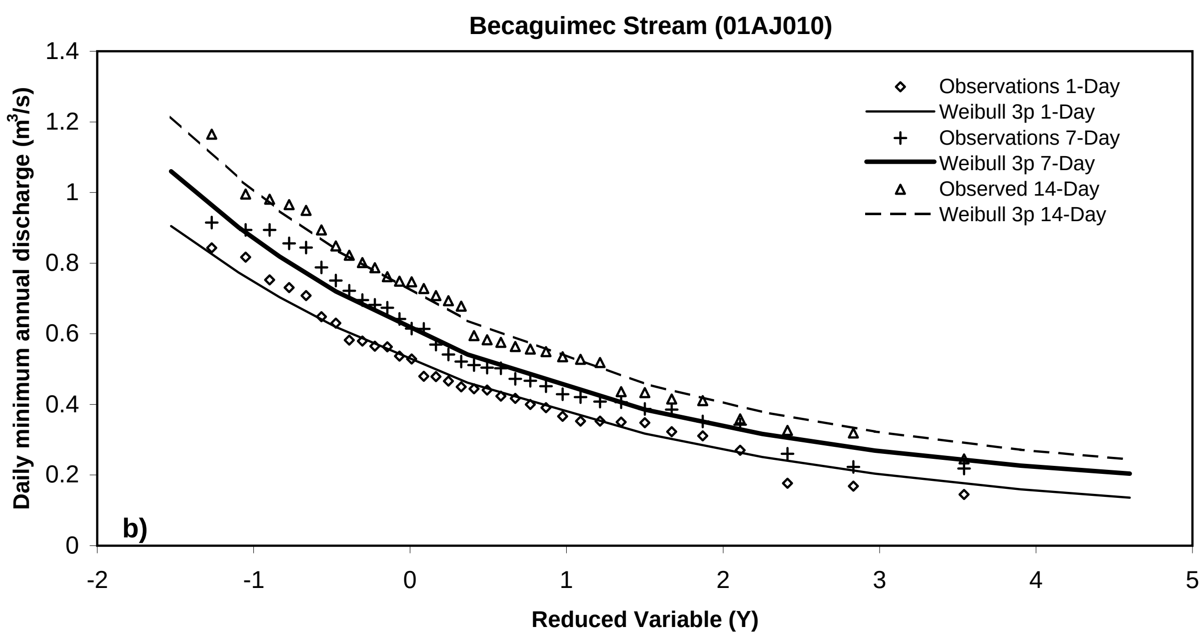
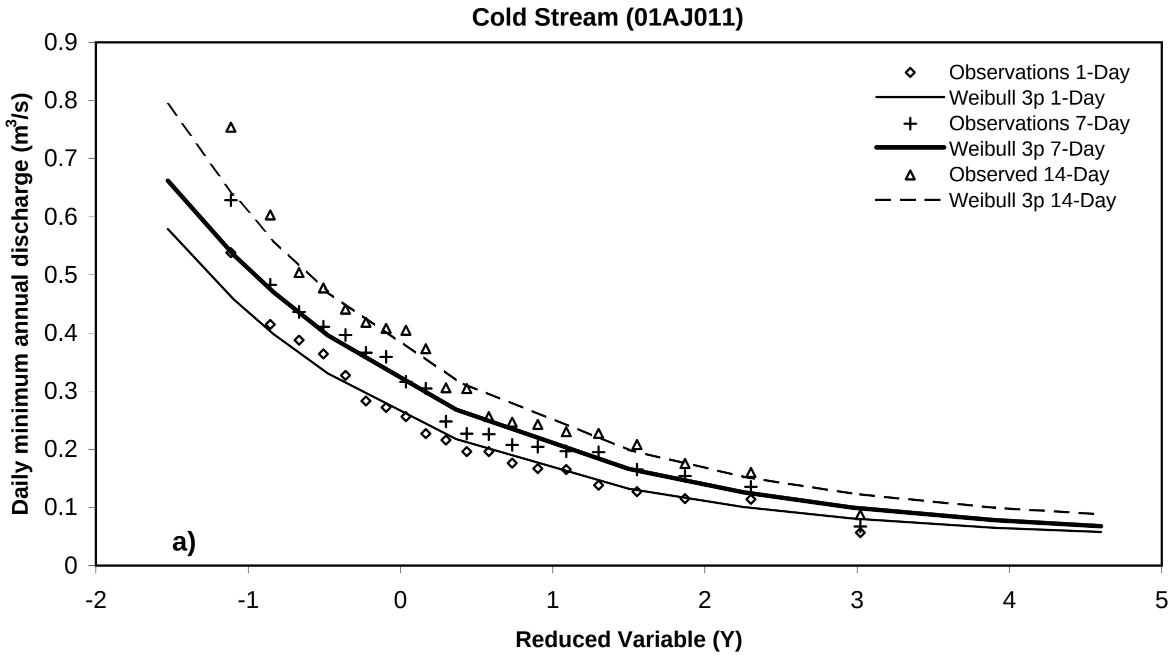


Figure A3. Fitted minimum annual discharge using the 3 parameter Weibull distribution; a) Big Presque Isle Stream, b) Becaguimec Stream



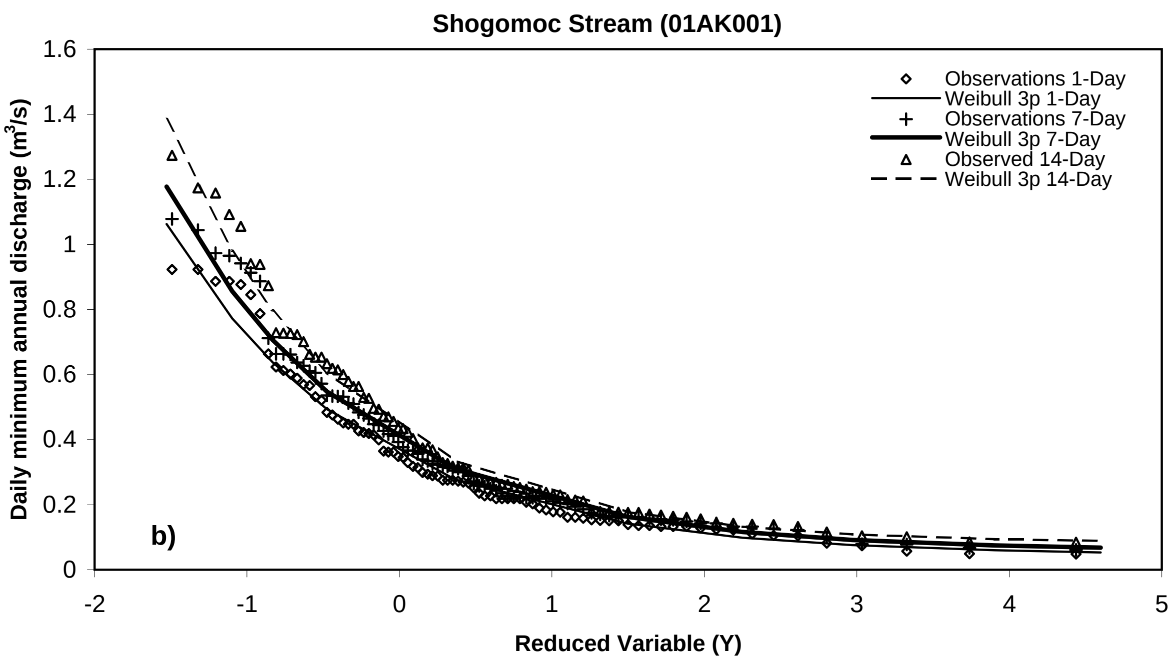
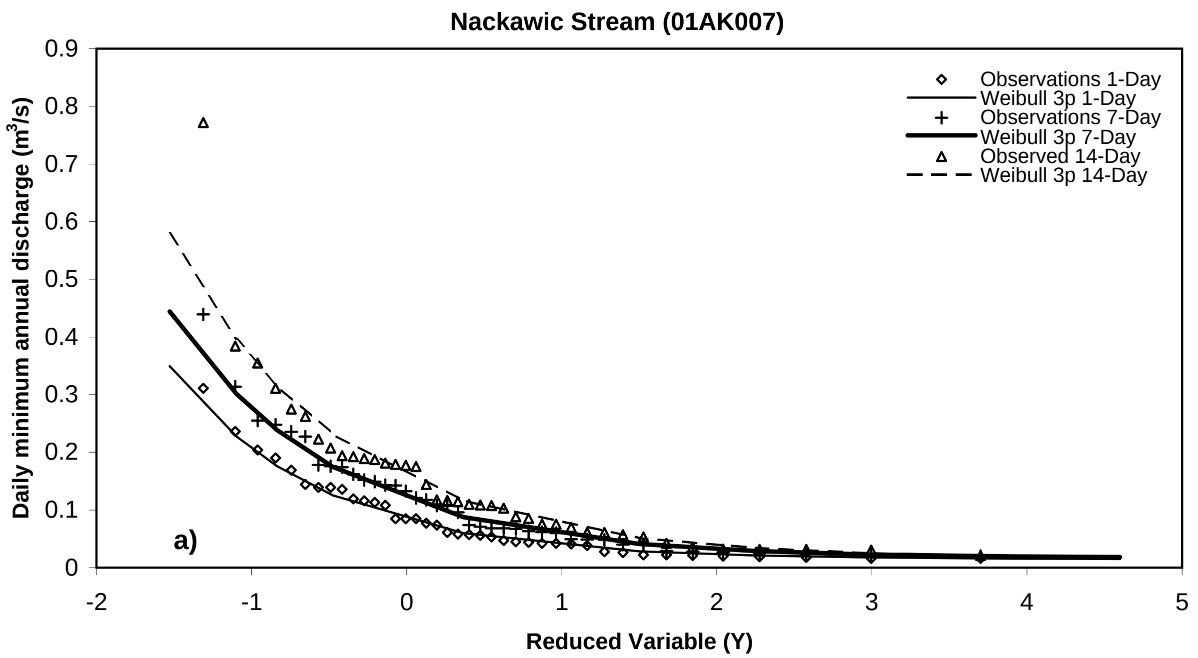


Figure A4. Fitted minimum annual discharge using the 3 parameter Weibull distribution; a) Cold Stream, b) Shogomoc Stream



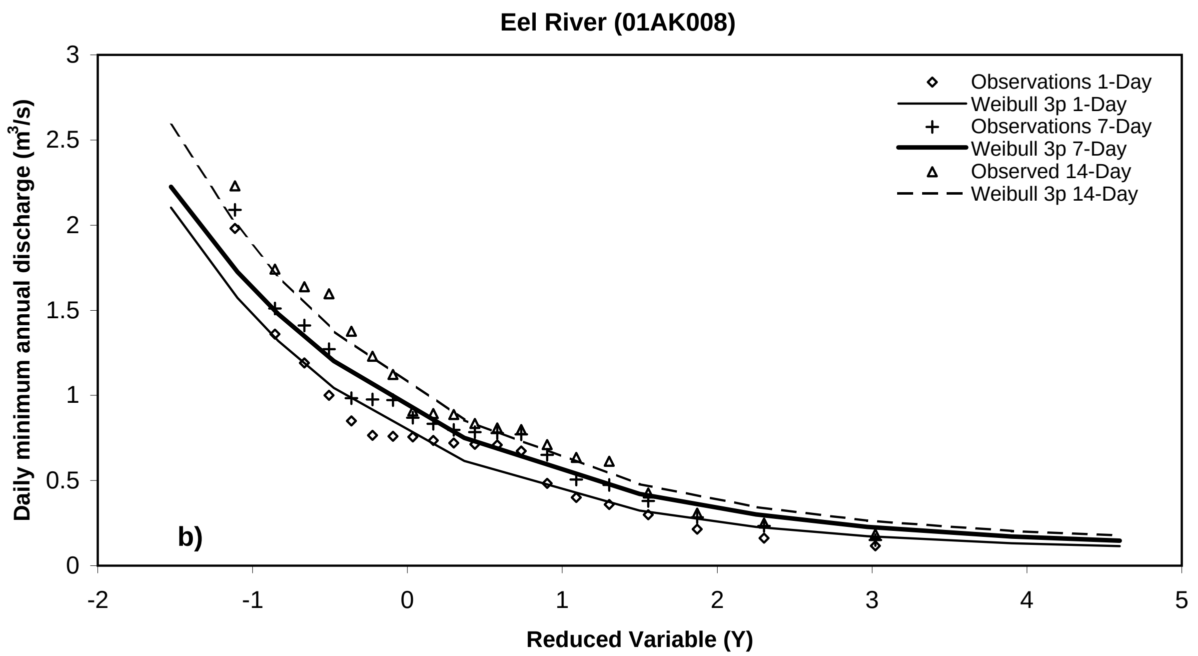


Figure A5. Fitted minimum annual discharge using the 3 parameter Weibull distribution; a) Nackawic Stream, b) Eel River

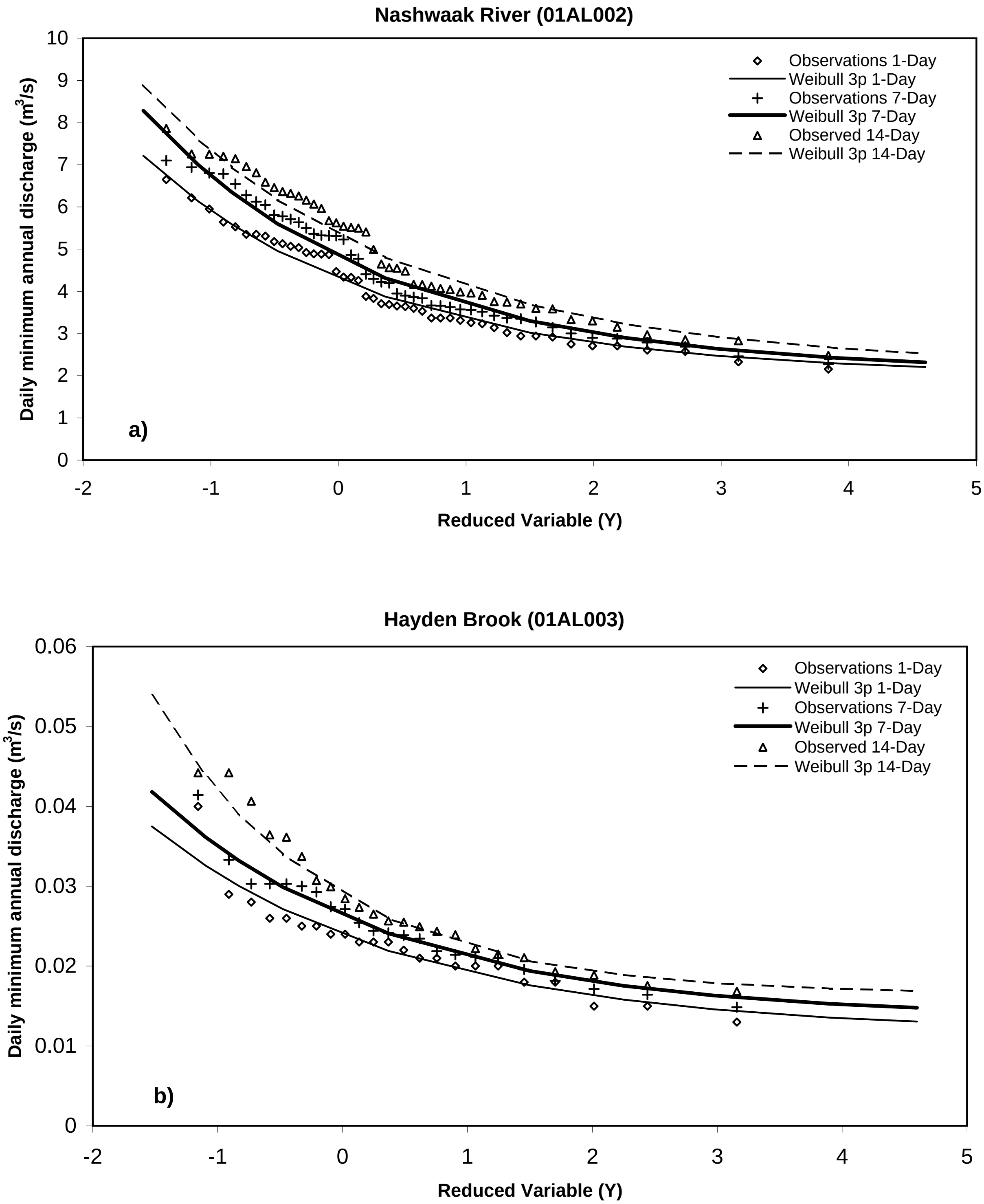
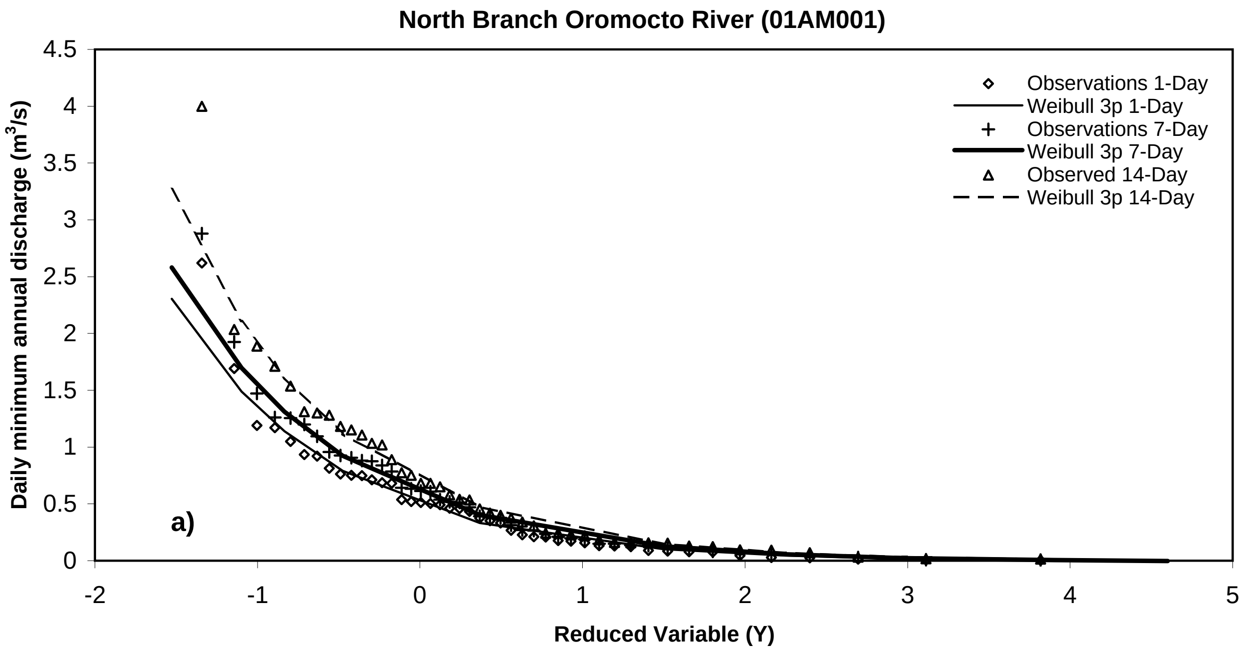


Figure A6. Fitted minimum annual discharge using the 3 parameter Weibull distribution; a) Nashwaak River, b) Hayden Brook



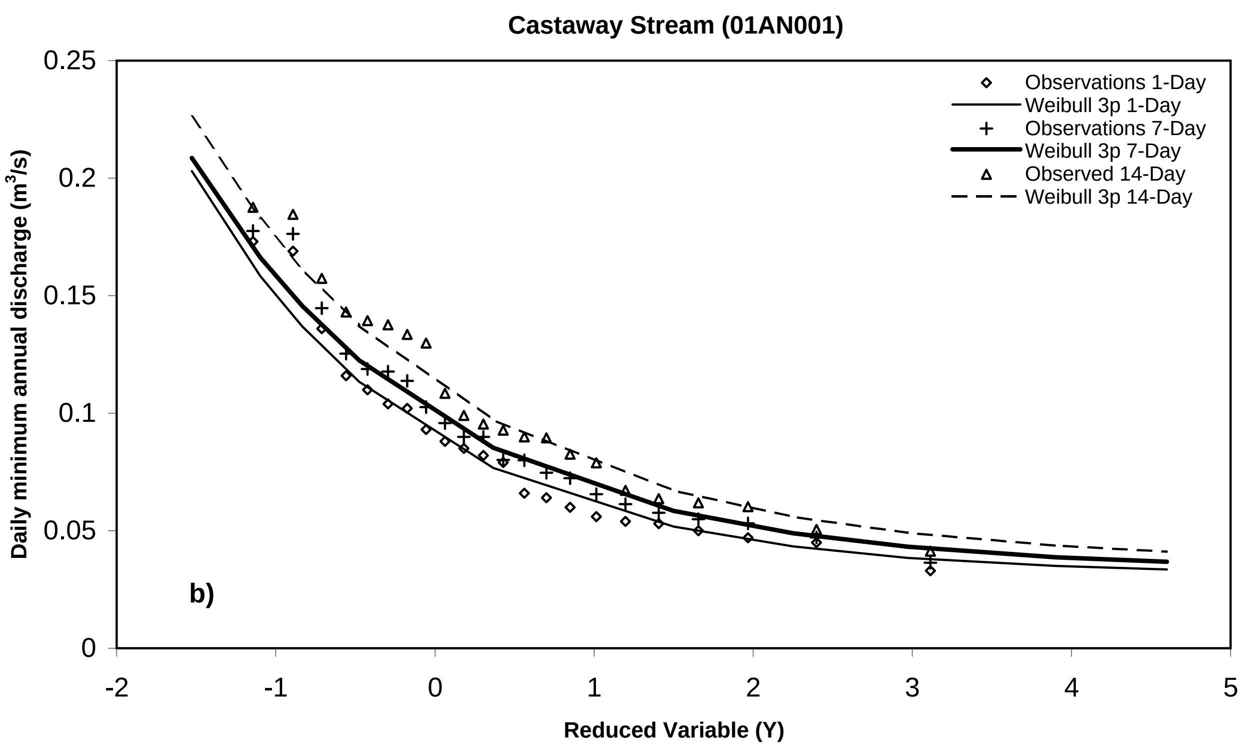
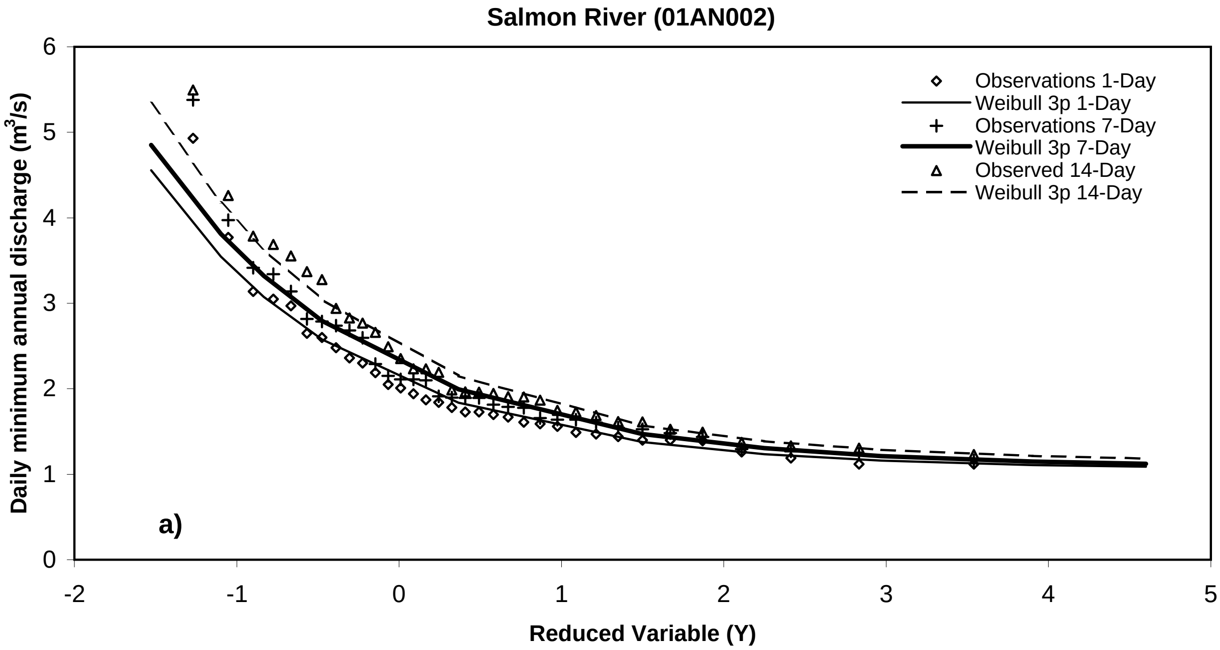


Figure A7. Fitted minimum annual discharge using the 3 parameter Weibull distribution; a) North Branch Oromocto River, b) Castaway Stream



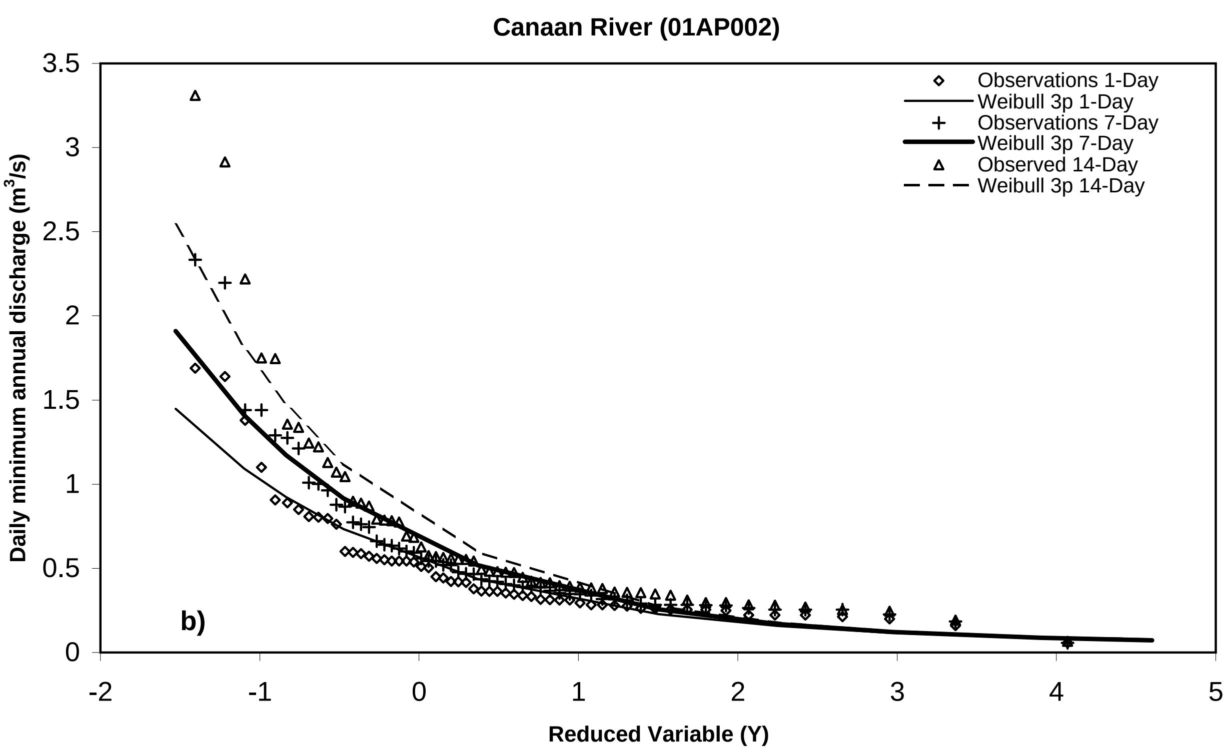
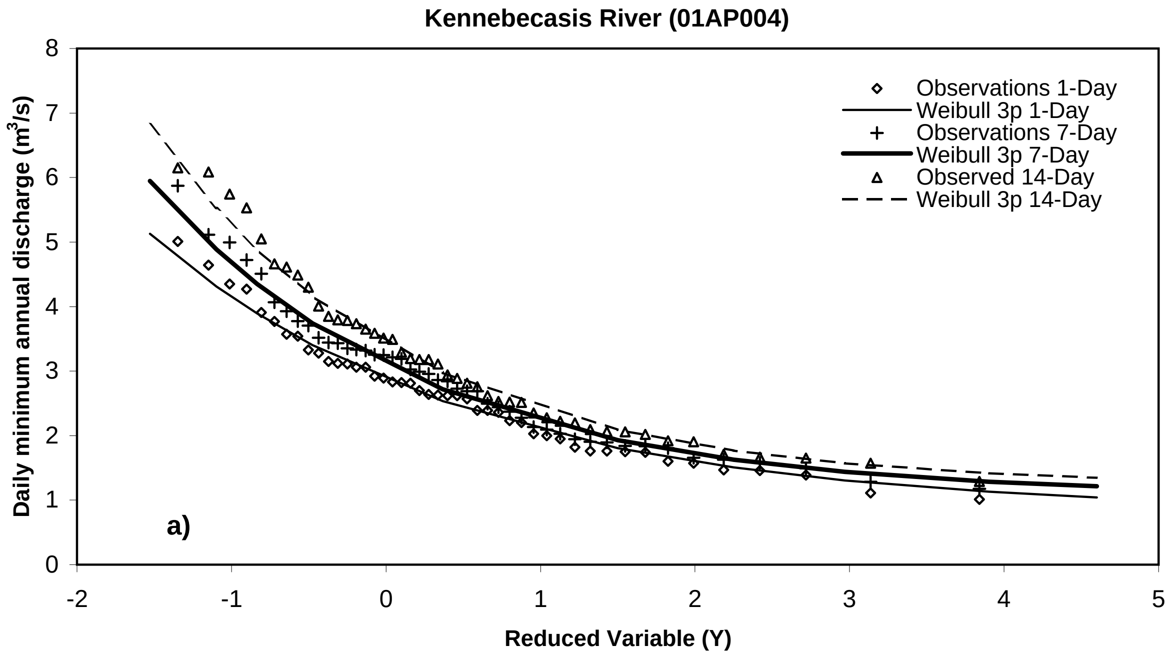


Figure A8. Fitted minimum annual discharge using the 3 parameter Weibull distribution; a) Salmon River, b) Canaan River



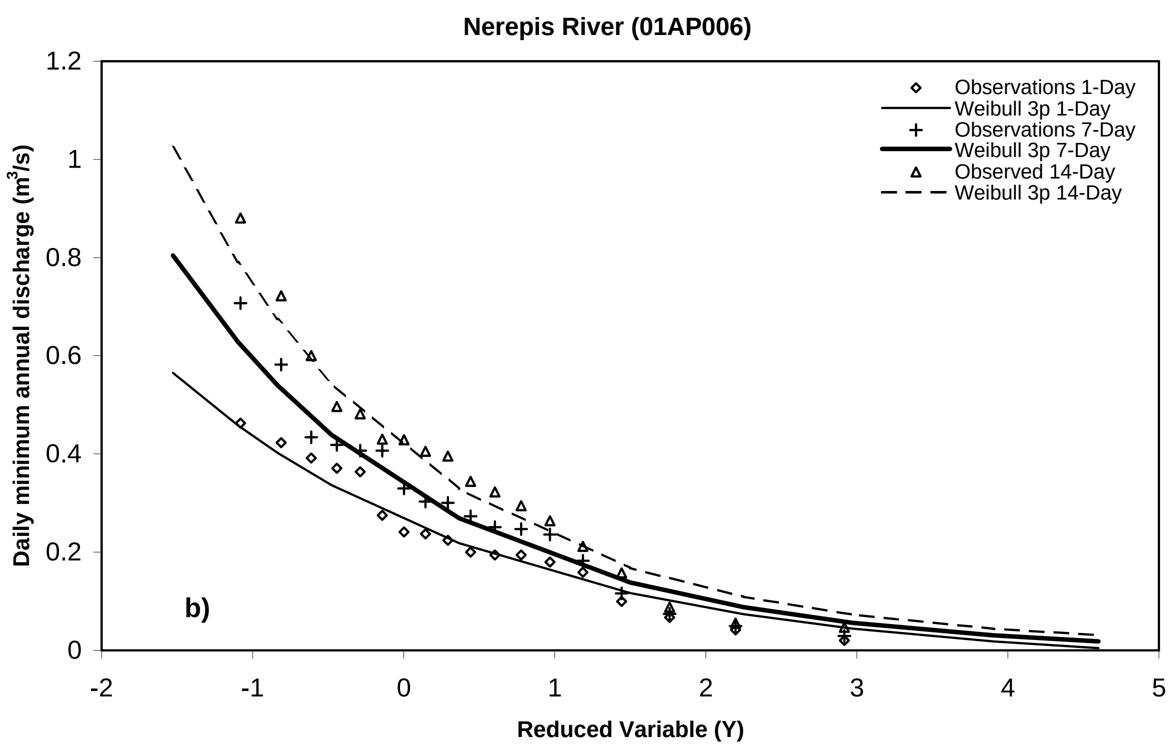
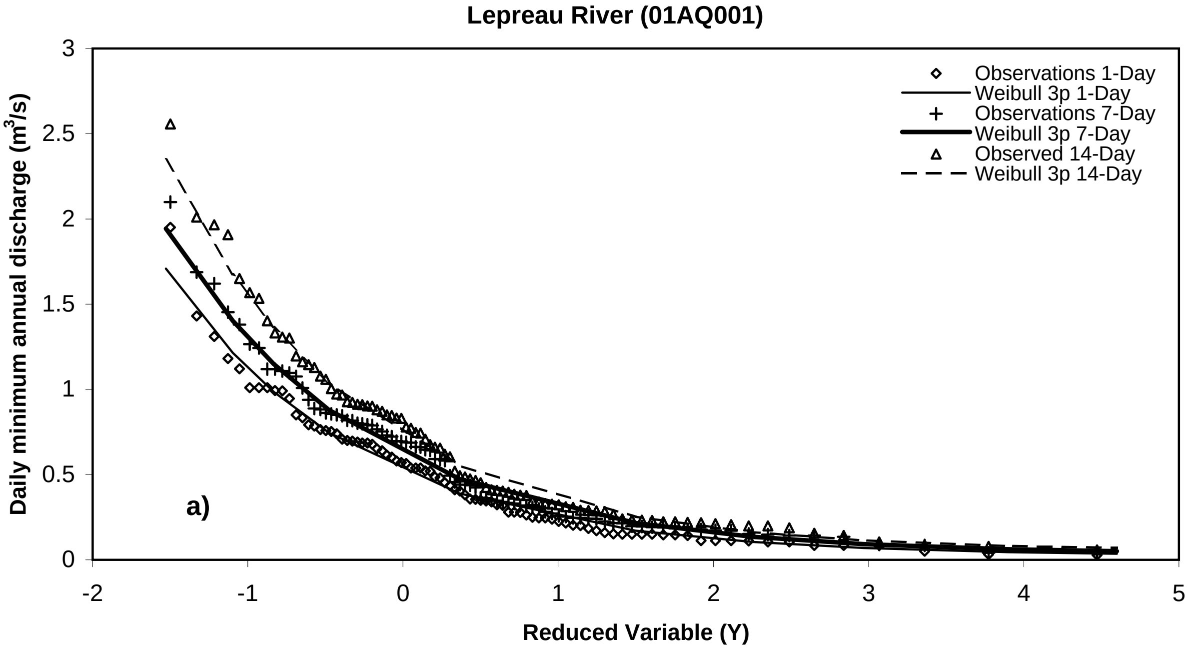


Figure A9. Fitted minimum annual discharge using the 3 parameter Weibull distribution; a) Kennebecasis River, b) Nerepis River



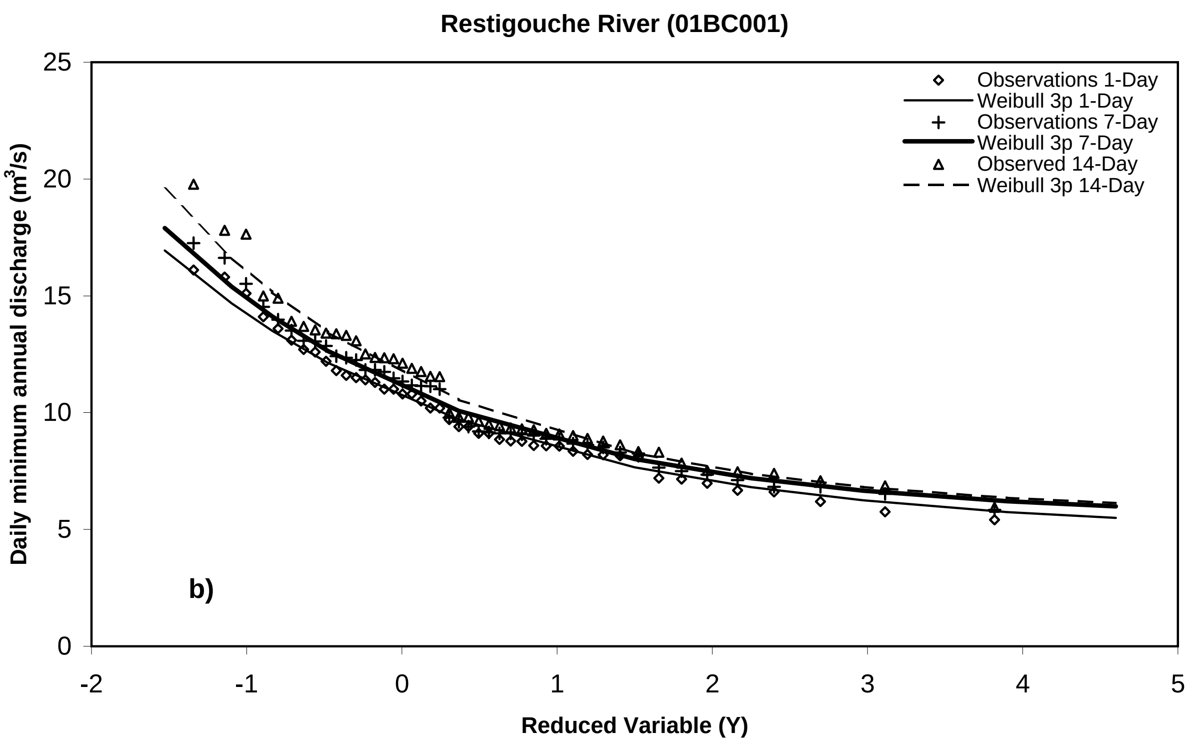
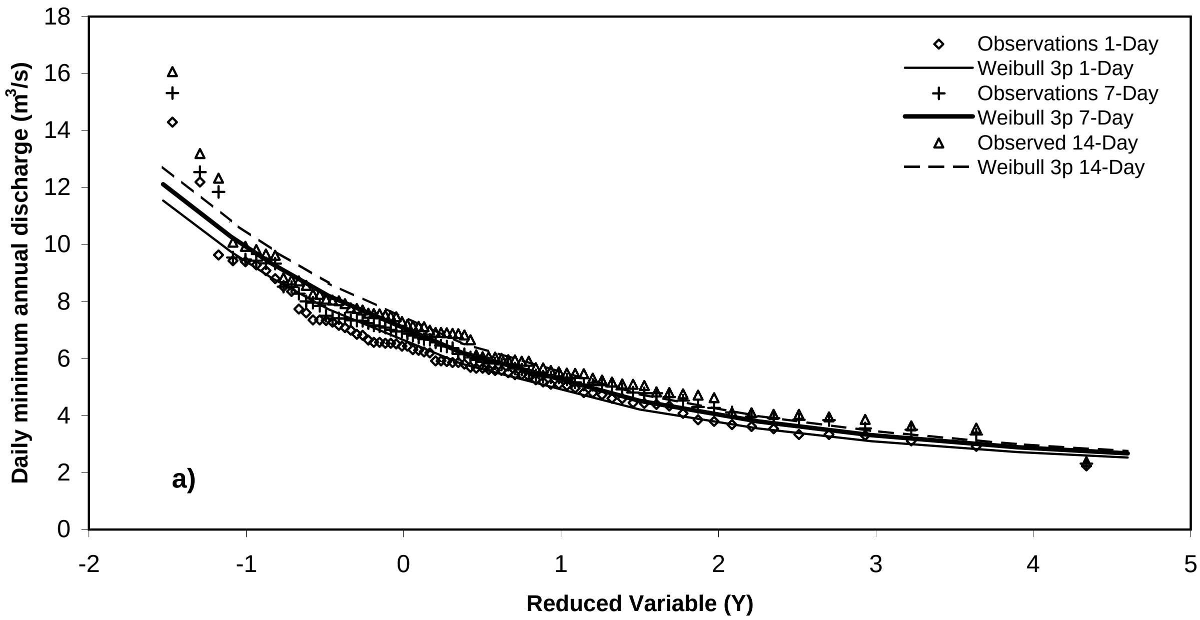


Figure A10. Fitted minimum annual discharge using the 3 parameter Weibull distribution; a) Lepreau River, b) Restigouche River

Upsalquitch River (01BE001)



Tetagouche River (01BJ001)

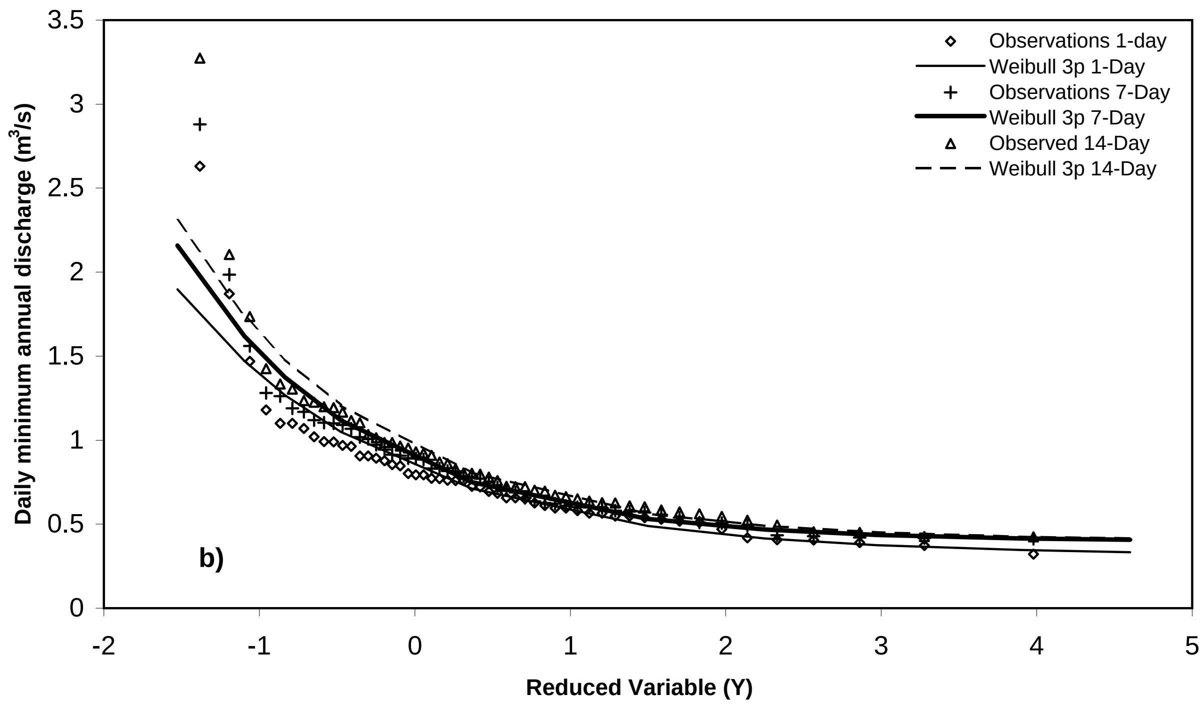
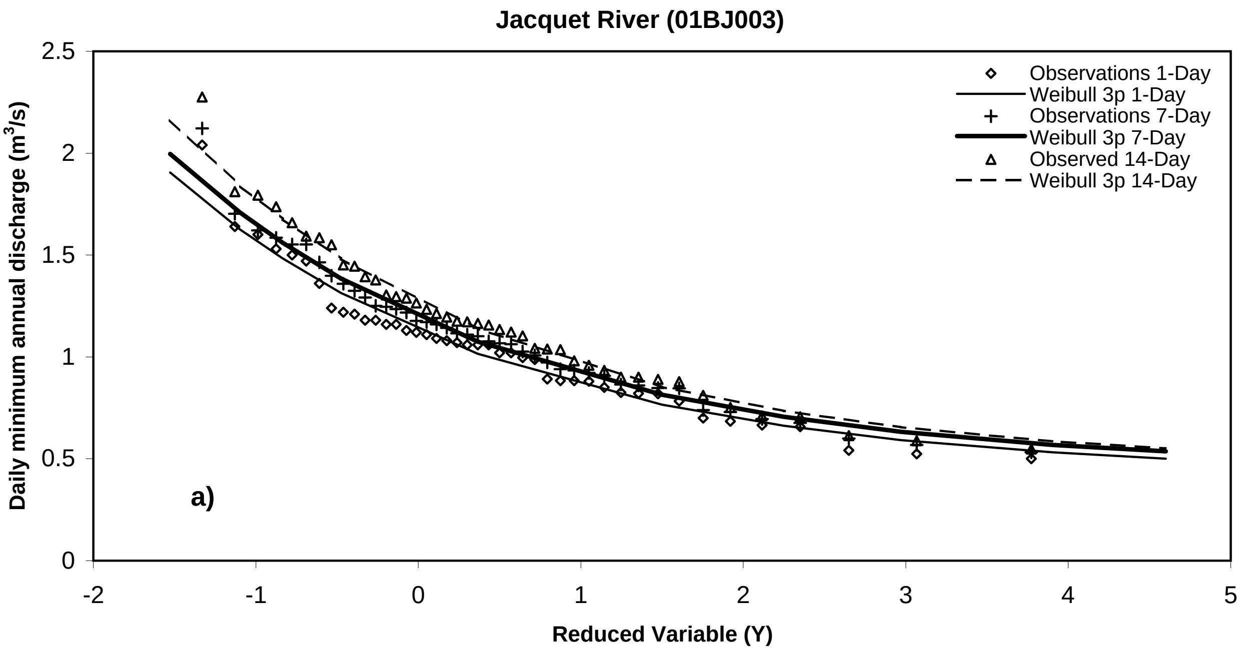


Figure A11. Fitted minimum annual discharge using the 3 parameter Weibull distribution; a) Upsalquitch River, b) Tetagouche River



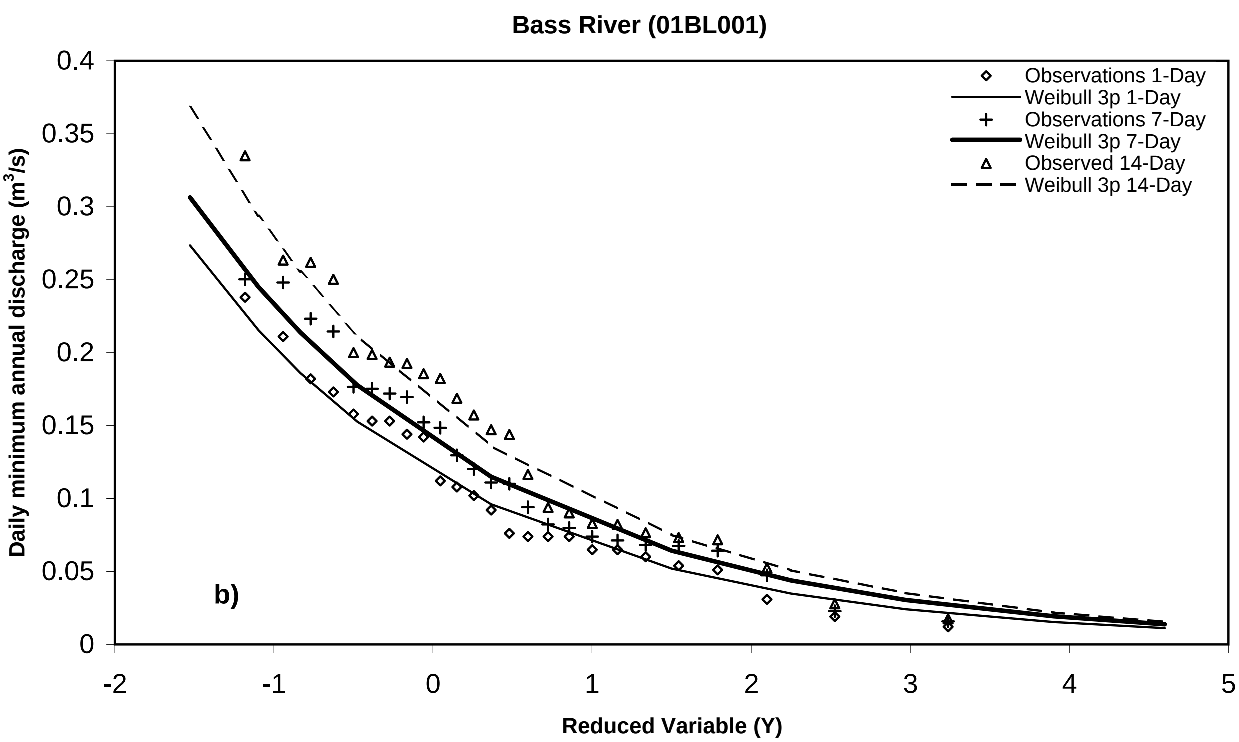
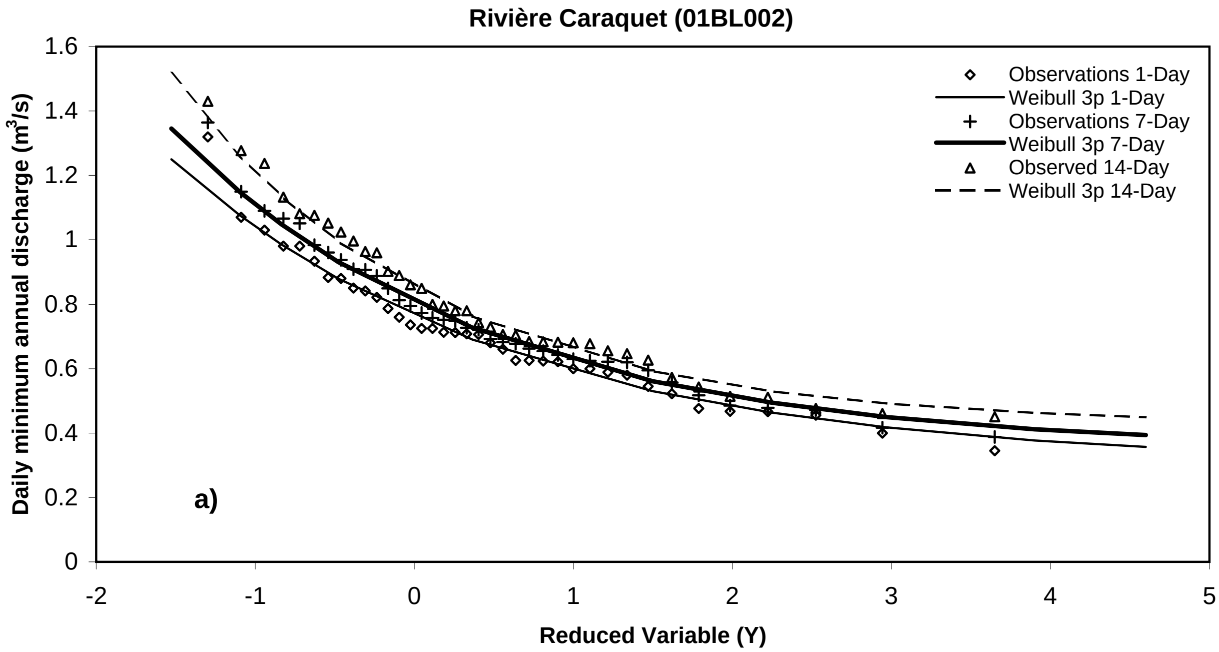


Figure A12. Fitted minimum annual discharge using the 3 parameter Weibull distribution; a) Jacquet River, b) Bass River



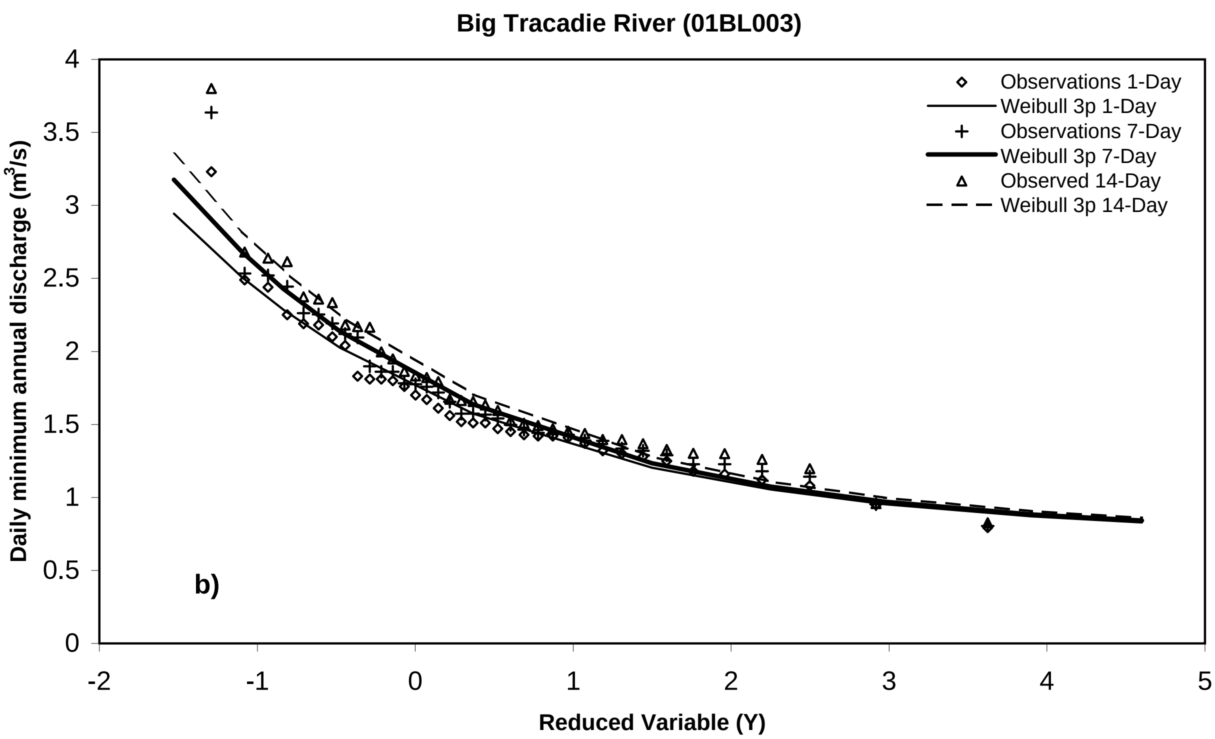
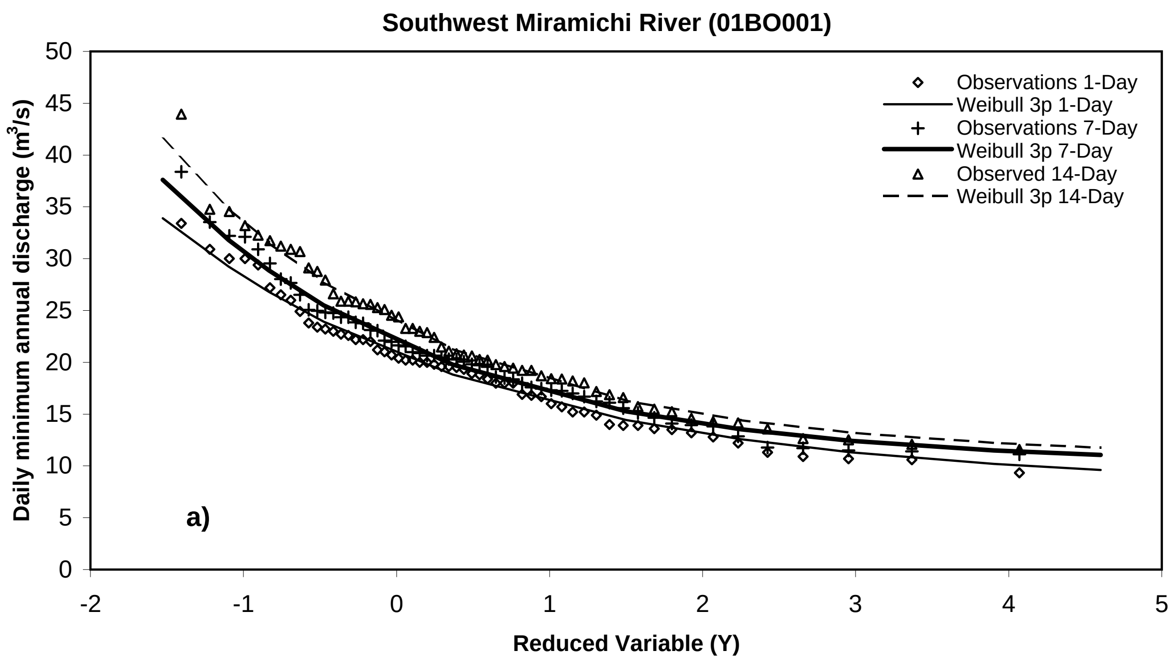


Figure A13. Fitted minimum annual discharge using the 3 parameter Weibull distribution; a) Rivière Caraquet, b) Big Tracadie River



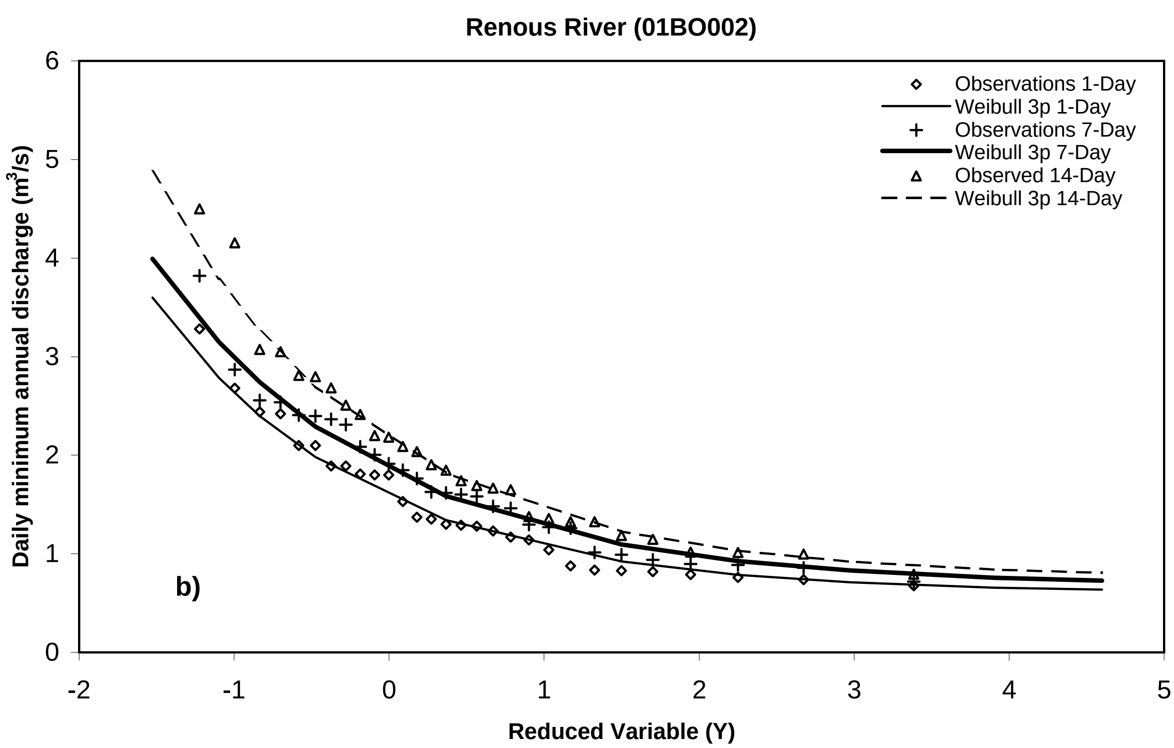
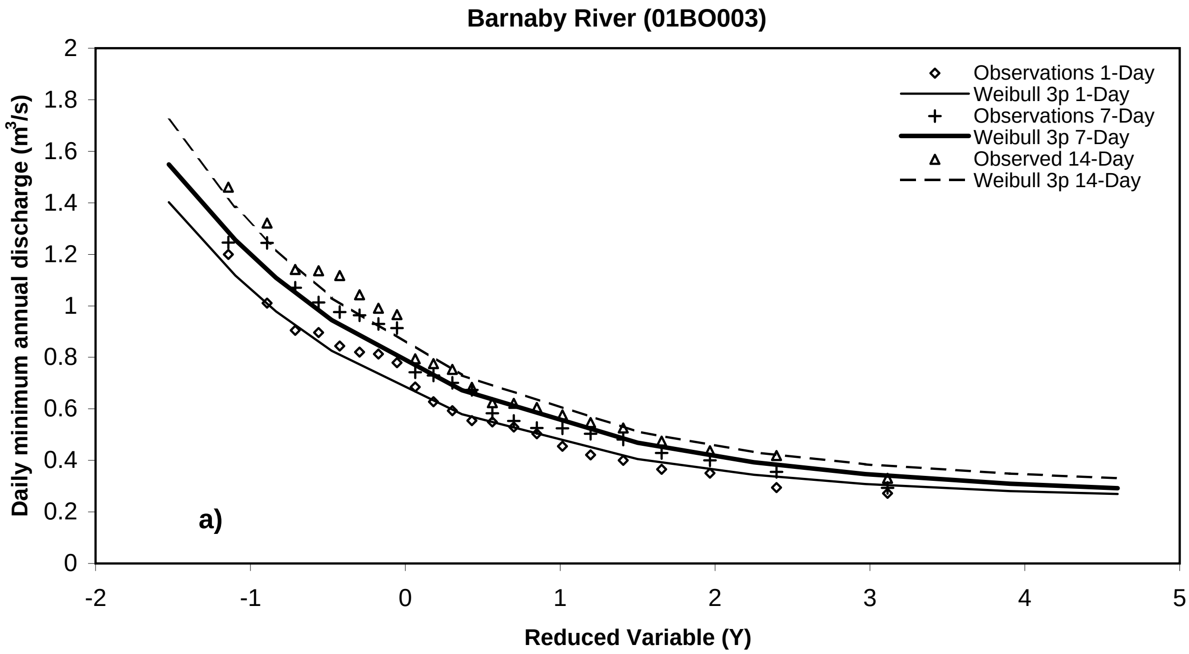


Figure A14. Fitted minimum annual discharge using the 3 parameter Weibull distribution; a) Southwest Miramichi River, b) Renous River



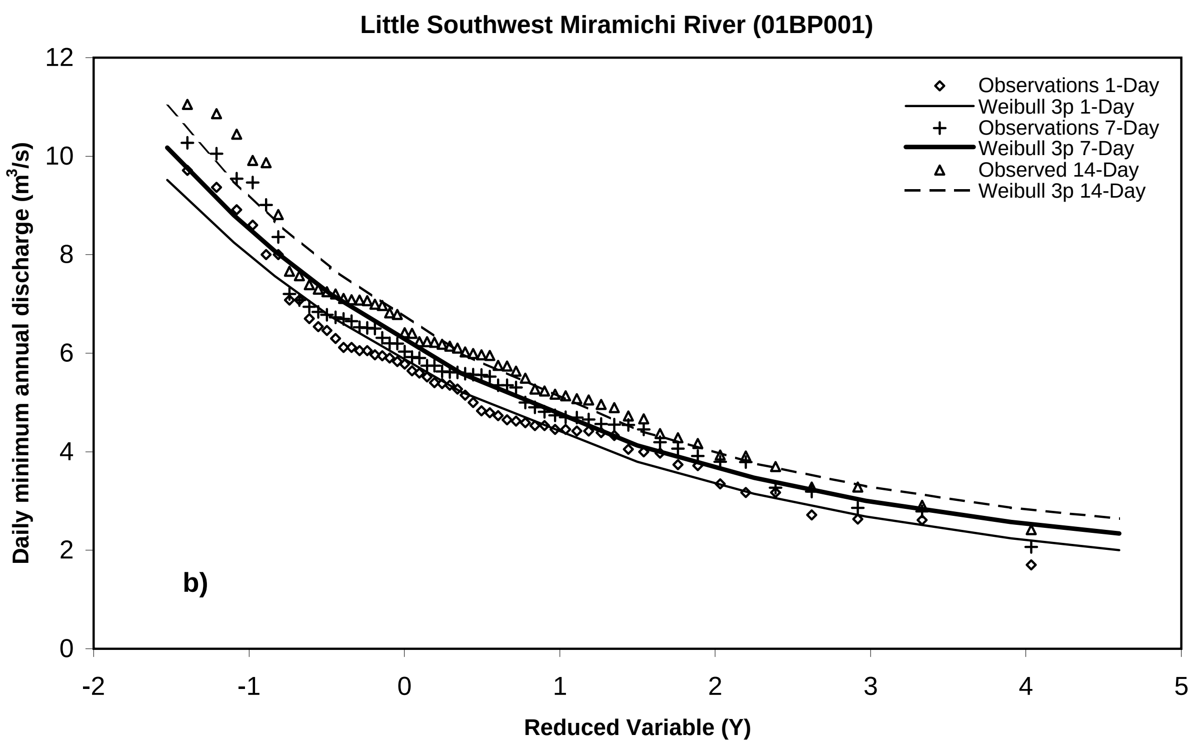
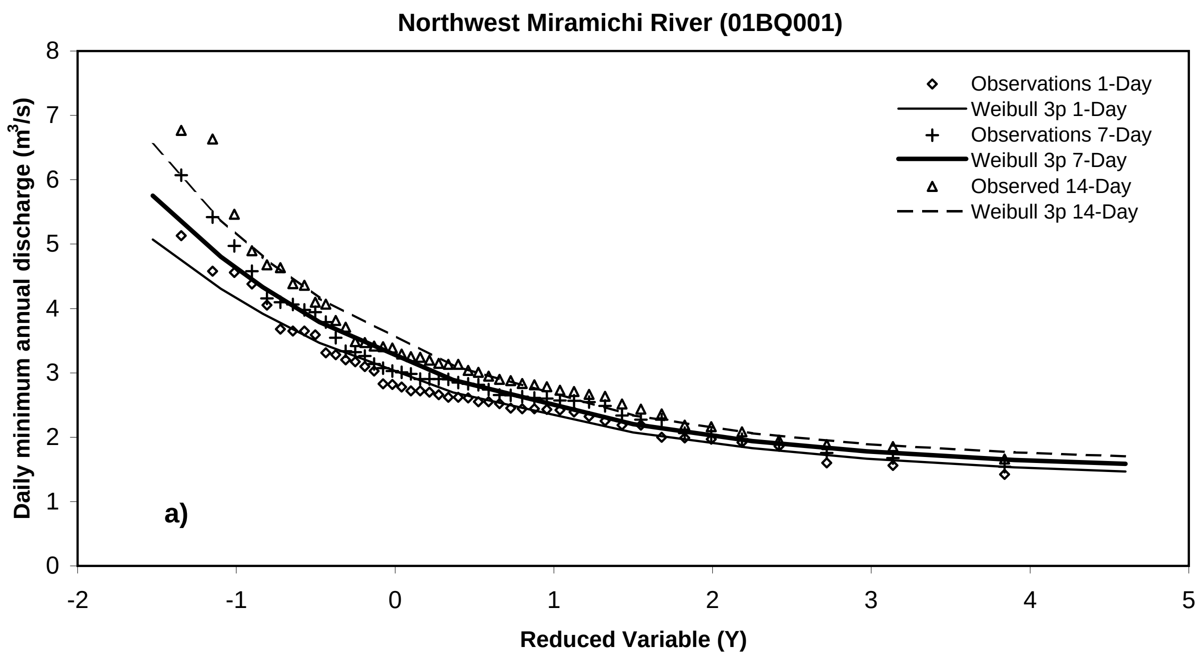


Figure A15. Fitted minimum annual discharge using the 3 parameter Weibull distribution; a) Barnaby River, b) Little Southwest Miramichi River



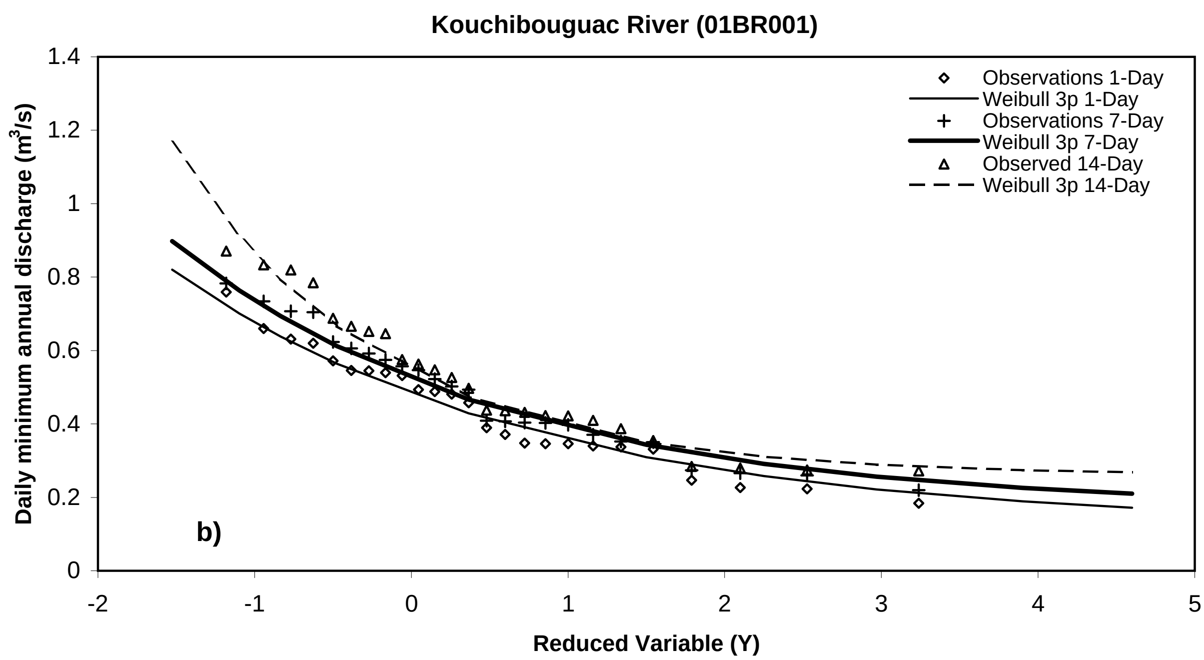
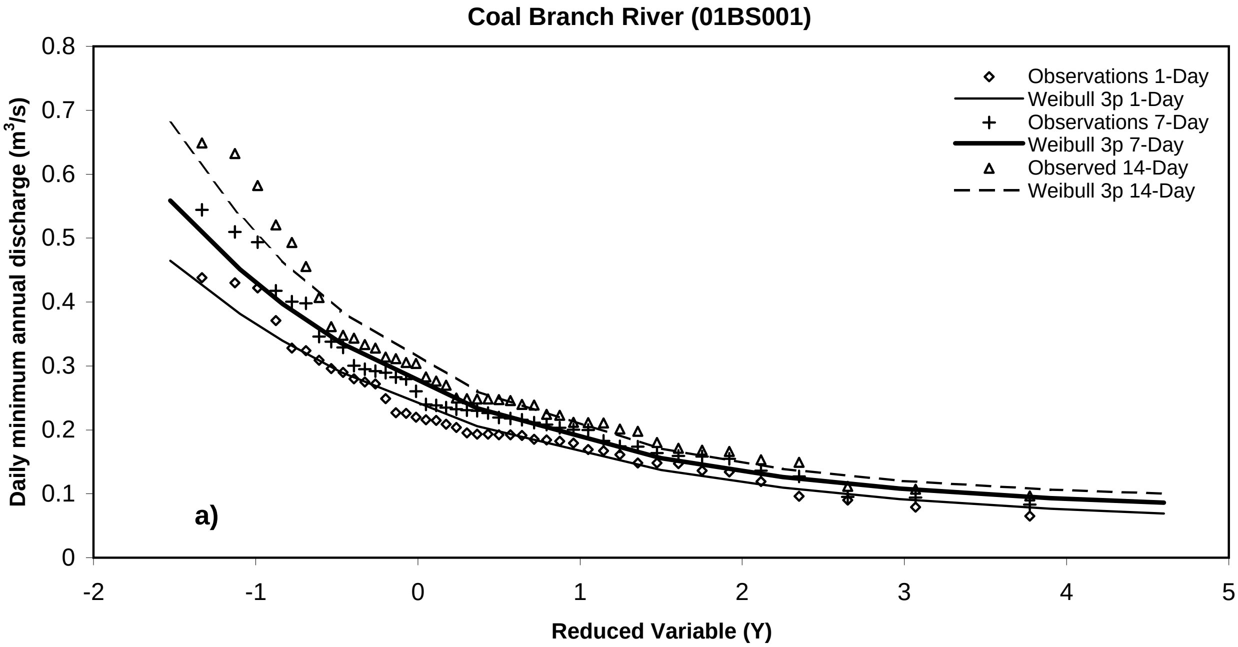


Figure A16. Fitted minimum annual discharge using the 3 parameter Weibull distribution; a) Northwest Miramichi River, b) Kouchibouguac River



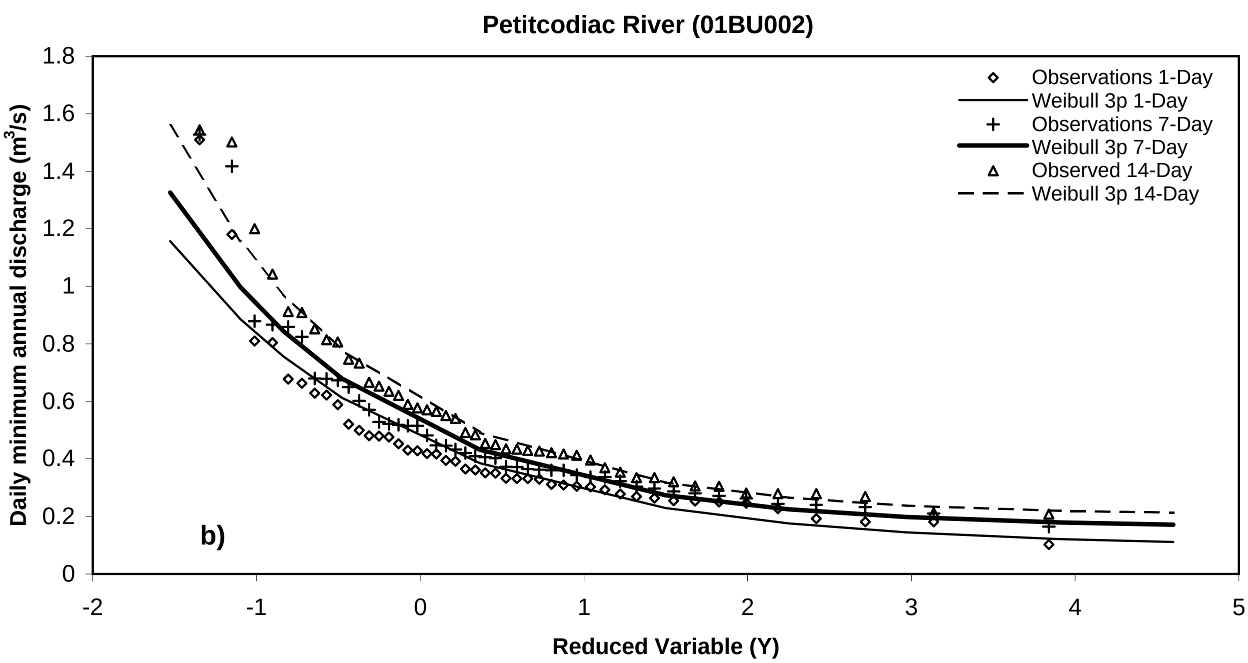


Figure A17. Fitted minimum annual discharge using the 3 parameter Weibull distribution; a) Coal Branch River, b) Petitcodiac River

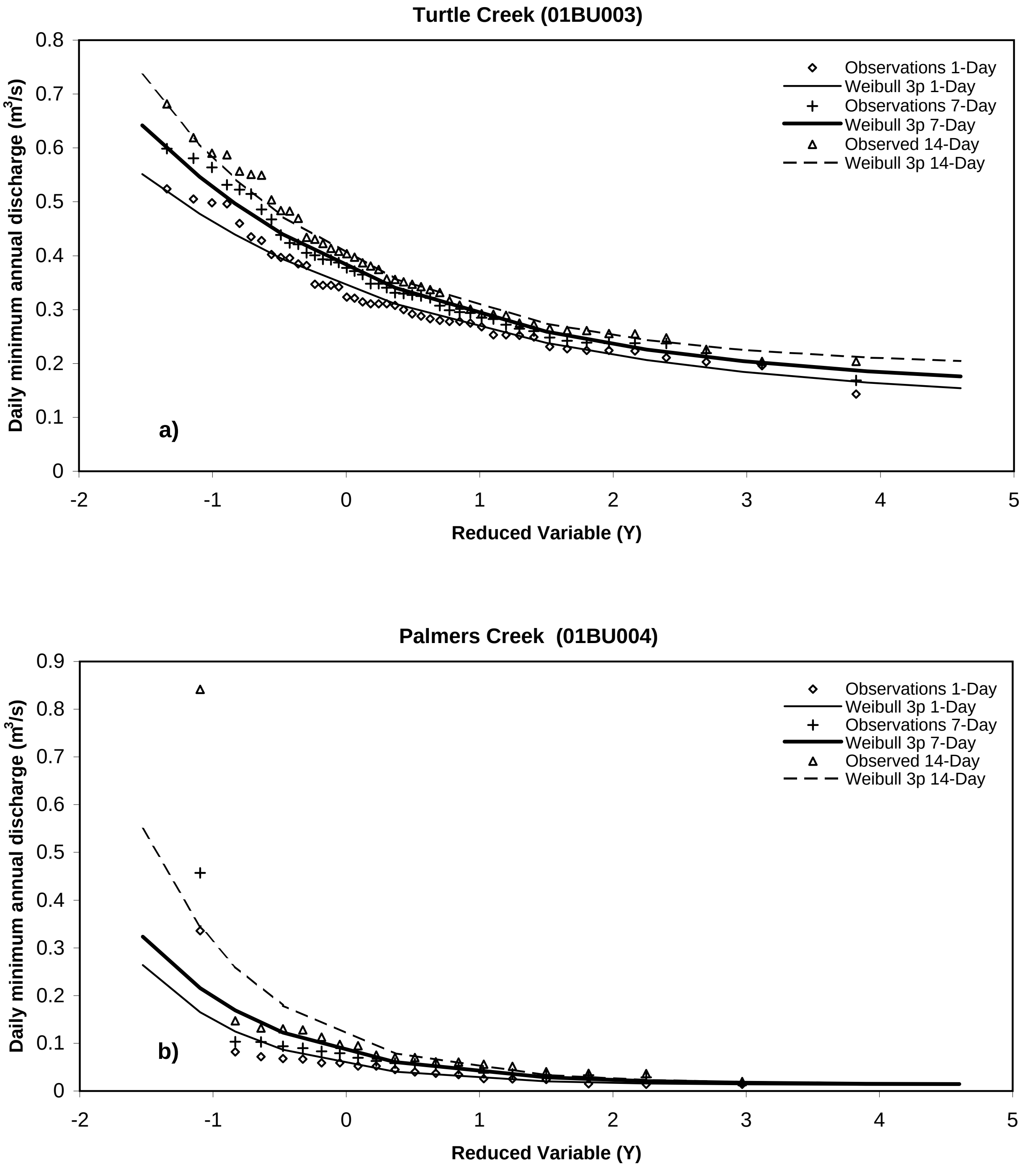
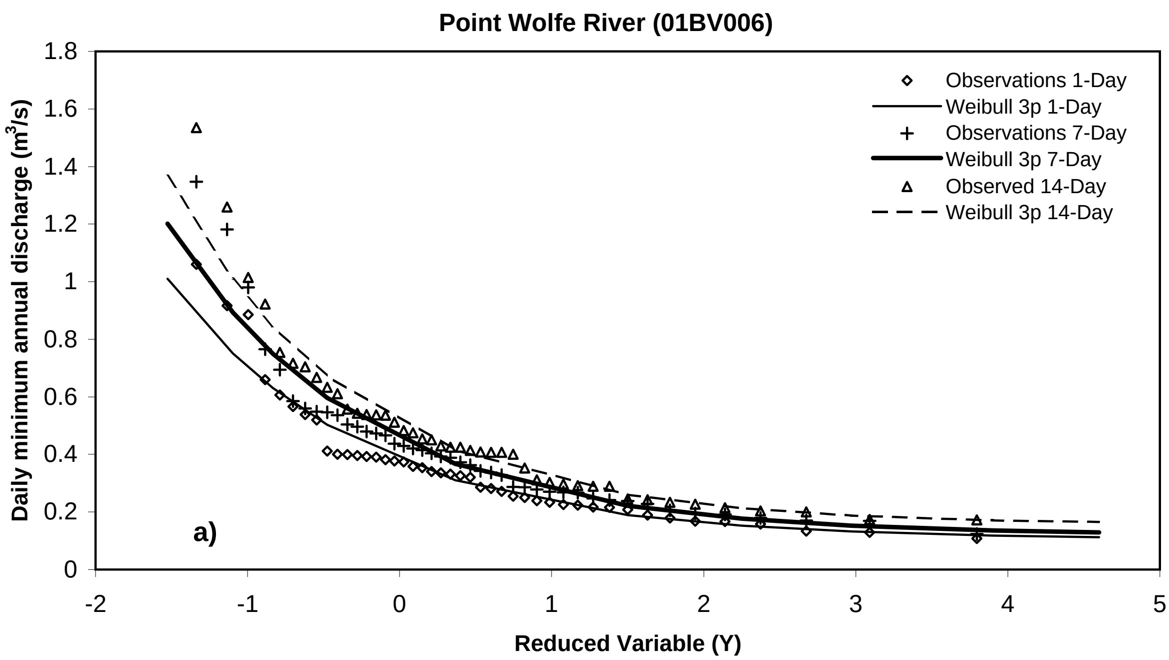


Figure A18. Fitted minimum annual discharge using the 3 parameter Weibull distribution; a) Turtle Creek, b) Palmers Creek



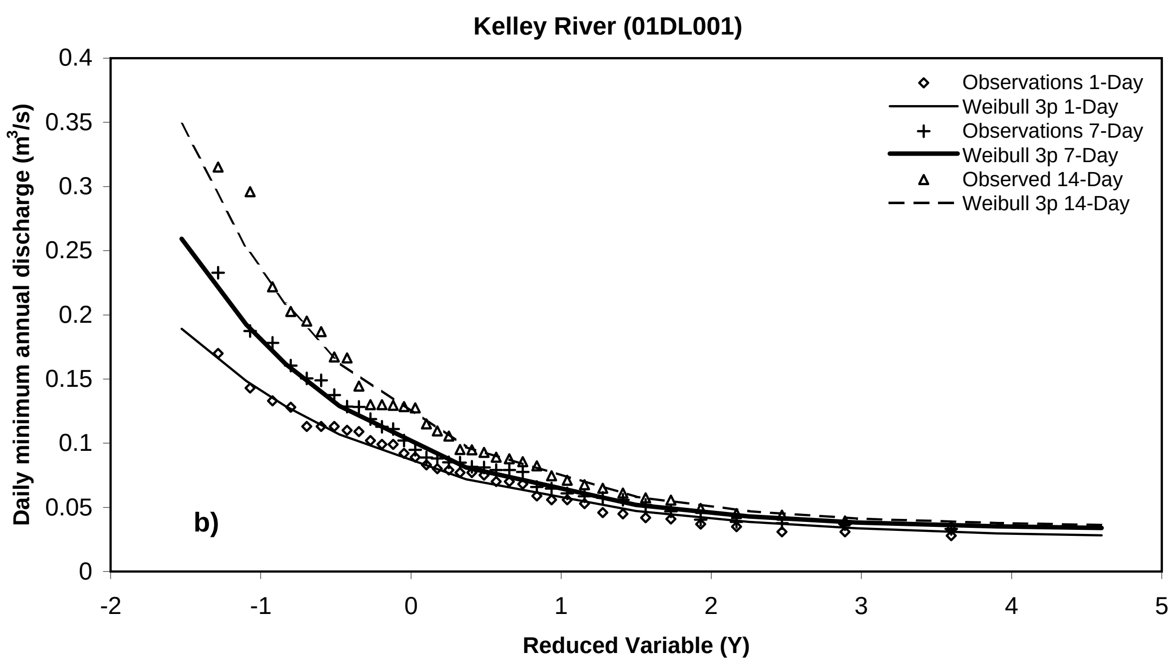


Figure A19. Fitted minimum annual discharge using the 3 parameter Weibull distribution; a) Point Wolfe River, b) Kelley River