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RESEARCH ARTICLE

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Characterization of natural and environmental flows in New Brunswick, Canada

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Abstract

A good understanding of the natural flow regime plays an important role in many hydrological studies. Also important in such studies is the quantification of environmental flows. This study focuses on flow metrics that best describe the natural flow regime and the hydrological characteristics for rivers in New Brunswick (Canada) as well as quantifying environment flows for these rivers. New Brunswick rivers have a mean annual flow (MAF) of approximately 23 L s^{-1} km^{-2}, which is also reflective of the water availability. The frequency analysis showed that low flows (T = 2–50 years, where T is the recurrence interval) were all below the 10% MAF. Environmental flow methods based on the MAF and flow duration analysis (median flow) showed good regional regression equations. However, flow duration methods showed high variability especially at flows between Q_{80} and Q_{100}. Flow targets based on the 25% MAF, Q_{50} and 70% Q_{50} were used to estimate environmental flows, particularly during low-flow periods (winter and summer). Results showed that the 70% Q_{50} method should be used with caution in summer as this method provided flows in the range of 15–16% of MAF. Other methods provided environmental flows higher than 15% MAF, thus, providing better flow protection for aquatic habitat. When comparing water availability for off-stream use (river flow–environmental flow), different parts of New Brunswick were found to be deficient in flows (i.e., river flows less than environment flows—no extractable water) during the summer and winter low-flow periods.

KEYWORDS
environmental flows, high and low flows, instream flows, natural flows regime

1 | INTRODUCTION

Environmental flows play a key role in water resources management for a variety of activities, e.g., river engineering, river restoration, water resources planning, as well as for the overall functioning and health of river ecosystems. As such, many facets of our daily lives depend on water availability and water security, both of which are linked to river hydrology and environmental flows (Cook & Bakker, 2012). For example, studies have shown that the natural flow regime plays a key role in the functioning of river ecosystems (Poff et al., 1997), and streamflow is recognized as a key ecological component worth protecting. Notably, water security (i.e., meeting human and aquatic water demands) is becoming increasingly important not only for fish habitat and fisheries management but also for the protection of water quality, quantity, and the sustainability of water supplies in many parts of the world (Grey & Sadoff, 2007).

Water withdrawals can affect the natural flow regimes, fish habitat, and aquatic life in general. Studies are showing that water withdrawal (e.g., irrigation, hydroelectric, drinking water, etc.) is currently increasing worldwide and such off-stream water usages can have a negative impact on downstream fish populations (Green et al., 2015). Therefore, the scarcity of water, especially during low-flows periods, can result in a direct conflict between the protection of aquatic habitat and human water use. This requires water resources and fisheries managers to rely on data and a good understanding of water availability, hydrologic regimes as well as important fisheries requiring protection. To address issues of water use (instream and off-stream), the understanding of both the natural flow regime and environmental flow requirements (instream flows) are essential because both are linked. The concept of environmental flows relates to the quantity of water required in rivers to sustain an acceptable level of life of aquatic biota at various phases of their development (Tennant, 1976; Wesche & Rechard, 1980; Annear et al., 2004; Caissie, Caissie, & El-Jabi, 2015). Environmental flows can also include other instream use such as recreational activities, navigation, and others. It is recognized that the complexity of environmental flow studies is highly dependent on the specific objectives of the project, data availability, the resource requiring protection, and the magnitude of the project (Beecher, 1990; Annear et al., 2004; Linnansaari et al., 2013).

The present study will initially focus on characterizing the natural flow regime, namely, through the calculation of the mean annual flow (MAF), the mean monthly flows (MMF), and flow duration characteristics. Daily runoff characteristics will also be calculated to provide a better understanding of the spatial and temporal flow variability (Caissie & Robichaud, 2009). The study will quantify extreme events through an analysis of high and low flows. The timing of high and low flows (winter and summer) will also be quantified. The second part of the study will focus on quantifying environmental flows for each river using various approaches and different flow targets. Four hydrologically based environmental flow methods will be used in the present study, namely, (a) fixed percentages of the MAF (e.g., 25% MAF), (b) the Q_{50} or median flow duration method, (c) 70% of Q_{50} flow duration method, and (d) Q_{90} flow duration method. Different environmental flow targets will be applied, thus, providing a range of potential environmental flows. Finally, regional characteristics of flow metrics will be studied using regression analysis in order to estimate water availability and environmental flows for ungauged basins.

2 | MATERIALS AND METHODS

2.1 | Data and study region

Hydrological and environmental flow analyses were carried out using historical data from 54 hydrometric stations of which 51 are located in New Brunswick (Canada), two stations were located in Quebec, and one station was located in the province of Nova Scotia (Figure 1). The province of New Brunswick is located in eastern Canada and has a maritime climate with a mean annual air temperature ranging between 5.8°C in the south and 3.2°C in the north. The three stations located in the nearby provinces (two Quebec and one Nova Scotia) were used to increase the number of stations for the regional analysis (e.g., regression equations). All data used in this study were collected from the Archive Hydrometric Data Online from Environment Canada (https://ec.gc.ca/rhc-wsc/ accessed April 15, 2014). Data extracted included daily discharge data as well as extreme values, that is, annual maximum and minimum daily discharges data.

2.2 | Natural flow regimes

Characteristics of the natural flow regime were described using the MAF, the mean monthly flow (MMF) and a flow duration analysis. The MAF provides valuable information on the water availability (total volume of water) for a given river whereas the MMF provides information on the distribution of such flows on a seasonal basis (monthly distribution). A flow duration analysis was carried out for each hydrometric station, as it provides information on the timing of specific flows, that is, percentage of time a specific flow is equal or exceeded within a given time period. Flow duration analysis uses a nonparametric cumulative distribution function of daily discharges and ranks flows from the highest to the lowest. Then flows of different

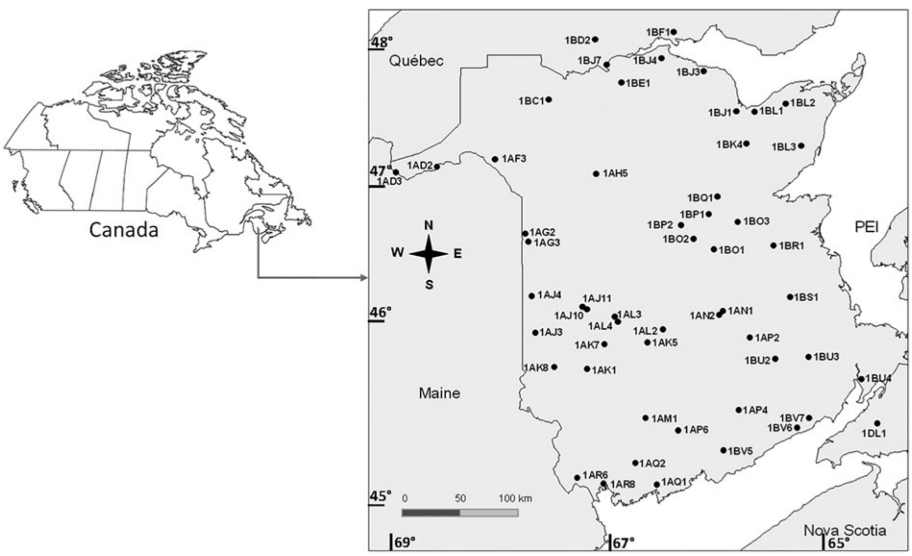


FIGURE 1 Location of selected hydrometric stations in New Brunswick (54 stations)

frequencies (or percentiles) are determined (e.g., 50% or median flow Q_{50}, 90% or Q_{90}, etc.).

In describing the natural flow regime, extreme events were also quantified, as high flows are important for maintaining channel morphology as well as the dilution capacity of rivers, whereas low flows can limit habitat in both summer and winter and can contribute to high temperatures in the summer. A frequency analysis was carried out using the 54 studied stations. The maximum and minimum daily discharges by year were extracted from the database and fitted to the generalized extreme value (GEV) distributions for both high and low flows. For low flows, the 2 and 3-parameter Weibull distribution were also used for comparative purposes with the GEV. Both the GEV and Weibull frequency distribution functions were used in this analysis, and flows were estimated for recurrence intervals of 2, 5, 10, 20, 50, and 100 years for high flows and recurrence intervals of 2, 5, 10, 20, and 50 years for low flows. The maximum likelihood method was used for estimating parameters for all distributions. The Cumulative Distribution Function (CDF), $F(x)$, for the GEV distributions is given by the following equations:

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

where k, σ, and μ are shape, scale and location parameters, respectively.

As for the Weibull distribution, the CDF is given by the following equation:

$$F(x) = 1 - \exp\left[-\left(\frac{x-\gamma}{\beta}\right)^{\alpha}\right], \quad (2)$$

where α, β, and γ are shape, scale and location parameters, respectively (and where $\gamma \equiv 0$ for 2-parameter Weibull distribution).

Following the frequency analysis, an analysis of high and low-flow periods (both magnitude and timing) was carried out using a 30-day running mean (mean of 30 days). This analysis was carried out to provide a better estimate of the high and low-flow period/timing throughout the year (rather than using the magnitude and timing of a single daily discharge, which does not necessarily reflect the true high and low-flow period; Thistle & Caissie, 2013). For this analysis, the spring high-flow period was studied as well as both winter and summer low flows.

2.3 | Environmental flow assessment

The following hydrologically based environmental flow methods were used: The 25% MAF method, the median monthly flow (Q_{50}) method, 70% Q_{50} method, and 90% flow duration method (or Q_{90}), and different environmental flow targets were considered on a seasonal basis (Table 1). These environmental flow targets have been selected based on previous studies (e.g., Caissie et al., 2015; Caissie & El-Jabi, 1995). The upper target calculates higher environmental flows (higher flows to be left in the river) whereas the lower target is less restrictive (more water available for extraction). Both these targets should represent a potential range of environmental flows. It should be noted that the selection of these methods (as well as lower and upper targets) are only for the purpose of assessing potential water availability for off-stream use. In fact, the selection of environmental flow methods can be site/project specific and could be somewhat different based on a variety of criteria (e.g., type and importance of species to protect, size of the river, size of the project, etc.). Nonetheless, the upper and lower target presented in the present study should provide a preliminary assessment of potential environmental flow range as well as potential water availability for off-stream use.

TABLE 1 Potential range (upper/lower) of environmental flow targets by seasons

Month	Season	Lower target	Upper target
Jan Feb Mar	Winter	70% Q_{50}	Q_{50}
Apr May Jun	Spring	25% MAF	Q_{90}
Jul Aug Sep	Summer	70% Q_{50}	25% MAF
Oct Nov Dec	Autumn	25% MAF	Q_{50}

Note. MAF: mean annual flow.

Following the calculations of environmental flows, the water availability for off-stream use can be calculated from the difference between the MMF and the environmental flow targets (lower or upper target).

2.4 | Regionalization of streamflow characteristic and environmental flows

Streamflow characteristics and environmental flows differ from one drainage basin to another and result of single station analysis only applies to gauged streams. As many water resource projects are undertaken in ungauged basins, there is a need for the development of regional equations. Regional regression analysis consists of establishing a relationship between flow metrics (mean flows, high and low flows, etc.) or environmental flows and physiographic parameters describing the basin. With the discharge as the dependent variable and physiographic factors as the independent variables (in this case, drainage area), a regression was performed to evaluate the a and b coefficients of the following equation:

$$Q = a\,(DA)^{b}, \quad (3)$$

where, a and b are regression coefficients, (DA) is the drainage area (km^2), and Q represents different flow metrics (MAF, Q_{50}, high or low flows for different recurrence intervals, m^3/s). In the present study, the parameters a and b were calculated using nonlinear regression.

Once the regional regression equations were obtained for mean, median, high, and low flows, then characteristics of environmental flows by the different methods were studied on a monthly basis for the province. The mean upper or lower environmental flow target for each month was calculated for the province reflecting the potential water availability for off-stream use. In order to study the spatial variability of water availability throughout the province, data from each station were used to produce a heat map (using ArcGIS and kriging) showing which area of the province has more (or less) available water in September and February (summer and winter low flow months).

3 | RESULTS

3.1 | MAF and MMF

Figure 1 presents the location of the 54 hydrometric stations analysed in the present study, and some relevant characteristics are presented in Table 2. The number of years of record varies between 11 and 93 with a mean value of 39 years. The smallest drainage basin is the Narrows Mountain Brook at 3.89 km^2 whereas the largest river is the Saint John River at Fort Kent at 14,700 km^2. The MAF varied between 0.098 m^3/s (Narrow Mountain Brook) and 279 m^3/s (Saint John River at Fort Kent).

The overall MAF (all stations combined) was 23 L s^{-1} km^{-2}, and this flow is reflective of the water availability for New Brunswick rivers (Figure 2a). The MMF were relatively low in winter (January/February ~12 L s^{-1} km^{-2}) at approximately half (50%) of the MAF but increased in the spring to reach peak values in April and May (63.6 L s^{-1} km^{-2}; 54.4 L s^{-1} km^{-2}). In the spring, the variability was high, particularly in May (SD = 20.5 L s^{-1} km^{-2}; Figure 2a). The summer low flow months occurred mainly between July and September (flows ~9–11 L s^{-1} km^{-2} and close to 40%–50% of MAF) and showed the lowest flow variability (SD ~2.6– 3 L s^{-1} km^{-2}; Figure 2a). In autumn, the MMFs were close to 24 L s^{-1} km^{-2} (November/December) and very close to the mean overall normalized flow (MAF) of 23.0 L s^{-1} km^{-2}. Also shown in Figure 2a is the median monthly flows where values were very close to the MMF. Figure 2a shows that the MMFs were higher than the MAF only during 4 months of the year, namely, during the spring (April and May) and autumn (November and December).

Daily runoff characteristics were analysed for New Brunswick rivers, as it provides finer details on the flow distribution within the year. The average daily discharge time series for all stations in New Brunswick is presented in Figure 2b. Daily runoff characteristics (mm) are presented rather than discharge (or normalized flows) to compare flows of the various size rivers within the province. Two lines of particular interest were also added to this figure, namely, the MAF (at 2 mm; blue) and the 25% MAF (0.5 mm; red). The 25% MAF is of interest as it can represent an approximate value for environmental flows (annual basis). This figure shows a high variability in runoff among rivers, particularly in spring and late autumn. The winter low-flow period was generally between January 31 (day 31) and March 2 (day 61), and minimum flows were close to 0.8 mm per day. The low-flow period was followed by the spring high flows, which peaked around May 1 (day 121; reaching values of 7.3 mm; Figure 2b). The summer low-flow period generally extended between August 23 (day 235) and September 17 (day 260) with minimum values in the range of 0.62–0.65 mm. A higher flow period was also observed in autumn (2–2.5 mm), generally between October 28 (day 301) and December 12 (day 346).

3.2 | Flow duration analysis

A flow duration analysis was carried out for each hydrometric station. With the single station flow duration analysis results, a regional flow duration curve was calculated (Figure 3). This figure shows flows corresponding to different percentages (from 0 to 100%) from the flow duration analysis, and flow variability is presented using box plots. The normalized flow duration curve showed flows between 577 L s^{-1} km^{-2} at 0% and 0.838 L s^{-1} km^{-2} at 100%. The normalized Q_{50} (at 50%) was calculated at 11.3 L s^{-1} km^{-2}, which is approximately half (50%) of the MAF. The flow variability was high at 0% (SD = 245 L s^{-1} km^{-2}; coefficient of variation, Cv = 0.48) but the lowest at 10% (SD = 9.45 L s^{-1} km^{-2} Cv = 0.17). For flows between 20 and 70% on the flow duration curve, the Cv generally increased from 0.23 to 0.32. However, a significant increase in the flow variability was observed at lower flows ($Q_{80,}$ Cv = 0.36; Q_{90}, Cv = 0.42; Q_{100}, Cv = 0.80; Figure 3). The normalized MAF calculated at 23.0 L s^{-1} km^{-2} (see above) corresponded to a flow that is exceeded 28% of the time on the flow duration curve (Figure 3). This means that the flows in New Brunswick rivers are generally below the MAF 72% of the time in a given year (i.e., 263 days of the year).

3.3 | High and low-flow frequency analysis

For the high-flow analysis, the GEV distribution was used exclusively because this distribution provided a good fit for all stations. In the case of low flows, results of the Anderson–Darling statistics favoured the GEV over 2-parameter Weibull (2p) and the 3-parameter Weibull (3p) most of the time. In fact, 87% (47/54) of the stations favoured the GEV distribution for low flows, followed by 11% (6/54) for the Weibull (2p) and 2% (1/54) for the Weibull (3p) distribution function.

For the Saint John River at Fort Kent, which has the largest drainage area (14,700 km^2), the 2-year flood and 2-year low flow were estimated at 2,352 m^3/s and 31.7 m^3/s, respectively. These flows correspond to the highest estimated 2-year flood (and low flow) in New Brunswick. Conversely, the lowest estimated 2-year flood and low flow were at Narrows Mountain Brook (drainage area of 3.89 km^2) with values of 1.18 m^3/s and 0.006 m^3/s, respectively.

High and low flows (in contrast with the MAF and Q_{50}) were calculated for New Brunswick rivers (Figure 4). The 2-year flood represents approximately 10 times the MAF with a median value of 213 L s^{-1} km^{-2} whereas the 100-year median flood was calculated at 559 L s^{-1} km^{-2} (i.e., approximately 2.62 times the 2-year flood). The high-flow variability was similar among rivers up to a 25-year flood; however, higher return floods showed slightly higher variability. Low flows were also analysed (Figure 4). The median value for the 2-year low flow was 1.96 L s^{-1} km^{-2}, which represented 8.5% of MAF. In contrast to high flows, low flows showed much higher variability among rivers, particularly for the 25 and 50-year

TABLE 2 Analysed hydrometric stations in New Brunswick

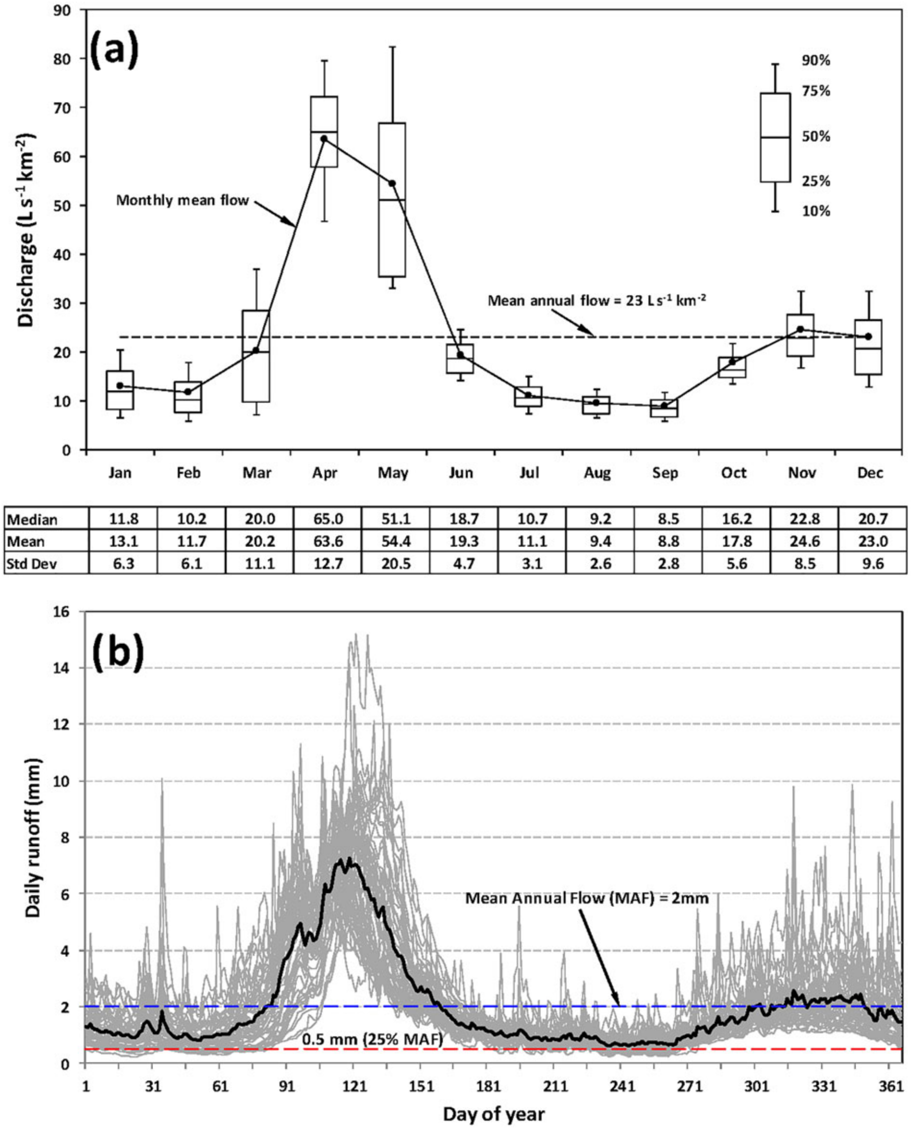
Station ID	Station name	DA (km^2)	Period of record	*N*	MAF (m^3/s)
01AD002	Saint John River at Fort Kent	14,700	1927–2012	86	279.2
01AD003	Saint Francis River at outlet of Glasier Lake	1,350	1952–2012	61	25.6
01AF003	Green River near Rivière-Verte	1,150	1963–79,1981–1993	30	26.4
01AG002	Limestone River at Four Falls	199	1968–1993	26	3.64
01AG003	Aroostook River near Tinker	6,060	1975–2010	36	114.4
01AH005	Mamozekel River near Campbell River	230	1973–1990	18	4.1
01AJ003	Meduxnekeag River near Belleville	1,210	1968–2010	43	25.2
01AJ004	Big Presque Isle Stream at Tracey Mills	484	1968–2010	43	9.82
01AJ010	Becaguimec Stream at Coldstream	350	1974–2011	38	7.6
01AJ011	Cold Stream at Coldstream	156	1974–1993	20	3.16
01AK001	Shogomoc Stream near Trans Canada Highway	234	1919–40,1944–2012	91	4.99
01AK005	North Nashwaak Stream near Royal Road	26.9	1966–1993	28	0.54
01AK007	Nackawic River near Temperance Vale	240	1968–2010	43	4.94
01AK008	Eel River near Scott Siding	531	1974–1993	20	10.5
01AL002	Nashwaak River at Durham Bridge	1,450	1962–2010	49	35.8
01AL003	Hayden Brook near Narrows Mountain	6.48	1971–1993	23	0.177
01AL004	Narrows Mountain Brook near Narrows Mountain	3.89	1972–2010	39	0.098
01AM001	North Branch Oromocto River at Tracy	557	1963–2010	48	12.3
01AN001	Castaway Brook near Castaway	34.4	1972–81,1983–1993	21	0.874
01AN002	Salmon River at Castaway	1,050	1974–2012	39	22
01AP002	Canaan River at East Canaan	668	1926–40,1963–2011	64	13.5
01AP004	Kennebecasis River at Apohaqui	1,100	1962–2011	50	25.5
01AP006	Nerepis River at Lepreau	293	1976–1993,2009–2010	20	6.94
01AQ001	Lepreau River at Lepreau	239	1919–2011	93	7.32
01AQ002	Magaguadavic River at Elmcroft	1,420	1917–32,1943–2011	85	33.5
01AR006	Dennis Stream near Saint Stephen	115	1967–2012	46	2.78
01AR008	Bocabec River above Tide	43	1967–1979	13	1.095
01BC001	Restigouche River below Kedgwick River	3,160	1963–2010	48	68.4
01BE001	Upsalquitch River at Upsalquitch	2,270	1919–32,1944–2010	81	41.1
01BJ001	Tetagouche River near West Bathurst	363	1923–33,1952–1994	54	7.65
01BJ003	Jacquet River near Durham Centre	510	1965–2011	47	10.7
01BJ004	Eel River near Eel River Crossing	88.6	1968–1983	16	2.11
01BJ007	Restgouche River above Rafting Ground Brook	7,740	1969–2010	42	163.4
01BK004	Nepisiquit River near Pabineau Falls	2,090	1958–1974	17	45.2
01BL001	Bass River at Bass River	175	1966–1990	25	3.16
01BL002	Southwest Caraquet River at Burnsville	173	1970–2010	41	3.64
01BL003	Tracadie River at Murphy Bridge Crossing	383	1971–2011	41	8.36
01BO001	Southwest Miramichi River at Blackville	5,050	1919–32,1962–2012	65	118.1
01BO002	Renous River at McGraw Brook	611	1966–1994	29	14.7
01BO003	Barnaby River below Semiwagan River	484	1973–1994	22	9.68
01BP001	Little Southwest Miramichi River at Lyttleton	1,340	1952–2010	61	33.1
01BP002	Catamaran Brook at Repap Road Bridge	28.7	1990–2010	21	0.637
01BQ001	Northwest Miramichi River at Trout Brook	948	1962–2010	49	21.6
01BR001	Kouchibouguac River near Vautour	177	1931–32,1970–1994	27	3.74
01BS001	Coal Branch River at Beersville	166	1964–2011	47	3.69
01BU002	Petitcodiac River near Petitcodiac	391	1962–2011	50	8.07
01BU003	Turtle Creek at Turtle Creek	129	1963–2010	48	3.61
01BU004	Palmer's Creek near Dorchester	34.2	1967–1985	19	0.934
01BV005	Ratcliffe Brook below Otter Lake	29.3	1961–1971	11	0.995
01BV006	Point Wolfe River at Fundy National Park	130	1964–2011	48	5.11
01BV007	Upper Salmon River at Alma	181	1968–1978	11	7.05

(Continues)

TABLE 2 (Continued)

Station ID	Station name	DA (km^2)	Period of record	*N*	MAF (m^3/s)
01BD002	Matapedia Amont de la Rivière Assemetquagan, QC	2,770	1970–91,1995,1997	25	57.7
01DL001	Kelley River at Eight Mile Ford, NS	63.2	1970–96,1999–2011	40	1.85
01BF001	Rivière Nouvelle au Pont, QC	1,140	1965–2000	36	25.9

Note. MAF: mean annual flow.



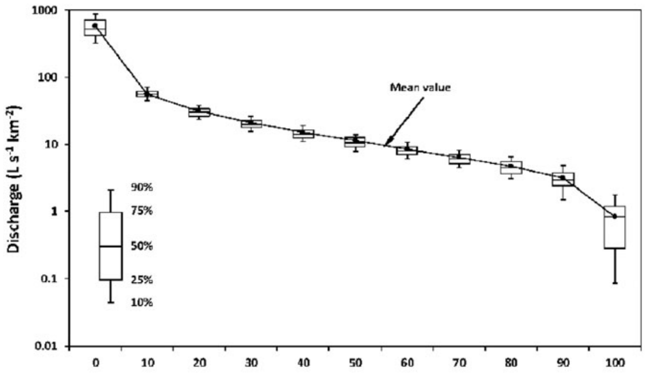
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Median	11.8	10.2	20.0	65.0	51.1	18.7	10.7	9.2	8.5	16.2	22.8	20.7
Mean	13.1	11.7	20.2	63.6	54.4	19.3	11.1	9.4	8.8	17.8	24.6	23.0
Std Dev	6.3	6.1	11.1	12.7	20.5	4.7	3.1	2.6	2.8	5.6	8.5	9.6

FIGURE 2 Normalized flow in New Brunswick, (a) box plot of mean monthly flows (L s^{-1} km^{-2}) and (b) average of daily runoff characteristics (mm) for all analysed stations (darker line represents the mean of all stations) [Colour figure can be viewed at wileyonlinelibrary.com]

low flow (Figure 4). For instance, the 50-year low flow showed at median value of 0.80 L s^{-1} km^{-2} (representing approximately a 3.5% MAF), and the variability was very high (flow ranging from 0.008 L s^{-1} km^{-2} to 3.2 L s^{-1} km^{-2}).

3.4 | Regional flow characteristics

A regression analysis between different flow metrics and drainage area was carried out. These flow metrics included the MAF, the median flow (Q_{50}), as well as high and low flows for different recurrence intervals. Results are presented in Table 3 where the MAF showed among the highest coefficient of determination (R^2) at 0.995, followed by the median flow (R^2 = 0.989). High flows also showed high R^2 with values between 0.956 and 0.996. Low return floods (i.e., Q_{F2}) showed the highest R^2 (0.996) where the 100-year floods showed the lowest R^2 (0.956). The explained variability of low flows (R^2 of regression equations) was much lower than high flows, and the coefficient of determinations were between 0.799 (T = 50 years) and 0.875 (T = 2 years; Table 3).



Median	513	55.3	30.1	19.7	14.1	10.5	7.98	6.08	4.40	2.89	0.836
Mean	577	56.2	31.5	21.2	15.2	11.3	8.48	6.37	4.65	3.14	0.838
Std Dev	245	9.45	7.10	5.47	4.16	3.24	2.58	2.02	1.58	1.23	0.673

FIGURE 3 Box plot of New Brunswick normalized flow duration curve (L s^{-1} km^{-2}), number of analysed stations n = 54

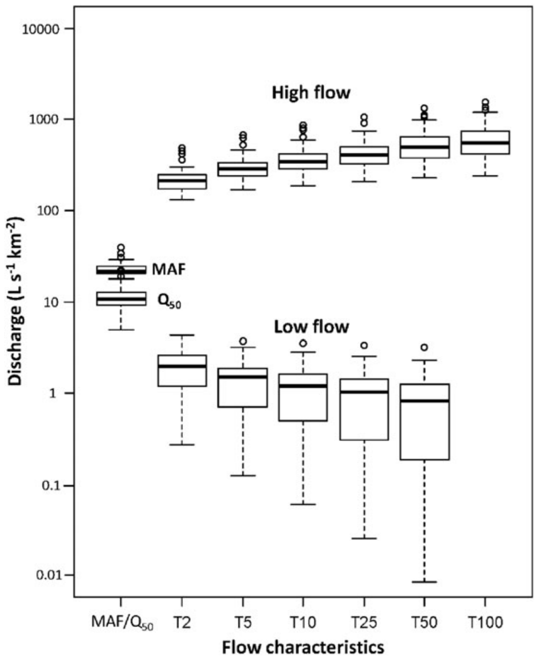


FIGURE 4 Summary flow characteristics for mean annual flow, median flow (Q_{50}) as well as high and low flows for different recurrence intervals in New Brunswick (n = 54 stations)

TABLE 3 Regional regression equations for mean, median, high, and low flows of different recurrence intervals in New Brunswick

Parameter	Equation	R^2
Mean annual flow (MAF)	$Q_{MAF} = 0.0354\ DA^{0.936}$	0.995
Median flow (Q_{50})	$Q_{50} = 0.0197\ DA^{0.923}$	0.989
High flow	$Q_{F2} = 0.2724\ DA^{0.945}$	0.996
	$Q_{F5} = 0.4511\ DA^{0.918}$	0.993
	$Q_{F10} = 0.6378\ DA^{0.894}$	0.989
	$Q_{F20} = 0.8898\ DA^{0.869}$	0.982
	$Q_{F50} = 1.3712\ DA^{0.834}$	0.970
	$Q_{F100} = 1.8944\ DA^{0.807}$	0.956
Low flow	$Q_{L2} = 0.00481\ DA^{0.920}$	0.875
	$Q_{L5} = 0.00370\ DA^{0.917}$	0.840
	$Q_{L10} = 0.00334\ DA^{0.911}$	0.824
	$Q_{L20} = 0.00302\ DA^{0.908}$	0.813
	$Q_{L50} = 0.00279\ DA^{0.899}$	0.799

High and low flows were also studied in terms of both timing and magnitude of events, which were characterized using a 30-day average flow period. The timing of summer and winter low flows are shown in Figures 5a,b. These results show that most stations (35/54 = 65%) experienced their summer low flow over a very short period, within a 10-day period, that is, between August 28 (day 240) and September 7 (day 250; Figure 5a). In terms of winter low flows, a few stations experienced their winter low flows in January (between day 10 and 20); however, most of the winter low flows occurred between February 9 (day 40) and March 11 (day 70; Figure 5b), that is, over a 30-day period. No significant relationships were observed between the magnitude and the timing of both summer and winter low flows.

Results for the high-flow analysis revealed that the timing of the spring high-flow period was generally bimodal (Figure 5c) where high flows were within two groups, that is, peak flows that occurred before and after day 115 (April 25). Results of high-flow magnitude (30-day mean) versus timing showed that earlier spring high flows tended to be lower in magnitude (Figure 5d). For instance, rivers with peak flows occurring around April 15 (day 105) were generally close to 70 L s^{-1} km^{-2} (based on the regression line) whereas peak flows occurring around May 10 (day 130) were generally 93 L s^{-1} km^{-2} (i.e., representing an increase of 23 L s^{-1} km^{-2}).

3.5 | Environmental flow assessment

The mean normalized environmental flow values were calculated for each method (Figure 6a). The bars represent the MMF where the lines represent the mean value of different environmental flow methods (methods outlined in Table 1). The MMF varied between 63.6 L s^{-1} km^{-2} (April) and 8.8 L s^{-1} km^{-2} (September) for the province of New Brunswick (see also Figure 2a for mean month flow variability). Environmental flows by different methods varied between 2.1 L s^{-1} km^{-2} in September (Q_{90} method) and 50.1 L s^{-1} km^{-2} in April (Q_{50} method). During high-flow months (April and May), it is also important to have high flows or flushing flows to maintain geomorphological characteristics of rivers.

Based on the upper and lower targets identified in Table 1, Figure 6 b shows potential range of environmental flows for New Brunswick rivers in comparison with the MMF. This figure shows that the upper environmental flow target could be in the range from 5.8 L s^{-1} km^{-2} (summer) to 10–17 L s^{-1} km^{-2} (winter and autumn) with a mean value (all months) of 10.6 L s^{-1} km^{-2}. The lower target was less variable and was generally between 3.6 L s^{-1} km^{-2} (summer) and 5–8 L s^{-1} km^{-2} (winter and spring) with a mean overall value of 5.5 L s^{-1} km^{-2}.

Based on the lower target objective, it can be calculated from Figure 6b that the water availability for off-stream use is approximately 7 L s^{-1} km^{-2} in winter (January and February) followed by spring high water is availability (57.8 L s^{-1} km^{-2} in April and 48.6 L s^{-1} km^{-2} in May). Here, the water availability for off-stream use is calculated from the difference between the MMF and the lower target environmental flow in Figure 6b (e.g., water availability for off-stream use for January = 13.1–6.1 = 7.0 L s^{-1} km^{-2}). The

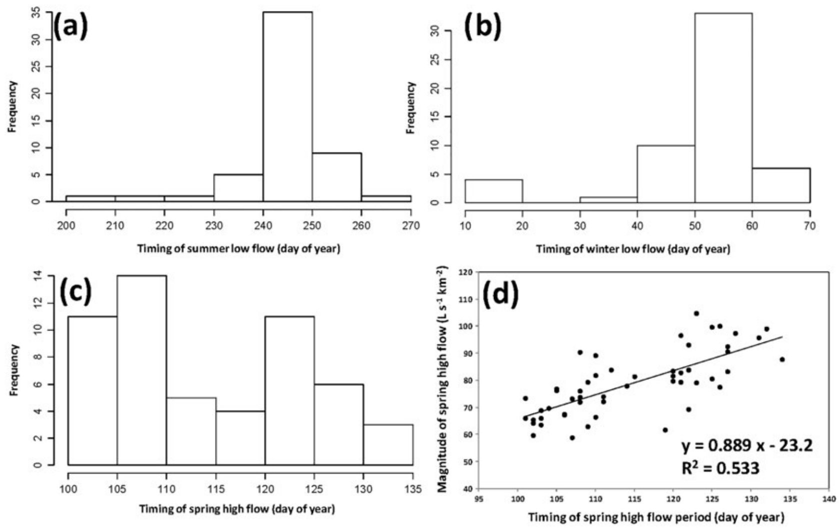
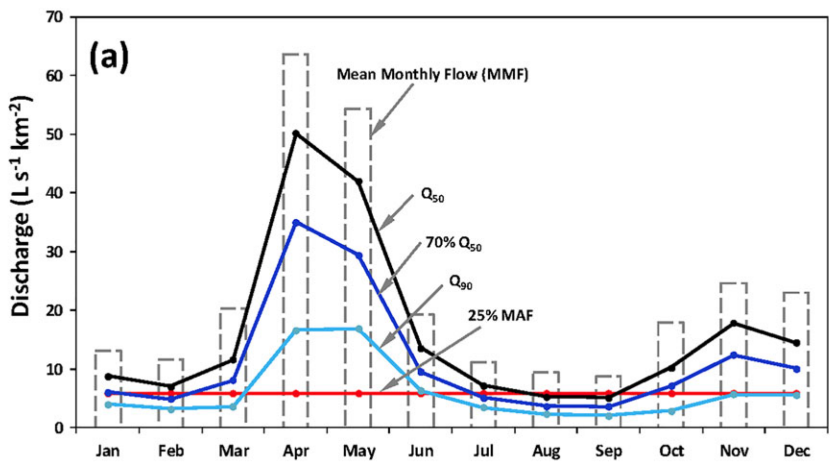
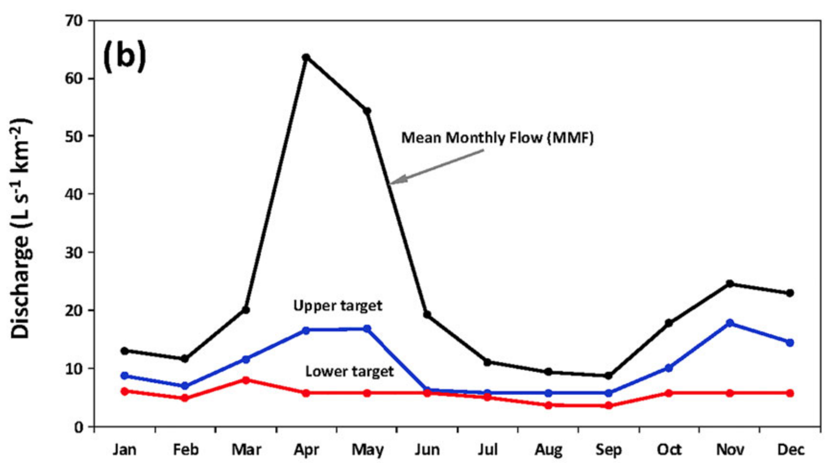


FIGURE 5 Results of (a) the timing of summer low flows (30-day average flow condition), (b) the timing of winter low flows (30-day average flow condition), (c) the timing of spring high flows (30-day average flow condition) as well as (d) the magnitude versus timing (day of year) for spring high flows for New Brunswick rivers (n = 54 stations)



MMF	13.1	11.7	20.2	63.6	54.4	19.3	11.1	9.4	8.8	17.8	24.6	23.0
25% MAF	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8
Q_{50}	8.8	7.0	11.6	50.1	42.0	13.6	7.2	5.3	5.1	10.2	17.8	14.5
70% Q_{50}	6.1	4.9	8.1	35.0	29.4	9.5	5.1	3.7	3.6	7.1	12.4	10.1
Q_{90}	4.0	3.2	3.6	16.6	16.9	6.3	3.4	2.3	2.1	2.9	5.7	5.6



MMF	13.1	11.7	20.2	63.6	54.4	19.3	11.1	9.4	8.8	17.8	24.6	23.0
Upper target	8.8	7.0	11.6	16.6	16.9	6.3	5.8	5.8	5.8	10.2	17.8	14.5
Lower target	6.1	4.9	8.1	5.8	5.8	5.8	5.1	3.7	3.6	5.8	5.8	5.8

FIGURE 6 Results of (a) mean monthly flows and various environmental flow methods and (b) potential environmental flow targets for New Brunswick [Colour figure can be viewed at wileyonlinelibrary.com]

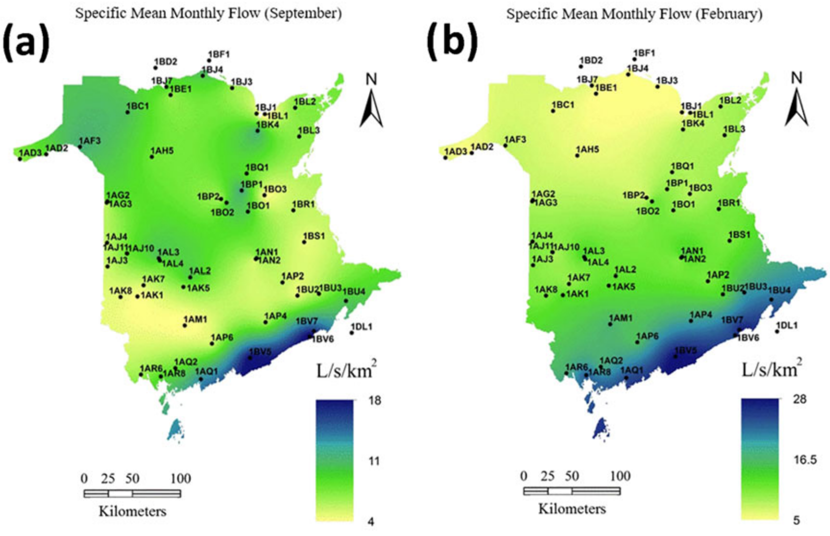


FIGURE 7 Specific mean monthly flows across the province of New Brunswick in (a) September and (b) February [Colour figure can be viewed at wileyonlinelibrary.com]

summer low-flow period showed the lowest water availability for off-stream use at 6 L s^{-1} km^{-2} (July), 5.7 L s^{-1} km^{-2} (August) and 5.2 L s^{-1} km^{-2} (September). Notably, the month of September is the month with the lowest flows and with the lowest water availability for off-stream use. If the upper target would have been used in September, then less water would be available for off-stream use (e.g., 8.8–5.8 = 3.0 L s^{-1} km^{-2}; September).

Figure 6b presents a general overview of off-stream flow potential for the whole province; however, there could be regions within the province with more (or less) water that could influence specific area in terms of off-stream water use. A closer look at river flows during the month of September (Figure 7a; i.e., the month with the lowest flows) revealed that an environmental flow target of 3.6 L s^{-1} km^{-2} (lower target; Figure 6b) would result in some area of the province where water would not be available for off-stream use whereas other parts of the province would have some water available. For instance, the northern and most southern part of the province would have water available for off-stream use (green and blue areas; 11 L s^{-1} km^{-2} to 18 L s^{-1} km^{-2} as values are higher than 3.6 L s^{-1} km^{-2}; Figure 7a). However, many rivers in the southern part of the province would not have enough water (e.g., yellow section where flows are close to 4 L s^{-1} km^{-2} and also close to the environmental flow target of 3.6 L s^{-1} km^{-2}; Figure 7 a). Similar results would be obtained for the month of August. During the winter low-flow period, it is the northern part of the province that would be water deficient (February; Figure 7b). For instance, the February environmental flows would be in the range of 4.9 L s^{-1} km^{-2} (lower target; Figure 6b), and Figure 7b shows that rivers in the northern part of the province have about the same amount of water (yellow portion of Figure 7b; 5 L s^{-1} km^{-2}). Under such condition, no water would be available for off-stream use without proper storage facilities (e.g., ponds, reservoirs, etc.).

4 | DISCUSSION AND CONCLUSION

The present study shows the importance of flow distribution within the province of New Brunswick and that water availability for off-stream use (i.e., for extraction) is not equally available at different times of year and within different parts of the province. The first part of the study looked at the annual and monthly flow characteristics. The overall MAF was calculated at 23 L s^{-1} km^{-2}, which represents the overall water availability in the province. This flow is exceeded 28% of the time on the flow duration curve. This discharge is also similar to values reported in previous studies in New Brunswick (Caissie & Robichaud, 2009). On a monthly basis, the province showed two low-flow periods (winter and summer; Figure 2a) where water availability for off-stream use can be limited. Winter and summer monthly flows were approximately half of the MAF. The northern part of the province experiences more severe winter low flows compared with the southern part of the province. The more severe winter low-flow period in the north is mainly due to the precipitation falling in the form of snow whereas the south part of the province can experience more rain in winter. The summer low-flow period (July to September) is mainly due to higher evapotranspiration rates (as monthly precipitation is evenly distributed throughout the year; Caissie & Robichaud, 2009). The high-flow period corresponds to the month of April and May. Rivers in the southern part of the province tended to have their high-flow period in April where rivers in the north tended to have their high-flow period in May. The high-flow period (or flushing flows in the case of water releases from dams) is important during this time of year to maintain river channel morphology. Flows close to the bankfull discharge or a 2-year high-flow are generally required.

The flow duration analysis revealed that the Q_{50} is approximately 50% of the MAF, and flows that are exceeded over 80% of the time on the flow duration curve (i.e., Q_{80}–Q_{100}; low flows) show a high spatial variability. As such, flow duration metrics (for percentages greater than 80%) should be used with caution, especially during low-flow months, as extremely low environmental flows could be obtained (e.g., values below 10% MAF; Figure 3). Environmental flows below 10% MAF are generally not recommended in the protection of fisheries and aquatic resources (Caissie & El-Jabi, 2003).

High and low-flows are also important when studying river flow regimes and water availability/variability. In New Brunswick, the GEV distribution was favoured for both high and low-flow analysis.

The GEV showed a very good fit in previous studies for floods when compared with the 3-parameter lognormal distribution (Aucoin, Caissie, El-Jabi, & Turkkan, 2011). In the present study, the GEV provided the best fit for low flows over the Weibull distribution (2 and 3-parameter distribution). These results (in favour of the GEV distribution for low flows) are different than previous studies where the 3-parameter Weibull distribution was used (Caissie, LeBlanc, Bourgeois, El-Jabi, & Turkkan, 2011). Regional regression equations showed the best results for the MAF, Q_{50}, and high flows. Low-flow frequency regression equations showed more variability (lower R^2). Low flows (T = 2 to 50 years) were all below the 10% MAF (median values; Figure 4).

From an environmental flow perspective, it is the low-flow months (both winter and summer) where water availability for off-stream use can become a problematic issue. Daily runoff characteristics showed that although the winter low flows are of similar magnitude to summer low flows (between 0.6 mm and 0.8 mm or between 6.9 L s^{-1} km^{-2} and 9.3 L s^{-1} km^{-2}; Figure 2b), the winter low flows experienced more variability, likely due to winter thaw periods, which occur sporadically in some rivers. Daily runoff characteristics showed that both the spring and autumn high-flow periods showed the greatest spatial/flow variability. This could have some implications on water availability especially in autumn where flows for some rivers were lower than 1 mm (or 11.6 L s^{-1} km^{-2}; Figure 2b). Water use and withdrawals during the autumn period can potentially have some impacts on migrating fish during low-flow years. For instance, Atlantic salmon generally ascend rivers to spawn in New Brunswick between mid-October to mid-November, and flow is an important factor (Chaput, 1995; Fleming, 1996; Mitchell & Cunjak, 2007). Low-flow years exacerbated by water withdrawals or flow modifications could potentially affect the accessibility of fish to spawning habitats during this period of the year.

Monthly flow targets based on the 25% MAF, Q_{50} and 70% Q_{50} methods were used to estimate environmental flows, particularly during low-flow months. These environmental flow methods provided flows in the range of 15–25% MAF, which are considered in the range of acceptable environmental flows (Caissie et al., 2015; Tennant, 1976). Some caution was pointed out when applying the 70% Q_{50} method in summer, as low environmental flows were observed (e.g., 3.7 L s^{-1} km^{-2} in August and 3.6 L s^{-1} km^{-2} in September; lower target; Figure 6b). These flows represent close to 15–16% MAF. Baseflow conditions can be an important factor for the calculation of environmental flows (Caissie et al., 2015). For instance, rivers with good baseflow conditions showed higher Q_{50} and 70% Q_{50} during low flows.

When calculating environmental flows using flow duration methods (e.g., Q_{50}), good data are required due to a higher spatial variability of flow metrics (compared to the MAF). Notably, the MAF showed slightly better regional characteristics (higher R^2), and as such, the MAF is slightly better adapted for studies of ungauged sites. Similar results were observed in the study of Caissie and El-Jabi (1995). When factoring environmental flows in the calculation of water availability for off-stream use, both winter and summer low-flow periods have reduced water availability. The period between mid-August and mid-September is the period where water is the most limited throughout the province (Figure 2b). In New Brunswick, a spatial variability in flows is also present during low-flow months (February and September; Figure 7). As such, water is not available for off-stream use in some parts of the province because river flows are generally equal to the environmental flows (yellow area; Figure 7).

In conclusion, this paper focused on flow metrics describing the natural flow regime and streamflow characteristics as well as environmental flows to determine potential water availability for off-stream use. Regardless of the method used for environmental flow assessment, the analysis should focus on protecting the river ecosystem as a whole using the best available knowledge of both biotic and abiotic conditions. As pointed out in this study, the river hydrology and corresponding flow metrics are key factors in environmental flow assessments and extremely important in the protection of rivers' ecosystems.

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