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HYDROLOGICALLY BASED ENVIRONMENTAL FLOW METHODS APPLIED TO RIVERS IN THE MARITIME PROVINCES (CANADA)†

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ABSTRACT

The demand for water withdrawal continues to increase worldwide. These water withdrawals from rivers can affect fish habitat and aquatic life. As such, environmental flow assessment methods are used in order to protect rivers against excessive water withdrawals. The concept of environmental flow relates to the quantity of water required in rivers to sustain an acceptable level of living conditions for aquatic biota at various phases of their development. For many agencies, environmental flow methods are essential in environmental impact assessments and in the protection of important fisheries resources. The present study deals with the evaluation of hydrologically based environmental flow methods within the Maritime Province of Canada. In total, six hydrologically based environmental flow methods were compared using data from 52 hydrometric stations across the region. Some methods provided adequate environmental flow protection (e.g. 25% mean annual flow and Q_{50} flow duration method); however, other methods did not provide adequate flow protection (e.g. Q_{90} flow duration method and 7Q10 and 7Q2 low-flow frequency). The 70% Q_{50} method provided adequate flow protection only under good baseflow conditions and should be applied with extreme caution. The present study shows the importance of the hydrologic flow regime, particularly as it pertains to the baseflow component, as a significant determinant in the level of instream flow protection. © 2014 Her Majesty the Queen in Right of Canada. *River Research and Applications* © 2014 John Wiley & Sons, Ltd.

KEY WORDS: environmental flow; instream flow; low flow; flow duration; baseflow

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INTRODUCTION

Studies are showing that water withdrawal demands from rivers (e.g. irrigation, hydroelectric, and drinking water) are currently increasing worldwide (Postel *et al*., 1996). Such water withdrawals can affect fish habitat and aquatic life in many ways. For example, the extraction of water can affect the ability of a stream to dilute contaminants as well as impact the thermal regime (Caissie, 2006). The scarcity of water, especially during low flows and droughts, can result in a direct conflict between the protection of aquatic resources and water use. This requires water resources and fisheries managers to rely on conflict management to resolve these issues. For many agencies, environmental flow methods are essential in environmental impact assessments and in the protection of important fisheries resources (e.g. salmonids).

The demand for water is expected to increase in the future, and it is estimated that over 50% of the total accessible runoff is already being used worldwide (Postel *et al*., 1996). To address water withdrawal issues, the concept of environmental flow (or instream flow) was developed among hydrologists, engineers, biologists, and water resource managers (Tennant, 1976; Wesche and Rechard, 1980; Annear *et al*., 2004). This concept of environmental flow 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. Environmental flow requirements can also include other instream uses such as recreational activities, navigation, and others.

Environmental flow studies have received more attention over the past decades as a result of a growing awareness for the protection of the environment as well as increased water demands. As such, several studies have been undertaken with the objectives of evaluating river flows and environmental flow requirements (Caissie and El-Jabi, 1995a; Dunbar *et al*., 1998; Tharme, 2003). The complexity of environmental flow studies is highly dependent on specific objectives, data availability, and the resources requiring protection as well as the magnitude of projects (Beecher, 1990). For example, Annear *et al*. (2004) described the environmental flow evaluation process as having five riverine components (i.e. hydrology, geomorphology, biology, water quality, and connectivity) as well as public involvement and legal/institutional components. As outlined in these studies, various methods are available in the literature to

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conduct environmental flow studies, and they have generally been classified into different categories (IEC Beak Consultants Ltd, 1985; King *et al*., 2003; Tharme, 2003; Acreman and Dunbar, 2004). In the present study, we will group environmental flow methods into four categories: (1) hydrologically based methods; (2) hydraulic methods; (3) habitat preference methods; and (4) holistic approaches. In addition, various environmental flow methods can be found in each of these categories. For instance, Tharme (2003) identified over 200 different assessment methods worldwide.

Among the different environmental flow methods, the habitat preference methods are considered to be the most complex for assessing flow requirements of aquatic species (Bovee, 1982; Stalnaker *et al*., 1995). However, this approach is also the most difficult and expensive to apply. Flows are generally selected where the habitat preference is maximized for single or multiple species. Validation of habitat preference methods is lacking, particularly for those linking predicted 'usable' habitat to population densities and river productivity (Hudson *et al*., 2003).

The hydraulic methods involve analysing some hydraulic features for a specific segment of a watercourse (Hamilton and Kosakoski, 1982). This approach assumes a direct relation between hydraulic characteristics (e.g. area or wetted perimeter) and fish habitat. For example, it is assumed that a 20% reduction in wetted perimeter will result in a 20% reduction in available habitat. Environmental flows are generally selected where habitat (i.e. represented by the wetted perimeter) decreases more rapidly as a function of discharge (Hamilton and Kosakoski, 1982).

Hydrologically based assessment methods are considered to be the simplest method, as they rely mostly on historic streamflow data and do not require any fieldwork (Wesche and Rechard, 1980). Hydrologically based methods rely on the assumption that if the streamflow and hydrologic character of a river are protected, then aquatic biota within the river ecosystem will also be protected. The concept of protecting the hydrologic character of a river is also promoted in the natural flow paradigm (Poff *et al*., 1997), which suggests that protecting the flow regime should also protect the river ecosystem. The environmental flow assessment becomes a matter of determining to what extent can we depart from the natural flow regime (through water extraction and modifications) without impacting too much the river ecosystem.

Historically, some hydrologically based instream flow methods have been applied as 'minimum flow' where everything above a given discharge is 'fair game' for water extractions. This often resulted in a 'flatlined' streamflow hydrograph, which had significant impacts on rivers (Annear *et al*., 2004). Currently, most scientists would agree that any well-applied methods (including hydrologically based methods) should be performed with the consideration of streamflow variability in order to maintain some level of ecosystem integrity (Poff *et al*., 1997). Hydrologically based methods can be used in various projects and conditions (e.g. at the preliminary stage of large assessment projects); however, they are often the only available methods for small projects. Consequently, it is important to understand and compare these environmental flow methods in order to determine their respective level of flow protection within the context of a project and the geographical setting in which they are applied.

The idea or the concept of 'benchmarking' environmental flows has been proposed in some studies (e.g. Linnansaari *et al*., 2012). The fundamental objective of benchmarking is to be able to compare results of different approaches using similar criteria [e.g. percentage of changes in streamflow from natural and percentage of mean annual flow (MAF)]. This approach can be an effective means of comparison of environmental flow methods.

Historically, within the Maritime Provinces of Canada [New Brunswick (NB), Prince Edward Island (PEI), and Nova Scotia (NS)], a derivative of the Tennant method, that is, the 25% MAF method, was used to calculate environmental flows in order to assess water withdrawal projects. The 25% MAF was not necessarily set unilaterally but was used as a guiding principle during environmental flow assessments. The concept was that when a river discharge is above the 25% MAF, then some level of water extraction or modification was permitted. However, when the river discharge was below the 25% MAF, no pumping or diversion should occur, and the river should regain its natural flow regime. As such, flows below the 25% MAF represent 'hands-off' flows. During the early 1990s, many proponents requested that this method be evaluated in order to study if other environmental flow methods could also be used within the region. A few studies were carried out (Caissie and El-Jabi 1995a, 1995b), and other environmental flow methods of neighbouring provinces or states (e.g. New England) were included in these studies. These studies demonstrated that both the 25% MAF method and the Q_{50} (median flow applied on a monthly basis) seemed to provide adequate environmental flow protection in the context of hands-off flows in the Maritime Provinces. In addition, these studies showed that the 25% MAF method was best for ungauged basins (applied using regional regression equations), as the Q_{50} method showed relatively high spatial variability and high variability as a function of drainage basin size (Caissie and El-Jabi, 1995b). This was especially true for the Q_{50} method during low-flow months (July–Sept). Nevertheless, the Q_{50} method could be applied in many cases, provided that good flow data were available. Following these studies, some provinces (e.g. NB and PEI) used 70% of Q_{50} as environmental flows; however, this approach was never fully evaluated.

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Therefore, the objectives of the present study were to compare commonly used hydrologically based methods within the Maritime Provinces, including the 70% Q_{50} method. Presently, over 20 years of additional data have been added at each hydrometric station; as such, this study will also provide an updated environmental flow analysis within the region. The specific objectives are as follows: (i) to calculate environmental flows using six hydrologically based methods; (ii) to compare results from various methods using different percentages of the MAF as benchmarks; and (iii) to provide guidance on which methods are most appropriate for environmental flow evaluations in the region.

METHODS

Hydrologically based instream flow assessment methods

In the present study, six hydrologically based environmental flow methods were used and compared. These methods were as follows: (i) the 25% MAF method; (ii) the median monthly flow (Q_{50}) method; (iii) the 70% Q_{50} method; (iv) the Q_{90} method (flow equalled 90% of the time) on a monthly basis; (v) the statistical low-flow frequency method (7Q10, 7-day low flow with a 10-year recurrence interval); and (vi) the 7Q2 method (7-day low flow with a 2-year recurrence interval).

As described above, most hydrologically based environmental flow methods are generally applied as 'hands-off flow' or 'cut-off flow' approaches. So water withdrawal occurs for flows above such cut-off flows. Flushing flows (not discussed with the present study) as well as other flow characteristics can be equally important for geomorphologic or other riverine processes (Poff *et al*., 1997).

25% of mean annual flow method. The 25% MAF method was mainly derived from the Tennant (1976) method. Notably, most fixed percentage of MAF methods are based on observations from the Tennant method (Reiser *et al*., 1989; Caissie and El-Jabi, 1995a). The Tennant method has been criticized as not being applicable outside the region that it was developed (i.e. Nebraska, Wyoming, and Montana); however, it is not the application of the Tennant method *per se* that is important, but rather underlying principles of the method. For instance, the Tennant method was developed by studying various changes in the percentage of widths (W), depths (D), and velocities (V) in relation to a reduction in flow (expressed as a percentage of the MAF). Changes in these so-called hydraulic geometry characteristics (W, D, and V) were studied for many rivers and cross sections by Tennant (1976) as well as in other studies worldwide (Park, 1977). These studies noted that the hydraulic geometry characteristics (W, D, and V) follow power functions related to the discharge, which can also be expressed as a percentage of MAF, as described by Caissie and El-Jabi (2003). Figure 1 provided an illustrative example of a power function of $W/\overline{W}$ as a function of $Q/\overline{Q}$, where $\overline{W}$ represents the river width at the MAF and $\overline{Q}$ represents the MAF. Tennant (1976) as well as others (Park, 1977; Caissie and El-Jabi, 2003) showed that the river width (as well as D and V) does not decrease rapidly, initially, with a reduction in discharge. However, there becomes a point where river width decreases more rapidly with a reduction in flow (particularly at low flows). These power functions can be used to set environmental flow targets. Tennant (1976) showed from field observations, that when flows decrease from 30% MAF to 10% MAF, the habitat conditions experienced significant changes and rivers became significantly dewatered. These observations can be applied to many rivers and regions. Another key observation of Tennant (1976) was that conditions of aquatic habitat were similar for most rivers at similar percentages of MAF.

These are important conclusions from the Tennant (1976) method, which can arguably be applied in many different hydrologic settings, meaning that when rivers are within 60–30% MAF, the reduction in river hydraulic parameters is within acceptable levels to maintain good fish habitat. At flows between 30% and 10% MAF, these same hydraulic parameters decrease more rapidly with decreasing discharge, and fish habitat is in transition from fair to degraded conditions. Under lower-flow conditions, Tennant (1976) noted that available fish habitat generally decreased rapidly to zero, hence his minimum flow recommendation of 10% MAF to sustain short-term survival habitat for aquatic biota.

The 25% MAF method operates under the same premise as the Tennant method in that aquatic habitat conditions are likely similar for most rivers at similar percentages of

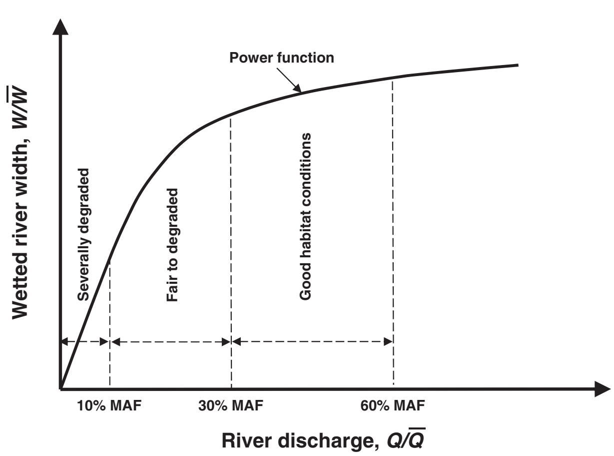

Figure 1. Illustration of the wetted river width power function in relation to the river discharge [expressed as a percentage of the mean annual flow (MAF)] and habitat conditions

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MAF. In the present study, the percentage of MAF will be used as a 'benchmark' to compare the different environmental flow methods. When environmental flow values are within 30–10% MAF, these values will be considered at fair to degraded conditions (Figure 1). Instream flows lower than 10% MAF will be considered as severely degraded habitat conditions.

The Q_{50} and the 70% Q_{50} flow duration methods. The median monthly flow (Q_{50}) method was developed for the New England region by the USFWS (1981) with the basic assumption that the median monthly flow (flow available 50% of the time each month) should be sufficient to protect aquatic habitat during different periods within the year. This approach has been applied differently for gauged and ungauged basins. When a watercourse has a drainage basin area greater than 130 km^2 and hydrometric records are available, the median monthly flow (or Q_{50}) can be calculated for each month and used for environmental flow purposes. When the preceding criterion is not met (e.g. small ungauged basins), a regional aquatic base flow (ABF) was proposed (USFWS, 1981). They recommended the August median monthly flow of $5.5 \times 10^{-3}\,m^3\,s^{-1}\,km^{-2}$ or $5.5\,L\,s^{-1}\,km^{-2}$, which was based on a regional analysis of streamflow data. Selecting the Q_{50} for the month of August was based on the fact that this is a low-flow month that also experiences high water temperatures. The ABF approach was later modified by Kulik (1990), who suggested calculating the Q_{50} for each month using daily flows rather than monthly means.

Environmental flow assessment methods based on median monthly flows (i.e. Q_{50}) suggest that the median flow should be able to sustain or protect fish populations as they have evolved to maximize their fitness to such habitat and flow conditions at different times of year. This means that months that naturally experience lower flows should have lower environmental flow values and vice versa. In the application of the Q_{50} method, one should be aware that low-flow months can occur at different times of the year (e.g. winter/summer). The Q_{50} method was evaluated within the Maritime Province, and results showed that it was comparable with the 25% MAF method during most low-flow months (Caissie and El-Jabi, 1995a, 1995b).

A variant of the Q_{50} method, which was applied within Maritime Provinces, is the 70% Q_{50}; however, this approach was never evaluated or compared with other methods. As such, it is part of the objective of the present study to evaluate the applicability of this approach and its implication as an environmental flow method.

The 90% flow duration method (Q_{90}). This method, similar to the Q_{50} method, uses daily flow duration data for every month of the year for the period of record. Based on the NGPRP (1974), flow recommendations are expressed in terms of minimum monthly flow. The recommended flow for each month is the one that equalled or exceeded 90% of the time (90th percentile or Q_{90}) in a flow duration analysis. This environmental flow method assumes that Q_{90} will provide an adequate level of fish habitat protection within some flow regime. Prior to the flow duration analysis, NGPRP (1974) recommended a statistical analysis for each month to discount extreme flow events (low-flow and high-flow months). This method was mainly developed and applied for the prairie region; it has not been applied within the Maritime Provinces. Nevertheless, it will be applied in the present study for comparative purposes only. As in previous studies (Caissie and El-Jabi, 1995a), the complete time series will be used in the calculation of the Q_{90}.

Statistical low-flow frequency methods (7Q10 and 7Q2). These methods involved a statistical low-flow frequency analysis of minimum daily flows during a given sample period, for example, 7 days. The 7Q10 corresponds to the minimum flow established over an average of seven consecutive days having a 10-year recurrence interval (Chiang and Johnson, 1976). The 7-day minimum low flows are calculated for each year, and these values are then fitted to a low-flow distribution function. The Type III extreme-value distribution function (or three-parameter Weibull) is often selected to assess such low flows (Kite, 1978). The 7Q10 is not an environmental flow method *per se* (Annear *et al.*, 2004); however, it has been applied when stream water quality problems have been an issue and sometimes identified with other environmental flow methods (Reiser *et al.*, 1989). This approach is not applied within the Maritime Provinces. In the case of the 7Q2 method, the 7-day minimum flows are calculated for a 2-year recurrence interval. This approach has been applied as an environmental flow method in the neighbouring province of Quebec (Belzile *et al.*, 1997). Also, a very closely related statistics of this method, that is, the mean annual 7-day low flow (MALF) has been applied in New Zealand rivers (Snelder *et al.*, 2011). Results of the application of the 7Q10 method have produced very low instream flow values compared with other instream flow methods (Caissie and El-Jabi, 1995a). However, it was not the case for the 7Q2 method applied in Quebec. In fact, for larger river systems, the 7Q2 can provide flows that are in the range of other environmental flow methods. As such, this approach will be evaluated within the Maritime Provinces to see how it compares with other methods.

RESULTS

Within the Maritime Provinces, 52 hydrometric stations were analysed; 24 stations in NB, 23 stations in NS, and five stations in PEI. The distribution of these stations within the

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Maritime Provinces is shown in Figure 2. Table 1 presents the river name, station number, the province, the MAF, the drainage area, and other relevant flow statistics. The drainage area varied between 5.59 km^2 (Emerald Brook, PEI) and 14 730 km^2 (Saint John River, NB) whereas the MAF varied between 0.093 and 282 $m^3 s^{-1}$ for these same rivers. The runoff or MAF per drainage area for these rivers varied between 13.5 and 47.5 $L s^{-1} km^{-2}$. The median flow (Q_{50}), calculated on an annual basis, was generally close to half of the MAF (Table 1). NS experienced higher runoff with a mean value of 32.5 $L s^{-1} km^{-2}$ whereas PEI and NB showed similar mean values, around 20 $L s^{-1} km^{-2}$. From the flow duration analysis, the ratio of Q_{90} over Q_{50} was calculated as it can be an indicator of baseflow conditions (i.e. from groundwater contribution or other basin storage such as lakes or swamps). For instance, a high value of Q_{90}/Q_{50} generally means a good baseflow component within the river system and a correspondingly more stable flow regime (Burn *et al.*, 2008). This is also represented by a flatter flow duration curve. This analysis is important as baseflow conditions may have an influence on environmental flows. Figure 3a shows the ratio (Q_{90}/Q_{50}) as a function of drainage for the studied rivers in the Maritime Provinces. This figure shows that all rivers in PEI have values higher than 0.3, as this province is known to have important groundwater flow. In NB, values were generally higher than 0.2; however, a significant number of rivers showed values higher than 0.3, particularly those rivers that are larger than 1000 km^2. NS rivers showed the lowest Q_{90}/Q_{50} ratios with values generally lower than 0.3, with many rivers having values lower than 0.2 (16 of 23 stations or 70% of the stations). From Figure 3a, two contrasting sites were selected (station 1CB4, PEI, and 1EG2, NS; see Figure 2 for location) to show their respective flow duration curve. Figure 3b shows the flow duration analysis of these two contrasting sites. Station 1CB4 is the Wilmot River (PEI) with a drainage area of 45.4 km^2 and a Q_{90}/Q_{50} of 0.55 (Figure 3a). Station 1EG2 is the Gold River (NS) with a drainage area of 370 km^2 and a Q_{90}/Q_{50} of 0.08. Figure 3b shows that, indeed, the flow duration of the Wilmot River (1CB4, PEI) is much flatter and experiencing less severe low flows compared with that of the Gold River (1EG2, NS). Flow statistics in Table 1 and Figure 3 will be used to contrast flow regimes and their relative importance in the overall environmental flow assessment.

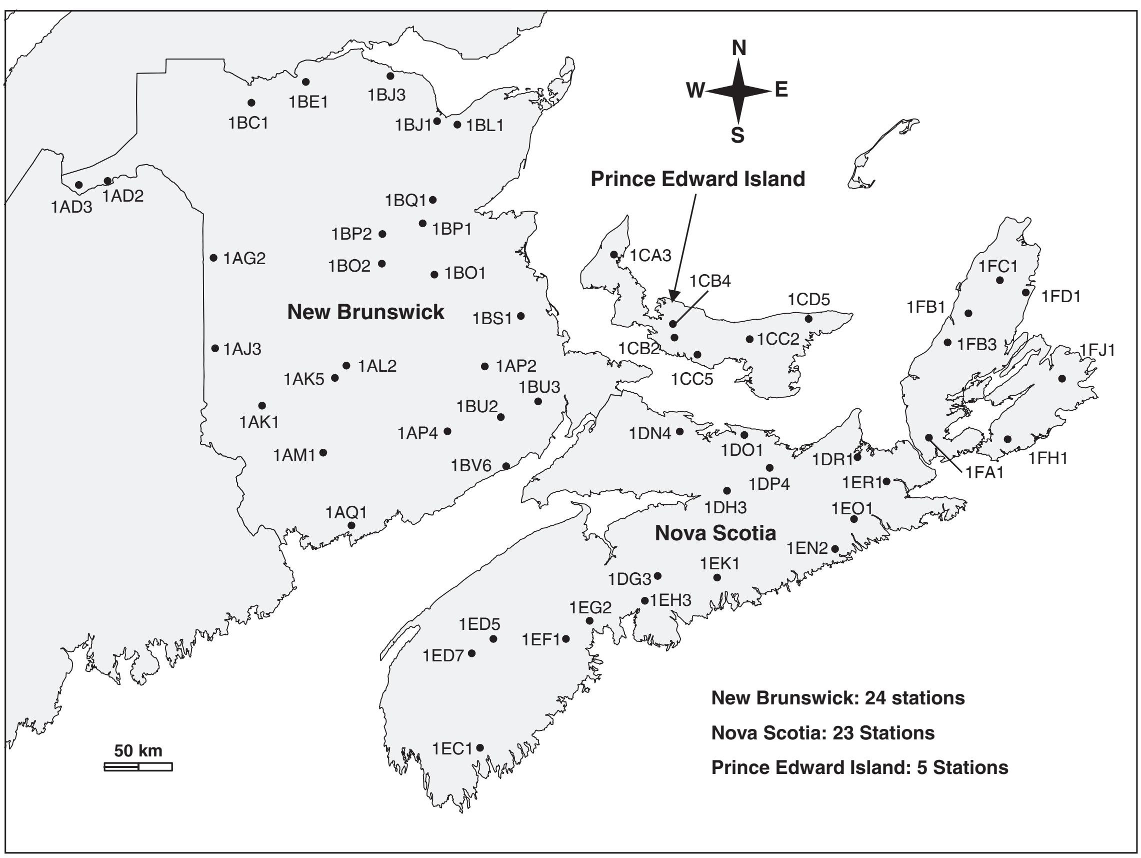

Figure 2. Location of the 52 hydrometric stations studied within the Maritime Provinces. Station names in figure have been shortened, 01AD002 = 1AD2 (see Table 1 for details)

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Table I. Studied hydrometric stations, drainage area, and streamflow statistics within the Maritime Provinces

River name	Station	Province	MAF ($m^3 s^{-1}$)	A (km^2)	MAF/A[a]	Q_{50} ($m^3 s^{-1}$)	Q_{50}/A[a]
Saint John River	01AD002	NB	282.000	14 730.00	19.1	140.000	9.5
St. Francis River	01AD003	NB	25.700	1350.00	19.0	12.800	9.5
Limestone Stream	01AG002	NB	3.640	199.00	18.3	1.820	9.1
Meduxnekeag River	01AJ003	NB	25.200	1210.00	20.8	11.200	9.3
Shogomoc Stream	01AK001	NB	5.100	234.00	21.8	2.600	11.1
Middle Branch Nashwaaksis	01AK005	NB	0.536	27.00	19.9	0.234	8.7
Nashwaak River	01AL002	NB	35.800	1450.00	24.7	18.400	12.7
North Branch Oromocto R.	01AM001	NB	12.300	556.00	22.1	5.950	10.7
Canaan River	01AP002	NB	13.500	668.00	20.2	5.800	8.7
Kennebecasis River	01AP004	NB	25.300	1100.00	23.0	13.900	12.6
Lepreau River	01AQ001	NB	7.380	238.00	31.0	4.390	18.4
Restigouche River	01BC001	NB	68.400	3160.00	21.6	34.300	10.9
Upsalquitch River	01BE001	NB	41.400	2270.00	18.2	19.100	8.4
Tetagouche River	01BJ001	NB	7.760	362.00	21.4	2.970	8.2
Jacquet River	01BJ003	NB	10.600	510.00	20.8	4.000	7.8
Bass River	01BL001	NB	3.160	175.00	18.1	0.850	4.9
Southwest Miramichi River	01BO001	NB	119.000	5050.00	23.5	63.800	12.6
Renous River	01BO002	NB	14.700	611.00	24.0	6.910	11.3
Little Southwest Miramichi R.	01BP001	NB	33.100	1340.00	24.7	17.400	13.0
Northwest Miramichi River	01BQ001	NB	21.600	947.00	22.8	10.100	10.7
Coal Branch River	01BS001	NB	3.670	166.00	22.1	1.540	9.3
Petitcodiac River	01BU002	NB	8.030	391.00	20.5	3.490	8.9
Turtle Creek	01BU003	NB	3.610	129.00	28.0	1.730	13.4
Point Wolfe River	01BV006	NB	5.090	130.00	39.2	2.860	22.0
Beaverbank River	01DG003	NS	3.010	96.90	31.1	1.700	17.5
Fraser Brook	01DH003	NS	0.240	10.10	23.7	0.130	12.9
Wallace River	01DN004	NS	8.890	298.00	29.8	5.300	17.8
River John	01DO001	NS	6.590	249.00	26.5	3.110	12.5
Middle River of Pictou	01DP004	NS	2.640	92.20	28.6	1.420	15.4
South River	01DR001	NS	4.980	177.00	28.1	2.740	15.5
Roseway River	01EC001	NS	16.900	495.00	34.1	13.100	26.5
Mersey River (site 1)	01ED005	NS	20.900	723.00	28.9	16.700	23.1
Mersey River (site 2)	01ED007	NS	8.530	295.00	28.9	6.110	20.7
LaHave River	01EF001	NS	35.600	1250.00	28.5	24.100	19.3
Gold River	01EG002	NS	11.100	370.00	29.9	7.380	19.9
East River	01EH003	NS	0.776	26.90	28.8	0.527	19.6
Musquodoboit	01EK001	NS	20.800	650.00	32.0	12.400	19.1
Liscomb	01EN002	NS	15.900	389.00	40.8	9.800	25.2
St. Marys River	01EO001	NS	43.400	1350.00	32.1	26.400	19.6
Clam Harbour River	01ER001	NS	1.610	45.10	35.8	0.873	19.4
River Inhabitants	01FA001	NS	6.960	193.00	36.1	3.980	20.6
Northeast Margaree	01FB001	NS	17.400	368.00	47.3	10.700	29.1
Southwest Margaree River	01FB003	NS	12.800	357.00	35.9	11.600	32.5
Cheticamp River	01FC001	NS	2.560	190.00	13.5	1.080	5.7
Wreck Cove Brook	01FD001	NS	1.470	31.00	47.5	0.767	24.7
Grand River	01FH001	NS	4.500	120.00	37.5	3.600	30.0
Salmon River	01FJ001	NS	8.270	199.00	41.6	4.360	21.9
Carruthers Brook	01CA003	PEI	0.954	46.80	20.4	0.490	10.5
Wilmot River	01CB004	PEI	0.930	45.40	20.5	0.637	14.0
Emerald Brook	01CB006	PEI	0.093	5.59	16.6	0.053	9.5
Winter River	01CC002	PEI	0.663	37.50	17.7	0.426	11.4
Morell River	01CD003	PEI	3.580	147.00	24.3	2.540	17.3
Mean value[a]							
NB					22.7		10.9
NS					32.5		20.4
PEI					19.9		12.5

[a]Expressed in litres per second per square kilometre.

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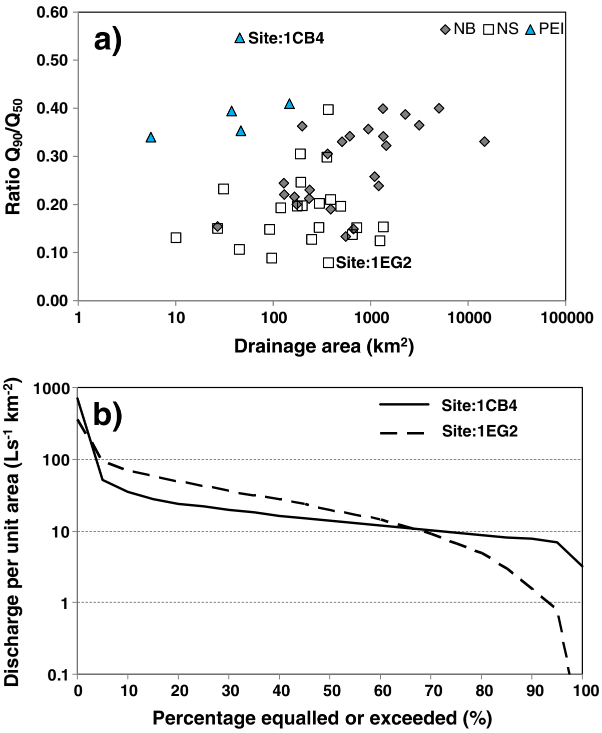

Figure 3. Baseflow index and flow duration analysis of selected sites; (a) baseflow index (Q_{90}/Q_{50}) as a function of drainage area, (b) comparison of flow duration curve of selected sites (1CB4 and 1EG2). NB, New Brunswick, NS, Nova Scotia; PEI, Prince Edward Island. This figure is available in colour online at wileyonlinelibrary.com/journal/rra

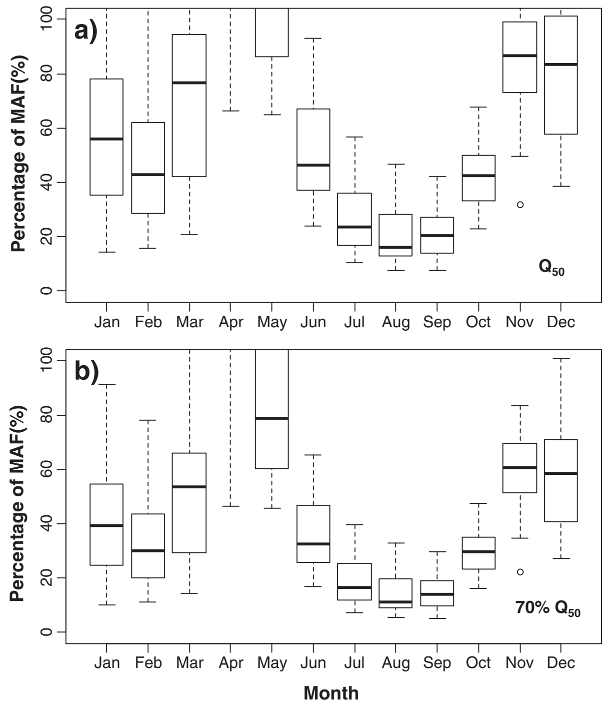

Figure 4. Box plot of results for (a) the Q_{50} method and (b) the 70% Q_{50} methods expressed as a percentage of the mean annual flow (MAF). Note: Only values below 100% MAF are presented for clarity during low-flow months

Results of the application of the Q_{50} and the 70% Q_{50} methods are presented in Figure 4. These two methods are generally applied on a monthly basis. This figure shows the environmental flows for each method expressed as a percentage of the MAF. Table 2 also presents the 25 percentile, median, and the 75 percentile calculated in Figure 4. An analysis of variance was also carried out to determine significant differences among months and methods ($p < 0.05$). During the winter months, the application of the Q_{50} method shows environmental flows as low as 14–20% MAF for some stations (e.g. Bass River and Jacquet River, NB); however, most stations showed values greater than 30% MAF (Figure 4a). Median values by month were generally between 40% and 180% MAF (Table 2). No significant differences were observed among winter months (January–March). The Q_{50} method showed among the lowest values during the summer, in particular during July–September (Figure 4a). Median values were 23.6% (July), 16.1% (August), and 20.2% MAF (September; Table 2). No significant differences were noted between these months; however, summer values were significantly lower than winter values. Some stations experienced Q_{50} as low as 8–10% MAF (mainly in NB and NS). Autumn flows (Q_{50}) were higher with median values greater than 40% MAF. Figure 4b presents the results of the 70% Q_{50} method, the modified Q_{50} method. Percentages of MAF in winter were slightly lower than the Q_{50} method and reached values of close to 10% MAF, however, only for a few stations. Median values were generally higher than 30% MAF in winter (Table 2) and not significantly different among months. Similar to the previous methods, the summer period was more problematic (July–September) with median values of 16.5% (July), 11.3% (August), and 14.2% MAF (September; Table 2). These values are significantly lower than the Q_{50} method ($p < 0.05$). Some stations showed environmental flows that were as low as 5% MAF, and many stations showed values lower than 10% MAF (mainly in August).

Results of the Q_{90} method are presented in Figure 5. This method was also applied on a monthly basis. Winter median values were generally higher than 15% MAF; however, a few stations showed values as low as 5–9% MAF. These stations were mainly NB rivers (Tetagouche, Jacquet, and Bass Rivers). Summer environmental flows were also low by this method, in particular during August and September. Summer median flows were 9.0% (July), 5.8% (August), and 6.5% MAF (September; Table 2). Many stations showed values lower than the 10% MAF. No significant differences were observed among summer months; however, summer values were significantly lower than winter values (with the exception of February and July).

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Table II. Median instream flow values by different methods expressed as a percentage of the mean annual flow (% MAF)

Method		Annual	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	25%		35.5	28.8	42.7	154.3	86.5	37.2	17.1	13.0	14.2	33.4	73.5	58.0
Q_{50}	Median		56.2	42.9	76.5	178.2	112.6	46.3	23.6	16.1	20.2	42.5	86.6	83.4
	75%		77.0	61.8	94.2	223.1	181.0	66.9	35.7	28.2	26.9	50.0	99.2	100.1
	25%		24.8	20.1	29.9	108.0	60.6	26.0	12.0	9.1	10.0	23.4	51.4	40.6
70% of Q_{50}	Median		39.3	30.0	53.5	124.7	78.8	32.4	16.5	11.3	14.2	29.7	60.6	58.4
	75%		53.9	43.3	65.9	156.2	126.7	46.8	25.0	19.7	18.8	35.0	69.4	70.1
	25%		17.7	12.8	14.6	57.3	35.5	14.4	6.4	3.2	3.2	7.0	21.6	23.7
Q_{90}	Median		20.9	16.4	20.4	75.6	48.7	20.5	9.0	5.8	6.5	10.8	26.2	29.1
	75%		28.5	23.0	29.1	93.9	71.7	33.0	19.5	13.3	11.9	15.5	31.7	39.6
	25%	1.4												
7Q10	Median	3.6												
	75%	8.3												
	25%	5.0												
7Q2	Median	8.2												
	75%	12.9												

Results of the low-flow frequency approach are presented in Figure 6 for both the 7Q10 and 7Q2. The low-flow frequency calculations were carried out using yearly data. Median values were 3.6% MAF (7Q10) and 8.2% MAF (7Q2) (Table 2) and significantly different ($p = 0.024$). The 7Q10 approach showed values of as low as 2% MAF, particularly in NB (five stations) and NS (14 stations). Notably, four of these stations in NS (Beaverbank River, Fraser Brook, East River, and Clam Harbour River) experienced minimum flows of $0\ m^3\ s^{-1}$; therefore, experiencing intermittent flows during some years. The 7Q10 and 7Q2 approaches showed many stations that experienced values less than 10% MAF. As such, the 7Q10 and 7Q2 methods showed values (percentage of MAF) that were significantly lower than the Q_{50} and 70% Q_{50} methods (but not different than the Q_{90} method).

Figure 7 provides a summary of the number of stations that showed environmental flows less than 10% MAF. For methods that were applied on a monthly basis, the month of August showed the lowest environmental flows. Therefore, this month was used for comparative purposes. For example, five stations of a total of 52 stations (9.6%) showed environmental flows less than 10% MAF for the Q_{50} method. For the 70% Q_{50} method, the number of stations with environmental flows less than 10% MAF increased to 20 stations (38%). In the case of the Q_{90} approach, 35 stations (67%) showed environmental flows less than 10% MAF whereas the 7Q10 method showed 43 stations (83%). The 7Q2 method showed similar results to the Q_{90} method with 34 stations (65%) having environmental flows less than 10% MAF.

DISCUSSION

The present study focused on applying and comparing hydrologically based environmental flow methods within

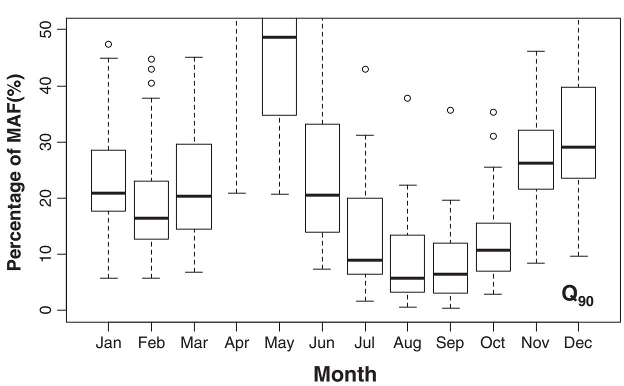

Figure 5. Box plot of results for the Q_{90} method expressed as a percentage of the mean annual flow (MAF). Note: Only values below 50% MAF are presented for clarity during low-flow months

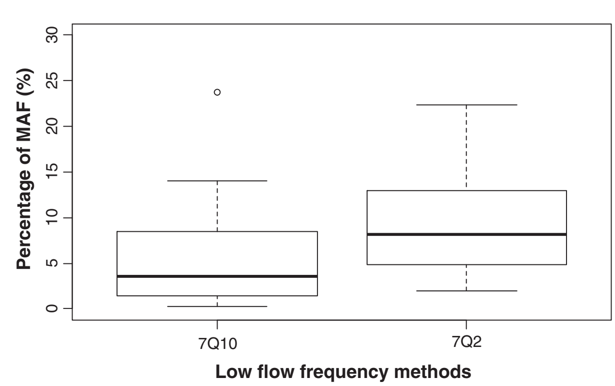

Figure 6. Box plot of results for the 7Q10 and 7Q2 methods expressed as a percentage of the mean annual flow (MAF). Note: Only values below 30% MAF are presented for clarity during low-flow months

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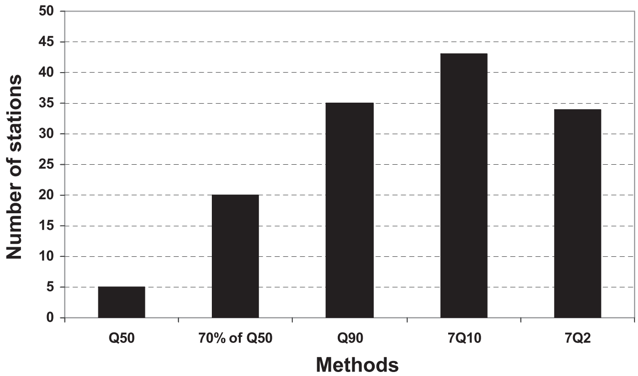

Figure 7. Results of the number of stations by the different methods that calculated environmental flows below the 10% mean annual flow

the Maritime Provinces (Canada). Hydrologically based methods remain among the most widely used methods worldwide (Reiser *et al*., 1989; Dunbar *et al*., 1998; Tharme, 2003; Acreman and Dunbar, 2004). These methods are still widely used because of their simplicity and because they are sometimes the only methods available for some projects (i.e. small projects). Nevertheless, hydrologically based methods are also used in larger projects to bring some context and focus of more complex approaches (e.g. habitat modelling), particularly when comparing approaches. As such, they play a key role in the environmental flow assessments at all levels, and they should be thoroughly studied for their effective application.

When conducting environmental flow assessments, there is a growing need for a comparison of methods, that is, some ways of comparing the level of 'habitat protection' of various methods. In the present study, specific flows (based on a percentage of the MAF) from the Tennant method (i.e. 30% MAF and 10% MAF) were used as benchmark flows to compare the level of protection among methods. The assumption is that flows higher than 30% MAF generally represent very good to excellent habitat conditions (Figure 1). Flows between 30% and 10% MAF represent fair to degraded habitat conditions, whereas flows below the 10% MAF represent severely degraded habitat conditions. The percentage of MAF is a good benchmark flow statistics to compare environmental flow methods. The MAF is also a good indicator of the water availability (volume of water for fish habitat vs volume of water for offstream use) as well as being related to hydraulic geometry characteristics, for example, depth, velocity, and river width (Tennant, 1976; Park, 1977; Caissie and El-Jabi, 2003; Figure 1).

Another important issue in the application and comparison of environmental flow methods is the scientific defensibility or validity of methods. Based on current knowledge, hydrologically based methods are as good as any other environmental flow approaches (e.g. hydraulic rating and habitat preference methods). In fact, none of the environmental flow methods have been developed on the basis of tested relationships between the flow regime alteration and ecological responses. As such, many scientists recognize that there are currently no truly scientifically defensible environmental flow assessment methods, as methods are based on common sense rather than scientific proof and validation (Castleberry *et al*., 1996; Acreman and Dunbar, 2004). This means that hydrologically based methods are as credible as any other methods, provided that they are applied correctly using the best available information and good judgement.

In the present study, results of the Q_{50} method showed environmental flows that were generally between 13% and 28% MAF during summer low-flow months (August and September; Figure 4a and Table 2). These flows represented fair to degraded habitat conditions based on benchmark flows. Winter flows were generally higher than 30% MAF; therefore, the Q_{50} in winter represented good habitat conditions. The Q_{50} method provided flows that were within expectable environmental flows in winter and summer; however, good flow duration data are required for the application of this method. This method requires good hydrometric data because Q_{50} values on a monthly basis can show relatively high spatial variability and Q_{50} can also be a function of the basin size (Caissie and El-Jabi, 1995a, 1995b). In fact, these studies showed that larger rivers tended to have higher Q_{50} during the summer months compared with small streams. They also showed that, because of the spatial and basin size variability, the flow duration methods were more difficult to regionalize than methods based on the MAF. Consequently, the MAF provided better flow estimates for ungauged basins than the flow duration methods. The MAF estimates also show less variability as a function of sample size (e.g. years of record) compared with the flow duration approach (Caissie *et al*., 2007).

Results from the 70% Q_{50} method showed expectable environmental flows during winter months (generally higher than 20–30% MAF, representing good habitat conditions; Figure 4b and Table 2); however, summer values were between 9% and 20% MAF. At flows approaching or below the 10% MAF, some caution should be exercised when applying this method, as summer environmental flows may be too low. A closer look at the results from this method showed that baseflow conditions (using the Q_{90}/Q_{50} baseflow index) have an influence on environmental flows (Figure 8). For a high baseflow index (>0.25), the 70% Q_{50} method provided flows that were generally higher than the 10% MAF. All PEI rivers and many rivers in NB showed values greater than 15% MAF. Rivers in NB that showed values lower than 10% MAF were mainly small basins, generally less than 600 km^2, with a corresponding

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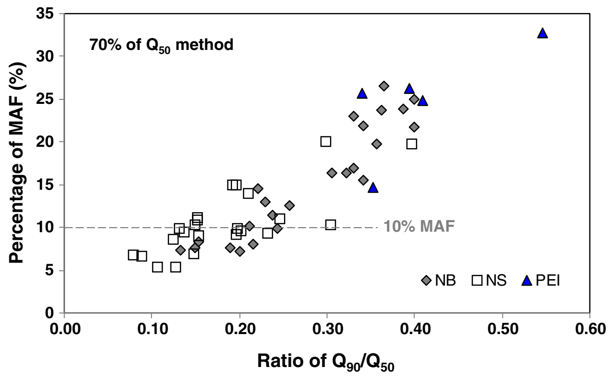

Figure 8. Results of the percentage of mean annual flow (MAF) by the 70% Q_{50} as a function of the baseflow by provinces. This figure is available in colour online at wileyonlinelibrary.com/journal/rra

baseflow index of less than 0.25. Most rivers in NS showed low environmental flows by the 70% Q_{50} method, which is reflective of the fact that these rivers have a low baseflow index. In fact, 18 of 23 rivers (78%) showed values lower than 12% MAF, and most NS rivers showed Q_{90}/Q_{50} of less than 0.25 (Figure 8). These results show that the 70% Q_{50} approach has limited applications, mainly to large rivers or small rivers with a good baseflow component; otherwise, very low environmental flows (<10% MAF) are expected.

The Q_{90} environmental flow method produced very low environmental flows within the study region (between 3% and 13% MAF during the low-flow months of August and September; Figure 5 and Table 2). With such low environmental flows, it can be argued that this method does not provide adequate environmental flow protection in the study area. Similar conclusions were reached by Caissie and El-Jabi (1995a). The Q_{90} (or sometimes Q_{95}) calculated from a flow duration analysis often represents extreme low flows in rivers. Nevertheless, these flow values have been reported as environmental flow targets in some studies (NGPRP, 1974; Acreman and Dunbar, 2004; Acreman *et al*., 2008). They should be applied with caution as rivers could be significantly dewatered when using this approach. Such low flows may also result in loss of growth potential of some aquatic species (Armstrong and Nislow, 2012). Results of the present study showed that this method will most likely be applicable only to rivers having a significant baseflow component. For example, PEI rivers do represent rivers with such a high baseflow component. In these rivers, the Q_{90} represented between 18% and 35% MAF. The 35% MAF value was from the Wilmot River (PEI), which showed the highest baseflow contribution among all Maritime Province rivers (Figure 3a; $Q_{90}/Q_{50} = 0.55$). For such rivers, it can be shown that even under some of the lowest-flow conditions, good habitat conditions would be maintained by baseflow.

Results of the 7Q10 method generally showed environmental flows between 1% and 8% MAF (Figure 6 and Table 2). This method provided flows even lower than the Q_{90} approach and should not be used within the study area as an environmental flow method. In fact, most studies that have described this method had similar conclusions (Reiser *et al*., 1989; Annear *et al*., 2004). Notably, this approach was derived to address water quality dilution thresholds and thus provides little protection for river ecosystems.

The 7Q2 method, which has been applied in the province of Quebec (Belzile *et al*., 1997), generally resulted in very low environmental flows (5–13% MAF) within the Maritime Provinces (similar to the 7Q10, with a few exceptions). One such exception was the Wilmot River (PEI), which showed a 7Q2 of 24% MAF (site described earlier). This river experienced relatively ‘high’ low flows. This was also the case for some large Quebec rivers, which showed values of 7Q2 in the range of 20–40% MAF (Belzile *et al*., 1997; Caissie and El-Jabi, 2003). Some studies have reported the MALF in their environmental flow study (Snelder *et al*., 2011). It should be pointed out that both the 7Q2 and MALF are very closely related flow statistics. This is because the 2-year recurrence interval of the 7Q2 has a probability of 0.5, thus representing the central tendency (mean) of the distribution function. The MALF is obtained by calculating the mean annual minimum flows rather than fitting these values to a low-flow frequency distribution. In fact, for Maritime Province rivers, the 7Q2 values were approximately 94% of the MALF (i.e. $7Q2 = 0.94 \times MALF$; $R^2 = 0.99$; $p < 0.001$). Nevertheless, MALF values, as described by Snelder *et al*. (2011), represent in most cases very low environmental flows.

The strength of hydrologically based methods lies in both their simplicity of application and their focus on protecting the hydrologic character of rivers as a whole. In the protection of the hydrologic character of the river, it is equally important to protect flow variability in order to maintain some ecological integrity (Poff *et al*., 1997). Protecting flow variability would also include flushing flows, not described in the present study, but also important in environment flow assessments. It should be noted that not all environmental flow methods focus on the river *per se*. This is the case for the habitat preference methods, which generally focus on specific or multiple fish species (mainly highly prized fish). Such a focus on specific or multiple fish species can, in some cases, result in a significant ‘philosophical shift’ in environmental flow assessments. As such, the focus on protecting a specific fish species can be in some cases detrimental to the river ecosystem as a whole. For example, this condition can occur when habitat modelling is carried out in a large river using juvenile fish as the targeted species (low depth and velocity requirements). It can be shown under these conditions that maximizing the habitat preference for

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juvenile fishes can result in very low environmental flows, which could potentially be harmful to the river as a whole. Hydrologically based methods can be very useful in these situations to help bring a riverine context to the environmental flow process. Notably, hydrologically based methods should not be viewed as only useful in the preliminarily analyses of large projects but also as an approach that can bring context within large projects to prevent unduly low environmental flows.

In conclusion, regardless of the method used for environmental flow assessment, the analysis should always be carried out with the consideration of as many riverine components as possible (Annear *et al*., 2004). In many cases, factors unrelated to flow could have an impact on important fisheries and fish populations (e.g. water temperature and sedimentation) and should be considered. Therefore, the assessment 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 the present study, the river hydrology and corresponding baseflow conditions are key factors in environmental flow assessments and extremely important in the protection of fish habitat.

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