Setting Critical Environmental Flow Thresholds for Drought Response: Coldwater River Case Study

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1. Introduction

The purposes of this document are to: (1) identify biological concepts that are relevant for setting critical environmental flow thresholds; and (2) describe methods for setting such thresholds as required for drought response planning. The procedure described herein requires a historic hydrometric record from across a number of years. The initial statistically-based threshold can be adjusted based on experience and may be revised in consideration of other factors including temperature and the environmental values within the reaches of interest.

2. Two related but distinct terminologies: the critical period concept versus the critical environmental flow threshold

2.1 The critical period concept

When setting the environmental flow needs, it is important to understand the critical period concept as a habitat bottle neck in fish population limitations. The critical period is a phase of high density-dependent mortality through territorial defence (Allen 1969, Grant and Kramer 1990) during which the strength of a year class is determined (May 1974). The critical period has three components including a species specific life-stage, a time period, and a mechanism for mortality. Flow-related mortality mechanisms can occur in summer or winter (Nickelson et al. 1992a); thus all low flow seasons should be considered as candidate bottlenecks (**Figure 1**).

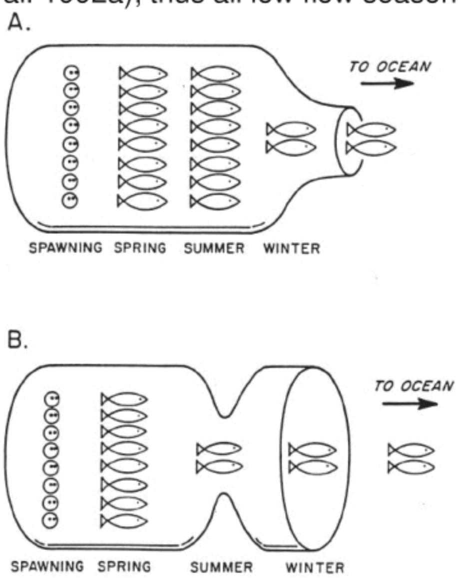

Figure 1. **Habitat bottlenecks occurring during (A) the winter, and (B) the summer.** Reproduced from (Nickelson et al. 1992b).

In California streams that support juvenile salmon and steelhead, the critical period includes the summer season when living space and food resources for juvenile age classes are limited by streamflow and water temperatures (Burns 1972). Similarly, in Wyoming streams that support juvenile and adult salmonids, stream flow levels during the six week period between August 1 and September 15 determine the habitat space and thus stream carrying capacity (Binns 1982). The terms "summer critical period streamflow is used when the critical period concept is applied to environmental flow needs assessments, it is important to also consider all possible mortality mechanisms such as streamflow, food limitations, temperature and predation when identifying the limiting factors that determine age- or size-specific population dynamics. If such processes are important, additional considerations are required beyond those described herein. Inadequate stream discharge during the critical period streamflow have been related to diminished numbers and biomass of salmonids supported by a given stream (Binns 1982, Binns and Eiserman 1979). Streams with persistent deficient CPSF support poor fish abundance.

2.2 Critical Environmental Flow Threshold

During times of water scarcity, the Water Sustainability Act (WSA) provides legislative provisions to prevent irreversible harm to the aquatic ecosystem streams by protecting the remaining flow through restricting water users. In the WSA, the critical environmental flow threshold is defined as the flow level below which significant harm to the aquatic ecosystem is likely to occur (see the glossary for exact wording). Thus, it is a flow threshold within a specific critical period below which accelerated mortality rates are expected to cause an irreversible decline in the population of concern.

3. Methods for setting critical environmental flow thresholds

3.1 Limiting factors and the fish periodicity table

The methods in this step are as follows:

Construct a fish periodicity chart for each species of concern. Review the available information on target fish populations and flag any life stages that are known to limit production at the population level. Select a hydrologic parameter that can be used to assess flows for each species-specific life stage. For example, in flow-regulated Mission Creek, specific hydraulic constraints for rainbow trout production occur during spring adult migration, spring spawning, and summer juvenile rearing (Wightman and Taylor 1978). The limiting factors include both flow quantities and flow ramping practices (Wightman and Taylor 1978). In Mission Creek, flow-related constraints for kokanee occur during the fall adult migration, spawning, and winter incubation (Wightman and Sebastian 1979).

Ideally, a single hydrologic statistic will be selecting for evaluating the specific hydrological process associated with each limiting factor. For example, to determine the degree to which flow quantity limits rainbow trout production during the migration and spawning period, an appropriate statistic could be the number of days during the period with flows above the target flow threshold (Table 1). To identify potential population impacts from adult fish stranding resulting from dam operation in Mission Creek, a second statistic could be the maximum down-ramping rate during the receding limb of the freshet (Table 1). This statistic can be calculated from the daily water level readings from the Water Survey of Canada gauging station of interest. To assess the degree to which current or proposed water use will limit production during the summer juvenile rearing stage, a statistic with a proven relationship to salmonid productivity during this life stage could be considered. In Washington State, the minimum of the 60-day average discharge during the summer rearing period is related to juvenile salmonid productivity (Beecher et al. 2010). A slightly modified 30-day mean is suggested in the Mission Creek example (Table 1). While other low flow statistics have come into favour because of their widespread use for other applications, it is important to understand their biological relevance.

For example, the $7Q_{10}$ (the lowest flow present for 7 consecutive days) was developed specifically for water treatment applications to ensure that receiving water are of a sufficient quantity to meet dilution targets and as such have no relevance for ensuring that the needs of stream dwelling biota are met (Annear et al. 2004).

Using the limiting factor approach, it is also possible to identify a biological response indicator that can be used to assess the actual biological outcome from the conditions associated with each hydrologic indicator (Table 1), thereby creating an opportunity for an effectiveness evaluation of the flow regime. For example, in Mission Creek, to assess the effectiveness of summer flow provisions, the abundance and size of age 1+ rainbow trout parr could be measured (Table 1) within the context of suitable rearing spaces.

Remember that EFN science is a blend of biology, ecology and hydrology. Identify any opportunities to improve the integration of these three disciplines. The limiting factor approach creates a linkage between the fish periodicity chart and the hydrological analysis. When compared to a hydrological analysis that uses mean monthly flows, an approach that uses hydrologic indices that are linked to limiting factors may provide stronger rationale and justification for decisions and better opportunities for evaluations including formal hypothesis testing. This approach may also help to reduce the total number of hydrologic indices from 12 (one for each month) to a smaller set that is well suited for incorporation into water management operations typical of major watersheds in the Okanagan. Application of this approach in streams without detailed hydrologic records will remain a challenge but could still prove useful.

Table 1. Life history stages, example limiting factors, hydrologic indicators and biological indicators for kokanee and rainbow trout in Mission Creek for use in environmental flow needs assessments.

Species/ Event	Life Stage	Known Limiting Factor	References	Hydrologic Indicator #1	Hydrologic Indicator #2	Hydrologic Indicator #3	Hydrologic Indicator #4	Biologic Response Indicator #1
Kokanee	Adult migration	Yes	Wightman and Taylor 1978	Number of days during migration period with flow above target				Tracking and enumeration of adult spawners
	Spawning	Yes	Wightman and Taylor 1978	Number of days during spawning period with flow above target				Redd counts, egg deposition and fry abundance monitoring
	Incubation	Yes	Wightman and Taylor 1978	Minimum of the 30-day mean discharge during winter incubation period	Maximum downramping rate when flows les than target	Minimum instantaneous flow		Fry outmigration and/or fry surveys
	Rearing	No						
	Juvenile migration	No						

Species/ Event	Life Stage	Known Limiting Factor	References	Hydrologic Indicator #1	Hydrologic Indicator #2	Hydrologic Indicator #3	Hydrologic Indicator #4	Biologic Response Indicator #1
Rainbow trout	Adult migration	Yes	Wightman and Sebastian 1979	Number of days during migration period with flow above target	Maximum downramping rate during freshet recession (Mission Creek June 1992, fish kill of adult adfluvial rainbow trout due to stranding)			Enumeration of adult spawners (historically completed at fishway at Smithson-Alphonse Dam). Tracking of adult spawners.
	Spawning	Yes	Wightman and Sebastian 1979	Number of days during spawning period with flow above target				Proportion of adult spawners by year class Redd counts, egg deposition and fry abundance monitoring
	Incubation	No		Minimum of the 30-day mean discharge during spring/summer incubation period	Maximum down-ramping rate when flows less than target	Minimum instantaneous flow		Egg-to-fry survival. Fry outmigration and/or fry surveys
	Rearing	Yes	Wightman and Sebastian 1979	Minimum of the 30-day mean discharge during summer rearing period	Maximum downramping rate when flows les than target	Minimum instantaneous flow	Number of days with temperatures greater than lethal threshold	Abundance and size of 1+ parr in suitable meso-habitats (e.g., riffles, glides).

Species/ Event	Life Stage	Known Limiting Factor	References	Hydrologic Indicator #1	Hydrologic Indicator #2	Hydrologic Indicator #3	Hydrologic Indicator #4	Biologic Response Indicator #1
Rainbow trout	Over-wintering	No		Minimum of the 30-day mean discharge during winter rearing period	Maximum downramping rate when flows les than target	Minimum instantaneous flow		Number of survivors going to the migrant stage; ratio of late winter pre-migrants into Fall pre-migrants
	Juvenile Migration	No		Minimum of the 30-day mean discharge during migration period	Maximum downramping rate when flows les than target	Minimum instantaneous flow		Number of potential migrants in ratio to number of smolts entering Okanagan Lake

3.2 Setting critical environmental flow thresholds for the summer rearing period

Follow these steps:

1. Calculate the Long Term Mean Annual Discharge (LT MAD) for the 14 year standard period from 1996 – 2010.
2. For highly regulated streams, naturalize the LT MAD. For coastal streams, much of the regulated flows occur in the summer and this quantity does not influence the magnitude and accuracy of LT MAD estimates.
3. Calculate relevant benchmark flows including 5, 10 and 20 % LT MAD.
4. Calculate the rolling 30-day mean flow for each day within the entire period of record.
5. Select a subset of dates for calculating the critical period streamflow (CPSF) of interest (e.g., summer CPSF = July 1 – Sept. 30, winter CPSF = Nov. 1 – Feb. 28).
6. For each year, identify the minimum value for the rolling 30-day mean flow within each critical period of interest. For regulated streams, this single value for each year represents the **residual** 30-day mean low flow for the critical period of interest (e.g, summer CPSF).
7. For the years of record, estimate the 1-in-20 year low flow from the annual series of 30-day mean low flows.
8. For regulated streams, naturalize the lowest value for the annual 30-day mean residual low flow. As an important perception check, flow records prior to flow regulation on the same stream may be useful to realize what flow restoration or rebound is possible. Neighbouring streams with natural flow regime may also be used with the same purpose.
9. Examine the distribution of minimum values in comparison to relevant benchmark flows (5, 10 and 20 % LT MAD).
10. Compare: (1) the lowest value of the 30-day mean residual low flow; (2) the lowest value of the 30-day mean naturalized low flow; and (3) 5% LT MAD. Whichever is greater is the critical environmental flow threshold.
11. Refer to the frequency distribution information to determine the return interval for the critical flow.

Note that the authors have developed an R Script to complete the basic steps of this process for suitable Water Survey of Canada stations of interest (Appendix A). Suitable stations include those with year-round operation for a period of record of at least 10 years. Advanced calculations are required for stations with seasonal records, shorter periods of record, and where available data is outside the standard period of 1996 - 2010.

Scenario 1: Calculating the 30-day low flow during the critical period for summer rearing for a stream with a natural flow record – Coldwater River near Brookmere [08LG048]

Flow data at this station from the Jan. 18, 2017 version of the HYDAT database included the period of record from 1965-2014. For calculation of LT MAD, licenced diversions upstream from the station are limited to domestic purposes, therefore this raw data is considered as a natural flow record. Consistent with Lejbak and Uunila (2017), we used the years 1996 – 2010 as the standard period for calculation of LT MAD. This 14 year period includes a wide range of flows near historic the maximum and minimum values on record (Figure 2).

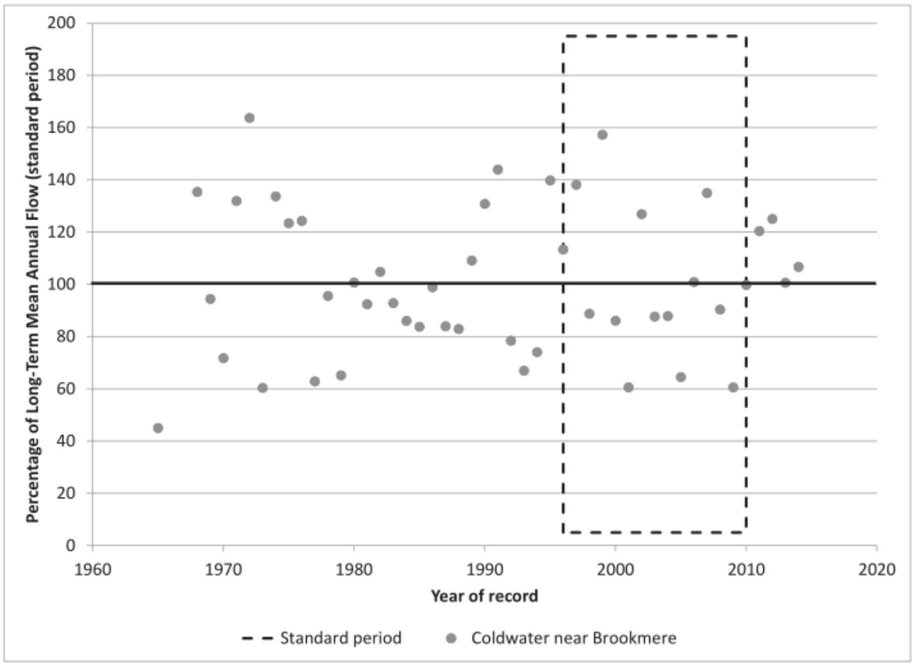

Figure 2. Estimates of mean annual flow (expressed as % of LT MAD for the standard period of 1996-2010) for the Coldwater River near Brookmere (08LG010). All estimates were derived using monthly mean flows from the HYDAT database.

The values for 5% LT MAD and the Minimum summer 30-day low flow were similar at 0.34 and 0.33 respectively (Table 2, Figure 3 and Figure 4). For this station, the critical flow environmental flow threshold corresponds to the 0.5 percentile (roughly 1 in 200 year low flow).

Table 2. Summer flow statistics for Coldwater River near Brookmere (08LG048) for the period of record from 1965-2014.

Flow statistic	Value (m^3/s)
Natural LT MAD	6.7
5 % LT MAD	0.34
10 % LT MAD	0.67
20 % LT MAD	1.34
Minimum value of 30-day low flow	0.33 (Sept. 14-Oct. 13,1994)
Critical Environmental Flow Threshold	0.34

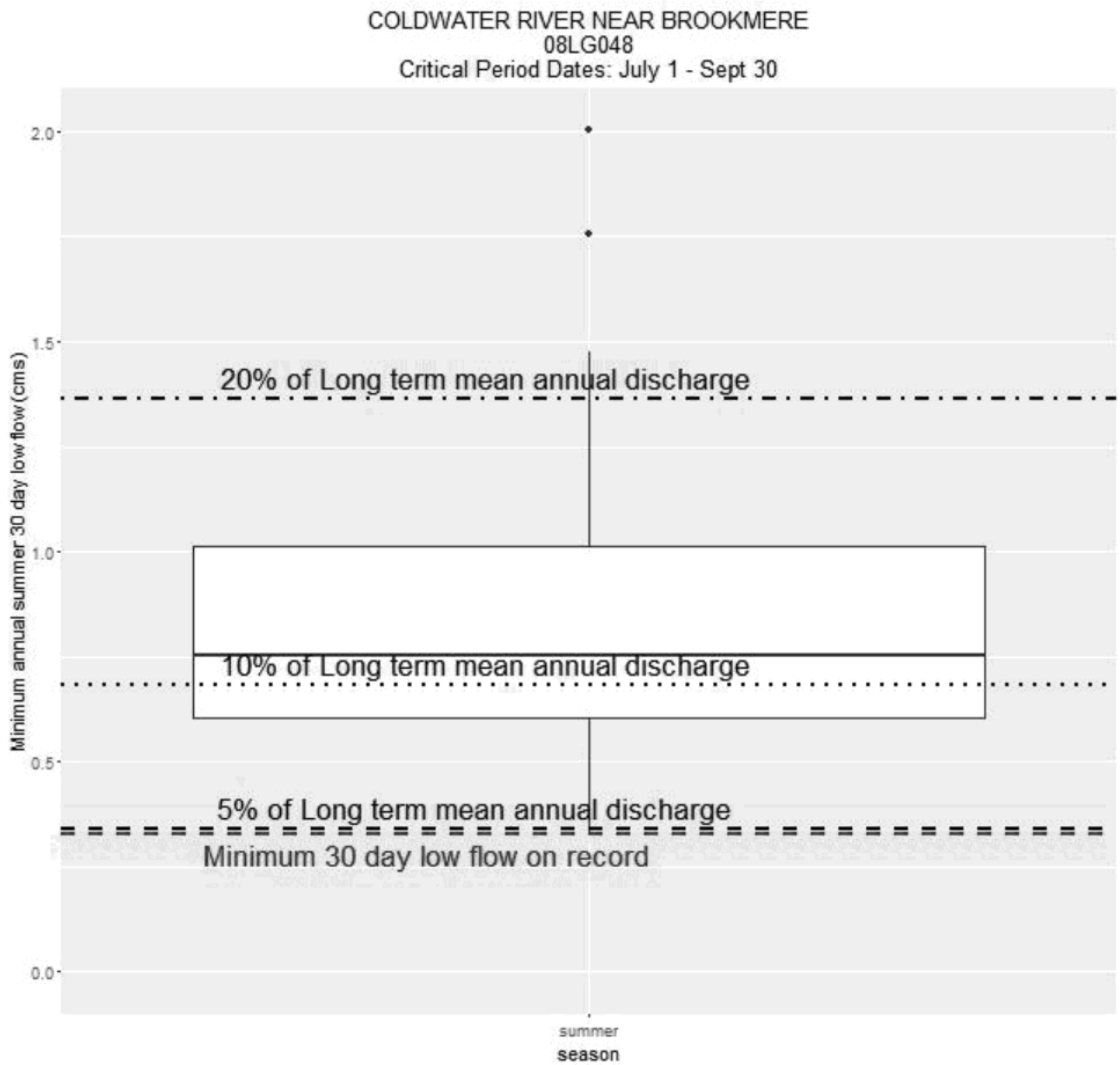

Figure 3. Frequency distribution of summer 30-day low flow values with 5, 10 and 20 % LT MAD benchmark flows.

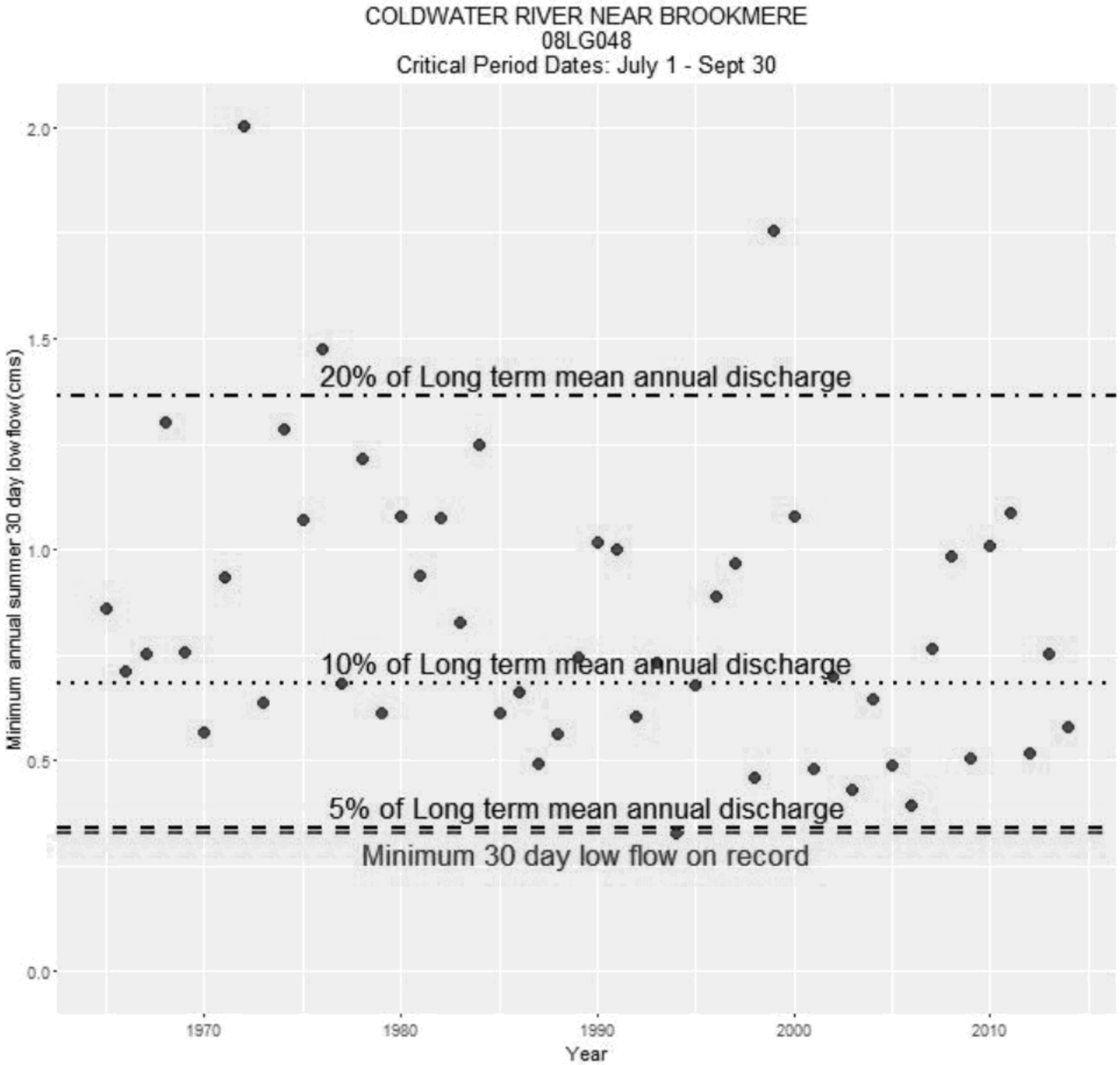

Figure 4. Plot of summer 30-day low flows by year with 5, 10 and 20 % LT MAD benchmark flows.

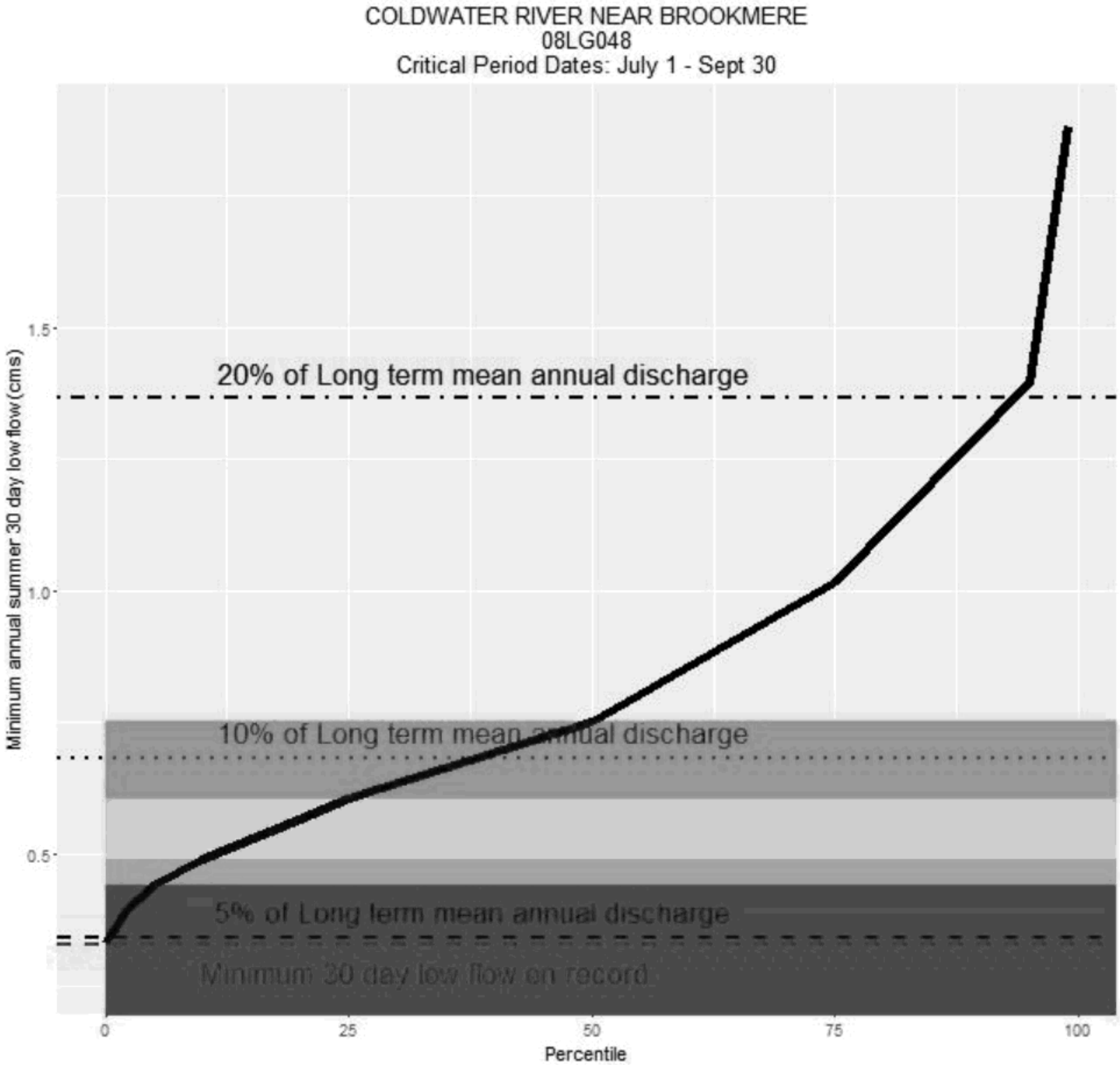

Figure 5. Summer 30-day low flow by percentile with 5, 10 and 20 % LT MAD benchmark flows and drought level flows (green = Level 1, yellow = Level 2, orange = Level 3, red = level 4).

Scenario 2: Calculating the 30-day low flow during the critical period for summer rearing for a stream with significant baseflow withdrawals - Coldwater River at Merritt [08LG010].

Estimating actual water demand

Flow naturalization requires information on the actual water demand. Two types of water users include institutional and agricultural. Institutional water users include purveyors, from which actual water use records are often available. Such records are not typically available from agricultural users. In the Province of British Columbia, the standard approach for determining the agricultural water demand is to apply a water demand model. See: http://waterbucket.ca/aw/2015/03/05/agriculture-water-demand-model/

Such models have been used to estimate agricultural demand in the most areas of the province where water shortages due to agricultural use are known to occur. These models rely on the best existing information on factors including:

1. the extent of irrigated land by crop type;
2. evapotranspiration based on climate;
3. water holding capacity based on soil type;
4. irrigation efficiency; and
5. whether the supply is sourced the surface through a POD on a water body or from a groundwater well.

As a result, the value provided by the model is an estimate. There are a number of important considerations when using these estimates for flow naturalization purposes. First, where a significant portion of demand is provided by groundwater, it can be difficult to determine the percentage of that supply that is obtained from hydraulically connected aquifers; however, such an estimate should be developed. Secondly, the demand is variable from year to year depending on the climate. A water metering program coupled with detailed information on aquifer type is the only way to obtain the true demand over a number of years. In most cases, this level of information is not available. Therefore, the first step in the exercise will be to work with BC Agriculture to determine the best available source of agricultural water demand information for your area of interest.

What is the residual LT MAD?

We used a number of approaches for estimating the residual LT MAD for this station lacking records throughout the entire standard period from 1996 – 2010. The three approaches included: (1) applying a correction factor to known years; and (2) using the 36 years of record between 1965 and 2013; and (3) correction by average percent increase between the Coldwater River near Brookmere station and the Coldwater River at Merritt station (Table 3). The results from these three methods are: (1) correction factor approach = 8.2 m^3/s; (2) LT MAD from 36 years of record = 8.1 m^3/s; and (3) application of average % difference: 6.7 m^3/s * 1.17 = 7.8 m^3/s. We selected the median value of 8.1 m^3/s as the residual LT MAD for Coldwater River at Merritt.

Table 3.Estimating LT MAD for Coldwater at Merritt during the standard period of 1996 – 2010 by applying a yearly correction factor.

Year	Brookmere[1] MAD (cms)	Brookmere LT MAD (cms)	Brookmere Correction Factor	Merritt[2] MAD (cms)	Merritt LT MAD from Correction Factor	Merritt MAD - Brookmere MAD (cms)	Brookmere to Merritt (% increase)
1965	3.0	6.7	0.45	7.2	16.0	4.2	58%
1968	9.1	6.7	1.35	12.3	9.1	3.2	26%
1969	6.3	6.7	0.94	7.7	8.1	1.3	17%
1970	4.8	6.7	0.72	5.9	8.3	1.1	19%
1971	8.8	6.7	1.32	11.2	8.5	2.3	21%
1972	11.0	6.7	1.64	14.7	9.0	3.7	25%
1973	4.0	6.7	0.60	5.1	8.4	1.0	20%
1974	9.0	6.7	1.34	12.9	9.6	3.9	30%
1975	8.3	6.7	1.23	10.7	8.7	2.5	23%
1976	8.3	6.7	1.24	10.2	8.2	1.8	18%
1977	4.2	6.7	0.63	4.6	7.3	0.4	9%
1978	6.4	6.7	0.96	8.0	8.3	1.6	20%
1979	4.4	6.7	0.65	5.4	8.3	1.0	19%
1980	6.7	6.7	1.01	8.5	8.4	1.7	20%
1981	6.2	6.7	0.92	7.7	8.3	1.5	19%
1982	7.0	6.7	1.05	8.6	8.2	1.6	18%
1983	6.2	6.7	0.93	7.5	8.1	1.3	17%
1984	5.8	6.7	0.86	6.2	7.2	0.4	7%
1985	5.6	6.7	0.84	6.6	7.9	1.0	15%
1986	6.6	6.7	0.99	8.0	8.1	1.4	17%
1987	5.6	6.7	0.84	7.2	8.6	1.6	22%
1988	5.6	6.7	0.83	6.5	7.9	1.0	15%
1989	7.3	6.7	1.09	8.4	7.7	1.1	13%
1990	8.8	6.7	1.31	9.8	7.5	1.0	11%
1991	9.6	6.7	1.44	11.4	7.9	1.7	15%
1992	5.3	6.7	0.78	5.9	7.5	0.6	11%
1993	4.5	6.7	0.67	4.8	7.2	0.3	6%
1994	5.0	6.7	0.74	5.3	7.2	0.4	7%
2006	6.8	6.7	1.01	7.0	7.0	0.3	4%
2007	9.0	6.7	1.35	10.8	8.0	1.7	16%
2008	6.1	6.7	0.90	6.4	7.1	0.3	5%
2009	4.1	6.7	0.61	4.0	6.7	0.0	0%
2010	6.7	6.7	1.00	7.4	7.4	0.7	10%
2011	8.1	6.7	1.20	9.1	7.6	1.1	12%
2012	8.4	6.7	1.25	11.5	9.2	3.1	27%
2013	6.7	6.7	1.01	7.3	7.3	0.6	8%
Average	**6.6**		**0.99**	**8.1**	**8.2**	**1.5**	**17%**

How much water are we using?

For the purposes of flow naturalization for the Coldwater River at Merritt, the most recent estimates of annual and summer water demand were obtained from the study titled "Nicola River Watershed Present and Future Water Demand Study" (Summit Environmental Consultants Inc. 2007). For naturalizing the LT MAD, the total water use was estimated as 0.191 m3/s (Table 4 and Table 5). This value was added to the residual LT MAD to provide an estimate of the naturalized LT MAD (Table 7).

Table 4. Summary of estimated annual water demand by sector for the Coldwater River basin (Summit 2007).

Sector	Annual demand
Agriculture	2948 ML/year
Industrial	80 ML/year
Business	83 ML/year
Domestic	2068 ML/year
Institutional	213 ML/year
Recreation	637 ML/year
Total	**6029 ML/year**
Total	**0.191 m^3/s**

Table 5. Summary of monthly water demand by sector for the Coldwater River basin (Summit 2007).

Month	Agricultural (m^3/s)	Total (m^3/s)
jan	0.000	0.062
Feb	0.000	0.056
mar	0.000	0.061
apr	0.013	0.100
may	0.186	0.307
jun	0.241	0.364
jul	0.276	0.453
aug	**0.232**	**0.393**
sep	0.127	0.227
oct	0.038	0.107
nov	0.000	0.061
dec	0.000	0.061
Average	**NA**	**0.188**

Table 6. Correction factor (by year) for adjusting mean annual discharge to the standard time period based on records for WSC stations including Seymour River near Seymour Arm, Barrier River near the mouth, and Fishtrap Creek near McLure. Mean annual discharge estimates were based on daily flow records for all stations of interest.

Year	Coldwater at Brookmere	
	MAD	% of LT MAD
1996	7.6	113.5
1997	9.3	138.4
1998	5.9	88.9
1999	10.5	157.6
200	5.8	86.2
2001	4.1	60.7
2002	8.5	127.1
2003	5.9	87.8
2004	5.9	88.0
2005	4.3	64.6
2006	6.8	101.1
2007	9.0	135.2
2008	6.1	90.5
2009	4.1	60.6
2010	6.7	99.9
Average	6.7	100.0

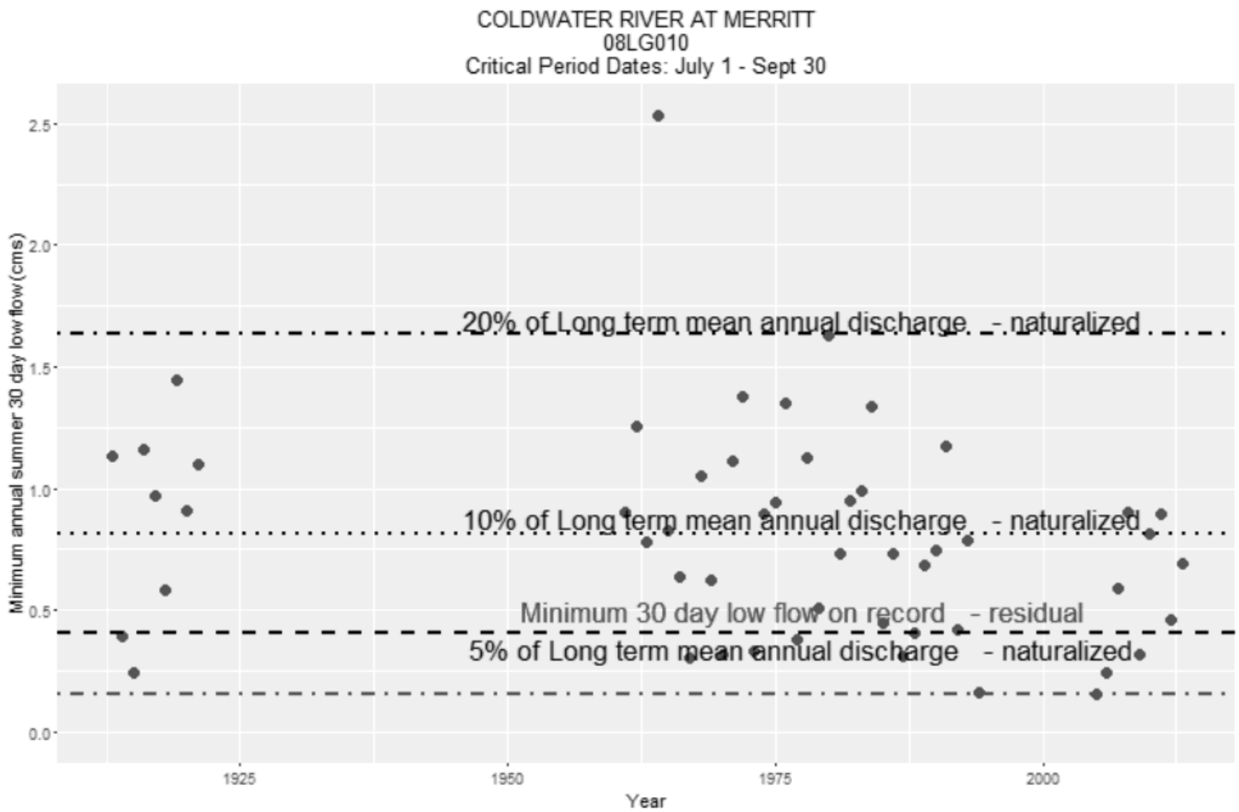

Figure 6. Plot of summer 30-day low flows by year with 5, 10 and 20 % LT MAD benchmark flows.

Table 7. Flow statistics for Coldwater River at Merritt (08LG010) for the period of record from 1913-2013.

Flow statistic	Value (m^3/s)
Residual LT MAD	8.16
Estimated annual demand	0.19
Naturalized LT MAD	8.35
5 % LT MAD	0.41
10 % LT MAD	0.68
20 % LT MAD	1.37
Minimum value of 30-day low flow - residual	0.16
Average date of 30-day low flow	Sept. 8
Date weighted estimate of demand	0.27
Minimum value of 30-day low flow - naturalized	0.43
Critical Environmental Flow Threshold	0.43

Plausibility checks for naturalized flow estimates

When naturalizing flows, it is important to confirm that the estimates are plausible. The approach of adding the estimated water demand back into the residual flow is not the only method for naturalizing flow. Complete a review of the available hydrometric data and consider any alternative approaches that could be applied.

Applying Regional Runoff Estimates

A number of regional runoff models are available for validation of your estimates of LT MAD (e.g., Coulson and Obedkoff 1998, Ptolemy 2011). The work by Ptolemy (2011) is noteworthy because it was based on flow information from streams with short periods of record, seasonal records, and is summarized at the ecosection scale; in contrast, Coulson and Obedkoff (1998) limited their analysis to stations with annual records for longer periods. A characterization of unit runoff is available for the region (Figure 7) and also specifically for the Coldwater River watershed (Figure 8). Based on this approach, the long-term mean annual flow for the Coldwater River at Merritt is 8.69 m^3/s (Table 8).

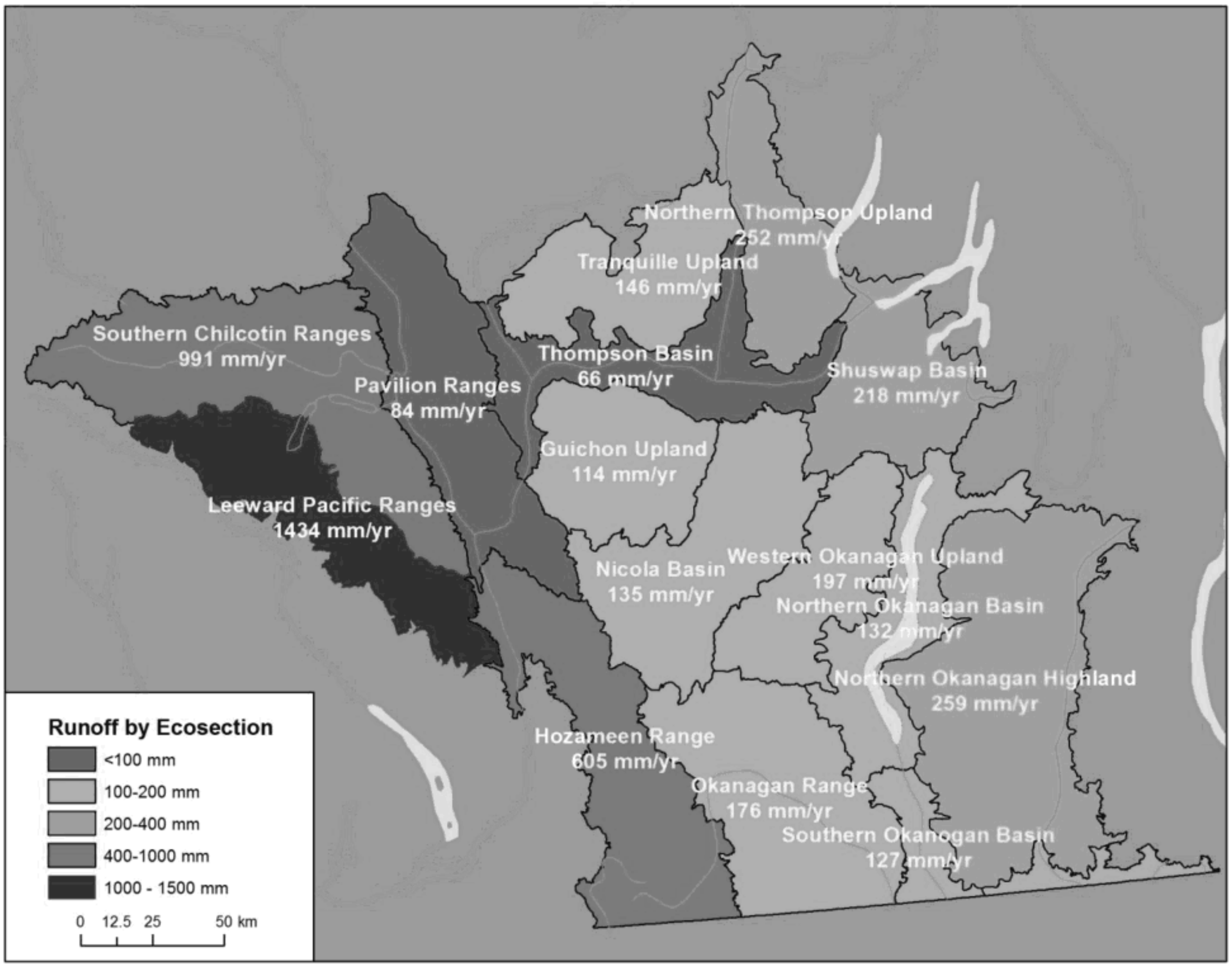

Figure 7. Predicted annual runoff by ecosection within the Southern Interior EcoProvince (Ptolemy 2011)

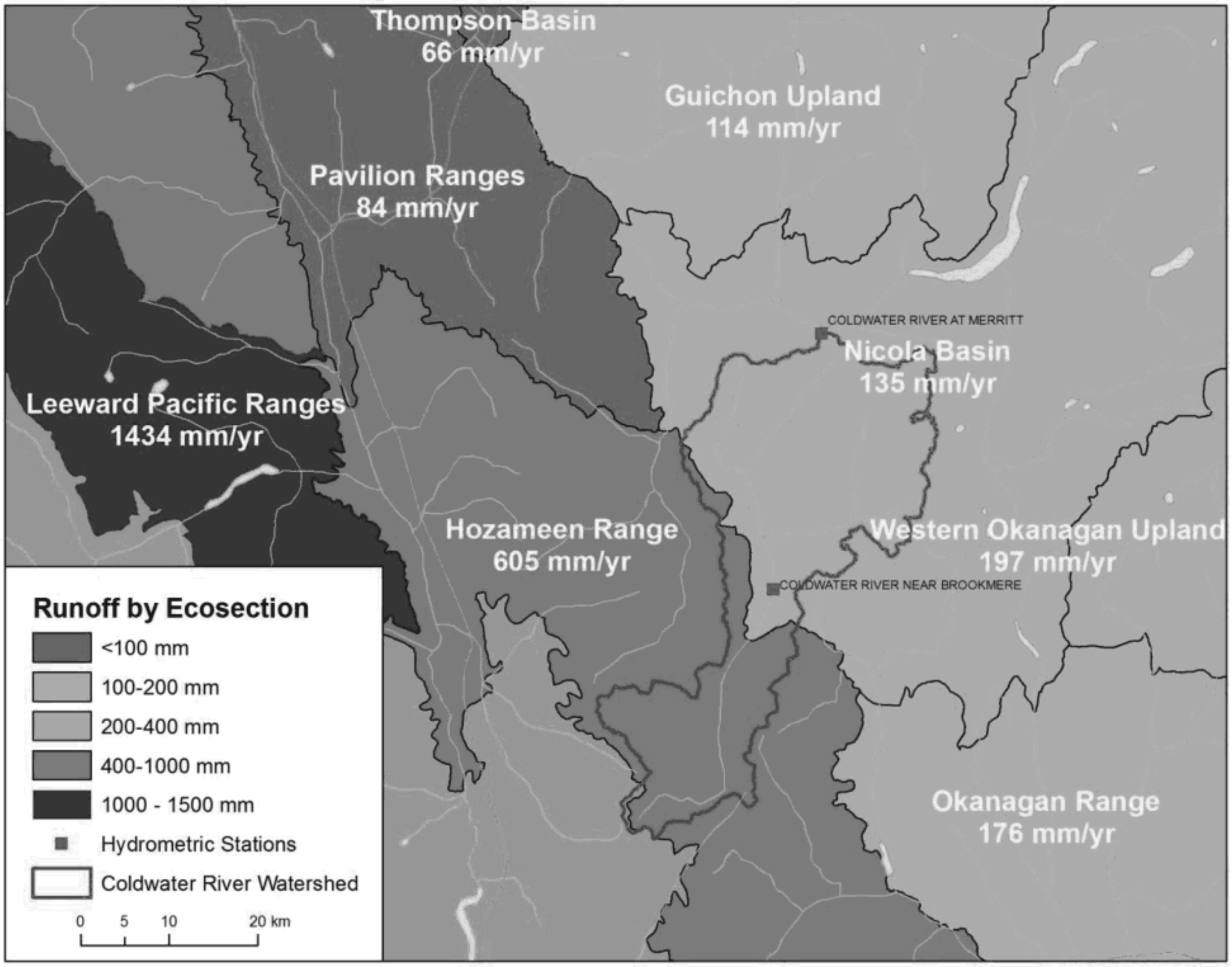

Figure 8. Coldwater River watershed boundary and runoff by ecosection from (Ptolemy 2011).

Table 8. Estimate of long-term mean annual discharge for the Coldwater River based on runoff estimates from Ptolemy (2011).

Ecoregion	Ecosection	Mean runoff (mm/year)	Area (km^2)	Long-term Mean Annual Discharge (m^3/s)
Thompson-Okanagan Plateau	Nicola Basin	135.31	591.72	2.54
Northern Cascade Range	Hozameen Range	604.81	320.57	6.15
Total			912.28	8.69

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Glossary

“critical period” is a phase of high mortality during which the strength of a year class is determined.

"critical environmental flow threshold": (WSA), in relation to the flow of water in a stream, means the volume of water flow below which significant or irreversible harm to the aquatic ecosystem of the stream is likely to occur;

Section 86 Declaration of a significant water shortage provides for restrictions to all water users to protect the critical environmental flow threshold.

"critical environmental flow threshold": (biological), it is a flow threshold within a specific critical period below which a jump in mortality rates are expected to cause an irreversible decline in the population of concern.