BC Ministry of Environment Winter Flows Project

FINAL

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Prepared by:

Todd Hatfield

Ecofish Research Ltd.

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The BC Ministry of Environment Winter Flows Project depended on critical input from a technical review team made up of experts in stream biology, hydrology and water allocation (Mike Bradford, Allan Chapman, Darren DeFord, Andrew Paul, Ron Ptolemy, Jordan Rosenfeld, Chris Schell, Chelton van Geloven, Dave Wilford). Their input is greatly appreciated. Jennifer Turner was the MOE project lead and her excellent input and direction were essential. The project was led by a diverse consultant team from Ecofish Research Ltd. (Todd Hatfield, Adam Lewis, Sean Faulkner and Katie Healey), Compass Resource Management (Michael Harstone), D. Bustard and Associates (Dave Bustard), and Northwest Hydraulic Consultants (Dave Andres).

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF APPENDICES

1. BACKGROUND

The purpose of this report is to summarize results from BC Ministry of Environment's "Winter Flows Project." The government of BC is undertaking a modernization of the *BC Water Act*, including the incorporation of additional environmental considerations such as environmental flows. MOE completed the Winter Flows Project to better understand the effect of water withdrawals during the winter period, especially during the period of ice cover. A consultant team led by Ecofish Research Ltd. was awarded a contract to review existing information and to develop decision-support tools.

A Technical Review Team was assembled to provide technical feedback and advice at strategic points during the assessment and development of winter flow requirements. Terms of reference were developed for the review team and are included as Appendix A of this report. The review team consisted of:

- Mike Bradford, Fisheries Scientist, DFO
- Allan Chapman, Hydrologist, OGC
- Darren DeFord, Water Stewardship Officer, FLNRO, Prince George
- Andrew Paul, Provincial Instream Flow Needs Biologist, Alberta SRD
- Ron Ptolemy, Instream Flow Specialist, MOE, Victoria
- Jordan Rosenfeld, Stream Ecology Scientist, MOE, Vancouver
- Chris Schell, Environmental Assessment Biologist, FLNRO, Smithers
- Chelton van Geloven, Source Water Protection Hydrologist, FLNRO, Prince George
- Dave Wilford, Research Hydrologist/ Team Leader, FLNRO, Smithers

DFO	*Department of Fisheries and Oceans, Canada*
OGC	*Oil and Gas Commission, Canada*
FLNRO	*Ministry of Forests, Lands and Natural Resource Operations, BC*
Alberta SRD	*Alberta Sustainable Resource Development*
MOE	*Ministry of Environment, BC*

The team provided feedback at three formal meetings; two internet meetings (February 6 and March 9, 2012), and one all-day workshop (March 29, 2012). Information in this report is informed by input from the Technical Review Team, but does not represent a consensus view, and there was no formal sign off of the report by the Team.

2. LITERATURE REVIEWS

The consultant team produced two literature reviews for the project, which provided background for technical discussions and evaluations:

Faulkner, S., T. Hatfield, S. Buchanan, D. Bustard, and A. Lewis. 2012. Salmonid winter ecology in interior BC streams and implications of winter water withdrawal. Consultant's report prepared by Ecofish Research Ltd. and Solander Ecological Research Ltd. for the Ministry of Environment, British Columbia.

T. Hatfield. 2012. A review of environmental flow methods for use in the British Columbia Winter Flows Project. Consultant's report prepared by Ecofish Research Ltd. and Solander Ecological Research Ltd. for the Ministry of Environment, British Columbia.

The reports are included as Appendix B and Appendix C of this report.

2.1. Winter Ecology Review

The primary objective of the report is to analyse and synthesize existing scientific information relevant to BC on winter flow sensitivity (low flows and under ice conditions) related to health of fish populations and ecosystem functions. Of particular interest is the influence of flow on fish habitat in winter and the effects on fish populations and ecosystem functions.

The main questions addressed in the report are:

1. What is "winter"?
2. What do fish do in winter?
3. How does habitat change in winter?
4. What effect does water withdrawal have on winter habitat?

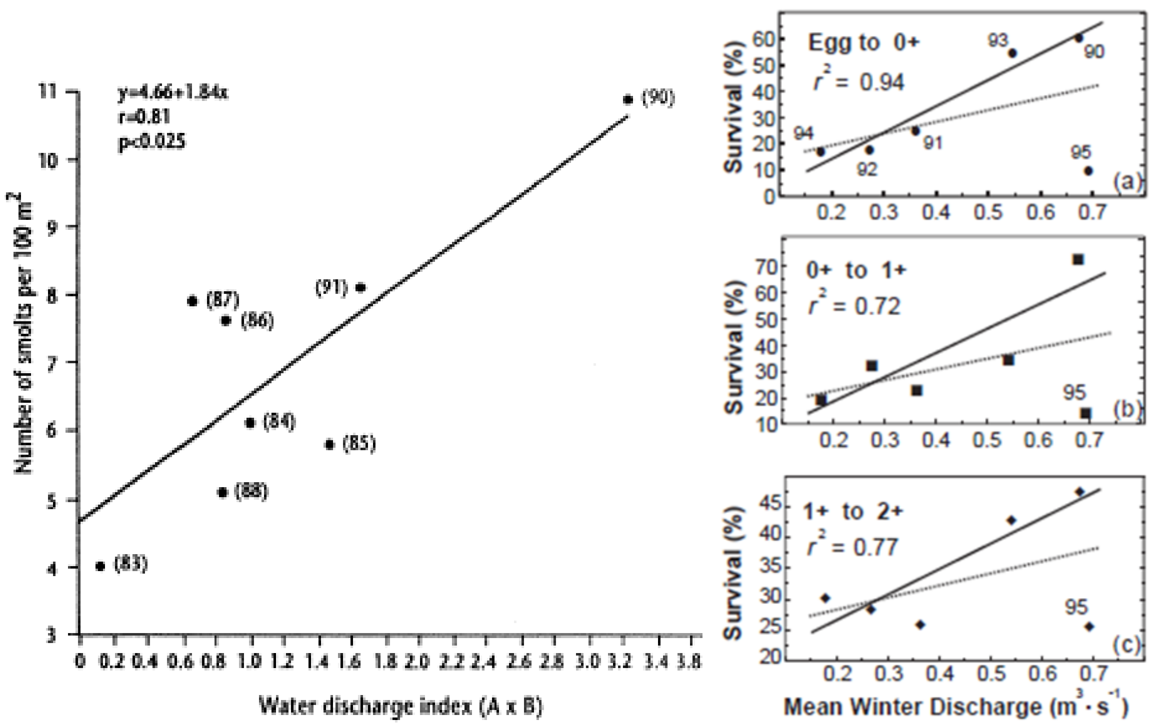
The information used to answer these questions is also used to explore impact pathways associated with winter flow reductions on fish and fish habitat.

The available information on winter ecology of salmonids in northern streams is limited, especially in comparison to information availability for the open water period. However, there are some broadly consistent findings across multiple studies that deserve to be emphasized during policy development for winter flow abstractions. The first is provided by Cunjak (1996) in a seminal review: flow in winter is strongly related to conditions for cover from adverse conditions, shelter from predators, and provision of food. He suggests the relative priority of ecological importance follows the order in this list.

The second point is that there is broad support in the scientific literature for the notion that withdrawal during winter has an ecological effect, especially in interior streams that naturally have low winter flows. Two examples of such a relationship are reproduced in Figure 1. There are other studies that demonstrate this effect, although usually with lower quality data; and there are many studies that demonstrate this effect indirectly with habitat measures (wetted area, useable area, etc.), but without the population response data.

Examining the relationships in Figure 1 it is straightforward to conclude that withdrawal would have a negative effect on fish populations, and one can even quantify the effect for these streams. Most instream flow specialists would accept these relationships as generalized responses to withdrawal. Thus, a small withdrawal would have a smaller effect than a large one. The tougher questions are what is "acceptable" or what would constitute a "low risk?" Clearly, there remains a question of how to accommodate the trade-off between environment and human water uses.

Figure 1. Two examples of ecological performance in relation to winter flow.



The left panel is taken from Hvidsten (1993) and shows the relationship between production of Atlantic salmon parr and winter discharge in River Orkla, Norway. The right panel is taken from Cunjak *et al.* (1998) and shows the relationship between survival of three life stages of Atlantic salmon and winter discharge in Catamaran Brook, New Brunswick.

2.1. <u>Existing Environmental Flow Assessment Methods</u>

The primary objective of the methods review is to provide a review of existing environmental flow assessment (EFA) methods as background for discussion of assessing the influence of flow (and therefore water withdrawals) on fish habitat in winter. We provide a brief history of EFA methods and a review of various approaches to EFAs, including hydrologic, hydraulic, habitat-rating and holistic methods. Hydrologic methods are reviewed in the greatest detail, since they are most relevant to producing a desktop risk assessment tool.

Based on the reviews of different standard-setting and empirical methods, our knowledge of biological resources in British Columbia, and our experiences with water use decisions here and abroad, we believe that various aspects of existing hydrologic (aka historic flow) methods can provide the foundation for good water management decisions for setting winter low flow requirements. The following are some of the primary considerations when selecting an appropriate desktop method.

1. A selected method should build on the strengths of the BC Instream Flow Needs (BCIFN) method (Hatfield *et al.* 2003), the Alberta Desktop Method (Locke and Paul 2011), and the BC-modified Tennant Method (Ptolemy and Lewis 2002). The selected method should preserve key aspects of the natural hydrograph that maintain the physical aspects of streams on which fish and other ecosystem components depend (Richter *et al.* 1996, Poff *et al.* 1997, Richter *et al.* 1997, Trush *et al.* 2000).
2. The method should accommodate ecological values and risk. This would be consistent with DFO's risk management framework (Fisheries and Oceans Canada 2011), and could include several risk levels, as has been done in other jurisdictions (e.g., Beca 2008). Specific to ecological risk evaluation, we recommend that one or more risk categories be developed based on the presence of priority species (e.g., species at risk or other species management concerns) or regionally important habitats (e.g., an important spawning area), with the understanding that priority species and habitats may vary within and among regions.
3. There is compelling evidence that small streams are more sensitive to water withdrawals than larger streams (e.g., Hatfield and Bruce 2000, Rosenfeld *et al.* 2007, Bradford and Heinonen 2008). We therefore recommend that explicit consideration be given to stream size in any standard-setting method.
4. Standard-setting methods based on historic flows use hydrology information as a proxy for biological performance because flows are typically easier to obtain (measure or synthesize) than ecological metrics like fish abundance. Reasonable efforts should be made to ensure that the hydrology is in fact a good proxy for biology, so that the standard protects what it sets out to protect. The Building Block Methodology (King and Louw 1998) is a useful guide for linking flows to environmental performance, and the BC-modified Tennant thresholds (Ptolemy and Lewis 2002) describe the essential building blocks.
5. In-depth and detailed reviews are typically required for complex projects or those with intensive resource use. Lewis *et al.* (2004) describe methods appropriate for assessing small hydropower projects in BC, and these should be viewed as the core of any empirical environmental flow assessment in BC. Thus, any project that wishes to abstract more water than that made available by a standard-setting method may be required to undertake detailed studies as described in Lewis *et al.* (2004). This approach is consistent with that proposed in Hatfield *et al.* (2003).

3. APPROACH TO WINTER FLOWS ASSESSMENT

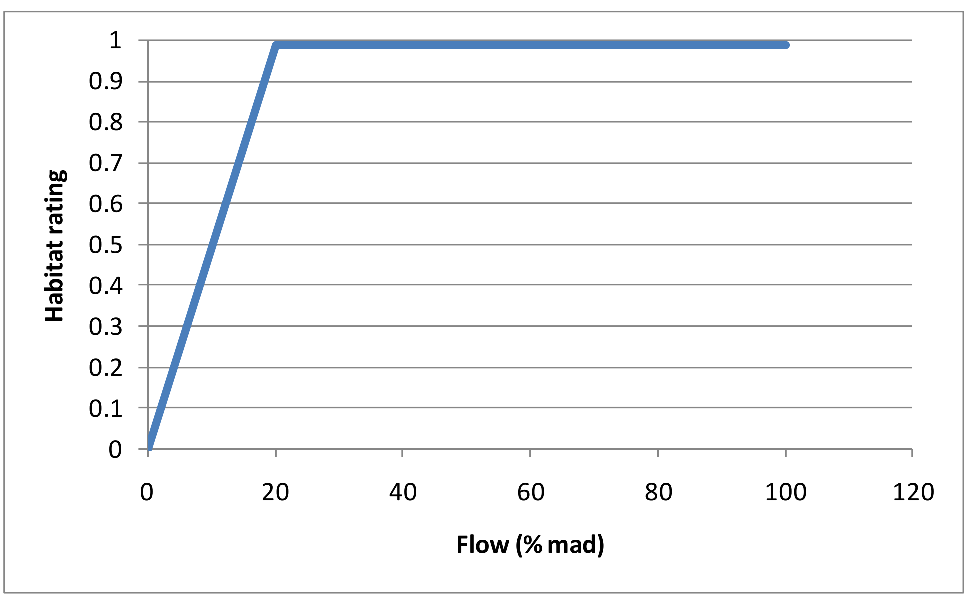
Performance measures (PMs) were developed to evaluate different alternatives for winter withdrawals (i.e., withdrawal scenarios) in British Columbia. PMs are modelled outputs that describe predicted responses to the alternatives. They are used to:

- compare alternatives accurately and consistently;
- expose trade-offs;
- generate productive discussion about better alternatives;
- prioritize information needs; and
- communicate the rationale for and improve the transparency of decisions.

A proposal for a set of environmental PMs to evaluate various winter withdrawal alternatives was developed and circulated to the Technical Review Team. The crux of the proposal was a habitat rating curve based on MOE's past and ongoing use of 20% mean annual discharge (MAD) as a metric of environmental performance. The information base and methods used in the derivation of this metric and the general rationale for its use in setting environmental flows are described in Ptolemy and Lewis (2002).

For the context of assessing winter flow alternatives we developed a habitat rating curve in which all flows of 20% MAD or greater were assigned a score of 1. All flows below 20% MAD were assigned a score based on a linear relation between 0 and 1 (Figure 2). This simple rating curve means that a flow of just under 20% MAD will score close to the maximum, whereas a substantially lower flow will score proportionally less. The rating curve is the same for all streams, regardless of size, morphology, fish community, or other factors.

Figure 2. A habitat rating curve based on MOE's environmental performance metric of 20% MAD.



The rating curve is a useful tool for evaluating winter withdrawal alternatives, but we caution against its universal use. At face value, the curve suggests that water above 20% MAD is of no additional ecological value and this is simply not the case. A quick look at the BC Modified Tennant thresholds indicate ecological functions of higher flows. Even in winter there are examples of higher flows contributing additional value. The rating curve in Figure 2 was explicitly designed for evaluating winter withdrawal alternatives, and any extension beyond this application should be done carefully.

With a habitat rating curve in hand we can then undertake analyses of streamflow records in different regions. We selected records from several Water Survey of Canada (WSC) gauges in northeastern BC that span a range of stream sizes and have a reasonably long period of record. We modeled a range of fixed withdrawals, ranging from 0% to 50% withdrawal of daily flow, along with the BCIFN (Hatfield *et al*. 2003) and variants of the Alberta Desktop Method (Locke and Paul 2011).

Several PMs were calculated for each alternative, then tabulated and graphed for different gauges in northeastern BC (e.g., Table 1 and Figure 3). The following briefly describes the performance measures and the methods for calculation.

Industry PMs:

- mean annual diversion (m^3) — the total diversion volume for each year of record is calculated, and the average taken for all years.
- mean days/yr with no diversion — the total number of days in each year in which no diversion occurs, and the average taken for all years.
- mean max duration/yr with no diversion — the maximum number of consecutive days in each year in which no diversion occurs, and the average taken for all years.

Winter hydrology PMs:

- February min flow — the minimum flow across all years on record in the month of February.
- February median flow — the median flow across all years on record in the month of February.
- February max flow — the maximum flow across all years on record in the month of February.

Fish PMs:

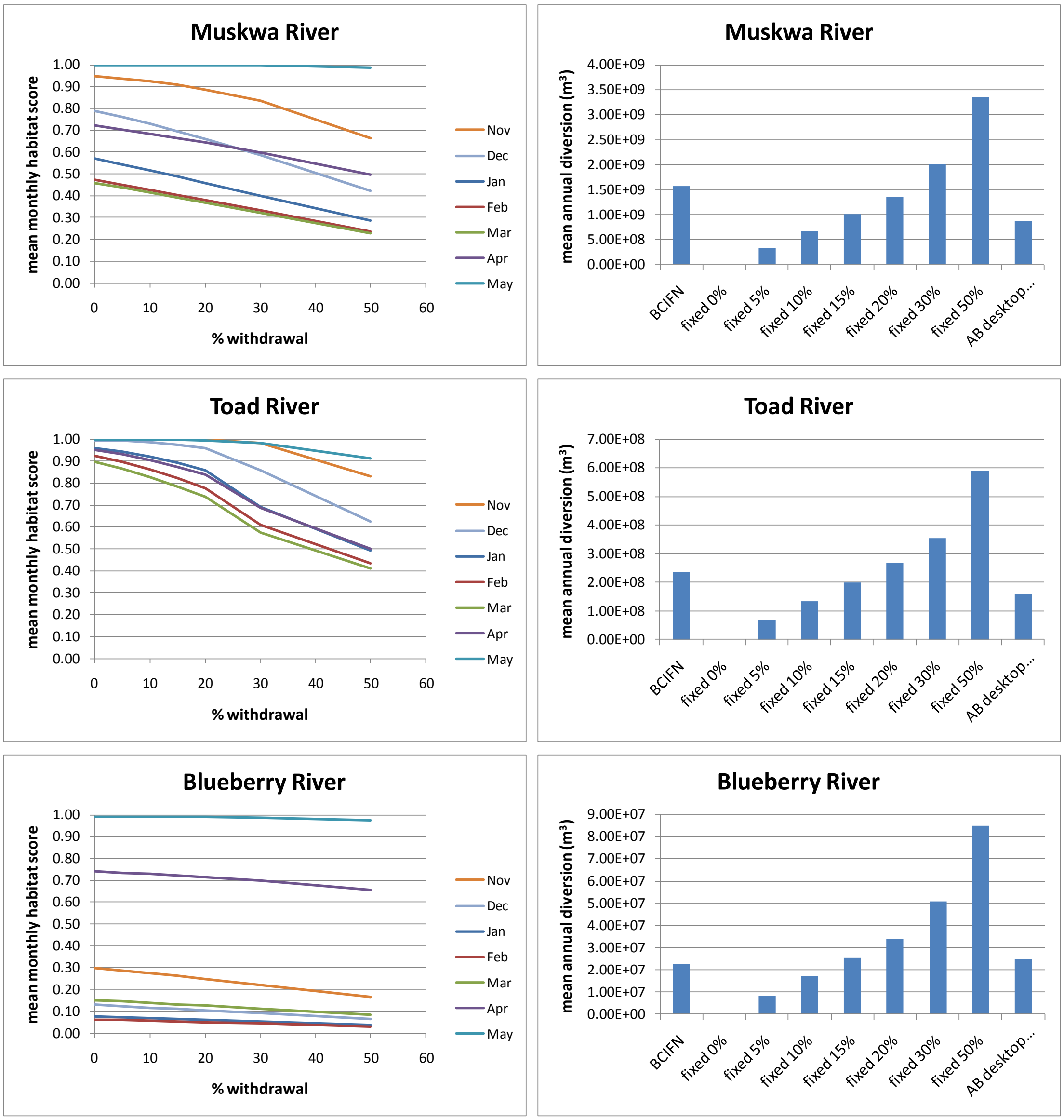
- mean days/yr > 20% MAD — the total number of days in each year in which flows exceed 20% MAD, and the average taken for all years

- mean annual rearing score — the "rearing score" is calculated for each day on record using the habitat rating curve, the average score is calculated for each year, and then the average taken for all years
- mean monthly rearing score — the "rearing score" is calculated for each day on record using the habitat rating curve, the average score in January is calculated for each year, and then the average taken for all years. The same is then done for February through December.

Table 1. Calculated performance measures for different alternatives, using historic streamflow records of Toad River (WSC 10BE004, latitude 58.855°, longitude 125.383°, mean basin elevation 1591.9 masl, MAD 43.354 cms). Similar tables can be constructed for other gauges.

TOAD RIVER ABOVE NONDA CREEK	natural	fixed 5%	fixed 10%	fixed 15%	fixed 20%	fixed 30%	fixed 50%	BCIFN	AB desktop (0.15, 80)	AB desktop (0.15, 90)
mean annual diversion (m^3)	0	6.70E+07	1.34E+08	2.01E+08	2.68E+08	4.02E+08	6.70E+08	2.36E+08	1.62E+08	1.82E+08
mean days/yr with no diversion	365.00	0.00	0.00	0.00	0.00	0.00	0.00	260.70	74.09	33.50
mean max duration/yr with no diversion	365.00	0.00	0.00	0.00	0.00	0.00	0.00	116.90	34.36	18.59
February min flow	3.68	3.50	3.31	3.13	2.94	2.58	1.84	3.68	3.68	3.68
February median flow	8.31	7.89	7.48	7.06	6.65	5.82	4.16	8.31	7.39	7.06
February max flow	14.30	13.59	12.87	12.16	11.44	10.01	7.15	9.84	12.16	12.16
mean days/yr > 20% MAD	305.32	288.90	273.00	258.70	245.40	223.20	188.80	305.30	269.70	265.70
mean weighted 20% MAD/yr	0.98	0.97	0.96	0.95	0.93	0.89	0.80	0.98	0.96	0.96
mean habitat score/yr in November (20% MAD rating curve)	1.00	1.00	1.00	1.00	1.00	0.99	0.88	1.00	1.00	1.00
mean habitat score/yr in December (20% MAD rating curve)	1.00	0.99	0.99	0.98	0.96	0.91	0.69	1.00	1.00	1.00
mean habitat score/yr in January (20% MAD rating curve)	0.96	0.94	0.92	0.89	0.86	0.76	0.55	0.96	0.94	0.91
mean habitat score/yr in February (20% MAD rating curve)	0.92	0.90	0.86	0.82	0.78	0.68	0.49	0.92	0.87	0.84
mean habitat score/yr in March (20% MAD rating curve)	0.90	0.86	0.83	0.78	0.74	0.65	0.46	0.90	0.82	0.80
mean habitat score/yr in April (20% MAD rating curve)	0.95	0.93	0.91	0.87	0.84	0.75	0.56	0.95	0.92	0.90
mean habitat score/yr in May (20% MAD rating curve)	1.00	1.00	1.00	1.00	1.00	0.99	0.94	1.00	1.00	1.00
mean habitat score/yr in June (20% MAD rating curve)	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
mean habitat score/yr in July (20% MAD rating curve)	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
mean habitat score/yr in August (20% MAD rating curve)	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
mean habitat score/yr in September (20% MAD rating curve)	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
mean habitat score/yr in October (20% MAD rating curve)	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

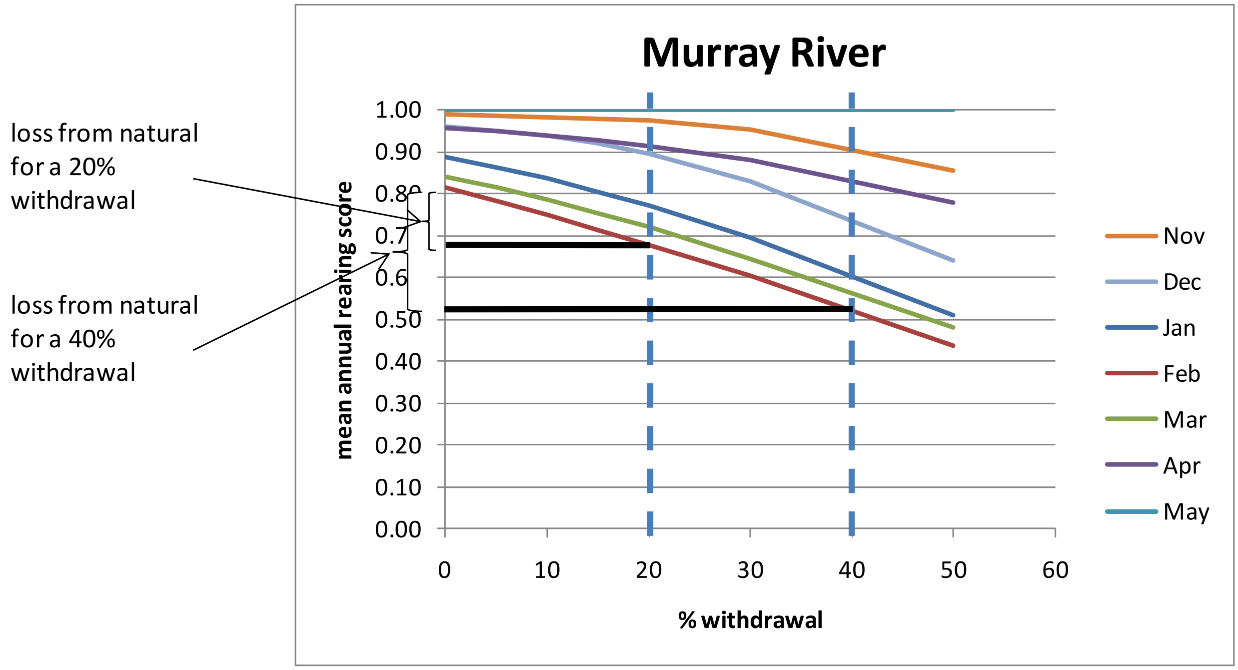
Figure 3. Performance measures for fish and industry for the Muskwa, Toad and Blueberry rivers in northeastern BC, in relation to modeled winter withdrawals. Similar graphs can be constructed for other gauges.



The habitat response to withdrawal (left graphs in Figure 3) shows that response varies among months, and is dependent on the characteristics of the hydrology of the streams. Even under natural conditions with no withdrawals there can be periods in which the rearing score is low, because frequently flow may be well below 20% MAD.

These data can be used to construct a metric that measures percentage loss of habitat over any period of interest. A schematic of how the metric is calculated is shown in Figure 4 for two withdrawal scenarios on the Murray River.

Figure 4. Demonstration of calculation of habitat loss relative to natural for two withdrawal scenarios in the month of Feb for the Murray River.



Results from PM calculations were tabulated for 10 gauges in northeastern BC and used as the basis for discussion with the Technical Review Team.

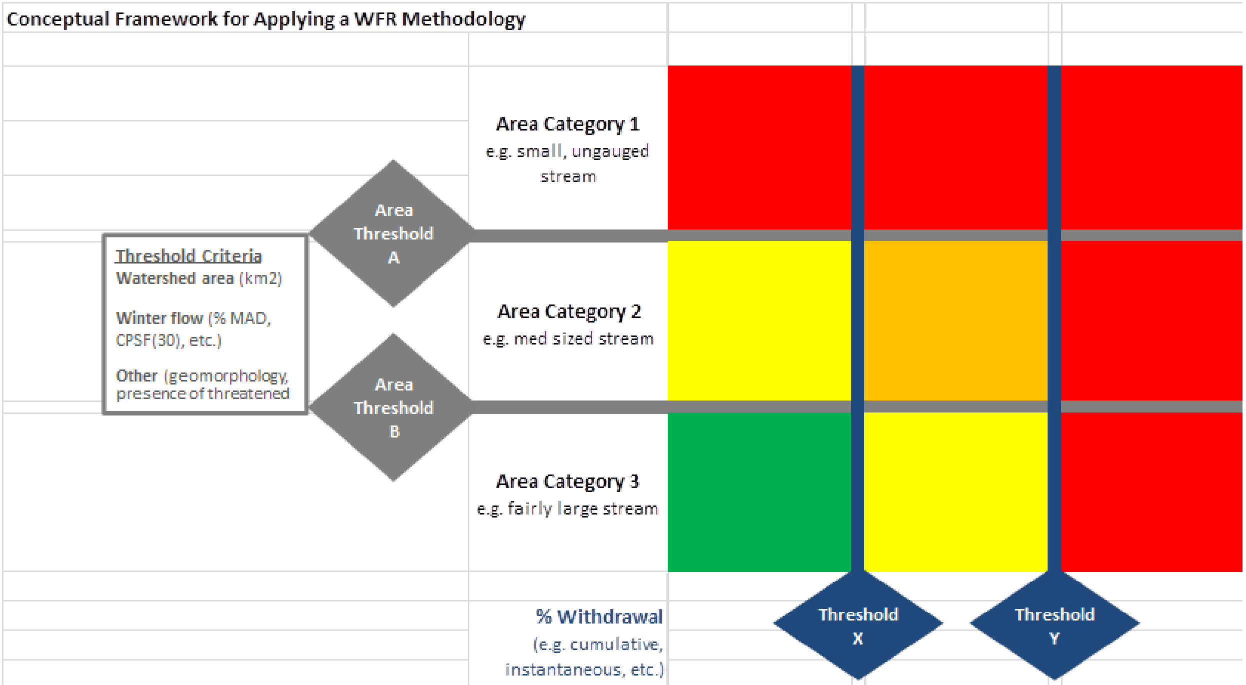
4. WORKSHOP FEEDBACK

An all-day workshop was held in Victoria, BC on March 29th, 2012, facilitated by Michael Harstone, Compass Resource Management, and attended by the following participants:

Mike Bradford, DFO (on the phone)
Randy Cairns, MOE
Allan Chapman, OGC
Darren DeFord, FNLRO
Todd Hatfield, Solander Ecological Research Ltd.
Adam Lewis, Ecofish Research Ltd.
Jean-Sebastian Moore, PhD intern with MOE Ecosystems Protection and Sustainability Branch
Andrew Paul, Alberta Fish and Wildlife
Robin Pike, MOE
Ron Ptolemy, MOE
Jordan Rosenfeld, MOE
Zsolt Sary, FNLRO
Jen Turner, MOE
Chelton Van Geloven, FLNRO (on the phone)
Dave Wilford, FNLRO
Regrets: Chris Schell, FLNRO

The focus of the workshop was a discussion of risk categories and water permitting scenarios. A conceptual framework was presented and discussed, which developed a two-dimensional risk matrix based on withdrawal amounts and criteria such as stream size, morphology, resource values and sensitivity (Figure 5). The conceptual framework was explored through the possible application to different example streams in northeastern BC.

Figure 5. A conceptual framework for determining winter flow requirements.



* MAD = mean annual discharge; CPSF = critical period stream flow.

4.1. Discussion of scenarios

- In northeastern BC the largest demand for water is for unconventional gas. As background to understanding water diversions in this region, the following information was presented:
  - There is potential for year round demand of water, except typically during spring ice break-up.
  - 50-1000 m^3/day (0.58 – 11.58 L/sec) represents typical diversion requests, and an average of 100 m^3/day (1.65 L/sec).
  - Maximum instantaneous rate per approval is typically 14 L/sec through OGC permits, although there may be multiple approvals on one stream. (14 L/sec is the typical size of an industrial water pump.)
  - In practice, the period of pump operation can range widely.
  - The largest water use is for hydro-fracking, but most companies use water stored in borrow pits for this activity.
  - There can be wide variation in actual volumes used versus approved, but the anticipated actual demand is 5-10 Million m^3/year (~0.16-0.32 m^3/sec).
  - The current OGC approach is to:
    - Calculate watershed supply in m^3/month.
    - Calculate "availability" as 15% of monthly mean.
    - Ensure allocated amount does not exceed this value.

- The following issues with the current approach were identified during the workshop:
    - There is a need for relating daily or monthly use to instantaneous rates, which are more relevant for assessing ecological impacts.
    - Since water availability is based on means there is a need to accommodate variability in winter supply. For example, 15% of the monthly mean may be considerably greater than 15% of the instantaneous flow during a period of very low flow.
    - OGC perspective is that demand is a fraction of supply, within measurement error on the larger streams. For larger diversions on smaller streams, monitoring could be a requirement of the approval.
    - OGC is working on how to address water availability during periods of low flow (e.g., implementation of an "ecosystem base flow").

4.2. Discussion of risk categories.

- The conceptual framework with stream categories (Figure 5, y-axis) and withdrawal thresholds (Figure 5, x-axis) was widely supported, but the application of these thresholds was based on a number of (intuitive) variables, such as:
    - Absolute amount of winter flow volume.
    - Withdrawal % relation to MAD.
    - Variance of low winter flows (e.g., minimum in relation to mean).
    - Resource values (e.g., presence of listed fish species).
    - Attributes of hydraulic geometry (e.g. critical depth).

- There was general agreement in the workshop with the following:
    - Baseline conditions (i.e., the reference condition) should describe natural flow conditions in all cases. In some cases this may require "naturalizing" the hydrologic record to account for existing water diversions and other alterations (e.g., storage and large-scale land changes).
    - Diversions from smaller streams tend to be higher risk than diversions from larger streams.
    - Use of the OGC hydrology model can be used to assign risk thresholds to streams, based on runoff or stream discharge.
    - Medium and high risk thresholds do not by default mean no water diversion is allowed, but there may be additional information requirements as a condition of approval.
    - There is general support for the framework, but there is a need to operationalize it to define thresholds and information requirements.

4.3. Example Streams

Three stream examples were presented and discussed: Muskwa River, Blueberry River, and Halfway River.

Muskwa River

- Representative of a large river in northeastern BC.
- The majority of the group stated that diversion of up to 10% of instantaneous flow would be low risk to the environment under most conditions.
- As context it was noted that it would be difficult to measure a 10% withdrawal let alone the biological response.
- It was noted that it may be medium risk if flows were close to the minimum February flow.
- More comfort in using the benchmark of 80% exceedance flow.
- Less caution may be needed for short term approvals in comparison to longer term licences.

Blueberry River

- Representative of a small river in northeastern BC with very low winter flows (%MAD is low and median winter flow is low).
- OGC stated that a river like this would be classified as a system in which no winter withdrawals would be permitted, or only under exceptional circumstances (e.g., high water conditions, or for very restricted water uses).
- Allowing any diversions would require additional information, e.g., fish presence.
- The majority of the group stated that most diversions were thought to be in the high risk category.

Halfway River

- Representative of mid-size river in northeastern BC.
- In a wetter ecoprovince, and from a flow perspective it is lower risk than Muskwa River.
- However, this is an example of how local knowledge can influence risk tolerance. For example, presence of bull trout (local knowledge) gives higher resource values, which may mean lower risk tolerance or greater information requirements (e.g., refer to biologists on winter needs for bull trout); groundwater inputs are known to be significant and provide a more stable baseflow.
- The majority of the group stated that a precautionary approach was warranted in this situation: grant water approval with safeguards (e.g., low-flow cut-off using gauging station, fish clause).

5. RISK ASSESSMENT FRAMEWORK FOR WINTER WITHDRAWALS

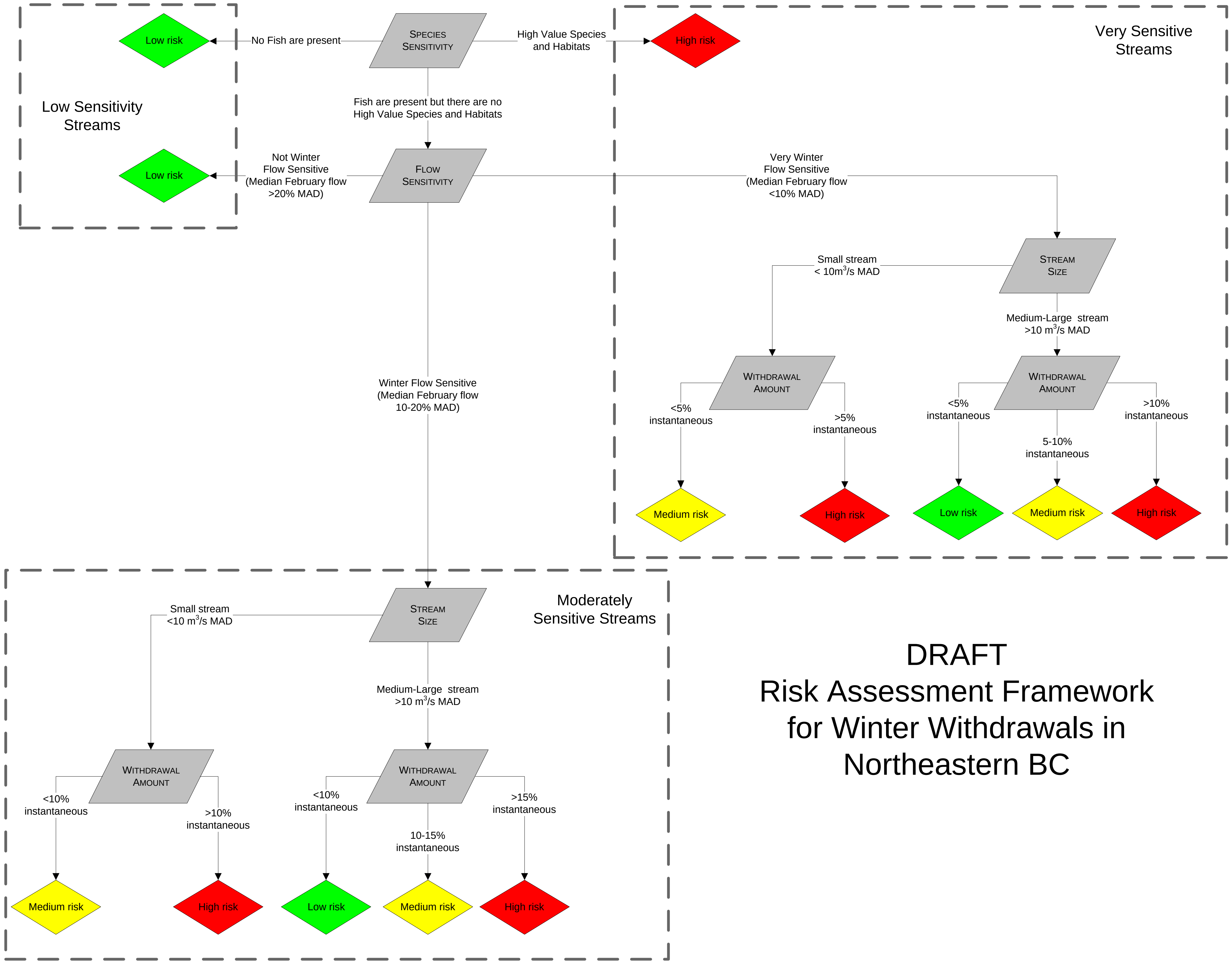
Building on results and discussion from throughout the Winter Flows Project we have developed a "Risk Assessment Framework for Winter Withdrawals in Northeastern BC." The assessment framework is presented as a decision tree, with four nodes:

1. species sensitivity
2. flow sensitivity
3. stream size, and
4. withdrawal amount.

The decision tree is depicted in Figure 6. Each of the nodes is discussed separately along with some of the operational issues associated with each decision point. It is essential to understand the logic and details incorporated into this framework, which are presented as text in Sections 5.1 and 5.2.

The concepts presented in the risk assessment framework are understood and accepted at the conceptual level, however, the specific quantitative classification presented is based on professional opinion. As such, the application of the framework is intended to provide decision-makers with a preliminary evaluation of environmental risk associated with winter water withdrawals. Many other factors, such as proximity to lakes with winter outflow, natural groundwater inputs, and natural variability among years will inform water allocation decision making. One crucial point needs to be made here: the framework needs to be applied while using a longitudinal or "downstream view." There should be a commitment to not creating greater downstream effects, which may arise from spatially variable habitat sensitivity or via cumulative effects of withdrawal. In other words, the framework should not be applied simply to the condition at the POD. Instead, one needs to also consider possible downstream effects and whether the cumulative withdrawal along the length of the river may bump it into a higher risk category. A simple example would be a withdrawal just upstream of a critical spawning area; clearly, downstream effects should be considered. Implementing a downstream view could be challenging, but is necessary to meet the objectives of protecting environmental values.

Figure 6. Decision tree depicting the DRAFT Risk Assessment Framework for Winter Withdrawals in northeastern BC.



5.1. Nodes

Species sensitivity.

This is the first node in the decision tree and represents the over-riding concern for species and habitats that are classified as "High Value." This node allows local information on specific environmental concerns to receive priority consideration during water allocation decisions. Determinations of whether a stream has High Value Species and Habitats should be data-driven and use the following criteria:

- The stream in question has stream-dependent species with Conservation Framework designation of 1 or 2.
- The stream in question has been given Sensitive Stream status (e.g., *Fisheries Sensitive Streams, Temperature Sensitive Streams*) or Protected River status under the B.C. *Fish Protection Act.*
- There is a *Wildlife Management Area(s)* with streamflow-related objectives.

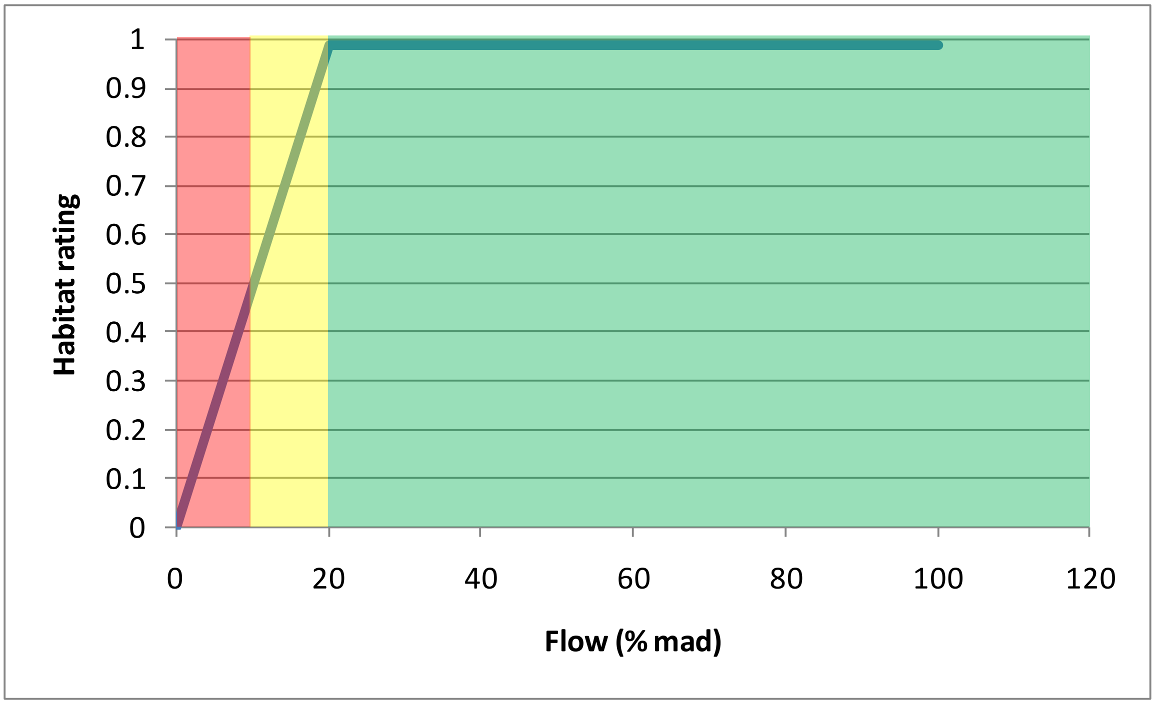
If there are no fish present, withdrawals on the stream are considered low risk, though downstream effects on fish-bearing waters should always be evaluated using criteria described in the rest of the framework. For example, it will be necessary to understand whether withdrawal at this site imposes unacceptable risk in downstream fish-bearing waters, or whether the withdrawal interacts with existing permits and licences to create high risk at downstream sites. Withdrawals at any site must not be exempt from being evaluated for cumulative impacts from existing demand. Fish presence or absence should be demonstrated using existing standards conducted by qualified individuals, and all streams should be considered fish-bearing by default.

Flow sensitivity.

The second node in the decision tree assesses natural flow conditions in winter and whether the stream should be considered "flow limited." This node addresses natural habitat conditions for stream-dependent biota, but the measure can also be used to infer natural water availability for allocation. During the Winter Flows Project we used a generic habitat rating curve based on %MAD (Figure 2) to assess the effect of withdrawals, but participants also used the rating curve to classify streams based on typical winter flows. Those streams with very low winter flows were treated with more caution than those with more abundant winter flows. We suggest dividing the rating curve into three zones, as depicted in Figure 7, and categorizing streams based on median February flows. The three zones are:

1. Not winter flow sensitive (median February flow >20 %MAD)
2. Winter flow sensitive (median February flow 10-20 %MAD)
3. Very winter flow sensitive (median February flow <10 %MAD)

Figure 7. The generic habitat rating curve used in the Winter Flows Project is divided into three categories to reflect natural flow sensitivity in different streams in northeastern BC.



The use of %MAD as a reference flow has flaws, particularly for comparing streams in different regions, but its calculation is straightforward and there is precedent in using this as a reference point. At some point, it may be possible to base the metric on an exceedance flow value in the lowest flow winter month, but it can be operationalized at this time with the following shortcuts for northeastern BC:

- define winter as (Dec 1 to Apr 15),
- select Feb as lowest winter flow month,
- base MAD on best available information,
- where necessary, find a correction factor for translating mean flows (i.e., mean monthly or mean annual discharge) into an exceedance flow like median.

Stream size.

As noted earlier, there is compelling evidence that small streams are more sensitive to water withdrawals than larger streams (e.g., Hatfield and Bruce 2000, Rosenfeld *et al.* 2007, Bradford and Heinonen 2008). During the Winter Flows Project there was consistent support for a stream size filter, but additional work is required to determine appropriate stream size categories for the risk assessment framework. For the present we suggest using the following categories, based on MAD:

- medium-large stream (>10m^3/s MAD),
- small stream (<10 m^3/s MAD).

Selection of these categories is informed by analysis of WSC hydrometric data from northeastern BC. During additional evaluation of appropriate stream size categories it may be useful to explore the use of reference streams, hydraulic geometry relationships, unit area drainage, and basin size to validate the selection of categories.

Withdrawal amount.

The final node in the decision tree is withdrawal amount. The thresholds for withdrawal categories have been informed by discussions during the Winter Flows Project and relevant literature (e.g., Rogers and Biggs 1999, COSEWIC 2010, Ohlson *et al.* 2010, Locke and Paul 2011, Richter *et al.* 2011). Risk ratings for withdrawals differ among categories of stream sensitivity. In all cases risk ratings refer to cumulative instantaneous withdrawals (i.e., not an average) relative to natural flows, and therefore include all upstream withdrawals. The values presented are intended to provide guidance as described below based on current understanding of risk.

5.2. <u>Risk Categories</u>

Low Risk.

- A stream deemed to be at "Low Risk" from winter withdrawals means that there are no high value resources or habitats present (see definition in Section 5.1), that there is sufficient natural water availability in winter, and that cumulative water withdrawals are below a specified threshold of concern. "Low risk" does not mean "no risk," but supplementary information is likely not needed for low risk winter withdrawals

Medium Risk.

- A stream deemed to be at "Medium Risk" from winter withdrawals means that the stream is fish-bearing or there are other stream-dependent biota requiring consideration, that the aquatic environment is flow limited in winter, or that cumulative water withdrawals are greater than a specified threshold of concern Supplementary information may be requested from applicant or the approval or licence may include terms and conditions to minimize impacts to environmental flow needs.

High Risk.

- A stream deemed to be at "High Risk" from winter withdrawals means that there are high value resources or habitats present, that the aquatic environment may be very flow limited in winter, or that cumulative water withdrawals are greater than a specified threshold of concern. More rigorous analysis of the potential risk or approval/licence terms and conditions are likely.

6. CONCLUSION AND NEXT STEPS

The Risk Assessment Framework for Winter Withdrawals in Northeastern BC was developed in response to ongoing applications for winter water withdrawals throughout British Columbia, especially in the northeast, and the desire to incorporate environmental considerations into the water allocation decision process. The Framework presented here is a decision tree with several decision nodes that require water allocators to explicitly consider several environmental factors. The Framework was developed with the input of a Technical Review Team made up of experts from the fields of biology, hydrology and decision-making. The criteria used and the thresholds described in the Framework are based on relevant scientific literature and discussion at three meetings with the Technical Review Team. Although there is some subjectivity in the selection of these criteria and thresholds, we recommend that they be assessed in a pilot study, monitored for effectiveness, and adjusted where necessary.

In addressing the tougher questions of what level of risk is "acceptable," the Risk Assessment Framework is a useful indicative tool in preliminary planning stages. More detailed information would be required in later planning stages, in cases indicated as medium or high risk, and where cumulative water withdrawal requests exceed thresholds of probable concern. It is worth reiterating that "low risk" does not equate to "no risk," and additional work may be required to reduce risk in some instances, such as the consideration of an ecosystem base flow during periods of extreme low flow.

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8. APPENDIXES

Appendix A. Terms of Reference for Technical Review Team.

Appendix B. Faulkner, S., T. Hatfield, S. Buchanan, D. Bustard, and A. Lewis. 2012. Salmonid winter ecology in interior BC streams and implications of winter water withdrawal. Consultant's report prepared by Ecofish Research Ltd. and Solander Ecological Research Ltd. for the Ministry of Environment, British Columbia.

Appendix C. T. Hatfield. 2012. A review of environmental flow methods for use in the British Columbia Winter Flows Project. Consultant's report prepared by Ecofish Research Ltd. and Solander Ecological Research Ltd. for the Ministry of Environment, British Columbia.

Technical Review Team – Terms of Reference

Introduction

This Terms of Reference, or Team Charter, provides guidance on the terms, conditions, and process for participation on the Technical Review Team.

Project Scope of Work

The Winter Flow Requirements project consists of two main parts:

1. Reviewing and assessing science-based information on winter low flows and flows under ice conditions relevant to BC, and
2. Developing decision-support tools to be used for guiding risk assessments of water diversions for the Province.

The Technical Review Team will support a Team of Consultants tasked with carrying out this work.

Technical Review Team Mandate

The overall purpose of the Review Team will be to provide technical feedback and advice at strategic points during the assessment and development of winter flow requirements. Participants on the Review Team will be expected to:

- Abide by these Terms of Reference and code of conduct;
- Agree to the overall process and guiding principles;
- Attend and openly participate in all meetings; and
- Read background materials sent out in advance of each meeting.

While the specific tasks and nature of the technical meetings may depend on the nature of the preliminary analysis, it is expected that the Review Team will be asked for advice in relation to:

- Reviewing relevant background information;
- Sharing information and data sources that support analysis efforts;
- Commenting and/or providing judgements on:
    - How winter flow conditions have been characterized
    - A meta-analysis of winter flow studies
    - Desk top methods for determining instream flow needs
    - Risk based thresholds associated with ecosystem stress (e.g., thermal and connectivity)
- Discussing knowledge gaps and recommending possible future studies

Deliverables

The goal of the Technical Review Team will be a series of broadly supported recommendations in relation to the Consultants' analysis work and reports on winter flow requirements. While consensus of the Review Team's recommendations will be sought, it is not mandatory and in those areas of technical disagreement the reasons will be provided.

Schedule

In total, three Technical Review Team meetings are anticipated for this project. The first two meetings are considered interim and tentatively scheduled for the beginning of February and March 2012. The final meeting is scheduled for the end of March 2012 and will review the project findings on winter flow requirements.

Guiding Principles

The development of winter flow requirements will be guided by the following principles:

- Work within existing legal framework;
- Develop flow recommendations from the perspective of protecting environmental resources;
- Minimize review costs;
- Maximize consistency and transparency;
- Use the best available information from all sources[1];
- Be explicit about uncertainties in information sources and predictions; and
- Be explicit about trade-offs both within (e.g., different species and life stages of fish) and among (e.g., ecosystem vs. human) target water uses.

The Technical Review Team may discuss and agree to other principles, which can be added to the core list above.

Code of Conduct

All members of the Technical Review Team will endeavour to:

- Support a fair, transparent and collaborative process;
- Treat others with courtesy and respect, and let opposing views co-exist;
- Listen attentively with an aim to understand;
- Be concise in making a point;

[1] Recognizing that information can come from many sources with varying degrees of detail, every attempt will be made to be systematic in the documentation of all sources; and make all information transparent and open to peer review (with the exception of confidential or proprietary information).

- Speak in terms of interests rather than anchoring on a specific solution or position;
- Avoid disruption of meetings (e.g., cell phones, caucusing at the table, etc.);
- Use the "parking lot" for issues that fall outside the meeting agendas;
- Aim to achieve consensus on issues being addressed

In the event of technical disagreements, the facilitator(s) will use a structured and systematic approach to help clarify the underlying assumptions, biases, and potentially competing hypotheses in order to move forward. In forwarding a decision or recommendation in which there are dissenting viewpoints, these viewpoints shall be included.

In the event of personal or process related disagreements, the facilitator(s) will make every effort to resolve the issue(s) at the table and, if necessary, between meetings.

Consultant Team

The Consultant Team is responsible for carrying out the work and providing the Technical Review Team with the background information and preliminary analysis needed for their participation. The consultants are also responsible for facilitation of the Technical Review Team's workshops. The Consultant Team is comprised of members from Solander Ecological Research, EcoFish, Northwest Hydraulic Consultants and Compass Resource Management.

Communications

All materials distributed by the consultants during the course of this project should be considered draft and as such confidential. Accordingly, Technical Review Team members are asked to not forward nor distribute these materials to anyone external to this project.

Changes to Terms of Reference

The terms of reference may be amended by the Technical Review Team.

Salmonid winter ecology in interior BC streams and implications of winter water withdrawal

Prepared for:

BC Ministry of Environment
Water Protection and Sustainability Branch
c/o 395 Waterfront Crescent, 4th Floor
Victoria, B.C., V8W 9M2

March 2012

Prepared by:

Faulkner, S., T. Hatfield, S. Buchanan, and A. Lewis.[1]

ECOFISH RESEARCH

Ecofish Research Ltd.

[1] Certifying professional

Published by Ecofish Research Ltd., Suite F, 450 8th St., Courtenay, B.C., V9N 1N5

Citation:

Faulkner, S., T. Hatfield, S. Buchanan, D. Bustard, and A. Lewis. 2012. Salmonid winter ecology in interior BC streams and implications of winter water withdrawal. Consultant's report prepared by Ecofish Research Ltd. and Solander Ecological Research Ltd. for the Ministry of Environment, British Columbia.

Certification:

Disclaimer:

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

The British Columbia Ministry of Environment (MOE) is leading efforts to review and analyze science-based information on winter low flows and flows under ice conditions, and to develop decision-support tools for guiding risk assessments of water diversions in British Columbia (BC). This report is part of a larger project referred to as the MOE Winter Flows Project. The primary objective of the report is to conduct a literature review, and to analyse and synthesize existing scientific information relevant to BC on winter flow sensitivity (low flows and under ice conditions) related to health of fish populations and ecosystem functions. Of particular interest is the influence of flow on fish habitat in winter and the effects on fish populations and ecosystem functions.

The main questions addressed in the report are:

1. What is "winter"?
2. What do fish do in winter?
3. How does habitat change in winter?
4. What effect does water withdrawal have on winter habitat?

The information used to answer these questions is then used to explore impact pathways associated with winter flow reductions on fish and fish habitat.

2. METHODS

Detailed reviews of winter ecology of stream fishes and the effects of winter flows are available in the published literature (e.g. Cunjak 1996; Huusko et al. 2007; Brown et al. 2011). These documents and a variety of supporting documents were assembled from our library, online services (e.g., Google Scholar, NRC Journals, American Fisheries Society, and Wiley Science), and a number of sources specific to BC (e.g., MOE reports and data, DFO technical and manuscript reports, and consultant's reports). We summarized information from these sources to review winter low flow conditions and flow-stressors (e.g., water withdrawals) related to health of fish populations and ecosystem functions from BC and relevant jurisdictions (e.g., Canada, Alaska, and other similar climates).

We assessed whether sufficient quantitative information is available to conduct a meta-analysis of winter low flow conditions in reference research sites in Canada, USA and elsewhere to determine if common flow thresholds exist (e.g., % of long term mean annual discharge (LT MAD), % of natural flow) or if a range of flow related to health of fish populations and ecosystem functions is useful, in a predictive way. A meta-analysis combines the results from multiple studies to address a set of related hypotheses. An effective meta-analysis requires quality data with similar metrics (e.g., differences or means) for comparison, and suffers from an absence of null-result studies, which are rarely published but yet can provide significant insight. Null-results occur when an experimental outcome does not show an otherwise expected result or when an experimental result is not significantly different from what is expected under the null hypothesis. After examination of the available data we determined that information is not sufficient to support a quantitative meta-analysis, so we provide a narrative review only.

3. LITERATURE REVIEW

3.1. What is "winter"?

3.1.1. Ice Processes in Streams and Rivers

In defining winter ice processes in streams the following information is based on reviews by Huusko et al. (2007), Brown et al. (2011) and NHC (2011) and references included within.

For this review, we use Cunjak's (1996) definition of winter:

> "the period immediately following egg deposition by autumn-spawning salmonids (and coincident with a decline in water temperature) and extending until the loss of all surface ice (often accompanied by a major spate and snowmelt) and prior to any reproductive activity by spring spawning, non-gadid fish."

This definition is more appropriate than the calendar definition of the period between the winter solstice and the spring equinox within the Northern Hemisphere, because freezing water temperatures and ice are often present in north-temperate streams well before December and last as long as frigid air temperatures and moderate water discharge persist. These freezing water temperatures and ice can have a large influence on stream fish habitat. Streams with substantial ice formation are the focus of our review, which are typical conditions in most interior British Columbia streams.

Many factors affect the formation of ice on streams. The rate of water cooling and ice formation depends on the flow, depth and the meteorological conditions (e.g. temperature). Under conditions with similar air temperatures and solar radiation, shallow streams will cool faster than deep streams and ice will appear after a shorter period of sub-zero temperatures. If there is a local source of warmer water such as a large reservoir or significant groundwater, longitudinal temperature gradients from the source develop along the river in response to the heat loss/gain at the water surface. Timing and amount of snow accumulation have large effects on ice development. Whether precipitation in the winter comes as snow, or mix of rain and snow, also has an effect and may be related to latitude, longitude and elevation of the stream. The morphology of the stream or river—the slope, shape and physical character of the channel—also have a critical role in ice processes. In general, morphology and corresponding ice formation processes are different for small steep rivers, large rivers and regulated rivers: small steep rivers are characterized by turbulent flows, large rivers are characterized by calm laminar flows, and regulated rivers are characterized by varying flows (Table 1). Although these are general characterizations, individual mesohabitat units within these systems (e.g. small steep rivers or large rivers) will have both dynamic and stable ice formation depending on flow conditions at a smaller spatial scale. The formation and presence of ice may also influence variables that affect ice processes (Huusko et al. 2007).

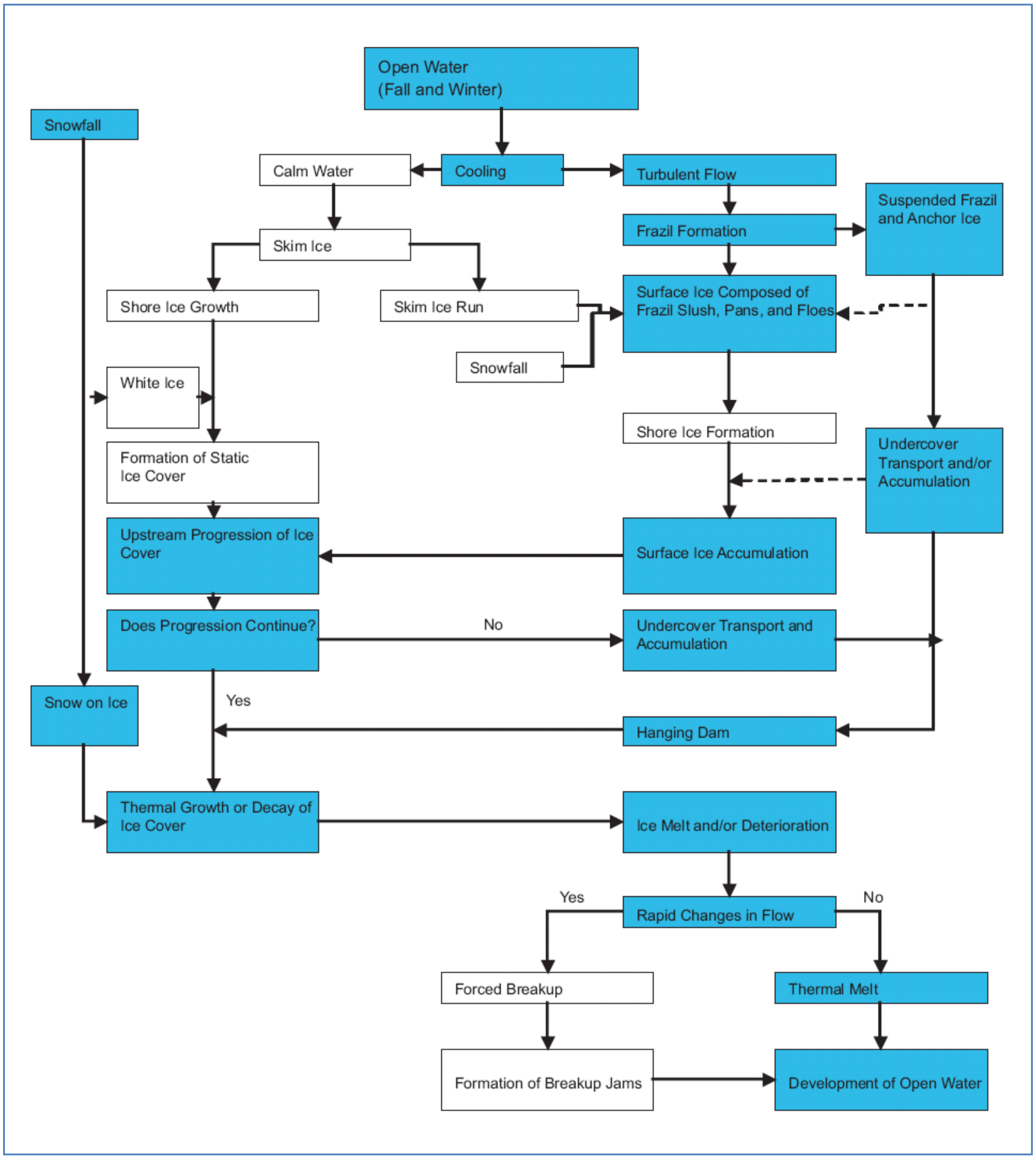
Under calm conditions, most of the ice-related processes are confined to the surface of the stream. A threshold velocity of <0.6 m/s (Ashton 1986) has been widely used and is accepted today as a general 'rule-of-thumb' for static ice formation (Stickler et al 2010). This is because the turbulence level is insufficient to entrain ice and supercooled surface water, even though the turbulence may be sufficient to prevent the formation of vertical gradients in temperature. That is, ice will form on the surface and stay on the surface if the mean value of the vertical turbulent velocity fluctuations at the water surface is less than the rise velocity of a frazil ice particle that forms at the surface. This is analogous to the rise of a bubble or the settling of a sediment particle within the water column. Since the type and thickness of an ice cover depends on the hydraulic forces that are exerted on the ice cover during its formation, calm rivers and streams with low gradients and velocities generally produce relatively thinner and hydraulically-benign ice covers. Stream gradients of between 0.3 and 0.6% or greater have been suggested to be related to frazil/anchor ice formation (Tesaker 1994); however, others have suggested even lower gradients (0.1%; Stickler and Alfredsen). Stream size also influences ice processes. Ice production in small, steep rivers can be dynamic, with both melting and freezing occurring throughout the winter due to higher water velocities and turbulent flow, whereas ice conditions in large rivers are generally more stable (Huusko et al. 2007). Anchor ice can become a significant factor even in relatively large and slow rivers especially during very cold clear periods in the winter when there is no ice/snow cover with the repeated formation of anchor ice and subsequent melting during the day (Butler 1979). This process has also been observed on the Bulkley River which is a relatively gentle river (D. Bustard pers. comm. 2012).

Winter can be divided into three main periods: early winter (freeze-up), mid-winter (stable conditions) and late winter (ice break-up) (Huusko et al. 2007). A general description of the major ice processes during these periods is provided below. An overall schematic representation of ice processes from NHC (2011) is provided in Figure 1.

Table 1. Generalized ice processes over the course of winter in three types of rivers (from Huusko et al. 2007).

Ice regimes	River Type		
	Small, steep rivers	**Large rivers**	**Regulated rivers**
Early Winter Freeze-up	Border and skim ice Dynamic ice formation	Border and skim ice Ice over formation	Border ice Dynamic ice formation
Mid-Winter	Extended dynamic ice formation Anchor ice dams Local ice runs	Stable ice cover Dynamic ice formation in open riffles	Less surface ice Local ice runs Increased dynamic ice formation
Late Winter Ice break-up	Thermal ice break-up	Thermal ice break-up	Repeated mechanical ice break-ups throughout winter

Figure 1. A schematic representation of ice processes from NHC (2011).



3.1.2. Early Winter (Freeze-up)

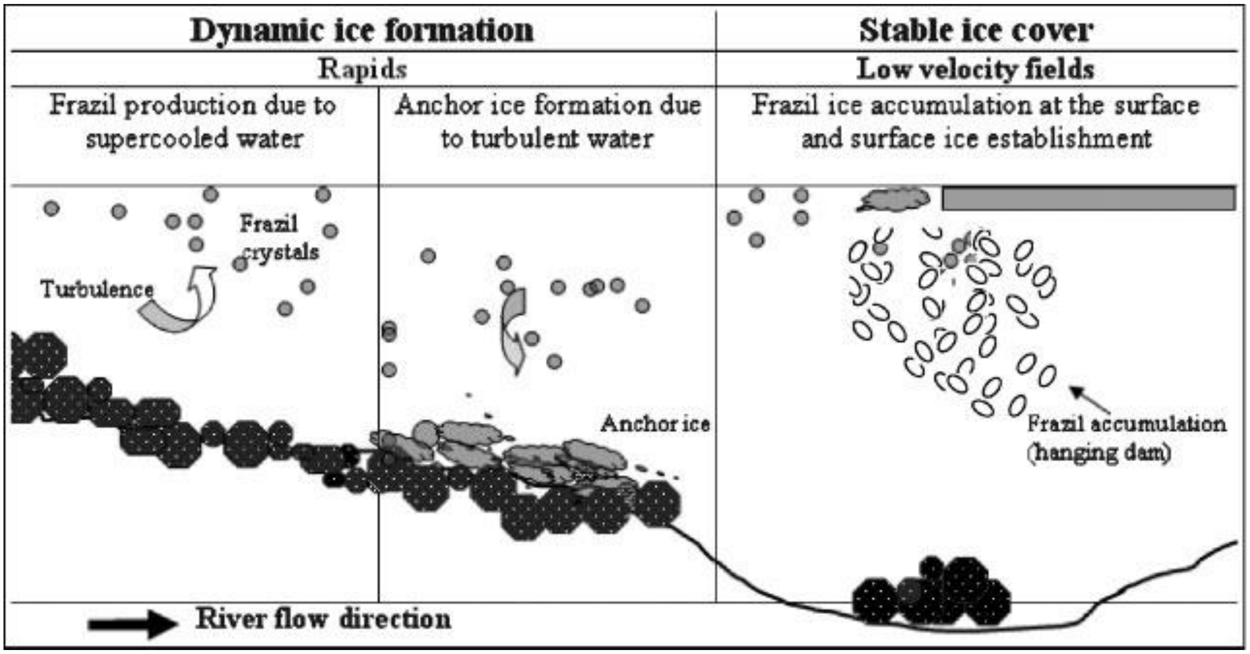
The ice formation process begins in the fall or early winter during open water when low temperatures and negative energy balances cool the water until it reaches the freezing point (Huusko et al. 2007). At the onset of freezing, border ice is formed along the stream margins and skim ice is formed in areas with low velocity (Figure 2; Huusko et al. 2007). Typically, in large, low gradient rivers this type of static ice formation continues until the river is completely covered; whereas in high gradient streams and river sections dynamic ice formation occurs due to super-cooling and turbulence (Brown et al. 2011). Super-cooling occurs when the entire water column cools to below 0°C and occurs in streams and rivers where current velocity, and turbulent mixing is sufficient to overcome stratification and produce a uniform water temperature within the stream (Brown et al. 2011). Supercooling levels are small, typically less than 0.1°C. In practical terms, supercooling occurs when little or no surface ice is present, the air temperature is sub-freezing, and the water flow is sufficiently turbulent to overcome stratification.

Frazil ice is typically associated with dynamic ice conditions in super-cooled water. Frazil production often has a diurnal cycle with growth during the night and little or no growth during the day (Huusko et al. 2007). However, during conditions with severe cold, frazil ice may also form during the day (Huusko et al. 2007). Frazil ice may be produced, adhere to submerged objects, and can accumulate in large quantities. When frazil ice accumulates on the stream bed this is known as anchor ice and when it adheres to the underside of surface ice it can form hanging dams.

Anchor ice in streams and rivers typically consists of small fluffy ice crystals, which often have a milky appearance and may form extensive, porous blankets over the streambed (Huusko et al. 2007; Brown et al. 2011). Characteristics of the anchor ice are related to specific flow conditions. In riffles with fast current, it can become quite thick and create anchor ice dams, which temporarily block much or all of the discharge causing large fluctuations in water levels (Maciolek and Needham 1952; Stickler et al. 2008). During anchor ice formation, flow conditions may be substantially altered (Kerr et al. 2002; Stickler et al. 2007) by both raising the riverbed and by smoothing out irregularities on the river bottom (Huusko et al. 2007). Normally, anchor ice is found in highly turbulent, shallow rapids with rough substrates, but it can also occur in deep areas. Anchor ice has been observed to lift from channel beds during early daylight hours following cold nights when frazil ice is formed. This can also occur in a daily cycle during the clear cold periods when anchor ice forms at night and melts/lifts during the day, which was described by Butler (1979). Anchor ice can transport large amounts of sediment, gravel, and aquatic invertebrates downstream (Kempema et al. 2002). It is common to see frazil slush on the surface of streams or rivers after a period of frazil ice production (Brown et al. 2011). Frazil slush is composed of anchor ice lifted from the bottom and frazil ice crystals, either singly or flocculated together. Since ice is buoyant, the frazil slush can consolidate on the water surface and pack or clump together into large floes (Brown et al. 2011).

Hanging dams are formed when frazil ice is deposited on the underside of surface ice in areas with reduced water velocity, such as pools. In some cases, these hanging dams can extend to the riverbed. Once a hanging dam is formed, it may last until spring (Brown et al. 2000). Hanging dams can become quite large (e.g., extending across the channel of large rivers and up to a kilometre or more in length), restrict water flow, and increase current velocities through pools, transforming pools into areas with high current velocities (Cunjak and Caissie 1994; Brown et al. 2000).

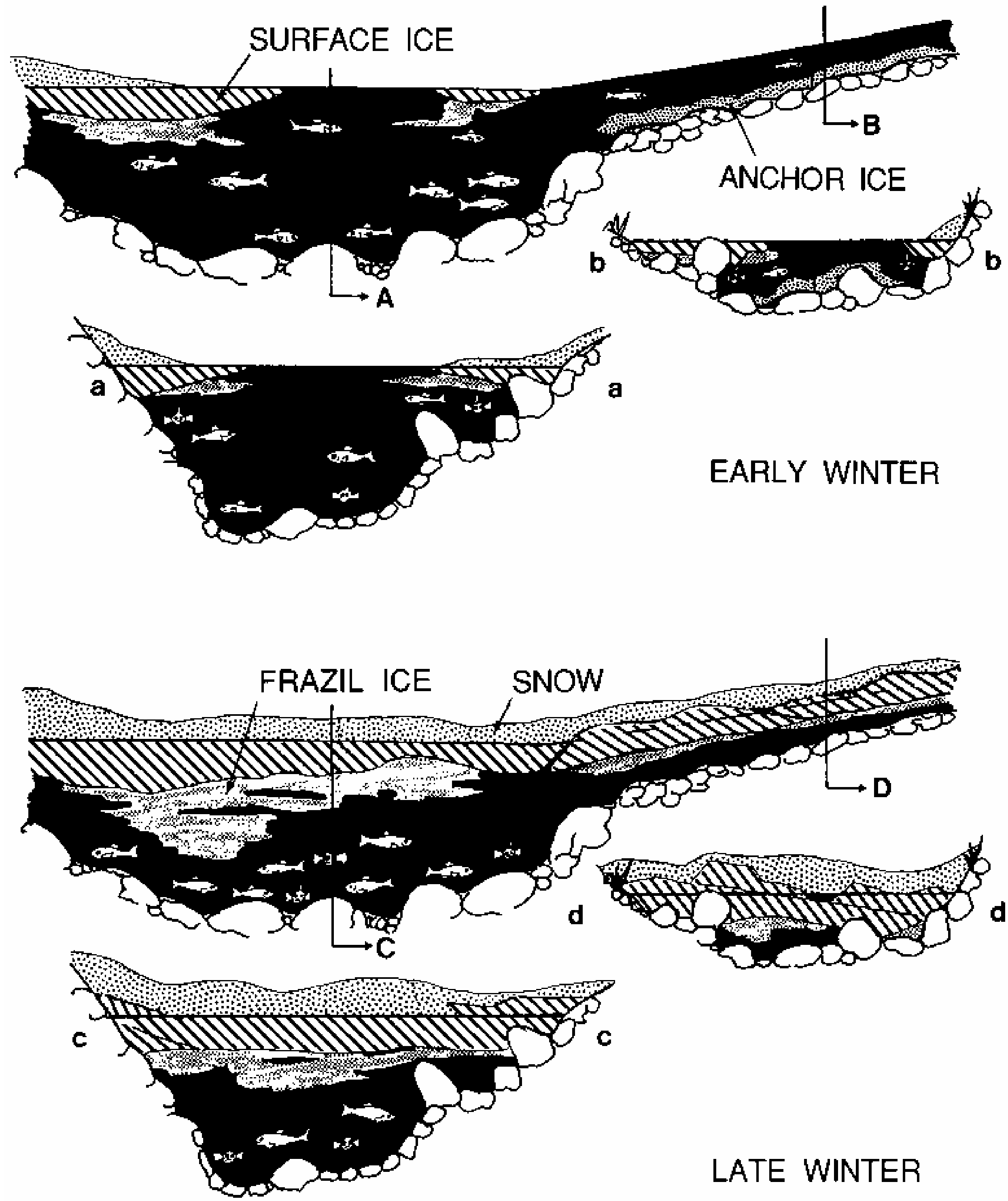
Figure 2. A schematic illustration of ice formation in rivers from Huusko et al. (2007)



3.1.3.Mid-Winter

Local meteorology, topography and individual stream characteristics influence icing conditions during mid-winter. In large, low gradient streams and rivers this period is characterized by a stable, ice-covered state with ice-free openings in riffles. The insulating effects of an early and deep snow cover on a stream will have a large bearing on subsurface ice formation during the mid-winter period. Small, high gradient streams may undergo an extended period of dynamic ice formation before reaching stable winter conditions (Huusko et al. 2007). Ice development in higher elevation streams has also been shown to be associated with the snowpack and its insulating effects (Chisholm et al. 1987). As discussed in Section 3.1.1, surface ice formation is normally prevented by the high velocity, turbulent water flow. Partial or full ice cover may still form in these streams due to frazil ice accumulations. These frazil ice accumulations may occur where frazil ice adheres to solid objects, clustering into large structures, or form anchor ice dams (Huusko et al. 2007). Anchor ice dams affect stream morphology by raising the water level and creating backwatered areas that may freeze over (Huusko et al. 2007). Dynamic ice conditions may also be present throughout the winter with ice forming and thawing in response to variable winter temperatures in streams where stable ice formation does not occur (e.g. high gradient, low to mid elevation streams). A representation of the change in habitat availability in a temperate stream riffle and pool as winter progresses and ice accumulates is provided in Figure 3 (from Cunjak 1996). The presence of surface ice and snow cover also influence dynamic ice conditions. During underwater and under ice observations in Sagehen Creek, Needham and Jones (1959) found that when ice and snow were present anchor ice formation was much less than pre- ice and snow cover.

Figure 3. Representation of the change in habitat availability in a temperate stream riffle and pool as winter progresses and ice accumulates (from Cunjak 1996).



3.1.4. Late Winter (Ice break-up)

Ice break-up is one of the most significant hydrological events of the year (Prowse 1994; Prowse and Culp 2004). The conditions that lead to ice break-up fall between two extremes, mechanical break-up and thermal break-up (Huusko et al. 2007, Brown et al. 2011). During an ideal thermal break-up, ice cover deteriorates through warming and the absorption of solar radiation, and melts in place, with no increase in discharge and little or no movement of ice. At the other extreme is the more complex and less understood mechanical breakup. Mechanical breakup results from an increase in discharge and requires no deterioration of ice cover. The increase in discharge fragments the ice cover and these fragments are transported downstream by the current. This can cause considerable scouring of the stream and in some instances riparian areas and an increase in sediment transport (Cunjak et al. 1998; Prowse and Culp 2004). Water quality issues can also occur at this time as snow and ice melt (Prowse and Culp 2004).

Most ice breakups fall somewhere between the extremes of thermal and mechanical break-up (Brown et al. 2011). Ice jams may occur where the ice fragments accumulate and severe and sudden flooding can result upstream of the ice jams, or when they release. In some cases surface ice cover can fill the entire channel with chunks of ice and create ice jams that flood large upstream segments of streams or rivers and adjacent floodplain and leave downstream segments dewatered (Brown et al. 2011).

3.1.5. Summary

Ice processes in streams are controlled by meteorological conditions, flow, depth, and water velocity. Static ice formation is associated with slow velocity and occurs in low gradient sections such as pools and areas along stream margins (Ashton, 1986). A threshold of <0.6 m/s (Ashton 1986) has been widely used and is accepted today as a general 'rule-of-thumb' for static ice formation (Stickler et al 2010). Above this velocity threshold dynamic ice processes (frazil/anchor ice) occur. Stream gradients of between 0.3 and 0.6% or greater have been suggested to be related to frazil/anchor ice formation (Tesaker 1994); however, others have suggested even lower gradients (0.1%; Stickler and Alfredsen). These thresholds can be used to divide streams or stream sections into steep and low gradient where different ice processes will occur.

3.2. <u>What do fish do in winter?</u>

Literature reviews on winter ecology of fish have been conducted by Cunjak (1996), Huusko et al. (2007) and Brown et al. (2011). The following information is based largely on these reviews and references therein. The focus of our review is on fish habitat in streams in relation to ice formation. A lot of the work is based on different fish species than found in BC; however, Atlantic salmon and brook trout provide good proxies for species such as rainbow trout/steelhead and char such as Dolly Varden and bull trout. We do not review the physiological response of fish to winter conditions. Causes and consequences of winter mortality of fishes were reviewed by Hurst (2007). The factors influencing winter mortality and suspected primary sources of winter mortality are shown in Figure 4. Catastrophic events that may cause mortality are not included in this figure.

Cunjak (1996) suggests that suitable physical habitat features (e.g., low velocity areas, instream cover), are the primary factor regulating stream fish populations in winter because reduced metabolic demands at low water temperatures lessen, or eliminate, time spent feeding and defending territories. Many studies have suggested that winter habitat selection is based on minimizing energy expenditure (Bustard and Narver 1975; Cunjak 1988a; Griffith and Smith 1993; Riehle and Griffith 1993). Assuming the principal factor governing the choice of winter habitat is to minimize energy expenditure, Cunjak (1996) proposed a relative priority in selecting winter habitat (Table 2). Access to food is still required in winter to avoid starvation, but food is of relatively lower importance than during the growing season. In experimental winter conditions with no predation, Parish et al. (2004) showed a distinct advantage for parr to expend energy to feed during winter.

Figure 4. Schematic representation of factors influencing winter mortality in fishes. Primary sources of winter mortality (in boxes) are influenced by environmental conditions (intrinsic, abiotic and ecological) directly or indirectly (indicated by processes). Likely interactions between mortality sources are indicated by dashed lines (from Hurst 2007).

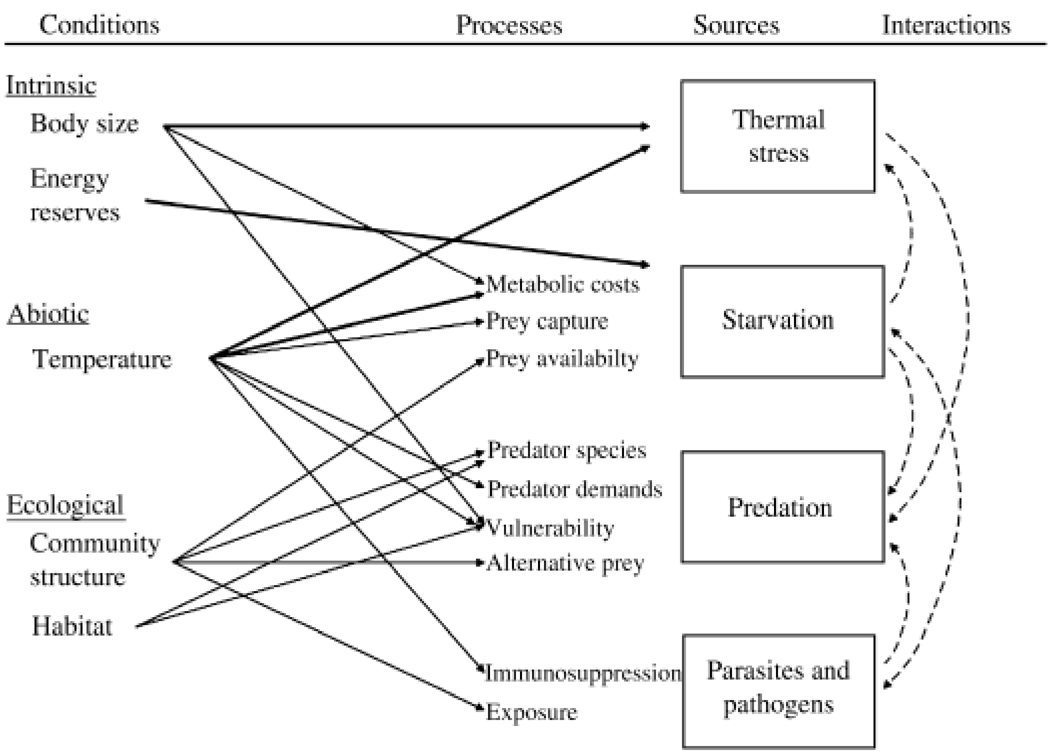


Table 2. Generalized criteria for winter habitat selection by fishes in natural, coldwater streams, listed in order or relative importance (from Cunjak 1996).

Relative priority[a]	Habitat criterion	Example(s) of selected habitat
1	Protection from adverse physicochemical conditions (e.g., ice, low oxygen, winter freshets), and access to refugia or alternate winter habitats	Suitable water depth, instream cover, floodplain habitat and side-channels, source of aeration, groundwater discharge zones, subice corridors
2	Protection from predators	Suitable water depth, instream cover
3	Access to food	Low-velocity (micro)habitats and concomitant shift to nocturnal, benthic feeding pattern

[a]Relative priorities can vary among life stages and for different streams depending on availability of food, on water temperature (and metabolic demand), on local predator density, and on the stability of environmental conditions.

3.2.1. Movement to winter habitat

The slowing of metabolism of fish with decreasing temperatures during fall and winter affects the behaviour and habitat use by fish in lotic environments (Cunjak 1996, Brown et al. 2011). As water temperature decreases in autumn fish shift to low velocity areas to conserve energy (Cunjak 1996) and obtain shelter from predators (Valdimarson and Metcalfe 1998). In general salmonids tend to move to habitat with increased water depth, reduced water velocities and suitable cover (Cunjak 1996, Hiscock et al. 2002; Huusko et al. 2007, Brown et al. 2011). This may require small-scale microhabitat shifts, movements to different mesohabitat and macrohabitat, or even greater migrations if suitable habitats are not available in the stream (Bjornn 1971; Huusko et al. 2007). Movements may therefore vary from a few meters to hundreds of kilometers (Rimmer et al. 1983; West et al. 1992; Gowan et al. 1994; Young 1998). Not surprisingly, if appropriate overwintering habitat is present in summer habitat no substantial movement is required (Rimmer et al. 1983; Heggenes and Dokk 2001). Within-river shifts between reaches (e.g., between summer positions in riffles and overwintering sites in low velocity areas or in warm groundwater or lake outlet areas) are typical for adult salmonids (Cunjak and Power 1986b; Brown and Mackay 1995; Simpkins et al. 2000). Such movements generally coincide with the decline of water temperature below a critical temperature. Typically, the shift occurs at water temperatures between 3 and 6°C (Hillman et al. 1987; Jakober et al. 1998; Bramblet et al. 2002). In addition to temperature, an increase in discharge, and possibly even changes in day length or prey availability are thought to play a role in the timing of autumnal habitat shifts (Peterson 1982; Huusko et al. 2007).

Species and size affect the type of habitat shifts displayed. Small fish seek cover in interstitial space in the stream substrate, whereas large-bodied individuals may have to move into slow velocity areas to find suitable shelters from ice and predators (McMahon and Hartman 1989; Lindstrom and Hubert 2004). Slow velocity areas used for overwintering of salmonids may include pools, backwater areas, off-channel ponds (or alcoves), logjams, swamps, side channels, beaver ponds and tributaries, and the amount of available cover influences the number of fish that overwinter in an area (Tschaplinski and Hartman 1983; Bustard 1986; Swales et al. 1986; Meyer and Griffith 1997). Areas with these types of habitats are often limited in streams and rivers, so it is common for fish to be found in large groups or aggregations within more optimal habitats (Huusko et al. 2007).

Fish movement in winter is typically minimal and declines throughout the winter (Cunjak 1996, Jakober et al. 1998; Hiscock et al. 2002; Huusko et al. 2011). However, movement patterns can be complex and may be related to the stability of winter conditions (Huusko et al. 2007). The accumulation of frazil and anchor ice in preferred habitats may lead to long distance movements (Brown et al. 2000; Simpkins et al. 2000; Dare et al. 2002; Lindstrom and Hubert 2004). Salmonids have also been found to be more mobile in areas with unstable ice conditions compared to areas with stable ice conditions (Jakober et al. 1998, Brown et al. 2000; Simpkins et al. 2000). Movements of salmonids typically coincide with cold periods of frazil and anchor ice formation. Winter movement has been found to be more extensive in mid elevation streams where frequent freezing and thawing leads to variable surface ice cover and frequent supercooling (Jakober et al. 2008). Stable ice formation that concentrates flow (edge ice) and increases velocities may also reduce habitat usability and cause movements and redistributions of salmonids (Whalen et al. 1999). Small movements may also be related to declining flows through the winter. For example, Chinook or steelhead using interstitial cobbles along the edge may have to shift as flows decline and edge areas dewater.

Where salmonid movements related to ice formation have been identified, they have been attributed to changes in habitat suitability, primarily the physical exclusion properties of ice (Chisholm et al. 1987; Cunjak and Randall 1993; Brown and Mackay 1995).

3.2.1. Biotic Interactions/Aggregations

At low temperature, salmonids become less aggressive and territorial behaviour is reduced (McMahon and Hartman 1989; Heggenes et al. 1993; Hillman et al. 1987; Riehle and Griffith 1993; Griffith and Smith 1993). Reduction of territorial aggression may also result from limited availability of winter habitat (Cunjak 1996; Brown et al. 2011). Anchor or frazil ice formation can force stream salmonids into restricted areas, resulting in large aggregations of fish (Brown and Mackay 1995; Whalen et al. 1999; Brown et al. 2000). The effects of these large aggregations on fish may also depend on species/life stage. Coho salmon in aggregations were found to exhibit feeding and aggression while under cover at temperatures of 2.5°C (McMahon and Hartman 1989). Coho salmon abundance was found to be influenced by these social interactions and habitat features (structural complexity of wood debris) within stream habitat in the winter (McMahon and Hartman 1989). In addition, Hartman (1965) showed that due to small differences in habitat use by coho salmon and steelhead, these two species can co-exist in the same habitats during the winter. However, Harwood et al. (2002) showed that winter competition for refuges, both within and between species of salmonid, is likely to be intense if refuge availability is limited in the wild.

3.2.2. Diel activity

Huusko et al. (2007) provides a comprehensive discussion of diel winter activity of salmonids. Juvenile salmonids are active during both day and night in the summer, but become largely nocturnal in winter (Cunjak 1988b; Heggenes et al. 1993; Jakober et al. 2000; Heggenes and Dokk 2001; Hiscock et al. 2002); however, large individuals (25–60 cm) may remain active during the day (Heggenes et al. 1993). This nocturnal behaviour has been documented for Atlantic salmon (*Salmo salar)*, Chinook salmon (*O. tshawytscha*), coho salmon, brown trout (*S. trutta*), rainbow trout (*O. mykiss*), Arctic char (*Salvelinus malma*), bull trout (*S. confluentus*), and cutthroat trout (*O. clarkii*; Campbell and Neuner 1985; Cunjak 1996, Huusko et al. 2007, Brown et al. 2011). As Huusko et al. (2007) note though, most of these observations of nocturnal behaviour in winter are from streams without ice cover and this pattern may only be valid for these systems. Everest (1969) found Chinook salmon and steelhead deep into the boulder habitat with a layer of anchor ice over it 5-10 cm deep in an Idaho stream. These fish must be staying in this habitat for longer periods and not making diurnal forays. He speculated depth and velocity over the rocks were of little importance except how they influence intrasubstrate water movement.

Temperature is believed to be the major determinant of when fish shift to nocturnal only activity (Rimmer et al. 1983; Campbell and Neuner 1985; Heggenes et al. 1993; Huusko et al. 2007). The temperature for when this seasonal change to nocturnal behaviour occurs also varies widely among studies and species, ranging from 5 to 13°C (Huusko et al. 2007). Nocturnal activity may also be affected by other factors that interact with temperature. These factors may include light intensity, social status, life history strategy, age, and predation risk (Heggenes et al. 1993; Valdimarson and Metcalfe 1998; Huusko et al. 2007). Flow may also influence nocturnal activity; Robertson et al. (2004) found a reduction in night activity during high flow periods in late winter.

The change to nocturnal behaviour has been related to adverse physical conditions associated with ice formation (Huusko et al. 2007). Due to increased ice formation at night, the risk of being trapped in anchor ice is greater at night (Heggenes et al. 1993; Whalen et al. 1999). Frazil and anchor ice has been observed to form and disperse on a daily cycle, forming at night and dispersing during the day (Maciolek and Needham 1952). Therefore, leaving the river bottom before nightfall would reduce the risk of being trapped by ice (Huusko et al. 2007). Everest (1969) found that juvenile Chinook salmon and steelhead were in the substrate under anchor ice cover. Another factor believed to cause the switch to nocturnal behaviour is predation risk by diurnal endothermic predators (Heggenes et al. 1993; Valdimarson and Metcalfe 1998). When given a choice fish clearly preferred cover that allowed them to hide but offered little shelter from the current, suggesting that the primary function of nocturnal behaviour is concealment from predators (Valdimarson and Metcalfe 1998). However, velocities examined in this experiment were low and ranged from 0 to 0.036 m/s; and reducing metabolic demands may become more important at higher velocities. The peak feeding of juvenile rainbow trout has also been shown to correspond with this diel behaviour (Riehle and Griffith 1993).

3.2.3. Habitat Use

Diel changes in activity lead to changes in microhabitat use (Huusko et al. 2007). During the day juvenile salmonids typically use cover in coarse substrates, aquatic vegetation, large woody debris, deep slow flowing water and at night they leave the cover and enter the water column (Cunjak 1996, Huusko et al. 2007). At night salmonids have been found to be associated with stream margin habitat (Cunjak 1988b; Whalen et al. 1999). The maximum availability of winter microhabitats for resident stream fish communities may be achieved where complexity of instream structure and form is conserved. Habitat quality may be more important than quantity in winter (Cunjak 1996). For example, Stickler et al. (2008) and Linnansarri et al. (2009) found high site fidelity and good performance (estimated by growth rate) during winter for Atlantic salmon parr that had access to areas with suitable cover such as low substrate embeddedness.

3.2.3.1. Velocity and depth

As discussed above, salmonids typically move into deep, low velocity microhabitats during late fall and display nocturnal behaviour (Cunjak and Power 1986b; Baltz et al. 1991; Simpkins et al. 2000; Heggenes and Dokk 2001; Maki-Petays et al. 1997, 2004). In general, when examining microhabitat use, the slow focal velocity areas of active fish in winter are situated in close proximity to high water velocity areas so that fish take advantage of high drift densities (Cunjak 1988b; Simpkins et al. 2000). However, several studies have reported use of shallow, fast velocity areas in winter especially for juvenile Atlantic salmon (Rimmer et al. 1983; Cunjak 1988b; Roussel et al. 2004).

The mean water column velocity and depth used by salmonids in winter varies from 0 to 60 cm/s and 0 to 400 cm, respectively (Huusko et al. 2007). These mean water column velocities and depths may not accurately reflect habitat use; however, data on focal velocities are sparse. Typical values of mean water column velocity and depth are <40 cm/s and 20 to 60 cm for juvenile *Salmo spp*. (Maki-Petays et al. 1997, 2004; Whalen et al. 1999; Heggenes and Dokk 2001), <30 cm/s and >40 cm for *Oncorhynchus spp*. (Everest 1969, Baltz et al. 1991; Harper and Farag 2004) and 20 to 80 cm/s and 150 to 400 cm for adult grayling (*Thymallus thymallus*; Nykanen et al. 2001, 2004a, 2004b), respectively. Winter depth and velocity suitability curves have been estimated for rainbow trout based on observations of Campbell and Neuner (1985) and professional judgment (Washington State 2008). In a study of overwintering habitat of westslope cutthroat trout in Cupola Creek near Golden BC, it was found that they were most abundant in pools greater than 0.5 m in depth (Oliver 2010). Diel differences in microhabitat use reported are most likely a reflection of differences in daytime and night time activity. Focal velocity is close to 0 cm/s when fish are in substrate cover during the day.

Parish et al. (2004) examined the effect of velocity on survival of Atlantic salmon parr overwinter in controlled raceways. They found that within these controlled environments higher velocities led to higher growth and survival over winter due to increased feeding. It should be emphasized that the velocities used in the experiment, high (12 cm/s) and low (6 cm/s), are both fairly low and within the range of what has been reported for use in the wild during winter (<40 cm/s) (Maki-Petays et al. 1997, 2004; Whalen et al. 1999; Heggenes and Dokk 2001).

3.2.3.2. Cover and Substrate

Juvenile salmonids have been found to seek cover during daytime in unembedded coarse substrates (Cunjak 1988b, 1996; Griffith and Smith 1993; Jakober et al. 1998; Stickler et al. 2008). However, salmonids are not always restricted to areas with coarse substrate during daytime in winter. Salmonids have also been found to use areas with smaller substrate for cover (as described by Huusko et al. 2007). At night, when salmonids are active, they are not restricted to coarse substrates. The majority of juvenile salmonids have been found on or close to the bottom during night, over silt, sand and gravel habitats, even when cobble and rubble substrates dominate (Heggenes et al. 1993; Heggenes and Dokk 2001). This substrate selection at night may be a reflection of selection for slower water velocities.

In addition to coarse substrate, salmonids also find cover in winter under large woody debris, aquatic vegetation, undercut banks, surface turbulence and ice (Baltz et al. 1991; Heggenes et al. 1993; Riehle and Griffith 1993; Cunjak 1996; Huusko et al. 2007). Large-bodied fishes may also seek cover in deep water (Cunjak 1996, Huusko et al. 2007). Woody debris is a preferred source of cover for brook trout (*S. fontinalis*), cutthroat trout, brown trout and coho salmon; however, during frazil ice events these fish may be forced to move into other areas (Brown et al. 1994; Cunjak 1996). Coho salmon and steelhead (*O. mykiss*) abundance have been found to be highest in pools with abundant instream cover and riparian cover (Swales et al. 1986). Hunt (1971) showed that by adding cover structures to Lawrence Creek, brook trout overwinter survival improved which led to overall standing crop improvements, angler use and yield.

Although, cover selection may differ by species and age/size class, the importance of unembedded coarse substrate cannot be ignored. This habitat is thought by many authors to be critical for overwintering (Cunjak 1996, Stickler et al. 2008, Huusko et al. 2007; Brown et al. 2011) and may be more important than depth and velocity (M. Stickler pers. comm. 2012). Linnansarri et al. (2009) found that a section of stream enhanced with large substrate supported juvenile salmon in autumn, winter, and early spring regardless of ice conditions, whereas the control section, with a limited amount of in-stream cover failed to provide suitable parr habitat during all study periods. However, when surface ice was present in the control reach it provided cover and increased the amount of suitable habitat during winter so that by mid-winter the entire control reach was being used by salmon parr during both study years. Jakober et al. (1998) also found that use of submerged cover by bull trout and cutthroat trout decreased following the formation of surface ice.

3.2.3.3. Role of Groundwater as Habitat Variable

Groundwater influences, if present, create areas of warmer water with a stream. The release of warm reservoir water in regulated rivers may also create warmer water conditions. Warm water may also be released from natural lakes. These warmer waters have been shown to attract fish during periods of cold water temperature (Huusko et al. 2007). Such behaviour has been documented for brook trout and cutthroat trout (Cunjak and Power 1986b, Brown et al. 1994; Brown and Mackay 1995). In the Morice River in BC, warm water released from Morice Lake keeps approximately 13 km of the river downstream from the lake ice-free, which attracts spawning fish (Bustard 1986). Specific observations of winter ice conditions in the Kemess Watershed indicated that ice-free areas in the watershed were indicative of groundwater. These groundwater fed seepages were key habitats in these upper watersheds and were used almost exclusively by Dolly Varden spawners (Bustard 1996). Bustard and Schell (2002) also outline the importance of lakes and groundwater inputs in northern interior BC streams, when water temperatures drop below 5°C. In the Yukon River drainage, Bradford et al. (2001) suggest that small streams with year round sources of groundwater are important overwintering habitat for juvenile salmon.

In some watersheds, groundwater influenced areas may represent the only ice free areas during winter and provide a place where all age classes may gather for overwintering (Brown et al. 1994; Huusko et al. 2007, Brown et al. 2011). The role of groundwater for overwintering habitat may differ by species. For example, Atlantic salmon parr have been shown to avoid spring sources, while brook trout prefer these areas (Cunjak 1996).

3.2.3.4. Role of Ice as Habitat Variable

Surface ice may provide important winter cover (Linnansarri et al. 2009), as densities of young-of-the-year rainbow trout were found to be two times greater in enclosures with 50% surface ice than in enclosures with 10% surface ice (Meyer and Griffith 1997). Surface ice also affects feeding as salmonids have been shown to feed less in areas lacking ice cover than in areas with full surface ice (Finstad et al. 2004a). In addition, it has been found that juvenile rainbow trout did not conceal themselves as often during daytime in coarse substrates when surface ice was present (Gregory and Griffith 1996). Border ice has also been shown to be used as overhead cover (Emmett et al. 1996; Stickler et al. 2007), and may be used while avoiding unstable frazil/anchor ice formation in open areas (Brown et al. 1994; Brown and Mackay 1995; Simpkins et al. 2000; Stickler et al. 2007). Bisaillon et al. (2007) found no evidence that surface ice cover limits fry or parr habitat and that surface ice may even provide protection against predation from birds and mammals, and thereby play a positive role in a fish's energy budget by decreasing resting metabolic rates and reducing energy loss during this time.

Frazil and anchor ice also affect microhabitat use by salmonids. The formation of frazil and anchor ice has been shown to cause cutthroat trout to move away from preferred woody-debris cover

(Brown et al. 1994; Brown and Mackay 1995). Salmonids have been observed moving to the bottom of deep pools or to shallow nearshore areas under shelf ice during frazil ice episodes (Jakober et al. 1998; Simpkins et al. 2000; Stickler et al. 2007). Frazil ice may also indirectly affect habitat use of fish by altering water velocities and depth. In pools, hanging dams create high near-bed water velocities. Brown trout have been found to move out of pools with hanging dams, but return when conditions are favourable (Brown et al. 2000).

3.2.3.5. Dissolved Oxygen

At low water temperatures metabolic rates of fish decrease, which reduces their demand for dissolved oxygen (DO); however, adequate DO is still component of winter habitat. Protection from adverse physiochemical condition such as low DO is considered the first priority in selection of winter habitat (Cunjak 1996). The availability of dissolved oxygen in rivers is a result of many factors that can be categorized as either sources or sinks (Cox 2003). The major sources of DO include: (1) reaeration from the atmosphere, (2) photosynthetic oxygen production, and (3) introduction of DO from other sources such as tributaries. The main DO sinks are: (1) oxidation of organic material, (2) degassing of oxygen in supersaturated water, (3) respiration by aquatic plants and animals, and (4) oxidation of reduced chemical species in sediments and groundwater. During winter, surface ice reduces reaeration from the atmosphere, and photosynthesis and inflows are usually low, which limits local production of oxygen and lateral transport of DO to some hydraulic units like side channels. In the Morice River, BC some sidechannels were found to be cut off during the winter, where the break-down of organic matter (mainly leaves from riparian area) led to low DO and mortality of juveniles that are unable to leave these sites (Bustard 1986). Although biological and chemical demands tend to also be lower in winter, a deficit may still arise, and low DO conditions may occur in some hydraulic units, with concomitant effects on habitat suitability for fish. In general, low DO may be a large potential problem in off-channel locations for species that use these areas (e.g. coho). Where fish are drawn into these areas during high spring or fall flows and then cannot survive the overwinter period due to inadequate through flows and low DO. Evaluations of off-channel pond habitat in the Telkwa River found that most of them were unsuitable for coho during the winter period due to low DO levels (Bustard 1986).

The proportion of groundwater during low winter flows may also influence levels of DO. Schreier et al. (1980) found that DO levels in Yukon rivers dropped as winter progressed and the proportion of groundwater with naturally low DO increased.

3.3. <u>How does habitat change in winter?</u>

Winter habitats of fish range from very stable to constantly changing due to variation in ice conditions and water temperatures (Brown et al. 2011). Static ice formation in streams is associated with slow-flow, low gradient sections such as pools and areas along stream margins (Ashton, 1986).

For example, the threshold of <0.6m/s (Ashton 1986) for static ice formation has been widely used and is accepted today as a general 'rule-of-thumb' (Stickler et al 2010). In addition, ice processes in individual streams may also be driven by stream order and habitat type (Scruton et al. 1997). Scruton et al. (1997) examined habitat in first to fifth order streams, and found that snow canopy cover on first and second order streams created stable constant habitat features free of anchor and frazil ice, while the fifth order stream was characterized by dynamic icing conditions and large changes in physical habitat throughout the winter. However, icing conditions in individual systems are expected to vary considerably in relation to their latitude, longitude and elevation.

In some lotic environments, static ice cover forms early in the winter and remains in place throughout the winter. Deep snow can also bridge small streams and provide stable overwintering habitats (Chisholm et al. 1987; Hubert et al. 2000; Lindstrom and Hubert 2004). However, among reaches of streams or rivers subject to icing, habitats without complete surface ice or snow cover are likely to have dynamic ice conditions (Lindstrom and Hubert 2004; Brown et al. 2011). The areas of open surface water are subject to ambient air temperatures which may promote supercooling and frazil ice.

From the start of freeze-up, ice can occlude fish habitat and influence fish behaviour, as discussed above. Stationary ice can form in fish habitat resulting in occlusion for short periods or even for most of the winter (Chisholm et al. 1987; Brown and Mackay 1995; Jakober et al. 1998; Lindstrom and Hubert 2004). As winter progresses, stationary ice cover can increase in thickness until it excludes large portions of habitats used by wintering fish in streams and rivers (Chisholm et al. 1987; Brown et al. 2011). Consequently, in streams with static ice formation (i.e., low gradient streams or stream sections) fish must reside in the deepest parts of rivers in pockets of unfrozen water or in areas influenced by groundwater (West et al. 1992; Brown et al. 2011).

Lateral growth of ice from the stream margin concentrates flow and increase velocities causing habitats selected by Atlantic salmon parr to become more spatially distinct and physically more concentrated (Whalen et al. 1999). The redistribution of habitat and reductions in physical space caused by ice formation may lead to high temporal variability in overwintering habitat (Whalen et al. 1999). This mechanism (redistribution or loss of suitable habitat) may also explain the distribution and movements of fish in winter (Cunjak 1988b, Griffith and Smith 1993, 1995). These studies support the hypothesis that ice is an important force instigating juvenile salmon redistribution in winter (Whalen et al. 1999).

In the Yukon River drainage, Bradford et al. (2001) suggest that small streams with year round sources of groundwater are important overwintering habitat for juvenile salmon. However, groundwater may also result in the presence of aufeis. Aufeis is a thick layer of ice that develops in the stream channel, caused by the freezing of groundwater that is forced by hydrostatic pressure to flow over existing ice or snow (Kane 1981). This process can cause thick ice deposits that may occlude fish from affected areas. In areas covered by aufeis in January, Bradford et al. (2001) found no juvenile salmon the following May.

Ice cover affects flow hydraulics in a number of ways: roughness and shear stress operate on both the bed and the bottom of the ice cover, and average velocity may be reduced due to greater overall resistance or increased due to constraining the conveyance area of the flow (Waddle 2007). Waddle (2007) modelled habitat under ice using River2D and found that as the ice became thicker and more of the channel edge became frozen to the bed, low-velocity areas became occupied by ice, forcing the flow into the remaining conveyance area with concomitant higher velocities. That is, ice produced less flow area and higher velocities.

Dynamic ice formation, which dominates high gradient streams, may cause changes to habitat by a number of mechanisms. Frazil and anchor ice build up can limit overwintering habitat be excluding access to cover and occluding habitat. Anchor ice can accumulate into anchor ice dams that reach the water surface causing backwatering. Frazil ice can also build up under surface ice and cause hanging dams.

Frazil and anchor ice can build up to the water surface and occlude fish from entire pools or reaches (Brown et al. 2011). When anchor ice fills a pool, the water is forced to flow through the ice in one or more high-velocity conduits, at water velocities that are often unsuitable for fish to maintain position (Brown and Mackay 1995; Jakober et al. 1998; Whalen et al. 1999). Several researchers have observed that fish are forced to make larger numbers of movements when influenced by frazil ice or anchor ice. Whereas larger juvenile and adult fish may be forced from their habitats by anchor ice, small juvenile fish may not be influenced. For example, Atlantic salmon parr have been found to use anchor ice as cover (Stickler et al. 2008).

Thick deposits of anchor ice in riffles can create anchor ice dams causing a water level increase upstream from the ice dam, and decrease downstream from the ice dam (Brown et al. 2011, Turcotte and Morse 2011). Stickler et al. (2010) quantitatively studied dynamic ice formation in three steep streams and found the formation of anchor ice and anchor ice dams to be the most common dynamic ice process. These anchor ice dams were found to induce significant backwater effects by increasing wetted areas (maximum 43%) and water depths (maximum 241%) and reducing water velocities (maximum 70%). This transformed the stream environment from fast-flow areas to slow-flow areas. The anchor ice dams and backwatering effects also changed the longitudinal profile initiated surface ice formation due to the reduced water velocities and contributed to the formation of stable static ice cover. Stickler et al. (2010) suggested that steep streams may significantly change character on a short time scale because of dynamic ice processes. Anchor ice dam formation may thereby benefit the winter ecology of stream biota. However, Turcotte et al (2011) found that ice cover in steep channels may not reach 100% cover because heat from relatively warm ground water inputs and heat from head loss along the stream may prevent sustained complete ice cover and cause degradation of the anchor ice dams.

Frazil ice can affect fish habitat by forming hanging dams, which may form frequently in cool-temperate and colder climates (Brown et al. 2011). Hanging dams may fill more than 80% of the volume of pools (Cunjak and Caissie 1994) causing much higher water velocities in the pools than in open water conditions (Brown et al. 2000). Hanging dams can cause difficulties for fish during winter, but they are often unnoticed because they form under ice and are difficult to observe. Increased water velocities coupled with reduced pool volume can change pools from suitable to unsuitable overwintering habitat. Radio-tagged fish have been shown to move out of pools where hanging dams formed, but often returned to the same pools after the hanging dams were no longer present (Brown et al. 2000; Lindstrom and Hubert 2004). Hanging dams can remain in place for a few days or from fall freeze-up to spring breakup (Brown et al. 2000).

Anchor ice formation and dispersal may also cause wide fluctuations in streamflow. Maciolek and Needham (1952) found that the daily formation of anchor ice at night and dispersal of anchor ice during the day led to lower flows at night that dewatered secondary channels and higher flows during the day that scoured the stream with ice fragments (Maciolek and Needham 1952).

There is conflicting evidence of winter being a bottleneck to fish production. Ice formation and ice processes may pose limitations to habitat as discussed above; however, it is unclear if this limits fish populations. Studies have also shown that if the stream section does not have suitable winter habitat fish leave: for example brook trout in Lawrence Creek (Hunt 1971), and Chinook Salmon in Lemhi Creek Idaho (Bjornn 1971). From a review of available literature and their own empirical study Carlson et al. (2009) found that overwinter mortality of fishes does not consistently exceed mortality during other seasons. Also, they concluded that larger fish size is not always better for overwinter survival and is often worse. Overwinter survival of Chinook salmon fry in the Yukon was also not dependent on fish size (Bradford et al. 2001). Webster and Hartman (2007) also found no bottleneck to brook trout during the winter and suggest that brook trout do not starve in winter.

Furthermore, it has been suggested that the highest mortality is related to a physiological response to the onset of winter conditions rather than a habitat reduced effect. Linnansarri and Cunjak (2010) found the highest decline in apparent survival (19.4 to 33.3% of the study population) occurred prior to ice formation during early winter acclimatization. Apparent survival then improved during the period affected by subsurface ice and was further improved when surface ice was prevailing. Bisaillon et al. (2007) also showed that fry to parr overwinter mortality of Atlantic salmon was positively related to conditions conducive to frazil and anchor ice formation in early winter (number of days in November with mean air temperature below -10°C). Early winter was also suggested to a critical period in first winter survival of juvenile salmonids by Meyer and Griffith (1997). Although the importance of winter habitat cannot be discounted, these studies suggest that habitat limitations may not be the only factor affecting fish populations during winter.

3.4. What effect does water withdrawal have on winter habitat?

Low flows in Canadian streams can occur in both summer and winter and can be stressful for fish and other aquatic biota. Low flows can cause a reduction in habitat availability, food production, and water quality and can accentuate the effects of river ice during the winter (Bradford and Heinonen

2008). Bradford and Heinonen (2008) reviewed the impact of low flows on aquatic resources in small streams as well as instream flow methods and the empirical support for them. They conclude that there remains substantial uncertainty in the prediction of impacts of flow reductions due to a lack of understanding of the relationship between flow and fish populations. They suggest a risk-based approach is needed that explicitly acknowledges the uncertainty in both the hydrology and biology, for decision-making in water management. However, they also conclude that the weight of evidence supports a negative effect of withdrawal during winter.

Water withdrawal during low flow periods may compound other stresses. According to Cunjak (1996), "water withdrawal and its direct influence on reducing available habitat (wetted space) probably impacts stream fish populations more than any other winter alteration of streams." Yet, very little work has been done to quantitatively assess effects of winter water withdrawal on fish and fish habitat.

Water withdrawal in winter may cause a reduction in temperature and overall accumulated thermal units over winter (Cunjak 1996). This can severely impact fishes that are poorly adapted for activity at low temperatures and fishes that may be at their physiological limits near the northern limit of their distributional range (Cunjak 1996). Withdrawals of water that substantially reduce stream flow can also accelerate icing characteristics that may reduce connectivity between important summer and winter habitats (Cunjak 1996). This either precludes fish from accessing their preferred habitats or strands those already occupying disconnected habitats. Systems characterized by low flow in winter are particularly sensitive to withdrawals of water in winter. Deleterious effects will occur if flow reductions and accelerated icing limit or block access to important overwintering habitat. This is amplified where suitable winter habitats are rare and where fish demonstrate strong site fidelity for particular wintering areas (Cunjak 1996). Water withdrawal on systems with complex floodplains and side channel habitat may also exacerbate effects, where water withdrawals could lead to dewatering and mortality of fishes. Under natural conditions in the Morice River, stranding has been observed during lowest flows in late winter, which would be accentuated by winter water withdrawal. In fact, flow releases during this period were considered an important compensation option (Bustard 1986). At Kemess Creek, reduced winter flows due to tailings dam construction were the largest concern in terms of flows. As a result large and costly efforts were undertaken to store water for winter release to maintain winter flows so bull trout fry and yearling in downstream side channels were not subject to increased dewatering in late winter (Bustard 2011).

Water withdrawal and its direct influence on reducing available habitat (wetted space) probably impacts stream fish populations more than any other winter alteration of streams (Cunjak 1996). The situation may be most apparent in shallow streams and may be exacerbated by ice conditions (West et al. 1992). When winter discharge was kept low in a regulated stream, juvenile rainbow trout were found to be excluded from near-bank concealment habitat that had held a high density of fish throughout a previous winter (Griffith and Smith 1995). In addition, it has been suggested that the impact of winter water withdrawal may be more severe at low-elevation sites because of habitat exclusion by surface and subsurface ice accumulation (Chisholm et al. 1987). However, elevation is only one of the factors influencing these ice processes. Chisholm et al. (1987) also suggest that there is a lack of suitable methods for determining winter streamflow needs under these conditions.

Gibson and Myers (1988) found that there were positive relationships between winter discharge (mean February discharge) and survival of underyearling Atlantic salmon in five rivers examined in eastern Canada. Cunjak et al. (1998) examined the relationship between winter discharge and interstage survival (egg to 0+, 0+ to 1+ and 1+ to 2+) for Atlantic salmon on Catamaran Brook, New Brunswick. Catamaran Brook is characterized by freeze-up in late November, a four-month period of ice growth and a spring break up in March-April. For their study winter flow was defined as average daily flow from November 1 to March 31. Average winter flows during the study ranged from 0.176 m^3/s to 0.691 m^3/s, or 29% to 114% of LT MAD, as measured at the hydrometric gauge at river km 9.5 (based on description this is assumed to be Water Survey Canada (WSC) Station Catamaran Brook at Repap Road Bridge (01BP002)). LT MAD for WSC Station Catamaran Brook at Repap Road Bridge (01BP002) is 0.607 m^3/s (R. Ptolemy pers, comm. 2012). They found a strong relation between winter discharge and interstage survival (egg to 0+, 0+ to 1+, and 1+ to 2+) in 5 of 6 years. That is, summer abundance of juvenile Atlantic salmon was highest following winters with high streamflow, presumably due to greater habitat availability beneath ice cover (Cunjak et al. 1998). However, the lowest measured interstage survival was related to an atypical midwinter, dynamic ice break-up triggered by a rain-on-snow event that resulted in severe scouring of the stream-bed and redds. The interannual variability in Atlantic salmon parr abundance could largely be explained by density-independent (environmental) constraints to winter survival.

In a more recent study in Catamaran Brook, Linnansarri and Cunjak (2010) found that the highest decline in apparent survival of Atlantic salmon parr occurred prior to any ice formation and coincided with early winter acclimatization period, a period that is characterized by dynamic temperatures and discharges. For Catamaran Brook this period roughly corresponds to the month of November. Furthermore, the apparent survival was highest during the year with most stable discharges. This study suggests that flow conditions during the different periods of winter may affect overall survival and that stabilizing flows may result in better survival.

Hvidsten (1993) examined smolt production of Atlantic salmon in relation to hydro-power development on the Orkla River, Norway. Smolt production was found to increase considerably after regulation, especially in relation to higher winter discharges. The low winter discharges were increased five-fold after storage regulation. In the two years before regulation low winter discharge was 1.7 (2% MAD) and 2.2 m^3/s (3% MAD), whereas after regulation low winter flow ranged from 11.1 (16% MAD) to 34.2 m^3/s (48% MAD). MAD for the Orkla River was taken from Thorstad et al. (1993) to be 71 m^3/s. Hvidsten (1993) compares smolt production to indices of low winter flow for the previous three winters. They found no correlation between the final winter's discharge and smolt production. However, products of winter discharge indices for the last two and three years were found to be positively correlated to smolt production. The author suggests that smolt production increased due to reduced mortality during the ice-covered period and as a result of increased food items. The results of this study appear to be largely influenced by low smolt production in 1983 and corresponding low water discharge index and the high smolt production in 1990 and corresponding high low water discharge index.

Bisaillon et al. (2007) examined the over-winter mortality of Atlantic salmon egg to fry (0+) and fry to parr (1+) in relation to hydro-climatic variables on the Trinite River, Quebec. Their results indicated that egg to fry over-winter mortality was high (83% to 93%) but inversely related to winter coldness (defined by accumulated freezing degree-days between October 1st and January 31st) and positively related to winter low discharge (defined by the ratio of November to February mean discharges). The relationship between egg to fry survival and winter low discharge is believed to be due to freezing mortality of eggs (Bisaillon et al. 2007). Fry to parr overwinter mortality ranged from 42% to 73% between years. Overwinter mortality was found to be inversely related to winter coldness (cumulated freezing-degree days in January and February) with the highest mortality during the mildest winters. The inverse relation to coldness is believed to be due to the formation of a complete and stable ice cover. Overwinter mortality was also found to be positively related to conditions conducive to frazil and anchor ice formation in early winter (number of days in November with mean air temperature below -10°C) with the highest mortality during years with conditions most conducive to frazil and anchor ice.

Krimmer et al. (2011) studied the effects of midwinter flow reduction (50–75%, reduction in discharge in 4 h daily pulses) on the physical habitat and on the behaviour and physiology of overwintering brook trout in a small mountain stream. This stream was not under ice conditions and the flow reduction did not result in significant lowering of temperature or formation of surface or subsurface ice. Flow reduction was shown to result in reduced stream width, reduced depths, reduced undercut bank cover and lower velocities. The number of daily movements increased during flow reduction, but were limited to small-scale relocations (<10 m). Availability of preferred undercut bank cover was reduced during flow reduction. Fish did not lose mass, condition or show effects of stress or bioenergetics from the flow reductions. The authors hypothesized that no effects were observed because access to preferred cover remained available and suggest that undercut banks are critical winter habitat rather than substratum cover for brook trout. However, substratum cover was not available in this system.

Mitro et al. (2003) examined the discharge to abundance relationship during winter (January 15 to March 31) for the spring abundance of age-0 rainbow trout in Henrys Fork of the Snake River, Idaho. Spring abundance was found to be related to autumn abundance and mean discharge during the second half of winter (January 15 to March 31). An experimentally high discharge in the second half of winter showed that the discharge abundance model accurately predicted spring abundance. Higher discharge may provide more bank habitat at a critical time for survival. Generally, no ice forms in this study area, and it seems unlikely that this relationship would hold for streams that undergo icing because shallow edge habitat is reduced in winter regardless of flow (Waddle 2007).

Dare et al. (2002) found that declining discharge in winter (20.9 to 5.7 m^3/s) for a period of 14 to 21 days had little effect on subadult cutthroat and brown trout in a regulated river during the winter.

The flow reduction led to decreased water depths and velocities, increased pool area and dewatered riffles. Following flow reductions, both species were observed at locations with above average water depths and slower water velocities, especially pools with abundant cover. It is generally believed that pools provide a more stable environment for fish during variable discharge (Heggenes et al. 1993; Jakober et al. 1998; Simpkins et al. 2000) and this stability attracts and concentrates salmonids during winter (Brown and Mackay 1995). The effect of variable and low discharge could not be statistically linked to the use of pools; however, the importance of pool habitat in winter was evident (Dare et al. 2002). Discharge was also not linked to downstream movements, suggesting that cutthroat and brown trout are resilient to short-term decreases in discharge, as long as sufficient pool habitat is available.

Waddle (2007) found that flow reductions under ice conditions led to a greater decrease in hydraulically suitable habitat (WUA) in comparison to open water conditions; however, the study used summer habitat suitability criteria for this assessment. Waddle (2007) also compared pool habitat at a natural flow condition (0.608 m^3/s) and a reduced flow (0.325 m^3/s) under ice cover. For the majority of cases, a decrease in discharge of 0.283 m^3/s from the observed condition resulted in lower pool area, as defined by the depth and velocity thresholds. However, no under-ice observations of fish were made in this study to confirm the actual degree of habitat use. Since shallow edge habitat is reduced by icing in winter regardless of flow there may not be a simple relationship with discharge in a stream with stable winter flow (Waddle 2007).

Robertson et al. (2004) examined the effect of increased flow on movement and microhabitat use of Atlantic salmon parr in winter by simulating hydropeaking operations. Flow was increased from 1.3 m^3/s to 5.2 m^3/s for 24 h periods. The study site was ice free during early and late winter. In mid-winter, the first increase in flow removed the ice cover present in the mainstem stream (20% ice cover) and ice was only present in stream margins. These flows did not affect fish habitat use or displacement and had little effect on fish activity within diel periods. Stranding rates during flow reduction were also very low (only one fish).

A multi-year study of the effect of flow reduction on the Kemess mine provides empirical evidence of fish response to reduced overwinter flows (Bustard 2011). Water storage and winter releases have been conducted throughout the project to ensure that winter flows did not drop below natural low flows downstream from the tailings dam with releases occurring from January through April. The goal of these releases was to retain viable overwinter habitat in South Kemess Creek and to ensure side channels in lower Kemess Creek did not experience lower winter flows leading to stranding and dewatering of side channel habitats, which are heavily used by bull trout fry and yearlings (Bustard 2011). Anchor ice is common in the lower reaches Kemess Creek during cold early winter periods prior to surface ice and snow cover. Monitoring to date shows that bull trout fry densities have increased in South Kemess Creek with the modified flow regime, while juvenile bull trout densities are about one-half of the pre-development levels (Bustard 2011). This is believed to be due to increased habitat due to reduced flows during spring freshet. There has been no detectable trend in bull trout fry and parr densities in the lower creek subject to the new flow regime (Bustard 2011). A constructed side channel with a fixed-flow intake in South Kemess Creek with habitat characteristics mimicking a productive channel in lower Kemess Creek has also been found to have bull trout juvenile densities that are approximately three times those measured in South Kemess Creek (Bustard 2011). This is believed to be due to the stabilized flow.

Flow reductions over winter may also influence egg incubation of fall spawning species. Decreased temperatures may result in delayed hatching and emergence and if they are subject to freezing conditions they could suffer from increased mortality. Williamson (2006) conducted work on bull trout spawning areas in the Davis River on Williston Lake and demonstrated how small changes in incubation temperatures can result in significant changes to bull trout egg/alevin development in these northern interior streams. Cope and MacDonald (1998) describe mechanisms that favoured successful spawning and incubation to survive severe winter conditions. These included early spawning leading to early hatch and ability of alevins to migrate interstitially in response to substrate freezing.

3.4.1.Summary

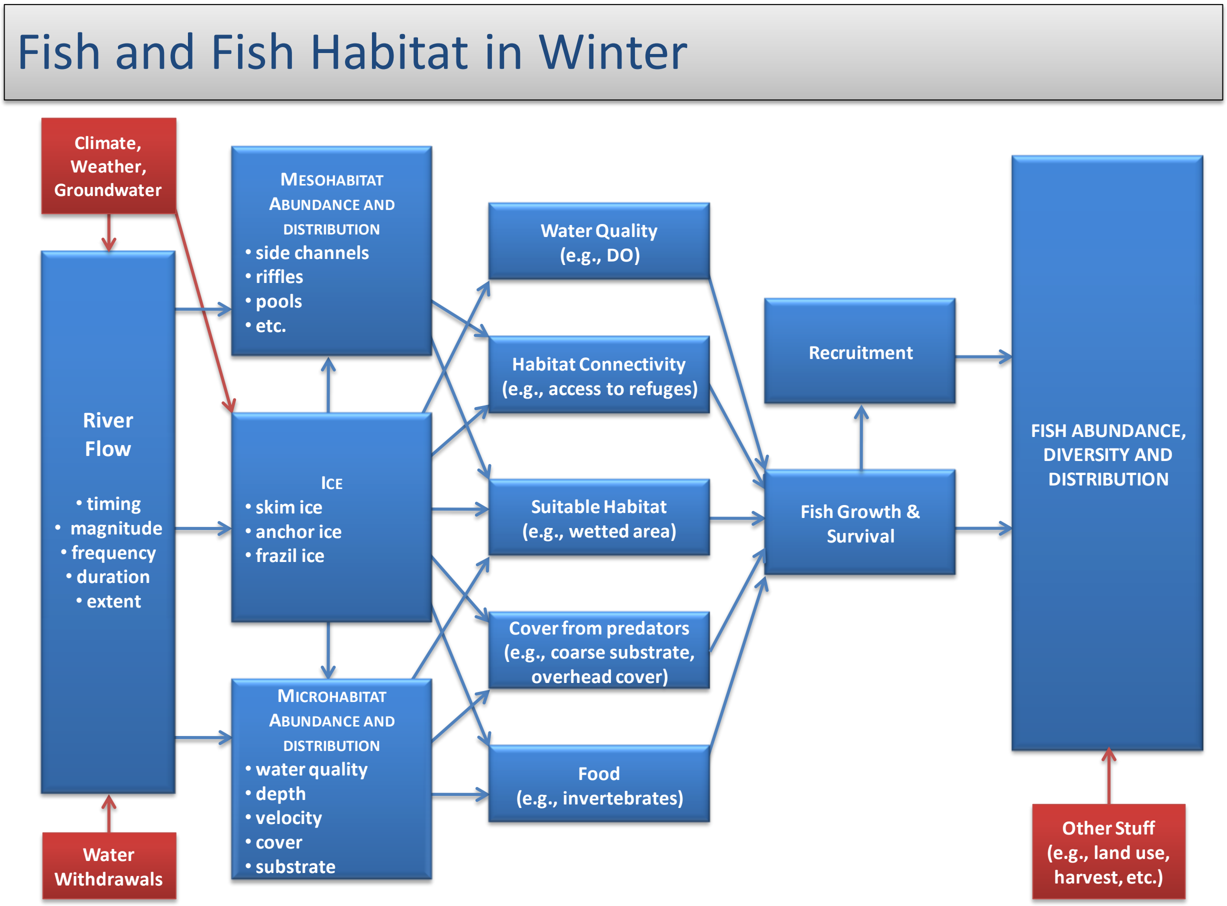
In general, the literature suggests that winters with higher flows result in higher survival of fish (Gibson and Meyers 1988; Hvidsten 1993; Cunjak et al 1998; Mitro et al 2003; Bisaillon et al. 2007), though short term flow reductions may have little effect (Dare et al. 2002; Krimmer et al. 2011). Given the different metrics that have been used in these studies, it is unclear if there is a general threshold or relationship between winter flow and survival. For example, the average winter flow (November 1 to March 31) assessed by Cunjak et al. (1998) ranged from 29 to 114% MAD, while the minimum winter flows assessed by Hvidsten (1993) ranged from 2 to 48% MAD. The higher flows are thought to provide more overwintering habitat and lead to better survival.

The overwinter survival rate may differ throughout the winter. Linnansarri and Cunjak (2010) found that highest decline in apparent survival occurred prior to ice formation during early winter acclimatization. Apparent survival then improved during the period affected by subsurface ice and was further improved when surface ice was prevailing. Linnansarri and Cunjak (2010) also found that apparent survival was highest during the year with most stable discharge. Stable flow conditions during the winter may also be an important factor to overwintering survival.

3.5. Impact Pathways

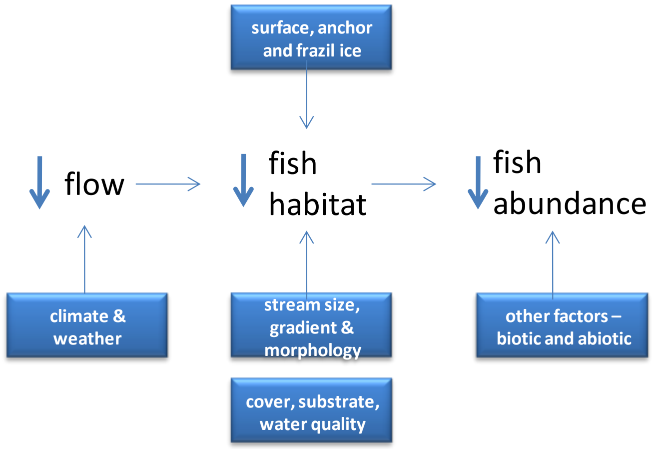
Water withdrawals affect fish and fish habitat in winter in a number of ways, and the magnitude and type of effect will vary depending on the magnitude of withdrawal and the physical and biological setting. This section describes the most plausible impact mechanisms that apply to water withdrawals during winter under ice, and reviews the evidence in support of whether the mechanism is valid in most instances. Figure 5 is an influence diagram that describes the main impact mechanisms and the impact pathways and interactions that may occur during winter withdrawals. Simple pathways are described and discussed in several subsections.

Figure 5. Influence diagram showing the primary impact mechanisms between water withdrawals and fish abundance, diversity and distribution.



3.5.1. Suitable Habitat - Hydraulics

__**Hypothesis**__: water withdrawals in winter under ice affect the amount of suitable winter habitat (as determined by velocity, depth and cover). Less habitat leads to reductions in fish abundance, through density-dependent mechanisms like competition and predation.



Cunjak (1996) suggests that water withdrawal and its direct influence on reducing available habitat (wetted space) probably impacts stream fish populations more than any other winter alteration of streams. A reduction in wetted space may correspond to a reduction in fish habitat depending on the specific microhabitat requirements of fish during winter. The situation may be most apparent in shallow streams and may be exacerbated by ice conditions (West et al. 1992). Although habitat may be limiting it is unclear if it is hydraulic habitat or another factor.

Microhabitat selection by fish during winter is summarized in Section 3.2.3. During the winter, in general salmonids typically use deep, low velocity microhabitats and display nocturnal behaviour (Cunjak and Power 1986b; Baltz et al. 1991; Simpkins et al. 2000; Heggenes and Dokk 2001; Maki-Petays et al. 1997, 2004); however, salmonids are also associated with stream margin habitat (Cunjak 1988b; Whalen et al. 1999). There are species and age class differences in habitat selection. Some studies have reported use of shallow, fast velocity areas especially for juvenile Atlantic salmon (Rimmer et al. 1983; Cunjak 1988b; Roussel et al. 2004).

In general, water withdrawals during winter may lead to a decrease in water depth and velocities, increased pool area and reduced riffle area (Dare et al. 2002). Although the overall wetted area may be reduced by withdrawals, there may actually be an increase in suitable overwintering habitat due to reductions in velocity and the increase in total area of pool habitat. This effect depends on specific stream morphology and the maintenance of connectivity to these overwintering pool habitats.

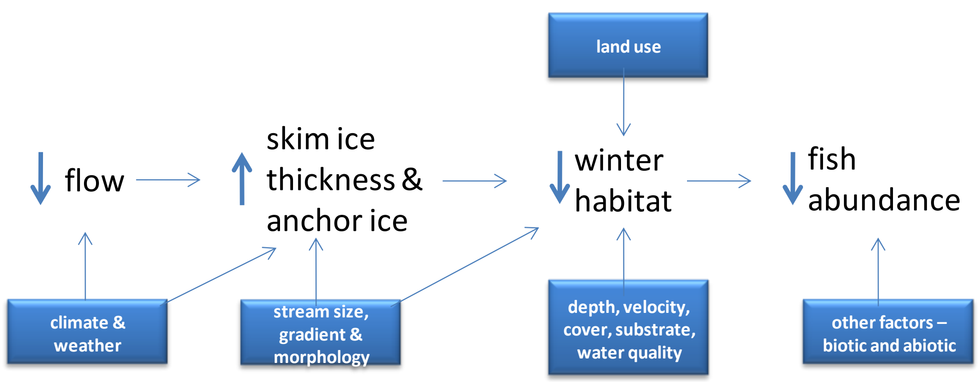
Icing may also affect fish habitat under decreasing flow conditions. The process of streams freezing at their margins can concentrate flows to the middle of the channel and reduce usable habitat. Frazil and anchor ice formation may also lead to local increases in velocity and an overall decrease in habitat. Frazil ice can build up in pools and water flow may be restricted to high velocity conduits. The formation of hanging dams can also lead to increases in velocity in pools. Anchor ice dams on the other hand result in backwatering, which tends to increase depth and decrease velocity upstream of the dam (Stickler et al. 2010, Brown et al. 2011, Turcotte and Morse 2011). These increased depths and decreased velocities may increase suitable winter habitat at least temporarily.

Although depths and velocities may be suitable, these are only two of the variables important for overwinter habitat. Cover, and in severe environments groundwater seepage, may be required to keep habitats from icing up during critical periods. In northern BC interior streams it seems important to have areas where fish, especially emerging fry, can retreat from the mainstem snowmelt freshet. For example, South Kemess Creek with a reduced snowmelt freshet is now a more hospitable environment for bull trout fry (Bustard 2011). This is probably a result of lower velocities in the confined channel of the lower creek.

The relationship between flow and habitat may depend on individual stream characteristics, although there is general evidence of winter limitations. Survival has been shown to be positively related to winter flows suggesting that there is at least some density-dependence in winter. Density-dependence in winter was also supported by Carlson et al. (2008), who showed that at low water levels, an increase in population density was associated with a reduction in survival and that at high trout densities an increase in flow was associated with an increase in survival. However, these studies did not provide the relationship between habitat and flow. Although density-dependent factors may affect survival they may be less critical than density independent factors such as extreme weather in early winter leading to channel freezing, anchor ice mid-winter freshets as outlined in Cunjak (1996).

3.5.1. Occlusion of Winter Habitat

Hypothesis: water withdrawals in winter increase skim ice thickness and the production of anchor ice and thereby reduce the amount of suitable winter habitat for fish. Reduced habitat availability causes reductions in fish abundance.



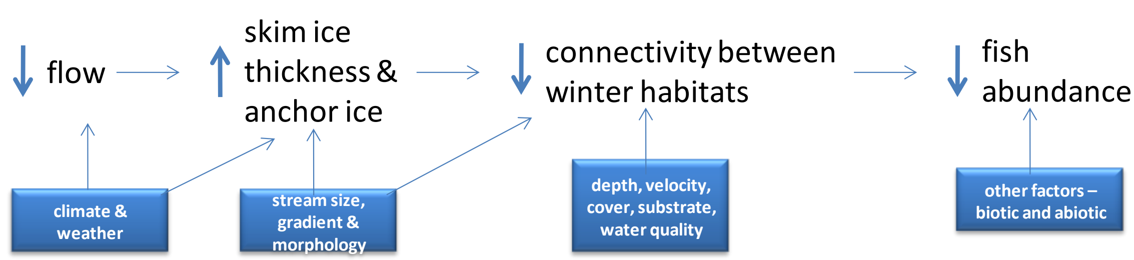
This is essentially a variant of other habitat hypotheses, but may not be tied specifically to hydraulic properties at a microhabitat scale. Static ice can form in fish habitat resulting in occlusion for short periods or even for most of the winter (Chisholm et al. 1987; Brown and Mackay 1995; Jakober et al. 1998; Lindstrom and Hubert 2004). In addition, frazil and anchor ice can build up to the water surface and occlude fish from entire pools or reaches (Brown et al. 2011). A reduction in flow may lead to the increase in static ice thickness and the build up of frazil and anchor ice. These ice processes can lead to a reduction in suitable habitat or occlusion of habitat. Bustard (1986) found that during a very cold early winter period, shallower side channels were frozen solid and caused direct freezing mortality to juveniles.

A reduction in flow can accelerate the formation of skim ice and lead to an increase in overall ice thickness. Stable flows and reduced water velocities may also promote thicker ice cover, reducing heat loss and frazil generation, which may mitigate or improve overwintering conditions in pool habitats (NHC 2011). However, lower flows over the winter may lead to the development of ice that extends more deeply and further, especially in early winter very cold periods.

Frazil ice formation may occur when velocities are >0.6 m/s. This frazil ice may then be deposited under surface ice as hanging dams, in pools, or on substrate as anchor ice. All of these may occlude large portions of fish habitat. Anchor ice typically occurs in areas with high turbulence, where frazil ice is transported to the stream bed (Ashton 1986). A reduction in flow may accelerate frazil and anchor ice formation if velocity is maintained. Lower flows may also reduce pool volumes, increasing the concentrations of frazil and occurrence of ice-filled pools. The occlusion of habitat may cause aggregations of fish as fish move out of affected areas, assuming connectivity to suitable habitat remains.

3.5.2. Winter Habitat Connectivity

Hypothesis: water withdrawals in winter increase skim ice thickness and the production of anchor ice and thereby reduce the connectivity between suitable winter habitats for fish. Reduced habitat connections cause reductions in fish abundance by limiting opportunities for fish movements to escape adverse conditions.



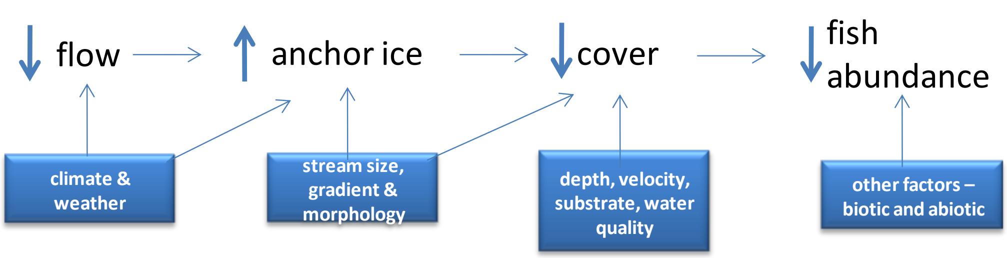
This is essentially a variant of other habitat hypotheses, but may not be tied specifically to hydraulic properties at a microhabitat scale. This may be a good mechanism to focus on for setting a stream size limit for withdrawals; however, channel characteristics, and the occurrence and location of groundwater may also need to be considered. This mechanism may be particularly important in systems with side-channel habitats and has been observed on the Morice River side channel habitats (Bustard 1986).

Flow reductions may lead to fragmentation of habitat if the lower flows cause barriers to form. Movement barriers in the mainstem may occur when flows drop below a level that allows free passage of fish throughout a stream (e.g., dewatering of a riffle, creation of an impassable falls), or when access to important side channel, back channel, off-channel or tributaries is blocked. Lower flows in early winter may also lead to quicker cooling and more severe ice during cold early winter periods without snow cover. Withdrawals may increase icing characteristics which can further disconnect important summer and winter habitats (Cunjak 1996). For example, surface ice may not create a barrier at a relatively high flow, but could conceivably block fish movement if water elevation was lower at the time of ice formation. Fragmentation of habitat may lead to stranding of fish in isolated pockets, with potential consequences to individuals and the fish population. Isolated fish may then be frozen in ice or concentrated in remaining overwintering habitat (deep pools fed from subsurface flows or groundwater inputs). However, high densities of fish in the remaining pools may be subject to predation from birds in spring as they open up (Bustard 1986).

In general, overwintering habitat (described in Section 3.2) may include areas such as pools, off-channel habitat, or areas near sources of ground water (Cunjak 1996, Huusko et al. 2007). The overwintering habitats used may vary by stream, fish species or life stage and may be critical to the fish population present in the stream. These important overwintering areas may need to be defined on a stream by stream basis to assess connectivity under reduced flows.

3.5.3. Cover During Winter - Predation

Hypothesis: water withdrawals in winter increase skim ice thickness and the production of anchor ice and thereby reduce the available cover for juvenile fish. Reduced cover leads to greater predation risk or movement of fish out of affected areas and ultimately causes reductions in fish abundance.



A reduction in flow may lead to increased formation of surface, or frazil/anchor ice depending on hydraulic conditions (<0.6 m/s and >0.6 m/s, respectively; Ashton 1986). Where conditions conducive to frazil and anchor ice formation exist after water withdrawal their effect on fish habitat may be amplified. The formation of anchor ice has been shown to be extensive enough to limit access to important interstitial cover in coarse substrate (Huusko et al. 2007, Brown et al. 2011). However, this may be related to fish size, as small Atlantic salmon have been observed using anchor ice as cover (Stickler et al. 2008) and Everest (1969) found Chinook and steelhead fry in boulder/cobble cover under a layer of anchor ice. Selection of cover types may differ by species and age/size class, but the importance of unembedded coarse substrate is thought by many authors to be a critical component of overwintering habitat (Cunjak 1996, Stickler et al. 2008, Huusko et al. 2007;

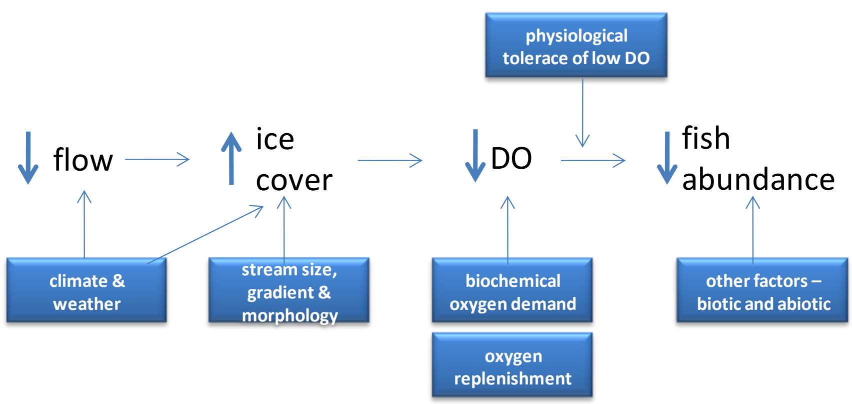
Brown et al. 2011) and may be more important than depth and velocity (M. Stickler pers. comm. 2012).

In addition to coarse substrate, salmonids find cover in winter under large woody debris, aquatic vegetation, undercut banks, surface turbulence and ice (Baltz et al. 1991; Heggenes et al. 1993; Riehle and Griffith 1993; Cunjak 1996; Huusko et al. 2007). Flow reductions may also lead to a decrease in access to many of these cover types, regardless of ice formation, if they tend to occur at stream margins. The stream margin habitat has been described as providing important winter habitat (Mitro et al. 2003; Krimmer et al. 2011) in streams that are not naturally subject to icing.

If flow reductions also lead to an increase in surface ice cover, this may offset some of the losses of other cover types. Surface ice has been shown to be used as cover by many species of fishes (Meyer and Griffith 1997; Linnansarri et al. 2009). Where surface ice is present fish may also not conceal themselves during the day and become day active during the winter (Gregory and Griffith 1996; Jakober et al. 1998).

3.5.1. Dissolved Oxygen

Hypothesis: water withdrawals in winter increase ice cover and thereby reduces oxygen exchange with the air. Reduced dissolved oxygen (DO) leads to less usable habitat, which in turn causes reductions in fish abundance. In some cases, lower flows cause additional water residence time in side channels or other hydraulic units, which may limit DO in these habitats. Also under some situations lower flows may result in higher proportions of groundwater with lower natural DO levels (Schreier et al. 1980).

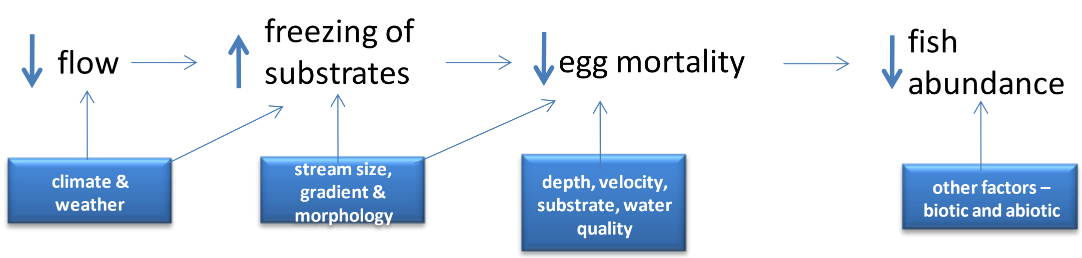


In general, water withdrawals during winter may lead to a decrease in water depth and velocities, increased pool area and reduced riffle area (Dare et al. 2002). This can promote increases in surface ice cover. However, the promotion of surface ice and its stabilizing effect in winter is generally considered to have a positive effect on fish habitat. Very little of the available literature discusses impacts of surface ice in relation to dissolved oxygen in lotic environments, and this is likely an issue primarily in stagnant or very low velocity habitats (e.g. off-channel habitats and small lakes). In two side channel pools with ice cover and little subsurface exchange during winter, low DO was found to cause mortality of juvenile salmon and steelhead in the Morice River (Bustard 1986). The issue of reduced DO in relation to winter water abstractions was considered sufficiently plausible in the Phase 2 Water Management Framework for the Athabasca River to warrant considerable efforts applied to DO modeling and follow up monitoring (Hatfield and Ohlson 2010, Ohlson et al. 2010).

Turcotte et al. (2011) found that ice cover in a steep channel does not typically reach 100% because heat from ground water and head loss oppose the formation of complete ice cover. Groundwater also has a large bearing on open water in winter and lower flows may lead to larger influence from groundwater. The amount of open water required to replenish DO in ice covered streams would be related to the oxygen demand. The oxygen demand would depend on many factors including but not limited to the number of fish present in the pool and breakdown of organic matter.

3.5.2. Incubation During Winter

Hypothesis: water withdrawals in winter decrease temperatures and cause an increase in icing and these can cause a delay in hatching and emergence of fry or an increase in freezing mortality of eggs. Reduced habitat availability causes reductions in fish abundance.

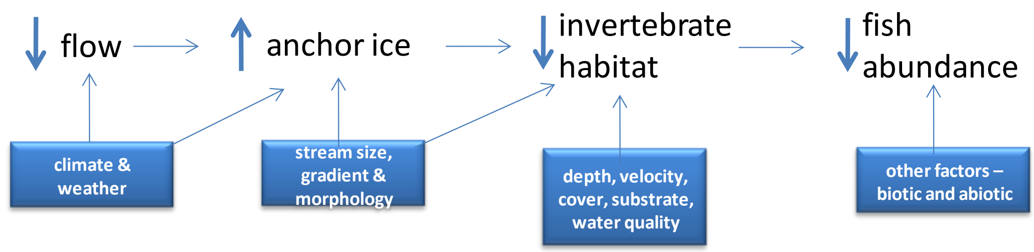


Flow reductions over winter may influence egg incubation of fall spawning species. Reduced flows may result in an increase in icing and freezing mortality of eggs. Species such as bull trout and Dolly Varden are known to select spawning habitat in areas influenced by groundwater (McPhail 2007; Bustard 1996). These habitats are less likely to have increased icing due to water withdrawal, and selection of these habitats may negate these impacts. However, impacts may occur in spawning areas without groundwater sources. Increased icing may lead to direct freezing mortality of eggs (Reiser and Wesche 1979). Low winter flows have been shown to result in decreased survival of Atlantic salmon egg to fry survival and freezing mortality of eggs was suggested as the mechanism (Chadwick 1982; Bisaillon et al. 2007).

Lakes and their associated stable flows and temperatures may also be important to winter incubation in some systems. For example, in the Morice River most of the Chinook salmon spawning occurs in the river section below Morice Lake, which does not freeze over in the winter (Bustard and Schell 2002). Similarly most sockeye salmon (*O. nerka*) spawning is below Kidprice Lake, again a stable incubation environment with ice-free and stable flows (Bustard and Schell 2002). In contrast, coho salmon spawners seem to focus on areas of upwelling and groundwater (Bustard 1986). Pink salmon (*O. gorbuscha*) have been observed to use side-channels where there seems to be a trade-off between selecting areas that are ice-free (i.e., have warmer temperatures), but end up having lower dissolved oxygen due to groundwater inflows (Envirocon 1984). These are critical factors especially pre-hatching when eggs cannot respond to reduced flows or freezing in the redds.

3.5.1. Food During Winter

Hypothesis: water withdrawals in winter affect the amount of suitable winter habitat (as determined by velocity and depth) for invertebrates. Less habitat for invertebrates leads to less food for fish and ultimately, reductions in fish abundance.



Feeding was suggested to be a lower priority in winter habitat selection by Cunjak (1996). Winter feeding is generally thought to be required for sustaining a minimal level of metabolic activity rather than for growth (Cunjak et al. 1988b, Cunjak 1996). However, it is clear that fish do feed during winter, even at low temperatures and reduced activity (Forseth et al. 2001 Cunjak 1996, Huusko et al. 2007), and if food intake does not meet energetic demands fish have to catabolise their energy reserves. Night time holding habitat is often located near high velocity areas to take advantage of high drift densities (Cunjak 1988b; Simpkins et al, 2000). Assimilation efficiency is typically low in winter (Cunjak and Power 1987), meaning there may be little benefit to selecting habitats with greater access to food if additional energy is required to capture that food.

As previously discussed, an increase in anchor ice formation may occur as a result of flow reduction. This may lead to occlusion of invertebrate habitat; however, the relationship between invertebrate production and habitat suitability in winter is unclear (Cunjak 1996). Cunjak (1996) suggests that invertebrate abundance and biomass remain relatively high in winter especially where winter growing species are present (Plecoptera and some Ephemeroptera).

3.5.1. Other Factors

Additional potential pathways affecting winter fish survival have also been identified, but there is less known about these effects or they appear to be less likely to operate as primary mechanisms of fish mortality during winter. These potential impact pathways include:

- rapid release of contaminants with snow melt/ice melt (low pH or other contaminants),
- physiological changes at freeze up or break up,

- habitat effects during freeze up (hydrograph recession due to ice growth and hydraulic storage),
- habitat effects during break up (scouring of bed and banks, increase in suspended sediments),
- length of winter (long duration of low temperatures during which food assimilation is slow and growth is poor, and reserves are limited), and
- climate/weather (extent of ice formation is clearly related to temperature, snow cover, etc.)

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A review of environmental flow methods for use in the British Columbia Winter Flows Project




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Todd Hatfield, Ph.D., R.P.Bio.

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Table of Contents

1. INTRODUCTION

1.1. Environmental flow assessment

Environmental flow assessments (EFA) are conducted to support decision-makers and water managers in their determination of how much water should be left in streams to maintain aquatic and riparian ecosystems, or species of particular concern. The term "environmental flows" is given preference here over "instream flows" because it more accurately reflects the rationale for setting flow targets in regulated rivers where environmental considerations and concerns extend beyond the wetted area of the river, such as the adjacent riparian community. Environmental flows are defined as "the quantity, quality and timing of water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend on these ecosystems." (Global Environmental Flows Network 2011). Both environmental and socioeconomic benefits are recognized in this definition, which is referred to as the "Brisbane Declaration" and was agreed to at the 10th International River symposium and Environmental Flows Conference, held in Brisbane, Australia, on September 3 to 6, 2007.

We assume that those reading this report are already familiar with many of the existing EFA methods, and the regulatory and political contexts in which they are normally applied. The objective of this report is not to provide an exhaustive review of EFA methodologies, but to review enough material to provide necessary context and to validate the applicability of select desktop environmental flow methodologies for winter low flow conditions in British Columbia. Those interested in more background material on EFA methods and rationales may wish to consult extensive reviews such as EPRI (2000), Hatfield *et al.* (2003) or Tharme (2003).

2. ENVIRONMENTAL FLOW ASSESSMENT METHODS

2.1. A brief history of EFA methods

The ecological study of rivers and the development of environmental flow methods is a relatively new area of inquiry. When this field of study emerged in the 1970s, the initial focus was on determining flows necessary to preserve charismatic aquatic species (e.g., salmon, trout). The focus has since shifted from a narrow concept of "minimum flows" to restoring or maintaining a broader spectrum of organisms and communities, and methods that allow consideration of socioeconomic values. As a result, more recent techniques have increased the capacity of scientists and water managers to define flows that maintain the full spectrum of riverine species, processes, and services.

Even in light of the progress that has been achieved, determining and setting environmental flows remains exceedingly difficult. Specifically, the crux of the problem is that "it is virtually impossible to predict the future states of a system when it is disturbed" (Moyle et al. 2011). For instance, Moyle *et al.* (2011) discuss the following challenges to setting environmental flows:

- Ecosystems are not stable equilibrium systems,

- Social objectives evolve,
- Fish evolve,
- Streams adjust,
- Climate changes,
- Fish populations vary,
- Habitat selection is conditional,
- Spatial and temporal scales matter, and
- Other background considerations, like
  - Science and dispute resolution,
  - Models and environmental flow assessment,
  - Objective and subjective methods,
  - Science and environmental flow assessment.

Despite these challenges, many techniques have been developed to determine environmental flows (aka Instream Flow Needs, or IFN). Several reviews of these methods and their respective strengths and weaknesses have been conducted (Jowett 1997, EPRI 2000, Instream Flow Council 2002, Tharme 2003). In one case, over 200 assessment techniques were identified that have been employed around the world (Tharme 2003). The fact that so many assessment techniques have been and continue to be developed emphasizes the frustration with the existing methods and the need for their improvement.

In practise, more than one method may be used during an assessment. As methods are also often classified in different ways (Jowett 1997, Summit Environmental Consultants 1998, Sawada et al. 2002, Tharme 2003), they may span several classifications. The following discussion follows Tharme's classification of hydrologic, hydraulic, habitat-rating, and holistic methods.

2.2. A brief review of methods

"Standard-setting" and "empirical" methods bracket a continuum of approaches. Standard-setting methods and are primarily office-based, "desktop" scoping exercises that make use of existing information to predict an appropriate schedule of environmental flows. Since there is considerable uncertainty regarding the predicted effects of a given project, desktop methods are often explicitly conservative (i.e., biased in favour of environmental protection). In comparison, empirical methods require that the stream of interest be visited and that biological and physical data be collected. The ultimate goal of both methods is to protect environmental resources, but the amount of information, time, and cost needed to perform an assessment may be substantially different. Generally, the best approach combines methods, so that easily obtained information is supported by detailed, site-specific studies, where it is deemed necessary.

Hydrologic approaches (sometimes called historic flow methods) currently hold the greatest promise for use as a desktop method for streams in British Columbia. We recommend that the selected method build on the strengths of three useful existing methods: (1) the British Columbia Instream Flow Needs (BCIFN) method (Hatfield et al. 2003), (2) the Alberta Desktop Method (Locke and Paul 2011), and (3) the BC-modified Tennant Method (Ptolemy and Lewis 2002). Overall, the chosen method should sustain key aspects of the natural hydrograph that maintain the physical aspects of streams on which fish and other ecosystem components depend (Richter et al. 1996, Poff et al. 1997, Richter et al. 1997, Trush et al. 2000).

2.3. Hydrologic methods

2.3.1. Tennant Method

The Tennant Method (Tennant 1976), also known as the Montana Method, has been a very influential method for determining flow needs for fish and continues to be widely used throughout the world (Reiser et al. 1989, Jowett 1997). The method is founded on 17 years of experience on hundreds of cold-water and warm-water streams and has been tested with field studies on 11 streams in Nebraska, Wyoming, and Montana (Tennant 1976). These tests used empirical hydraulic data from cross-channel transects combined with subjective assessments of habitat quality. Relationships between flow and aquatic habitat quality were defined based on these measurements, which were found to be similar for each of the study streams. From this, stream flow recommendations were developed based on percentages of mean annual discharge (MAD, Table 1).

Table 1. Environmental flow regimens for fish, wildlife, recreation and related environmental resources, as described in Tennant (1976). Flows are expressed as percentages of MAD.

	% MAD	
	October - March	**April - September**
Flushing or Maximum	200%	200%
Optimum Range	60-100%	60-100%
Outstanding	40%	60%
Excellent	30%	50%
Good	20%	40%
Fair or Degrading	10%	30%
Poor or Minimum	10%	10%
Severe	0-10%	0-10%

There are several advantages to the Tennant Method: it is easy to implement, requires no field work, it is based on a single hydrologic statistic (i.e., MAD) that is easy to obtain, and decisions based on the Tennant Method have withstood numerous court challenges in the United States (Christopher Estes, pers. comm.). Critiques of the Tennant Method assert that a weakness of the method stems from its reliance on professional judgement and its lack of biological validation. The Tennant Method was also specifically developed for the mid-western United States and thus may not be appropriate for the diverse streamflow patterns found in BC.

2.3.2. Modified-Tennant Method

Since the original Tennant Method was devised for a specific region, it was not always simple to apply it to other geographic locations. The method has since been adapted to other regions, such as the Texas Method which has modified the Tennant Method to account for the flashy streamflows common in that region, and which uses median annual discharge rather than mean annual discharge (MAD).

Natural variations in monthly flow have also since been incorporated into the method (Tessman 1980). This type of modification is common, and has led to the development of adapted methods that are more applicable to regions with different hydrological and biological cycles (e.g., see Estes (1995) for modifications appropriate for Alaska, and Locke (1999) for modifications appropriate for Alberta).

The advantages of Modified Tennant Methods are the same as the original method: no field work is required, ease of implementation, and they are based on a single hydrologic statistic (or a set of statistics that are easy to obtain). The modified methods may also provide a better fit to geographic regions outside Montana. Several of the disadvantages of the original method also remain in the modified methods, including the high degree of professional judgement embedded in the modified methods and the lack of biological validation. The potential need to further modify the method for sub-regions within BC may also be considered a disadvantage.

2.3.3. BC Modified-Tennant Method

The BC Modified-Tennant Method is a modified method that incorporates local biological and physical information (see Ptolemy and Lewis 2002). The method provides Tennant-like streamflow criteria for fish throughout the province (Table 2). The major modification in the BC Modified-Tennant Method is that the timing window for each flow threshold is adjusted depending on the fish life history and ecological information for the target stream. This requires that all pertinent information be compiled into a species periodicity chart, including data for species and life stages present, the timing of key biological activities such as spawning, incubation, migration, active rearing, overwintering, and specific ecological needs such as geomorphological considerations (see Estes and Orsborn (1986) for this approach).

Following the compilation of these data requirements, a schedule of flow requirements is developed that details appropriate flows for week-long time blocks (Table 2). The range of "appropriate" flows is determined by the ecological requirements at the time, and the selection of flow criteria for each ecological requirement. Any conflicts between requirements are typically resolved by defaulting to the highest flow within each time block.

Table 2. Summary of BC modified-Tennant recommended flows to satisfy biological and physical needs in British Columbia streams (from Ron Ptolemy, BC Ministry of Environment, personal communication).

Biological or Physical Requirement	% MAD	Duration per annum
Short-term biological maintenance	10	days
Juvenile summer to fall rearing	20	months
Over-wintering	20	months
Riffle optimization	20	months
Incubation	20	months
Kokanee spawning	20	days-weeks
Smolt emigration	50	weeks
Gamefish passage at partial barriers	50 to 100	days
Large fish spawning/migration	148*MAD^-0.36	days-weeks
Off-channel connectivity/riparian function	100	weeks
Channel geomorphology/sediment flushing	>400	1 to 2 days

The advantages of the BC modified-Tennant method are similar to other modified-Tenant methods. The method is a desktop method requiring little or no field work (provided that information for species distributions and life history timing is sufficient), the method is based on a single hydrologic statistic (MAD) that is easy to obtain, and the method represents a direct attempt to develop flow guidelines that are relevant for BC. A distinct advantage of this method is that there is a history of using the method on BC streams. Nonetheless, as with the other modified methods, the reliance on professional opinion and lack of biological validation are commonly cited as disadvantages of the method.

2.3.4. Alberta Desktop Method

The Alberta Desktop Method (Locke and Paul 2011) for setting environmental flows has emerged relatively recently. The approach is based on natural historic flows and provides specific withdrawal rules. These rules result in an ecologically based flow regime that incorporates the spatial and temporal flow conditions that are necessary to ensure long-term protection of aquatic environments. The method relies on observed or modelled daily or weekly flows over a long period of record; however, a minimum record length is not specified.

The method is intended to protect aquatic environments in the absence of site-specific studies, however, the supporting documentation suggests that more detailed, site-specific studies should be deferred to. These site-specific data may provide support for greater protection (i.e., less withdrawal) or additional flow abstraction. Although current support and discussion of the method have primarily focused on instream conditions for fish (Clipperton et al. 2002, Clipperton et al. 2003, Locke and Paul 2011), the method still explicitly attempts to retain aspects of the hydrograph that are critical for the maintenance of both instream and riparian habitats.

Flow abstraction rules are provided under this method for each week of the year. Where insufficient data are available, the time step may be expanded to monthly or seasonal time steps. A "cut-off" point is established for each time period, below which no water abstractions are permitted, and the maximum instantaneous diversion is 15% of flows in excess of the cut-off. Each week has an established cut-off flow (or "ecosystem base flow"), defined as the 80% exceedance (i.e., 20th percentile) for that period. The Environmental Flow recommendation under the Alberta Desktop Method thus specifies that no abstractions of water should be permitted for the lowest flows that occur up to 20% of the time. During higher flows, 15% of the natural flow can be abstracted (i.e., 80% of the time). This approach implies that water is not available for abstraction in one out of five years within each time step and that a full 15% of instantaneous flow may not be available when stream flow exceeds the threshold (e.g., a full 15% withdrawal may not be possible if the flow is just slightly above the threshold).

The Alberta Desktop Method is an inexpensive, rapid, desktop exercise that requires only reliable flow records, or synthesized data. A key strength to the method is that it is flexible, as it provides flow abstraction rules that respond to natural patterns of water availability, rather than prescribing a fixed seasonal schedule of flow thresholds that apply to all streams. There is some risk that the criteria developed in Alberta will be applied in different contexts and different geographic regions, without a sufficient understanding of the ecological implications of doing so. This risk is likely minimal, since the thresholds set by the method are relatively conservative. This conservative threshold itself may also be problematic in cases where demand exceeds the availability specified by the method, which is likely a common outcome. The flow rules of this method also do not scale to stream size, even though sensitivity to withdrawal has been shown to be related to stream size (Hatfield and Bruce 2000, Rosenfeld et al. 2007). Issues associated with connectivity to off-channel habitats on certain landscapes may also be affected by the 15% abstraction rule: during high flow periods this quantity may represent a substantial volume of water; that in turn affects connectivity (Ghamry et al. 2009).

Overall, the Alberta Desktop Method is appropriate for use at the reconnaissance level of water-resource development, or where water needs are fairly light and not continuous. The method can be considered as one of the better researched desktop methods, in that a wide variety of metrics were used to assess the efficacy of the method's rules (Locke and Paul 2011).

2.3.5. BC Instream flow thresholds for fish and fish habitat

The British Columbia Instream Flow Thresholds for Aquatic Habitat were designed to ensure streamflow levels are maintained throughout the year at a quantity that protects fish and fish habitat. The thresholds were explicitly designed to avoid HADD (harmful alteration, disruption or destruction of fish habitat) for small hydropower projects, but may serve as a reference point for other water uses. Under the BC Instream Flow Thresholds, applicants and reviewers are guided through a two-tiered assessment of fisheries concerns related to environmental flows: (1) a coarse screening filter and (2) a detailed assessment level. Preliminary data and information pertinent to fish and fish habitat must be provided by applications that hope to meet these guidelines' flow thresholds, including a project description, daily hydrologic data estimated from regional stations or collected from the stream of interest, biological data including fish presence determined through existing records or direct sampling, and reconnaissance-level fish habitat information. Applications that move to the detailed level will have to provide information at both the screening and detailed levels. Detailed information needs must include: geomorphology, water quality, fish biology, fish habitat, lower trophic levels, ecological function, and cumulative effects.

Two sets of flow thresholds are available, and are calculated from historic flow data: one for non-fish bearing streams and another for fish-bearing streams. Two data requirements are therefore mandatory under these guidelines. The first is the establishment of fish presence or absence, and the second is an adequate time series of mean daily flows. The entire period of record should be used (when data is reliable), and a minimum 20-year continuous record should form the baseline so that natural flow variation is reflected.

Flow thresholds differ for fishless and fish-bearing streams. The flow threshold for non-fish bearing streams is a minimum flow release equivalent to the median monthly flow during the low flow month. The flow threshold for fish-bearing streams is a seasonally-adjusted threshold for alterations to natural stream flows. Details specific to the calculation of these thresholds and further considerations are provided in Hatfield *et al.* (2003).

The BC Instream Flow Thresholds also require proponents to demonstrate that project flows will be adequate to support fish during migration and spawning periods. Although this requirement is site-specific, this action would typically require investigation of passage over flow-dependent barriers, or provision of pulse flows in rain-dominated systems.

The BC Instream Flow Threshold Guidelines provide an inexpensive and rapid standard-setting method that requires only reliable flow record, or synthesized data, and a good understanding of fish distribution. The method was approved by MOE and DFO. It is flexible, since flow thresholds are calculated based on natural patterns of water availability, and can therefore be adapted to different streamflow patterns throughout the province (e.g., rain, snow, or combined rain and snow hydrographs). Although the method has not been formally validated in terms of biotic response to implemented flow changes, the method was tested against a variety of other metrics to assess the efficacy of the method's rules (Hatfield et al. 2003). As with the Alberta Desktop Method, it is appropriate for reconnaissance level of water-resource development.

The threshold rules do not vary with stream size or type and therefore do not account for differences in sensitivity to withdrawal that are related to stream size (Hatfield and Bruce 2000, Rosenfeld et al. 2007). Consequently, there is risk that the method may not perform equally in all geographic regions and river types. As the thresholds are relatively conservative, this risk is considered to be low. Common criticisms of the method are that the method does not account for consumptive uses and it does not allow much water to be allocated to out of stream users. Since the thresholds are conservative, most projects undertake site-specific studies rather than adhere to these flow threshold criteria.

2.3.6. Other historic flow methods

Historic flow methods rely entirely (or almost entirely) on a long-term time series of recorded or estimated flows in the target stream. Generally, a fixed percentage of flow or a derived flow index is specified to maintain an ecosystem feature at a predetermined level. These flows may be set at an annual, seasonal, or less often, monthly, biweekly, or weekly time steps. The criteria are typically derived using expert judgement, comparisons between similar river types, and statistical analysis.

The methods described in sections 2.3.2 to 2.3.5 comprise the most 'popular' and best known approaches, but other approaches that rely on historic flows to produce environmental flow guidelines do exist. For instance, King *et al.* (1999) noted that there are at least 15 frequently referenced, hydrology-based methodologies, but many are region-specific or context-specific in their application. Jowett (1997), Dunbar *et al.* (1998), King *et al.* (1999), and Instream Flow Council (2002) review a variety of these methods (e.g., Hoppe, New England aquatic base flow, Northern Great Plains, Lyon, 7Q10, and Basque methods).

The key advantage of methods based on flow records is that they are typically inexpensive and rapid desktop exercises that only require historic flow records or synthesized data. A key strength of historic flow methods is that they do not specify fixed flow levels, but reflect natural patterns of water availability. In general, the weakness and limitation of many historic flow methods is the risk that the criteria developed for a given method will be applied across different geographic regions and river types, without sufficient understanding of the ecological implications. Overall, historic flow methods are most appropriate at a reconnaissance level and in cases where no negotiation is involved in the decision-making process.

2.4. Hydraulic methods

Hydraulic methods (Jowett 1997, Tharme 2003) determine environmental flow needs based on relationships between discharge and some hydraulic measure of a stream (e.g., wetted width, depth, etc.). The relationships are assumed to be indicative of ecological requirements. Examples of hydraulic methods include:

- Wetted Perimeter Method (Gippel and Stewardson 1998)
- Toe-Width Method (Swift 1976, Swift 1979)
- Riffle Analysis (Stalnaker and Arnette 1976)

Hydraulic methods are not standard-setting techniques, but it is straightforward to modify them for that purpose. For instance, policy can set the proportion of wetted width as the threshold and set the appropriate locations for placement of transects (e.g., in riffle habitats), thus making the method quick and efficient. Alternatively, one could set a flow threshold based on analysis of wetted width data from many streams in BC.

Hydraulic methods are relatively easy to implement and require minimal amounts of data to be collected. A major weakness is that they can be subjective (EA Engineering Science and Technology 1986, Gippel and Stewardson 1998), and therefore error prone. Other limitations include: lack of biological validation of hydraulic thresholds, independent assessments have indicated poor performance (Gippel and Stewardson 1998), and translating hydraulic relationships to "no HADD" thresholds may be difficult.

2.5. Habitat-rating methods

Habitat-rating methods develop relationships between flow and continuous measures of habitat availability. Examples of habitat-rating methods include:

- Habitat Quality Index (Binns and Eiserman 1979)
- IFIM / PHABSIM (Bovee 1982)
- PHABSIM prediction (Hatfield and Bruce 2000)
- MesoHABSIM (Parasiewicz 2001)

The Instream Flow Incremental Methodology (IFIM) is the best known habitat-rating approach. IFIM was developed in the 1970s by physical and biological scientists in the U.S. Fish and Wildlife Service (Reiser et al. 1989, Stalnaker et al. 1995). The method is the most widely used approach in the U.S. (Reiser et al. 1989), is commonly used throughout the world (Tharme 2003), and has remained state of the art as a result of its continuous refinement.

The IFIM is based on a collection of computer models called the physical habitat simulation model (PHABSIM). This simulation incorporates hydrology, stream morphology, and microhabitat preferences to generate relationships between river flow and habitat availability (Bovee 1982). Habitat availability is measured by an index known as the weighted useable area (WUA), which is the weighted area of a stream that is weighted by its suitability for use by an organism. PHABSIM allows habitat-flow relationships to be developed for any life stage of any species and indicates how these hydraulic habitats increase or decrease in area with discharge fluctuations, which in turn provides a simple negotiation and management tool.

This approach is different from most standard-setting techniques in that it is time consuming, expensive, and technical (Armour and Taylor 1991). The IFIM was a substantial milestone in the development of environmental flow methodologies (King et al. 2003), but has nevertheless attracted considerable criticism (Mathur et al. 1985, Scott and Shirvell 1987, Armour and Taylor 1991, King and Tharme 1994, Williams 1996, Moyle et al. 2011). Despite these many critiques, PHABSIM is still considered valid by many because it is fish-based, site specific, and more flexible and refined than many of the alternatives.

2.6. Holistic methods

Holistic methods have been developed partly in response to other methods that have a narrow focus on one (or a few) ecological elements and in some cases to accommodate consideration of socioeconomic values. Examples of holistic methods include:

- Building Block Methodology / DRIFT (King and Louw 1998, King et al. 2003, King and Brown 2006)
- Index of Hydrologic Alteration / Range of Variability Approach / Ecological Limits Of Hydrologic Alteration (Richter et al. 1996, Richter et al. 1997, Poff et al. 2010)
- Structured Decision Making (SDM) Approach (Ohlson 2008)

These methods are clearly not standard-setting techniques, though they may have an application where proponents wish to deviate from the output of a standard-setting technique or if there is a need to engage in planning over a larger geographic scale.

2.7. Recommendations for a standard-setting technique

Based on the reviews of different standard-setting and empirical methods in Sections 2.3 to 2.6, our knowledge of biological resources in British Columbia, and our experiences with water use decisions here and abroad, we believe that various aspects of existing historic flow methods can provide the foundation for good water management decisions for setting winter low flow requirements. The following are some of the primary considerations for this process.

Standard-setting method

Historic flow approaches hold the greatest promise for use as a standard-setting method for determining winter low flow requirements in BC. Ultimately, a selected method should build on the strengths of the BCIFN method (Hatfield et al. 2003), the Alberta Desktop Method (Locke and Paul 2011), and the BC-modified Tennant Method (Ptolemy and Lewis 2002). These methods, along with variants or hybrids, should be assessed for performance using a variety of performance measures to ensure they perform satisfactorily. The selected method should preserve key aspects of the natural hydrograph that maintain the physical aspects of streams on which fish and other ecosystem components depend (Richter et al. 1996, Poff et al. 1997, Richter et al. 1997, Trush et al. 2000).

Ecological values and risk

There is an explicit consideration and evaluation of ecological risk based on fish presence and absence under the BCIFN method (Hatfield et al. 2003). For instance, the thresholds allow considerably more water abstraction on fishless streams than on fish-bearing streams. This approach is consistent with DFO's risk management framework (Fisheries and Oceans Canada 2011), and could be extended to include additional risk levels, as has been done in other jurisdictions (e.g., Beca 2008). Specific to ecological risk evaluation, we recommend that one or more additional risk categories be developed based on the presence of priority species (e.g., species at risk or other species management concerns) or regionally important habitats (e.g., an important spawning area), with the understanding that priority species and habitats may vary within and among regions.

Scaling for stream size

There is compelling evidence that small streams are more sensitive to water withdrawals than larger streams (e.g., Hatfield and Bruce 2000, Rosenfeld et al. 2007, Bradford and Heinonen 2008). We therefore recommend that explicit consideration be given to stream size in any standard-setting method. Some jurisdictions (e.g., New Zealand, Germany) give small streams greater protection than larger rivers (Dunbar et al. 1998, Beca 2008), but most jurisdictions do not explicitly give special management status to small streams. This may simply be a result of a lag between policy and science. Of the standard-setting methods discussed in this report, the absence of consideration to stream size is considered one of the potential drawbacks to the Alberta Desktop Method (Andrew Paul, ASRD, personal communication), and other methods.

Building blocks

Standard-setting methods based on historic flows use hydrology information as a proxy for biological performance because flows are typically much easier to measure (or synthesize) than ecological metrics like fish abundance. Reasonable efforts should be made to ensure that the hydrology is in fact a good proxy for biology, so that the standard protects what it sets out to protect. The Building Block Methodology (King and Louw 1998) is a useful guide for linking flows to environmental performance, and the BC-modified Tennant thresholds (Ptolemy and Lewis 2002) describe the essential building blocks. Some key questions remain that will be important for future management decisions, including:

1. What fish species occur in BC streams?
2. What are the species of management concern?
3. What is their typical life history timing?
4. How does their range and biology vary within this region?
5. How is their basic biology (e.g., rearing, spawning, overwintering, migration) related to the hydrograph?
6. Are there other stream-dependent species (e.g., birds, frogs, etc.) that are of management concern?

Empirical methods

More in depth and detailed reviews are typically required for complex projects or those with intensive resource use. Two-tiered (or multi-tiered) review and approval processes are common in many jurisdictions (Kulik 1990, Dunbar et al. 1998). In general, environmental reviews are triggered under the British Columbia Environmental Assessment Act (BCEAA) and the Canadian

Environmental Assessment Act (CEAA). A number of initiatives have emerged to streamline review processes, and one important thrust to standardize data capture and analysis methods in BC. Lewis *et al*. (2004) describe methods appropriate for assessing small hydropower projects in BC, but these should be viewed as the core of any empirical environmental flow assessment in BC. Thus, any project that wishes to abstract more water than that made available by a standard-setting method should undertake detailed studies as described in Lewis *et al*. (2004). This approach is consistent with that proposed in Hatfield *et al*. (2003).

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