# Rationale for Multiple British Columbia Instream Flow Standards to Maintain Ecosystem Function and Biodiversity

**Draft for Agency Review**

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# 1 INTRODUCTION

The British Columbia Instream Flow Standards for Fish, Biodiversity and Ecosystem Maintenance ("the Standards") represent a meta-analysis of previous habitat-flow studies, original new analysis, specialized stream inventory, stream gauging records, and stock assessment. This work supports the rapid desk-top or office-based method for setting instream flows to protect fish and fish habitat in British Columbia streams. The standards rely on a systematic review and statistical analysis of science-based fish-habitat-flow surveys. They include biological, ecological and geomorphologic factors affecting fish habitat. They rely on empirical field data and use a weight of evidence approach that includes stock assessment information and watershed profiles. These Standards are meant to apply to all nine BC EcoProvinces and so are designed to use site specific flow and fish periodicity information. The Standards act as a coarse filter to identify biodiversity concerns prior to major water allocation decisions.

During phase I of the project to develop these Standards, the review team identified the need for an expanded rationale to support the draft instream flow standards and formalization of references and supporting photographs. This draft document provides a rationale. This document is intended for internal use only and serves to provide a summary of the existing rationale for phase II of standard development. The information herein may be reorganized and combined with other information to support the standards; therefore analyses and findings should be interpreted as interim in that they may be changed and updated.

The Standards are an adaptation of Tennant's (1975, 1976) seasonal flow recommendations to calibrate the percentages of mean annual discharge ("MAD") to local hydrometric, geomorphic and ecological conditions at various times of the year. The flow standards broadly relate to earlier efforts of Tennant (1976) and others (Binns 1982) with standard reference to "naturalized" mean annual discharge as the common denominator. A key feature of these approaches is to relate instream flow needs to naturalized hydrographs, avoiding standards based on degraded stream conditions that would not protect fish habitat.

Productive BC streams have hydrographs quite different from the Montana norm on which the Tennant method is based. During the growing season and critical streamflow period (the driest month during the growing season), BC streams have flows that would be interpreted as fair or poor using the Tennant method, yet support abundant fish populations. As a result of these and other differences, stream flow percentages identified by Tennant (1976) do not provide the specificity and flexibility required to protect habitat in British Columbia.

The Standards build on the existing practise of prescribing percentages of MAD for BC streams (Newcombe and Ptolemy 1985). The BC Instream Flow Standards are built on the principles of the Tennant method, yet they are substantially better because they incorporate fish periodicity information and ecological information. The Tennant method has been modified in other jurisdictions to increase applicability 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). From a regulatory perspective, a potential advantage of the modified Tennant approach is the legal precedent set by its acceptance in U.S. courts (Estes 1998).

Leopold (1994) captures the nature of rivers by showing with empirical data from around the globe that streams have predictable hydraulic geometry and symmetry in hydraulic relationships. Stream width, depth and velocity vary systematically in relation to mean annual discharge. The principal hydraulic parameters are highly correlated to discharge as power functions. Fish respond to hydraulics in a non-random fashion and show fidelity to certain habitats across different channel types suggesting that "flow standards" based on hydraulic geometry are universal.

Building on the base of hydraulic geometry, this method incorporates the concept of hydraulic diversity and defines flow coefficients (% MAD levels) to protect specific ecological functions. These flow coefficients were developed over three decades of stream surveys of various kinds that captured the response of habitat and fish behaviour to flow change.

The draft BC Instream Flow Standards are based on ongoing field investigations, instream flow studies on BC streams, and the corporate memory of experienced fisheries field staff within senior government. In combination, these provide a scientifically defensible rationale for the standards. Workshops during the development of the standards indicated a general acceptance of the standards; however, some team members requested a more thoroughly documented rationale to facilitate a critical review. Such a review is necessary because third parties will scrutinize these standards, perhaps in an adversarial manner. It is anticipated that the trial application of these standards using hydrology and biological data on streams well-known to the sceptics will improve confidence that this method will protect fish habitat.

## 2 METHODS

Based on the information provided by the Province during Phase 1, there appeared to be adequate information to support the standards. It was assumed when this project was initiated that the existing supporting information is adequate to provide sufficient rationale to the standards. However, this document does not include the analysis of new data to support the rationale, a task that is ongoing as part of Standards development. Accordingly, this document is limited to documenting and presenting in summary form the information that was earlier identified. In some cases, particular studies reported earlier were not available.

To document the rationale, the supporting information was assembled and reviewed to identify key findings and parameter values relevant to the Standards. The head office of the Ministry of Water, Land and Air Protection was visited where Ministry staff had assembled available (non-archived) data and reports, memos, etc., relevant to the standards. Each report or file was reviewed, and the following information was recorded:

Source: reference to the citation
Citation: the citation for the report or a description of the data provided
Stream: Gazetted stream name
Methods: Type of assessment used: e.g. PHABSIM; wetted width, biological response to flow correlation, single transect, plunge pool.
Sample size: number of transects used to establish recommendation
Recommendation type: optimum, minimum, preferred, or unspecified
Target: species or habitat on which the recommendation focussed.
Value: flow in cms
Page: in source where recommendation value is found
MAD: mean annual discharge of the stream, in the reach where the recommendation is made
MAD source: the document, WSC database, or annotations in the document made by MWLAP staff
% MAD: recommendation value divided by MAD
No. flow levels measured: number of different flows at which habitat measurements were taken
Min flow measured: in cms
Max flow measured: in cms
Comments: on utility of recommendation
Peer review ready: is this a final version of an investigation with clear objectives, detailed methods, data including appendices to support summary values?
Issues likely in peer review: weaknesses of analysis in the context of supporting a rationale for a flow standard.

An additional task that was proposed as part of this study was to obtain published studies and newer documents that may not be available through agency personnel that were alluded to by team members during the workshop, including primary literature on ecological flows. A detailed literature review was undertaken during the preparation of the Phase 1 document and is ongoing. Some of the most relevant literature is cited here. The final technical Standards document will present the complete literature review.

## 3 FINDINGS FROM THE REVIEW OF DATA PROVIDED FOR PHASE 1

The data identified in a table summary by the Ministry for phase 1 of the study consisted of

- 32 studies on fish rearing and insect production flows
- 18 studies on optimized wetted width (PMC analysis) with minimum flows at riffles (10% MAD "severe" flow of Tennant [1976]).
- 40 studies on spawning and migration flows.
- 7 studies on channel maintenance or flushing flows.

- 21 studies on wetland, sidechannel and off-channel linkage flows.
- 7 studies on "rearing" flows and optimization of hydraulic diversity in canyon reaches.
- 26 studies on adult steelhead passage flows at partial barriers within canyons.

These data were provided in an Excel spreadsheet that identified Region, Stream, Watershed Code, fish species , MAD (cms), fish flow (cms), coefficient %MAD, MAD (cfs), fish flow (cfs), comments, study, and methods. Outputs using cfs were designed to compare to some USA models using the same units of flow. To document these studies and review their findings, a visit to MWLAP offices was made and dozens of files containing reports, raw data, memoranda, and primary publications were provided. Note that the terms of this assignment did not include finding the original material: that was the responsibility of the Ministry. Within the files provided, 25 reports were provided that contained flow recommendations for a specific river within British Columbia. Some of these reports were brief memoranda or summarized field observations that were the basis of a flow recommendation. Detailed information was collected on each report, as described above in the methods. From this review, 64 recommendations were identified, including reports identified in Phase 1 and new reports provided by the Ministry. These recommendations were made by a variety of methods including: weighted usable area (PHABSIM), wetted width (hydraulic analysis and cross-sectional analysis), behavioural studies including radio telemetry and fence operations, and air photo analysis and habitat-at-reach scale surveys at a fixed or known flow. Detailed information (as described in the methods above) from each study and the flow recommendation is available in an Excel spreadsheet (BC IFS Rationale Appendix 1.xls).

Of the studies on fish rearing and insect rearing flows identified in Phase 1, 8 reports were provided for review. An additional report, by Griffiths on the Nanaimo River, is likely available from other sources but was not provided. Of the 15 reports not obtained, file data was available in the past; however, during the recent move into new offices in the past year the files were reorganized and were unavailable for audit. These data may be available in the future as Ministry staff work through the files; however, they were not available for review and may not be available within the time frame for the development of the Standards. Of the eight reports, six were ready for peer review. One on Black Creek by Komori Wong Environmental was not yet ready for peer review, as it is a work in progress. Additional information on this study, in the form of a memo provided by Ron Ptolemy, greatly improves the analysis, but the memo and report should be integrated into a single document prior to peer review. Another report, by G. Kapahi on Nile Creek, appeared to rely on a single cross section to set flows and was not considered adequate to withstand peer review. A table listing each of the 24 studies identified is provided in Appendix 2. It is important to note that reports unavailable or not yet ready for peer review, although potentially useful, may pose a weakness in any peer review depending on the strength of readily available evidence.

Of the 36 studies on spawning and migration flows identified in Phase 1, 10 (28%) were provided for review. Of the 26 missing studies, several may be obtained by contacting other agencies; however, no citation was provided so no clear direction could be given to a librarian, and therefore this step was not undertaken. Of the 10 available studies, four were not ready for peer review. One is the memo by Ron Ptolemy on Black Creek that analyses the results of the work by Komori Wong. The memo should be integrated into the report; also, additional data is being collected at higher flows, so that this work is not yet complete and so not ready for peer review. Three other studies were not ready for peer review, all by G. Kapahi, and apparently based on a single cross section in each stream.

The missing or archived reports represent most of the information that has been brought forward to support the standards for rearing and spawning flows. Ptolemy's assessment of available data is that all the tabled fish flows are considered accurate regardless of whether documents are retrievable for audit purposes. (Similar meta-analysis databases are not supplied to reviewers (Hatfield and Bruce 2000) to audit key information such as HSI curves or transect selection.) Despite incomplete and full records, the standards are supported by the audited data and criteria. The reduced data set supports the 20% MAD conservation flow for rearing and insect flows (Figure 1). Similarly, the reduced data set supports the curvilinear conservation flow - MAD relationship for migration and spawning flows (Figure 2). At this time we can view the missing studies as 1) the corporate memory of MWLAP staff, or 2) historic studies whose data has been lost, or 3) additional studies that, although missing documentation, probably support the standards given that the review of 1/3 of the reports did provide support.

Additional studies identified during the review of data at MWLAP offices provide limited additional support for the 20% MAD conservation flow for rearing and insects. Most of the additional data came from the Flow Limitation Assessment Project (FLAP) in the early 1980's. Figure 3 shows the data provided during phase I, the new studies, the FLAP studies, and the 20% MAD conservation flow.

Additional studies identified during the review of data at MWLAP offices provide additional support for the 30% to 200% MAD conservation flow for spawning and migration. Three studies were older and completed as part of the Flow Limitation Assessment Project (FLAP) in the early 1980's. Figure 4 shows the data provided during phase I, the new studies, the FLAP studies, and the 30% to 200% MAD conservation flow. The best-fit line for the Phase 1 data shown by the solid blue power function departs from the criteria when MAD exceeds 84 cms.

## Figure 1:

Scatterplot and trend of ideal rearing flow (juveniles only) and mean annual discharge for study streams in British Columbia using the Riffle Analysis.

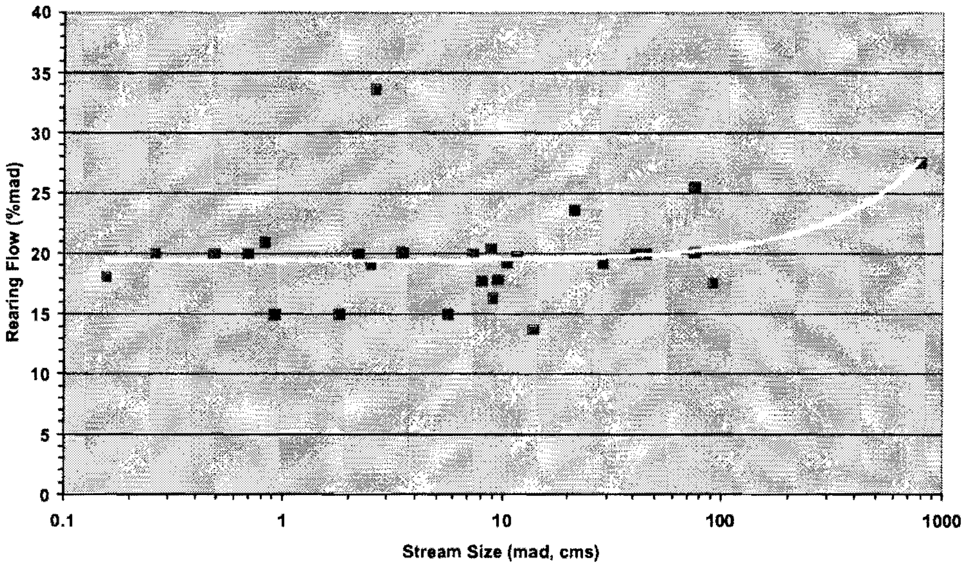


**Figure 2:** Relationship between conservation flow for spawning and rearing and mean annual flow with the Phase I data set (open triangles) and a subset of those data with reports ready for peer review (closed circles).

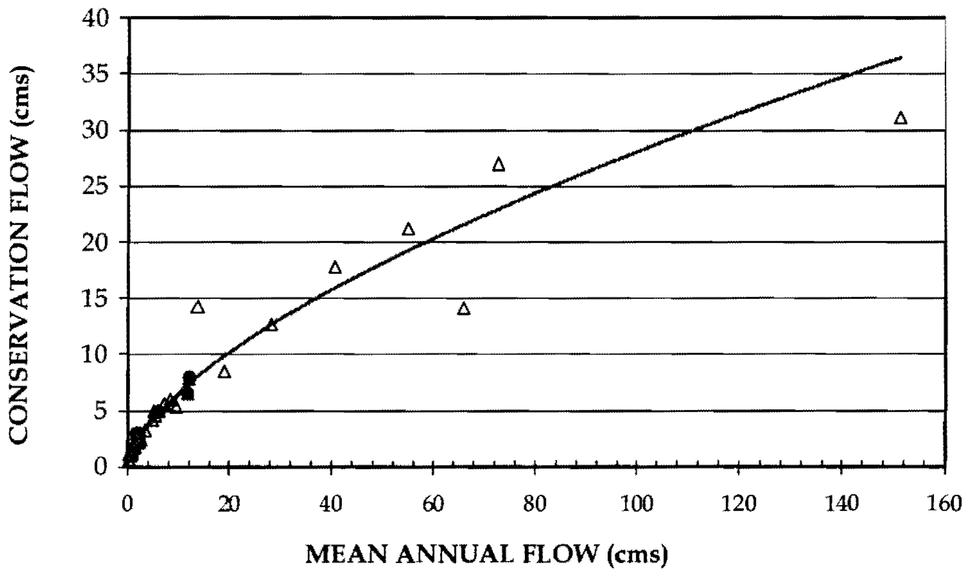


**Figure 3:** **Relationship between conservation flow for rearing/insects and mean annual flow with the original data set (open triangles), newer studies (closed diamonds), and older FLAP studies (open diamonds).**

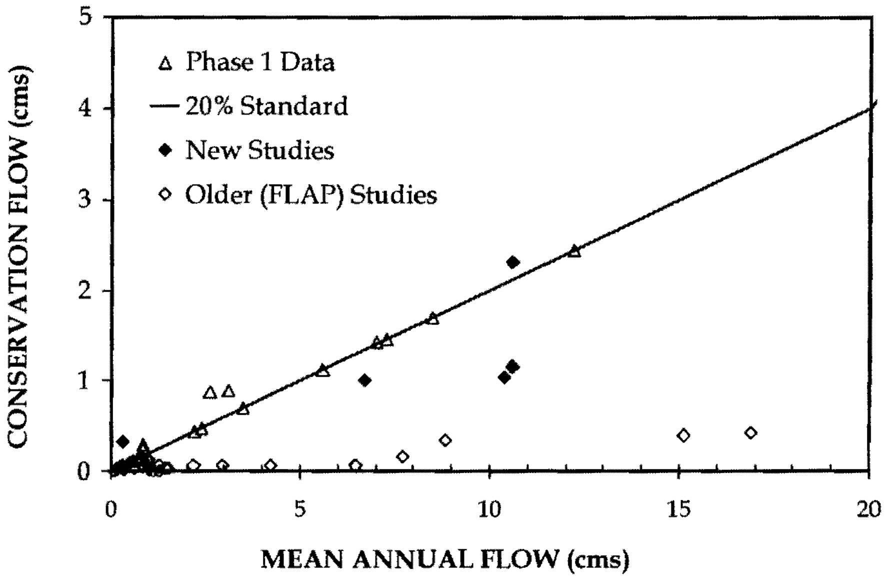
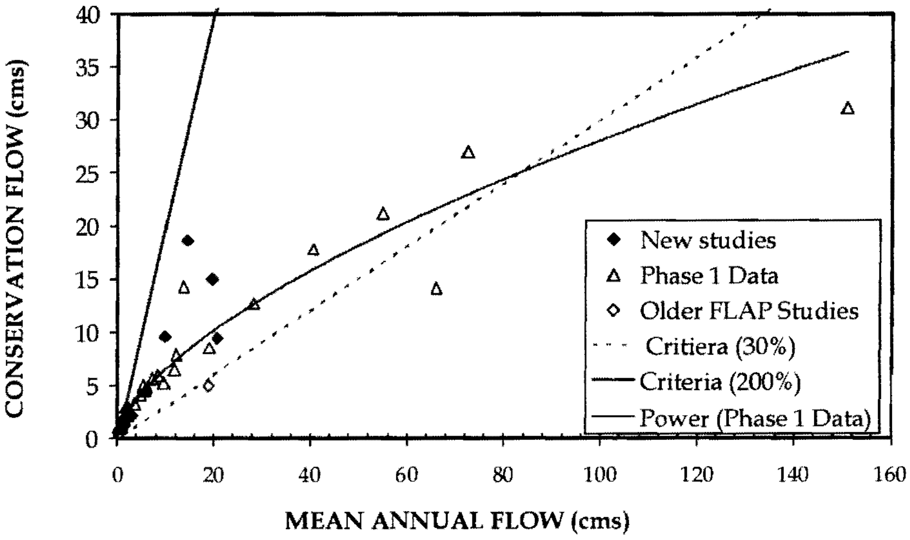


**Figure 4:** **Relationship between conservation flow for spawning and migration and mean annual flow with the original data set (open triangles), newer studies (closed diamonds), and older FLAP studies (open diamonds).**



# 4 RATIONALE

The rationale for the Standards follows from the results of numerous studies completed in the Province, but it is equally based on a logical framework that ties together the physical and biological aspects of streams. The rationale is developed by first articulating the links between hydrology and stream geomorphology to justify the use of mean annual discharge (MAD) as the primary metric for describing stream size. Stream morphology is described quantitatively by defining stream hydraulic relationships that are in turn related to microhabitat and fish behaviour, defining the link between physical conditions and fish habitat use. Finally, fish habitat is linked to productive capacity, the crucial performance measure in the Fisheries Act. Once this framework has been constructed and supported by reference to the scientific literature, empirical evidence from British Columbia and other jurisdictions is brought forward to support a link between stream flow and fish production.

## 4.1 Stream Geomorphology

Over time, the physical forces of gravity and friction shape river channels. The volume and gradient of a stream determine its power – the ability to move sediment and cut through bedrock. Higher flows have greater power to shape the channel than lower flows but because very high flows are rare and short-lived, they may not have formed the part of the channel where water is most often found. Stream flows are variable on an hourly, daily, and annual basis, but they show regular annual patterns with average seasonal values falling within a predictable range. We can express stream size at a given location as a statistic to serve as a benchmark against which to compare streams and also to compare flows at a fixed station over time. The statistic most commonly used is MAD, the average daily flow observed within a calendar year, averaged over the period of record and corrected to a longer period of common reference. MAD is the total volume of flow ($dam^3$) that passes through a cross-section ("at-station") in a year divided by the number of seconds in a year (365×24×60×60) to yield a measure in cms or L/s as appropriate to stream size.

MAD plays a small role in forming the channel, given that during a typical year the flow is higher than average 25% of the time and has greater power to move sediment. However, because MAD tends to be highly correlated to the channel forming flow (Leopold and Maddock (1953) found that MAD occurs at a frequency of 25% in most rivers) it can be used as a proxy for the relative size of stream channels. This frequency means that in about 91 of 365 days, the flow value of 100% MAD is exceeded. On an annual basis, there are about 265 days where the discharge is less than the MAD. Simply put, MAD is a relatively large flow.

When we refer to flow or stream size in the following document, we will be using mean annual flow as the metric for this parameter. The widespread availability of MAD as a flow statistic provides an important practical reason for this adoption. Since the large flows that form stream channels are proportional to MAD, we can compare stream channels on the basis of MAD.

Channel forming flows mobilize the largest substrate, also known as bed armour. The largest material can be moved by only the largest flows. Lower flows play a role in forming the channel because they are capable of transporting finer sediments whose erosion and deposition can affect channel form. The competence of a given flow to move stream sediment increases with flow, but channel-specific differences in hydraulic conditions, sediment density, and compaction make it difficult to predict the channel forming flow. Channel forming flows initiate and maintain bed material movement, which is closely correlated with stream velocity, but is also affected by slope, channel shape, depth, and particle size. Despite the difficulty in predicting channel-forming flows, suspended sediment load can be expressed in general terms with a simple power function with flow:

$L=pQ^j$

where L is suspended load and P and J are constants (Ritter 1978). Suspended load increases in a continuous fashion with flow, suggesting that channel forming flows cover a range of flow. Despite this, at a single cross section, most of the sediment may be mobilized at a particular flow.

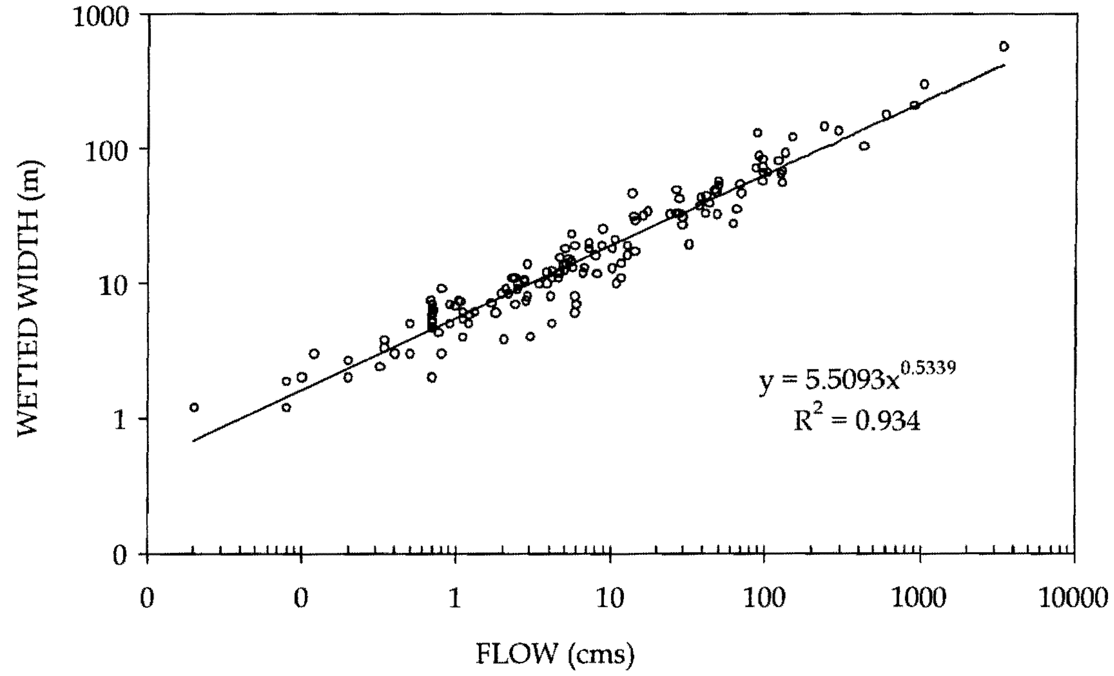
## 4.2 Stream Hydraulics

Stream hydraulics describe the physical properties of water movement in stream channels. When flow increases, more water must pass a given point per unit time, and therefore stream width, depth, and velocity tend to increase. The rate of increase of each parameter differs, but the relationships between stream flow and these parameters are consistent across streams. Empirical studies of river channels differing in size by four orders of magnitude demonstrate consistent relationships between each parameter and river flow and in the ratios of parameters. Width, depth and velocity are related to flow through power relationship of the form $X = aQ^b$, where x is the stream hydraulic parameter of interest, a is the coefficient, and b is the power function. Typically the relationships are expressed in a logarithmic form and plotted on log-transformed axes. Typical values of the exponent are 0.26 for width, 0.40 for depth, and 0.34 for velocity (Leopold and Maddock 1953) for "at a station." Typical values for "downstream" changes are 0.5 for width, 0.4 for depth, and 0.1 for velocity.

The coefficients of each relationship have been measured at hundreds of cross-sections in dozens of streams. From these studies, it is apparent that although values of these coefficients vary, they fall within a specific range with typical values characteristic of most streams. This consistency across stream channels allows us to predict hydraulic parameter values, given a particular cross-section, and the relationship between these parameters and flow. According to Leopold (1994), despite variation about each exponent, within any river basin the channel width varies as the square root of the discharge, whether the discharge value is MAD or bankfull. Equally noteworthy, velocity is comparable for small and large streams or great rivers. Small streams have a velocity from 15 cm/s to 150 cm/s, and the largest of all rivers 60 cm/s to 201 cm/s.

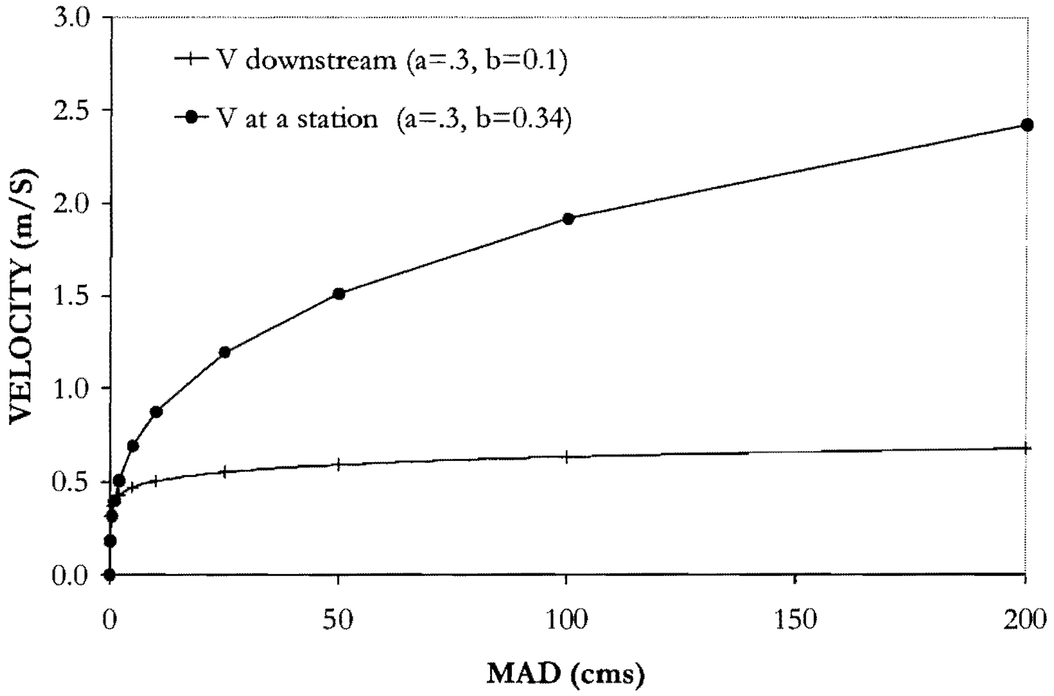
The literature distinguishes hydrometric relationships developed at at-a-station from those developed downstream because the exponents of the relationships differ. Downstream relationships are those developed by analyzing different stations, analogous to comparing streams of different MAD. In developing Standards for instream flow, we are mostly interested in defining relationships at-a-station, but we do wish to understand how these vary with stream size across the Province to provide a reality check on how well the literature-based models apply. **Figure 5** shows a plot of mean reach wetted width with MAD for BC streams (Ptolemy 2002 unpublished data); the regression is consistent with the downstream width exponent of 0.5. The variance about the trend line (7% unexplained variance) is related to bed material with sand-bed cases (like the lower Fraser River) showing greater width than predicted, and confined or entrenched bedrock canyon streams showing much reduced widths (e.g. Campbell River Elk Falls Canyon width = 30 m and MAD = 86 cms).

**Figure 5: Scatterplot and trendline of reach mean wetted width and mean annual discharge for BC streams. Uncoded for channel type.**



Width and depth increase with flow, both at-a-station and also among stations. Velocity increases with %MAD at-a-station but surprisingly shows little change with MAD in downstream (among station) relationships (Leopold and Maddock 1953). Figure 6 shows theoretical relationships for velocity with a coefficient of 0.3, with an exponent of 0.1 for downstream stations and 0.34 at-a-station. The normal range in the velocity exponent of 0.1 to 0.8 (Park 1977) reflects the influence of mesohabitat type. Riffles have the highest velocity of all mesohabitat units, regardless of flow level. Velocity changes slowly with increases in flow across downstream stations (i.e. when comparing rivers of different sizes). In contrast, velocity changes more rapidly at-a-station. This characteristic may have important consequences for the Standards as it suggests that a fixed percentage of mean annual flow may provide adequate velocity at all stations throughout a watershed.

**Figure 6: Empirical mean channel velocity to flow relationships based on typical hydrometric equation parameters. Information taken from Leopold and Maddock (1952).**

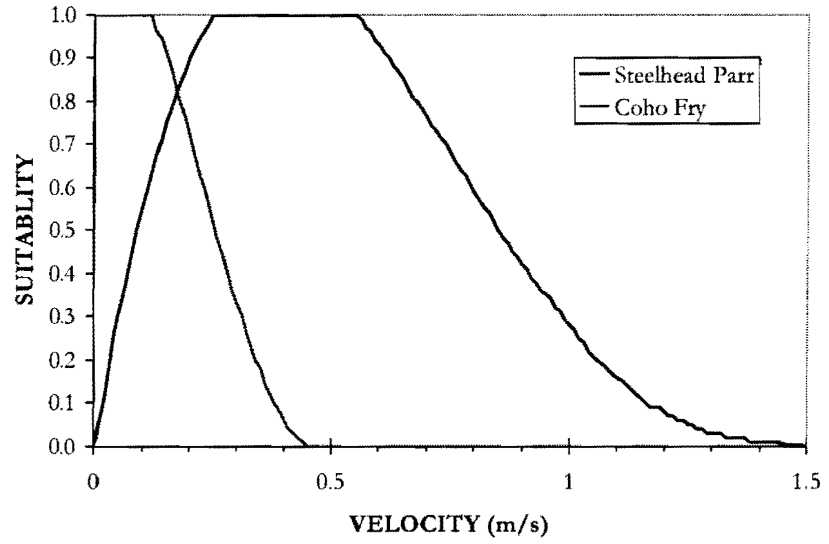


## 4.3 Fish Behaviour and Habitat

We extend hydrometric relationships to include fish by linking fish behaviour to stream hydraulic parameters. By direct observation and through experimental manipulation, the relationship between fish behaviour and hydraulic parameters has been parameterized in habitat suitability index curves. These curves show the relative use of habitat at different values of hydraulic variables. Reliable curves can be constructed when fish presence is measured consistently and accurately over the full range of conditions available over many streams. Typically, observations of fish habitat are rolled up into a histogram or a probability-of-use curve that is scaled to one. These indices demonstrate that fish are more commonly found at specific parameter values and imply that fish can discriminate these values (either directly or indirectly by sensing covarying parameters) and that these habitat choices have adaptive significance, conferring higher fitness.

Describing the typical observed pattern of habitat use, we observe fish more often at low to intermediate stream depths and velocities than at more extreme values. There are distinct differences in habitat use between species and life histories. For example, steelhead parr use consistently higher water velocities than do coho salmon fry (Figure 7). These differences in microhabitat use may drive the observed differences among rivers in the abundance of species.

**Figure 7: Habitat suitability curve for velocity for steelhead parr and coho salmon, based on BC Provincial data.**



Although the survival benefit of occupying a specific depth or velocity is difficult to measure, Fausch (1984) does a convincing job of measuring the energetic benefits of specific stream positions, an approach that has been used by others. Considering how depth and velocity influence access to food (high velocities deliver more food), energy expenditure (velocity refuges reduce the cost of holding), and risk of predation (deep habitats offer protection from avian predators), it is impossible to ignore the potential adaptive significance of habitat choices. The premise of many instream flow methods is that habitat use reflects fish preference and results in higher growth and survival. We admit this premise, and it forms the basis of this rationale.

Many species of fish are facultative rather than obligate riverine species. As a result, many species have generalized velocity preferences (Aadland 1993) that reflect their adaptation to slow water conditions. Although this plasticity in behaviour is undoubtedly adaptive, there is a hazard, when evaluating habitat suitability in rivers, in relying on habitat use data developed for species with preference for low velocities. The use of such data will lead to prescriptions of lower flows than required for obligate-river species of fish and benthic invertebrates (Aadland 1993). In addition, pool-oriented fish (particularly in small streams) may depend on food produced in other mesohabitats such as riffles, rapids and cascades (Aadland et al. 1991), which have different hydrometric relationships than do pools. Although several investigators (Orth and Maughan 1982; Irvine et al. 1987; Holtby and Hartman 1982; Aadland 1993) have stated that predictable relationships between habitat area and fish populations cannot be expected in streams limited by food, where this food is largely stream invertebrates produced in riffles, predictable relationships may be found.

Instream flow determinations based on the behaviour of fish that prefer low velocity mesohabitats may underestimate rearing flows required by fast-water specialists. Instream flow assessments should target species that occupy flow-sensitive mesohabitats (Aadland 1993). This leads to a focus on riffles and the use of riffle or wetted perimeter analysis in instream flow determinations (Stalnaker and Arnette 1976). A focus on riffle specialists as key indicators in instream flow setting and reliance on riffles analysis has been followed by BC instream flow practitioners since the mid-1970s.

### 4.4 Fish Habitat, and Productive Capacity, and Flow

Fish habitat is the physical space used directly by fish or relied upon indirectly by fish for survival. Fish habitat in streams can be parameterized as the combination of physical conditions used by fish, essentially a physical subset of the variables that define a niche. The Fisheries Act defines fish habitat as: "Spawning grounds and nursery, rearing, food supply and migration areas on which fish depend, directly or indirectly, in order to carry out their life processes." The no net loss principle of the Policy for the Management of Fish and Fish Habitat demands no net loss of 'productive capacity of fish habitats', defined as "the maximum natural capability of habitats to produce healthy fish, safe of human consumption, or to support aquatic organisms on which fish depend." A clear definition of productive capacity has been elusive. Minns (1995a) adopts Ricker's (1975) definition of production (new body mass per unit time, per unit area) and refines this for fish as "the sum of all production rates for all co-occurring fish stocks with a defined area of ecosystem."

It is difficult to measure fish production even in simple situations, such as a single stock in a small lake. By comparison, the task of estimating the production of multi-species assemblages of anadromous fish appears daunting. Minns (1995) identifies biomass and other biological indices as well as surrogate habitat variables as alternatives to measuring fish production. Production is commonly inferred from standing stocks of fish, assuming consistent ratios of production to biomass, but these and all other surrogate measures require supporting work to validate their utility.

Fish production has been measured in British Columbia and other jurisdictions by a variety of methods. Within British Columbia, estimates of adult spawning populations of salmon and steelhead are essentially estimates of production. For these species the escapement of returning adults represents the cumulative production of aquatic and marine habitats, minus the saltwater and fresh water catch. Differences between streams in long-term average spawning populations reflect differences in the fresh water environment, at least over restricted geographic areas within which the influence of marine factors is similar. The influence of the marine environment and variation in annual catch typically confounds such data. Unfortunately, more direct estimates, such as counts of smolts, or multi-year studies of resident salmonid growth and abundance, are insufficient in number to allow us to link fish production to flow. Given this, we accept the less precise relationships between flow and production that we expect to find in the available data.

Flow has been described as a 'master variable' (Poff *et al.* 1994) that controls a suite of physical variables that in turn influence fish production. Flow affects stream surface area, velocity, and depth, but also a host of other physical variables such as light penetration, rates of sedimentation and erosion, and temperature. With the *apriori* hypothesis that flow is positively correlated with fish abundance or components of fish survival and spawning success, we examined the literature for supporting evidence. A high profile link between fish production and river flow is published in the landmark 'Pacific Salmon Life Histories'. Healey (1991) shows that chinook salmon spawning populations correlate with river flow over two orders of magnitude (5-500 + cms). Smoker (1955) found a correlation between the commercial catch of coho salmon and annual runoff, summer flow, and lowest monthly flow in 21 western Washington basins 2 years prior, despite potential confounding spawner-recruit influences. Mathews and Olson (1980) analysed data from Washington and showed that summer baseflows were correlated with total coho production for Puget Sound streams. Rushton (2000) reported a remarkably strong fit ($R^2$= 98%) between numbers of coho smolts produced in Bingham Creek (Washington) over ten years and 60-day mean summer low flows. Wolff et al. (1990) found that resident trout responded to flow increases in Douglas Creek with a four-to-six fold increase in biomass (habitat surveys showed a doubling of stream wetted width and weighted usable area for adult fish increased by five-fold).

A positive association between fish habitat and flow has frequently been observed. Burns (1971) found a correlation (r=0.898) between stream surface area and salmonid biomass in seven streams in northern California. Binns and Eiserman (1979) were able to predict standing stocks based on flow and other habitat variables. Jowett (1992) correlated brown trout standing stock with habitat area and food production. Baran (1995) correlated brown trout standing stock with habitat in 15 streams in the Pyrenean mountains. Lewis (1969) reported high densities of rainbow and brown trout in pools with greater currents and higher insect drift rates from riffles.

Coho salmon in Carnation Creek (MAD 0.829 cms) provide an informative BC example of habitat constraints to fish production (Holtby and Hartman 1982; Hartman and

Scrivener 1990). In a multi-year study (1973-1999) measuring coho salmon growth, survival and biomass, mean rearing flows varied from 0.01 cms (~1% MAD, August 1985) to 0.17 cms (~20% MAD, August 1976). The lowest recorded flow period was in August 1994 (0.007 cms, 0.8% MAD): the lowest coho smolt yield was observed the following spring. Flows of 30-day duration prior to annual stock surveys in September were positively correlated with coho abundance, though little variance was explained ($R^2$=0.25, d.f. = 18). Riffles were more sensitive to flow change than pools: riffle area increased by 1.87X while pool area increased by only 1.14X. Holtby and Hartman (1982) hypothesized that the correlation between abundance and flow was explained by the superior conditions in riffles at higher flows. They emphasized the importance of the duration of low flow events, rather than just the magnitude. In Carnation Creek, riffles produce most of the benthic insects, and low events reduce riffle area and the drift of insects into areas where coho juveniles typically hold. This suggestion fits well with the positive correlations between current velocity and quantity of drifting insects reported in the literature (Cutis 1959; Waters 1969; Giger 1973; McCaly 1968; Pearson et al. 1970; Banks 1974).

Although a few studies have found no correlation between streamflows and fish abundance (Irvine 1987), this may be explained by the complex life histories of salmonids, multiple habitat-bottlenecks, inaccuracy of reach-level surveys, and the many factors that influence their abundance (e.g. critical seeding rates, complex food webs, density-independent factors such as floods) and confound fish-flow relationships.

Stalnaker et al. (1995) describe and provide examples of habitat bottlenecks and impacts on productive capacity. Habitat limitations to production may arise in several ways. Ecologists have generally found (Bovee et al. 1994):

1. there may be several consecutive and independent habitat events that can affect adult populations (such as fisheries, spawning habitat, fry/parr rearing habitat, temperature regime, adult feeding territories);
2. limiting events often occur multiple times over variable time scales;
3. habitat may be co-limited at both high and low flows and by the rate of change of flow events;
4. the smallest amount of habitat available during the year may not be limiting productive capacity (such as during the winter when fish are inactive and not defending territories); and
5. mesohabitat types not directly utilized by the fish species (such as macroinvertebrate habitat as it affects downstream food supply for fish) may be more important than the habitat directly used by the species (with implications on which HSI curves might be used in a PHABSIM survey).

Correlations between habitat and flow and fish abundance and flow provide circumstantial evidence for a causal link between fish production and flow. Other factors influenced by flow, such as physical habitat, have a more direct link to fish production, and correlations between these and fish production may be stronger. However, the fundamental assumption underlying the Standards is that flow influences fish production or sustained population levels; therefore, it is important to show that this relationship exists.

The correlation between production and river flow supports the development of the standards in a general sense, but it does not provide specific guidance regarding the level of flow required to maintain fish production within a channel. Our specific interest is the percentage of flow retained in a stream, rather than the absolute flow, and how this affects fish production. Examining the escapement of chinook salmon to the Nechako River, Bradford (1993) found that returns were lower when that population spawned in the upper river where the level of flow reduction from regulation was greater. From this he concluded that regulation was responsible for the relatively poor escapement of chinook to that river, though the specific mechanism of limitation was not identified. Smith (2000) suggested that wild steelhead abundance, as indexed by angler catch-per-angler-day, is lower in more northern, snow-melt driven watersheds where high summer flows reduce juvenile habitat. This suggestion seems plausible when comparing streams from biogeoclimatic zones with different hydrology (Smith examined streams influenced by snowmelt and rainfall type hydrology). His results do not refute the hypothesis that habitat increases with increasing flow, but rather suggest a dome-shaped function, where fish production is depressed at higher levels of flow. Research at Snow Creek (Olympic Peninsula; data from T. Johnson 1992) suggests that steelhead parr and smolt production over a summer baseflow range of 7-44% MAD was unaffected (r =0.20; d.f. = 8) and perhaps confounded by winter floods. Steelhead parr and smolt counts (Lirette et al. 1985) completed on the Quinsam River during 1976-84 provide some support for summer rearing flow benefits for production at flows near 20%mad but marginal or no benefits at higher flows. As an index of summer baseflows, mean August flows ranged from 15 to 23% MAD. The high counts relative to other streams the following spring suggested no significant correlation for the negative trend. However, the variance about the mean response was low (CV= 21%).
The Vancouver Island data are of particular interest because of the intensity of water use in that Region, both for hydropower and for consumption. The decline in steelhead populations on Vancouver Island is well known and is currently the subject of a recovery plan directed by MWLAP. The decline undoubtedly relates to marine conditions but also may reflect freshwater factors (Smith and Ward 2000). To remove the effects of recent declines in abundance, we calculated the mean annual angler catch for the period 1968-1982 and plotted this against the proportion of flow remaining in the channel during the critical stream flow period[1] (CSFP flow divided by mean annual flow). On Vancouver Island rivers, there was a correlation between annual catch and the CSFP % MAD. Campbell River is an outlier in this data set, with a CSFP %MAD of 60%: so too is the Cowichan River, with an annual steelhead catch double that in other streams. The data could be fit to an asymptotic relationship with an optimum of 10 to 20 %, but also to a dome shaped function with a peak between 10 and 20 %. This relationship is partly driven by the correlation between river size and catch shown in Figure 10, as MAD is the denominator in the CSFP %MAD metric.

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[1] Critical streamflow period is the period of lowest flow during the growing season. The term arises from Binns (1982) in his modelling of "large" resident trout biomass in Wyoming. Binns rating was highest for streams with CSFP>55%mad and lowest for streams with CPSF<10%mad.

To test if instream flows are a factor explaining the decline in steelhead abundance, we calculated the decline in angler catch and regressed this on the fraction of mean annual flow remaining in the river channel. The decline was calculated as the slope of a linear function between total annual catch and year, divided by the mean annual catch over all years. This yielded a rate of decline in percent decrease in the average population size per year. The rate of decline ranged from 0% to -11%, indicative of the general decline. The rate of decline was plotted against the %MAD flow during the CSFP (Figure 10).

There is a significant relationship between the decline of steelhead populations on Vancouver Island and the fraction of MAD present during the CSFP. Of particular interest is that the populations exhibiting the least decline had a CSFP % MAD of between 10 and 20%. This supports the 20% standard for instream flow and may indicate that streams retaining higher percentages of annual flow during the CSFP have more habitat. The outliers in this relationship are Campbell and lower Puntledge rivers, both regulated streams with relatively high flows during the CSFP. The significance of the relationship rests on three small streams with low annual catch: Black Creek, French Creek, and Trent River. Available smolt counts for all three cases, though limited, show that steelhead smolt yields (#/100 m2 wetted area) in the mid-1980s (when the streams were at carrying capacity) are lowest for Black Creek (0.3 smolts/Unit), where regulated baseflows are zero, and highest for the Trent River (1.8 smolts/Unit). Alternative explanations for the decrease in catch in these three rivers are: anglers may prefer to fish in larger rivers than they did in the past; and changes in angling regulations over time have reduced opportunities more severely on small streams. These alternatives could be tested through a more detailed examination of both the catch and streamflow data for each stream.

In contrast to the positive relationship between flow and habitat observed in the steelhead catch data, Bradford *et al.* (1997) found that only stream length and, to a lesser extent, latitude were useful in predicting mean coho smolt abundance. At first glance, this appears to refute the hypothesis that stream flow determines fish abundance. However, the behaviour of coho is consistent with this finding for, as shown in Figure 7; coho salmon prefer substantially lower velocities streams than do steelhead trout and typically rear in smaller streams. In large watersheds, juvenile coho occupy tributaries to the mainstem and off channel habitats that may be less sensitive to flow changes than mainstem habitats. Bradford's data also show the highest coho production in streams with substantial wetland, productive riparian areas (terrestrial insect source), or ponds and lake habitats (e.g. Black Creek).

In summary, we have identified positive correlations between fish production and flow for chinook salmon and steelhead trout and use this as evidence of the importance of flow as a master variable controlling fish production. Further, the fraction of stream flow remaining in the channel during the growing season explains both the historic annual catch in Vancouver Island streams, and the decline in angler catch. Other hypotheses can explain the observed relationships.

More detailed analysis of the data would be required to improve our understanding of the mechanisms underlying these relationships. Specifically, it would be useful to examine the return of steelhead over time to identify the response of steelhead and salmon populations to changes in the percent of annual flow during critical life history periods. This task is outside the scope of this report and is identified here for further examination in Phase II of the Standards project.

**Figure 8.** **Relationship between river flow and chinook salmon spawning population size in British Columbia. Taken from Healey 1991.**

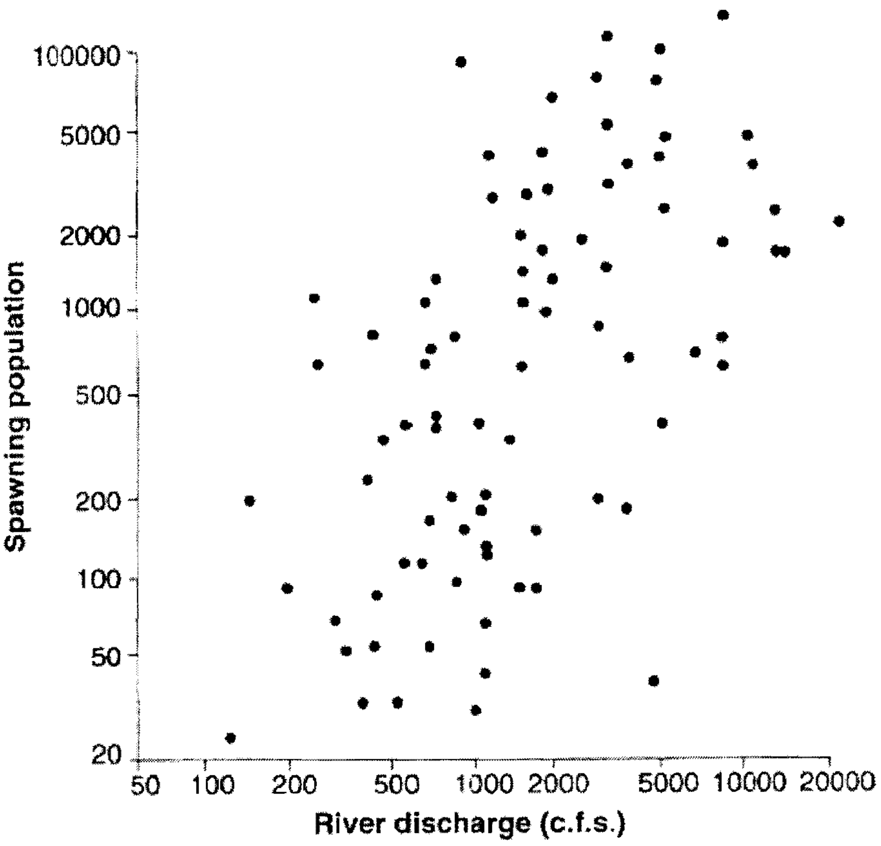


Figure 9. **Relationship between historic mean annual steelhead catch (1968-1982) and the fraction of annual stream flow present during the critical stream flow period.**

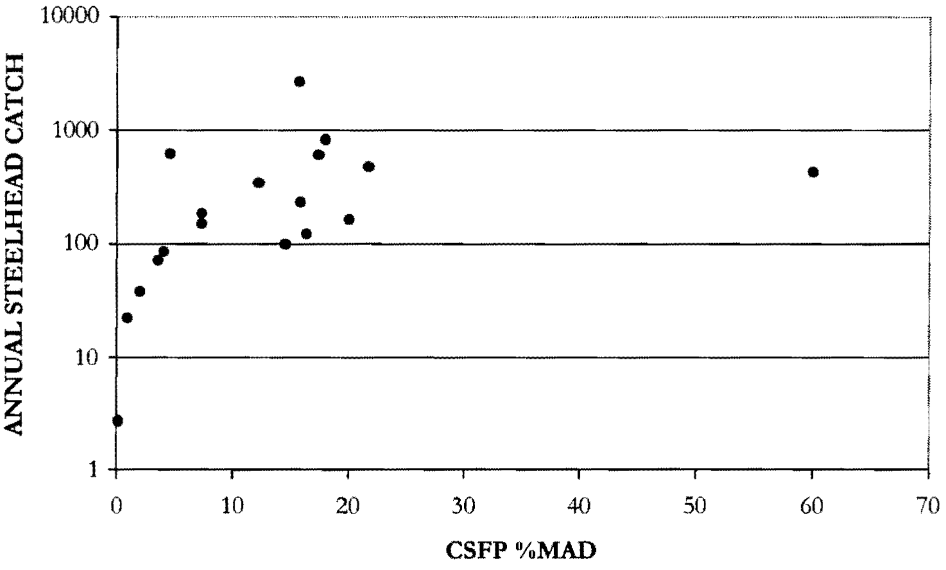
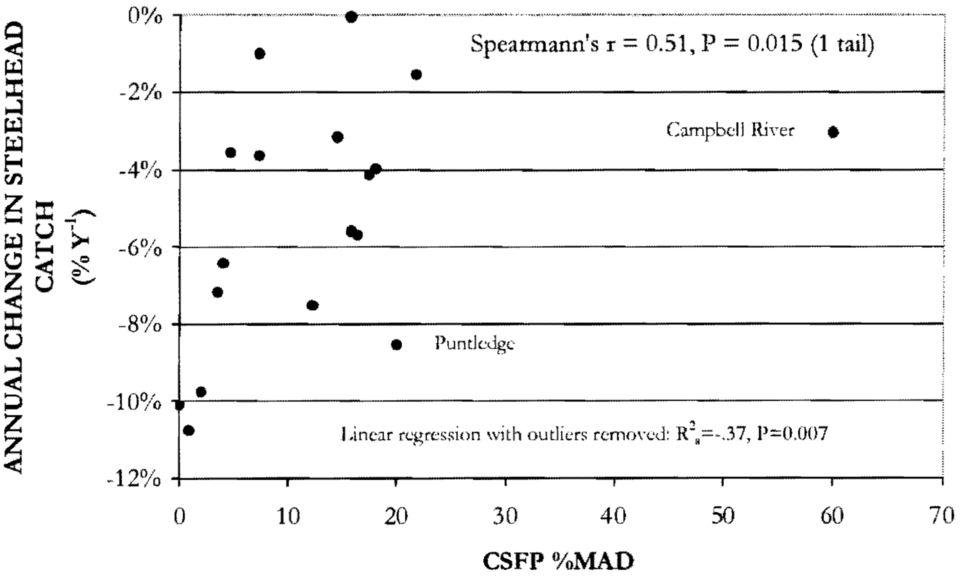


**Figure 10. Relationship between the decline in steelhead angler catch in Vancouver Island streams and the fraction of annual stream flow present during the critical stream flow period.**



# 5 STANDARDS

## 5.1 Rearing and Insect Flows

The Standards for rearing fish are based on sustaining the physical habitat required by rearing fish and their food. This requires that the microhabitat characteristics preferred by rearing fish and their food be maximized while maintaining adequate depth and velocity in food producing habitats.

Ptolemy has identified key factors that underlie the 20% MAD standard for fish rearing, over-wintering, and insect production.

1. Habitat increases with increasing flow to an optimum threshold level at-station.
2. Based on studies conducted in British Columbia and elsewhere, the threshold is similar across a wide variety of stream sizes, supporting a standard with a fixed %MAD (see section 3).
3. Empirical hydrometric relationships provide some support for a fixed %MAD standard for stream velocity.
4. The most sensitive mesohabitats to flow change are riffles (this applies to rapids and cascades too).
5. Flows in riffles are set by first looking at WW in respect to toe-width to ensure adequate coverage of the riffles using PMC the as criterion. Velocities are then assessed to ensure that mean velocities are adequate to provide fish and insect habitat.
6. Depths and velocities in riffles must meet threshold values to function properly.
7. Aquatic insect drift is a known fish production constraint and is a direct function of transport from riffles to pools and other fish holding areas.

In this section we examine both the 10% and 20% MAD standards and compare them to other estimates of streamflow requirements, specifically PHABSIM estimates of habitat and the point-of-maximum curvature (PMC) in riffles. The existing Provincial standard (Ptolemy Method) is more holistic than the flows derived strictly from PHABSIM analyses because flows for insect production and fish over-wintering are explicitly incorporated.

### 5.1.1 Rearing Flows

The Ptolemy method prescribes a 10% MAD standard to maintain wetted width and meet velocity and depth thresholds. The 10% standard is based on riffle analysis, as described below. The 20% MAD standard is set based on optimal rearing for juvenile fish derived from the studies reviewed in Section 3. Several of the studies used to support the 20% MAD standard are based on weighted usable area curves collected using PHABSIM or similar methods, thus the Ptolemy method is partly based on known transect and photographic results and criteria (PHABSIM). All the studies use PMC and velocity targets in riffles. Most recent riffle examinations are also well annotated with "at-station" photographs similar in details to those used by Tennant (1976) and Binns (1982).

The maintenance of adequate wetted width is evaluated with point-of-maximum curvature (PMC) analysis (Nelson 1980). The wetted perimeter or Riffle Analysis is described in Annear et al. (2002) and is designed for the analysis of riffle mesohabitats. The method is a standard setting technique that requires moderate field effort. BC data on unconfined channel geometries suggest the toe-width of riffles is nearly fully inundated at flows near 10%±3%MAD. Since riffles are particularly sensitive to flow reductions, flows that wet these habitats are more than sufficient to wet glides, flats, runs and pools, and they serve as a benchmark for potential dewatering and stranding of insects, eggs, and fish. The PMC result for BC streams is consistent with the "severe" flow of Tennant (1976) and Binns (1982), since at this break-point significantly reduced insect production is observed: streams with this baseflow tend to be poor resident trout producers. The rearing equations of Collings et al. (1972) and the Washington State "toe-of-bank width" methods provide similar flow estimates to the breakpoint of wetted perimeter at riffles in alluvial channels.

The second feature of the 10% MAD standard is the maintenance of adequate velocities and depths in riffles. Guidelines for mean water column velocities in riffles at baseflows are generally 31-46 cm/s (Thompson 1972). Aadland (1993) suggested velocities exceeding 60 cm/s for fast-riffle guilds. Banks et al. (1974) and Stalnaker and Arnette (1976) identified optimum food producing riffles in areas of fines-free, coarse substrate, velocities of 46-107 cm/s, and depths of 15-90 cm. Stalnaker and Arnette (1976) provide hydraulic criteria for aquatic insects with some taxa (*Rhithrogenia, Ephemeralla, Simulium, Hydropsyche, Baetis, Arcynopteryx*) showing preference for high velocities (range: 30-113 cm/s). These velocities are typically provided in riffles at a flow of 10% MAD.

PHABSIM integrates the effect of changes in flow on wetted width, depth, and velocity with habitat suitability to calculate the weighted quantity of habitat. A meta-analysis of PHABSIM-based instream flow studies throughout western North America used regression analysis to develop predictions of habitat vs. flow relationships (Hatfield and Bruce 2000). This analysis provides habitat vs. flow relationships in streams of different sizes and geographical locations for several salmonid species (or all salmonids as a group) at each of four life stages. These relationships depend strongly on the underlying habitat suitability indices and transect location, which may vary greatly dependent on the method of determination and the investigator. For example, HSI curves for swift-water fish (longnose dace adults or steelhead parr) are applied to only those mesohabitats where they occur most frequently, such as rapid-cascades-riffles. The meta-analysis speaks only to habitat needs of rearing and spawning salmonids and does not incorporate other requirements for instream flows (e.g. other species, or geomorphic and substrate issues). The WUA approach is designed with negotiation in mind and incremental changes of habitat with flow; however, it does not address insect drift rates and fish response to these, both of which increase with increased flow and velocity.

A key finding of the meta-analysis is the log-normal relationship between flow and the proportion of annual streamflow required to provide optimum habitat. This contrasts with the 20% MAD standard, which is linear. Figure 11 shows a graphical depiction of the meta-analysis optima for juvenile steelhead fry and parr and the 20% MAD rearing standard. Differences between the 20% MAD standard and the steelhead parr optima are quite striking. The ratio of the two flows increases from 10% at 0.1 cms to 350% at 1000 cms.

The magnitude of the difference in the 20% MAD standard and the meta-analysis optimum can be made clearer with examples. For example, on the middle Ash River (MAD 23.8 cms) the meta-analysis optimum (based on revised formulas provided by Todd Hatfield) is 6.89 cms (29% MAD), 43% higher than the 20% MAD Provincial standard of 4.8 cms. PHABSIM generated estimates of habitat in riffles were greatest at 4.0 cms for fry and 9.0 cms for parr. Assuming a log-normally shaped habitat-flow relationship and using this to predict the continuous habitat-flow function, the Provincial standard provides 86% of the optimum habitat.

In smaller streams, the difference between the 20% standard and the meta-analysis optimum flow is even larger. The optimal flow for steelhead parr rearing in the Little Qualicum River (MAD = 8.59 cms) is 48% MAD (4.15 cms), more than double the observed flow during the critical streamflow period (1.66 cms). The existing Provincial standard of 20% MAD suggests a threshold flow of 1.72 cm, which exceeds the CSFP flow, though not by much.

In small streams, the difference between the 20% standard and the PHABSIM optimum flow is alarming. Using Carnation Creek as an example (MAD 0.829 cms, latitude = 48.9 °N), the meta-analysis suggests an optimum rearing flow of 0.19 cms for steelhead fry and 1.06 cms for steelhead parr. Flows of this magnitude in Carnation Creek are typical in winter, but exceed mean monthly flows from April through to October. The ratio of Provincial flow standard to the meta-analysis optima is 0.16 (the meta-analysis recommends a flow 6.4X higher). Further, the meta-analysis optima for steelhead parr is 128% MAD, 8 times higher than the CSFP flow.

Figure 11. **Relationships of rearing and spawning instream flow requirements versus mean annual discharge, based on the Ptolemy Method (in red) and PHABSIM meta-analysis (steelhead fry in black; steelhead parr in blue).**

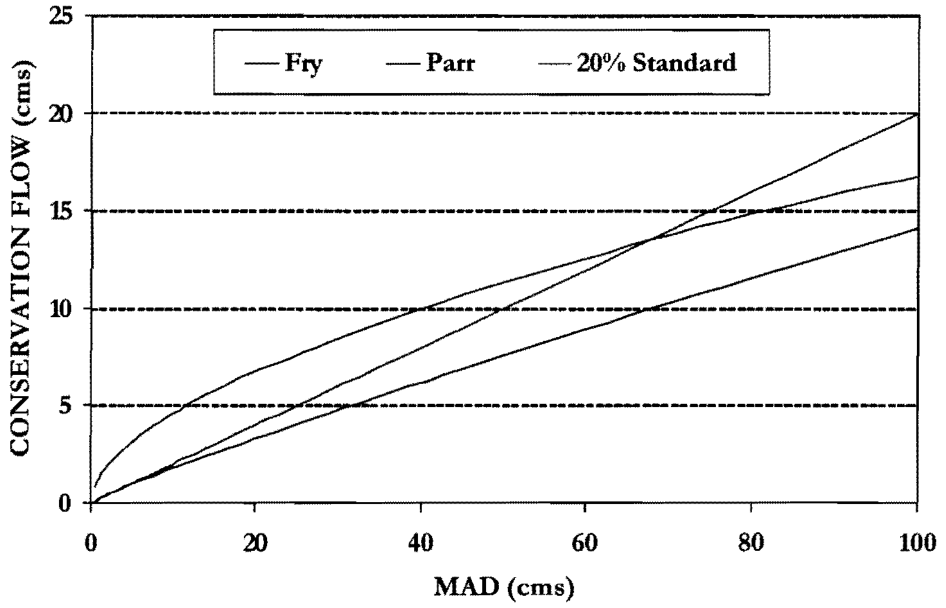
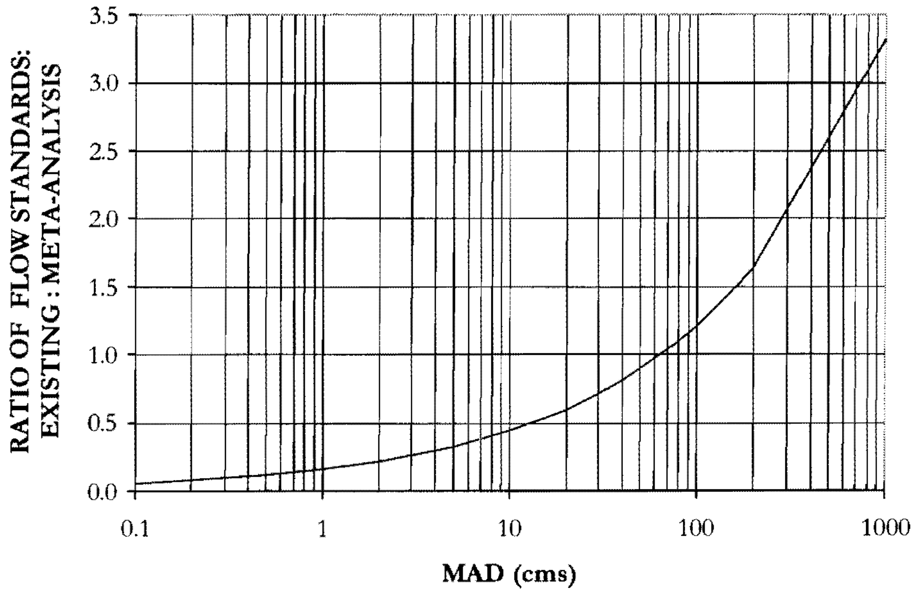


Figure 12. **Ratio of conservation flows for steelhead juveniles prescribed by the existing 20% standard and the PHABSIM meta-analysis versus MAD. Note the log scale on the X axis.**



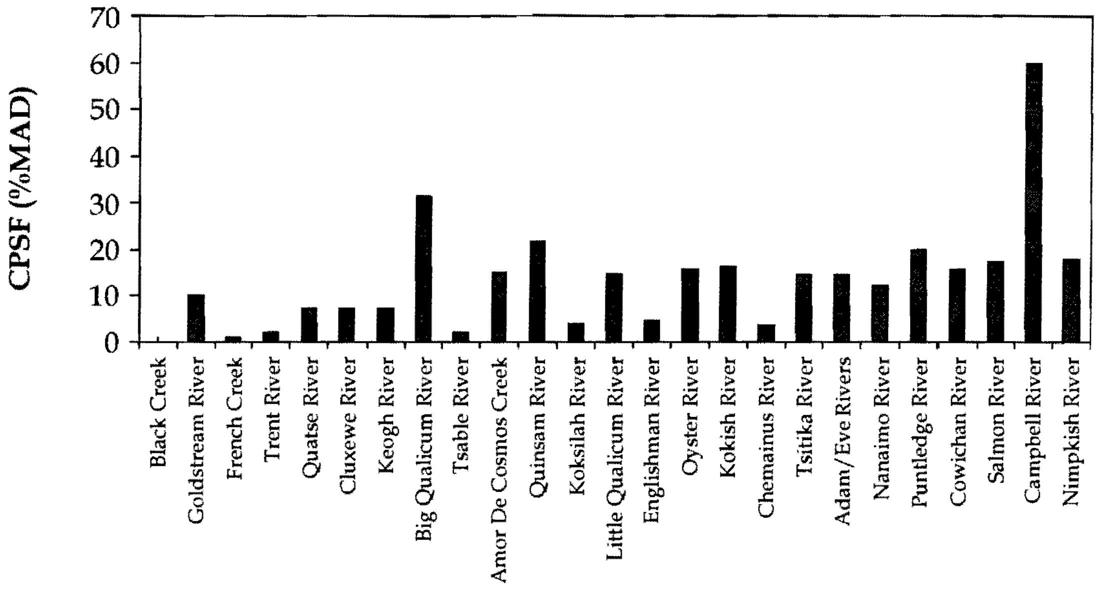
The 20% MAD standard for Carnation Creek is supported by the Washington State "toe-width" model using watershed predictors for rearing flows (Collings 1974). Applied to the Carnation Creek watershed area of (3.9 mi$^2$, 10 km$^2$), the models predict a flow of 8.2 cfs (233 L/s) or 28%mad (standard error 62%).

The empirically-derived observation that velocity changes relatively little between streams flowing at the same % MAD may provide justification for fixed %age of streamflow proposed in the standard. Figure 6 shows how velocity changes very little with increasing flow when comparing downstream stations (a comparison of stream sizes) at the same flow stage. Given constant habitat preferences, the consistency of the velocity-flow relationships suggests that a fixed flow stage would provide equivalent quality habitat.

It should be noted that there are many BC streams with 30-day summer baseflows below 10% MAD that sustain significant smolt production (Figure 13). One noted and much researched example is the Keogh River (CPSF = 7% MAD), which has produced 7,000 steelhead per year at capacity (Johnston et al. 2000). This suggests the "severe" classification in Tennant's narrative may not apply to streams sustaining small fish (smolt size and smaller) or in the winter season when fish territoriality is minimal and winter baseflows are very low. Winter production of aquatic insects and fish in winter refuge habitats would still be affected by flows <10% MAD and icing should they occupy riffles, cascades or rapids.

The large difference between the 20% MAD standard and the optimum meta-analysis prediction in small streams reflects, in part, the mechanics of PHABSIM analysis. Despite the appearance of subjectivity, PHABSIM requires many decisions during the planning, data collection, and analysis phases, each of which can have a large effect on the outcome of a study. Typically these decisions are made collaboratively by those conducting and reviewing the study to increase confidence in the results. The influence of these decisions on the outcome of PHABSIM is well known (Railsback 1999). An understanding of the effects of individual decisions is lost in meta-analysis results. We can assume that the effect of these decisions is averaged, such that the meta-analysis prediction provides a typical result. However, this assumption is unlikely to be true in BC applications, given that the meta-analysis model is comprised mostly of older US studies, with few studies of BC rivers. Beyond differences in hydrology, geomorphology, and biology between BC and the US, American jurisdictions routinely made decisions during the data collection or modelling that we would not make. For example, few BC HSI curves were used in the meta-analysis studies and the transects in most of the studies were probably not located on riffles, but rather spread across all mesohabitats.

Figure 13: **Present critical period streamflow (CPSF) in selected steelhead streams in Region 1. 30-day Summer baseflows expressed as percentage of naturalized mean annual discharge. Flows<<10%mad more severe.**



Fisheries agencies caution the use of PHABSIM studies since they involve a non-linear sequence of procedures and involve highly subjective decisions including selection of specific computer models and parameters, weighting schemes and transect location (WDOE 1996 Instream Flow Study Guidelines). Annear et al. (2002) caution PHABSIM users to take care in setting minimum flows with the technique.

> Practitioners should not prescribe a minimum instream flow standard by recommending the maximum habitat value from the weighted usable area/discharge graph for a single life stage of a single species: doing so can result in unrealistically high recommendations that damage the credibility of the entire study and study team.

If the meta-analysis optima were applied as a Standard, users would base the conservation flow on a single life stage. As an example, on the Ash River users would have to choose among optimum streamflows for steelhead of 12% MAD for fry, to 29% MAD for parr, to 51% MAD for adult. Differences between life stages in timing would easily resolve some of the trade-offs, and users could default to the higher optimum within a season for concurrent life stages. More troublesome would be the choice between species, which as Figure 7 shows, may have very different habitat preferences. Although such decisions must be made in any detailed instream flow assessment, the meta-analysis tool does not provide any guidance on this matter. In contrast, the 20% standard for rearing considers requirements for insects, fry and parr life stages. Rather than providing an instream flow standard, the meta-analysis optimum and the tool itself may have greater utility for evaluating the consequences of the Standards proposed here.

The final concern regarding the meta-analysis optimal prediction as a standard is a practical one. In the foregoing analysis, the meta-analysis leads one to conclude that larger numbers of steelhead trout would be supported if higher levels of flow were maintained. By extension, Carnation Creek could probably support chinook salmon if substantially higher levels of flow were provided. Species that require faster and deeper water will generally be more abundant in larger streams. Unfortunately, the provision of higher than natural flows is not possible: we are concerned here with how much flow levels can be reduced without reducing productive capacity. For the purposes of setting standards, providing optimal habitat is impractical because on many streams it will require higher than natural flow levels to be maintained.

### 5.1.2 Insect Flows

The 20% standard considers flows and certain target velocities for insects based on the premise that steep, wetted channels provide adequate habitat for insect production and other swift-water taxa. The wetted width or perimeter to flow relationship is used to prescribe a conservation flow, and the point of maximum curvature on the function indicates the optimized flow for wetting particular transects. The relationship is drawn preferentially from riffles, relying on the assumption that habitat in pools, runs, and other hydraulic unit types will be adequate when the habitat in riffles is optimized (Bovee 1974).

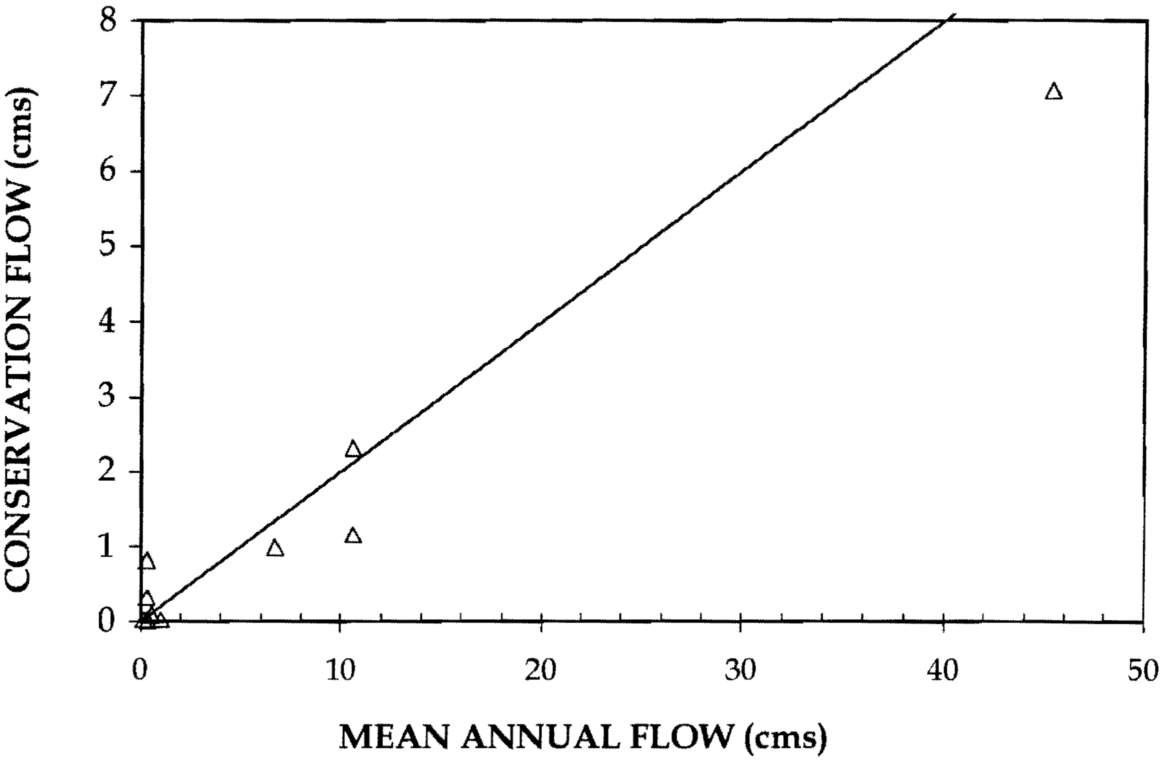
Hydraulic geometry analyses on BC streams show greater rates of change in wetted width, velocity, and depth in riffles than in other hydraulic units (mesohabitats), supporting the idea that riffles are more sensitive to flow change, an observation made by others (Bovee 1974, Stalnaker and Arnette 1976). The literature provides other good reasons to focus on riffles. Hogan and Church (1989) showed that pools and runs became more riffle-like as flow increased at-a-station. At low flows, riffles were shallower and faster than pools and runs but at high flows the differences between the units all but disappeared. Hydraulic unit composition within a reach changes with flow at-a-station: at very low flows, riffles dry up, leaving a series of disconnected pools. This observation implies that the power of instream flow assessments will be greatest if focussed on riffles, since they show the greatest change in habitat per unit of flow change. Similarly, the Standards can be most easily supported with habitat-flow relationships drawn from riffles. This does not mean that only riffles produce fish, or that other mesohabitats can be ignored in instream flow assessments, or that only riffles should be considered when calculating compensation for habitat loss.

Riffles can also be used to support adult passage (non-barrier type) or migration criteria or standards since minimum depths are typically found there. The reported passage depths are provided by Reiser and Bjornn (1979) and depths are correlated to fish size and species (e.g. summer Chinook at 30 cm).

The focus on riffles appears to conflict with the use of microhabitat characteristics to generate weighted usable area for PHABSIM relationships. However, the literature shows fish are more strongly associated with microhabitat than mesohabitat. Shirvell (1990) showed how juvenile fish rearing in streams respond to microhabitat conditions, specifically the conditions created by physical structures such as boulders and woody debris, rather than the structures themselves. Fish respond on the microhabitat scale (depth, velocity, light) rather than the mesohabitat scale (pools, runs, riffles). For example, feeding steelhead parr typically select sites with low light intensity (to reduce predation risk) and velocity shears (to maximize net energy gain by balancing low holding velocities with proximity to high flow velocities and drift). Fortunately, microhabitat conditions are ordered within streams to form mesohabitats that provide convenient strata for analysis. In short, particular combinations of microhabitat characteristics are found most frequently in particular mesohabitats easily recognized by biologists as riffles, rapids, cascades, glides, flats, runs and pools.

Criteria for rearing and insect production have been assessed on a stream-specific basis by examining wetted width. Flows meeting the standard must provide adequate coverage in riffles, typically 50% of toe-width. Studies following this method provide considerable support for the 20% MAD standard. Research in other jurisdictions (Washington toe-width method) supports 20% MAD as an appropriate "rearing flow standard" for small to medium-sized streams (MAD<141 cms); however, the Collings model produces slightly higher flows.

Figure 14. **Conservation flows recommended by studies using wetted width (open triangles) and the 20% MAD standard (red line).**



The conservation flow for insects has been defined as the flow providing adequate coverage in riffles. This flow has typically been estimated by identifying the point of maximum curvature (PMC) in a plot of wetted width against flow. The PMC represents the point of maximum change and can be determined reliably with mathematical techniques, providing that the relationship is curvilinear. In practise, the PMC is often not apparent and may disappear when cross sections are aggregated into a mean. Dunbar et al. (1998) and Annear et al. (2002) suggest that PMC and lower flows are detrimental to aquatic insect production as stream temperature and water quality often become critical at very low flows. However, even where a PMC exists, there may be no particular biological importance to the corresponding flow level.

The PMC is a graphical representation of a trade-off between water flow and width. There are a number of problems with this approach:

1. The flow corresponding to the PMC may be found at 80% of the maximum channel width, or much less, even down to 50%.
2. Given the subjective nature of the PMC, different instream flow practitioners may vary in their PMC determination, leading to inconsistent instream flow recommendations.

3. PMC results where transects are placed through insensitive mesohabitats (pools, glides, flats, runs) show a flat width-flow curve even at near-zero flows (Hamilton and Kosakoski 1982; Wightman and Ptolemy 1989; Griffith 1990; Eliasen and Senger 2000; Ptolemy 2002, unpublished data and photographs).
4. Careful placement of transects is required for useful results.

Although the PMC method is useful in resource valuation to analyze trade-offs, the PMC is of less use for the protection of fish habitat where no net loss is the goal.

Based on the relationships between wetted width and flow observed in BC streams, flows of 10% MAD are judged to represent a key threshold below which there are severe impacts to fish and insects. These impacts include loss of physical space for fish rearing, loss of insect production, loss of insect drift, and increased fish stranding.

### 5.1.3 Canyon or Confined Channel Geometry Influences on Fish Flows (possible site-specific variances from the norm)

Leopold (1994) and others have noted that at a given discharge, different streams or rivers show quite different values of width and depth. Those that have fine-grained cohesive or bedrock banks tend to be deep and narrow. Those with sandy, friable banks tend to be wide and shallow. It's not too surprising that departures from width-depth-velocity versus flow functions might be expected in canyon streams. These sites are often the focus of micro-hydro development, leading us to ask if lower levels of flow can provide aquatic protection in these channels?

At this time there are too few data that confidently define standards in confined channels. In six cases that have been examined, a flow of roughly one-half of the standard derived on unconfined channels appears adequate to protect habitat and hydraulic diversity. Optimum rearing flows in these habitats are about 10% MAD with short-term maintenance flows of about 5% MAD. Flows of 5%MAD are low and must only be considered in the absence of stream temperature, winter icing (Cunjak 1994) or water quality issues. The lack of data from confined channels on which to base instream flow standards suggests caution when applying standards of 5% or 10% MAD. Where streamflows under proposed regulation are less than 10% MAD, adaptive management can be used to define an adequate flow level.

## 5.2 Spawning and Migration Flows

The Standards for fish spawning and migration are based on sustaining the physical habitat required by adult fish for migration and spawning. Upstream migration of salmonids primarily occurs at higher stream flows and is usually triggered by increases in flows (temporary natural freshets). The actual flows required to encourage migration in a particular stream vary in different parts of the stream network and at different times of the year, often being lower as spawning approaches.

The stream-size-dependent 30% MAD to 200% MAD conservation flow covers both migration and spawning and includes several PHABSIM studies. Migration standards are based on the observed fish response to known flows (Biological Response Correlations cf. Annear et al. 2002): examination of multiple years and flow variation on counts of migrating spawners (flash board counts, fence counts, radio telemetry, fish counters, angler catch surveys) over a broad range of streams and fish species).

The flows prescribed by this standard range from 30 or 200% but vary dependent on stream size (Figure 15). The equation to calculate the flow standard is:

$\%MAD_{spawning} = 148*(MAD)^{-0.36}$,

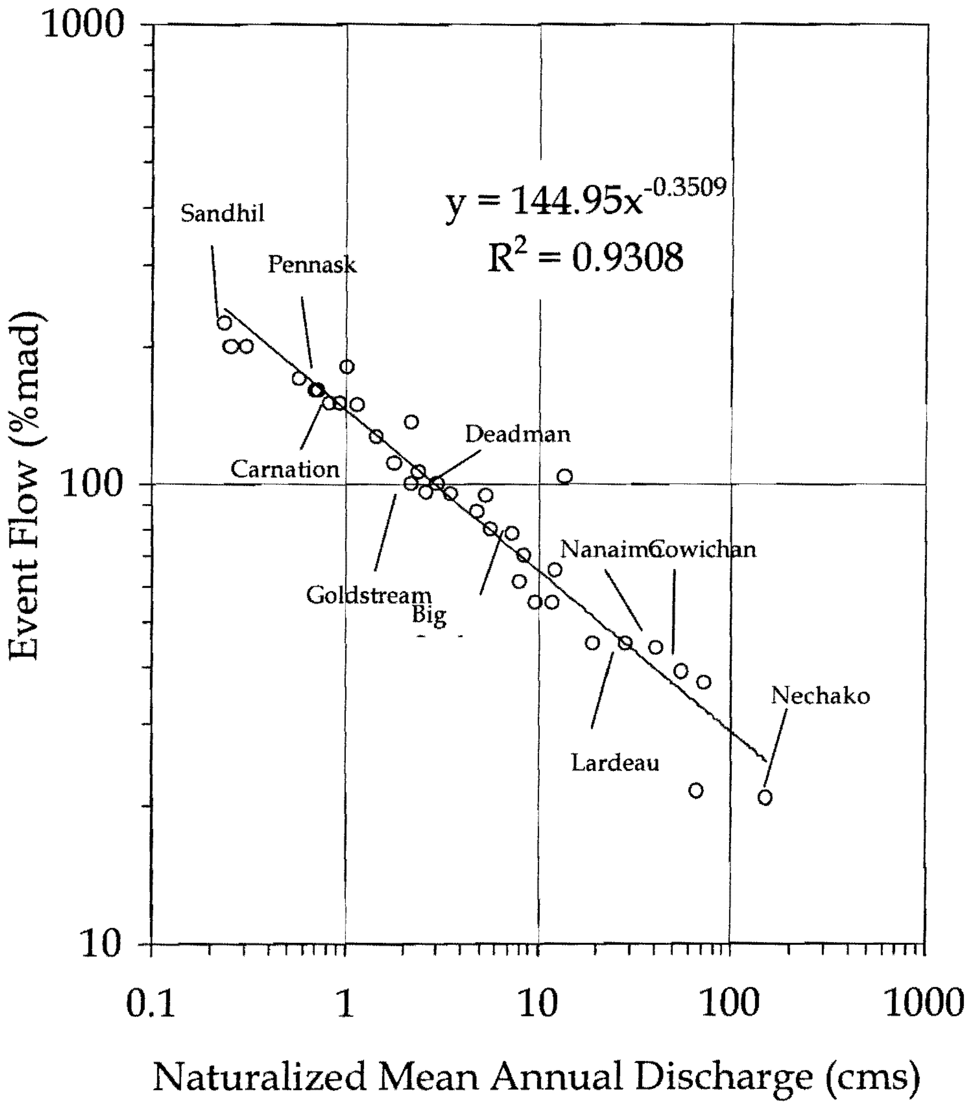
where MAD is the mean annual discharge in cms.

The empirical data are similar to the PHABSIM meta-analysis optima; however, the underlying hydraulic measures at some sites confirm moderate-high flows are needed for passage (depth over riffles) and spawning (moderate velocities in pool/run tailouts). The standard prescribes slightly higher flows (10 to 30%) than the meta-analysis predictions over most stream sizes.

The B.C. spawning flow standard applies to large trout and Pacific salmon and has been derived using methods similar to those used to calculate similar flows for Atlantic salmon. Solomon et al. (1999) used radio telemetry data from several studies on radio-tagged salmon in rivers of South West England (small rivers) and flow records. Solomon found that the threshold flow required to induce salmon to enter a river from the sea varied from 101% to 284% of the Q95 (the flow or Q exceeded 95% of the time). The percentage was inversely related to stream size, and as fish moved further upstream, the percentage of the Q95 needed to maintain migration also increased. In another study on Atlantic salmon (Stewart 1973), peak migration occurred at a flow of 0.2 cms per m channel width in alluvial streams.

The standard should be applied with consideration of fish size. Smaller species such as pink salmon and kokanee successfully migrate and spawn at flows near 20% MAD. Differences in species-specific flow standards relate to lower minimum passage depths (12 cm) compared to larger fish ( 24 cm) (Reiser and Bjornn 1979).

**Figure 15: Scatterplot of Nominal Migration/Spawning Flows for Trout/Salmon in BC Streams. Empirical fish observations over a range of flows per stream case.**



## 5.3 Wetland Linkage Flows

Flows that protect aquatic, riparian, wetland, and floodplain resources apply to stream reaches where floodplains are known to be present, but also to streams with small quantities of these habitats. It is now widely recognized that the maintenance and restoration of the lateral linkages across the floodplain is vital for sustaining the ecological integrity of rivers and sustaining fish populations (Junk 1989; Petts 1989; Welcomme 1995; Sommer et al. 2000). The geomorphic and ecological functions of properly timed and sized flood flows are described in detail by Poff et al. 1997.

Flows required to maintain connectivity with side channels and off channel habitats and to maintain channel form have been estimated from the empirical studies provided. Burns et al. (1988) estimated that side channel connectivity was provided at 45.4% MAD, however, this recommendation was made in the context of supporting the existing minimum flow. Rood and McNeil (1987) identified 265% MAD as the flow that wetted major backchannels, with bed material movement at 397% and fine sediment flush at 116%. Linkage to most side-channel types was maintained at 82%MAD on the Nechako River. The Campbell River WUP (unpublished data) has premised a flow maintenance of 79 cms or 92%MAD for side-channels based on both transect and visual observations of fish using the side-channels. Generally flows of at least 100% MAD (dependent on entrenchment or confinement) are required to provide good connectivity with wetlands, riparian zone, sidechannels, and tributary streams. Over-wintering studies and free movement of juvenile coho in Carnation Creek occurred at flows near 100% MAD (Brown and McMahn 1987) during fall in-migration and spring out-migration. To minimize fish stranding associated with side-and off-channel stranding the Campbell River WUP (Anon. 1997) identified a threshold flow of 79 cms (92% MAD). The 79 cms flow also provides connections to the riparian zone (Hamilton and Buell 1976). Observations and photographs by Craig et al. (2000) on the Ash River below Elsie Lake showed complete channel coverage and water connection with the riparian zone at flows of 17.6 cms or 83% MAD. Griffith (1990) provided evidence at 26 "at-station" transects located in five reaches of the Nanaimo River that 97% coverage of the channel width occurs near 82% MAD, however this was considered generally insufficient for wetland, sidechannel and off-channel connectivity.

## 5.4 Ecological and Channel Forming Flows

Flushing and channel maintenance flows are a significant fisheries or ecological issue in large hydro-electric projects or similar large-scale water developments across the globe (Reiser et al. 1985; Annear et al. 2002). Flushing flows are naturally occurring short-term flows that remove fine sediment from gravel (Reiser et al. 1989) which favours improved egg incubation and benthic invertebrate production. By comparison, channel maintenance flows are of greater magnitude and duration which form the channel size and influence riparian zones by sediment deposition or prevention of riparian growth encroachment into the channel.

Investigations of flushing and channel maintenance in BC have used the three broad approaches as profiled by Annear et al. (2002) to determine flushing and channel maintenance flows. The three methods include (1) empirical, (2) sediment transport modelling (Meyer-Peter formula; Einstein method), and (3) office-based hydrological methods such as Tennant's 200%mad criterion). The empirical evidence is based on periodic stream monitoring of both biological and physical characteristics of streams including with naturally variable high flows and treatment streams with reduced high flows (Big Qualicum River, Coquitlam River). Some studies involve visual examination of bed state and fines infilling; others include scour monitors (FFIP studies, Hogan et al. 1998), freeze-core gravel and suspended sediment monitoring (Ptolemy 1989) or egg-to-fry survival modelling (Holtby and Scrivener 1989).

The results suggest that flows in excess of 400% MAD are required as flushing flows which is double the magnitude that Tennant recommended (200% MAD, 1975) and is larger than the 300% MAD typically needed to fill the channel to the floodplain. Flows of 800%mad or higher are required for general bedload transport.

Initial mobilization and bedload transport flows have been described for Coquitlam River by Rood (2001) which relate respectively to bankfull discharge of 110 and 200 cms or 390-700% MAD for Reaches 2 and 3 (boulder controlled); the naturalized MAD is 28 cms for this stream. Rood (2000) provided comparable results for the Cheakamus River (Reach 6) with flows of 320-680 cms or 470-1000% MAD. Major sediment transporting events have been described for small streams such as Carnation Creek (Hogan et al.1998) where a threshold flow of 10 cms or 1200% MAD was observed. Flows of 10 cms caused a mean gravel scour of about 1cm depth.

Chronic sand embeddedness has been noted in the Big Qualicum River and Coquitlam River following flow regulation where maximum daily flows are usually below 400% MAD. Bankfull discharges of 400-800% MAD were described for Alaska streams by Estes and Osborne (1986) after calibration of the Tennant recommendation to local hydrologic patterns. Various researchers have cautioned that flushing flow determination is affected by local hydrology and channel geomorphology however a threshold of 400% MAD seems to apply broadly.

### 5.5 Passage Flows at Partial Natural Barriers

Fish passage problems at natural barriers (falls, chutes, cascades) have been noted by many observers within British Columbia. These partial barriers may operate on a seasonal basis dependent of the ability of species, stock, fish size, fish condition, stream geometry, plunge pool depth, stream temperature and flows (Stuart 1962). Despite contrary opinions that often rely on cursory physical reconnaissance, but little actual observation of fish passage, some races of steelhead and char appear to be able to consistently pass waterfalls or fast chutes each year. Physical differences between summer and winter races of steelhead and differences in their timing of migration, allow spatial separation and reproductive isolation within the same stream. To better understand flow conditions promoting upstream passage, several sites have been examined with concurrent observations of passage success and flow conditions.

High velocities or large drops create partial barriers in narrow canyon habitats, often at locations where large bolders span the channel. Removal of these barrier is not a preferred solution because such restrictions maintain natural fish stock integrity by maintaining isolation. Passage can be provided at these locations by maintaining complex hydraulics (back-watering, by-pass conduits, etc.) with an adequate range of flow. Regulated flows can impact passage, possibly barring a stock from critical habitat and leading to its extinction.

Powers and Osborn (1985) have investigated barriers and have suggested a classification system to analyze individual cases. Reiser and Bjornn (1979) provide some maximum leap heights and velocities that individual species can attain. Despite these attempts, modelling the hydraulic environment to set passage criteria in canyons appears infeasible (Larsen and Williams 2000), reflecting the complexity of channel geometry and high bed roughness. For example, despite modelling and some field evaluation, a study on the Kokish River (Cascade Environmental Services, unpubl.MS) recommended an instream flow of by 3.6 cms (20%MAD), which was found during field investigation by MWLAP staff (Ptolemy and Wightman) to be too low.

MWLAP data on steelhead passage consist of twenty-six cases containing two races of steelhead present per stream. In all cases, stream temperature and flow were important determinants of fish passage. Relatively narrow flow-temperature time windows were identified in this analysis, suggesting that steelhead passage is a discrete event. Passage typically occurred with receding flows following a freshet or at the end of snowmelt. Some streams such as Sooke River appear to have barrier heights that steelhead should pass (<4m) however natural passage flows in mid-summer are often too low for summer steelhead (<50%mad). To facilitate passage, a broad range flow of moderate magnitude (50 to 100%MAD) are required with a duration of days to weeks within the migration window.

While the MWLAP data set is focussed on steelhead, there are some observations for other species. For example, bull trout appear to pass barriers as challenging as those ascended by steelhead on the Coquihalla River.

# 6 SUMMARY

Considering studies of fish-habitat flow relationships in BC streams by several methods including weighted usable habitat and wetted width/perimeter and biological response, Ptolemy has developed the British Columbia Instream Flow Standards for Fish. Previous studies on fish flow relationships were reviewed and provide compelling support for the Standards. Alternative standards such as those predicted from PHABSIM optima and Collings and Swift methods were considered in this review and are compared to the Standards.

The Standards have been expressed as the percentage of annual streamflow (%MAD) in the stream, consistent with observations that this metric is proportional to channel forming flows, and the broad use of the Tennant approach with calibration in North America (Annear et al. 2002). Fish production in salmon and steelhead streams has been compared to %MAD to corroborate the prescribed flows. General agreement has been found between the Standards and previous studies of fish-flow relationships and the Standards. Additional studies may be obtained that would further strengthen and support the rationale for the Standards, but may not be needed in the development of this coarse filter of flow needs for ecosystem function and biodiversity.

## 7 REFERENCES

Aadland, L.P. 1993. Stream habitat types: their fish assemblages and relationships to flow. North American Journal Fisheries Management. 13: 790-806.

Aadland, L.P., C.M. Cook, M.T. Negus, H.G. Drewes, and C.S. Anderson. 1991. Microhabitat criteria for selected stream fishes and a community oriented approach to instream flow assessments. Minnesota Department of Natural Resources, Section of Fisheries, Investigation Report 406, St. Paul.

Annear, T.L. et al. 2002. Instream flows for riverine resource stewardship. Instream Flow Council. 411 p.

Anon. 1997. Campbell River interim flow management strategy. Campbell River Hydro/Fisheries Advisory Committee. 51pp.

Banks, R.L, J.W. Mullan, R.W. Wiley, and D.J. Dufek. 1974. The Fontenelle Green River trout fisheries-considerations in its enhancement and perpetuation, including test flow studies of 1973. FWS, Salt Lake City, Utah. 74p.

Baran, P.B., M. Delacoste, F. Dauba, J.M. Lascaux, and A. Lascaux. 1995. Effects of reduced flow on Brown Trout (*Salmo trutta L.*) populations downstream dams in French Pyrenees. Regulated Rivers: Research & Management 10:347-361

Binns, N.A. 1982. Habitat quality index procedures manual. Wyoming Game and Fish Department. 209pp.

Binns, N.A. and F.M. Eiserman. 1979. Quantification of fluvial trout habitat in Wyoming. Trans. Amer. Fish. Society 108:215-228.

Bovee, K. D., B. L. Lamb, J. M. Bartholow, C. B. Stalnaker, J. Taylor, and J. Henriksen. 1998. Stream habitat analysis using the instream flow incremental methodology. Biological Resources Division Information and Technology Report United States Geological Survey, Fort Collins, Colorado, USA.

Bovee, K.D. 1974. The determination, assessment, and design of "instream value" studies for the Northern Great Plains Region. Univ. Montana. Final Report EPA Contract No. 68-01-02413. 204pp.

Bovee, K.D., T.J. Newcomb, and T.J. Coon. 1994. Relations between habitat variability and population dynamics of bass in the Huron River, Michigan. National Biological Service Biological Report 22. 79pp.

Bradford, M.J. 1993. Trends in abundance of Chinook salmon of the Nechako river, British Columbia. Can. J. Fish. Aquat. Sci. 51: 965-972.

Bradford, M.J., G.C. Taylor, and J.A. Allan. 1997. Empirical Review of Coho Salmon Smolt Abundance and the Prediction of Smolt Production at the Regional Level. Trans. Amer. Fish. Soc. 126, No. 1, p. 49-64.

Brown, T.G., and T. McMahon. 1988. Winter ecology of juvenile coho salmon in Carnation Creek: Summary of findings and management implications, p. 108-117. *In* T.W. Chamberlin [ed.]. Proceedings of the Workshop: Applying 15 years of Carnation Creek results. Pacific Biological Station, Nanaimo, B.C. 239pp.

Burns, J.W. 1971. The carrying capacity for juvenile salmonids in some northern California streams. Calif. Fish and Game, 57(1): 44 - 57.

Collings, M.R. 1974. Generalizations of spawning and rearing discharges for several Pacific salmon species in western Washington. USGS, open-file report. 39pp.

Craig, J., McCulloch, B. Smith, and H. Wright. 2000. Observations of fish and habitat impacts stemming from BC Hydro flow ramping below the Elsie Lake dam (Ash River), June 15 and 16, 2000. B.C. Conservation Foundation, Nanaimo, B.C. B.C. Conservation Foundation, Nanaimo, B.C. Unpublished MS with photographs.

Cunjak, R.A. 1996. Winter habitat of selected stream fishes and potential impacts from land-use activity. Can. J. Fish. Aquat. Sci. 53 (Suppl. 1): 267-282.

Curtis, B. 1959. Changes in a river's physical characteristics under substantial reductions in flow due to hydro-electric diversion. Calif. Fish and Game 45(3): 181-188.

Dunbar, M.J, A. Gustard, M.C. Acreman, and C.R.N. Elliott. 1998. Overseas approaches to setting river flow objectives. Environment Agency, Bristol, U.K. (R&D Technical report W6B [96]4).

EA Engineering Science and Technology. 1986. Instream flow methodologies. Electric Power Research Institute, Palo Alto, California, USA.

Eliasen, R., and R. Senger. 2000. Preliminary technical report on flow and channel characteristics of the upper Little River, Comox, Vancouver Island, B.C. Fisheries and Oceans Canada, Coastal BC South, Nanaimo, B.C. 28pp.

Estes, C.C. 1998. Annual summary of instream flow reservations and protection in Alaska. Fishery Data Series No.98-40. Anchorage: Alaska Department of Fish and Game.

Fausch, K. D.1984 Profitable stream positions for salmonids: relating specific growth rate to net energy gain. Can. J. Zool. 62: 441-451

Fisheries and Oceans Canada. 1986. Policy for the management of fish habitat. Fish Habitat Management Branch, Department of Fisheries and Oceans, Ottawa, Canada.

Fisheries and Oceans Canada. 1998. Decision framework for the determination and authorization of harmful alteration, disruption or destruction of fish habitat. Minister of Public Works and Government Services Canada.

Giger, R.D. 1973. Stream flow requirements for salmonids. Oregon Wildl. Comm. Job Final Rep., Project AFS 62-1. 117p.

Griffith, R.P. 1990. Nanaimo River: Instream flow requirements for recreational fisheries. For: Nanaimo River Basin Water Management Plan, B.C. Ministry of Environment, Nanaimo. 92pp.

Hamilton, R., and J.W. Buell. 1976. Effects of modified hydrology on Campbell River salmonids. Fisheries and Marine Services, Tech. Rep. Ser. No. PAC/T-76-20; 156pp.

Hamilton, R.E., and G.T. Kosakoski. 1982. Water requirements for the fish resources of the Englishman River, Vancouver Island. Can. Manuscript Rep. of Fish. and Aqua. Sci. 1676: 41pp.

Hartman, G.F., and J.C. Scrivener. 1990. Impacts of forestry practices on a coastal stream ecosystem, Carnation Creek, British Columbia. Canadian Bulletin of Fisheries and Aquatic Sciences 233.

Hatfield,T. and J. Bruce. 2000. Predicting salmonid habitat-flow relationships for streams from Western North America. North American Journal of Fisheries Management 20: 1005-1015.

Healey, M.C. Life history of chinook salmon (*Oncorhynchus tshawytscha*). P. 311-394 in Pacific Salmon Life Histories, C. Groot and L. Margolis eds. UBC Press, Vancouver, B.C.

Higgins, P.S., and M.J. Bradford. 1996. Evaluation of a large-scale fish salvage to reduce the impacts of controlled flow reduction in a regulated river. N. Amer. Jour. Fish. Manag.:16(3): 666-673.

Hogan, D.L. and M. Church.1989 Hydraulic geometry in small, coastal streams: progress toward quantification of salmonid habitat. Can. J. Fish. Aquat. Sci. 46: 844 - 852.

Holtby, L.B., and G.F. Hartman. 1982. The population dynamics of coho salmon (*Onchorhynchus kisutch*) in a west coast rain forest stream subject to logging. *In the Proceedings of the Carnation Creek workshop, A 10-year review. 24-26*

*February, 1982.* Edited by G.F. Hartman. Pacific Biological Station, Nanaimo, B.C. pp.308-347.

Irvine, J.R., I.G. Jowett, and D. Scott. 1987. A test of the Instream Flow Incremental Methodology for underyearling rainbow trout (*Salmo gairdnerii*) in experimental New Zealand streams. New Zealand Journal of Marine and Freshwater Research, Vol. 21, pp. 35 - 40.

Jowett, I. G. 1997. Instream flow methods: a comparison of approaches. Regulated Rivers: Research and Management 13:115-127.

Jowett, I.G. 1992. Models of the abundance of large brown trout in New Zealand rivers. N. Am. J. Fish. Manage., Vol. 12, pp. 417 - 432.

Junk, W.J., P.B. Bayley, and R.E. Sparks. 1989. The flood pulse concept in river-floodplain systems. Pages 110-127 *in* D.P Dodge, editor. Proceedings of the International Large River Symposium. Special Publication of the Canadian J. Fish. Aquat. Sci. 106.

Larsen, E.W., and J.G. Williams. 2000. Measuring and modeling the hydraulic environment for assessing instream flows. N. Amer. J. Fish. Man. 20: 1016-1028.

Leopold, L. 1994. A view of the river. Harvard University Press, Cambridge, Massachusetts.

Leopold, L.B. and Maddock, T. Jr. 1953. The hydraulic geometry of stream channels and some physiographic implications. U.S. Geol. Survey. Prof. Paper 252.

Lewis, S.L. 1969. Physical factors influencing fish populations in pools of a trout stream. Trans. Amer. Fish. Soc. 98: 14-19.

Locke, A. 1999. The Tessman calculation in Alberta. Alberta Environmental Protection document.

Marshall, D.E. and E.W. Britton. Carrying capacity of coho salmon streams. Can. Man. Rep. Fish. and Aquatic Sci. 2058.

Mathews, S.W., and F.W. Olson. 1980. Factors affecting Puget Sound coho salmon (*Oncorhynchus kisutch*) runs. Can. J. Fish. Aquat. Sci. 37: 1373-1378.

McClay, W. 1968. Effects of controlled flow reductions on aquatic insects in a stream riffle. M.Sc. thesis, Montana State Univ., Bozeman, Montana. 29p.

Minns, C.K. 1997. Quantifying "no net loss' of productivity of fish habitats. Can. J. Fish. Aquat. Sci. 54: 2463-2473.

Newcombe, C.P. and R.A. Ptolemy. 1985. The use of prescribed percentages of mean annual discharge to recommend instream flows for fish in British Columbia (the Montana Method Revisited). In Instream Flow Methods. Department of Fisheries and Oceans Workshop on Instream Flow Methods. Vancouver and Nanaimo B.C.

Orth, D.J., and P.M. Maughan. 1982. Evaluation of the incremental methodology for recommending instream flows for fishes. Transactions of the American Fisheries Society 111: 413-445.

Park, C.C. 1977. World-wide variations in the hydraulic geometry exponents of stream channels: an analysis and some observations. Jour. Hydrol. 33: 133-146.

Pearson, L.S., K.R. Conover, and R.E. Sams. 1970. Factors affecting the natural rearing of juvenile coho salmon during the summer low flow season. Oregon Fish. Comm. MS, Portland , Oregon. 64pp.

Petts, G.E. 1989. Perspectives for the ecological management of rivers. Pages 3-26 *in* J. A. Gore and G.E. Petts, editors. Regulated Streams: Advances in Ecology. New York: Plenum Press.

Poff, N.L., J.D. Allan, M.B. Bain, J.R. Karr, and others. 1997. That natural flow regime: A paradigm for river conservation and restoration. Bioscience 47: 1805-1818.

Powers, P.D, and J.F. Osborn. 1985. Analysis of Barriers to Upstream Fish Migration: An investigation of the physical and biological conditions affecting fish passage success at culverts and waterfalls. Final Project Report for BPA. Contract DE-A179-82BP36523. Project No. 82-14.

Railsback, S. 1999. Reducing uncertainties in instream flow studies. Fisheries 24(4): 24-26.

Reiser, D.W., and T.C. Bjornn. 1979. Habitat requirements of anadromous salmonids. General Tech. Rep. PNW-96. Pacific Northwest Forest and Range Experimental Station. Forest Service, U.S. Dept. of Agriculture, Portland, Oregon. 54pp.

Ricker, W.E. 1975. Computation and interpretation of biological statistics of fish population. Bull. Fish. Res. Board Can. 191.

Rimmer, D.M. 1985. Effects of reduced discharge on production and distribution of age-0 rainbow trout in semi-natural channels. Transactions of the American Fisheries Society 114: 388-369.

Ritter, D.F. 1978. Process geomorphology. Wm. C. Brown Company, Dubuque Iowa, 603 p.

Rood, R.M, and C.R. Neill. 1987. A study of some aspects of geomorphology of the Nechako River. Prepared for: Fisheries and Oceans Canada, Vancouver, B.C.

Rushton, C.D. 2000. Instream flows in Washington State: Past, Present, and Future. Dept. of Ecology, Olympia, WA.

Scouras, J.G., and P.S. Higgins. 1995. Preliminary assessment of the upstream passage and rearing flow requirements of steelhead trout (*Oncorhynchus mykiss*) and coho salmon (*O. kisutch*) in the Salmon River (Vancouver Island). Report No.EA94-14, B.C. Hydro, Safety and Environment, Strategic Fisheries Project: v+69 p. (29p. + app.).

Shirvell, C.S. 1990. Role of instream rootwads as juvenile coho salmon (*Oncorhynchus kisutch*) and steelhead trout (*O. mykiss*) cover habitat under varying streamflows. Can. J. Fish. Aquat. Sci. 47: 852-861.

Smith, B. and B.R. Ward. 2000. Trends in wild adult steelhead (Oncorhynchus mykiss) abundance for coastal regions of British Columbia support the variable marine survival hypothesis. Can. J. Fish Aquat Sci. 57: 271-284.

Smith, B.C. 2000. Trends in wild adult steelhead (*Oncorhynchus mykiss*) abundance for snowmelt-driven watersheds of British Columbia in relation to freshwater discharge. Can. J. Fish. Aquat. Sci. 57: 285-297.

Smith, I.M. and M.J. Sale. 1993. Standardizing instream flow requirements at hydropower projects in the Cascade Mountains, Washington. In: Proceedings of the international conference on hydropower. (Ed: Hall,WD) American Society of Civil Engineers, New York, 286-295.

Smoker, W.A. 1955. Effects of streamflow on silver salmon production in western Washington. Doctoral dissertation. University of Washington. Seattle, WA.

Solomon, D.J., H.T. Sambrook, and K.J. Broad. 1999. Salmon migration and river flow. R and D Publication 4. Bristol: Environmental Agency.

Sommer, T.R., M.L. Nobrigua, W.C. Harrell, W. Batham, and W.J. Kimmerer. 2001. Floodplain rearing of juvenile Chinook salmon: Evidence of enhanced growth and survival. Can. J. Fish. Aquat. Sci. 58(2): 325-333.

Stalnaker, C., B.L. Lamb, J. Henriksen, K. Bovee, and J. Bartholow. 1995. The instream flow incremental methodology: A primer for IFIM. Biological Report 29, U.S. Department of the Interior, National Biological Service, Washington, D.C. 45pp.

Stalnaker, C.B., and J.L. Arnette. 1976. Methodologies for the determination of stream resource flow requirements: An Assessment. U.S. Fish and Wildlife Service, Office of Biological Services, Western Water Allocation. Utah State University, Logan.

Stewart, L. 1973. Environmental engineering and monitoring in relation to salmon management. International Atlantic Salmon Foundation. Special Publication Series 4(1): 297-316.

Strahler, A.N. 1964. Quantitative geomorphology of drainage basins and channel networks; In Chow, V.T., Editor, *Handbook of Applied Hydrology* (McGraw-Hill, New York), Section 4-11.

Stuart, T.A. 1962. The leaping behaviour of salmon and trout at falls and obstructions. Freshwater and Salmon Fisheries Research (28): 1-46.

Tennant, D.L. 1975. Instream flow regimes for fish, wildlife, recreation, and related environmental resources. Completion Report. Billings, MT: U.S. Fish and Wildlife Service.

Tennant, D.L. 1976. Instream flow regimes for fish, wildlife, recreation, and related environmental resources. Fisheries 1(4): 6-10.

Thompson, K.E. 1972. Determining streamflows for fish life. *In* Proceedings Instream Flow Requirement Workshop, Pacific N.W. River Basins comm.., Portland, Oregon. pp.31-50.

Waters, T.F. 1969. Invertebrate drift-ecology and significance to stream fishes. In Symposium on salmon and trout in streams, H.R. McMillan Lectures in Fisheries, Univ. of B.C., Vancouver, B.C. pp. 121-134.

Welcomme, R.L. 1995. Floodplains. Relationships between fisheries and the integrity of river systems. Regulated Rivers: Research and Management 11: 121-126.

Wightman, J.C., and R.A. Ptolemy. 1989. Evaluation of available trout habitat in the upper Cowichan River in response to flows (1987). Unpublished MS. Recreational Fisheries Program, B.C. Environment Ministry, Nanaimo. 81pp.

Wolff, S.W., T.A. Wesche, D.D. Harris, and W.A.Hubert. 1990. Brown trout population and habitat changes with increased minimum low flows in Douglas Creek, WY. Biological Report 90(1). U.S. Dep. of the Interior, Fish and Wildlife Service, Washington, DC.

## APPENDIX 1: DETAILED INFORMATION ON REPORTS PROVIDED BY MWLAP FOR REVIEW AS PART OF THIS STUDY.

See BC IFS Rationale Appendix 1.xls`

# APPENDIX 2: LIST OF STUDIES IDENTIFIED BY MWLAP FOR REVIEW.

| Spawning and migration flows | | | Naturalized | | | | | |
|---|---|---|---|---|---|---|---|---|
| Region | Stream | Fish species | mad | Fish flow | Coefficient | mad | Fish flow | Comments |
| | | | (cms) | (cms) | %mad | cfs | cfs | |
| 1 | Colquitz River | Coho and Searun Cutthroat trout | 0.567 | 1 | 170 | 20.0 | 35.3 | fence operation; flow stage range of 50 to 280%mad |
| 1 | Craigflower Creek | Coho and Searun Cutthroat trout | 0.307 | 0.6 | 200 | 10.8 | 21.2 | fence operation; late Nov. for coho |
| 1 | Sandhill Creek | Chum salmon and Searun Cutthroat trout | 0.235 | 0.53 | 225 | 8.3 | 18.7 | observed fish movement,fence operation, and spawning behaviour |
| 1 | Sooke River | Chum salmon | 11.8 | 6.5 | 55 | 417.0 | 229.7 | IFIM analysis (Hamilton and Graham 1979) |
| 1 | Goldstream River | Steelhead | 2.2 | 3 | 136 | 77.7 | 106.0 | radio tracking of adult steelhead |
| 1 | Goldstream River | Coho/Chinook salmon and Steelhead | 2.2 | 2.2 | 100 | 77.7 | 77.7 | stream transect and rating of habitat at different flows |
| 1 | Koksilah River | Salmon and Steelhead | 9.63 | 5.3 | 55 | 340.3 | 187.3 | Collings Method (FLAP) |
| 1 | Cowichan River | Chinook salmon | 55 | 21.23 | 39 | 1943.5 | 750.2 | were less successful in trials; release target is 14 cms |
| 1 | Chemainus | Coho salmon | 19.1 | 8.54 | 45 | 674.9 | 301.8 | Collings Method (FLAP) |
| 1 | Nanaimo River | Chinook salmon | 40.5 | 17.8 | 44 | 1431.1 | 629.0 | migration occurs |
| 1 | Carnation Creek | Coho and Chum Salmon | 0.824 | 1.24 | 150 | 29.1 | 43.8 | fence operation |
| 1 | Big Qualicum | Salmon and Steelhead | 7.3 | 5.66 | 78 | 258.0 | 200.0 | fence operation/optimization of spawning habitat |
| 1 | Qunsam River | Salmon and Steelhead | 8.49 | 6 | 70 | 300.0 | 212.0 | observed fish movement and spawning behaviour |
| 1 | Keogh River | Salmon and Steelhead | 5.6 | 4.5 | 80 | 197.9 | 159.0 | fence operation; data available but not organized or analysed |
| 1 | Black Creek | Coho | 1.8 | 2 | 111 | 63.6 | 70.7 | Fence count and timing info; mid-October movement with first flow pulse of sufficient size |
| 1 | Trent River | Coho | 3.48 | 3.3 | 95 | 123.0 | 116.6 | Hamilton |
| 1 | Cowie Creek | Coho | 1.15 | 1.7 | 148 | 40.6 | 60.1 | Hamilton |
| 1 | French Creek | Coho | 2.41 | 2.55 | 106 | 85.2 | 90.1 | Collings Method (FLAP) |
| 1 | Salmon River | Salmon and Steelhead | 12.2 | 7.9 | 65 | 431.1 | 279.2 | conditions |
| 1 | Rosewall Creek | Salmon and Steelhead | 2.62 | 2.51 | 96 | 92.6 | 88.7 | Collings Method (FLAP) |
| 1 | Oyster River | Salmon and Steelhead | 13.7 | 14.3 | 104 | 484.1 | 505.3 | Collings Method (FLAP) |
| 1 | Nile Creek | Coho Salmon | 1.016 | 1.83 | 180 | 35.9 | 64.7 | Hamilton |
| WA | Snow Creek | Salmon and Steelhead | 0.69 | 1.1 | 160 | 24.4 | 38.9 | fence operation |
| 2 | Salmon River | Coho, Steelhead and Searun Cutthroat | 1.44 | 1.8 | 127 | 50.9 | 63.6 | fence operation; adult coho captures mainly in November |
| 2 | Campbell River | Coho, Steelhead and Searun Cutthroat | 0.938 | 1.4 | 150 | 33.1 | 49.5 | fence operation; adult coho captures mainly in November |
| 2 | Cheakamus River | Pink Salmon | 66 | 14.1 | 21.4 | 2332.2 | 498.2 | dewatered redds at 17%mad; DFO mapping |
| 3 | Pennask Creek | Lake Resident Rainbow Trout | 0.723 | 1.16 | 160 | 25.5 | 41.0 | observed fish movement,fence operation, and spawning behaviour |
| 3 | Mission Creek | Lake Resident Rainbow Trout | 8 | 4.9 | 61.3 | 282.7 | 173.1 | observed fish movement and trap at Smith-Alphonse Dam; high flows and critical temps factors |
| 3 | Salmon Arm | Chinook Salmon | 4.82 | 4.21 | 87 | 170.3 | 148.8 | Mean Monthly Flow for July when migration primarily occurs; counting fence |
| 3 | Adams River | Sockeye | 72.5 | 27 | 37 | 2561.8 | 954.1 | IPSC studies of fish behavior over many years |
| 3 | Deadman River | Steelhead | 3 | 3 | 100 | 106.0 | 106.0 | 1984 adult monitoring; Temps>8 required; April Mean flow = 103%mad |
| 3 | Bonaparte River | Salmon and Steelhead | 5.32 | 5 | 94 | 188.0 | 176.7 | Fishway counts |
| 4 | Lardeau River | Gerrard Rainbows | 28.2 | 12.7 | 45 | 996.5 | 448.8 | Mean April Flow when spawners present (Hartman 1969) |
| 7 | Cheslatta | Chinook and Sockeye | 151 | 31.1 | 20.6 | 5335.7 | 1098.9 | DFO observations |
| 5 | Hazeltine Creek | Lake Resident Rainbow Trout | 0.254 | 0.5 | 200 | 9.0 | 17.7 | mid-April spawning migration observed in 1991 |
| 5 | Hazeltine Creek | Lake Resident Rainbow Trout | 0.254 | 0.53 to 1.69 | 373 | | | observed spawning peaked by May 30/91 at flows near 0.53 cms |

| Fish rearing and insect production flows | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Region | Stream | Fish species | mad | Fish flow | Coefficien | PMC Flow | PMC Flow | Comments |
| | | | (cms) | (cms) | %mad | cms | %mad | |
| 1 | Colquitz River | Coho and Searun Cutthroat trout | 0.567 | 0.113 | 20 | 0.057 | 10 | wetted perimeter analysis and photo record |
| 1 | Craigflower Creek | Coho and Searun Cutthroat trout | 0.307 | 0.061 | 20 | 0.03 | 10 | mean monthly flow for May where 90% channel (@riffles) width is wetted |
| 1 | Sandhill Creek | Chum salmon and Searun Cutthroat trout | 0.235 | 0.047 | 20 | 0.024 | 10 | habitat and video record at known flows |
| 1 | Sooke River | | 11.6 | 2.3 | 20 | 1.16 | 10 | Riffle Analysis and PHabSim |
| 1 | Goldstream River | Steelhead | 2.2 | 0.44 | 20 | 0.22 | 10 | Riffle Analysis and PHabSim |
| 1 | Goldstream River | Coho/Chinook salmon and Steelhead | 2.2 | 0.44 | 20 | 0.22 | 10 | transect analysis and direct fish observation |
| 1 | Cowichan River | Chinook salmon | 45 | 9 | 20 | 9 | 20 | Riffle Analysis and PHabSim |
| 1 | Nanaimo River | Chinook salmon | 40.5 | 8.1 | 20 | | | Riffle Analysis and PHabSim |
| 1 | Carnation Creek | Coho Salmon | 0.824 | 0.17 | 21 | 0.08 | 10 | wetted area of riffle changes with flow; maximum coho biomass at 20%mad |
| 1 | Big Qualicum | Salmon and Steelhead | 7.3 | 1.46 | 20 | | | |
| 1 | Simms Creek | Ct and Coho | 0.259 | 0.052 | 20 | 0.035 | 14 | Riffle Analysis and PHabSim |
| 1 | Willow Creek | Ct and Coho | 0.483 | 0.097 | 20 | 0.04 | 8 | Riffle Analysis and PHabSim |
| 1 | Quinsam River | Salmon and Steelhead | 9.5 | 1.7 | 18 | | | |
| 1 | Keogh River | Salmon and Steelhead | 5.6 | 0.84 | 15 | | | 1986 Survey of Riffle Coverage and Hydraulics |
| 1 | Black Creek | Salmon and Steelhead | 1.8 | 0.27 | 15 | | >9 | Riffle width linear increase from zero to 9%mad; 80% of toe-width wetted at 9%mad; critical flow where disconnect to braids occurs |
| 1 | Trent River | Coho | 3.48 | 0.7 | 20 | | | |
| 1 | Nile Creek | All | 1.01 | | | 0.13 | 13 | Hamilton surface width |
| 1 | French Creek | Coho | 2.5 | 0.478 | 19.1 | 0.24 | 10 | Riffle Analysis and PHabSim |
| 1 | Rosewall Creek | All | 2.62 | 0.88 | 34 | | | Collings |
| 1 | Salmon River | Salmon and Steelhead | 13.8 | 1.9 | 14 | 0.97 | 7 | Riffle Analysis and PHabSim |
| 7 | Nechako R | Chinook salmon | 151 | 56.6 | 37.5 | | | Prof judgement |
| WA | Snow Creek | Salmon and Steelhead | 0.69 | 0.138 | 20 | | | wetted perimeter analysis and photo record |
| 8 | Mission Creek | Rainbow and kokanee | 8 | 1.42 | 18 | 0.53 | 7 | HEC2, IFIM, wetted perimeter |
| 8 | Powers Creek | Rainbow and kokanee | 0.91 | 0.14 | 15 | | | Prof judgement |
| 8 | West Kettle River | Rainbow trout | 10.4 | 2 | 19.2 | 1 | 10 | Riffle Analysis and PHabSim; 50% toe-width exposed at flows of 0.48 cms |
| 8 | Kettle River | Rainbow trout | 74.5 | 15 | 20.1 | | | Riffle Analysis and PHabSiml Large Residents |
| 8 | Kettle River | Fast-water Inverts | 74.5 | 19 | 25.5 | | | Riffle/Rapid Analysis and PHabSiml Large Residents |
| 8 | Kettle River | Simulidae | 74.5 | 31 | 41.6 | | | Riffle/Rapid Analysis and PHabSiml Large Residents |
| 4 | Redfish | Rainbow and kokanee | 0.845 | 0.3 | 36 | | | Prof judgement |
| 4 | Harrop | Rainbow and kokanee | 0.85 | 0.25 | 30 | | | Prof judgement |
| 4 | Kokanee | Rainbow and kokanee | 3.1 | 0.9 | 30 | | | Prof judgement |