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Considerations for defining reference points for semelparous species, with emphasis on anadromous salmonid species including iteroparous salmonids

Considérations sur la définition de points de référence pour les espèces sémelpares, particulièrement les espèces de salmonidés anadromes, y compris les salmonidés itéropares

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TABLE OF CONTENTS

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ABSTRACT

The document was prepared in support of an advisory process meeting to produce a technical guidance document to assist science practitioners responsible for developing the science elements of the Precautionary Approach (PA) framework. It reviews the use of reference points in the assessment and management of semelparous species and anadromous salmonids including iteroparous salmon. Semelparous species and anadromous salmonids are treated collectively and separately from other aquatic species because they share a number of life history and population dynamic characteristics which are distinct from those of other aquatic organisms. In British Columbia and Yukon, the Wild Salmon Policy (WSP) guides the implementation of the precautionary approach in the management of fisheries on Pacific salmon. In the WSP, biological benchmarks are developed for four main classes of indicators: trends in abundance, abundance, fishing mortality, and spawning ground distribution as data permits. These indicators are further integrated into a single category of biological status. There are no management actions which are associated directly with a given status or benchmark. Rather, the biological benchmarks aid in the development of fishery reference points along with socio-economic factors and issues related to risk tolerance. Reference points for Atlantic salmon have been used to advise fisheries management since the 1970s. The use of a conservation objective defined as a limit reference point and the fixed escapement strategy has been adopted in Canada, by national governments in Europe and by international organisations. Candidate fishery reference points and WSP benchmarks are similar to the general list of reference points proposed in a number of publications for other species. Stock and recruitment models have a long and established history in Pacific and Atlantic salmon stock assessment and provision of science advice for fisheries management. Empirical methods consisting of life history models that use life history process parameters borrowed from a large range of studies on the species of interest are considered. In data limited situations for unstudied populations but for which information exists from other populations, reference points are frequently transported based on values from studied populations which are standardized using an exchangeable and transportable metric.

RÉSUMÉ

Le document a été préparé dans le cadre d'une réunion de processus consultatif destiné à produire un document d'orientation technique pour aider les praticiens scientifiques chargés de mettre au point les éléments scientifiques du cadre d'approche de précaution (AP). Il examine l'emploi de points de référence dans l'évaluation et la gestion des espèces sémelpares et des salmonidés anadromes, notamment des saumons itéropares. Les espèces sémelpares et les salmonidés anadromes sont traités ensemble et séparément des autres espèces aquatiques, car leur cycle biologique et la dynamique de leurs populations présentent plusieurs caractéristiques communes, qui les distinguent des autres organismes aquatiques. En Colombie-Britannique et au Yukon, la Politique concernant le saumon sauvage (PSS) oriente la mise en œuvre de l'approche de précaution dans la gestion de la pêche du saumon du Pacifique. Dans le cadre de la PSS, des points de référence biologiques ont été mis au point pour quatre catégories principales d'indicateurs : tendances de l'abondance, abondance, mortalité par pêche et répartition des frayères, dans la mesure des données disponibles. Ces indicateurs sont ensuite intégrés dans une seule catégorie de situation biologique. Aucune mesure de gestion n'est associée directement à une situation ou à un point de référence donnés. Les points de référence biologiques sont plutôt un des éléments contribuant à la définition de points de référence avec les facteurs socio-économiques et les questions liées à la tolérance au risque. Les points de référence définis pour le saumon de l'Atlantique servent à orienter la gestion de la pêche depuis les années 1970. Le Canada, des gouvernements européens et des organisations internationales ont adopté l'utilisation d'un objectif de conservation défini comme point de référence limite et d'une stratégie d'échappées fixes. Les points de référence pour la pêche et les points de référence de la PSS sont semblables à ceux de la liste générale proposée dans de nombreuses publications concernant d'autres espèces. Depuis très longtemps, les modèles de stock et de recrutement sont utilisés dans l'évaluation des stocks de saumon du Pacifique et de l'Atlantique et dans l'élaboration d'avis scientifique concernant la gestion des pêches. Dans ce cadre, ont été prises en compte plusieurs méthodes empiriques composées de modèles de cycles biologiques qui reposent sur des paramètres de processus de cycle biologique tirés d'une vaste gamme d'études sur l'espèce concernée. Quand les populations sont insuffisamment étudiées et que les données sont limitées, mais qu'il existe des renseignements provenant d'autres populations, il est fréquent que les points de référence soient transposés à partir des valeurs des populations étudiées, qui sont normalisées au moyen d'une mesure échangeable et transférable.

1. INTRODUCTION

This review of the present use of reference points in the assessment and management of semelparous species and anadromous salmonids was prepared in support of an advisory process meeting to produce a technical guidance document to assist science practitioners responsible for developing the science elements of the Precautionary Approach (PA) framework (DFO 2009a). This review is directed at considerations for setting reference points for semelparous species, with emphasis on anadromous salmonid species including iteroparous salmonids. This distinction from other aquatic organisms is the result of specific aspects of their life history and their use of distinct aquatic habitats. Most principles for evaluating reference points for other species apply equally to this group of species. The major differences arise around the management strategy for exploitation of these species and the development of decision rules.

2. LIFE HISTORY SPECIFICS

Semelparous species and anadromous salmonids are treated collectively because they share a number of life history and population dynamic characteristics which are distinct from life history features in numerous other aquatic organisms.

Individuals in semelparous species undertake a single reproductive event in their life cycle and die after spawning. Semelparous species in Canada include the Pacific salmon species (*Onchorynchus* sp. 6 species) and the eulachon (*Thaleichthys pacificus*) in the Pacific (Levesque and Therriault 2011), and the American eel (*Anguilla rostrata*) and the sea lamprey (*Petromyzon marinus*) on the east coast of Canada. Because of semelparity, spawing stock abundance is determined exclusively by the abundance of first time spawning individuals and as a result there is no opportunity for spawning stock to accumulate over years. Consequently, there are generally few age groups in the spawning population originating from a restricted number of year classes.

Fisheries on this group of species have been on first time spawning and maturing animals. Although there are some examples of fisheries on these species at non-maturing life stages (Pacific salmon historically, Atlantic salmon high seas fisheries at West Greenland and the Faroes Islands), the majority of the exploitation takes place on mature animals returning to the coast and rivers to spawn, when they are concentrated at higher density than at earlier life stages and have reached their maximum size at age. The exception to this pattern has been fisheries on the catadromous American eel which take place over many years and life history stages from the elver stage (juvenile stages returning to the coast and rivers from the spawning area in the Sargasso Sea), to yellow eels of various ages and on silver eels (the mature, seaward migrating stages).

Anadromous Atlantic salmon (*Salmo salar*) and some other iteroparous but short lived species such as rainbow smelt (*Osmerus mordax*), Atlantic silverside (*Menidia menidia*) and small pelagic species such as sardines have life history characteristics which are similar to those of semelparous species, i.e. a dominant component of the annual spawing stock is comprised of first time spawners and there are few year classes in the annual spawning run. Although Atlantic salmon are iteroparous and as many as seven multiple spawnings have been recorded in some populations in the North Atlantic, the spawning runs are dominated by first time spawners (Chaput et al. 2006).

The anadromous salmonid species utilize two distinct environments to complete their life cycle and population structuring at the scale of an individual river, and in Pacific salmon to subwatershed scale, is highly evolved. Recruits return with high fidelity to the natal spawning locations. In salmonid species that spend an extended period of time in freshwater as juveniles, density-dependent population regulation is well established, occurring in the first year or two of freshwater residency (Jonson et al. 1998; Elliott 2001; Gibson 2006). For Atlantic salmon that spend from two to six or more years in river before going to sea, all the observed density-dependent effects occur in freshwater with survival at sea being density-independent. This contrasts with some Pacific salmon species for which population density regulation at sea has been demonstrated (Hansen and Quinn 1998).

Anadromous salmonid spawning and rearing habitat is highly spatially structured and anadromous salmonid females deposit a few (single digit) batches of hundreds to thousands of eggs in excavated gravel redds. As a result, the total progeny from a given year’s spawning can be subjected to highly heterogeneous survival and growth conditions within a large watershed while a batch of 100s to 1000s of individuals sharing a redd from a single female would be subjected to locally highly homogenous survival conditions. In this context, the most appropriate spawning stock unit for modelling population dynamics would be the number of individual female fish in the spawning run, rather than the total number of eggs or biomass of spawners, as is used in many other species. Note that for Atlantic salmon, however, stock status is generally assessed relative to the estimated total number of eggs, with adjustments for increasing fecundity with body size (see section 3.2).

For these reasons, the management of semelparous and anadromous salmonid species has been extensively focused on escapement goals to ensure a level of spawning that would provide fishing and species benefits in the subsequent generation (Chadwick 1985).

3. CURRENT STATE OF DEVELOPMENT OF REFERENCE POINTS

3.1 Pacific salmon

Summary

In British Columbia and Yukon, the Wild Salmon Policy (WSP; DFO 2005) guides the implementation of the precautionary approach in the management of fisheries on Pacific salmon as outlined in *A Framework for the application of Precaution in Science-based Decision Making about Risk.* The WSP is analogous to, but much more detailed than the *A fishery decision-making framework incorporating the Precautionary Approach* (DFO 2009a) document which is used extensively for the management of groundfish fisheries. The implementation of the WSP began with the publication of the policy in 2005 and implementation continues to progress and evolve.

Pacific salmon fisheries can range from large-scale, mixed-stock commercial fisheries using purse seines to small, terminal, single-stock First Nations food, social and ceremonial fisheries using dipnets or rod and reel. Similarly, the data quality and quantity range from sporadic, low quality data to one of the best and longest escapement data series in the world. Pacific salmon are short lived, semelparous species with annual abundances that can systematically vary over 100 fold during a time span of four years for a single conservation unit. These wide-ranging attributes make management and the assessment of the status of Pacific salmon a unique challenge.

There are currently 400+ Pacific salmon Conservation Units (CU). For each CU, biological benchmarks are developed for four main classes of indicators: trends in abundance, abundance, fishing mortality, and spawning ground distribution as data permits. These indicators are further integrated into a single category of biological status (red, amber, or green). However, there are no management actions which are associated directly with a given status or benchmark. Rather, the biological benchmarks aid in the development of fishery reference points (i.e., the point at which a management action will take place) along with socio-economic factors and issues related to risk tolerance. Due to the large number of CUs, many of which are data deficient, and the mixed-stock nature of many of the fisheries on Pacific salmon, management reference points tend to be developed for aggregations of CUs.

3.1.1 Policy basis

Wild Salmon Policy (WSP)

Canada's Policy for Conservation of Wild Pacific Salmon (DFO 2005), here after referred to as the Wild Salmon Policy (WSP), is the policy framework for the conservation and sustainable use of wild Pacific Salmon. The WSP does not amend or override existing legislation, government agreements and policies. Details on existing legal framework and policies currently in place that affect management of Pacific Salmon are described in the WSP Appendix 1. The WSP provides additional, Pacific salmon specific, policy guidance and will be implemented in accordance with guidance provided to Federal Departments by the Privy Council Office publication entitled "*A Framework for the application of Precaution in Science-based Decision Making about Risk*." (Canada Privy Council Office 2003). WSP biological benchmarks do not determine COSEWIC or SARA listing/status, escapement goals, total allowable catch amounts, allowable exploitation rates, or allocation of catch.

In order to achieve the WSP goal, six strategies are outlined in the policy (DFO 2005). In particular, Strategy 1, 'Standardized Monitoring of Wild Salmon Status', Action Step 1.2 'Develop criteria to assess CUs and identify benchmarks to represent biological status' and Action Step 1.3 'Monitor and Assess Status of CUs' provide a starting point for the development of fisheries reference points. However, Strategy 4, 'Integrated Strategic Planning', is where overall biological status of Pacific salmon is integrated with mechanisms influencing status (habitat and ecosystems) and socio-economic and mixed-stock fisheries considerations. At a minimum, the strategic plans developed in Strategy 4 "must be capable of maintaining and restoring all CUs above their established lower benchmarks with an acceptable degree of certainty within a defined time frame". These strategic plans "will inform the development of annual fishing plans" (DFO 2005). This review focuses mostly on Strategy 1 of the WSP – biological status.

3.1.2 WSP biological benchmarks with three status zones

In Strategy 1 of the WSP, 'Standardized Monitoring of Wild Salmon Status', status for each of the 400+ Pacific Salmon CUs (CU methodology described in Holtby and Ciruna 2007) are determined using a toolkit of possible classes of indicators that include abundance, trends in abundance, distribution of spawners and fishing mortality (Holt et al. 2009). In the WSP, three biological status zones include Red, Amber, and Green that reflect a continuum from poor to healthy status. For each indicator used to assess status, a lower and upper benchmark is identified to delineate, respectively, the Red-to-Amber and Amber-to-Red status zones (Holt 2009; Holt et al. 2009; Holt and Bradford 2011). In the WSP, the "lower benchmark between Amber and Red will be established at a level of abundance high enough to ensure there is a substantial buffer between it and any level of abundance that could lead to a CU being considered at risk of extirpation by COSEWIC”. The WSP upper benchmark “will be established to identify whether harvests are greater or less than the level expected to provide, on an average annual basis, the maximum annual catch for a CU, given existing environmental conditions” (DFO 2005). Statuses across the suite of indicators evaluated (that may include abundance, trends in abundance, distribution and fishing mortality*)* are being integrated to produce a final single biological status for each CU.

3.1.3 Reconciling status zones in the WSP and status zones in the PA

The WSP will be implemented in accordance with guidance provided to the Canadian Federal Departments by the Privy Council Office publication entitled “*A Framework for the application of Precaution in Science-based Decision Making about Risk*” (Canada Privy Council Office 2003). The WSP broadly incorporates the five principles of precaution included in Canada’s precautionary framework: the application of the precautionary approach is a legitimate and distinctive decision-making approach within a risk management framework; decisions should be guided by society’s chosen level of risk; application of the precautionary approach should be based on sound scientific information; mechanisms for re-evaluation and transparency should exist; and a high degree of transparency, clear accountability, and meaningful public involvement are appropriate.

Specific to DFO, the subsequent policy “A fishery decision-making framework incorporating the Precautionary Approach” (DFO 2009a), describes a general fishery decision-making framework for implementing a harvest strategy that incorporates the Precautionary Approach (PA). Conceptually, the DFO’s Precautionary Approach (PA) framework (DFO 2009a) and DFO’s WSP (DFO 2005) both address the intent of Canada’s obligations to the PA. In particular, both documents describe three stock status zones. In the case of DFO’s PA framework, the three status zones are Critical, Cautious, Healthy, versus the WSP’s Red, Amber, Green, both of which are describing a continuum of poor to healthy stock status. The Critical-Cautious zone boundary under the PA, defined as the Limit Reference Point (LRP), is the level below which productivity is sufficiently impaired to cause serious harm to the resource but above the level where the risk of extinction becomes a concern. The Cautious-Healthy boundary in the PA, defined as the Upper Stock Reference Point (URP), is the stock level threshold below which the removal rate is reduced. The stock status zone above the URP is the Healthy zone. In comparison, the WSP lower benchmark “between the Amber and Red status zones will be established at a level high enough, given uncertainty in the data, to ensure that there is a substantial buffer between it and any level of abundance that could lead to a CU being considered at risk of extinction by COSEWIC”. In the context of fisheries management, the buffer will also account for uncertainty in the control of harvest management and the level of risk tolerance to uncertainty. The WSP states that “the level of risk tolerance requires consultation with First Nations and others being affected by the level of risk tolerance”. The WSP further defines the habitat and ecosystem status for each CU.

The figures in DFO’s PA, however, are specific to the prosecution of fisheries. The reference points described, therefore, are specific to abundance/biomass (limit reference point and upper stock reference) and fishing mortality (removal reference), and in doing so, differ from the WSP by prescribing reference points that trigger management actions. In contrast, biological benchmarks in the WSP are not prescriptive for fisheries management and include a number of benchmarks across the full suite of indicators available for a CU (abundance, trends in abundance, distribution and fishing mortality). So for each CU in the WSP there may be more than one pair of upper and lower benchmarks used across indicators to evaluate a final integrated biological status across conservation units.

DFO’s PA is one piece of the WSP’s Strategy 4 that uses integrated statuses for each CU across a number of indicators to develop Strategic Management Plans.

Although conceptually, WSP lower and upper abundance and fishing mortality benchmarks somewhat align to the limit reference point (LRP), the upper stock reference point (URP) and the fishery removal rate, as described in the DFO PA policy, they are not identical. First, WSP biological benchmarks are specific to the identification of integrated biological status across indicators for each CU to guide implementation of Strategy 4, ‘Integrated Strategic Planning’. WSP’s Strategy 4 is where overall biological status of Pacific salmon is further linked with mechanisms influencing status (habitat and ecosystems) and socio-economic and mixed-stock fisheries considerations. At a minimum, the Strategic Plans developed in Strategy 4 “must be capable of maintaining and restoring all CUs above their established lower benchmarks with an acceptable degree of certainty within a defined time frame”. These strategic plans “will inform the development of annual fishing plans” (DFO 2005). Therefore, these WSP benchmarks are not intended to be prescriptive for fisheries management. The biological benchmarks from Strategy 1 of the WSP are integrated with habitat benchmarks, ecosystem status, and socio-economic factors to determine fishery reference points in strategy 4 of the WSP.

3.1.4 WSP biological benchmarks and fishery reference points presently developed and used for management of Pacific salmon stocks

Harvest rules are established in a separate step from the biological benchmarks. Biological benchmarks are incorporated but do not define the harvest rules for Pacific salmon. The tools available to develop benchmarks and hence fishery reference points, in large part, are a function of data quality. Minimum data requirements for developing WSP benchmarks and evaluating biological status are provided in Holt et al. (2009). Key sources of information common to all Pacific salmon assessments are derived from the annual escapement monitoring programs. Those programs provide the basis for establishing fishery reference points and other science advisory products including WSP benchmarks used for determinations of biological status. Indicators of production at juvenile life stages are available for a small subset of CUs that allow partitioning of data by life stage. Additional information sources include those derived from catch monitoring to estimate fishing mortality and recruitment. Benchmarks based on distributional criteria within a CU are the least advanced and are not part of the present toolkit for determining biological status.

The high annual cost of escapement monitoring is directed to a few CUs with consistent mark-recapture experiments or annual fence counts as opposed to low quality and often inconsistently applied visual methods with high observation error. Except for a few CUs with a sufficient time series of high quality data, it will not be possible to apply the full suite of assessment tools to establish benchmarks or fishery reference points for all metrics (abundance, trends in abundance, distribution and fishing mortality). Data quality is highest for sockeye and generally poorest for pink and chum salmon. This trend is more apparent in recent years with reductions in budgetary resources. The majority of CUs are data limited to the extent that benchmarks of abundance trends may be the only reliable tool for establishing fishery reference points. Nevertheless, we have limited experience in formalizing fishery reference points based on benchmarks of abundance trends. That being said, declining trends in escapement and productivity for stocks of concern have been the basis of empirical approaches for managing stocks of concern in the Region.

Several approaches are used to provide science advice for setting benchmarks. These include:

1) production models to directly estimate key management parameters where suitable time-series of data exist;

2) habitat-based meta-analyses for data limited populations based on the relationship between habitat availability and abundance inferred from well-studied populations;

3) Pacific Salmon Treaty (PST) approaches for monitoring stock distribution, survival and exploitation rates of stocks intercepted in Canada and US salmon fisheries based on coded-wire tagging (CWT) studies; and,

4) empirical approaches based on trends in abundance and productivity.

Under WSP Strategy 4, fisheries management plans require the integration of biological, habitat and ecosystem information for a CU with socio-economic information. Further, fisheries are frequently prosecuted in a mixed-stock environment, so fishery reference points are frequently applied to aggregates of conservation units or stocks. Reference points and their use in harvest control rules will need to consider:

1) performance measures that assess trade-offs between the cost/risks associated with over-fishing and extinction and the benefits of harvest,

2) implications of differences in productivity among stocks in mixed-stock fisheries not considered in WSP benchmarks that focus on individual CUs, and

3) a risk tolerance level that reflects the attitude of those affected by the outcome of management decisions (i.e. loss of biodiversity of weak stocks in mixed-stock fisheries).

Therefore, WSP biological benchmarks are only a starting point for developing fishery reference points for Pacific salmon in contrast to the fishery reference points described in DFO's PA. Although, mixed-stock reference points are specific to aggregates of CUs, the performance of fishery reference points relative to conservation objectives will be evaluated on the probability of individual CUs exceeding the red status zone.

Approaches presently used to guide fisheries management decisions for managed Pacific salmon in the remainder of this section are from the Integrated Fisheries Management Plans for B.C. stocks

Fraser River sockeye

Sockeye originating from the Fraser River, Barkley Sound and the north coast Skeena-Nass River regions are presently exploited in large-scale, mixed-stock fisheries in marine and riverine locations during the annual seasonal migration to the spawning grounds. Those fisheries are intensively managed in-season with weekly updates of abundance to assess stock and fishery performance relative to pre-season management objectives. Table 3.1.1 summarizes the reference points and objectives for the main sockeye fisheries in B.C. Fraser sockeye fisheries are managed as four overlapping management (timing) groups (Early Stuart, Early Summer, Summer and Lates) (Table 3.1.1). Only small components of the total harvest are taken near terminal spawning areas outside mixed-stock fisheries in most years. Tactics for managing incidental catches of non-target CUs and pink, chum, Chinook, coho and steelhead include exploitation rate restrictions, time/area fishery closures and selective fishing practices using alternate gear types.

For Fraser sockeye, the approach used to develop fishery reference points has evolved within an on-going stakeholder advisory process called the Fraser River Sockeye Spawning Initiative (FRSSI). In support of the FRSSI process, a simulation model is being used to evaluate trade-offs in meeting escapement objectives and long-term catch. The FRSSI escapement strategy was fully implemented in 2007 and has been updated annually through the annual pre-season IFMP planning process. The model is used to evaluate the potential long-term effects of future productivity scenarios, alternative SR model structures and adult mortality from fishing and other causes on projected catch and escapement. A 3-zone Total Allowable Mortality (TAM) Rule accounts for the total mortality due to fishing and other sources of adult mortality (Cass et al. 2004). Future productivity scenarios are driven by MCMC samples of the joint posterior parameter distribution for each of the modelled stocks assuming Ricker and Larkin dynamics. Model projections for all of the 19 modelled stocks are done simultaneously. The effects of timing differences among populations in the fishery is accounted for by specifying the degree of timing over-lap based on the average historical timing estimated for each modelled stock.

There are four TAM rules used for Fraser Sockeye, one for each management aggregate: Early Stuart, Early Summer, Summer, and Late. The FRSSI process does not model in-season management procedures such as tactics to meet allocation requirements among gear types or individual fishery locations in space and time.

The TAM rule (Figure 3.1.1) is guided by the following:

- Low to no fishing at very low run sizes. Currently the model includes a 10% exploitation rate to simulate test fishing impacts and incidental harvest from non-target fisheries.

- Declining total allowable mortality at low run sizes to meet conservation objectives for individual stocks and reduce process-related challenges at this critical stage (e.g. uncertain run size). The shape of the TAM rule below the Upper Fishery Reference Point is designed to maintain a fixed escapement between it and the Lower Fishery Reference Point. The lower abundance benchmark is theoretically below the lower fishery reference point for all CUs within the management aggregate.

- Fixed total allowable mortality rate of 60% at larger run sizes. This cap is less than exploitation at MSY estimated from stationary SR models for the modelled stocks. This was a precautionary policy choice to ensure robustness against uncertainty (e.g. estimates of productivity and capacity, changing run-size estimates, implementation error) and to protect populations that are less abundant, less productive, or both.

The current version of the model can address both stationary productivity as well as time-varying productivity. However, future productivity trends is a model input as the model does not solve and extrapolate future trends from recent trends. This feature is primarily used as a sensitivity analysis to test the robustness of harvest rules to time-varying productivity.

A wide range of escapement strategies (e.g., fixed escapement goal, fixed exploitation rate, abundance based harvest rules) have been assessed using the FRSSI model. The performance of each harvest strategy has been assessed using indicators that reflect the objectives of (1) remaining above the interim escapement benchmark of individual CUs with a specified probability and (2) accessing catch-related benefits from the aggregate of CUs in mixed-stock fisheries. All four management groups, except the Early Summer and Late groups, consist of CUs with suitable stock-recruitment data to simulate projections based on Larkin model dynamics. The Early Summer management group has 4 CUs, and the Late Run management group has 2 CUs, that are data deficient in that regard.

Interim escapement benchmarks have been used in the FRSSI model to date, but we are in progress of converting to WSP abundance benchmarks. The model is continually under development. Recent model changes have allowed those participating in the escapement planning process to evaluate: 1) the effect of productivity assumptions on a stock by stock basis, 2) the effect of grouping stocks into alternate run timing groups, and 3) the effect of alternative TAM levels above the stock reference point that is presently set at 60%. In that context, because reference points are explicitly linked to the shape of the TAM rule, altering the shape of TAM rule can shift limit reference points higher or lower when comparing the probabilities of maintaining the stock above a given limit. All else being equal, higher removal rates to allow higher yield at abundant stock sizes, will shift limit reference points higher with perhaps the undesirable effect of a higher frequency of fishery closures. From this perspective it is difficult to establish reference points independent of a harvest control rule (TAM rule in the case of Fraser sockeye).

Barkley Sound sockeye

Sockeye returning to Barkley Sound (Somass River) on the west coast of Vancouver Island consist of 3 CUs (Sproat, Great Central and Henderson lakes). The annual migration timing of Sproat and Great Central Lake sockeye are very similar. Fisheries on those CUs are managed as an aggregate. The timing of Henderson Lake sockeye, although generally later, overlaps the more productive Sproat and Great Central Lake CUs. Henderson sockeye are managed using time/area closures to avoid significant impacts of fisheries targeting the Sproat-Great Central aggregate. Fishery openings are set depending on in-season abundance estimates from test fisheries.

During the development phase of the present management framework for Barkley Sound sockeye, several types of harvest strategies were explored (fixed escapement, fixed exploitation rate and abundance based harvest rules). A variable harvest control rule strategy was determined to best meet the agreed principles developed with stakeholder input. The HCR was developed iteratively by evaluating the trade-offs of different harvest rate levels over varying categories of stock abundance. Increasing levels of fishing opportunity were identified at critical, low, moderate, and high abundances. In the management of Barkley Sound sockeye, harvest allocations among the various fishery sectors depended on the abundance level and sector priorities (Figure 3.1.2). FSC fisheries have priority access for planning and management at low run sizes with some base level of FSC fisheries exclusive of other sectors. Overall, harvest rates at lower stock sizes were increased during the development process to accommodate sport fishing and early gill net opportunities. Decision rules for each sector and fishery are adjusted depending on abundance using management tools specific to their fishery (e.g. time, area, gear, effort restrictions). Lower biological benchmarks for Sproat and Great Central, based on results from multi-year lake surveys, and fishery reference points identified in Figure 3.1.2 were agreed to by participants in a stakeholder-driven process. The limit reference point was developed based on the potential for stock rebuilding to commercial abundance within one generation. The upper reference point, where commercial fisheries would begin, was based on the estimate of S_{msy} assuming a Ricker model. The only reference point for Henderson sockeye is a target escapement and limit exploitation rate defined as an average exploitation in the range of 15% for commercial plus FSC fisheries.

Skeena-Nass sockeye

The Skeena River is the second largest producer of sockeye in B.C. There are significant challenges in the management of Skeena River salmon with overlaps in the timing distributions of more than 20 sockeye CUs in addition to chum, coho, and steelhead; each with varying levels of conservation risk and assessment data quality problems. Recent attention on the conservation of co-migrating steelhead and other species has pointed out the need for a formal assessment of trade-offs in management objectives needed to develop mixed-stock fishery reference points (Walters et al. 2008).

The largest Skeena sockeye producers are the enhanced stocks from the spawning channels at Babine Lake. Co-migrating sockeye CUs from various spawning and rearing systems migrate up the Skeena throughout the salmon season. Wild stocks are generally less productive than the enhanced stocks. Skeena sockeye are harvested in mixed-stock fisheries in marine approach areas in Alaska and Canada and within the Skeena watershed. Co-migrating sockeye are managed as an aggregate in mixed-stock fisheries in Alaska and Canadian waters. A primary concern of fisheries management is shaping fisheries to balance the harvest of large, more productive (enhanced) runs versus the risk of over-fishing less productive wild CUs and to reduce fishery impacts on other species of concern in the Skeena watershed. These measures include non-retention of some species, gear and fishing modifications, and specific time closures or sockeye harvest rate reductions when weak stocks are present. The main inseason tool for estimating the relative abundance of sockeye is the Skeena River test-fishery.

WSP benchmarks for individual salmon CUs in the north and central BC have not yet been formally established. A HCR is used to manage commercial Skeena sockeye fisheries. The HCR specifies a limit reference point for the aggregate of co-migrating populations (400,000 sockeye) for all fisheries. FSC fisheries have first priority and can occur in excess of the LRP. Commercial fisheries only occur at a run of 1.05 Million sockeye. Above that level the allowable exploitation rates is determined from the HCR for commercial Area 4 fisheries (Figure 3.1.3). Walters et al (2008) noted that exploitation rates of Skeena sockeye have been held below levels considered optimal for the more productive enhanced stocks in order to protect the wild stock components and meet escapement targets.

Nass sockeye (4 CUs) are managed to meet commitments of the PST and the Nisga’a Treaty. Management objectives include the recovery of the Fred Wright Lake CU. Net fisheries in the principal mixed-stock fishery for Nass sockeye (Area 3) have been restricted during the peak of the timing of that CU to minimize harvest impacts. Other constraints include co-migrating chum salmon that are also a conservation concern. Nass sockeye are in-part managed along with co-migrating Skeena salmon species due to the overlap in the stock distribution.

Chinook

The basis for managing fisheries impacting Chinook from Alaska to Oregon is the Chinook abundance based management system developed within the PST process. A similar approach is used to manage coho within the PST process. Harvest regimes are based on annual estimates of abundance that take into account all fishery induced mortalities and are designed to meet MSY or other agreed biologically-based escapement and/or harvest rate objectives; with the understanding that harvest rate management is designed to provide a desired range of escapements over time. Biologically-based escapement goals are presently being developed within the PST process. For data limited stocks (only 3 CUs in B.C. have adequate SR data), estimates of S_{msy} and F_{msy} are being derived from the habitat-based meta-analysis approach (Section 5).

Two types of Chinook fisheries are identified in the PST agreement: Aggregate Abundance Based Management (AABM) fisheries and Individual Stock Based Management (ISBM) fisheries.

AABM fisheries are mixed-stock fisheries that intercept and harvest migratory Chinook salmon from many stocks. AABM fisheries for Chinook salmon are managed to achieve a target catch corresponding to a target harvest rate index and each year's abundance index derived from pre-season abundance forecasts. Canada would further constrain its fisheries to achieve its escapement objectives if the general obligations of the Treaty do not meet its objectives. Escapement objectives defined in the PST are the spawning escapements that produce MSY (defined as S_{pa}, the spawning abundance precautionary reference point). A spawning abundance limit reference point, S_{lim}, established in the PST language is 85% of MSY. The fishing rate, F_{lim} in the PST language, is the fishing rate at S_{lim}.

For most of the AABM and ISBM fisheries, there is an escapement goal range representing the target for the aggregate of the indicator stocks in each mixed-stock fishing area (Northern BC, WCVI, Upper Strait of Georgia, Lower Strait of Georgia, Fraser River). Most stocks are associated with an exploitation rate indicator system that is assumed to represent the catch distribution, exploitation and survival rates of the aggregate stock.

Coho

Under the PST abundance-based management (ABM) regime for Canadian coho stocks, exploitation rates are constrained for each PST Management Unit (MU) depending on the biological status classified by low, moderate, or abundant. Annual categorization of status determines the limit exploitation rate range for each MU. Under the Agreement, Canada and the U.S. are required to establish escapement goals or exploitation rate limits (ERs) that achieve MSY, determine ER at MSY for each MU, and establish ERs for each MU and status category (low, moderate, and abundant). Until such time as the Parties provide the MU ER targets, the PST Agreement identifies ER ceilings for the following MU status categories:

Status	**Total Exploitation Rate**
Low	**≤20%**
Moderate	**21% – 40%**
Abundant	**41% – 65%**

Pink

Pink salmon assessment data is of low quality and routine escapement monitoring has not occurred for several generations for almost all CUs. Most of the 19 CUs in the Region are managed to empirically determined escapement targets and inseason tactics based on test fisheries.

Inner South Coast pink salmon (Johnstone Strait and the Strait of Georgia), follow a strict 2 year life cycle, such that even-year runs and odd-year runs are functionally distinct (Van Will et al. 2009b). Formal reference points have not been developed for Inner South Coast pink stocks. However, operational Management Escapement Goals (MEG) were developed by interviewing a range of experts and these have been in use since they initially were established in the 1970s (Anderson and MacKinnon 1979). The MEGs are used as the operational equivalent for long-term benchmarks reflecting highly productive stocks (i.e. high sustainable yields) (Van Will et al. 2009b).

The fishery for odd-numbered year Fraser River pink salmon is the only targeted fishery for pinks with established pre-season reference points and a harvest control rule. Pink runs to the Fraser in even-number years are negligible and there is no directed fishery in those years. Odd-year pink salmon returns to the Fraser River consist of a single CU managed in mixed-stock fisheries along with Fraser sockeye and other non-target salmon species. Routine escapement monitoring of odd-year Fraser pinks that could be used to assess performance of management procedures was decreased in the mid-1990s and then discontinued altogether after 2001 due to budget constraints. Inseason tactics for managing Fraser pinks are determined from weekly estimates of run size using test fishery CPUE relationships to historic escapement numbers. Recent developments in acoustic sampling methods show promise in estimating escapement for the system. Conservation constraints for co-migrating stocks of concern such as Late run and Cultus sockeye, Interior Fraser coho and Interior Fraser steelhead constrain the ability to harvest the available Fraser pink TAC.

Chum

Assessment data used as the basis for stock assessment advice for fisheries management is considered poor. Like other species, the quality of data for chum has degraded in recent generations. The lack of adequate escapement monitoring even in the most productive systems has prevented direct estimates of key parameters (S_{msy}, F_{msy}) used to develop biologically-based reference points.

Formal reference points have yet to be developed for Inner South Coast chum stocks. However, operational Management Escapement Goals (MEG) have been identified for each of the management areas and the major systems within each management area. The MEGs (Ryall et al. 1999) represent the best estimate by local experts and are used as the operational equivalent for long-term benchmarks reflecting highly productive stocks (i.e. high sustainable yields) (Van Will et al. 2009a). In order to ensure sufficient escapement levels, while providing more stable fishing opportunities, a fixed harvest rate strategy was implemented in 2002. The HCR for the Johnstone Strait fishery has a limit stock reference point (one million chum) for the aggregate (nine CUs) and a fixed limit removal rate (20%) above the LRP. Of the overall 20% exploitation rate in Johnstone Strait, a 16% exploitation rate is allocated to the commercial sector, and the remaining 4% is set aside to satisfy FSC and recreational harvest requirements and to provide a precautionary buffer to the commercial exploitation.

Fraser River chum fisheries (two CUs) are harvested in the Fraser River after migrating through coast mixed-stock fisheries primarily in Johnstone Strait. The Fraser fishery is managed to an escapement goal (800,000 chum) using inseason abundance estimates based on the in-river Albion test fishery. The HCR specifies an exploitation rate of <10% at abundance < 800,000 chum for First Nations fisheries. Abundance estimates of 800,000 to 916,000 chum specify an ER of about 10%. At high abundance (>1 Million) a limit ER for the commercial fishery is ≤15% plus low impact First Nations and sports fisheries removals.

Mixed-stock commercial fisheries in northern B.C., targeting more productive sockeye and pink salmon, intercept weak and data deficient chum stocks. Estimates of chum productivity are unavailable. This represents a significant challenge in assessing the trade-offs between maintaining biodiversity of less productive north coast salmon and the socio-economic benefits of harvesting the targeted and more productive stocks. Inseason tactics to avoid chum in commercial fisheries for other species include time/area closures, non-retention and gillnet mesh-size restrictions.

Table 3.1.1. Reference points and management objectives and strategies for sockeye salmon reported in the South Coast and North Coast Integrated Fisheries Management Plans (IFMP) for Pacific salmon.

IFMP stock	Number of CUs	Reference Points (RPs)	Management Objectives and Strategies
Cultus Lake	1	Modelled using population viability analysis. Exploitation Rate (ER) Limit Reference Point (LRP) is the lesser of the value set for co-migrating Late Run Fraser sockeye or ER based on recovery objectives for Cultus sockeye.	Stock of concern[1]. Reduce ER in known areas of significant impact. Limit ER to a maximum of 20-30%.
Sakinaw Lake	1	Interim target escapement based on theoretical minimum viable population analysis to maintain genetic diversity.	Stock of concern. Re-establish a self-sustaining, naturally spawning population.
Nimkish Lake	1	No explicit RPs.	Stock of concern. Time/area closures to minimize the impact of fisheries of co-migrating target CUs.
Fraser Early Stuart	1	Abundance-based 3-zone Total Allowable Mortality (TAM) Rule. Lower and upper stock reference escapement set to meet performance objectives of remaining above the interim benchmark for the CU based on simulated stock trajectories. TAM fixed at 60% at escapements above the upper escapement RP.	All Fraser River Management Groups intensively monitored inseason using test-fisheries and in-river acoustic sampling. Time/area closures apply to reduce ER non-target, co-migrating CUs.
Early Summer Fraser sockeye	11	SR models applied to 7 of 11 CUs. Abundance-based 3-zone TAM Rule. See Early Stuart for details.	See Early Stuart for details.
Fraser Summer	4	SR models applied to all CUs. Abundance-based 3-zone TAM Rule. See Early Stuart for details.	See Early Stuart for details.
Fraser Late	6	SR models applied to 6 of 8 CUs. Abundance-based 3-zone TAM Rule. See Early Stuart for details.	See Early Stuart for details.
Barkley Sound	3	SR models available for 2 CUs. Abundance-based multi-zone Harvest Control Rule (HCR) for aggregate abundance. RPs developed iteratively based on cost:benefit of variable ERs over critical, low, moderate and high abundances. Lower escapement RP established based on lake survey capacity estimates for Sproat and Great Central Lake CUs.	Test-fishery monitoring used to measure abundance inseason. Time/area closures apply to contrain ERs on the co-migrating Henderson Lake CU.
Okanagan River	1	Abundance-based 3-zone HCR. Upper abundance RP based on habitat survey estimates.	Inseason abundance estimated at Wells Dam, Washington State.

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[1] escapement <25% of target or rapid decline in escapement trend

IFMP stock	Number of CUs	Reference Points (RPs)	Management Objectives and Strategies
Rivers and Smith Inlet	4	SR models available for 2 CUs. Current escapements have been well below target since mid-1990s.	Stock of concern. No commercial fisheries and very limited FSC fisheries since mid-1990s to promote recovery from persistent and very low abundance levels.
Skeena River	22	SR models available for Babine wild CU. Abundance-based 3-zone harvest control rule based on the aggregate abundance measured inseason in the Skeena (Tyee) test fishery. Habitat-based lake-capacity estimates available to estimate benchmarks for some CUs.	Stock of concern. Reference points are designed to rebuild individual wild stocks of concern co-migrating with enhanced Babine Lake sockeye.
Nass River	4	Aggregate escapement goal derived from SR models for individual stock components. Fish-wheel monitoring of abundance in the Nass system and a mark-recapture program on some species are used to measure inseason abundance.	Stock of concern. Surplus abundance is harvested in accordance with PST and the Nisga'a Treaty obligation. ER set to rebuild the Fred Wright Lake CU (stock of concern). Time/Area restrictions and non-retention of non-target stocks/species.

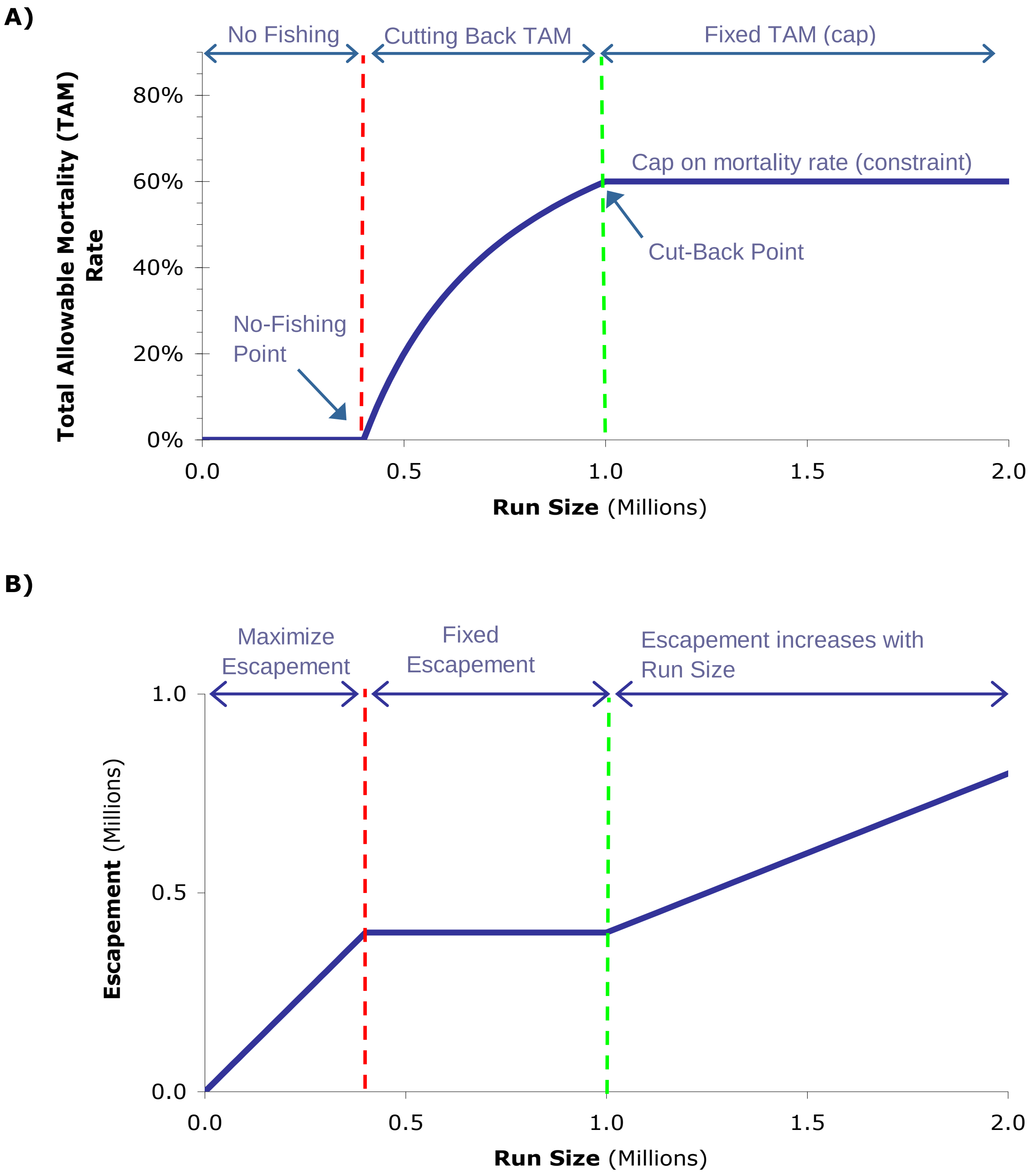
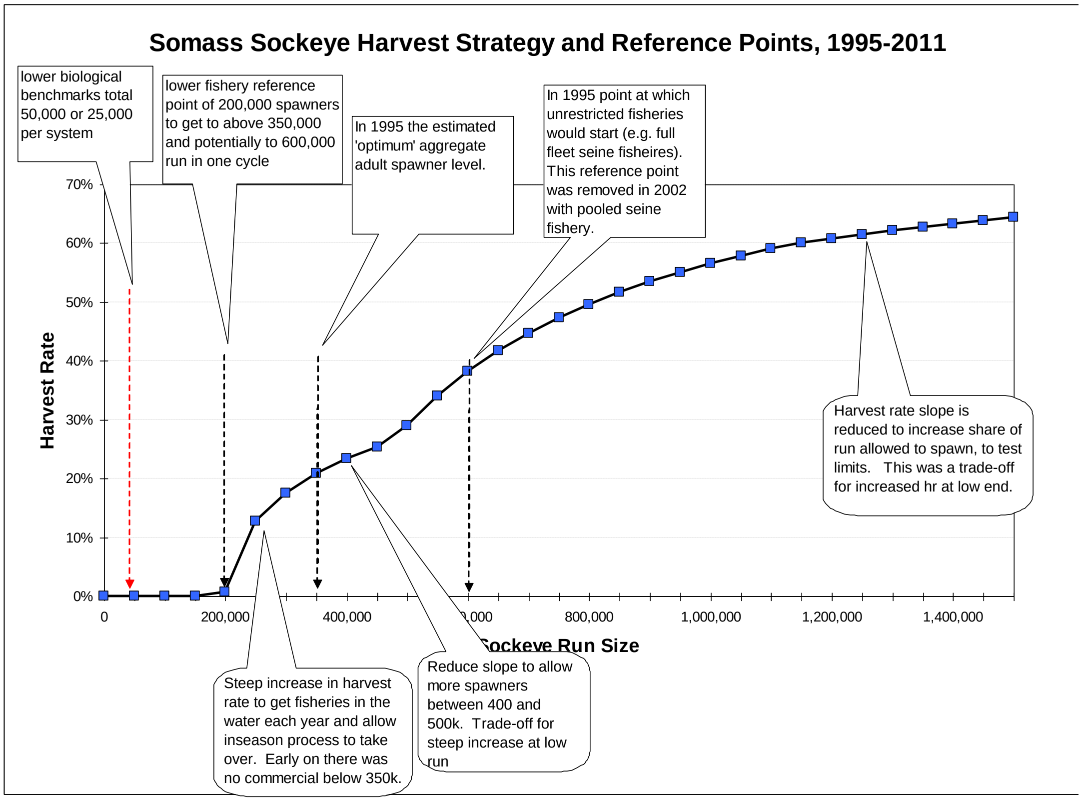


Figure 3.1.1. Schematic of an example of a Total Allowable Mortality (TAM) rule showing responses of the total mortality rate (upper panel A) and the escapement (lower panel B) on the vertical axes relative to increasing run sizes on the horizontal axes associated with a fixed escapement management strategy defined by a minimum escapement level (red dashed vertical line) and a maximum allowable mortality rate (shown as the stock level at which the maximum rate occurs, green dashed vertical line). The example shown is for Fraser River sockeye.



Somass Sockeye Harvest Strategy and Reference Points, 1995-2011

lower biological benchmarks total 50,000 or 25,000 per system

lower fishery reference point of 200,000 spawners to get to above 350,000 and potentially to 600,000 run in one cycle

In 1995 the estimated 'optimum' aggregate adult spawner level.

In 1995 point at which unrestricted fisheries would start (e.g. full fleet seine fisheires). This reference point was removed in 2002 with pooled seine fishery.

Harvest rate slope is reduced to increase share of run allowed to spawn, to test limits. This was a trade-off for increased hr at low end.

Steep increase in harvest rate to get fisheries in the water each year and allow inseason process to take over. Early on there was no commercial below 350k.

Reduce slope to allow more spawners between 400 and 500k. Trade-off for steep increase at low run

Figure 3.1.2. Schematic of the for the Barkley Sound (Somass River) harvest control rule showing the relationship between the harvest rate (vertical axis, as a percentage) and the run size (horizontal axis, as number of fish). The red dashed vertical line is the lower benchmark of 50,000 fish and the three vertical black lines of increasing width represent sequentially differing reference points of run size.

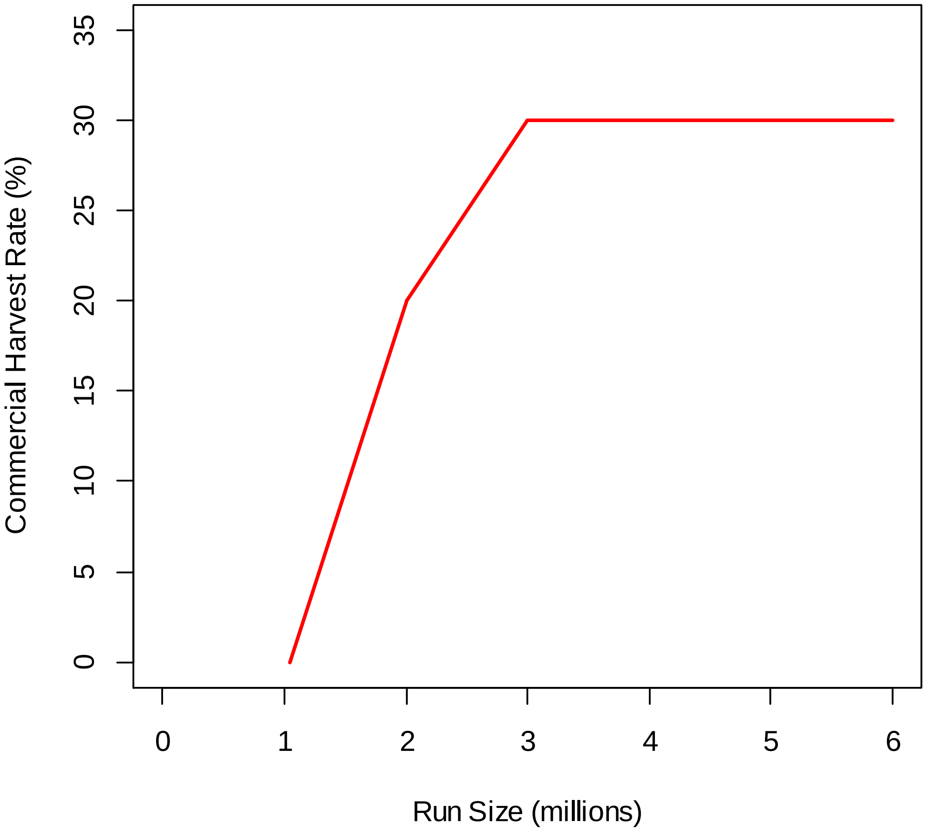


Figure 3.1.3. Schematic of the Skeena River sockeye harvest control rule for the mixed-stock commercial fishery showing relationship between the commercial harvest rate (vertical axis, expressed as a percentage) and the run size of fish (horizontal axis, expressed in millions of fish).

3.2 Atlantic salmon

Most of the information presented in this section is taken from the review of conservation definition for Atlantic salmon by Potter (2001) and Chaput (2006).

Reference points for Atlantic salmon have been informally used to advise fisheries management since the 1970s. After the Supreme Court of Canada (Sparrow) Decision of 1990, conservation for Atlantic salmon in Canada was formally. Management then as now was formulated on a fixed escapement management strategy with abundance above the conservation requirement considered surplus and therefore exploitable (CAFSAC 1991a, 1991b; Chaput 1997). This approach was put in place before the PA concept was developed. The use of a conservation objective defined as a limit reference point and the fixed escapement strategy has been adopted by national governments in Europe and by the international organisation that manages the exploitation of Atlantic salmon in the high seas fisheries (North Atlantic Salmon Conservation Organisation; NASCO). It is also considered by the International Council for the Exploration of the Sea (ICES) for a group of species that are short-lived and for which the majority of the spawning stock in any year is comprised of new recruitment rather than growth of previously mature animals.

The following section provides details of the history of reference points and management advice for Atlantic salmon in Canada, Europe and in the international forum where high seas fisheries are managed.

3.2.1 Canada

Reference points for Atlantic salmon have been informally used to advise fisheries management since the 1970s. The basis of the definition of these reference points is from the work of Elson (1957, 1975) that considered the levels of egg depositions that would result in a maximum production of smolts or earlier juvenile stages. In 1977, the Canadian Atlantic Fisheries Scientific Advisory Committee (CAFSAC) Anadromous Subcommittee referred to the closure of commercial salmon fisheries and restriction in angling fisheries as responses to the spawner abundances in two of the three major New Brunswick rivers (Saint John and Miramichi) declining to less than 25 percent of the estimated optimum spawning escapement (Anon. 1977; p. 1). The optimum spawning escapement was considered to be the spawner abundance that provided maximum stock recruitment at the smolt stage (Anon. 1977; p. 4).

In 1978, an Atlantic Salmon Task Force was established to develop a resource management and development plan to maximize economic and social benefits of the salmon resource (Anon. 1978). Egg deposition rates to achieve smolt production potentials in the Maritimes, Québec, and Newfoundland were defined. For the Maritimes, an egg deposition rate of 240 eggs per 100 m^2, (168 eggs per 100 m^2 for two areas with poorer habitat quality), was considered sufficient to achieve potential smolt production levels of 1 to 3 smolts per 100 m^2 , these levels corresponding to production from poor to good habitat. For rivers in Québec, the smolt production potential was assumed to be 1.5 smolts per 100 m^2 because it was more northern than the Maritimes and generally had steeper gradients but an egg requirement of 240 eggs per 100 m^2 was chosen. For Newfoundland, smolt production potential was considered to vary between 2 and 3.5 smolts per 100 m^2 with corresponding egg deposition rates of 150 to 225 eggs per 100 m^2.

Based on a juvenile life history model and derived egg to smolt curves based on published or assumed inter-stage survival rates, Symons (1979) estimated that maximum production levels of 5 smolts per 100 m^2 for two year old smolts, 2 smolts per 100 m^2 for 3 year old smolts and 1 per 100 m^2 for 4 year old smolts would be achieved at egg deposition rates of 220, 165 to 220, and 80 per 100 m^2, respectively.

In October 1980, a workshop was convened to address the assessment capabilities for Atlantic salmon and what research was required to improve the assessments (Anon. 1981). The workshop attendees concluded that the existing database was insufficient for providing detailed and accurate advice on management measures to optimize production on a river-by-river basis. It was concluded that: “achieving potential egg depositions of 200 per 100 sq. metres of salmon rearing habitat or, where possible, at spawning levels associated historically with high levels of recruitment is adequate to conserve stocks and to retain future options” (Anon. 1981).

Following on the 1978-1980 task force (Anon. 1978, 1981), a discussion paper was published outlining the federal government policy and the course for salmon management in the future (DFO 1982). The first priority was to satisfy resource conservation requirements to achieve optimum sustainable yield which was defined as “the annual harvest in weight which can be taken from the stock year after year while maintaining stock size and allowing the greatest socio-economic benefit” (DFO 1982). The discussion paper also described the conservation objective.

> “Spawning requirements to achieve optimum sustainable yield to the fisheries and, insofar as possible, fullest production of the largest fish within the capabilities of the different rivers and their stocks, are assigned priority over allocations to the various user groups. The ultimate goal is to define spawning requirements by river system and tributary and according to individual stock and stock component. In preparation of annual fishing plans, utmost consideration will be given to resource conservation requirements since reduced spawning escapements would drastically affect future production and therefore stability in the fisheries.” (DFO 1982).

Through the early 1980s, there was a substantial amount of activity associated with defining spawning requirements. At that time, the reference levels were described as target spawning requirements. In 1983, target spawning requirements were established for 16 individual rivers as well as for the combined Salmon Fishing Area 13 in southwest Newfoundland based on 240 eggs per 100 m^2 of juvenile rearing area (Porter and Chadwick 1983). Target spawning requirements were also established for the Miramichi River (Randall 1985), the Restigouche River (Randall 1984), the Nepisiguit River and the Saint John River (Marshall and Penney 1983), all using a rate of 240 eggs per 100 m^2. In 1984, target spawning requirements were established for the LaHave River, Margaree River, St. Mary’s River, and the Stewiacke River, also based on the default egg deposition rate. For the Stewiacke River, habitat was weighted using a gradient variable which modified potential parr production (Amiro and McNeill 1986).

In 1985, the members of the 1978-1980 task group produced a table summarizing spawning requirements by salmon and grilse for 25 zones of Atlantic Canada (excluding Québec) (Anon. 1985). In 1986, a spawning requirement was established for Conne River (Newfoundland) based on an assumed recruit to spawner ratio of 4.5 to 1. The spawner requirement was calculated from the estimated stock size for 1981 to 1985 based on assumed exploitation rates in the angling and commercial fisheries.

Formal definition of conservation for Atlantic salmon

In 1990, the Supreme Court of Canada rendered a decision in the case of Regina vs Sparrow which recognized that aboriginal peoples food fisheries have first right of access to natural renewable harvestable resources, once conservation was assured. However, the court did not define conservation nor provide any guidance on how to determine when conservation needs were met.

In 1991, CAFSAC borrowed a definition from the United Nations Environment Program which defined conservation as:

> “That aspect of renewable resource management which ensures that utilization is sustainable and which safeguards ecological processes and genetic diversity for the maintenance of the resource concerned. Conservation ensures that the fullest sustainable advantage is derived from the resource base and that facilities are so located and conducted that the resource base is maintained.” (CAFSAC 1991a).

The subcommittee of CAFSAC then considered the operational translation of conservation for Atlantic salmon and it is in this regard that confusion arises as to whether the conservation level would be a limit or a target. They state:

> “CAFSAC then considered translating the definition as the spawning escapement below which CAFSAC would strongly advise that no fishing should occur. However, because this level cannot be defined with absolute precision, allowing the stock complex to fall to such a low abundance was regarded as involving unnecessary risks of causing irreversible damage to a resource’s ability to recover in a reasonable period of time.” (CAFSAC 1991a).

The subcommittee of CAFSAC then provided a reference level which in the current environment would be synonymous with a precautionary reference level.

> “CAFSAC, therefore, suggests as an operational translation of conservation the current target egg deposition rate of 2.4 eggs/m^2 of fluvial rearing habitat, and in addition for insular Newfoundland, 368 eggs/hectare of lacustrine habitat.” (CAFSAC 1991a).
>
> “The 2.4 eggs/m^2 reference level is assumed to provide a modest margin of safety for some instream adult losses between the time salmon enter into a river and subsequent spawning, as well as for disproportionate adult exploitation and unequal rate of recruitment of the multiple stocks comprising a river stock complex. CAFSAC considers that the further the spawning escapement is below the biological reference level, and the longer this situation occurs even at rates only slightly below that level, the greater the possibility exists of incurring the following risks, some of which may cause irreversible damage to the stock:
>
> - accentuation of annual fluctuations in run size and reduction in the long-term capability of the stock to sustain native food fisheries, recreational fisheries, or commercial fisheries;
> - increased susceptibility to extinction from genetic, demographic, or environmental catastrophes and consequent decreases in productivity;

> - permanent changes in demographic characteristics of the spawning population;
> - replacement in the ecosystem by other competing fish species of potentially less social and economic value.” (CAFSAC 1991a).

Subsequently, conservation requirements were confirmed or defined for 34 rivers in Atlantic Canada (CAFSAC 1991b). An additional (to fluvial habitat area requirements of 240 eggs per 100 m²) requirement of 368 eggs per hectare of lacustrine habitat or 105 eggs per hectare of lacustrine habitat for rivers of the northern peninsula of insular Newfoundland and Labrador was defined based on smolt production (O’Connell and Dempson 1995). More recently, an interim conservation requirement of 190 eggs per 100 m² of fluvial habitat was proposed for salmon rivers of Labrador, this value being derived from an egg to smolt recruitment relationship adjusted to eggs in the recruitment based on an assumed sea survival rate (Reddin et al. 2006).

An alternative reference point has been established for the salmon rivers of the province of Québec. The revisions consisted of two components (Caron et al. 1999):

- egg to egg stock and recruitment data were reconstructed for six rivers, and
- units of production in terms of m^2 of freshwater habitat were defined based on a weighting of habitat characterized by habitat type, substrate and width of stream, and degree days and relative juvenile densities within each of the habitat characteristics.

The egg deposition rate was defined from a stock and recruitment analysis based on the Ricker model with the optimum spawning escapement (S_{opt}) defined as the level of egg deposition which produced the maximum gain in eggs (Caron et al. 1999; Prévost et al. 2001). In terms of the revised habitat characterization, the 75th percentile of the distribution of S_{opt} was chosen as the reference level, equal to 1.67 eggs per UP (unit of production). This value was transported to 110 salmon rivers of Québec (Caron et al. 1999).

All the reference point definitions to date for Atlantic salmon, with the exception of rivers of Québec, are based on spawning requirements that will produce maximum smolt production (Table 3.2.1). This emphasizes the importance of the freshwater phase of the life cycle, in which density-dependent population regulation is most important (Elliott 2001; Jonsson et al. 1998; Gibson 2006). In contrast, density-dependent survival at sea of Atlantic salmon has yet to be demonstrated (Hansen and Quinn 1998; Gibson 2006).

More recently, the Wild Atlantic Salmon Conservation Policy (WASCP) identified lower and upper benchmarks against which to assess stocks status (DFO 2009b). The translation of the presently used conservation limit for Atlantic salmon within this benchmark framework has yet to be done and will need to be considered in the context of other departmental policies including the Precautionary Approach.

3.2.2 USA

For the few rivers along the eastern seaboard of the New England states, the conservation requirement has been defined based on the default value developed for eastern Canada; 240 eggs per 100 m² of fluvial habitat (Potter 2001) (Table 3.2.1).

3.2.3 France

Reference points for Atlantic salmon in France are based on an estimate of the maximum gain of eggs (termed S_{opt}) as derived from an egg to smolt stock and recruitment relationship (Ricker) from one river with eggs per recruit estimated using an assumed (measured from one stock) sea survival rate and adult characteristics (Prévost and Porcher 1996; Prévost et al. 2001). The reference point is in terms of eggs per habitat area, 475 eggs per 100 m² of riffle/rapid habitat (Table 3.2.1). As in Canada, total allowable catches by river are estimated based on a fixed escapement strategy with expected eggs in returns surplus to S_{opt} available for exploitation. For France, the average exploitable surplus was estimated at 350 eggs per 100 m², or an average exploitation rate of about 44% (Porcher and Prévost 1996).

3.2.4 UK (England & Wales)

A limit reference point for managing Atlantic salmon fisheries in UK (England & Wales) was developed based on an egg to smolt stock and recruitment relationship from the River Bush (UK Northern Ireland) and transported to rivers based on characterization of carrying capacities of different habitat types (Wyatt and Barnard 1997). Two relationships are required to derive the conservation limits (CLs): (i) an egg to smolt stock-recruitment curve and (ii) a replacement line which converts the smolts emigrating from freshwater to surviving adults (or their egg equivalents). The model used to derive a stock-recruitment curve for each river assumes that juvenile production is at a 'pristine' level for that river type. Similarly, marine survival rates for most river stocks were assumed to be equivalent to the rates estimated on UK monitored rivers (such as the North Esk in Scotland) in the 1960s and 1970s. Default survival values recommended for this purpose were 25% for 1SW salmon and 15% for MSW fish.

The CLs represent the minimum spawning stock levels below which stocks should not be allowed to fall. A reduction in spawner numbers below the CL would likely result in significant reductions in the number of juvenile fish produced in the next generation. In addition to the CL, an over-arching management objective has been established that a river's stock should be meeting or exceeding its CL in at least four years out of five (i.e. >80% of the time) (CEFAS and Environment Agency 2009). A management target (MT) is set for each river, representing a spawning stock level for managers to aim at in order to meet this objective. The value of the MT has been estimated using the standard deviation (SD) of egg deposition estimates for the last 10 years, where: MT = CL + 0.842*SD. The constant 0.842 is taken from probability tables for the standard normal distribution, such that the CL forms the 20th percentile of a distribution, the average (or 50 percentile) of which equates to the MT.

CLs and MTs have been set for 64 principal salmon rivers.

3.2.5 Ireland

In Ireland the maximum sustainable yield (MSY) is used to establish the conservation limit for individual stocks (Anon. 2011). This is the stock size that maximizes the long-term average surplus of fish. Egg to egg stock-recruit (SR) data from 15 European rivers are used in a Bayesian hierarchical analysis, with wetted area and latitude as covariates, to transport reference points to Irish rivers with limited or no SR data available (Anon. 2011; Ó Maoiléidigh et al. 2004). Based on the transported SR data, rivers are assigned a conservation limit (CL) (i.e. number of spawners). Harvest is only recommended on rivers that are expected to exceed their CL. Forecasting returns is based on the previous five years of returns which are determined by adult counts, angling statistics and commercial harvests. The harvest in numbers of fish is calculated as the catch option which provides a 75% chance that the CL will be met.

If there is a fishery on a mixed stock then harvest is only recommended if all stocks in the mixed fishery are expected to exceed CL. In the mixed stock fishery situation, the harvest is determined based on the expected returns and conditional on a 75% probability of simultaneously achieving the CL in the stocks exploited in the mixed stock fishery. In rivers with a high proportion of MSW stocks, the CL is calculated separately for 1SW and MSW stocks separately.

3.2.6 Norway

Norway uses egg density (eggs per m^2) as their reference point (Diserud et al. 2008; Hindar et al. 2008). Similar to North America, the egg requirement can vary between watersheds. Stock-recruit curves (egg to juvenile) were modelled for nine Norwegian rivers. The results of that modelling exercise determined that the egg density that produced maximum recruits was the most robust parameter. It was also determined that Norwegian rivers fall into four general categories of productivity and consequently spawning requirements: less than 1.5 eggs/m^2, 1.5 to 3 eggs/m^2, 3 to 5 eggs/m^2 and more than 5 eggs/m^2. Assigning rivers without SR data to one of the four spawning densities was done by expert opinion. Once an egg density was assigned to a river the spawning requirement was based on wetted area, extrapolated fecundity values, and average weight of females. Estimating the number of females in a river is based on catch statistics and proportion female in the population.

3.2.7 International Council for the Exploration of the Sea (ICES)

The definition of safe biological limits originally developed by ICES with respect to Atlantic salmon and adopted by the North Atlantic Salmon Conservation Organisation (NASCO), is the level of stock that will achieve long-term maximum sustainable yield (MSY) to fisheries (S_{msy}) (ICES 1993). Accordingly, the spawning stock at the MSY point on an adult-to-adult Atlantic salmon SR relationship was adopted as the conservation limit (CL). In 1993, the ICES Study Group on North American salmon fisheries provided a composite estimate of 2SW spawner requirements for rivers of North America for the provision of management advice for the West Greenland salmon fishery. The study group indicated that “optimal” numbers of smolts or returns would be ensured if there was an adequate supply of eggs to “saturate the fluvial habitat” (ICES 1993). Since the West Greenland fishery exploited primarily non-maturing 1SW salmon destined to return to homewaters to spawn as 2SW salmon, a composite spawner requirement for eastern North America, in terms of 2SW fish, was obtained by summing the 2SW requirement from the 37 salmon fishing areas and zones (ICES 1993).

There is a contradiction in the reference point definition used by ICES and the reference point definitions defined in Canada. Whereas ICES endeavours to define the reference point as the point of maximum sustainable yield (S_{msy} or S_{opt}), the reference points in Canada (except for Québec) are for maximizing smolt production (or maximum adult recruitment).

Recently, ICES has moved to management advice based on MSY. Under this paradigm, ICES has identified a group of species for which only one reference point value is defined, termed $B_{escapement}$. This point is considered for “short-lived” species and the use of a single reference value is justified as follows:

> The future size of a short-lived fish stock is sensitive to recruitment because there are only a few age groups in the natural population. Incoming recruitment is often therefore the main component of the fishable stock. In addition, care must be given to ensure a sufficient spawning-stock size as the future of the stock is highly dependent on annual recruitment. For short-lived species, estimates or predictions of incoming recruitment are typically very imprecise, as are any catch forecasts. For short-lived stocks, the ICES MSY approach is aimed at achieving

> a target escapement ($B_{msy\text{-}escapement}$, the amount of biomass left to spawn), which is more robust against low SSB and recruitment failure than a fishing mortality approach. The catch corresponds to the stock biomass in excess of the target escapement. No catch should be allowed unless this escapement can be achieved. (ICES 2010).

In this way, the ICES approach to $B_{escapement}$ is identical to the management strategy (fixed escapement) used to date and the defined reference points in Canada, Europe and for international management.

3.2.8 Interpretation of reference points (limit or target) and their use in management

All the reference points for Atlantic salmon are interpreted as limit reference points and in some cases fisheries management has responded by restricting fishing on certain life stages of salmon (for Quebec, mandatory catch and release of multi-sea-winter salmon when expected escapements are below spawner requirements) to closures of all fisheries (Chaput 1997; Crozier et al. 2003).

The management of Atlantic salmon in Canada, Europe and internationally is based on a fixed escapement strategy, with all fish in excess of this requirement considered surplus and available for harvest (most similar to pattern in Figure 3.1.2) (Crozier et al. 2003).

Use of reference points in management of Atlantic salmon homewater fisheries in Canada

In 1991, CAFSAC (1991a) formally defined conservation for Atlantic salmon as a level of egg deposition in individual rivers and in a subsequent advisory document provided preliminary estimates of surplus to conservation requirements for a number of rivers in eastern Canada (CAFSAC 1991b). These two documents established the reference points for subsequent fisheries management based on a fixed escapement policy with all fish in excess of this requirement considered surplus and available for harvest.

The management of homewater fisheries in eastern Canada now occurs on a river specific basis. In the Maritime provinces, large areas are closed to exploitation by all users because of low abundance, other rivers are open to modest Aboriginal fisheries and catch and release fishing, while most of the rivers of the Gulf Region are open to retention of small salmon in recreational fisheries, small and large salmon harvests in Aboriginal fisheries. In the province of Québec, there is a broad range of management in place, from closures to all fisheries of small rivers with returns of less than 100 salmon, retention of small salmon only, to retention of small and large salmon supported by inseason assessments. In Newfoundland and Labrador, river-specific management plans have been developed with exploitation based on the size and status of rivers relative to achieving conservation.

Management of high seas mixed-stock fisheries

Canada is a member of the North Atlantic Salmon Conservation Organisation (NASCO) whose main objective is to contribute to the conservation, restoration, enhancement and management of Atlantic salmon. Through the NASCO Convention, parties agreed to cooperate in the management of fisheries which exploit Atlantic salmon originating in rivers of other parties, the two principal fisheries being in the West Greenland and Faeroes Islands (Potter 2001). NASCO fulfills its responsibility for management of distant water fisheries through management measures derived from catch advice commissioned from ICES.

ICES has advised that the fisheries should be managed according to a fixed escapement policy with the objective of protecting spawning escapement in the several hundred salmon stocks subject to the mixed stock fisheries (Crozier et al. 2004). Since the adoption of the Convention for the Conservation of Salmon in the North Atlantic Ocean, the distant water fisheries at West Greenland and Faroes Islands have been regulated by internationally negotiated quotas, which have been greatly reduced and in some recent years have not been fished, due to locally negotiated arrangements with interested parties.

The definition of safe biological limits originally developed by ICES with respect to Atlantic salmon and adopted by NASCO, is the level of stock that will achieve long-term maximum sustainable yield (MSY) to fisheries (S_{msy} or S_{opt}) (ICES 1993). Accordingly, the spawning stock at the MSY point on an adult-to-adult Atlantic salmon SR relationship was adopted as the conservation limit (CL). In 1993, the ICES Study Group on North American salmon fisheries provided a composite estimate of 2SW spawner requirements for rivers of North America for the provision of management advice for the West Greenland salmon fishery.

The mixed stock nature of the North Atlantic salmon fishery poses important challenges. The aim of management is to regulate catches while achieving overall spawning escapement defined by conservation limits in the large number of generally small North American and European rivers. These differ in biological characteristics (especially size and fecundity), in status, and in productivity (Prévost et al. 2003). Low productivity stocks are particularly vulnerable in mixed-stock fishery situations (Chaput 2004). Acknowledging that conservation can only be achieved when production is occurring in all the available habitat (or by all the spawning components in the river), the formulation of fisheries management advice needs to take account of the complexity of the mixed-stock fishery being managed and the number of distinct production areas which must be seeded. As the number of these areas increases, the required number of fish that should be released from the fisheries must also increase (Chaput 2004). These considerations clearly become critical when considering mixed-stock fisheries that exploit stocks that are already well below conservation limit and especially if those stocks are of low productivity.

Table 3.2.1. Summary of conservation objectives for Atlantic salmon by region in eastern Canada.

Province / region	**Objective**	**Reference Point**	**Reference**
Canada			
Maritime provinces	Maximum freshwater production	240 eggs per 100 m^2 of fluvial habitat	CAFSAC 1991a, 1991b O'Connell et al. 1997
Insular Newfoundland	Maximum freshwater production	240 eggs per 100 m^2 fluvial habitat + 368 eggs per ha of lacustrine habitat or 150 eggs per ha of lacustrine habitat for the northern peninsula	CAFSAC 1991a, 1991b O'Connell and Dempson 1995
Labrador	50% of adult equilibrium point	190 eggs per 100 m^2 of fluvial habitat	Reddin et al. 2006
Québec	Maximum gain of eggs (S_{msy})	167 eggs per 100 m^2 of units of production	Caron et al. 1999 Prévost et al. 2001
International			
USA	Maximum freshwater production	240 eggs per 100 m^2 of fluvial habitat	Potter 2001
France	Maximum gain of eggs (S_{msy})	475 eggs per 100 m^2 of riffle/rapid fluvial habitat	Prévost and Porcher 1996
UK (England & Wales)	Maximum gain of eggs (S_{msy})	Varies by river based on habitat features	Wyatt and Barnard 1997
Ireland	Maximum gain of eggs (S_{msy})	Expressed as eggs per habitat area, varies with latitude of river	Ó Maoiléidigh et al. 2004
Norway	Maximum gain of eggs (S_{msy})	Expressed as eggs per habitat area for three categories of river productivity	Hindar et al. 2008; Diserud et al. 2008
ICES	Maximum gain (S_{msy})	Varies by region	ICES 1993

3.3 Other species

To date, no proposals for reference points for sea lamprey and eulachon have been developed.

3.3.1 American Eel

The American eel is a catadromous fish and eels in eastern North America are a panmictic population spawning in the Sargasso Sea (DFO 2010). The American eel can be long-lived, up to 40 years or more, and grow to lengths exceeding 110 cm and weights exceeding 4 kg. Female silver eels are generally larger and older than male eels. It is a long-lived species maturing at ages ranging from six to over 20 years and with males generally maturing at younger ages and smaller sizes than female eels. The American eel fisheries in eastern Canada target multiple life stages from elver stages which migrate from the spawning area to the coast and rivers of North America, through immature yellow eel in estuaries and coastal areas, to mature silver eels in rivers, estuaries and coastal areas as they migrate to spawn in the Sargasso Sea (DFO 2010). Chaput and Cairns (2011) proposed that mortality reference points could be determined for American eel using a spawning mass per recruit model (SPR) (Mace and Sissenwine 1993). The SPR model uses life history parameters to calculate the ratio of spawner potential produced under a scenario of anthropogenic mortality relative to a scenario where anthropogenic mortality is zero (%SPR) (Chaput and Cairns 2011). Recruitment data is not required and life history traits can either be measured or estimated. Accepting the ICES (2001) proposal that limit and target reference points should be developed for all fisheries, Chaput and Cairns (2011) recommended that the fishing mortality (F) that resulted in a 30% SPR (i.e. 30% of the spawner biomass had there been no fishing) be the limit reference point and that a 50% SPR be used as the target reference point.

The long-term goal expressed in the Canada Eel Management Plan is to rebuild overall abundance of American eel in Canada to its level in the mid-1980s. The immediate and short term goal is to reduce eel mortality from all sources by 50% relative to the 1997 to 2002 average (DFO 2010). The actions set out in the management plan are focused on reducing mortality due to the two known and most significant sources of mortality (fishing, dams) (DFO 2010).

4. CANDIDATE LIST OF REFERENCE POINTS AND BENCHMARKS

Candidate fishery reference points and WSP benchmarks in the case of Pacific salmon are similar to the general list of reference points proposed and discussed in a number of other fora and publications (Mace 1994; Myers et al. 1994; Rosenberg et al. 1994; Caddy and Mahon 1995; ICES 1997; Holt et al. 2009; Potter 2001). Reference points for spawning abundance and for removal rates can be derived based on the dynamics of the whole life cycle of anadromous species. When the focus is on the dynamics that occur in the freshwater life stage of anadromous species, only candidate reference points for abundance have been proposed.

As discussed in section 2, the specifics of the life history of anadromous salmonids suggest that the units for abundance-based reference points are best expressed in terms of number of fish rather than biomass. All units of measurement used to derive reference points of Pacific salmon are based on numbers of fish. Numbers of eggs are used in Atlantic salmon assessments to account for variation in fecundity.

The choice of management strategy influences the types of reference points which are required, some of those which have been applied to Pacific salmon fisheries management are illustrated in Figures 3.1.1 to 3.1.3. In the development of harvest strategies for Pacific salmon, simulations using harvest control rules (HCR) with a fixed exploitation rate over a wide range of stock size and a contingency to reduce the exploitation rate (ER) to near-zero at low abundances (Fig. 3.1.1) out performs fixed-escapement strategies. This form of HCR promotes stock rebuilding and avoids undesirable conservation risk. In general, fixed escapement strategies are not recommended except in single-stock fisheries and where habitat capacity is well determined. There is a need to reconcile reference points which have been used historically in a fixed escapement management strategy for anadromous salmonids to the reference points required in the PA framework. It is also not clear whether the ICES (2010) definition of $B_{escapement}$, proposed for short-lived species and which is interpreted to be used in fixed escapement management strategies can be translated to the PA.

In DFO's Salmon Policy documents (DFO 2005, 2009b), the Red, Amber, and Green biological status zones for conservation units (CUs) represent a continuum from poor to healthy status. In DFO's WSP, the "lower benchmark between Amber and Red will be established at a level of abundance high enough to ensure there is a substantial buffer between it and any level of abundance that could lead to a CU being considered at risk of extirpation by COSEWIC". The WSP upper benchmark, which delineates the Amber to Green status zone, "will be established to identify whether harvests are greater or less than the level expected to provide, on an average annual basis, the maximum annual catch for a CU, given existing environmental conditions." (DFO 2005). Biological status for Pacific salmon is integrated across a number of metrics including trends in abundance, abundance, fishing mortality, and distribution classes of indicators.

Although conceptually, WSP lower and upper abundance benchmarks and fishing mortality benchmarks somewhat align to DFO's "A fishery decision-making framework incorporating the Precautionary Approach" (DFO 2009a) limit reference point (LRP), upper stock reference point (URP) and fishery removal rate, they are not identical. First, the abundance and fishing mortality reference points in WSP do not combine the resultant integrated statuses from the full suite of possible metrics used (depending on data availability). It is the integrated statuses in the WSP that inform the overall biological status of a CU, not the individual metrics (e.g., abundance) in isolation. Second, development of fishery reference points require the integration of biological, habitat, and ecosystem statuses with socio-economic considerations, for fishing plans (see Strategy 4, WSP). Further, fisheries are frequently prosecuted in a mixed-stock environment, so the same fishery reference point is frequently used to manage an aggregated group of CUs. Therefore, the reference points presented in Table 4.2 and Table 4.3 are the inputs for developing fisheries reference points. Some of these also need to consider socio-economic and risk tolerance values as described in DFO's Fisheries Decision Making Framework Incorporating the Precautionary Approach.

It should be noted that assessment tools for determining benchmarks and fishery reference points are a function of the data quality. For Pacific salmon, and the 400+ CUs in the Pacific Region, there is only a small proportion with adequate information to employ all possible metrics. Furthermore, there has been limited experience in formalizing rules for determining reference points that incorporate metrics of trends in abundance, distribution within a CU or proposed indicators of trends in productivity in the implementation of the WSP.

A Target Reference Point (TRP) is a required element under the United Nations Fishery Agreement and the and in the FAO guidance on the application of the PA. DFO (2009a) states that the Upper Stock Reference can be a target reference point and determined by productivity objectives for the stock, broader biological considerations and social and economic objectives for the fishery. With the exception of Atlantic salmon populations in the UK, management targets have not been set for Atlantic salmon or Pacific salmon stocks and are not discussed further in this document.

4.1 Removal rate

The UN Agreement of Straddling Fish Stocks and Highly Migratory Fish Stocks (FAO 1995) recommends that F_{msy} (fishing mortality at maximum sustainable yield) be used as a LRP. DFO's Fisheries Decision Making Framework incorporating the Precautionary Approach (2009a) recommends that fishing mortalities remain below F_{msy}.

The fishing mortality reference point recommended by Holt et al. (2009) was F_{msy}. This benchmark was associated with a <25% probability of extinction over 100 years for populations with equilibrium abundances greater than 30,000 and a >75% probability of recovery to S_{msy} within three generations. This benchmark (F_{msy}) was also more robust to variability in stock productivity than other benchmarks explored. Alternative lower benchmarks include the slope at the origin of the stock-recruitment relationship (F_{max}), the median log-transformed recruits-per-spawner (F_{med}), and the slope at the origin of the smolt-recruitment relationship (Table 4.1). Without additional information to constrain the latter three alternative lower benchmarks, such as independent estimates of habitat capacity to act as Bayesian priors, their use as benchmarks may result in unsustainable rates of fishing compared to F_{msy}.

4.2 Limit abundance reference point

Limit reference points are defined to protect the resource from serious and irreversible harm. There are a variety of possible lower reference points (Table 4.2; Fig. 4.1). In simulation work conducted by Holt (2009) and Holt and Bradford (2011), performance of a suite of lower benchmarks was evaluated based on Pacific salmon life history dynamics (i.e. semelparity). In particular, the risk of extirpation and probability of recovery was evaluated for lower benchmarks over a variety of assumptions including patterns of intrinsic productivity, underlying modeled population dynamics, etc. The two benchmarks that were the most robust and indistinguishable in terms of extirpation risk and recovery potential for Pacific salmon type population dynamics were $S_{0.5Rmax}$ and S_{gen} (Table 4.2; Holt and Bradford 2011). Specifically, when equilibrium abundances were greater than 15,000 spawners, the probability of extirpation was very low (<5%) and the probability of recovery within three generations was high (>75%) (Holt and Bradford 2011). Simulations to assess extirpation risk imposed a harvest control rule so that the harvest rate was reduced to 10% when observed abundance fell below the benchmark. Simulations to evaluate the probability of recovery were done using a constant harvest rate of 10% from an initial spawner abundance equivalent to the lower benchmark.

For anadromous salmonid species for which density-dependent population regulation is manifested in the freshwater environment, abundance reference points derived from freshwater dynamic models could be considered more robust for defining limit reference points than those based on full life-cycle models. The reason for this is that survival and recruitment in the marine environment is considered to be density-independent and therefore resulting recruitment relative to spawning stock is determined by the output from freshwater. Provided the productivity in freshwater is stationary, then limit reference points defined on the basis of maintaining freshwater production levels would be robust to variations in marine productivity, calling for more frequent and larger reductions in exploitation when marine survival is poor with the objective of maintaining freshwater production to take advantage of better marine productivity periods. A number of candidate limit reference points can be derived from freshwater dynamic models, including $S_{0.5Rmax}$ (Table 4.2). The application of non-stationary models that account for low-frequency changes in productivity are used more frequently to characterize the population dynamics of salmon. There are no examples to date where limit reference points have been adjusted over time to account for non-stationary productivity.

Other candidate limit reference points which consider the distribution and density of spawners within the river are intuitively attractive as they account for the spatial complexity of the spawning habitat and the spatial population structuring which has evolved in a number of Pacific salmon species. Some of these metrics include minimum density of spawners per area (Table 4.2), the number of spawning groups with abundances greater than a threshold value (e.g. >100 spawners) or the number of spawning groups that contain some percentage (e.g. 80%) of the total abundance when ranked from most to least (Holt et al. 2009). Another possible limit reference point would relate spawner abundance to the spatial distribution (presence/absence) of juveniles, the spawner objective being defined as an abundance which results in the presence of juveniles in a given proportion (e.g. 90%) of surveyed sites within the accessible watershed. These latter reference levels, or benchmarks for Pacific salmon, have not received as much consideration as those based on spawners and recruits.

Reference points can be derived directly for semelparous species from stock and recruitment analyses. For iteroparous species like Atlantic salmon, reference points derived on the basis of recruitment to the maiden spawner abundance will underestimate the lifetime reproductive contribution and underestimate several population dynamic metrics.

4.3 Upper Stock Reference Point

The choice of upper stock reference points must be in part determined by the choice of the limit reference point. The DFO (2009a) policy on the PA states that “the USR, at minimum, must be set at an appropriate distance above the LRP to provide sufficient opportunity for the management system to recognize a declining stock status and sufficient time for management actions to have effect…while socio-economic factors may influence the location of the USR, these factors must not diminish its minimum function in guiding management of the risk of approaching the LRP”.

For the WSP upper abundance benchmarks based on stock-recruitment relationships, Holt et al. (2009) recommended 80% S_{msy}. This upper benchmark is commonly referenced in the literature and also complies with the WSP abundance indicator upper benchmark definition (see preceding sections). Further, this upper benchmark (80% S_{msy}) is consistent with DFO’s PA Framework (DFO 2006), which recommends an upper benchmark be equal to (or greater than) 80% S_{msy}.

Other candidates for the USR points could include S_{Rmax} as for example in the case of recreational fisheries where catch and release opportunities can be maximized at maximum recruitment.

Table 4.1. List of candidate removal rate reference points.

Acronym	***Description***	***Reference***
F_{msy}	Fishing mortality rate that provides equilibrium maximum sustainable yield	Various
F_{max}	Slope at the origin of the spawner-recruitment relationship (maximum log transformed recruits per spawner at low spawner abundance)	Mace (1994)
F_{med}	Median log-transformed recruits-per-spawner	Sissenwine and Shepherd (1987)
F_{sm}	Slope at the origin of the smolt-recruitment relationship (independent of freshwater productivity)	Bradford et al. (2000)
h*	Critical harvest rate that, if exceeded, will cause populations to decline to eventual extinction	Bradford et al. (2000)

Table 4.2. List of candidate limit reference points. Relative abundance levels for these candidate points is shown in Figure 4.1.

Acronym	***Description***	***Application***	***Reference***
$S_{0.5Rmax}$	Spawner abundance at 50% maximum recruitment	Juvenile production; Full life cycle	Various
$S_{0.5Rmsy}90$	90th percentile of Spawner abundance at 50% of recruitment at maximum sustainable yield	Full life cycle	Holt et al. (2009)
$S_{0.5Rmsy}$	Spawner abundance at 50% of recruitment at maximum sustainable yield	Full life cycle	Holt et al. (2009)
$0.4S_{msy}$	40% of spawner abundance at S_{msy}	Full life cycle	Holt et al. (2009)
S_{gen}	Spawner abundance that will result in recovery to S_{msy} in one generation in the absence of fishing under equilibrium conditions	Full life cycle	Holt and Bradford (2011)
N*	From the hockey stick model, the minimum spawners that will maximize freshwater production	Juvenile production	Bradford et al. (2000)
0.2K	10-20% of freshwater carrying capacity (the maximum recruitment that the freshwater habitat will support in the absence of fishing mortality) approximated from freshwater studies	Juvenile production	Johnston et al. (2002); Wood (2004)

Table 4.3. List of candidate upper stock reference points. Relative abundance levels for these candidate points is shown in Figure 4.1.

Acronym	***Description***	***Application***	***Reference***
S_{msy}	Spawner abundance for maximum sustainable yield (S_{opt})	Full life cycle	Various
$S^{+}_{0.9msy}$	Upper spawner level that yields 90% of MSY	Full life cycle	Chaput et al. (1998)
$0.8S_{msy}$	80% of spawners at S_{msy}	Full life cycle	Holt et al. (2009)
$S_{msy}90$	90th percentile of S_{msy} estimate	Full life cycle	Holt et al. (2009)
S_{Rmax}	Spawners for maximum recruitment	Juvenile production; Full life cycle	Various
$0.9S_{Rmax}$	Spawners for 90% of maximum recruitment. Useful for non-dome shaped stock recruit relationships	Juvenile production; Full life cycle	

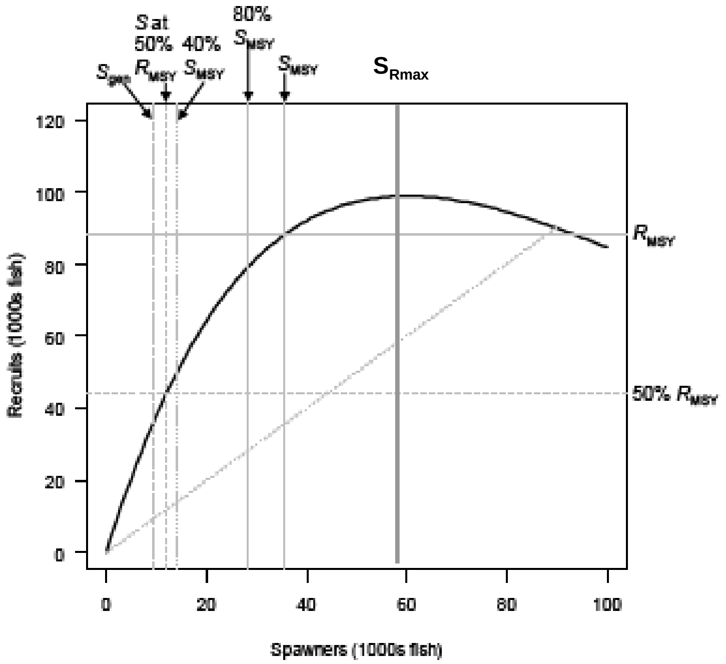


Figure 4.1. Example (Ricker-type) stock-recruitment relationship (solid black curve) for an example stock showing candidate reference points (marked on the top horizontal axis) as described in Tables 4.2 and 4.3. The diagonal dotted line is the replacement line where the number of recruits is equal to the number of spawners. Recruitment at S_{msy}, i.e, R_{msy}, and 50% of that value are marked on the right vertical axis. Figure from Holt et al. (2009) with modification.

5. LIST OF DERIVATION METHODS

5.1 Data rich

Spawner-Recruitment (SR) models have a long and established history in Pacific and Atlantic salmon stock assessment and provision of science advice for fisheries management. When a suitable time series of spawner and recruitment data are available, biological benchmarks based on S_{msy} and F_{msy} can be derived from production models in the form of assumed SR relationships (Ricker 1954; Hilborn and Walters 1992; Walters and Korman 2001).

SR models are the back-bone for assessments for the limited cases where suitable data exists such as the major Fraser River, Barkley Sound and Skeena River sockeye fisheries. High-production sockeye stocks have increasingly been afforded the highest standards of data monitoring compared to other stocks and species. Still, only a small proportion (<20%) of the 230 sockeye CUs in the Region have reliable escapement data for SR modeling approaches.

The standard Ricker model (Ricker 1954) has been used extensively in stock assessments of sockeye in B.C. and it is now standard practice to capture parameter uncertainty using Bayesian inference. Ricker stock and recruitment models have also been applied to Atlantic salmon data series from eastern Canada and for European stocks (Prévost et al. 2001; Prévost et al. 2003; O’Maioléidigh et al. 2004). Michielsen and McAllister (2004) found that the Beverton-Holt formulation was more likely than the Ricker formulation for the Atlantic salmon stock and recruitment data which they analysed although the Ricker model could not be ruled out.

Beverton-Holt models (Beverton and Holt 1957) have been used for analyzing Atlantic salmon spawner to juvenile data sets and as the underlying function in population viability analysis (Gibson 2006; Gibson et al. 2009a, 2009b). Gibson (2006) indicated that there was stronger support for the Beverton-Holt model compared with the Ricker model.

A subset of Fraser sockeye CUs exhibit persistent cycles in abundance. A variant of the Ricker model, the so-called, Larkin model (Ward and Larkin 1964; Larkin 1971; Walters and Staley 1987; Ricker 1997), has been explored as an alternative model to explain cycles. In the formulation of the Larkin model, three additional parameters are added to the Ricker model to estimate delayed-density dependence among cohorts in the 4-year generational period (e.g. Welch and Noakes 1990; Cass et al. 2004; Martell et al. 2008).

In the case of abundance metrics for Pacific Salmon, when escapement and return data are available, stock-recruitment relationships are used to identify the level of spawners below which yield is reduced. Specifically, Holt et al. (2009) recommended estimation of upper and lower abundance benchmarks using stock-recruitment relationships with prior information on carrying capacity in a Bayesian framework. Although in most cases the Ricker model form is most appropriate for modelling population dynamics for Pacific salmon populations, alternative forms such as the Larkin model that includes delay-density interactions, or the Beverton-Holt model, might be more appropriate.

Further, if productivity has been systematically changing through time, then considering recent productivity in the model form might also be appropriate (Grant et al. 2010, 2011). Several techniques have been explored to model the influence of time varying productivity on benchmark estimation and status assessment. These include fitting SR models to truncated SR data sets for Fraser sockeye to restrict analyses to specific time periods in the series (Grant et al. 2011) and non-stationary (Kalman filter) versions of the Ricker and Larkin models to derive estimates of time-varying productivity estimates over the entire time series of data (Dorner et al. 2007; Grant et al. 2011; Peterman and Dorner 2011).

There is evidence for depensatory mortality at low abundances for Cultus Lake sockeye (Bradford and Wood 2004) but quantitative evidence is lacking elsewhere. Variants of SR models have been use to model depensatory mortality in recruitment for Pacific salmon when spawner abundances were below a specified threshold (Bradford and Wood 2004; Chen et al. 2002; Holt and Bradford 2011; Routledge and Irvine 1999). The performance of candidate WSP biological benchmarks in evaluating extinction risk and recovery rates in models that include depensatory mortality was simulated by Holt et al. (2009) and has been considered in the assessment of harvest rules and reference points for Fraser sockeye.

Walters and Martell (2004) show that a state-space modelling approach can reduce bias in Ricker parameters when applied to sets of stocks that have been subject to shared environmental effects. Their approach can be applied to stocks subject to the same fishing mortality history and survival patterns (SR residuals). This approach was recently applied to Skeena sockeye (Walters at al. 2008) and is considered to be a superior method for assessment data for multiple stocks with blanks in the times series due to inconsistent escapement monitoring.

Schnute and Kronlund (1996) present alternative formulations for stock and recruitment functions that estimate directly management related parameters. The use of Bayesian methods has become widely used in stock recruitment analyses and hierarchical modelling approaches provide the means to incorporating information from multiple stocks and studies to assist in parameter estimation and in transport to stocks with limited information (Prévost et al. 2003; Michielsens and McAllister 2004).

5.2 Empirical methods

Empirical methods consist of life history models which are constructed based on life history process parameters borrowed from a large range of studies on the species of interest. Examples of empirical methods for defining reference points are the work of Symons (1979) and Korman et al. (1994).

Symons (1979) constructed a juvenile life history model for Atlantic salmon and based the life history functions on results from a variety of studies or assumed values when data were lacking. From these he defined stock and recruitment curves and using general sea survival and fecundity values, he transcribed the smolt to adult line onto the egg to recruit line and derived the replacement line. Symons (1979) concluded that maximum smolt production was attained asymptotically at high egg depositions, and optimal egg depositions and maximum smolt production decreased with increasing smolt age of the population.

The ASRAM model proposed by Korman et al. (1994) is an example of a life history model which attempts to quantify the ecological processes which define the population dynamics of Atlantic salmon. It was initially developed to assess the effect of acidification on the salmon stocks of the rivers of Nova Scotia (Canada). The ASRAM model quantifies the habitat for juveniles on the basis of a single physical variable, gradient. There are three "dynamic" parameters, i.e. expressed as a function of other variables, which modify survival. Fry survival rates are conditioned by gradient with the highest survival in 0.7% gradient reaches and declining at lower and higher gradients. Average lengths of age 1+ and 2+ parr are modelled relative to age specific parr densities. This in turn affects the age at smoltification and the average size of smolts. Increasing the time spent in freshwater increases mortality of parr to the smolt stage. The early marine survival is modelled as a sigmoid function of smolt length. All other parameters in the model are derived from the literature or from expert judgement and are fixed. Because ASRAM models the renewal of generations, it can be used to derive an egg to egg (or adult to adult) SR relationship and thus define spawning reference points.

The quality of assessment data for the majority of Pacific salmon CUs does not support the use of quantitative assessment models for setting fishery reference points. This is particularly the case for pink and chum salmon where funding constraints have eroded annual escapement monitoring programs. Empirical methods for setting WSP benchmarks and determining biological status often will rely on escapement trend information. Trend information is useful for assessing status but that information alone does not easily translate into fishery reference points. In the absence of quantitative information, empirically derived escapement target based on limited and low quality escapement monitoring is often the basis for managing terminal chum fisheries during the course of the fishing season. Inseason monitoring of relative abundance in test fisheries is often used as the principal method for setting inseason fishery targets along with inseason escapement monitoring. Other empirical methods rely on freshwater survey data of juvenile habitat capacity and indices of marine survival from very limited indicator systems with both freshwater and marine indices of abundance.

The use of Spawer per Recruit analyses using basic life history parameters, measured or inferred, is an example of an empirical approach for developing reference points (Mace and Sissenwine 1993). Chaput and Cairns (2011) provide an example of such an approach for American eel based on measured growth rates, probability of maturing and natural mortality from empirical relationships developed for the European eel. The case is made by these authors that basic life history data can be readily obtained from different regions of the species distribution and the reference levels would be tailored to those variations in life history characteristics.

5.3 Data Limited

Data limited situations includes cases where populations are not monitored and information from the same species is used to make predictions of population dynamics as well as the case for species with limited to no information on population dynamic processes.

In the first case of unstudied populations but for which information exists from other populations, reference points are frequently transported based on a spawner abundance value from studied populations which is standardized to an exchangeable metric representing the size of the population. For Atlantic salmon, the transport of reference points based on egg deposition requirements per unit of rearing area has been used since the early 1990s and most recently Bayesian hierarchical models have been used to transport reference points scaled to the area of juvenile rearing habitat to unstudied populations (Caron et al. 1999; Prévost et al. 2003; Michielsens and McAllister 2004; O'Maoiléidigh et al. 2004). Latitude was used as an additional conditioning variable for the transport of reference points across rivers in Europe (Prévost et al. 2003).

For sockeye, Chinook and coho CUs, habitat models have been developed for estimating habitat capacity and abundance-based benchmarks. When lake-rearing habitat is limiting production, estimates of juvenile sockeye production is assumed to be related to primary production capacity in a lake. A meta-analysis developed for Alaskan and BC sockeye rearing lakes is based in the relationship between maximum smolt abundance and lake rearing habitat (Shortreed et al. 2000). This is viewed as a cost-effective method for data-limited systems wherein habitat of sockeye rearing lakes is measured using lake surveys. Independent habitat capacity estimates and their variances are being used as Bayesian priors in SR models for some data limited Fraser and Skeena CUs. This has been shown to effectively reduce uncertainty in parameter estimates where juvenile production is assumed to be lake limiting.

A meta-analysis was developed for Chinook to generate escapement goals for Chinook as a cost-effective method in the absence of SR data for most Chinook CUs. Of the 72 Chinook CUs, only 3 are deemed to have adequate SR data to estimate key parameters for developing reference points. The analysis was motivated by the interest in the PST process to set escapement goals for Chinook stocks. Chinook productive capacity is shown to be related to freshwater habitat area in a meta-analysis of 25 Chinook populations distributed between Alaska and northern Oregon and representing a broad range of environments and life history types (Parken et al. 2006). The relationship can be used to estimate the key management parameters S_{msy} and S_{rep}, distributions of parameter uncertainty and associated fishery reference point. The meta-analysis approach is being explored by the PST Chinook Technical Committee. Estimates of F_{msy} can be derived from the same model by using Hilborn's (1985) approximation for estimating the Ricker *a* parameter and hence reference points based on F_{msy}. The use of habitat-based methods has extended the number of Chinook CUs with modelled fishery reference points to more than half of the Chinook CUs in the Region. The application of GIS for mapping spatial habitat data (i.e. accessible freshwater habitat area) is viewed as a promising tool for extending the habit-based approach further (Chuck Parken, DFO, pers. Comm.).

A habitat-based method has also proven to be a useful predictor of coho production in streams distributed from Alaska to Oregon based on relationships between stream length and smolt abundance (Bocking and Peacock 2004). Based on that method, smolt productive capacity and the number of spawners that are required in order to fully seed the available habitat and produce the maximum number coho smolts (S_{max}) were estimated for 102 coho streams (two CUs) in the Nass River areas using a habitat-based model.

Management reference points for some data-poor pink and chum salmon stocks have been derived using percentiles of historical escapement time series (Van Will et al. 2009a, 2009b) but beyond these, there is not much guidance which we can provide for developing reference points for species with very limited data.

5.4 Considerations for spatial structuring and mixed stock fisheries

As described in Section 2, anadromous salmonids are characterized by population structuring at the scale of individual rivers and in some Pacific salmon species down to subwatershed scale. Recruits return with high fidelity to their natal spawning locations. Fisheries on these species have historically occurred at times and locations where mature animals are returning to the coast and rivers to spawn and when they are concentrated at higher density than at other times of their life cycle. Populations are frequently mixed during their spawning migrations and although some fisheries can target specific populations due to differences in run timing, for a number of marine, coastal and frequently inriver fisheries, multiple stocks are prosecuted at the same time. Almost all the harvested catch of Pacific salmon that spawn in B.C. is from mixed-stock fisheries. Only in the very terminal systems or large single-stock rivers, for example, in the Yukon, can fisheries in the Pacific Region exploit stocks separately from one another. The fishery on Atlantic salmon at West Greenland which takes place in August to December annually catches salmon from most salmon producing rivers in eastern Canada and the USA as well as salmon originating from rivers in Europe (ICES 1993). These mixed-stock fisheries pose particular challenges to management of individual populations.

Sustained yield from mixed-stock fishery situations will always be less than yield when each stock is harvested separately due to differences in productivity among stocks, and due to environmental variation (the more uncorrelated and larger the random variability among stocks, the more yield is foregone) (Hilborn and Walters 1992).

Ideally, management of fisheries would occur such that “optimal” production takes place in all the populations subjected to exploitation. As such, the formulation of fisheries management advice should take account of the complexity of the mixed-stock fishery being managed, and the number of distinct production areas that are being exploited. Chaput (2004) illustrated that as the number of populations or areas being prosecuted in mixed-stock fisheries increases, the total escapement objective for the complex being exploited must be increased to ensure a given probability of simultaneously achieving the individual population reference levels (Figure 5.1). Alternatively, when evaluating management options based on forecasts, the catch options are presented on the basis of the probability of each stock unit achieving its reference point simultaneously relative to assumptions on exploitation rates of each stock in the mixed-stock fisheries (Chaput et al. 2005; Table 5.1). Increasing the reference levels as described above in an attempt to account for the number of stocks being exploited in a fishery or in an attempt to compensate for lower productivity will result in reduced catch options. The trade-off between reduced catch and protecting smaller or less productive populations must be recognized (Hilborn and Walters 1992). Harvest policy options for managing these trade-offs under the WSP for CUs in the “RED” status zone are under development within Strategy 4 (integrated strategic planning). Implementing Strategy 4 is in the early stages of development but policy options that balance trade-offs between conservation and sustainable use under the WSP will be made on a case-by-case basis. Under Strategy 4 there will be the need to consider the implications of all human impacts, including fishing, on each CU, the cost of recovery given prevailing socio-economic considerations and scientific uncertainty.

5.5 Quantifying uncertainty

Quantifying uncertainty in the development and use of reference points consists of three components: uncertainty associated with the derivation of the reference point, the probability level of the reference point estimate to be used in management, and uncertainty in the current status of the stock relative to the reference point.

Bayesian modelling approaches are now widely used in stock assessments and for the provision of management advice and these allow for a more complete quantification of these uncertainties. Hierarchical Bayesian methods are most appropriate in situations where reference points from data rich situations are transported to populations with limited to no information (Prévost et al. 2003; Michielsens and McAllister 2004). The uncertainties associated with intra-population stock and recruitment dynamics and inter-population variation of this dynamic within a set of exchangeable units can be quantified using these approaches.

From such Bayesian models, posterior distribution summaries of parameters of interest, including reference points, are very informative of uncertainties but most often only the point estimate is chosen, for ex. the mean or the median value, and used in management advice. In some cases, a value other than the median of the posterior distribution was selected; Caron et al. (1999) chose the 75th percentile rather than the median estimate of S_{opt} as the point value for the limit reference point to be used for management of Atlantic salmon fisheries. Alternatively, the full posterior distribution of the reference point could be retained and applied jointly to the posterior distribution of the population assessment metric. The marginal probability distribution of having met or exceeded the objective could then be derived and this would indeed be a full integration of uncertainties in the assessment and uncertainties of the reference points.

Table 5.1. *Example risk analysis results of fishery options at West Greenland relative to the objective of simultaneously meeting or exceeding the spawner requirements in the four northern regions (Labrador, Newfoundland, Québec, Gulf, and simultaneously) and of achieving an increase of 25% or greater in returns of 2SW salmon to the two southern regions (Scotia-Fundy and USA) relative to a predefined period (1998 to 2002) (Chaput et al. 2005).*

	Probability (%) of meeting or exceeding spawning requirement					Probability (%) of achieving a 25% or greater increase	
Harvest at West Greenland (t)	Labrador	Newfound-land	Québec	Gulf	Simultaneously to four northern areas	Scotia-Fundy	Simulta-neously to two southern areas
0	1.2	77.1	3.1	70.0	1.2	77.3	77.2
10	1.1	75.0	2.5	69.0	1.1	75.1	75.1
20	1.0	73.1	2.3	65.9	1.0	73.4	73.4
30	0.9	71.8	2.2	59.5	0.9	72.1	72.1
40	0.8	70.6	2.1	48.0	0.8	71.1	71.1
50	0.7	68.7	2.0	32.0	0.7	69.5	69.5
60	0.7	66.0	1.9	17.8	0.7	66.4	66.4
70	0.6	60.9	1.9	8.6	0.6	60.5	60.5
80	0.5	52.8	1.7	4.5	0.5	51.1	51.0
90	0.5	41.3	1.6	2.9	0.5	39.2	39.2
100	0.5	29.8	1.5	2.4	0.5	27.1	27.0

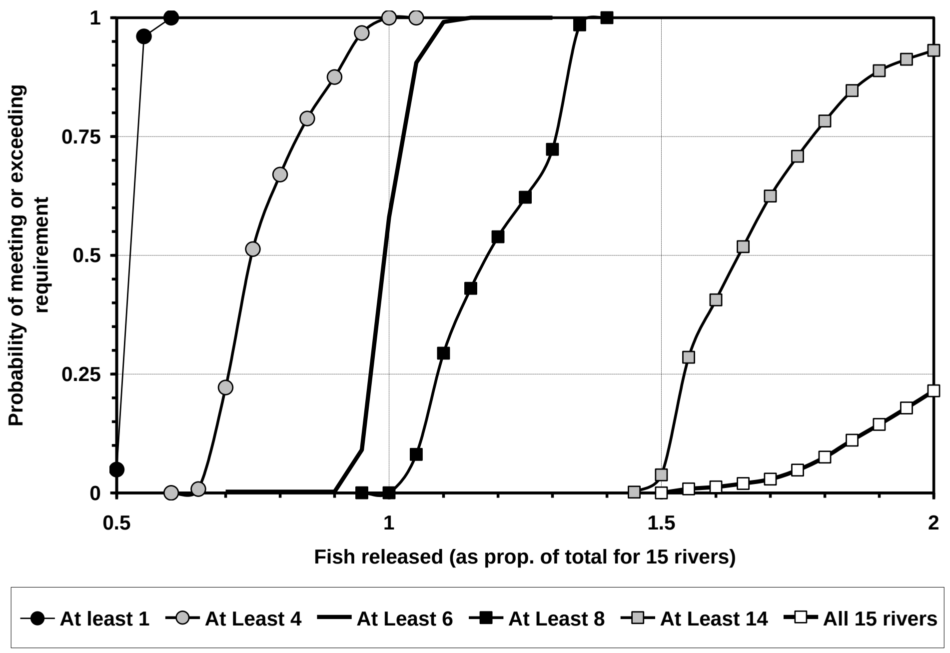


Figure 5.1. *Example probability profiles of meeting or exceeding individual river* S_{opt} *simultaneously in at least one river up to all 15 monitored rivers in the northeast Atlantic region, relative to the total fish escapement to the region's rivers. The sum of the spawner requirements for the 15 rivers equals 30,464 fish. Figure taken from Chaput (2004).*

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