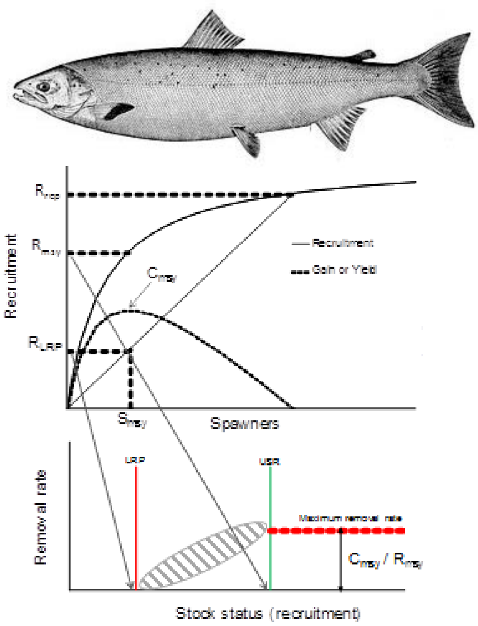
Fisheries and Oceans Canada | Pêches et Océans Canada
Ecosystems and Oceans Science | Sciences des écosystèmes et des océans

Gulf, Maritimes, and Newfoundland and Labrador Regions

Canadian Science Advisory Secretariat
Science Advisory Report 2015/058

DEVELOPMENT OF REFERENCE POINTS FOR ATLANTIC SALMON (*SALMO SALAR*) THAT CONFORM TO THE PRECAUTIONARY APPROACH



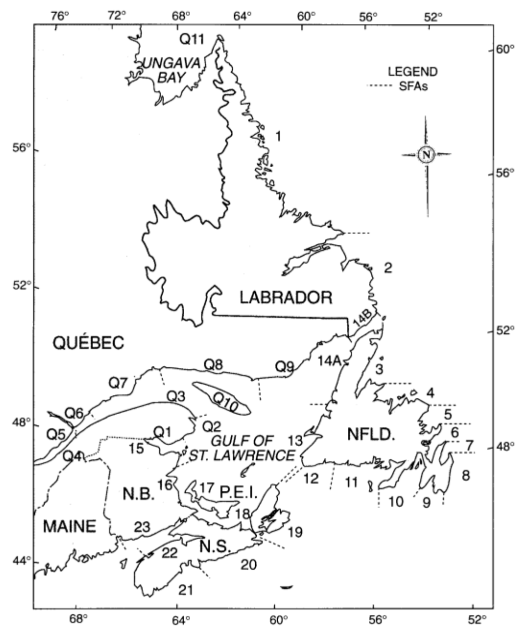


Figure 1: Atlantic salmon Fishing Areas in eastern Canada.

Context:

Fisheries and Oceans Canada (DFO) Ecosystems and Fisheries Management Branch asked DFO Science to develop reference points for Atlantic salmon that conform to "A fishery decision-making framework incorporating the Precautionary Approach" (DFO 2009a). The request follows on an action item associated with implementation of the Wild Atlantic Salmon Conservation Policy (WASCP; DFO 2009b) to review benchmarks / reference points for Atlantic salmon which conform to the Precautionary Approach (PA). Presently, there are five regionally specific reference values for Atlantic salmon in eastern Canada referred to as the conservation objective. By definition, the conservation objective is considered to be a limit reference point (CAFSAC 1991a). Management of Atlantic salmon is presently based on a fixed escapement objective with all fish above the conservation requirement considered surplus to spawning requirements and available for fisheries (CAFSAC 1991b). The conservation requirement defined by CAFSAC has been used both domestically and internationally to guide fisheries management actions including the provision of catch advice for the mixed-stock Atlantic salmon fishery at West Greenland. Individual river values based on the conservation requirement have also been proposed as limit reference points that conform with the PA for stocks in DFO Maritimes Region (DFO 2012).

This document provides advice on the development of reference points for Atlantic salmon that conform to the PA. The information used to develop this advice was presented at the science peer review of February 11-13, 2014 in Moncton, NB. Participants at the science review were from DFO Science, DFO Fisheries Management, from the province of Quebec, invited external experts, Aboriginal organizations, and non-government organizations.

SUMMARY

- The Limit Reference Point (LRP) should be defined on the basis of conservation of the salmon population, and unrelated to fishery exploitation objectives.
- The proposed LRP value is the egg deposition that results in less than a 25% chance that the realized smolt production from freshwater would be less than 50% of the estimated maximum recruitment.
- For small populations, conservation genetics should be considered in complement to stock and recruitment information to establish a LRP.
- At a minimum, the Upper Stock Reference point (USR) must be greater than the LRP and there should be a very low probability (<5%) of recruitment falling below the LRP when the stock is at USR and is exploited at the maximum removal rate. The choice of the USR will depend upon the objectives of the users and the risk profile and risk tolerance of the management strategy.
- If reference points are defined in terms of rates, such as eggs or spawners per wetted fluvial area, these reference points can be transferred if the habitat areas and biological characteristics of the stocks are known.
- Stock and recruitment modelling is the favoured approach for examining population dynamics and developing reference points for Atlantic salmon.
- The use of a Hierarchical Bayesian Model framework is an excellent approach for addressing exchangeability and transfer of reference points to unmonitored and data-poor populations.

INTRODUCTION

In 2009, Fisheries and Oceans Canada published the Sustainable Fisheries Framework that provides the basis for ensuring Canadian fisheries are conducted in a manner which support conservation and sustainable use. The framework is comprised of a number of policies for the conservation and sustainable use of fisheries resources including "A Fishery Decision-Making Framework Incorporating the Precautionary Approach" (DFO 2009a). The Fishery Decision-making framework (the PA) applies where decisions on harvest strategies or harvest rates for a stock must be taken on an annual basis or other time frame to determine Total Allowable Catch (TAC) or other measures to control harvests. This is the case for Atlantic salmon stocks from eastern Canada.

There are three components to the general decision framework for the PA:

1. Reference points and stock status zones (Healthy, Cautious and Critical) (Fig. 2),
2. Harvest strategy and harvest decision rules, and
3. The need to take into account uncertainty and risk when developing reference points and developing and implementing decision rules.

The first component of the framework, reference points and status zones, is the subject of this advisory report.

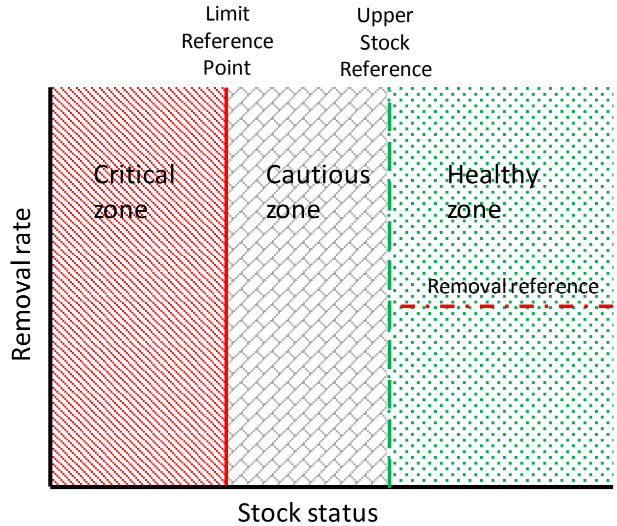


Figure 2. Standard Precautionary Approach diagram showing the three status zones and the reference points which delimit the zones.

The PA framework is generally presented as a two-dimensional plot with three status zones (Critical, Cautious, Healthy) with stock status on the x-axis and removal rate on the y-axis (Fig. 2). Along the stock status axis, the Limit Reference Point (LRP) corresponds to the boundary between the Critical and the Cautious stock status zones. The Upper Stock Reference (USR) point corresponds to the boundary between the Cautious and the Healthy stock status zones. A maximum removal reference is defined along the removal rate axis.

The LRP is defined as the stock level below which productivity is sufficiently impaired to cause serious harm (DFO 2009a). The USR is the stock level below which removals must be progressively reduced in order to avoid reaching the LRP. Under the PA framework, 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. The LRP is based on biological criteria and established by Science through a peer reviewed process (DFO 2009a). The USR would be developed by fishery managers informed by consultations with the fishery and other interests, with advice and input from Science (DFO 2009a).

The Removal reference is the maximum acceptable removal rate for the stock which would apply when the stock is in the healthy zone and includes all anthropogenic mortality. To comply with the United Nations Fisheries Agreement (UNFA), the Removal reference must be less than or equal to the removal rate associated with maximum sustainable yield (DFO 2009a).

Atlantic Salmon Biology

Anadromous Atlantic salmon (*Salmo salar*) are iteroparous (can spawn multiple times) but the dominant component of the annual spawning stock is comprised of first time spawners. The fisheries on Atlantic salmon occur primarily on maturing first time spawning animals, with limited marine fisheries on immature animals. As the spawning stock in any year is dominated by new recruitment, there is very limited accumulation of spawners over years, even in stocks with repeat spawners. Consequently, the management of Atlantic salmon has been extensively focused on achieving escapement goals to ensure a level of spawning that would provide fishing and species benefits in the subsequent generation.

Atlantic salmon utilize two distinct environments to complete their life cycle and population structuring at the scale of an individual river is highly evolved. Density-dependent population regulation is well established in the freshwater phase of the life cycle, occurring in the first year or two of freshwater residency and there is no evidence of density-dependent survival at sea.

In many stocks of Atlantic salmon, there is a strong sex bias in the sea age at maturity (O'Connell et al. 2006; Fig. 3). In Atlantic salmon populations that are dominated by one-sea-winter (1SW; grilse or small salmon) age at maturity, there is a high proportion of females in the returns and in the smolt migrants, with a high propensity for precocious male parr maturation. In salmon populations with multiple sea ages at maturity, males are more abundant in the returns of one-sea-winter salmon while females are more abundant in the returns of multi-sea-winter (MSW; two-sea-winter (2SW), three-sea-winter (3SW)) salmon; Chaput et al. 2006; O'Connell et al. 2006). There can also be important differences in abundances of the respective sea age groups in the annual returns to a river. Accordingly, stock status of Atlantic salmon is generally assessed relative to the estimated total number of eggs, with adjustments for increasing fecundity with body size.

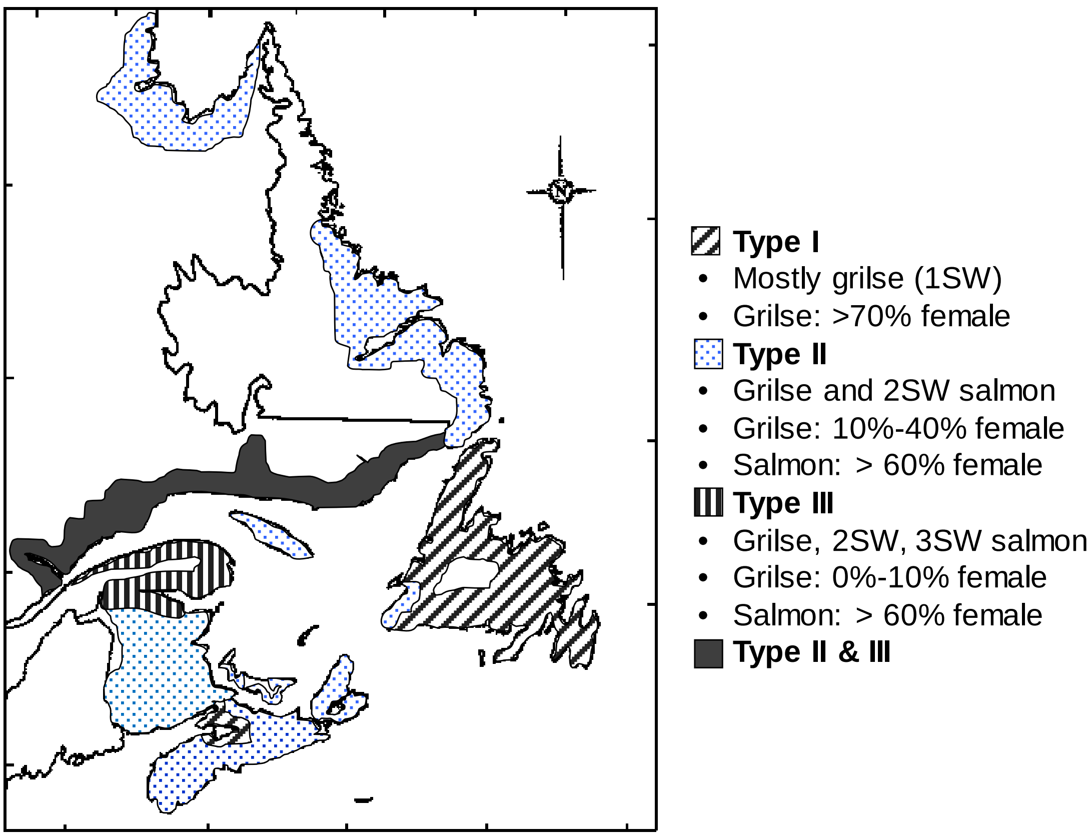


Figure 3. Distribution of generalized groupings of stock types of populations of Atlantic salmon in eastern Canada. Within each stock type area there may be a few stocks which belong to another stock type. Figure is adapted from Porter et al. (1986) and O'Connell et al. (2006).

Reference points presently defined for Atlantic salmon

Reference points have been informally used to provide advice for Atlantic salmon fisheries management since the 1970s (Chaput et al. 2013) and predates the development of the Sustainable Fisheries Framework (DFO 2009a).

In 1991, the Canadian Atlantic Fisheries Scientific Advisory Committee (CAFSAC) (1991a) formally defined conservation for Atlantic salmon as a level of egg deposition that would be applied to individual rivers, and in a subsequent advisory document provided values of the conservation requirements for a number of rivers in eastern Canada and advice on the surplus to conservation requirements which may be available (CAFSAC 1991b).

CAFSAC (1991a) indicated that the stock abundance level at which it would be strongly advised that no fishing should occur (i.e. the LRP) could not be defined with absolute precision and that 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. Subsequently, CAFSAC (1991a) proposed an operational translation of conservation as an egg deposition rate of 2.4 eggs per m^2 of fluvial rearing habitat, and in addition for insular Newfoundland, 368 eggs per ha of lacustrine habitat (or 150 eggs per ha for stocks on the northern peninsula of Newfoundland). CAFSAC considered that the further the spawning escapement was below the biological reference level, and the longer this situation occurred even at rates only slightly below that level, the greater the possibility of incurring a number of risks which could cause irreversible damage to the stock. Conservation requirements for different regions of eastern Canada based on this approach vary among the regions of eastern Canada (Table 1).

Table 1. Summary of presently defined conservation objectives for Atlantic salmon by region in eastern Canada.

Province / region	Objective	Reference Point	Reference
Maritime provinces	Maximum freshwater production	240 eggs per 100 m^2 of fluvial habitat	CAFSAC (1991a, 1991b) ; O'Connell et al. (1997)
DFO Maritimes Region	50% of maximum recruitment	240 eggs per 100 m^2 of fluvial habitat	DFO (2012); Gibson and Claytor (2012)
Insular Newfoundland	Maximum freshwater production	240 eggs per 100 m^2 fluvial habitat + 3.68 eggs per 100 m^2 of lacustrine habitat or	CAFSAC (1991a, 1991b);
		+1.50 eggs per 100 m^2 of lacustrine habitat for the northern peninsula	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)

CAFSAC (1991a, 1991b) established regional 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 single reference point used within the context of a fixed escapement strategy does not conform to the Precautionary Approach framework as it does not set a maximum removal rate for the stock in the healthy zone nor does it define an USR at which the maximum removal rate would apply (Fig. 4). Although the removal rate does indeed fall to zero when the stock status declines to the conservation point, the removal rate rises continually thereafter whereas spawning stock becomes constant after abundance exceeds the conservation objective (Fig. 4). During the review of PA reference points for a variety of stocks in DFO's Maritimes Region, individual river conservation requirements based on 2.4 eggs/m^2 of fluvial rearing habitat that had been estimated by O'Connell et al. (1997) were proposed for use as LRPs for individual salmon populations in this region (DFO 2012, Gibson and Claytor 2012).

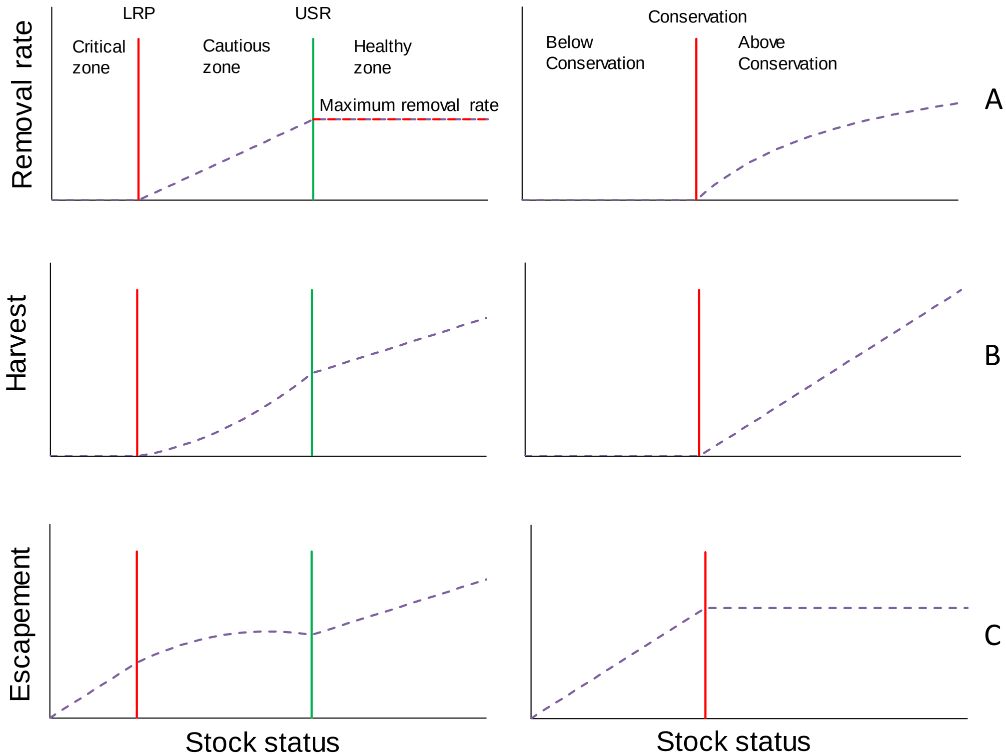


Figure 4. Comparison of the PA framework (left column) to the fixed escapement strategy with a single reference point approach (conservation, right column) relative to the stock status indicator for the removal rates (upper row A), harvests (B), and escapement (C). A linear removal rate line in the cautious zone of the PA framework is shown as an example only. Reference values on the stock status and removal rate axes are arbitrary and for illustration only.

The reference points and the population dynamics of Atlantic salmon have most often been presented as a stock and recruitment diagram with spawning stock abundance on the horizontal axis and the subsequent recruitment abundance resulting from the spawning stock on the vertical axis (Fig. 5). The conservation requirement for Atlantic salmon is expressed in terms of a spawning stock value. This is somewhat different from the PA framework that presents stock status on the horizontal axis and the removal rate on the y-axis (Figures 2 and 5). In the PA framework, the stock status axis refers to total stock abundance or an index of total abundance prior to fishing.

The single reference point and fixed escapement strategy used for Atlantic salmon can be reconciled with the PA framework by translating the recruitment indicator from the stock and recruitment plot onto the PA framework stock status indicator (Fig. 5). The recruitment that corresponds to the point of maximum sustainable yield (R_{msy}) corresponds to the B_{msy} value on the stock status axis of the PA. The spawning stock that generates R_{msy} is S_{msy} (also called S_{opt}) and the difference between R_{msy} and S_{msy} equates to C_{msy}, the catch at maximum sustainable yield. The ratio of C_{msy} to R_{msy} is F_{msy}, the maximum removal rate that would be advised in the healthy zone of the PA. If the removal rate is drawn as a linear decline from F_{msy} when the stock status is at R_{msy} and 0 at the LRP, then this strategy corresponds to a fixed escapement strategy, as presently used for Atlantic salmon management.

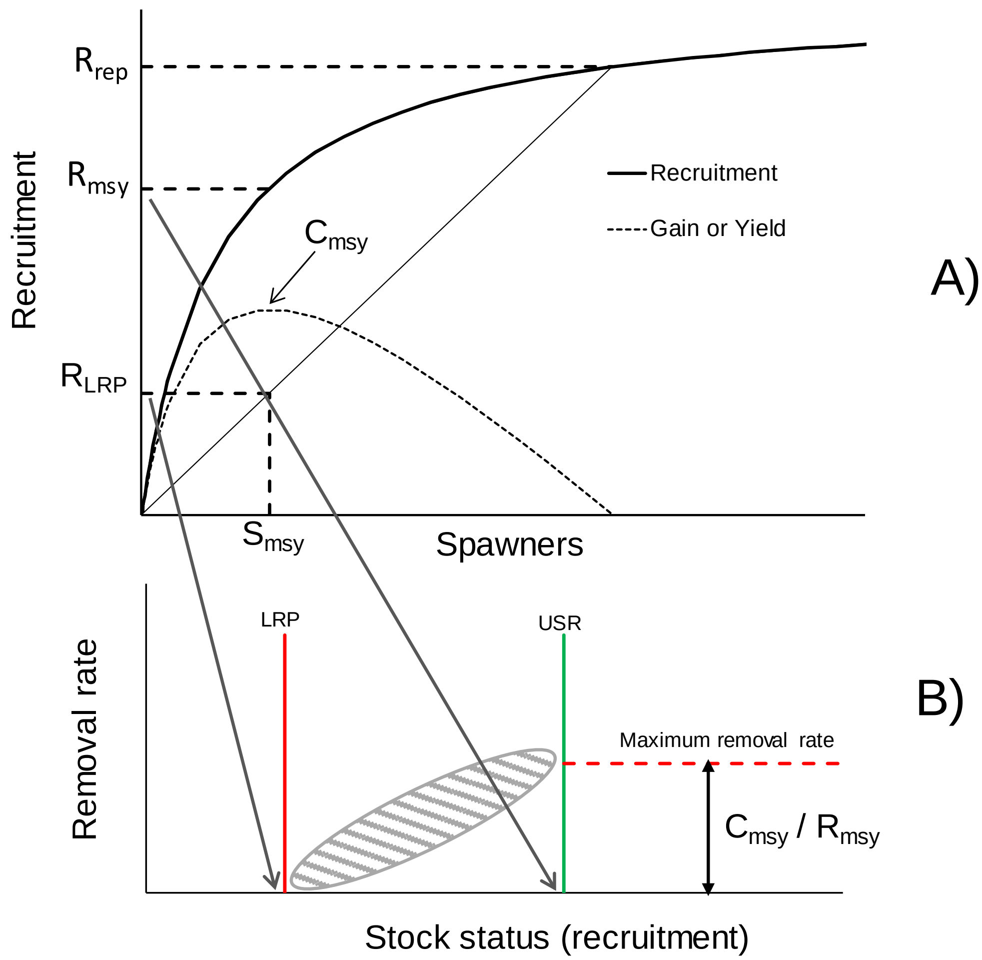


Figure 5. Transposing a spawning stock to recruitment relationship (upper panel A) to the removal rate and stock status axes (lower panel B) within the PA framework. The example is for an upper stock reference corresponding to R_{msy}, a limit reference point equal to S_{msy}, and a removal rate corresponding to F_{msy}. The exploitation rate in the cautious zone (grey hatched oval) could be defined on the basis of a risk analysis of the chance that abundance after exploitation would be less than the LRP. R_{rep} is the abundance at replacement.

ASSESSMENT

Candidate reference points for Atlantic salmon

Limit Reference Point (LRP)

The Limit Reference Point is defined as the stock level below which productivity is sufficiently impaired to cause serious harm (DFO 2009a). The Limit Reference Point should consequently be defined on the basis of conservation of the salmon population, and unrelated to fishery exploitation objectives. One strategy is to maintain production from freshwater to provide for sufficient numbers of adult returns, despite wide variations in environmental conditions in the marine environment, for the purpose of ensuring adequate opportunity for expression of the diversity of adult phenotypes and to maintain genetic variability. Thus there are a number of candidate reference points that could satisfy this objective:

- $S_{0.5Rmax}$ spawner abundance that produces 50% of maximum recruitment (Myers et al. 1994)

- S_{gen} spawner abundance that will result in recruitment to S_{MSY} in one generation in the absence of fishing under equilibrium conditions
- S_{opt} spawner abundance that results in maximum potential surplus production (S_{msy})
- S_{LRP} spawner abundance that results in a risk of <= 25% of recruitment being less than 50% of maximum recruitment.

The two reference points most robust and indistinguishable in terms of extirpation risk and recovery potential for a Pacific salmon type population dynamics were $S_{0.5Rmax}$ (and by definition S_{LRP}) and S_{gen} (Holt et al. 2009). All the reference points above can be derived from full life cycle stock and recruitment relationships but only $S_{0.5Rmax}$ and S_{LRP} can be derived from stock and recruitment relationships that consider only the freshwater phase of the life cycle.

As a minimum, the LRP should be determined based on a risk analysis of the spawning escapement that results in an agreed probability of the recruitment being less than 50% R_{max}. A risk tolerance of no greater than 25% of recruitment being < 50% R_{max} is proposed. If other reference points are considered for the LRP, they should be assessed relative to the S_{LRP} defined above and the chosen LRP should not be less than S_{LRP}.

For small populations, genetic diversity can decrease dramatically, which increases the risks of inbreeding depression and ultimately extinction (Frankham et al. 2014). As a result, conservation genetics should be considered in complement to stock and recruitment information to establish a LRP. Effective population size (Ne) is a useful genetic index used in conservation management to evaluate the extent of inbreeding risk, and could represent an appropriate complementary tool to stock and recruitment. Additionally, for conservation purposes, maintaining 90% of genetic diversity over 100 years, as used for other species, could be an appropriate target (Frankham et al. 2014).

Upper Stock Reference (USR)

The choice of the USR is in large part determined by the choice of the limit reference point. The PA policy states:

> "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" (DFO 2009a).

The definition of the USR will depend upon the management objective for the resource; for example maximizing yield in harvest fisheries or maximizing fishing opportunities in the case of recreational fisheries. A number of candidate reference points could be considered:

- 80%Bmsy recruitment corresponding to 80% of Rmsy as per the PA policy.
- Rmsy: recruitment at Smsy.
- X%Rmax: a percentage (X%) of maximum recruitment expected for the stock.

No recommendation for a specific Upper Stock Reference is made as the choice of the USR will depend upon the objectives of the users and the risk profile and risk tolerance of the management strategy. Upper stock reference points are best determined using full life cycle considerations as recruitment could be subject to reduced productivity and therefore increased risk of the stock abundance falling to the LRP. At a minimum, the USR must be greater than the LRP and there should be a very low probability (<5%) of the recruitment falling below the LRP when the stock at USR is exploited at the maximum removal rate.

Removal rate reference

DFO (2009a) indicated that the maximum removal rate in the healthy zone should not exceed the value corresponding to F_{MSY}. The maximum removal rate in the healthy zone could be calculated once the upper stock reference level is defined. The maximum removal rate could be set as the ratio of the maximum realized catch (R_{USR} – S_{USR}) when recruitment is at R_{USR}, i.e. (R_{USR} – S_{USR}) / R_{USR}.

Considerations for variations in productivity, particularly sea survival, of Atlantic salmon

As indicated previously, Atlantic salmon utilize two distinct environments to complete their life cycle. Density-dependent population regulation is well documented in the freshwater phase (Jonson et al. 1998; Elliott 2001; Gibson 2006). In contrast, marine mortality is generally considered to be density-independent.

The modelling of stock and recruitment relationships and the development of reference points are challenged by two opposing considerations:

- the need for a long time series of contrasting abundance with which to adequately estimate life history parameters, versus
- the risk that systematic and sustained changes in the life history parameters being estimated will occur.

A directional and sustained change in life history parameters over time is referred to as non-stationarity, which contrasts with short term stochastic variation. The consequences of non-stationarity are that observations from the past may not be indicative of current and future conditions, and may therefore bias our understanding of population dynamics, reference points, and expectations.

There is substantial evidence of sustained changes in some life history characteristics of Atlantic salmon, particularly in survival at sea over the past 40 years. In many monitored stocks, return rates of smolts to a first spawning have declined over the past two decades, with the most important declines occurring in the late 1980s and early 1990s.

Evidence of sustained changes in the population dynamics parameters in the freshwater phase of the life cycle is weak. With the exception of situations where freshwater habitat has been degraded (for example through acid precipitation, installation of barriers, degradation of habitat by siltation), there is little evidence of the type of abrupt and sustained changes noted for the marine environment, although survival in freshwater, from eggs deposited to subsequent smolts produced, is highly variable among cohorts.

Consequences of non-stationarity on development of reference points for Atlantic salmon

Changes in productivity in either the freshwater or marine phase of the life cycle will have consequences on the derivation of reference points. The effects of lower productivity, manifest in either phase, will reduce adult recruitment. Reduced recruitment rates (recruits per spawner) result in lower reference point values.

Reference points based on full life cycle models may not be robust to systematic and sustained changes in the density independent dynamics occurring at sea. As density-dependent population regulation is considered to occur during the freshwater phase, if the average productivity in freshwater has not changed, then limit reference points defined on the basis of maintaining a portion of the freshwater carrying capacity (R_{max}) would be robust to temporal changes in average conditions during the marine phase. The proposed LRP ($S0._{5Rmax}$) as well as S_{gen} have been shown by simulation in Pacific salmon to be robust to changes in productivity (Holt et al. 2009).

Approaches for defining reference points

Stock and recruitment modelling is the favoured approach for examining population dynamics and developing reference points for Atlantic salmon. The status of Atlantic salmon populations based on assessments of adult returns and spawners is annually reported for 60 to 70 stocks in eastern Canada (ICES 2013). Studies of population dynamics that encompass estimates of spawners, juvenile abundance, smolts, adult returns, age structure, and year class reconstruction have been examined in fewer rivers and this limited amount of information on individual salmon populations poses a challenge to the development of reference points to guide management actions.

Bayesian approaches that provide a framework for incorporating multiple levels of uncertainty are well developed and can be applied to single population stock and recruitment analyses. Hierarchical Bayesian Modelling (HBM) provides a framework for incorporating information from multiple stock and recruitment series, and accounting for the additional uncertainties associated with multiple stock and recruitment time series. HBM approaches are widely used in stock assessments and have been used to model stock and recruitment time series from monitored Atlantic salmon populations in eastern Canada and in Europe (Prévost et al. 2001, 2003). Hierarchical Bayesian methods are most appropriate in situations where information from data rich situations can assist in the estimation of stock and recruitment parameters of stocks with sparse data. The uncertainties associated with intra-population stock and recruitment dynamics and inter-population variations of these dynamics within a set of representative rivers can be quantified using these approaches.

Model fitting diagnostics repeatedly have shown that the Beverton-Holt stock and recruitment model is a better representation of Atlantic salmon stock and recruitment dynamics than the Ricker model. Beverton-Holt models generally estimate higher survival rates at the origin than Ricker models. The slope at the origin is a key stock and recruitment dynamic parameter which defines the productive potential of the population and therefore the value of the LRP. The LRP value is inversely related to the slope at the origin.

Model results from Beverton-Holt are preferred to those from Ricker. If the choice of Ricker over Beverton-Holt results is made on the basis of lower estimates of survival rate at the origin for Ricker models, and as a result higher LRPs, this should be clearly stated to managers. Such a choice represents a prior decision of the risk tolerance which should be prescribed by managers.

There may be situations when the modelling of empirical data and the derivation of LRPs results in a spawner abundance value for the LRP which is lower than the observed values for that stock in the available time series. In such cases, this should be communicated to managers along with the risk associated with using a low and unobserved value for that stock.

Considerations for compilation of data sets

Hierarchical models of stock and recruitment time series of adult to adult returns from 12 rivers in Quebec and for egg deposition and smolt production values for 14 rivers in eastern Canada have been developed. Covariables including the surface area of the freshwater rearing habitat, the presence of lacustrine habitat used by juvenile salmon, habitat quality metrics, and biological characteristics of the populations including the mean age of smolts or proxies such as latitude of the river, have been assembled. Several of these variables have been shown to be significant factors that modify population specific stock and recruitment parameters including carrying capacity and survival rates at low spawning stock abundance and consequently reference points.

Full life cycle data sets will be required to define the Upper Stock Reference point and the maximum removal rate reference point. The reconstruction of these data sets must take account of fisheries removals, repeat spawning components, and hatchery stocking.

Estimates of recruitment of adult salmon must include removals in fisheries. Failing to account for removals of adult salmon in fisheries biases the lifetime contribution of eggs from the recruits, i.e. lowers the productivity. Repeat spawners can make up important proportions of the spawning stock in some Atlantic salmon populations (O'Connell et al. 2006). When constructing recruitment time series of adult salmon, attempts should be made to account for the lifetime spawning contribution of cohorts. If only recruitment of adults at the maiden spawner stage is considered, the lifetime reproductive contribution of recruits will be underestimated and this will bias downward the estimation of a number of full life cycle reference points (S_{msy}, S_{rep}).

In some rivers of eastern Canada, juvenile salmon have been reared in hatcheries and then stocked to rivers. The contributions of hatchery origin salmon to total returns in some rivers can make up substantial proportions of the total returns (DFO 2014).If the contributions of hatchery fish are not excluded from the returns, the effect is to bias the productivity upwards, resulting in higher removal rate reference points and higher anticipated yield from the wild stock.

Incorporating uncertainty in the derivation of reference points

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.

The results of the hierarchical Bayesian analyses of egg to smolt time series show that the stock and recruitment dynamic of Atlantic salmon is highly variable and uncertain within and among stocks (Chaput et al. 2015). Consequently, reference points are defined with uncertainty. With Bayesian models, the uncertainty in the stock and recruitment dynamics within the individual stocks and among stocks can be incorporated in the derivation of the reference point. A specific value from the posterior distribution of the reference point can be chosen according to the level of risk tolerance defined by managers.

As indicated in the previous section, the proposed minimum LRP value would be the egg deposition that results in less than 25% chance that the realized smolt production from freshwater would be less than 50% of the estimated maximum recruitment (carrying capacity). The 25% risk level is provided as a default value in the absence of other guidance from management. The choice of the LRP can be made based on derived risk profiles as illustrated in Figure 6.

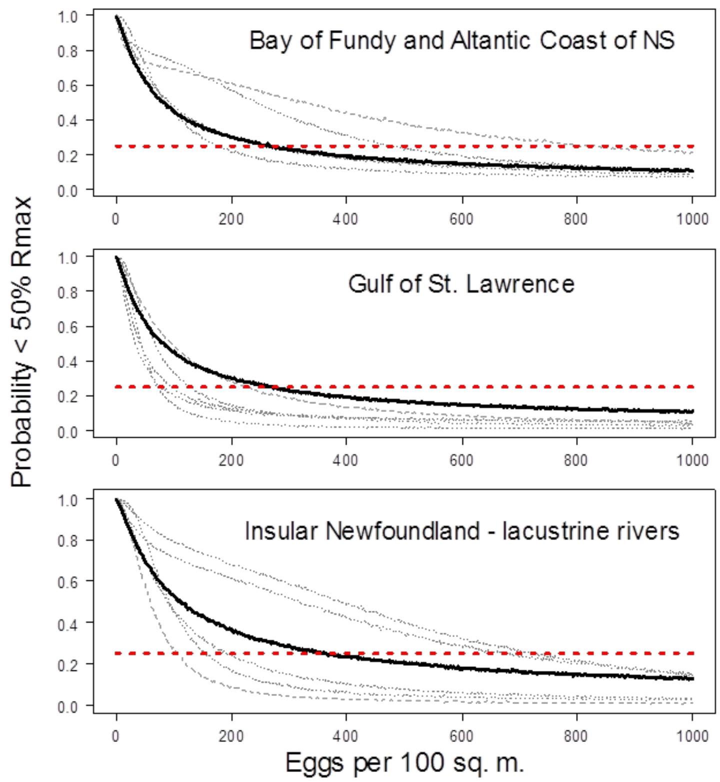


Figure 6. Example risk plots of recruitment being less than 50% Rmax for different levels of egg depositions for the 14 rivers with egg to smolt data and the posterior predictions for rivers grouped by fluvial only and lacustrine habitat categories. The stock and recruitment model was Beverton-Holt with the presence/absence of lacustrine habitat modelled as a covariate of Rmax. The light grey lines are the individual river profiles and the solid black lines are the predicted profile for rivers without lacustrine habitat (Bay of Fundy and Atlantic Coast of NS, upper panel; Gulf of St. Lawrence, middle panel) and with lacustrine habitat (Insular Newfoundland, bottom panel). The dashed horizontal red line is the 25% probability risk level and the corresponding egg deposition would be S_{LRP}.

Transferring reference points to unmonitored or data-poor rivers

Since it is not possible to obtain stock and recruitment data from all the rivers with Atlantic salmon populations in eastern Canada, consideration must be made to transferring reference values from monitored populations to rivers which lack such information. Scaling production and spawning stock on the basis of the amount of habitat area is the first scale of consideration for salmon. If reference points are defined in terms of rates, such as eggs or spawners per wetted fluvial area, these reference points can be transferred across a set of exchangeable rivers if the habitat areas are known.

The use of a HBM framework is an excellent approach for addressing exchangeability and transfer of reference points to unmonitored and data-poor populations. Covariates can be easily incorporated in this modelling framework. The transfer of reference points requires that the covariates which are used to model the stock and recruitment parameters are equally available in both the monitored and unmonitored populations. Covariates which have been used to date include the amount of freshwater habitat, the latitude of the river, the presence and amount of lacustrine habitat, the mean age of smolts, and the proportion of the eggs which are contributed by large (multi-sea-winter) salmon (O'Connell and Dempson 1995; Chaput et al. 1998; Prévost et al. 2003; Chaput et al. 2015). Figure 7 illustrates the options for transferring reference points among rivers based on exchangeability assumptions for habitat quantity, presence of lacustrine habitat, mean age of smolts and proportions of eggs from multi-sea-winter (MSW) salmon.

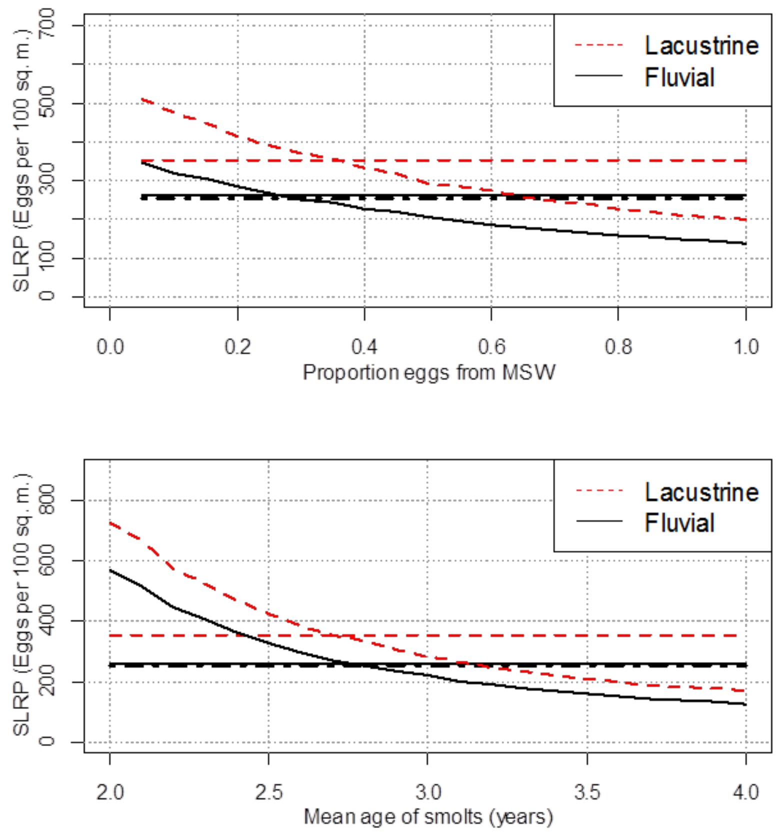


Figure 7. S_{LRP} (expressed in eggs per 100 m² of fluvial habitat) values from the HBM analysis with different exchangeability assumptions based on egg to smolt stock and recruitment data from 14 rivers in eastern Canada. The black horizontal dash-dotted line is the S_{LRP} value (252 eggs per 100 m²) corresponding to a model with only fluvial habitat area as a covariate. The black horizontal line (S_{LRP} = 260 eggs per 100 ²) and the red horizontal dashed line (S_{LRP} = 352 eggs per 100 m²) correspond to the S_{LRP} values for the model with the presence of lacustrine habitat as a covariate on the carrying capacity of fluvial habitat only rivers (black) and rivers with lacustrine habitat (red). The curved lines represent the S_{LRP} values for the model with presence of lacustrine habitat and with proportion of eggs from MSW salmon (upper panel) or mean age of smolts (lower panel) as covariates for rivers with only fluvial habitat (black solid line) and rivers with lacustrine habitat (red dashed line).

Age-specific or size-specific reference point values

Most reference points for Atlantic salmon have been defined on the basis of eggs in the spawning stock and in cases of full life cycle models with eggs in the recruitment. In most cases, eggs from all phenotypes of salmon are included in both the stock and recruitment variables. This assumes that eggs regardless of parent characteristics have an identical value to future recruitment (i.e. similar value in terms of survival, growth), and are unrelated to age or size at maturity (i.e. minimal heritability).

In a recent Recovery Potential Assessment for Atlantic salmon, the recovery objectives (abundance targets) were defined on the basis of the conservation egg requirement and translated into fish based on life history features and expected relative abundance of the age groups (DFO 2014).

Since there is more to population fitness than egg production, conserving all the phenotypes or exploiting the phenotypes equally may well be the soundest conservation measure as phenotype is partially heritable in Atlantic salmon. Even though the egg contribution (in terms of number of eggs) by small salmon may be minor in some stocks, the genetic composition and biological characteristics of all age, size, and sex groups are evolutionary legacies and all phenotypes should be assumed to be important elements of fitness of the population.

Sources of Uncertainty

The Atlantic salmon stock and recruitment analyses published to date have used point estimates of egg depositions and smolt or adult recruitments thus excluding the assessment uncertainties (observation errors). Including observation errors would result in greater uncertainty in the estimated stock and recruitment parameters and the derived reference points. If the limit reference point is chosen on the basis of the risk of exceeding 50% of maximum recruitment, the expectation is that the derived LRP for a chosen risk level will be higher if observation errors are incorporated.

Stock and recruitment time series are available from a small number of monitored rivers in eastern Canada. The monitored stocks range in latitude from 44.5ºN to 55.2ºN; this contrasts with Atlantic salmon rivers that range from 43.6ºN to 58.8ºN. In terms of biological characteristics, the smolt age distribution and the proportion of eggs from MSW salmon in the monitored rivers data set are representative of most Atlantic salmon stock characteristics with exception to the absence of rivers with mean smolt ages of four years or older which are characteristics of the stocks from Labrador and Ungava Bay (Chaput et al. 2006; O'Connell et al. 2006). It is assumed that the modelled stock and recruitment dynamics are representative of these rivers, conditional on the covariates (presence of lacustrine habitat, mean age of smolts, or proportion of eggs from MSW salmon) included in the models. The fourteen rivers in the egg to smolt time series analysis have currently defined conservation egg requirements ranging from 0.14 to 12.8 million eggs with 10 of the 14 rivers having defined conservation requirements greater than 1.0 million eggs (O'Connell et al. 1997). This contrasts with the 485 of 1,082 rivers in eastern Canada with defined conservation requirements for which over 59% of the conservation requirements are less than 1 million eggs. About 37% of the rivers with defined conservation requirements are in the range of the conservation requirements of the monitored rivers data set. Less than 5% of the rivers in eastern Canada are larger than the rivers in the monitored data set. The appropriateness of transporting reference points to rivers which are larger and smaller than those included in the stock and recruitment analyses is not known.

Based on analyses to date, there is some evidence in a few rivers of possible temporal changes in freshwater production but in most of the monitored stocks although freshwater production can be highly variable, there is limited evidence of systematic and sustained changes in productivity. In the populations of the Southern Upland Designatable Unit and the Outer Bay of Fundy Designatable Unit, a number of factors (low pH, changes in fish communities, and land use practices) are concluded to have contributed to reduced freshwater productivity (DFO 2013; DFO 2014). Based on contemporary stock and recruitment data, it was not possible to exclude lower carrying capacity and lower survival rate at low density for the two monitored stocks from this area (Nashwaak River, LaHave River) which contrasts with the modelled results for two other stocks in this area without contemporary data (Big Salmon River, Pollett River) for which these low productivity states were unlikely.

Generally stationary conditions in freshwater contrast strongly with the large reductions in sea survival that began in the mid to late 1980s for Atlantic salmon stocks in eastern Canada and Europe (Chaput 2012). The reduced sea survivals have persisted for several decades and there are no indications to date of any return to pre-1990 sea survival levels. If marine productivity has declined but freshwater productivity has not, consideration could be given to using only the freshwater portion of the life cycle to estimate reference points, or estimating adult recruitment based on a historically productive period.

There is evidence of autocorrelation in the stock and recruitment dynamics of several stocks in the monitored egg to smolt time series data. If autocorrelation is present, the variance is underestimated and consequently the limit reference point based on the probability of achieving a minimum level of smolt production will also be underestimated. Adding autocorrelation to the stock and recruitment model would be an important addition.

Reference points defined on the basis of freshwater dynamics only do not account for the differences and changes in marine return rates (which are a proxies for marine survival) of 1SW and MSW salmon and the lifetime reproductive rate of the stock is not considered. Under conditions of reduced marine survival, achieving spawning escapement at the LRP level does not guarantee that the subsequent adult recruitment will be sufficient to replace the spawners or meet the LRP. In these cases, to ensure that the LRP is respected, a higher spawning escapement may be advised.

CONCLUSIONS AND ADVICE

The Limit Reference Point can be defined on the basis of maintaining production from freshwater. Maintaining freshwater production provides some assurance for producing sufficient numbers of adult returns to ensure the diversity of adult phenotypes and genetic variability. At a minimum, the LRP (S_{LRP}) is defined as the abundance of spawners that results in less than 25% chance of recruitment (as smolts or adults) being less than half of maximum recruitment. The 25% risk level is provided as a default value in the absence of other guidance from management.

No recommendation for a specific Upper Stock Reference is made. The choice of the USR will depend upon the objectives of the users and the risk profile and risk tolerance of the management strategy. At a minimum, the USR must be greater than the LRP and there should be a very low probability (<5%) of the recruitment falling below the LRP when the stock at USR is exploited at the maximum removal rate.

To conform to the PA policy (DFO 2009a) the maximum removal rate in the healthy zone should not exceed the value corresponding to the removal at maximum sustainable yield (F_{MSY}). The maximum removal rate in the healthy zone could be calculated once the upper stock reference level is defined.

Changes in productivity in either the freshwater or marine phase of the life cycle will have consequences on the derivation of reference points. If the average productivity conditions in freshwater have not changed over time, then limit reference points defined on the basis of maintaining a portion of the freshwater carrying capacity (a portion of Rmax) would be robust to concerns about changes in productivity in the marine phase. The candidate LRPs ($S_{0.5Rmax}$; S_{LRP}) are robust to changes in marine productivity.

Model fitting diagnostics repeatedly have shown that the Beverton-Holt model is a better representation of Atlantic salmon stock and recruitment dynamics than the Ricker model. For that reason, model results from Beverton-Holt are preferred to those from Ricker. Beverton-Holt models generally estimate higher survival rates at the origin than Ricker models. The slope at the origin is a key stock and recruitment dynamic parameter and the LRP value is inversely related to the slope at the origin.

Full life cycle data represented by adult to adult time series will be required to define the Upper Stock Reference point and the maximum removal rate reference point. The reconstruction of these data sets must take account of fisheries removals, repeat spawning components, and hatchery stocking.

It is not possible to obtain stock and recruitment data from all the rivers with Atlantic salmon populations in eastern Canada. The use of a Hierarchical Bayesian Model framework is an excellent approach for addressing exchangeability and transfer of reference points to unmonitored and data-poor populations. The transfer of reference points requires that the covariates which are used to model the stock and recruitment parameters are equally available in both the monitored and unmonitored populations. Covariates that could be used include the amount of habitat, the latitude of the river, the presence and amount of lacustrine habitat, the mean age of smolts and the proportion of the eggs which are contributed by large (multi-sea-winter) salmon.

The appropriateness of transporting reference points to rivers which are larger and smaller than those included in the stock and recruitment analyses is not known. For small rivers with small spawner population sizes, other considerations based on effective population sizes and maintaining genetic variability should be considered.

SOURCES OF INFORMATION

This Science Advisory Report is from the February 11-13, 2014 zonal peer review meeting on the Development of Reference Points for Atlantic Salmon that Conform to the Precautionary Approach. Additional publications from this meeting will be posted on the Fisheries and Oceans Canada (DFO) Science Advisory Schedule as they become available.

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ISSN 1919-5087

Correct Citation for this Publication:

DFO. 2015. Development of reference points for Atlantic salmon (*Salmo salar*) that conform to the Precautionary Approach. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2015/058.

Aussi disponible en français :

MPO. 2015. Élaboration de points de référence pour le saumon de l'Atlantique (Salmo salar) conformes à l'approche de précaution. Secr. can. de consult. sci. du MPO, Avis sci. 2015/058.