



Fisheries and Oceans
Canada

Science

Pêches et Océans
Canada

Sciences

C S A S

Canadian Science Advisory Secretariat

Research Document 2009/058

S C C S

Secrétariat canadien de consultation scientifique

Document de recherche 2009/058

Indicators of Status and Benchmarks for Conservation Units in Canada's Wild Salmon Policy

Indicateurs de l'état des stocks et repères à l'intention des unités de conservation dans le cadre de la Politique concernant le saumon sauvage (PSS) du Canada

Carrie A. Holt, Alan Cass, Blair Holtby, Brian Riddell

Fisheries and Oceans Canada
Pacific Biological Station
3190 Hammond Bay Road
Nanaimo, BC V9T 6N7

This series documents the scientific basis for the evaluation of aquatic resources and ecosystems in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

La présente série documente les fondements scientifiques des évaluations des ressources et des écosystèmes aquatiques du Canada. Elle traite des problèmes courants selon les échéanciers dictés. Les documents qu'elle contient ne doivent pas être considérés comme des énoncés définitifs sur les sujets traités, mais plutôt comme des rapports d'étape sur les études en cours.

Research documents are produced in the official language in which they are provided to the Secretariat.

Les documents de recherche sont publiés dans la langue officielle utilisée dans le manuscrit envoyé au Secrétariat.

This document is available on the Internet at:

<http://www.dfo-mpo.gc.ca/csas/>

Ce document est disponible sur l'Internet à:

ISSN 1499-3848 (Printed / Imprimé)
ISSN 1919-5044 (Online / En ligne)

© Her Majesty the Queen in Right of Canada, 2009
© Sa Majesté la Reine du Chef du Canada, 2009

Canada

TABLE OF CONTENTS

1.	GLOSSARY	vii
2.	INTRODUCTION	1
2.1	A conceptual assessment framework	1
2.2	Benchmarks and Biological Reference Points	2
2.3	Benchmarks and the role of Science	3
2.4	Idealized framework for determining precautionary lower benchmarks	4
2.5	WSP framework for status determination	6
2.5.1	Identifying benchmarks	6
2.5.2	Indicators of status, incorporating uncertainties	8
2.5.3	Risk tolerance	11
2.6	Comparison to other assessment frameworks	12
2.7	Assessment of biological production status and enhancement	13
3.	Specific metrics to assess status	14
3.1	Spawner abundances	14
3.2	Trends in spawners	19
3.3	Distribution	20
3.3.1	Distribution of spawners among groups	21
3.3.2	Distribution of spawners among habitat types	25
3.3.3	Distribution of time-trends in spawner abundances	25
3.3.4	Spatial structure	26
3.4	Fishing mortality	27
3.5	Incorporating uncertainties into assessments	29
3.5.1	A qualitative approach for incorporating uncertainties	29
3.5.2	Simulation modelling to incorporate uncertainties and evaluate lower benchmarks	31
3.6	Non-stationarity	33
3.7	Data requirements	33
4.	APPLICATION OF BENCHMARKS TO TWO EXAMPLE CUs	36
4.1	Takla/Trembleur sockeye salmon	36
4.1.1	Data	36
4.1.2	Indicators of status	36
4.2	Hecate Strait Lowlands odd-year pink salmon	38
4.2.1	Data	38
4.2.2	Indicators of status:	38
5.	NEXT STEPS	39
6.	ACKNOWLEDGMENTS	40
7.	LITERATURE CITED	41
8.	APPENDICES	47

TABLE OF FIGURES

Figure 1. A hypothetical relationship between a lower benchmark (S_{LBM}) and the probability of achieving a target within a specified time. The deterministic S_{LBM} is the level of spawner abundance such that the target would be attained with certainty within the specified time following the particular management if there was no uncertainty, i.e., perfect knowledge. The precautionary S_{LBM} accounts for uncertainty in achieving the target.....	3
Figure 2. A diagram of the nine steps in an idealized framework for specifying a precautionary lower benchmark (see Table 1).....	6
Figure 3. Benchmarks and zones of biological status to be determined for each conservation unit (taken from the Wild Salmon Policy).....	7
Figure 4. Hierarchy for the assessment of biological status of Conservation Units, including four classes of indicators, quantifiable metrics within classes, and benchmarks on each metric... 9	9
Figure 5. Stock-recruitment relationship (solid black curve) for an example Conservation Unit with candidate benchmarks marked on the top horizontal axis: spawners at maximum sustained yield, S_{MSY} (upper benchmark, thick vertical solid line), 80% of S_{MSY} (upper benchmark, thin vertical solid line), spawner at 50% of the recruitment of S_{MSY} (lower benchmark, vertical short-dashed line), 40% of S_{MSY} (lower benchmark, vertical dotted line), and spawner abundance resulting in recovery to S_{MSY} in one generation in the absence of fishing under equilibrium conditions, S_{gen} (lower benchmark, vertical long-dashed line). 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 marked on the right vertical axis (horizontal solid and short-dashed lines, respectively).....	16
Figure 6. Takla/Trembleur sockeye log-transformed spawner abundances ($\log_e(S)$; hollow circles) (1950 through 2008), $\log_e(S)$ values smoothed with a four-year running mean (solid circles), and the best-fit line to those points for the last three generations (solid line). The dotted line is the decline in $\log_e(S)$ associated with a COSEWIC threatened designation (30% decline in abundance over three generations). The maximum and mean smoothed $\log_e(S)$ values over the entire time series are shown on the right.	20
Figure 7. Mean number of counting locations (i.e., spawning groups) with abundances greater than 100 fish (running average over four years or one generation, $t-2$, $t-1$, t , and $t+1$) for the Takla/Trembleur sockeye CU.....	22
Figure 8. Proportion of the total spawner abundances at each counting location (i.e., spawning group), ranked from the highest proportion (bottom) to the lowest (top) (running average over one generation or four years, $t-2$, $t-1$, t , and $t+1$) for the Takla/Trembleur sockeye CU. The numbers inside the bars represent the minimum number of counting locations required to make up 80% of the total abundance in each generation.	23
Figure 9. Cumulative proportion of total spawners for each spawning group, ranked in decreasing order of abundance for the four most recent generations of spawners in the Takla/Trembleur CU. AUC is area under the curve.	24
Figure 10. Histogram of linear rates of change of log-transformed spawner abundances, smoothed with a four-year running mean for all counting locations (spawning groups) within the Takla/Trembleur sockeye CU. Only counting locations with <50% missing data points over the last 15 years were included. The linear rate of change associated with 20% and 30% declines in abundances over three generations are shown with dotted and dashed lines, respectively. 92.3% of counting locations had rates of declines greater than those that required for COSEWIC vulnerable designation (i.e., greater than 30% decline).	26
Figure 11. An example two-dimensional assessment rule to combine information on biological status (X-axis) with the level of uncertainty in that status (Y-axis). The colour of the cell indicates the overall status that combines information on biological status and uncertainty.31	31

Correct citation for this publication:

Holt, C., Cass, A., Holtby, B., and Riddell, B. 2009. Indicators of status and benchmarks for conservation units in Canada's Wild Salmon Policy. DFO Can. Sci. Advis. Sec. Res. Doc. 2009/058. viii + 74 p.

ABSTRACT

The goal of Canada's Wild Salmon Policy (WSP) is to restore and maintain healthy and diverse salmon populations and their habitats for the benefit and enjoyment of the people of Canada in perpetuity. To achieve that goal, the WSP requires that biological status be assessed for all geographically, ecologically, and genetically distinct populations, or Conservation Units (CUs). One component of that assessment is identifying quantifiable metrics of biological status and benchmarks along those metrics. Here, we provide a toolkit of metrics and benchmarks of status, which will set the stage for future CU assessments. Specifically, we propose a multi-criteria approach for assessing status that uses information on current abundances, trends in abundance over time, distribution of spawners, and fishing mortality relative to stock productivity. That approach captures the multiple dimensions of population status that will be important to achieve WSP goals better than assessments based on abundances alone. Furthermore, any redundancy in information content among criteria may allow for increased flexibility when assessing stocks that differ widely in data quantity and quality. Here, we identify quantifiable metrics and candidate benchmarks drawn from the scientific literature and previous management experience. Using a simulation model, we further evaluate a subset of those benchmarks on two performance metrics: the probability of extirpation over the long term and the probability of recovery to a target. Finally, we apply those metrics and candidate benchmarks to two example CUs, Takla/Trembleur sockeye salmon (Early Stuart run-timing group of the Fraser River) and Hecate Strait Lowlands pink salmon (odd year).

RÉSUMÉ

Le but de la Politique concernant le saumon sauvage (PSS) du Canada vise à rétablir et de maintenir la santé et la diversité des populations de saumon et de leurs habitats, pour le bénéfice et le plaisir durables des Canadiens et Canadiennes. Pour réaliser l'objectif de la PSS, on doit évaluer la situation biologique de toutes les populations, ou des unités de conservation (UC), distinctes du point de vue géographique, écologique et génétique. Un des volets de cette évaluation consiste à préciser des mesures quantifiables de la situation biologique et des repères correspondants. Nous offrons ici une boîte à outils de mesures et de repères de la situation qui définissent les balises des futures évaluations des UC. De façon plus précise, nous proposons une approche à plusieurs variables pour l'évaluation de la situation qui fait appel aux renseignements sur l'abondance actuelle, aux tendances de l'abondance au fil du temps, à la répartition des géniteurs et à la mortalité par pêche en lien avec la productivité des stocks. Cette approche tient compte des multiples dimensions de la situation de la population, importantes pour l'atteinte des buts de la PSS, mieux que ne le feraient des évaluations fondées seulement sur l'abondance. En outre, toute redondance dans le contenu de l'information des critères permettrait une plus grande souplesse dans l'évaluation des stocks pour lesquels les données diffèrent considérablement sur le plan de la quantité et de la qualité. Nous précisons ici des mesures quantifiables et des repères candidats fondés sur la documentation scientifique et les expériences de gestion antérieures. À l'aide d'un modèle de simulation, nous évaluons plus à fond un sous-ensemble de ces repères en fonction de deux mesures de rendement : la probabilité de disparition de l'espèce d'un endroit donné à long terme et la probabilité de rétablissement par rapport à un objectif. Enfin, nous appliquons ces mesures et ces repères candidats à deux UC témoins, le saumon rouge des lacs Takla et Trembleur (groupe de remontes précoces de la Stuart du fleuve Fraser) et le saumon rose des basses terres du détroit d'Hécate (année impaire).

1. GLOSSARY

Benchmark: synonymous with biological reference point.

Biological Reference Point (BRP): a biological benchmark against which the attributes of a stock (e.g., abundance or fishing mortality rate) can be measured in order to determine its status.

Conservation Unit (CU): a group of wild salmon sufficiently isolated from other groups that, if lost, is very unlikely to recolonize naturally within an acceptable time frame (e.g., a human lifetime or a specified number of salmon generations).

COSEWIC: Committee on the Status of Endangered Wildlife in Canada.

Depensatory mortality: mortality rate that increases as the size of the population decreases.

Diversity (of salmon): the genetic variation and adaptations to different environments that have accumulated between populations of salmon (defined by the Wild Salmon Policy).

Inbreeding depression: Mating or crossing of individuals more closely related than average pairs in a population resulting in reduced fitness of progeny.

Lower benchmark: a reference point in biological status associated with significant losses in production between the Amber and Red zones, and which allows for a substantial buffer between it and any level of abundance that could lead to a CU being considered at risk of extinction by COSEWIC.

Metric: a quantifiable measure.

Production model: a quantitative representation of the production of recruits in one generation from spawners in the previous generation.

Productivity: number of recruits produced per spawner.

Risk: magnitude of a negative outcome weighted by its probability of occurrence.

Risk tolerance: attitude toward uncertainties in the occurrence and/or magnitude of a negative outcome.

Spatial structure: geographic relationship among spawning groups.

Spawning group: a sub-population within a CU, analogous to a counting location.

Upper benchmark: (or higher benchmark) a reference point in biological status associated with harvests at the level expected to provide, on an average annual basis, the maximum catch for a CU, given existing environmental conditions.

Wild salmon: salmon that have spent their entire life cycle in the wild and originate from parents that were also produced by natural spawning and continuously lived in the wild.

2. INTRODUCTION

“The goal of the Wild Salmon Policy is to restore and maintain healthy and diverse salmon populations and their habitats for the benefit and enjoyment of the people of Canada in perpetuity.”

~Wild Salmon Policy 2005

To achieve its goal, the Wild Salmon Policy (WSP) describes several strategies that will be adopted, the first of which is standardized monitoring of salmon status (Fisheries and Oceans Canada, 2005)(p.16-19). There are three action items under that strategy. The first item, the identification of Conservation Units (CU), has been completed (Holtby and Ciruna, 2007). The second action step requires the development of criteria to assess CUs and the identification of benchmarks to represent their biological status. The third action item is the actual determination of biological status for each CU. This document addresses the first part of the second item, namely, an examination of the criteria that are available for determining the status of a CU. Our overall goal is to provide a toolkit of metrics and benchmarks of biological status, which will set the stage for future assessments of CUs.

In the Introduction, we begin by attempting to clarify the bewildering terminology involved in any discussion of status. In Section 3, we outline quantifiable metrics for each class of indicators, candidate benchmarks drawn from the scientific literature and previous management experience, and a simulation model that evaluates performance of lower benchmarks on two criteria, probability of extirpation over the long term and probability of recovery to a target (see the Technical Documentation on the Evaluation of Benchmarks for Conservation Units in Canada's Wild Salmon Policy (Holt, 2009)). Using the simulation model we also compare the performance of lower benchmarks under various changes in productivity (to evaluate, for example, how precautionary benchmarks are given uncertainty in future trends in productivity, as well as uncertainties in other components of the fisheries system). In Section 4, the metrics and candidate benchmarks are applied to two example CUs, Takla/Trembleur sockeye salmon (Early Stuart run-timing group of the Fraser River) and Hecate Strait Lowlands pink salmon (odd year). Those two examples were chosen to demonstrate CUs with high quality (Takla/Trembleur) and poor quality (Hecate Strait Lowlands) data. Furthermore, Takla/Trembleur is of immediate management concern because of recent poor recruitments. Our intentions are to demonstrate the methodology developed in the previous sections, and not provide formal advice for those two CUs. We conclude with further steps required to assess status of CUs. As described in the WSP, benchmarks will "be determined on a case by case basis, depending on the species and types of information available" (p.18). Further work will be required to adapt these metrics and benchmarks to other CUs.

2.1 A conceptual assessment framework

We often confuse state and status because a reference frame is usually implicitly understood. If we were to declare that the temperature in a room was +10°X then nobody could determine the status of that room in the reference frame of human temperature preferences. If we were to then reveal that °X is a scale using Centigrade degrees relative to a

nominal value of 22°C, we would know immediately that the status of the room temperature was hot but not intolerably so¹. Revealing that the ambient noise level in the room was -45 dB(A) would indicate a quiet room but would not tell you whether there was enough light to read a book. In other words, to determine status one needs to specify a reference frame and a state variable and one or more benchmarks that are meaningful within the reference frame.

2.2 Benchmarks and Biological Reference Points

A biological reference point (BRP) is a benchmark against which an attribute of the stock (e.g., abundance) can be measured in order to determine its status (Caddy and Mahon, 1995). The two terms are used interchangeably in the fisheries literature, but, with the exception of this section, we use the term benchmark to be consistent with the Wild Salmon Policy. We use BRP only when referring to previous studies that used that term. Although reference points are often used to describe harvest rules (e.g., thresholds in abundances which trigger management actions), our description of benchmarks is intended describe zones of biological status only. Identifying harvest rules requires information on other habitat, ecological, and socio-economic factors not considered here (but included in Strategies 2, 3, and 4 of the Wild Salmon Policy, respectively).

Caddy and Mahon (1995) observed that BRPs are of two types. One type, which they termed a Target Reference Point or TRP, indicates “a state of a fishery and/or resource that is considered to be desirable and at which management action, whether during development or stock rebuilding should aim” (*ibid.* p. 8). The other type was termed a Threshold or Limit Reference Point (LRP), and “indicates a state of a fishery and/or a resource which is considered to be undesirable and which management action should avoid” (*ibid.* p. 8). These definitions are of conceptual conditions or states of a resource or of a fishery, and must subsequently be quantified to provide measurable targets or thresholds. In addition to the LRP and TRP, a Precautionary Reference Point (PRP) has also been defined (ICES, 1996). The PRP recognizes that the LRP defines a state that should be avoided and that it would be precautionary to instigate fisheries management responses before that state is reached so as to avoid it.

The LRP can be regarded as a benchmark giving information about a state of the resource that should be avoided to ensure that stocks and their exploitation remain within safe biological limits. Defined in this way the LRP is not prescriptive in any way. However, FAO's Code of Conduct for Responsible Fisheries (FAO, 1995) does link reference points to fisheries management actions as part of the Fisheries Precautionary Approach (*ibid.* p. 12-13). As the WSP makes abundantly clear, (e.g., p. 17) all sorts of considerations, of which stock state is just one, are made in managing fisheries. Consequently, the WSP benchmarks cannot be linked to any particular management action other than the very general ones of reducing or redirecting fisheries (*ibid.* p. 24) when it has been decided to reverse or stabilize a downward CU trajectory.

¹ Assuming that the person assessing status is familiar with °C, not old, in good health, and appropriately dressed.

2.3 Benchmarks and the role of Science

The proper role of Science is to determine the safe biological limit of the resource. That limit can be defined in a multitude of ways but, generally, it will be an abundance below which long-term average production would be compromised (a lower abundance on spawner abundances, or $S_{\text{lower benchmark}}$). Such a threshold will be determined within a specified production model for the resource, will be made with a set of assumptions, and should, as far as is possible, be free of any implicit assumptions of acceptable or unacceptable risk. This last attribute requires some explanation. In applying the model, there are many uncertainties. For example, because all models approximate nature, we are often not certain which production model is most appropriate. The parameter values of our particular model and the data used to estimate them are often highly uncertain. Describing and quantifying uncertainties has become very important in the provision of advice, but deciding what to do about them is the role of fisheries management. Why this is so is illustrated in Figure 1.

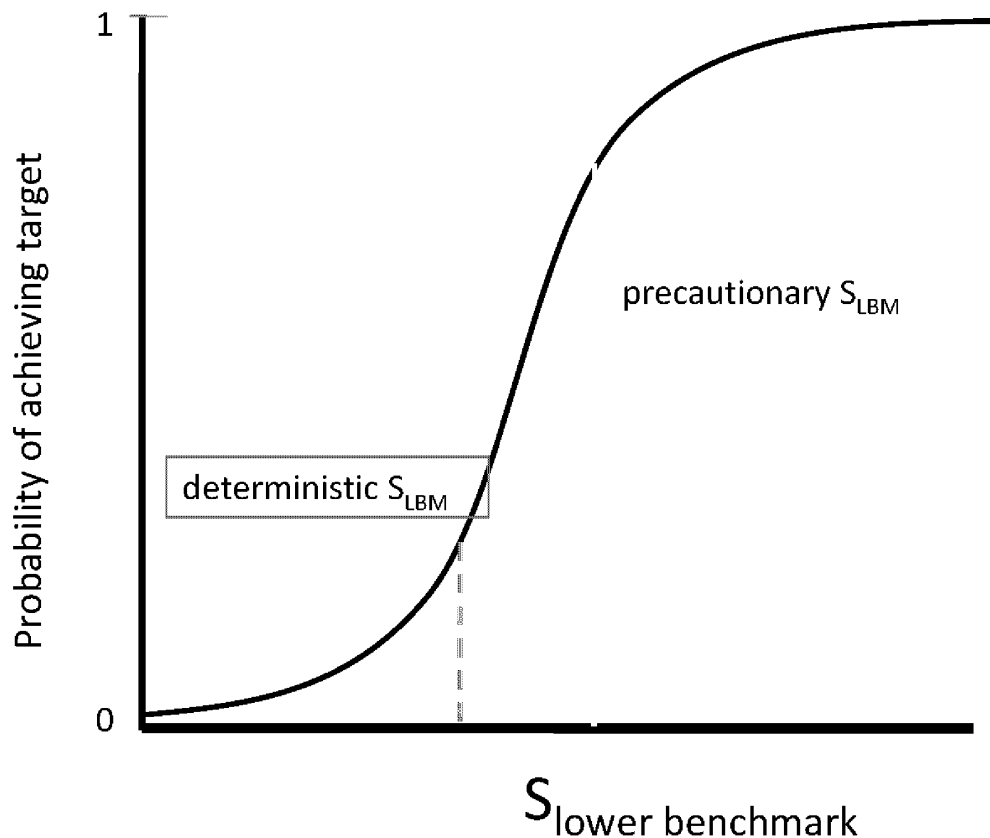


Figure 1. A hypothetical relationship between a lower benchmark (S_{LBM}) and the probability of achieving a target within a specified time. The deterministic S_{LBM} is the level of spawner abundance such that the target would be attained with certainty within the specified time following the particular management if there was no uncertainty,

i.e., perfect knowledge. The precautionary S_{LBM} accounts for uncertainty in achieving the target.

With a specified target, management action(s), and time allowed to achieve the target, and perfect knowledge of the fisheries system, it is possible to calculate the minimum level of abundance from which the population can successfully recover² (deterministic $S_{lower\ benchmark}$; Figure 1). Under the assumption of perfect knowledge, it would be known with certainty that recovery could not be achieved if there were fewer fish. As various types of uncertainty are incorporated into the model, it is possible to generate a relationship between the value of S where the specified management action was initiated and the probability that the target would be achieved within the specified time (precautionary $S_{lower\ benchmark}$; Figure 1). In addition to the model, the target, the allowable recovery time and all their associated uncertainties, the choice of a particular lower benchmark depends on the probability level assumed, i.e., the risk tolerance. Decisions about risk tolerance are largely political, although science should assist fisheries management in interpreting risk assessments (Hauge et al., 2007). The role for Science is to identify candidate benchmarks and, where possible, describe the probabilities of achieving the target under a set of assumptions (e.g., MSY in a given time frame in the absence of fishing) for each, and not to prescribe specific values. Alternatively, Science can provide a probability function that would specify a value of the lower benchmark given a level of risk tolerance (i.e., Figure 1 with axes reversed).

2.4 Idealized framework for determining precautionary lower benchmarks

An idealized framework for determining precautionary lower benchmarks is shown in Table 1 and Figure 2. The framework comprises nine steps which are each the responsibility of either Science or Fisheries Management. In this framework, fisheries management is a generic term for those requesting advice from Science. In the particular case of the WSP benchmarks, some of the steps are specified by the WSP itself.

The nine steps have already been mentioned but for clarity are tabulated here for an example reference frame specified as biological production. The inputs and outputs of each step are made specific to the WSP, as detailed in the Section 2.5.

² To recover: to reach or exceed target.

Table 1. The steps for determining a precautionary lower benchmark in an idealized assessment framework for an example reference frame (biological yield) and goal (maintenance of maximum yield). Other reference frames and goals are also possible. The providers are either Fisheries Management, FM, or Science.

Step	Provider	Input	Example output
1. reference frame	FM (WSP)	Policy specification	Specified as biological production (i.e., yield)
2. goal	FM (WSP)	Policy specification	Maintenance of maximum yield adjusted for current environmental conditions
3. time frame to achieve goal	FM	Unspecified	Number of years
4. fishery management actions	FM	Unspecified	Actions such as 10% total exploitation rate
5. model relating current state to a future state	Science	Production model	Ricker stock-recruitment model
6. deterministic upper benchmark	Science	WSP specification	Example, <i>MSY</i>
7. deterministic lower benchmark	Science	Outputs of steps 2, 3, 4, & 6	Lower benchmark
8. incorporate uncertainty into lower benchmark	Science	Quantification of known uncertainties including model choice, parameter estimation, current state, future state of modifiers (environment), and outcome/implementation uncertainty	Function relating possible values of the lower benchmark to the probability of achieving the goal within the time allowed
9. choice of risk tolerance	FM	Output of step 8	Selected lower benchmark

1. reference frame
2. goal
3. time frame for recovery
4. fishery management action(s)
5. production model
6. deterministic upper BM
7. deterministic lower BM
8. incorporate uncertainty

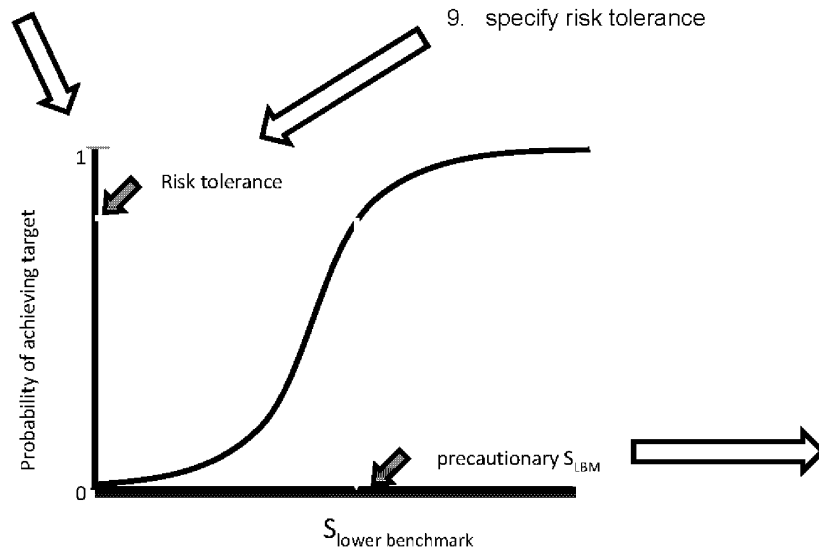


Figure 2. A diagram of the nine steps in an idealized framework for specifying a precautionary lower benchmark (see Table 1).

2.5 WSP framework for status determination

In this section we examine the framework for assessing biological status specified by the WSP (Fisheries and Oceans Canada, 2005)(p. 16-18), and begin populating Table 1 of the conceptual framework outlined in Section 2.4 for identifying benchmarks.

2.5.1 Identifying benchmarks

The Wild Salmon Policy describes an upper and a lower benchmark that delineate three zones in status: Green, Amber, and Red (Figure 3). Those benchmarks "identify when the biological production status of a CU has changed significantly" (Fisheries and Oceans Canada, 2005)(p.18). In particular, the upper benchmark could be "the level expected to provide, on an average annual basis, the maximum annual catch for a CU, given existing

environmental conditions", and where "there would not be a high probability of losing the CU" (p.18). In contrast, the lower benchmark 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 extinction by COSEWIC"(Fisheries and Oceans Canada, 2005)(p.18). To determine conservation status, COSEWIC considers a defined set of five criteria (Table 2 in (COSEWIC, 2006)). Of these criteria, only criterion D deals primarily with abundance (Table 2). In assessing the extinction risk of marine and anadromous fish species, COSEWIC has usually used criterion A (e.g., (e.g. COSEWIC, 2003a; COSEWIC, 2003b) since that criterion is most applicable to any species where the absolute abundance is either unknown or is too large for the other criteria to apply. Absolute abundance will not be known for many CUs of Pacific salmon since the methods used to estimate escapements mostly provide indices of abundance.

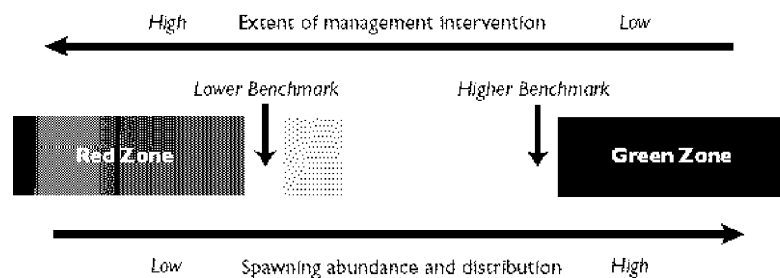


Figure 3. Benchmarks and zones of biological status to be determined for each conservation unit (taken from the Wild Salmon Policy).

Table 2. Details of the five criteria used by COSEWIC to infer conservation status and their general applicability to the WSP assessment framework (modified from (COSEWIC, 2006))

Criterion	Description
A. Declining Total Population	Status is determined by observed, estimated, inferred or suspected rates of decline in total population size over a defined period. Thresholds are dependent on whether or not the reduction or its causes have ceased or are understood or are reversible. Knowledge of declines can come from direct observation or may be inferred from such things as abundance indices, habitat loss, levels of exploitation, or other mortality factors.
B. Small distribution, and decline or fluctuation	Status is determined by either the extent of occurrence or the area of occupancy in conjunction with declines in either of them or in habitat quality, number of populations or number of individuals.
C. Small total population size and decline	Status is determined by both the number of mature individuals and either a continuing decline in number or a population structure that has most mature individuals in small and fragmented populations.
D. Very small population or restricted distribution	Status is determined primarily by the number of mature individuals but can be modified by the area of occupancy or human threats
E. Quantitative analysis	Status is determined by an estimated probability of extinction in the wild

In addition, the WSP states that the lower benchmark will use a "buffer [that] will account for uncertainty in data and control of harvest management" (p.18). By accounting for those uncertainties, the definition of the lower benchmark is consistent with the precautionary lower benchmark described in Section 2.4.

2.5.2 Indicators of status, incorporating uncertainties

To meet the requirements for benchmarks described in the WSP, we suggest four classes of indicators, the first of which, abundances (production), is clearly described in the WSP as one approach for assessing status (p. 17). To minimize COSEWIC listings (the second requirement), we suggest two additional classes of indicators: time trends in spawner abundances and distribution (the later is also suggested in the WSP as an indicator of status). Although COSEWIC criteria do not explicitly include fishing pressure relative to sustainable levels (i.e., relative to intrinsic productivity of the stock), we include that as a fourth class of indicators to assess the likelihood of continued trends in abundances (declines or increases) given current fishing effort. That fourth class differs from the first three in that it reflects an external stressor instead of an intrinsic property of the population. Figure 4 illustrates the hierarchical framework that relates indicators, quantifiable metrics within classes of

indicators (examples of which are shown in the right column of Table 3 and are described in more detail in Section 3), and benchmarks on each metric. The order in which we present classes of indicators is not meant to represent a priority for assessment. Instead the chosen metrics and their relative weight in the overall assessment will be CU-specific and vary according to data quality and quantity among other considerations.

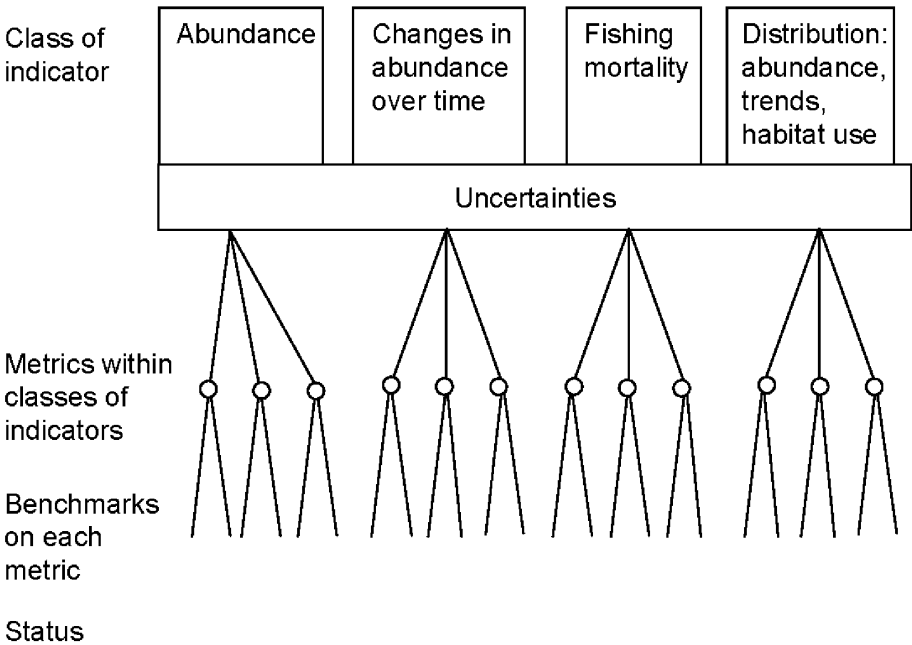


Figure 4. Hierarchy for the assessment of biological status of Conservation Units, including four classes of indicators, quantifiable metrics within classes, and benchmarks on each metric.

Table 3. List of classes of indicators and specific metrics to assess status of Conservation Units.

Class of indicator	Specific metric
Spawner abundance	Spawner abundance in the current year Geometric mean spawner abundance over the most recent generation
Trends in spawners	Reduction in spawner abundances over 3 generations or 10 years Probability that those declines are $\geq 25\%$ over 3 generations or 10 years Ratio of geometric mean of current generation to historical geometric mean (Pestal and Cass, 2007) Ratio of geometric mean of current generation to the highest generational geometric mean on record (Pestal and Cass, 2007)
Distribution	Number of spawning groups with abundances > 100 fish (or a percentage of total spawners), and change in that value over last 3 generations or 10 years Minimum number of spawning groups that comprise 80% of total abundance when ranked from most to least abundant, and change in that value over last 3 generations or 10 years Area under the curve of relationship between rank of spawning group (as a proportion of total number of groups) versus percent contribution of that group to the total abundance Proportion of spawning groups with a geometric mean abundance over the most recent generation with more than 1000 fish (adapted from, Interior Fraser Coho Recovery Team (2006)) Proportion of available habitat occupied by spawners Type of habitats used by spawners or juveniles (average stream order or ecoregion(s)), and change over time Proportion of spawning groups that have rates of change in abundances $\geq 30\%$ over 3 generations or 10 years Areal extent of spawners or juveniles in the CU, and changes over time
Fishing mortality	Fishing mortality in the current year Mean fishing mortality over the most recent generation

Uncertainties can be incorporated into status assessment (step 8 of the idealized assessment framework, Table 1) qualitatively by classifying the magnitude of uncertainties

into three zones (high, moderate and low), or quantitatively using a simulation model to evaluate probabilistic outcomes. For the qualitative method, the magnitude of measurement or observation errors is classified, in part, based on the method used to collect the data, such as visual surveys, fence counts, or mark-recapture experiments. Pestal and Cass (2007) provide a framework for classifying populations of sockeye salmon on the Fraser River according to the magnitude of uncertainty in the observed spawner data. We have adapted their methodology and the one from Crawford and Rumsey (2009) to classify CUs into the Red zone (high uncertainties), Amber zone (moderate uncertainties), and Green zone (low uncertainties), as described in more detail in Section 3.5.1.

A more rigorous and quantitative approach for accounting for multiples sources of uncertainties using probabilistic performance criteria (e.g. probability of achieving a goal or endpoint) is Monte Carlo simulation modelling. Moreover, one of the listing criteria for COSEWIC (criterion E) is derived from assessing the probability of extinction (i.e., a probabilistic criterion) using quantitative analyses such as simulation modelling. We used a simulation model that incorporated uncertainties in biological and management components of the fisheries system to evaluate lower benchmarks on two classes of indicators (spawner abundances and fishing mortality) with two performance criteria, the probability of extirpation to long term and probability of recovery to a target over one-three generation(s). For details on the structure of the simulation model and results, see the technical documentation on the Evaluation of Benchmarks for Conservation Units in Canada's Wild Salmon Policy (Holt, 2009). Further work will be required to develop models that relate performance metrics to benchmarks on the two remaining class of indicators, trends in spawner abundances and distribution of spawners.

2.5.3 Risk tolerance

"The determination of the lower benchmark, will include consideration of a risk tolerance" (Fisheries and Oceans Canada, 2005) (p.17). As discussed in Sections 2.3 and 2.4 consideration of risk tolerance is the responsibility of fisheries management and the adoption of any particular risk tolerance is the responsibility of the Minister of Fisheries and Oceans. Here we adapt a risk classification scheme for probabilities of population decline developed in DFO's "Fishery Decision-Making Framework Incorporating the Precautionary Approach" (2009), in order to categorize probabilities of realizing a specified outcome when evaluating lower benchmarks (Table 4).

Table 4. Example risk classification scheme adapted from DFO's "Fishery Decision-making Framework Incorporating the Precautionary Approach" (2009) for probabilities of realizing an outcome.

Probability of an outcome	Risk category
Less than 5%	Very low
5%-25%	Low
25%-50%	Moderately low
~50%	Neutral
50%-75%	Moderately low
75%-95%	High
>95%	Very high

This classification is similar to one provided by the Northwest Atlantic Fisheries Organization to aid in setting limit reference points (very low probability defined as $\leq 5\%$ and low probability defined as $\leq 20\%$) (Northwest Atlantic Fisheries Organization, 2004).

In the absence of alternative guidelines for categorizing probabilities of realizing outcomes, we follow the classification scheme in Table 4 when evaluating probabilities of extirpation over the long term and probabilities of recovery to a target for CUs. This scheme represents only one possible example; alternative guidelines on risk classification that are directly linked to stakeholder risk tolerances should be considered by fisheries management. To emphasize, Science is limited to providing a function that relates any plausible value of the benchmark to the probability of meeting a criterion (e.g., recovery to a target or extirpation). Fisheries management is responsible for identifying risk tolerance.

In Canada, Pestal and Cass (2007) provide an assessment framework for Fraser Rivers sockeye salmon based on three considerations: status, vulnerability, and direct human impacts, in order to "establish a consistent, transparent framework that translates general policies and objectives into practical guidelines for prioritizing assessment projects" (p.6). Although their goal is broad-reaching, one of the policies they consider is Canada's Wild Salmon Policy. Their indicators of status, vulnerability, and direct human impacts overlap with the indicators identified here. In particular, their measure of status includes current abundances, changes in abundance over time, and distribution over space; vulnerability includes productivity and diversity; and direct human impacts include fishing mortality.

2.6 Comparison to other assessment frameworks

The assessment framework identified here is consistent with previous frameworks for assessing viability of Pacific salmon stocks. For example, in the United States, technical recovery teams (TRTs) have been tasked with identifying performance conditions (viability criteria) that when met, indicate that a population is not likely to go extinct (McElhany et al., 2000). Although the goals of the TRTs differ somewhat from those of the Wild Salmon Policy, both include consideration of probabilities of extirpation. In one study by the TRTs, McElhany et al. (2006) identified what they considered to be the most important dimensions for population viability: abundance and productivity, spatial structure (including habitat use), and diversity. The last dimension, diversity, considers the minimum abundances required to

maintain genetic diversity for long-term population persistence. Although diversity is not explicitly included in our list of indicators, COSEWIC criteria D (very small population size, of <1000 fish for a "threatened" listing) allows for sufficient genetic diversity for long-term population persistence if populations are above that level (Bradford and Wood, 2004) (though Reed et al. (2003) suggest that 7000 is a more realistic minimum population size for long-term persistence).

2.7 Assessment of biological production status and enhancement

The roles of salmonid enhancement in conservation and production in Pacific Canada are discussed in the WSP and assurance is given that possible interactions of wild and enhanced fish will be managed through integrated planning (Strategy 4, p. 24-31) and through appropriate technical practices at enhancement facilities. While these generalities and assurances are quite appropriate for a policy document, the more mundane question of how to deal with enhanced fish in a status assessment are left open.

This general question is important to a status determination because the enhancement methods used in Pacific Canada and the locations of enhancement activity more often than not result in mixtures of wild and enhanced fish spawning naturally. However, the WSP is quite specific in restricting the policy, and hence the determination of status, to fish that are wild by definition. That definition (see glossary) has two important implications. First, the definition cannot be easily operationalized because the offspring of enhanced fish that spawned in the wild cannot be distinguished from wild fish. Second, given the levels and duration of enhancement in some areas, it is unlikely that there are any wild salmon remaining. For example, levels of enhancement in most chinook CUs around the Strait of Georgia have been intensive for decades and it is likely that few of the natural spawners in rivers like the Cowichan and Nanaimo Rivers are wild.

Populations that are dominated by hatcheries (i.e., with little or no contribution of wild fish) are not considered within CUs (e.g., hatchery production on Robertson Creek chinook salmon on the west coast of Vancouver Island are not included in neighbouring CUs) (Holtby and Ciruna, 2007), and are therefore omitted from WSP assessments. For populations that include both wild and hatchery-origin fish, we are unable to find any completely satisfactory manner to assess status. We could exclude those CUs where levels and duration of historical hatchery production are likely to have resulted in the extirpation or near-extirpation of wild fish. We doubt that this would seem reasonable to most Canadians since it would remove perhaps a third of chinook CUs and a fifth of coho CUs from consideration. An alternative is to remove first generation hatchery-origin fish from recruitment time series, but that option does not adhere to the strict definition of wild salmon given in the WSP since those hatchery-origin fish would continue to be tallied in spawner time series in the subsequent generation (and the resulting recruitment). This approach would consider the productivity of fish spawning in the wild instead of wild fish (as defined by the Wild Salmon Policy), which we consider a reasonable compromise.

The WSP excludes fish produced from managed spawning channels. That definition cannot be operationalized because the produced fish are almost never marked (i.e., not even

the first-generation fish can be recognized) and because the spawning channels are usually small parts of larger systems and so the fish that use them are a mix of enhanced and wild fish. We propose to include these fish in both recruitment and spawner time series if the channel management did not exclude natural mate selection and imposed the same sorts of control that fisheries can produce³.

Although there are a growing number of demonstrations that enhanced salmon are less fit than their wild counterparts (e.g. Araki et al., 2007; Goodman, 2005; Heath et al., 2003; Hindar et al., 2006; Jonsson and Jonsson, 2006; Utter, 2004), hatchery practices in B.C. might avoid some of the effects (Heggenes et al., 2006). DFO biologists generally assert that there are no definitive studies in BC and Pacific salmon where hatchery practices are substantially different from those in the US and Europe (C. Cross, pers. comm., Habitat Enhancement Branch, Fisheries and Oceans Canada, Vancouver). Only Goodman (2005) provides some guidance on the possible safe limits to enhancement for avoiding catastrophic losses to fitness.

Another way in which enhanced production may affect wild fish is through increased competition for limited resources in the marine habitat, potentially resulting in reduced body size and/or survival overall, or worse, a greater reduction in the survival of wild fish because of the competitive superiority of hatchery fish. This effect was proposed as the reason for the increasing proportion of hatchery coho in the Strait of Georgia during the 1980's and 1990's (e.g. Sweeting et al., 2003). However, more recent trends from the same authors suggests that variation in the relative abundance of hatchery and wild coho is due to interactions of release timing and oceanographic variability rather than density dependence (Beamish et al., 2008).

Although evidence suggests that enhancement may have deleterious effects on the fitness and production of wild fish, there is insufficient information to proceed further at this time in incorporating levels of enhancement into assessments of status, aside from the exclusion of first-generation hatchery fish from the spawner and recruitment time series.

3. Specific metrics to assess status

3.1 Spawner abundances

For Pacific salmon, understanding the relationship between spawner abundances and recruitment is essential for identifying the level of spawners (or benchmark) below which yield is reduced. Despite well-known pitfalls of stock-recruitment models (e.g., biased parameter estimates resulting from short or uninformative data), they have long been used as a basis for management decisions (Walters and Korman, 2001). Approaches to address some of those problems have been developed, such as Bayesian analyses that incorporate prior information on carrying capacity (Walters and Korman, 2001) and state-space models that incorporate uncertainties in spawner data (Walters and Korman, 2001). We suggest deriving upper and lower benchmarks on spawner abundances from stock-recruit relationships using

³ Namely, control of spawner numbers and timing, both of which are actively controlled by fisheries.

prior information on carrying capacity (where available) in a Bayesian approach. However, for some CUs, recruitment does not show a compensatory response with spawner abundances (i.e., a spawner-recruitment relationship does not exist) and/or the assumption of log-normal variability in recruitment does not hold (S. Cox-Rogers, pers. comm.). In those cases, status may be assessed using other metrics of status, such as those related to trends in abundance or distribution over time, current productivity, or spawner abundances relative to estimates of capacity, as appropriate.

Spawner abundance at maximum sustainable yield, S_{MSY} , has been embraced by many as a "target reference point" for management (e.g., Irvine et al. (2001), Tompkins et al. (2005)), and is recommended by the UN as a rebuilding target for overfished stocks (UN Agreement on Straddling Fish Stocks and Highly Migratory Fish Stocks, Annex II). Although the Wild Salmon Policy provides S_{MSY} as an example upper benchmark delineating Green and Amber zones, DFO's Fishery Decision-Making Framework Incorporating the Precautionary Approach (2009) (or simply DFO's Decision-Making Framework) recommends an provisional upper reference point for management to delineate "healthy" and "cautious zones" of 80% of S_{MSY} . To be consistent with DFO's Decision-Making Framework, we recommend an upper benchmark to be equal to (or greater than) 80% of S_{MSY} . Below that spawner abundance, populations are not considered healthy by the Framework and should not be included in the Green zone of the WSP.

While agreement on upper benchmarks is relatively close, consensus on lower benchmarks delineating Amber and Red zones has not been reached. One possibility is spawner abundances at a specified fraction of MSY recruitment (e.g., 0.5, Figure 5, Table 5 for populations that exhibit a Ricker stock-recruitment relationship). DFO's Decision-Making Framework suggests a provisional lower reference point (delineating "critical" and "cautious" zones) of 40% of biomass (or spawner abundances) at MSY (Figure 5, Table 5). Alternatively, Myers et al. (1994) propose spawner abundances at 50% of maximum recruitment as a lower benchmark below which "recruitment to a fish stock is seriously reduced" (Table 5), and Johnston et al. (2002) propose a limit reference point at a level of spawners that would result in recovery to S_{MSY} within one generation in the absence of fishing, under equilibrium conditions (Figure 5, Table 5). Although the minimum spawner abundance from which the population has recovered has also been suggested as a lower benchmark (Irvine et al., 2001), there is no evidence that such a benchmark would leave a "substantial buffer" between it and spawner abundances associated with a high probability of extirpation, or that abundances would rebuild in the future as they did historically.

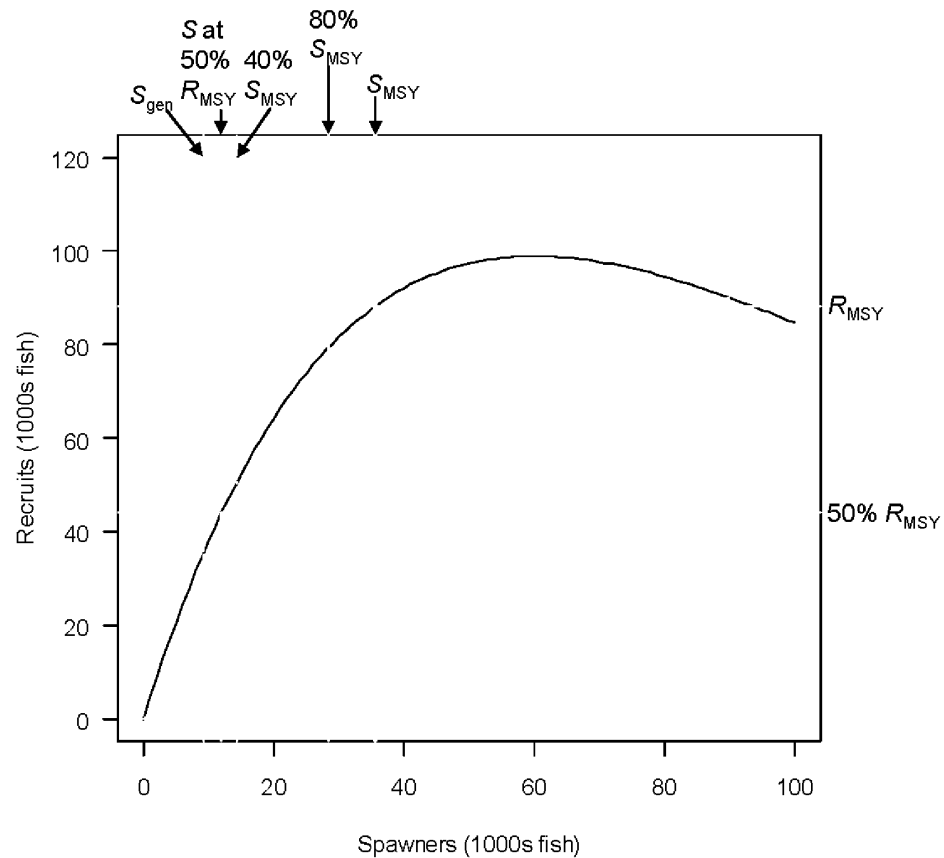


Figure 5. Stock-recruitment relationship (solid black curve) for an example Conservation Unit with candidate benchmarks marked on the top horizontal axis: spawners at maximum sustained yield, S_{MSY} (upper benchmark, thick vertical solid line), 80% of S_{MSY} (upper benchmark, thin vertical solid line), spawner at 50% of the recruitment of S_{MSY} (lower benchmark, vertical short-dashed line), 40% of S_{MSY} (lower benchmark, vertical dotted line), and spawner abundance resulting in recovery to S_{MSY} in one generation in the absence of fishing under equilibrium conditions, S_{gen} (lower benchmark, vertical long-dashed line). 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 marked on the right vertical axis (horizontal solid and short-dashed lines, respectively).

Table 5. Equations used to calculate benchmarks on spawner abundances. " a " is the productivity parameter of the Ricker spawner-recruitment relationship (i.e., $\log_e(\text{recruits/spawner})$ at low spawner abundances), and " b " is the spawner abundance at replacement (or equilibrium).

	Description	Label	Equation
Upper benchmark	Spawners at MSY	S_{MSY}	$S_{MSY} = b \cdot (0.5 - 0.07 \cdot a)$ (Hilborn and Walters, 1992; p.271)
	80% of spawners at MSY	80% S_{MSY}	
	90 th percentile of spawners at MSY	90 th percentile of spawners at MSY	From the posterior distribution of S_{MSY}
Lower benchmark	Spawners at 50% of MSY recruitment	S at 50% of R_{MSY}	$0.5 \cdot R_{MSY} = S' \cdot \exp(a \cdot (1 - S'/b))$, where S' is S at 50% of MSY and is solved numerically, and $R_{MSY} = S_{MSY} \cdot \exp(a \cdot (1 - S_{MSY}/b))$
	40% of spawner abundances at MSY	40% S_{MSY}	
	Spawners at 50% of maximum recruitment	S at 50% of R_{MAX} , S''	$0.5 \cdot R_{MAX} = S'' \cdot \exp(a \cdot (1 - S''/b))$, where S'' is S at 50% of R_{MAX} and is solved numerically, and $R_{MAX} = (b \cdot \exp(a - 1))/a$ (Ricker 1975)
	Spawners that would result in recovery to S_{MSY} in one generation in the absence of fishing	S_{gen}	$S_{MSY} = S_{gen} \cdot \exp(a \cdot (1 - S_{gen}/b))$, where S_{gen} is solved numerically
	90 th percentile of spawners at 50% of MSY recruitment	90 th percentile of spawners at 50% of MSY recruitment	From the posterior distribution of S at 50% of R_{MSY}

To incorporate uncertainty from inaccurate estimates of S_{MSY} (due to, for example, short time series of spawner and recruitment data) into the derivation of benchmarks, instead of the most-likely point estimate of S_{MSY} , the posterior probability distribution can be used. That distribution can be derived from Bayesian analyses that incorporate prior information on

spawner abundances at R_{MAX} (Appendix A, Fig. A 1, Fig. A 2, Fig. A 3, Fig. A 4, and Fig. A 5) or the productivity parameter. This approach is similar to one used by the Alaska Department of Fish and Game to account for uncertainty in management targets (Nelson et al., 2005) and by Bodtker et al. (2007) to evaluate escapement goals on Fraser River sockeye salmon. Careful consideration of the sensitivity of benchmark values to assumptions about the prior distribution will be required.

For some species and populations, the Ricker function may not be an appropriate representation of the spawner-recruit relationship because recruitment does not decline at high spawner abundances (i.e., overcompensation, a characteristic of the Ricker relationship, does not occur) or cycle-lines interact to create cyclic patterns in recruitment. In the first case, a Beverton-Holt recruitment function may better reflect asymptotic recruitment at high spawner abundances. Although some management parameters (e.g., S_{MSY}) and the related lower and upper benchmarks (e.g., 40% and 80% of S_{MSY}) can be calculated for the Beverton-Holt function (as described in Table 5 for the Ricker function), others cannot (e.g., S at R_{MAX}) (Hilborn and Walters, 1992) (p.272). For the second case, strong cyclic patterns in sockeye salmon recruitment in the Fraser River have prompted scientists to consider a Larkin model (Walters and Staley, 1987) when setting escapement goals for those stocks (Cass and Grout, 2006; Martell et al., 2008). That model includes the effects of biological interactions among cycle lines due to, for example, competition for food or common predators. Closed-form values of management parameters such as S_{MSY} that vary by cycle line are not available for the Larkin model. Numerical estimates for Fraser River stocks are currently being developed as part of DFO's Fraser River Sockeye Spawning Initiative to derive harvest control rules (A. Huang, Annacis Island, Fisheries and Oceans Canada), and are not estimated here. For demonstration purposes, we use the Ricker relationship as an example stock-recruitment model. However, that assumption was relaxed in simulation model that evaluated lower benchmarks.

When estimates of S_{MSY} are not available because recruitment and/or productivity data are missing, benchmarks can instead be derived from carrying capacity (the maximum recruitment that the freshwater habitat will support in the absence of fishing mortality) approximated from freshwater studies (e.g., Shortreed et al.(2001)). One possible lower benchmark is a percentage of carrying capacity, e.g., in the range of 10-20% as suggested by Johnston et al. (2002) as a "lower reference point" for B.C. steelhead, or 15% as applied to Skeena River sockeye salmon (Wood, 2004). In a similar way, an upper benchmark can be derived from a percentage of carrying capacity instead of S_{MSY} . For example, when the productivity parameter is 1.0 (~2.7 recruits/spawner at low spawner abundances), an upper benchmark of S_{MSY} is approximately equivalent to 40% of carrying capacity based on the relationship between S_{MSY} (derived in Table 5) and spawner abundances at maximum recruitment (equal to the ratio of spawner abundance at replacement and $\log_e(\text{recruits/spawners})$ at low spawners (Ricker, 1975)).

For some CUs where data on spawner abundances are not available or are of poor quality, fry or smolt abundances or body sizes may provide a rough indication of spawning status. For example, Bradford et al. (2000) used smolt and spawner density information to identify the carrying capacity of Black Creek coho salmon in units of smolts/km. In addition,

body sizes may correlate with spawner abundances insofar as density-dependent growth during freshwater stages results in small (large) juveniles when spawners are abundant (few) (B. Holtby, unpublished analyses). Furthermore, body condition of adults during return migration (as measured by body length and weight, physiological and genetic indicators of fish health, and/or the presence of parasites) may provide an indication of en-route and pre-spawning mortalities, and hence spawning success. Benchmarks for those metrics will be identified on a case-by-case basis where data exist.

3.2 Trends in spawners

We identified metrics of temporal trends in spawner abundances over the short term (the longer of three generations and ten years) and the extent of changes in spawner abundances over the long term (the historical record). Analyses based on recent data may be more appropriate if long-term climate or ecosystem changes prevent a CU from achieving historical unfished levels. On the other hand, those recent data may miss harvest-induced declines that have occurred over several decades, which are captured by long-term metrics. To identify underlying trends in spawner abundances independent of interannual "noise" (e.g., due to cyclic recruitment dynamics, and observation and assessment errors), spawner abundances were log-transformed and then smoothed with a four-year (or one generation) running mean.

One possible lower benchmark derived from short-term linear trends (i.e., the slope, or rate of change, of the line of best fit over recent years) is the linear trend associated with a reduction in abundances of 25% over the longer of 3 generations and 10 years, a proportional reduction that is lower than that resulting in a COSEWIC threatened listing (30% decline in abundance of spawners where causes are not known or are irreversible (COSEWIC, 2006)) (e.g., Figure 6 for one example CU, Takla/Trembleur- Early Stuart Run sockeye salmon). One possible upper benchmark is the linear trend associated with a fraction (e.g., 3/5) of that reduction (or, equivalently, a 15% reduction in abundance of spawners over the same period). Uncertainty in the assessment of trends due to incomplete sampling of CUs can be quantified using Bayesian estimation. In particular, the posterior probability distribution of the magnitude of declines can be estimated. Rather than the maximum likelihood estimates of the slope, a specified percentile (e.g., 10th) of the posterior probability distribution will better reflect the degree of uncertainty in those declines (e.g., Appendix A; Fig. A 5). A benchmark based on the 10th percentile of the slope will be smaller (representing a smaller decline in spawner abundances) than a benchmark that ignores uncertainty. Alternatively, sensitivity analyses can be used to assess how robust the results are to the inclusion or exclusion of counting locations with missing values.

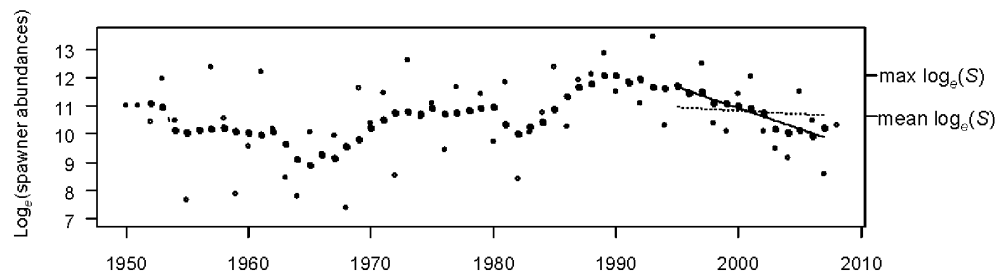


Figure 6. Takla/Trembleur sockeye log-transformed spawner abundances ($\log_e(S)$; hollow circles) (1950 through 2008), $\log_e(S)$ values smoothed with a four-year running mean (solid circles), and the best-fit line to those points for the last three generations (solid line). The dotted line is the decline in $\log_e(S)$ associated with a 25% decline over 3 generations (i.e., the lower benchmark). The maximum and mean smoothed $\log_e(S)$ values over the entire time series are shown on the right.

To capture long-term changes in abundances, Pestal and Cass (2007) suggest two metrics based on the ratio of the geometric mean of the current generation to two baselines: the long-term geometric mean and the highest generational mean. In addition, they propose a ratio of $\frac{1}{2}$ to delineate populations of moderate and low status (i.e., Green and Amber zones), and $\frac{1}{4}$ to delineate those of low and very low status (i.e., Amber and Red zones) based on a qualitative evaluation of expert opinion. These, as well as other metrics of rates of change in spawner abundances are currently under evaluation (Erin Porszt, School of Resource and Environmental Management, Simon Fraser University, Burnaby, British Columbia, V5A1S6).

3.3 Distribution

When multiple populations exist within a CU, the status of the "network of spawning groups" may be more important than the status of the aggregate or any individual population (i.e., spawning group). In particular, the long-term viability of a CU may depend on the genetic, habitat, and life-history diversity of the resident fish, because that diversity will provide the capacity for natural recolonization of populations that may be lost (McElhany et al., 2006). Although CUs are defined as mutually interchangeable groups of wild salmon with similar habitats, genetic structure, and ecological characteristics, some types and/or levels of diversity were not considered in CU designation (Holtby and Ciruna, 2007) and may be important for their long-term persistence. For example, to identify boundaries among CUs, habitats were classified into freshwater and marine adaptive zones based on two ecological classification schemes that considered patterns of climate, drainage density, gradient, hydrological characteristics, connectivity, marine circulation patterns (e.g., fjords and straights), among other factors (Augerot et al., 1999; Ciruna and Butterfield, 2005). Fine-scale features of habitats such as patterns of stream, lake, and wetland morphology and drainage basins $< 22,000 \text{ km}^2$ were not considered (Holtby and Ciruna, 2007), but may be

associated with adaptations of fish to their local environment (Kitanishi et al., 2009; Neville et al., 2006; Tallman and Healey, 1994). The CU classification scheme also used information on genetic population structure obtained from the analysis of microsatellite loci in hierarchical classification trees, calculated using clustering algorithms (Terry Beacham and the Pacific Biological Station Genetics Lab, Fisheries and Oceans Canada, Nanaimo, B.C., V9T 6N7). Although the maximum number of levels generated in the hierarchical classification trees was five, Holtby and Ciruna (2007) found that the third and fourth levels captured the major population groupings. Genetic variability at finer scales (fourth and fifth levels, i.e., within CUs) may represent adaptive and heritable diversity if that variability is associated with phenotypic or life-history traits. Information on ecological considerations such as spawn timing, migration, and smolt age was also included in the CU classification scheme when genetic information (to the level considered in the hierarchical classification trees) suggested CU boundaries that differed from habitat-derived boundaries. Therefore, variability in life-history traits associated with fine-scale genetic variability (fourth or fifth levels) was not considered, and may exist within CUs.

Although monitoring all components of diversity (habitat, genetic, and ecological) may be logistically difficult, indicators of distribution that use data on the arrangement, habitat, time trends in abundance, and location of spawning groups may provide surrogate measures of that diversity. We have identified candidate metrics that reflect four types of distribution: (1) distribution of spawners among spawning groups (or counting locations), e.g., Walters and Cahoon (1985), (2) distribution of spawners among habitat types (McElhany et al., 2006), (3) distribution in temporal trends, as described for Bristol Bay sockeye salmon populations (Rogers and Schindler, 2008), and (4) spatial structure of spawning groups, e.g., distance between spawning groups (McElhany et al., 2006). The example metrics we present are preliminary; further work is currently underway to identify metrics of distribution that reflect the diversity of spawning groups within CUs (S. Peacock and C. Holt, Pacific Biological Station, Fisheries and Oceans Canada). Our example metrics are meant to supplement, and not replace, other information currently available on genetic, habitat, and ecological diversity within CUs.

3.3.1 Distribution of spawners among groups

Most simply, the distribution of spawners across locations can be measured by the number of extant locations of spawners (one metric used by COSEWIC to assess distributional status) (COSEWIC, 2006). Two additional metrics of spawner distribution are the number of spawning groups with abundances >100 fish (e.g., Figure 7) (or the number with more than a certain percentage of the total spawner abundance to the CU, e.g., 5%), and the number of groups that contain some percentage (e.g., 80%) of the total abundance when ranked from most to least abundant. These metrics have an advantage over the simple count of spawning groups, of differentiating CUs that have a number of equally abundant spawning groups from those with a single dominant group and a number of very small groups. For highly concentrated CUs, when ranked from most to least abundant, the top 80% of the total abundance will be comprised of only one spawning group; for dispersed CUs, that 80% will consist of several (e.g., Figure 8). Trends over time in distribution may indicate changes in the locations or spawners or alterations in spatial structure. However, care must be taken to

ensure that apparent changes in distribution are due to changes in the status of the network of spawning groups rather than inconsistent sampling coverage over time.

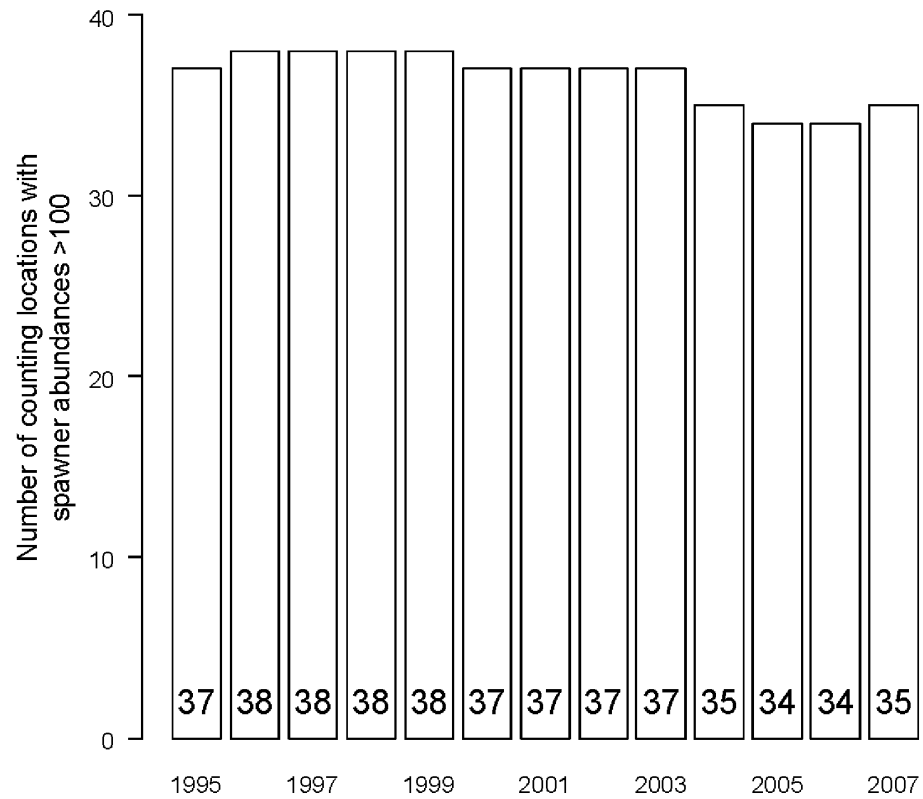


Figure 7. Mean number of counting locations (i.e., spawning groups) with abundances greater than 100 fish (running average over four years or one generation, $t-2$, $t-1$, t , and $t+1$) for the Takla/Trembleur sockeye CU.

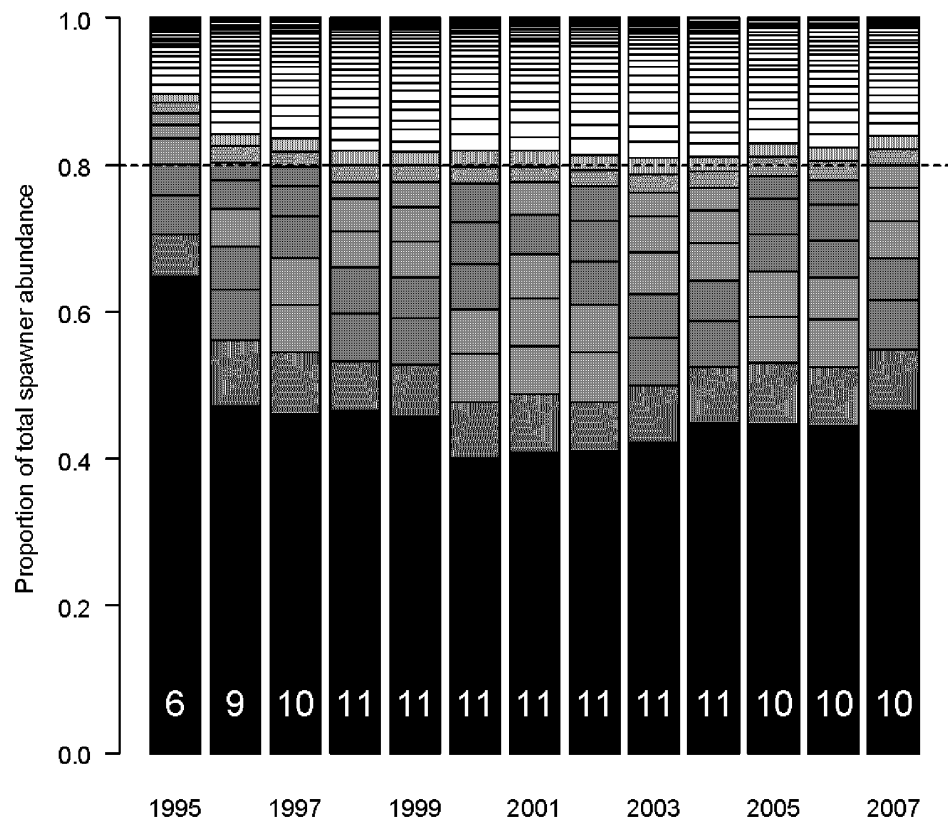


Figure 8. Proportion of the total spawner abundances at each counting location (i.e., spawning group), ranked from the highest proportion (bottom) to the lowest (top) (running average over one generation or four years, $t-2$, $t-1$, t , and $t+1$) for the Takla/Trembleur sockeye CU. The numbers inside the bars represent the minimum number of counting locations required to make up 80% of the total abundance in each generation.

An alternative metric of distribution proposed by Walters and Cahoon (1985) is the cumulative escapement over counting locations ranked by abundance (e.g., Figure 9). The area under the curve (AUC) of that relationship reflects the degree of concentration of spawners among groups. CUs with highly equitable distributions (i.e., all spawning groups at equal abundances) will have AUC values of 0.5 (representing a diagonal line from the origin to (1,1)); CUs with highly concentrated distributions will have values closer to 1.0

(representing a concave curve between the origin and (1,1) passing near (0,1)). AUC values of less than 0.5 are impossible due to the rank order of the X-axis.

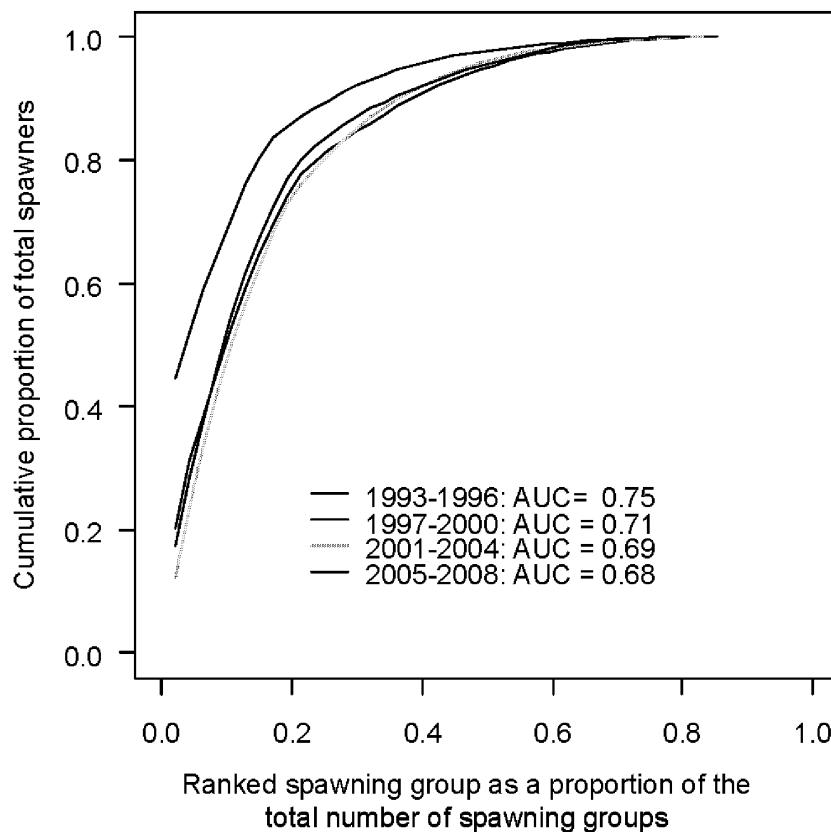


Figure 9. Cumulative proportion of total spawners for each spawning group, ranked in decreasing order of abundance for the four most recent generations of spawners in the Takla/Trembleur CU. AUC is area under the curve.

In addition, the Interior Fraser Coho Recovery Team (2006) provided a recovery objective for the distribution of coho salmon in the B.C. interior: generational average spawner abundances greater than 1000 fish for at least half of the sub-populations within each of the five interior Fraser populations. Their target was derived from simulation modelling of sockeye salmon (N. Schubert, Co-operative Resource Management Institute, Simon Fraser University, Burnaby, B.C., V5A 1S6, unpublished analyses) and other salmon species (McElhany et al., 2006), with the overall goal of ensuring viability of the entire Interior population of coho salmon.

3.3.2 Distribution of spawners among habitat types

CUs that cover a large spatial area with heterogeneous habitats may be associated with the expression of a wider variety of life-history traits than those that cover only a small area (or proportion of available habitat) or single habitat type and therefore may be better able to respond to changes in environmental conditions (Busch et al., 2008; McElhany et al., 2006). The extent of occurrence of a population and area of occupancy are included as IUCN Red list criteria (IUCN, 2001) and COSEWIC listing criteria (COSEWIC, 2006). For example, an area of occupancy of $< 2\,000\text{ km}^2$ will result in a "threatened" listing if the population is also declining or fluctuating (COSEWIC, 2006). Without a decline or fluctuations, an area of occupancy of $< 20\text{ km}$ is required for a "threatened" listing. Spatial extent of salmon within CUs can also be captured by metrics such as the total stream length available to spawners, accounting for blockages to fish passage.

Potential metrics of habitat diversity include the distribution of spawners across stream orders and the proportion of spawners using various microhabitats (e.g., beach versus stream habitat, for CUs that contain that fine-scale level of habitat diversity). Cooney et al. (2007) captured habitat diversity with the proportion of spawners occupying different ecoregions, which are classified by climate, soil, geology, vegetation and land-use (Cooney et al., 2007). Due to overlap with Strategy 2 of the Wild Salmon Policy, metrics and benchmarks on habitat type are not developed here.

3.3.3 Distribution of time-trends in spawner abundances

The distribution in temporal responses of spawning groups to environmental or anthropogenic stressors may be associated with the capacity of a CU to persist over the long term. A wide distribution of responses will be associated with an increased probability that at least one spawning group will persist under future environmental conditions. Variability in responses to common disturbances has been observed in asynchronous trends in productivity among neighbouring stocks of BC and Alaskan Pacific salmon that are exposed to similar conditions (Dorner et al., 2007; Rogers and Schindler, 2008). Those divergent responses may be associated with fine-scale habitat (e.g., at the lake scale (Rogers and Schindler, 2008)) and genetic variability. The proportion of individual spawning groups that exceed declines associated with benchmarks for aggregate spawners (as described in Section 3.2) or the spread (range or standard deviation) in the slope of the linear trends can be used as metrics of distribution in time trends (e.g., Figure 10).

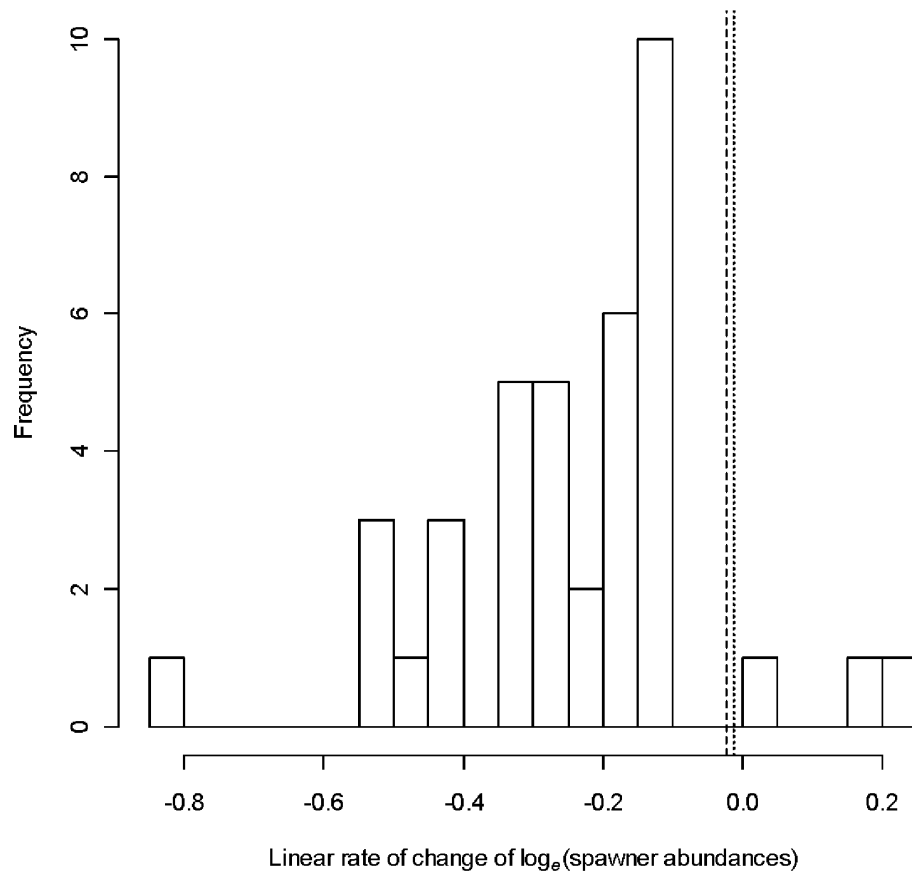


Figure 10. Histogram of linear rates of change of \log_e -transformed spawner abundances, smoothed with a four-year running mean for all counting locations (spawning groups) within the Takla/Trembleur sockeye CU. Only counting locations with <50% missing data points over the last 15 years were included. The linear rate of change associated with 15% and 25% declines in abundances over three generations are shown with dotted and dashed lines, respectively. 92.3% of counting locations had rates of declines greater than those that associated with the lower benchmark.

3.3.4 Spatial structure

Spatial structure of spawning groups within a CU reflects its vulnerability to a single catastrophic event (e.g., a flow blockage) and the likelihood of recolonization of locally depleted groups (McElhany et al., 2006). Spawning groups that are highly aggregated may be at greater risk of catastrophic loss due to single stressor, whereas those that are highly

dispersed may experience delayed recolonization. Qualitative assessments of the spatial extent and arrangement of spawning groups, connectivity, and risk of catastrophe will be valuable when considering spatial structure (as described in the viability criteria for ESA-listed Pacific salmon stock in the U.S.) (Busch et al., 2008).

With the exception of the benchmark developed by the Interior Fraser Coho Recovery Team and COSEWIC criteria (B and D), we do not provide benchmarks on metrics of distribution because of a lack of theoretical basis and data to identify specific levels that will result in reduced production and/or increased probabilities of extirpation. Instead, these metrics provide an overall picture of the distributional properties of a CU, which may indicate specific questions for further investigation. For example, a trend towards increasing concentration of spawners may warrant examinations into the causes and specific geographic location of the changes (e.g., is the trend due to an increase in abundance of one dominant spawning group or to a loss of several weak spawning groups?).

3.4 Fishing mortality

Fishing rates assess intensity of fishing pressure and, in some cases where information on spawner abundances is not available, benchmarks based on them may be more easily applied to management regulations than benchmarks on abundances. By maintaining fishing rates below acceptable levels, it may be possible to restore and maintain healthy populations without measuring spawner abundances directly. Although it might at first seem prudent to use F_{MSY} as an upper benchmark (delineating Green and Amber zones) "to provide, on an average annual basis, the maximum annual catch for a CU" (Fisheries and Oceans Canada, 2005) (p.18), the UN Agreement of Straddling Fish Stocks and Highly Migratory Fish Stocks (1995) recommends F_{MSY} be used as a "limit" or lower reference point. Furthermore, DFO's Fisheries Decision-Making Framework Incorporating the Precautionary Approach (2009) recommends that fishing mortalities remain below F_{MSY} . To be consistent with those initiatives and limit reference points used in other fisheries (e.g., Atlantic salmon as described by the North Atlantic Salmon Conservation Organization, and U.S. west coast groundfish, Pacific Fisheries Management Council), we suggest using F_{MSY} as a lower benchmark instead. Upper benchmarks can instead be derived from a percentage of F_{MSY} (e.g., 70%, a provisional upper benchmark until further information is available). Therefore, although a lower benchmark on fishing mortality of F_{MSY} may at first seem too precautionary (i.e., too high) to be consistent with lower benchmarks on spawner abundances that are $\ll S_{MSY}$ (e.g., S_{gen}), it is consistent with previous management experience and so we consider it as a candidate lower benchmark here. Note, the prioritization or weighting of conflicting indicators of status will be an important next step, highlighted by this example.

If estimates of F_{MSY} are too optimistic (i.e., are biased upwards), then benchmarks derived from those estimates may allow fishing rates to be higher than acceptable levels. Indeed, when derived from a Ricker spawner-recruitment relationship (Hilborn and Walters, 1992), estimates of the Ricker a parameter and hence F_{MSY} are usually biased upwards, especially when time series of data are short (see Table 6 for F_{MSY} equation). This bias results, in part, from measurement errors in spawner abundances and lack of independence between spawner and recruitment data (Walters and Martell, 2004). To reduce biases in F_{MSY} ,

a values can be estimated independently of the stock-recruitment relationships, from the mean $\log_e(R/S)$ observed historically (Gibson and Myers, 2004). Although that approximation will underestimate the true value (and hence F_{MSY}), it can set a useful lower bound. A newly developed approach for estimating stock-recruitment parameters that avoids many of the biases described above, uses time-series analysis to derive annual estimates of $\log_e(R/S)$ residuals that are shared among neighbouring stocks. That approach has been applied to Skeena River sockeye salmon to estimate benchmarks for management (Walters et al., 2008), but has yet to be rigorously tested in a simulation model.

Table 6. Equations used to calculate benchmarks on fishing mortality. " a " is the productivity parameter of the Ricker spawner-recruitment relationship and " b " is the spawner abundance at replacement (or equilibrium).

	Description	Label	Equation
Upper benchmark	Proportion of fishing mortality at MSY (e.g., 0.7)	$0.7 \cdot F_{MSY}$	$= 0.7 \cdot (-\log_e (1 - (0.5 \cdot a - 0.07 \cdot a^2)))$
Lower benchmark	Fishing mortality at MSY	F_{MSY}	$= -\log_e (1 - (0.5 \cdot a - 0.07 \cdot a^2))$
	Slope at the origin of the spawner-recruitment relationship	F_{MAX}	a (or mean \log_e (recruits/spawner))
	Median log-transformed recruits-per-spawner	F_{MED}	Median(\log_e (recruits/spawner))
	Slope at the origin of the spawning female-smolt relationship	F_{SM}	Derived from spawning female-smolt, as described in Bradford et al. (2000)

Alternative lower benchmarks on fishing mortality include the slope at the origin of the stock-recruitment relationship (F_{MAX} , as suggested by Mace (1993) (i.e., the maximum log-transformed recruits-per-spawner at low spawner abundances), the median log-transformed recruits-per-spawner (F_{MED} , as suggested by Sissenwine and Shepherd (1987)), and the slope at the origin of the smolt-recruitment relationship, a benchmark that is independent of variability in freshwater survival (Bradford et al., 2000).

We suggest fishing mortality relative to productivity as an indicator of status because it may detect unsustainable (high) fishing rates that may result in stock depletion. Although fishing mortalities greater than the lower benchmark will indicate that, if maintained, the fishing mortality may result in a threatened listing by COSEWIC (i.e., status in the Red zone), the converse is not necessarily true. Fishing mortalities below the lower benchmark may

result from reduced fishing pressure on severely depleted or commercially unviable stocks. Indeed, marine survival of several populations of North Coast salmon are below replacement despite near zero fishing mortality, suggesting the Green status on that metric for those CUs may be inappropriate as an overall indicator of status. Furthermore, historical time series on survival may be inappropriate for estimating productivity when parameters are time-varying (i.e., historical conditions are not representative of current conditions). Where possible, marine survival should be estimated annually from smolt abundances or fry abundances and recruitment to better inform current estimates of productivity.

We recommend that assessment on this metric be considered in combination with known management decisions and other indicators of status (e.g., trends in abundances and distribution) to distinguish among possible reasons for the observed status. Other anthropogenic stressors are considered in other strategies of the WSP (e.g., habitat modification under Strategy 2).

3.5 Incorporating uncertainties into assessments

3.5.1 A qualitative approach for incorporating uncertainties

To evaluate the degree of uncertainty in observed data when assessing status of sockeye salmon stocks in the Fraser River, Pestal and Cass (2007) proposed five categories of data quantity and quality based on the number of years with observations of spawner abundance and methods for collecting data (e.g., visual surveys, fence counts, and mark-recapture experiments). Crawford and Rumsey (2009) suggest an alternative classification scheme based in part, on the number of sub-populations within an assessment unit (e.g., CU) for which data is available. We have adapted those schemes to classify the data on spawner abundances and recruitment into three zones: Green (low uncertainties), Amber, (moderate uncertainties), and Red (high uncertainties), using criteria described in Table 7. Those guidelines may be further adapted to the specific characteristics of data in each CU.

Table 7. Criteria to categorize uncertainties in spawner and recruitment data into Green, Amber, and Red zones, adapted from Pestal and Cass (2007) and Crawford and Rumsey (2009).

Zone	Spawner data	Recruitment data
Green	<ul style="list-style-type: none"> • $\geq 50\%$ of known spawning sites with data • For the spawning sites with data, $\geq 50\%$ of years with observations in the last 3 generations and $\geq 50\%$ of years with observations in the last generation • Visual estimates calibrated with a fence or mark-recapture experiment • Sampling design unbiased with known precision 	<ul style="list-style-type: none"> • $\geq 50\%$ of years with observations in the last 3 generations and $\geq 50\%$ of years with observations in the last generation • Harvested in a single-stock fishery where catch can be attributed to a specific CU
Amber	<ul style="list-style-type: none"> • $\geq 25\%$ of known spawning sites with data • For the spawning sites with data, $\geq 50\%$ of years with observations in the last 3 generations and $\geq 50\%$ of years with observations in the last generation • Visual estimates only • Sampling design unbiased 	<ul style="list-style-type: none"> • $\geq 50\%$ of years with observations in the last 3 generations and $\geq 50\%$ of years with observations in the last generation • Harvested in a multi-stock fishery where catch cannot be easily attributed to a specific CU
Red	<ul style="list-style-type: none"> • $< 25\%$ known spawning sites with data • $< 50\%$ of years with observations in the last 3 generations or $< 50\%$ of years with observations in the last generation • Visual estimates only 	<ul style="list-style-type: none"> • $< 50\%$ of years with observations in the last 3 generations or $< 50\%$ of years with observations in the last generation • Harvested in a multi-stock fishery where catch cannot be easily attributed to a specific CU

Uncertainties in the data used to assess status may influence the overall assessment of a CU. For example, a CU that has a biological status in the Amber zone, but an uncertainty status in the Red zone may warrant an overall status of Red. One simple approach to combining information on biological status and uncertainty in the data is a two-dimensional assessment rule, as described in Figure 11. Although conceptually simple and easy to implement, this approach considers measurement errors only (and not natural variability,

errors in estimating benchmarks, or variability in outcomes of implementing fishing regulations), and does not evaluate the implications of those errors on the probability of extirpation over the long-term or probability of recovery to a target in the short term. Alternatively, a simulation modelling approach explicitly accounts for all major sources of uncertainties in a quantitative way and can evaluate the impacts of those uncertainties on probabilistic performance criteria.

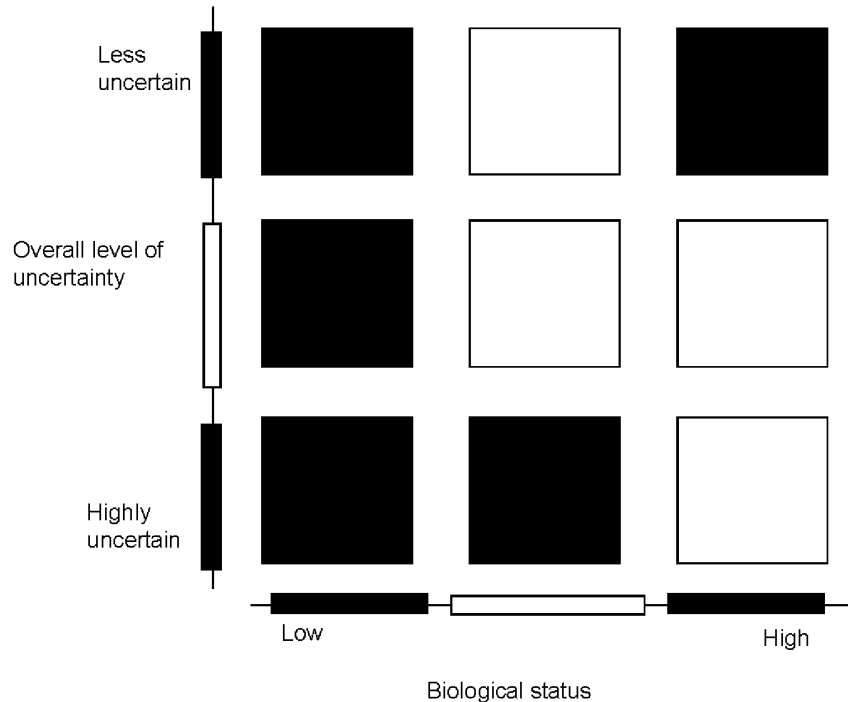


Figure 11. An example two-dimensional assessment rule to combine information on biological status (X-axis) with the level of uncertainty in that status (Y-axis). The colour of the cell (red= diagonal lines, amber= no lines or dots, green = dots) indicates the overall status that combines information on biological status and uncertainty.

3.5.2 Simulation modelling to incorporate uncertainties and evaluate lower benchmarks

Using a Monte Carlo simulation model, we evaluated benchmarks from two classes of indicators, spawner abundances and fishing mortality, on two probabilistic performance criteria: the probability of extirpation over 100 years and probability of recovery to a target (S_{MSY}) in one (or three) generations. That simulation model is described in the technical documentation on the Evaluation of Benchmarks for Conservation Units in Canada's Wild Salmon Policy (Holt, 2009); only a brief summary of the methods and results is given here. In particular, we compared the performance of lower benchmarks on spawner abundances along

a gradient in size (from 10-90% of recruitment MSY (R_{MSY} , i.e., recruitment at S_{MSY}), to three others that have been cited in the scientific literature or have been suggested for managing Pacific fisheries: spawner abundance at 50% of R_{MAX} , 40% of S_{MSY} , and S_{gen} , the spawner abundance that will result in recovery to S_{MSY} within one generation under equilibrium conditions. In addition, we compared the performance of lower benchmarks on fishing mortality along a gradient in size (from 50% to 150% of F_{MSY}), to two others from the literature, F_{MAX} (maximum log-transformed recruits-per-spawner at low spawner abundances) and F_{MED} (median log-transformed recruits-per-spawner). For both classes of indicators, we evaluated performance under a pessimistic (aggressive) management scenario, while still recognizing the lower benchmarks. For benchmarks on spawner abundance, we applied a constant escapement policy equivalent to the lower benchmark. For benchmarks on fishing mortality, we applied a constant fishing mortality rule equivalent to the lower benchmark. Our examples represent the worst-case scenario (i.e., high fishing effort and therefore high probability of extirpation and low probability of recovery); other harvest rules where escapement or harvest rates are adjusted according to observed spawner abundances or catches, will be associated with improved performance (reduced probability of extirpation and increased probability of recovery). Evaluating alternative harvest control rules in a simulation model is beyond the scope of this report, but will be necessary before implementing those rules in the fishery.

For metrics of spawner abundances, we found that the lower benchmark, S_{gen} , was associated with a relatively low probability of extirpation (probability <25%; risk classification adapted from DFO's "Fishery decision-making framework incorporating the Precautionary Approach" (2009)) over 100 years for populations with equilibrium abundances > 15,000 fish, and high probability of recovery to S_{MSY} within three generations (probability >75%) after accounting for uncertainties in all major components of the fishery system. Furthermore, the probabilities of extirpation over 100 years for S_{gen} were more robust to variability in stock productivity compared with benchmarks calculated from proportions of S_{MSY} . For metrics of fishing mortality, the lower benchmark F_{MSY} was associated with a relatively low probability of extirpation (probability <25%) over 100 years for populations with equilibrium abundances > 30,000, and high probability of recovery to S_{MSY} within three generations (probability >75%), and its performances was more robust to variability in stock productivity than other benchmarks on fishing mortality derived from the scientific literature.

Although simulation modelling has been embraced as a methodology for evaluating probabilistic outcomes to inform management decision (e.g., probability of extirpation (Dulvy et al., 2004)), the outputs of those models are highly sensitive to assumptions about model structure and parameter values. Mace et al. (2008) suggest that simulation models of population viability are more valuable for assessing relative performance of possible management decisions (e.g., evaluating performance of various benchmarks relative to one another or performance of a single benchmarks under various assumptions about model structure or parameterization) than for identifying the absolute probability of a specified outcome. We therefore recommend evaluating benchmarks on their relative performance and their sensitivity to model assumptions, in addition to (and perhaps with reduced emphasis on) absolute performance.

Based on our simulation model results, sensitivity analyses, and the preliminary risk classification scheme adapted from DFO's Decision-Making Framework (2009), we recommend a lower benchmark on spawner abundances derived from S_{gen} , and a lower benchmark on fishing mortality equivalent to F_{MSY} . S_{gen} was also chosen by the BC Ministry of the Environment as a limit reference point (a level of abundance "that defines a highly undesired state" (Johnston et al., 2002)(p.4)) for steelhead, *Oncorhynchus mykiss*, based on the results of a similar simulation modelling exercise. In the absence of data on stock productivity to calculate S_{gen} , the lower benchmark, 20% of carrying capacity, or spawner abundances at maximum recruitment, can be used as a proxy (Johnston et al., 2002). That recommendation differs from that of earlier analyses due to additional results showing reduced sensitivity of S_{gen} to a wide range in possible future productivities. The choice of F_{MSY} as a lower benchmark on fishing mortality is consistent with the recommendation of F_{MSY} as a "limit reference point" by the UN Straddling Fish Stocks and Highly Migratory Fish Stocks Agreement (1995). However, these recommendations on lower benchmarks will need to be re-evaluated once the risk tolerances of stakeholders are identified. One caveat of our simulations analyses is that the results apply to CUs where recruitment is derived from a stock-recruitment relationship. For some CUs, recruitment levels have been consistently below replacement, suggesting stock-recruitment models do not apply and benchmarks based on them are inappropriate. In those cases, we suggest deriving status from trends in abundances and distribution over time, current estimates of productivity, and abundances relative to freshwater estimates of capacity (but those capacity estimates will be insensitive to changes in marine carrying capacity and survival).

3.6 Non-stationarity

Non-stationarity is pervasive in fisheries systems. Temporal variability in biological processes and the parameters that describe them are driven by changes in physical and ecological conditions related to anthropogenic and natural stressors. Benchmarks that require long time series of historical data may not represent thresholds for current conditions. In scenarios dominated by non-stationarity, metrics reflecting recent trends in abundances or distribution over time, or current estimates of fishing mortality and productivity, may better reflect status than those that use stock-recruitment models based on historical data.

3.7 Data requirements

The application of indicators, metrics, and benchmarks to individual CUs will depend in part on data availability (Table 8). For example, when time series of spawner and recruitment data are available, status can be assessed from current estimates of spawner abundances and benchmarks derived from the spawner-recruitment relationship. When those time series are not available, spawner abundances may be assessed relative to independent estimates of capacity. Furthermore, when current estimates of spawner abundances are not available, it may be possible to assess status from fishing mortality relative to estimates of productivity. Except in a few CUs with high quality data, it will not be possible to apply the full suite of metrics and benchmarks to assess status.

Table 8. Matrix of data requirements for several metrics of biological status.

		Metric of biological status							
		Current spawner abundances relative to spawner-recruitment benchmarks ¹	Current spawner abundances relative to freshwater capacity	Trends in spawner abundances over time	Distribution of spawners across counting locations	Habitat use by spawners	Distribution of time trends of spawners across counting locations	Spatial arrangement of spawners across counting locations	Fishing mortality relative to estimates of productivity
Minimum data required									
Current estimate of aggregate spawner abundance	Relative index								
	Absolute measure	X	X						
Time series of aggregate spawner abundances (covering at least 3 generations)	Relative index								
	Absolute measure	X							
Capacity (estimated from freshwater production studies or models)		X	X						
Time series of recruitment (derived from spawners abundances and catches or fishing mortality, or run-reconstruction models)		X							
Current estimate of spawner abundances by counting location (relative or absolute)					X				

	Metric of biological status							
	Current spawner abundances relative to spawner-recruitment benchmarks ¹	Current spawner abundances relative to freshwater capacity	Trends in spawner abundances over time	Distribution of spawners across counting locations	Habitat use by spawners	Distribution of time trends of spawners across counting locations	Spatial arrangement of spawners across counting locations	Fishing mortality relative to estimates of productivity
Minimum data required								
Distribution of spawner groups across habitat types					X			
Time trends in spawner abundances by counting location (relative or absolute)						X		
Spatial location of spawning groups							X	
Time trends in spawner abundances for individual counting locations						X	X	
Current estimate of fishing mortality								X
Estimate of productivity or time series of fishing mortality								X

¹Relative estimates of spawner abundances may be used if benchmarks are based on those same relative measures.

4. APPLICATION OF BENCHMARKS TO TWO EXAMPLE CUs

4.1 Takla/Trembleur sockeye salmon

4.1.1 Data

Spawner abundances for Takla/Trembleur (Early Stuart) sockeye were estimated using a combination of visual surveys (ground and aerial, 41 streams 1950-2008, each with between one and 59 years of data) and a fence count at Dust Creek. Visual estimates of abundance were expanded to total annual abundances using a multiplication factor estimated from the fence count. Assessment methods have been consistent since 1987 when the fence was introduced, though refinements to the expansion factor have occurred since then. All visual estimates prior to 1987 have been expanded to total abundances (data available from Keri Benner, Fisheries and Oceans Canada, 985 McGill Place, Kamloops, B.C., V2C 6X6).

The optimum escapement of Takla and Trembleur lakes (number of adult spawners required to fully use the rearing capacity) was estimated to be 779 000 fish based on the relationship between seasonally averaged photosynthetic rate and juvenile sockeye production (Shortreed et al., 2001).

Estimates of sockeye recruitment to Takla and Trembleur lakes were derived from the Early Stuart run-timing group of the Fraser River (return years 1953 through 2007) (K. Forrest, Pacific Salmon Commission, 600-1155 Robson St., Vancouver, BC., V6E 1B5, pers. comm.), since that run-timing group is composed primarily of fish returning to those two lakes. Takla and Trembleur lakes contributed >99.9% of total escapement for Early Stuarts in all years except 1972 in which Takla and Trembleur fish comprised 98.6% of the total (K. Benner, pers. comm.). Recruitment estimates include the sum of spawning escapement, en-route mortality, and catch from marine and in-river commercial fisheries, marine and in-river test fisheries, Fraser River First Nations harvests, and recreational fisheries (Pacific Salmon Commission, 2001).

4.1.2 Indicators of status

Spawner abundances

Parameters of the stock-recruitment relationship were estimated in a Bayesian context with a normally distributed prior on the carrying capacity, i.e., spawner abundances at R_{MAX} (mean of the prior derived from Shortreed et al. (2001) (Appendix A, Fig. A 1 and Fig. A 2). The median of the posterior distribution varied by <10 000 fish when a uniform prior was used (dotted line, Fig. A 2) instead of an informative prior, suggesting that the posterior distribution was only weakly influenced by the prior, and conversely was strongly influenced by the data. We used Markov Chain Monte Carlo methods to generate the posterior distribution for model parameters. Upper benchmarks on S_{MSY} , 80% of S_{MSY} , and 40% of carrying capacity were estimated to be 396,000; 316,000; and 312,000 fish, respectively. The lower benchmarks, S_{gen} and 20% of carrying capacity were estimated at 118,000 and 156,000 fish, respectively. Additional benchmarks described in Section 3.1

and recommended previously by fisheries management or the scientific literature, were also calculated for comparison. Values for the alternative lower benchmarks ranged from 137 000 (S at 50% of R_{MSY}) to 170,000 (90th percentile of S at 50% $\cdot R_{MSY}$, a precautionary estimate of that value given uncertainty in the underlying data). The 90th percentile of S_{MSY} , a precautionary estimate of the upper benchmark, S_{MSY} , was almost twice as large as S_{MSY} itself (746,000 instead of 396,000). The current estimate of spawner abundances (2008) and generational mean (2005-2008) (29,835 and 27,371 fish respectively) fell below all lower (and upper) benchmarks for this class of indicators. The statuses of Takla/Trembleur sockeye salmon on this and the remaining classes of indicators are described in more detail in Appendix A.

Trends in spawners

Recent declines in spawner abundances were larger than those designated by most lower benchmarks (Figure 6). The probability that the slope of decline exceeded the lower benchmark was <0.001 (Fig. A 5). However, over the long term, the declines were relatively small. In fact, the ratio of the geometric mean spawner abundance to the long-term mean was greater than the upper benchmark, resulting in Green status on that metric.

Distribution

The number of spawning groups consisting of >100 fish declined from 37 in 1993-1996 to 35 in 2005-2008 for this CU (Figure 7). Ten spawning groups comprised the top 80% of total spawners in the most recent generation (2005-2008) (Figure 8). 68% of spawning groups currently have geometric mean spawner abundances that exceed 1000 fish (i.e., greater than the 50% threshold of the Interior Fraser Coho Recovery Team (2006)). The area under the curve (AUC) of the relationship between ranked spawner group and cumulative proportion of total spawners declined from 0.75 in 1993-1996 to 0.68 in the most recent generation (2005-2008) (i.e., the distribution is now more dispersed; Figure 9). That AUC values have decreased since 1993-1996, in large part due to the steep decline in one dominant spawning group, Driftwood, in the mid-1990s.

The slopes of the linear changes in log-transformed spawner abundances over the most current three generations ranged from -0.84 to +0.24 among spawning groups, 92% of which had declines that were below the lower benchmark associated with a 25% reduction in abundances (Figure 10). When only locations with no missing values were included, that percentage was 91%.

To assess distribution of spawners across spatial locations and habitat types in the Takla/Trembleur CU, further investigations are required in coordination with Strategy 2 of the Wild Salmon Policy.

Fishing mortality

Both the most recent estimate of fishing mortality ($F = 0.0791$ or equivalently, harvest rate = 7.6%, 2007) and the most recent generational mean ($F = 0.176$, harvest rate = 16.1%) fell in the Green zone, i.e., below all upper (and lower) benchmarks. Fishing mortalities have been relatively low in this CU since the mid 1990s.

Uncertainties in data

Uncertainties in spawner and recruitment data are relatively low for Takla/Trembleur sockeye corresponding to a Green status on that metric. Time series of spawner and recruitment data are continuous over the last three generations for over 80% of spawning groups, visual estimates of spawner abundances are calibrated with a fence count, and >98% of the Early Stuart run can be assigned to the Takla/Trembleur CU (i.e., recruits are harvested, for the most part, in a single-stock fishery).

4.2 Hecate Strait Lowlands odd-year pink salmon

4.2.1 Data

Spawner abundances for Hecate Strait Lowlands odd-year pink salmon have been estimated at 175 counting locations using visual ground surveys (1951 through 2005, data available from the NuSEDS database at the Pacific Biological Station, Fisheries and Oceans Canada, Nanaimo, B.C.). Although some information on relative abundances exist prior to 1950, in many cases those data are qualitative. Estimates of spawner abundances from 1950 until 1998 are highly uncertain due to changes in survey effort and personnel over that period, the absence of counting fences to standardize observed numbers, and the lack of documentation on multiplication factors used to expand observed numbers to total abundances (Brian Spilsted, Fisheries and Oceans Canada, 417 - 2nd Avenue West, Prince Rupert, B.C., V8J 1G8, pers. comm.). Since 1998, area-under-the-curve analyses have been used to estimate total spawners from observed abundances and run-timing, and the details of those methods have been recorded.

4.2.2 Indicators of status:

Spawner abundances

We were not able to identify benchmarks on spawner abundances for this CU for at least three reasons: catch data (and hence recruitment) have not yet been compiled due to difficulties in assigning area-wide catches to specific CUs, freshwater capacity is unknown, and stock-recruitment relationships have not been estimated.

Trends in spawners

The rate of change in log-transformed spawner abundances aggregated over all counting locations was positive over the last ten years, warranting a green status on that metric (Appendix B, Fig. B 1). The probabilities that the true rate of change in log-transformed spawner abundances was less than the upper and lower benchmarks (rate of change associated with 15% and 25% reduction in abundances, respectively) were less than the candidate threshold of 10%, (6.6% and 8.1%, respectively) warranting a Green status on that metric (Appendix B, Fig. B 2). Status was also Green for the metric describing the long-term extent of changes in spawner abundances (ratios of current geometric mean spawner abundance over the current generation to the historical mean and maximum).

Distribution

The number of spawning groups consisting of >100 fish increased from 33 in 1995 to 71 in 2001, and then declined to 34 in 2005 (Appendix B, Fig. B 3). The top 80% of ranked spawner abundances was comprised of eleven spawning groups in 2005 (Appendix B, Fig. B 4). Of the counting groups that were observed in 2005 (the most current year), 79% had geometric mean spawner abundances that exceeded 1000 fish (i.e., greater than the 50% threshold of the Interior Fraser Coho Recovery Team (2006)). The area under the curve of the relationship between ranked spawner group and cumulative proportion of total spawners was the same in 2005 as in 1995 (0.115) (Appendix B, Fig. B 5).

Linear rates of change in log_e-transformed spawner abundances over the most recent ten years ranged from -0.77 to +0.95, and 28.8% of spawning groups had declines that were below that associated with the lower benchmark (reduction in abundances > 25% over the time period) (Appendix B, Fig. B 6). When only locations with no missing values over the 10-year period were included, that percentage was 7.7%.

As for the Takla/Trembleur sockeye CU, further studies are required to assess distribution of spawners across spatial locations and habitat types in this CU.

Fishing mortality

We were not able to assess status on fishing mortality for this CU because catch data have not yet been compiled, as described in the "Spawner abundances" sub-section above.

Uncertainties

The estimates of spawner abundances are highly uncertain because visual estimates have not been calibrated with absolute numbers (e.g., from fence counts), field and analytical methods of assessment have varied over time, and those changes are not well documented. In addition, time series of catches have not been estimated, in part due to difficulties in assigning area-wide catches to CUs.

5. NEXT STEPS

In order to evaluate biological status of CUs, we recommend that the following steps be taken.

- (1) Develop qualitative guidelines for assessing status on the distribution of spawning groups within CUs (the third class of indicators).
- (2) Develop a stock assessment methodology to combine status on all classes of indicators and measures of uncertainty.
- (3) Where possible, reconstruct catch time series and compile recruitment data by CU.
- (4) Evaluate status using benchmarks selected above and data compiled in step (3) for all CUs. This step will be performed by staff within each area, with guidance from Science branch.

- (5) Consider alternative risk classification schemes associated with risk tolerances identified by stakeholders.

This document provides methodological background to perform those next steps, but several challenges remain. In particular, we provide a multi-dimensional assessment of status on four classes of indicators, but fisheries management may prefer a single overall assessment to inform decision making. Rules can be established to prioritize and combine data across metrics, but that integration will result in a substantial loss of information. "Multi-attribute analysis" is a field of decision analysis that developed in the 1970s to address this challenge (Keeney and Raiffa, 1976). It has been applied extensively to resource management (Herath and Prato, 2006; Nair and Sieberman, 1980) and could be used to combine information across metrics of status. A second challenge will be evaluating the status of CUs for which we have no or little information. One possible approach is to integrate information across neighbouring CUs that are believed to have similar dynamics, responses to stressors, and status. Combining that information can be done quantitatively (e.g., using hierarchical models or meta-analyses), or qualitatively. When integrating information over numerous CUs, the risks of overlooking a CU that may have diverging status on one or several indicators will need to be weighed against logistical difficulties of collecting data from all CUs on all dimensions of status. Finally, a preliminary status overview of all CUs may be required before data on CU-specific catch and/or fishing mortality are available to assess status and identify benchmarks on all classes of indicators. For CUs with high-quality spawner data, a preliminary assessment based on spawner abundances relative to estimates of freshwater capacity, time trends in spawner abundances, and/or distribution of spawners among counting locations may be valuable. Although these indicators will only provide a partial assessment of CU status, it will be a first step towards a complete assessment, and may highlight priority CUs where further analyses and/or data are required.

6. ACKNOWLEDGMENTS

We would like to thank Chris Wood, Michael Bradford, Michael Folkes, Neil Schubert, Steve Cox-Rogers, Jim Irvine, Ann-Marie Huang, Merran Hague (Fisheries and Oceans Canada), Jim Woodey (formerly with the Pacific Salmon Commission), Ian Guthrie (Pacific Salmon Commission) and Kendra Holt (Simon Fraser University) for their helpful advice. Brian Spilsted, Keri Benner (Fisheries and Oceans Canada), and Keith Forrest (Pacific Salmon Commission) provided information on data collection. Catherine Michielsens (Pacific Salmon Commission) reviewed an earlier version of this manuscript. Randall Peterman, Sean Cox (Simon Fraser University), and Carl Walters (University of British Columbia) provided helpful direction during early stages of the project development.

7. LITERATURE CITED

- Araki, H., Cooper, B., Blouin, M.S., 2007. Genetic effects of captive breeding cause a rapid, cumulative fitness decline in the wild. *Science* 318, 100-103, 10.1126/science.1145621.
- Augerot, X., Bottom, D.L., Rodgers, J.D., 1999. Proceedings of the North Pacific Salmon Workshop-Development of Pacific Salmon Ecoregions.
- Beamish, R.J., Sweeting, R.M., Lange, K.L., Neville, C.M., 2008. Changes in the population ecology of hatchery and wild coho salmon in the Strait of Georgia. *Trans. Am. Fish. Soc.* 137, 503-520.
- Bodtker, K.M., Peterman, R.M., 2007. Accounting for uncertainty in estimates of escapement goals for Fraser River sockeye salmon based on productivity of nursery lakes in British Columbia, Canada. *North American Journal of Fisheries Management* 27, 286-302.
- Bradford, M., Wood, C., 2004. A Review of Biological Principles and Methods Involved in Setting Minimum Population Sizes and Recovery Objectives for the September 2004 Drafts of the Cultus and Sakinaw Lake Sockeye Salmon and Interior Fraser Coho Salmon Recovery Plans. Fisheries and Oceans Canada.
- Bradford, M.J., Myers, R.M., Irvine, J.R., 2000. Reference points for coho salmon (*Oncorhynchus kisutch*) harvest rates and escapement goals based on freshwater production. *Canadian Journal of Fisheries and Aquatic Sciences* 57, 677-686.
- Busch, S., McElhany, P., Ruckelshaus, M.H., 2008. A Comparison of the Viability Criteria Developed for Management of ESA-listed Pacific Salmon and Steelhead. Northwest Fisheries Science Center, NOAA, pp. 30.
- Caddy, J.F., Mahon, R., 1995. Reference points for fisheries management. *FAO Fisheries Technical Paper*, pp. 83.
- Cass, A., Grout, J., 2006. Workshop to assess population dynamics of cyclic Fraser River sockeye and implications for management Fisheries and Oceans Canada, Science Branch.
- Ciruna, K.A., Butterfield, B., 2005. A hierarchical freshwater ecosystem classification for British Columbia: Ecological aquatic units for British Columbia (EAU BC). B.C. Ministry of the Environment, pp. 122.
- Cooney, T., McClure, M., Baldwin, C., Carmichael, R., Hassemer, P., Howell, P., McCullough, D., Schaller, H., Spruell, P., Petrosky, C., Utter, F., 2007. Viability

Criteria for Application to Interior Columbia Basin Salmonid ESUs. U.S. Dept. Commer. .

- COSEWIC, 2003a. COSEWIC assessment and status report on the Sockeye Salmon *Oncorhynchus nerka* Sakinaw population in Canada. Committee on the Status of Endangered Wildlife in Canada.
- COSEWIC, 2003b. COSEWIC assessment and status report on the sockeye salmon *Oncorhynchus nerka* (Cultus population) in Canada. Ottawa. Committee on the Status of Endangered Wildlife in Canada, pp. ix + 57 pp.
- COSEWIC, 2006. COSEWIC's Assessment Process and Criteria. Available at: http://www.cosewic.gc.ca/eng/sct0/assessment_process_e.cfm.
- Crawford, B.A., Rumsey, S., 2009. Guidance for monitoring recovery of salmon and steelhead- Draft. NOAA Fisheries Service- Northwest Region.
- Dorner, B., Peterman, R.M., Haeseker, S.L., Pyper, B.J., 2007. Reconstructed historical trends in productivity of 120 Pacific pink, chum, and sockeye salmon populations by using a Kalman filter. Canadian Journal of Fisheries and Aquatic Science in review.
- Dulvy, N.K., Ellis, J.R., Goodwin, N.B., Grant, A., Reynolds, J.D., Jennings, S., 2004. Methods of assessing extinction risk in marine fishes. Fish & Fisheries 5, 255-276.
- FAO, 1995. Precautionary approach to fisheries: Part 1 guidelines on the precautionary approach to capture fisheries and species introductions. pp. 34.
- Fisheries and Oceans Canada, 2005. Canada's Policy for the Conservation of Wild Pacific Salmon. pp. 57.
- Fisheries and Oceans Canada, 2009. Fishery decision-making framework incorporating the precautionary approach. Available at: <http://www.dfo-mpo.gc.ca/fm-gp/peches-fisheries/fish-ren-peche/sff-cpd/precaution-eng.htm>.
- Gibson, A.J.F., Myers, R.A., 2004. Estimating reference fishing mortality rates from noisy spawner-recruit data. Canadian Journal of Fisheries and Aquatic Sciences 61, 1771-1783, 10.1139/f04-102.
- Goodman, D., 2005. Selection equilibrium for hatchery and wild spawning fitness in integrated breeding programs. Can. J. Fish. Aquat. Sci. 62, 374-389.
- Hauge, K.H., Nielsen, K.N., Korsbrekke, K., 2007. Limits to transparency exploring conceptual and operational aspects of the ICES framework for providing precautionary fisheries management advice. ICES J. mar. Sci. 64, 738-743, 10.1093/icesjms/fsm058.

- Heath, D.D., Heath, J.W., Bryden, C.A., Johnson, R.M., Fox, C.W., 2003. Rapid Evolution of Egg Size in Captive Salmon. *Science* 299, 1738-1740, 10.1126/science.1079707.
- Heggenes, J., Beere, M., Tamkee, P., Taylor, E.B., 2006. Genetic diversity in steelhead before and after conservation hatchery operation in a coastal, boreal river. *Trans. Am. Fish. Soc.* 135, 251-267.
- Herath, G., Prato, T. (Eds.), 2006. *Using multi-criteria decision analysis in natural resource management*. Ashgate Publishing Ltd., Aldershot, England.
- Hilborn, R., Walters, C.J., 1992. *Quantitative Fisheries Stock Assessment*. Chapman and Hall, New York.
- Hindar, K., Fleming, I.A., McGinnity, P., Diserud, O., 2006. Genetic and ecological effects of salmon farming on wild salmon: modelling from experimental results. *ICES J. mar. Sci.* 63, 1234-1247, 10.1016/j.icesjms.2006.04.025.
- Holt, C.A., 2009. Evaluation of Benchmarks for Conservation Units in Canada's Wild Salmon Policy. DFO Can. Sci. Advis. Sec. Res. Doc. 2009/059. xii + 50p.
- Holtby, L.B., Ciruna, K.A., 2007. Conservation units for Pacific salmon under the Wild Salmon Policy. DFO Can. Sci. Advis. Sec. Res. Doc. 2007/070.
- ICES, 1996. Report of the comprehensive Fishery Evaluation Working Group. . pp. 68.
- Interior Fraser Coho Recovery Team, 2006. Conservation Strategy for Coho Salmon (*Oncorhynchus kisutch*), Interior Fraser River Populations. Fisheries and Oceans Canada.
- Irvine, J.R., Parken, C.K., Chen, D.G., Candy, J., Ming, T., Supernault, J., Shaw, W., Bailey, R.E., 2001. 2001 Stock Status Assessment of Coho Salmon from the Interior Fraser River. Fisheries and Oceans Canada.
- IUCN, 2001. IUCN Red List Categories and Criteria: Version 3.1. IUCN, Gland, Switzerland and Cambridge, UK, pp. 30.
- Johnston, N.T., Parkinson, E.A., Tautz, A.F., Ward, B.R., 2002. A Conceptual Framework for the Management of Steelhead, *Oncorhynchus mykiss*. Ministry of Water, Land, and Air Protection, BC Fisheries Branch.
- Jonsson, B., Jonsson, N., 2006. Cultured Atlantic salmon in nature: a review of their ecology and interaction with wild fish. *ICES J. mar. Sci.* 63, 1162-1181, 10.1016/j.icesjms.2006.03.004.
- Keeney, R.L., Raiffa, H., 1976. *Decisions with Multiple Objectives: Preferences and Value Tradeoffs*. John Wiley & Sons, Toronto.

- Kitanishi, S., Yamamoto, T., Higashi, S., 2009. Microsatellite variation reveals fine-scale genetic structure of masu salmon, *Oncorhynchus masou*, within the Atsuta River. *Ecology of Freshwater Fish* 18, 65-71, 10.1111/j.1600-0633.2008.00325.x.
- Mace, G.M., Collar, N.J., Gaston, K.J., Hilton-Taylor, C., Akçakaya, H.R., Leader-Williams, N., Milner-Gulland, E.J., Stuart, S.N., 2008. Quantification of extinction risk: IUCN's system for classifying threatened species. *Conservation Biology* 22, 1424-1442.
- Mace, P.M., Sissenwine, M.P., 1993. How much spawning per recruit is enough? *Canadian Special Publications in Fisheries and Aquatic Sciences* 120, 101-118.
- Martell, S.J.D., Walters, C.J., Hilborn, R., 2008. Retrospective analysis of harvest management performance for Bristol Bay and Fraser River sockeye salmon (*Oncorhynchus nerka*). *Canadian Journal of Fisheries and Aquatic Science* 65, 409-424.
- McElhany, P., Busack, C., Chilcote, M., Kolmes, S., McIntosh, B., Myers, J., Rawding, D., Steel, A., Steward, C., Ward, D., Whitesel, T., Willis, C., 2006. Revised Viability Criteria for Salmon and Steelhead in the Willamette and Lower Columbia Basins. Willamette/Lower Columbia Technical Recovery Team and Oregon Department of Fish and Wildlife.
- McElhany, P., Ruckelshaus, M.H., Ford, M.J., Wainwright, T.C., Bjorkstedt, E.P., 2000. Viable Salmonid Populations and the Recovery of Evolutionary Significant Units. U.S. Dept. Commer., NOAA Technical Memorandum NMFS-NWFSC-42.
- Myers, R.A., Rosenberg, A.A., Mace, P.M., Barrowman, N., Restrepo, V.R., 1994. In search of thresholds for recruitment overfishing. *ICES Journal of Marine Science* 51, 191-205.
- Nair, K., Sicherman, A., 1980. Making decisions on environmental problems. *Environment International* 3, 11-21.
- Nelson, P.A., Witteveen, M.J., Honnold, S.G., Vining, I., Hasbrouck, J.J., 2005. Review of Salmon Escapement Goals in the Kodiak Management Area. Alaska Department of Fish and Game.
- Neville, H.M., Isaak, D.J., Dunham, J.B., Thurow, R.F., Rieman, B.E., 2006. Fine-scale natal homing and localized movement as shaped by sex and spawning habitat in Chinook salmon: insights from spatial autocorrelation analysis of individual genotypes. *Molecular Ecology* 15, 4589-4602.
- Northwest Atlantic Fisheries Organization, 2004. Report of the NAFO Study Group on Limit Reference Points. NAFO SCS Doc. 04/12, pp. 72..

- Pacific Salmon Commission, 2001. Report of the Fraser River Panel to the Pacific Salmon Commission on the 2000 Fraser River sockeye salmon fishing season. pp. 51.
- Pestal, G., Cass, A., 2007. Fraser Sockeye Resource Assessment Framework: Using Qualitative Risk Evaluations to Prioritize Resource Assessment Activities for Fraser River Sockeye. Report submitted to Fisheries and Oceans Canada, pp. 74.
- Reed, D.H., O'Grady, J.J., Brook, W.B., Ballou, J.D., Frankham, R., 2003. Estimates of minimum viable population sizes for vertebrates and factors influencing those estimates. *Biological Conservation* 113, 23-34.
- Ricker, W.E., 1975. Computation and Interpretation of Biological Statistics of Fish Populations. Department of the Environment, Ottawa.
- Rogers, L.A., Schindler, D.E., 2008. Asynchrony in population dynamics of sockeye salmon in southwest Alaska. *Oikos* 117, 1578-1586.
- Shortreed, K.S., Morton, K.F., Malange, K., Hume, J.M.B., 2001. Factors Limiting Juvenile Sockeye Production and Enhancement Potential for Selected B.C. Nursery Lakes. Fisheries and Oceans Canada.
- Sissenwine, M.P., Shepherd, J.G., 1987. An alternative perspective on recruitment overfishing and biological reference points. *Canadian Journal of Fisheries and Aquatic Science* 44, 913-918.
- Sweeting, R.M., Beamish, R.J., Noakes, D.J., Neville, C.M., 2003. Replacement of wild coho salmon by hatchery-reared coho salmon in the Strait of Georgia over the past three decades. *N. Am. J. Fish. Manage.* 23, 492-502.
- Tallman, R.F., Healey, M.C., 1994. Homing, straying, and gene flow among seasonally separated populations of chum salmon (*Oncorhynchus keta*). *Canadian Journal of Fisheries and Aquatic Science* 51, 577-588.
- Tompkins, A., Riddell, B., Nagtegaal, D.A., 2005. A Biologically-based Escapement Goal for Cowichan River Fall Chinook Salmon (*Oncorhynchus tshawytscha*). Fisheries and Oceans Canada.
- UN. 1995. Straddling Fish Stocks and Highly Migratory Fish Stocks Agreement.
- Utter, F., 2004. Population genetics, conservation and evolution in salmonids and other widely cultured fishes: some perspectives over six decades. *Rev. Fish Bio. Fish.* 14, 125-144.
- Walters, C.J., Cahoon, P., 1985. Evidence of decreasing spatial diversity in British Columbia salmon stocks. *Canadian Journal of Fisheries and Aquatic Science* 42, 1033-1037.

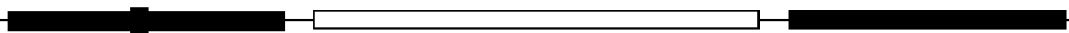
- Walters, C.J., Korman, J., 2001. Analysis of stock-recruitment data for deriving escapement reference points. In: Prévost, É., Chaput, G.s (Eds.), Stock, Recruitment and Reference Points: Assessment and Management of Atlantic Salmon. INRA, Paris, pp. 67-94.
- Walters, C.J., Lichatowich, J.A., Peterman, R.M., Reynolds, J.D., 2008. Report of the Skeena Independent Science Review Panel. A report to the Canadian Department of Fisheries and Oceans and the British Columbia Ministry of the Environment, pp. 144.
- Walters, C.J., Martell, S.J.D., 2004. Fisheries Ecology and Management. Princeton University Press, Princeton.
- Walters, C.J., Staley, M.J., 1987. Evidence against the existence of cyclic dominance in Fraser River sockeye salmon (*Oncorhynchus nerka*). Canadian Special Publications in Fisheries and Aquatic Sciences 96, 375-384.
- Wood, C., 2004. Managing biodiversity of Pacific salmon: lessons from the Skeena River sockeye salmon fishery in British Columbia. In: Neilsen, J., Dodson, J.J., Friedland, K., Hamon, T.R., Musick, J., Verspoor, E.s (Eds.), Fourth World Fisheries Congress. American Fisheries Society Symposium 49, Vancouver, B.C., pp. 349-364.

8. APPENDICES

Appendix A

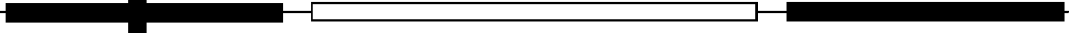
Status of Takla/Trembleur sockeye salmon according to various indicators grouped into four classes: spawner abundances, trends in abundance, distribution, and fishing mortality. Status is assessed relative to upper and lower benchmarks. Zone of status (Red, Amber, Green) is identified only for those metrics for which data and benchmarks are available. SRR is the stock-recruitment relationship. All other abbreviations are described in Table 5 and Table 6 in the text. See also Figs. A1-A5 below.

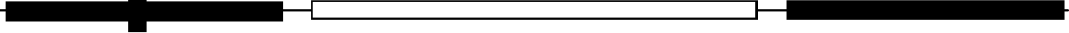
(1) Class of indicator: spawner abundance

Specific metric: Spawner abundance, S , in the current year (and geometric mean of the most recent generation)					
	Lower benchmark	Reference		Upper benchmark	Reference
	Spawner abundances that would result in recovery to S_{MSY} within one generation in the absence of fishing = 118,000	Johnston et al., 2002		80% S_{MSY} = 316,000	(Fisheries and Oceans Canada, 2009)
Current status (2008): 29,835 (geometric mean of last generation, 2005-2008 = 27,371)					
					

Specific metric: Spawner abundance, S , in the current year (and geometric mean of the most recent generation)					
	Lower benchmark	Reference		Upper benchmark	Reference
	20% of spawners at maximum recruitment estimated from freshwater production studies = 156,000	Johnston et al., 2002; Shortreed et al., 2001 (capacity estimate)		40% of spawners at maximum recruitment estimated from freshwater production studies = 312,000	Approximately equivalent to S_{MSY} , derived from equations in Table 5.
Current status (2008): 29,835 (geometric mean of last generation, 2005-2008 = 27,371)					

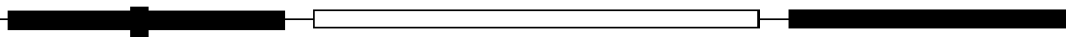
Specific metric: Spawner abundance, S , in the current year (and geometric mean of the most recent generation)					
	Lower benchmark	Reference		Upper benchmark	Reference
	S at X% of MSY recruitment (e.g., 50% = 137,000)	-		$S_{MSY} = 396,000$	Coho salmon, Irvine et al., 2001; chinook salmon, Tompkins et al., 2005; Alaska Pacific salmon, Nelson, 2005.
Current status (2008): 29,835 (geometric mean of last generation, 2005-2008 = 27,371)					

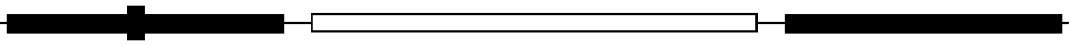
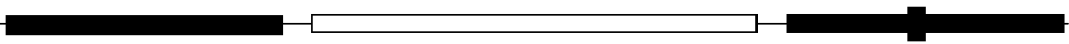
Specific metric: Spawner abundance, S , in the current year (and geometric mean of the most recent generation)					
	Lower benchmark	Reference		Upper benchmark	Reference
	40% of spawner abundances at MSY = 158,000	(Fisheries and Oceans Canada, 2009)		80% of spawner abundances at MSY = 316,000	(Fisheries and Oceans Canada, 2009)
Current status (2008): 29,835 (geometric mean of last generation, 2005-2008 = 27,371)					
					

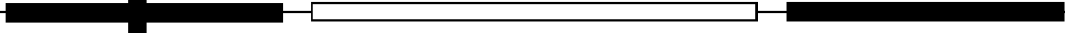
Specific metric: Spawner abundance, S , in the current year (and geometric mean of the most recent generation)		
	Lower benchmark	Reference
	S at 50% of maximum recruitment from SRR = 164,000	Myers et al., 1994
Current status (2008): 29,835 (geometric mean of last generation, 2005-2008 = 27,371)		
		

Specific metric: Spawner abundance, S , in the current year (and geometric mean of the most recent generation)					
	Lower benchmark	Reference		Upper benchmark	Reference
	90 th percentile of S at X% of MSY recruitment (e.g., 50%= 170,000)	-		90 th percentile of S_{MSY} = 746,000	Percentiles of S_{MSY} distribution used in Alaska to denote ranges around target, e.g., Kodiak; Nelson, 2005.
Current status (2008): 29,835 (geometric mean of last generation, 2005-2008 = 27,371)					
<div><div></div><div></div><div></div></div>					

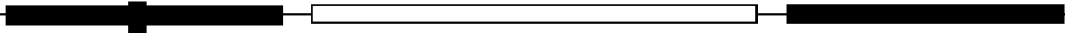
(2) Class of indicator: trends in spawner abundance

Specific metric: Linear rate of change in spawner abundances over 3 generations (where abundances are log _e -transformed and smoothed with a generational running mean)					
	Lower benchmark	Reference		Upper benchmark	Reference
	Rate of change = -0.024 (25% decline over three generations)	COSEWIC guidelines		Rate of change = -0.014 (15% decline over three generations)	-
Current status: -0.15					
					

Specific metric: Probability that rate of change over 3 generations $\geq X$, where X differs between lower and upper benchmarks					
	Lower benchmark	Reference		Upper benchmark	Reference
	Probability that linear rate or change ≤ -0.024 (i.e., change in abundances $\leq -25\%$) = 0.10	-		Probability that linear rate of change ≤ -0.014 (i.e., change in abundances $\leq -15\%$) = 0.10	-
Current status: >0.99 (for both values of X)					
					
Specific metric: Ratio of geometric mean spawner abundance of current generation to historical mean (1950-2008)					
	Lower benchmark	Reference		Upper benchmark	Reference
	1/4	Fraser River sockeye salmon; Pestal and Cass, 2007		1/2	Fraser River sockeye salmon; Pestal and Cass, 2007
Current status: 0.67					
					

Specific metric: Ratio of geometric mean spawner abundance of current generation to the highest generational geometric mean on record					
	Lower benchmark	Reference		Upper benchmark	Reference
	1/4	Fraser River sockeye salmon; Pestal and Cass, 2007		1/2	Fraser River sockeye salmon; Pestal and Cass, 2007
Current status: 0.15					
					

(3a) Class of indicator: distribution of spawning groups

Specific metric: Proportion of spawning groups with a geometric mean abundance over the last generation of more than 1000 fish (the population size that has a low risk of extinction over 100 years, Interior Fraser Coho Recovery Team 2006)					
	Lower benchmark	Reference			
	0.5	Interior Fraser Coho Recovery Team, 2006			
Current status: 28/41=0.68					
					

Specific metric: Minimum number of spawning groups that comprise 80% of total abundance, <i>D</i>					
	Lower benchmark	Reference		Upper benchmark	Reference
	Qualitative assessment			Qualitative assessment	
Current status: 10					

Specific metric: Mean inter-annual change in <i>D</i> over last three generations or ten years (which ever is greater)					
	Lower benchmark	Reference		Upper benchmark	Reference
	Qualitative assessment			Qualitative assessment	
Current status: +0.33					

Specific metric: Number of spawning groups with geometric mean abundances > 100 fish in most recent generation					
	Lower benchmark	Reference		Upper benchmark	Reference
	Qualitative assessment			Qualitative assessment	
Current status: 37					

Specific metric: Area under the curve of relationship between ranked order of spawning groups and cumulative proportion of total spawner abundances					
	Lower benchmark	Reference		Upper benchmark	Reference
	Qualitative assessment			Qualitative assessment	
Current status: 0.67 (current generation)					

(3b) Class of indicator: distribution of trends

Specific metric: Proportion of spawning groups that have linear rates of change in abundances over 3 generations (i.e., slopes of time trends) associated with changes in spawner abundances \leq -25%					
	Lower benchmark	Reference		Upper benchmark	Reference
	Qualitative assessment			Qualitative assessment	
Current status: 0.92					

(3c) Class of indicator: distribution over space and habitat

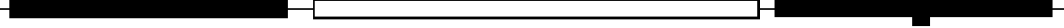
Specific metric: spatial extent (area of occupancy)					
	Lower benchmark	Reference		Upper benchmark	Reference
	2 000km ² (when combined with population declines or fluctuations), otherwise < 20km ²	COSEWIC criteria B and D			
Current status: Data from WSP strategy 2. To be determined.					

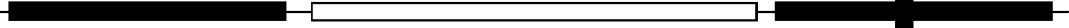
Specific metric: Change in spatial location of spawners or juveniles in the CU over time and spatial location of trends in spawner abundances					
	Lower benchmark	Reference		Upper benchmark	Reference
	Qualitative assessment	Adapted from McElhany et al., 2006		Qualitative assessment	Adapted from McElhany et al., 2006
Current status: Data from WSP strategy 2. To be determined.					

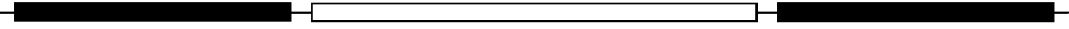
Specific metric: Change in the type of habitat used by spawners or juveniles, e.g., change in average stream order					
	Lower benchmark	Reference		Upper benchmark	Reference
	Qualitative assessment	McElhany et al., 2006		Qualitative assessment	McElhany et al., 2006
Status: Data from WSP strategy 2. To be determined.					

(4) Class of indicator: fishing mortality

Specific metric: Fishing mortality, F , over previous year (and mean over most recent generation)				
Lower benchmark F_{MSY} calculated from SRR parameters = 0.84, (or calculated from data directly = 0.73, C. Walters pers. comm.)	Reference UN Straddling Fish Stocks and Highly Migratory Fish Stocks Agreement (1995)	Upper benchmark $0.7 \cdot F_{MSY}$ calculated from SRR parameters = 0.59 (or calculated from data directly = 0.51, C.Walters pers. comm.)	Reference -	
Current status: 0.079 (includes all in-river mortality) (mean of most recent generation = 0.176)				
<div><div></div><div></div><div></div></div>				

Specific metric: Fishing mortality, F , over previous year (and mean over most recent generation)						
	Lower benchmark	Reference		Upper benchmark	Reference	
	F_{MAX} ; slope at origin of stock-recruit relationship = 1.42	Mace, 1993		$0.7 \cdot F_{\text{MSY}}$ calculated from SRR parameters = 0.42 (or calculated from data directly = 0.36, C.Walters pers. comm.)	-	
Current status: 0.079 (includes all in-river mortality) (mean of most recent generation = 0.176)						
						

Specific metric: Fishing mortality, F , over previous year (and mean over most recent generation)					
	Lower benchmark	Reference		Upper benchmark	Reference
	F_{MED} ; median recruits per spawner = 1.29	Mace, 1993; Sissenwine and Shepherd, 1987		$0.7 \cdot F_{MSY}$ calculated from SRR parameters = 0.42 (or calculated from data directly = 0.36, C.Walters pers. comm.)	-
Current status: 0.079 (includes all in-river mortality) (mean of most recent generation = 0.176)					
					

Specific metric: Fishing mortality, F , over previous year (and mean over most recent generation)					
	Lower benchmark	Reference			
	F_{SM} ; slope at origin of spawning females-smolt relationship (hockey stick model). No data	Bradford et al., 2000			
Current status: no data					
					

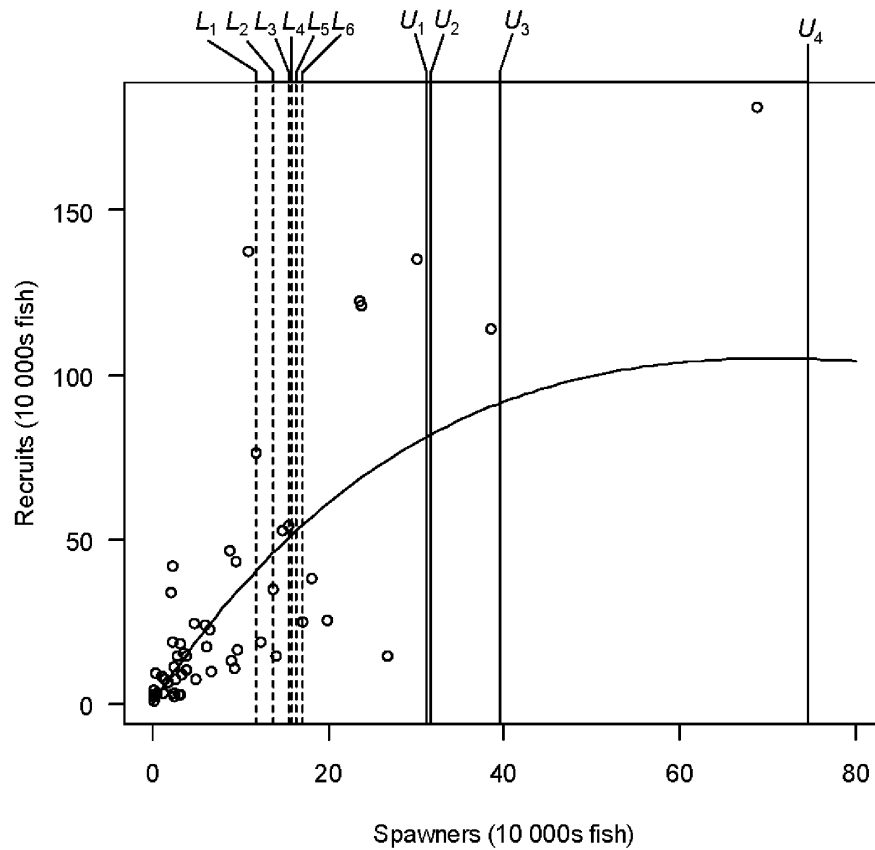


Fig. A 1. Stock-recruitment relationship for the sockeye salmon Takla/Trembleur Conservation Unit (1950-2002 brood years) with six lower benchmarks: L_1 = spawner abundance that would result in recovery to S_{MSY} in one generation under equilibrium conditions, S_{gen} ; L_2 = spawner abundance at 50% of MSY recruitment; L_3 = 20% of carrying capacity (spawners at maximum recruitment); L_4 = 40% of S_{MSY} ; L_5 = spawner abundance at 50% of maximum recruitment, L_6 = 90th percentile of spawners abundances at 50% of MSY recruitment, and four possible upper benchmarks: U_1 = 40% of carrying capacity; U_2 = 80% of S_{MSY} ; U_3 = S_{MSY} , and U_4 = 90th percentile of S_{MSY} .

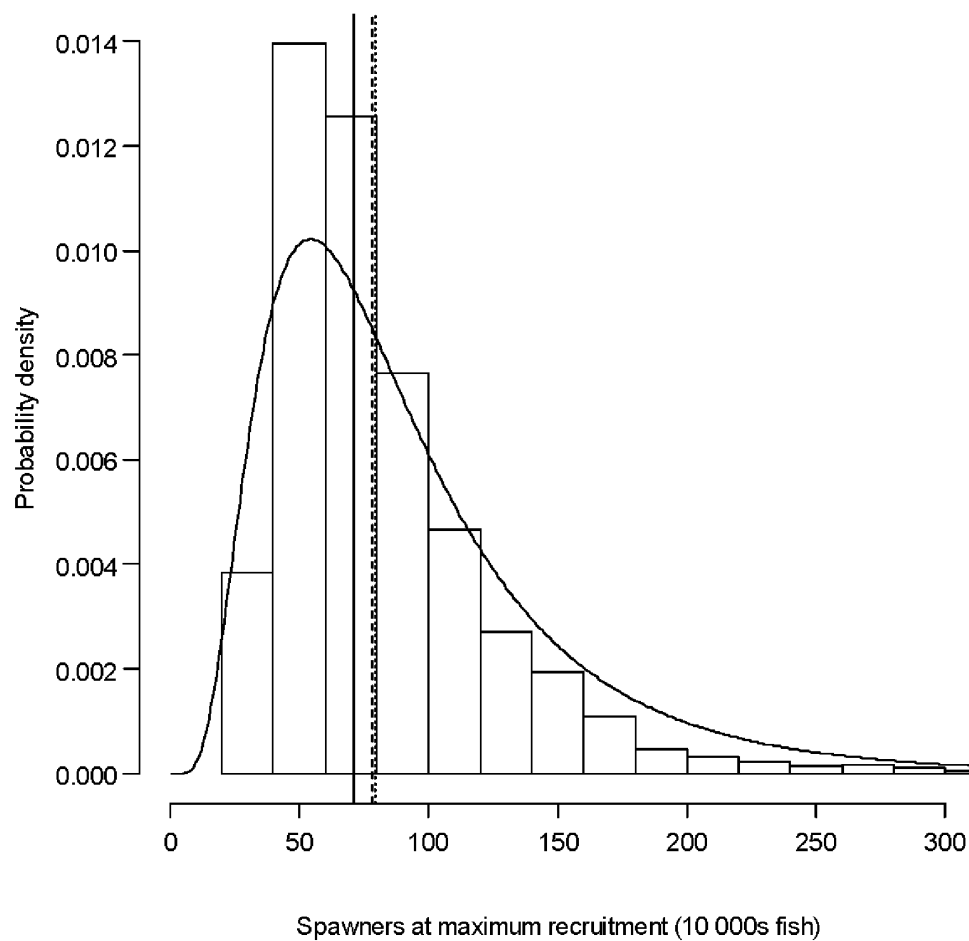


Fig. A 2. Probability density of the prior distribution (curve) and posterior distribution (bars) of spawner abundances at maximum recruitment for Takla/Trembleur sockeye salmon derived from Bayesian estimation (MCMC sampling, $n=1,000,000$ Monte Carlo trials, thinned every 400 to remove autocorrelation in the chain) of the stock-recruitment relationship. The dashed vertical line is the mean of the prior distribution, the dotted line is the median of the posterior estimate of carrying capacity assuming a uniform prior (i.e., a relatively uninformative prior), and the solid line is the median of the posterior distribution including prior information. The mean of the prior distribution corresponds to the spawners at maximum smolt production estimated from freshwater production studies (77.9×10^4 fish). The spread (i.e., standard deviation) of the prior was chosen to envelope the minimum and maximum observed spawner abundances from 1991 through 2000 (33.2×10^4 and 108.6×10^4 fish, respectively, Shortreed et al. 2001).

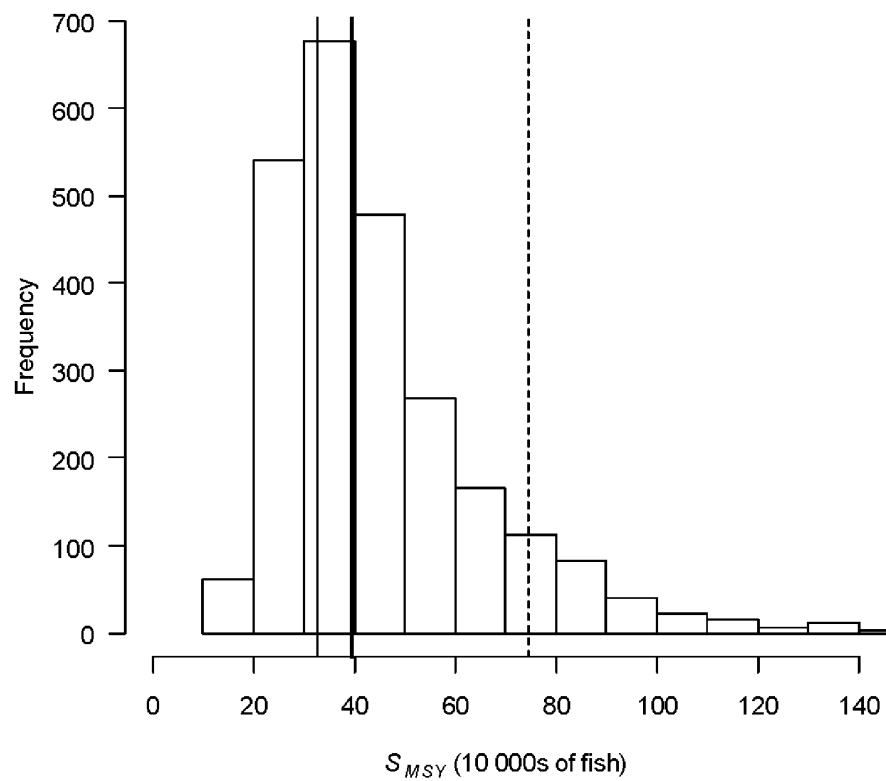


Fig. A 3. Histogram of posterior distribution of S_{MSY} for Takla/Trembleur sockeye salmon derived from Bayesian estimation (MCMC sampling) of the stock-recruitment relationship. The thin solid line is the maximum likelihood estimate of S_{MSY} , the thick solid line is the median value from MCMC samples, and the dashed line is the 90th percentile.

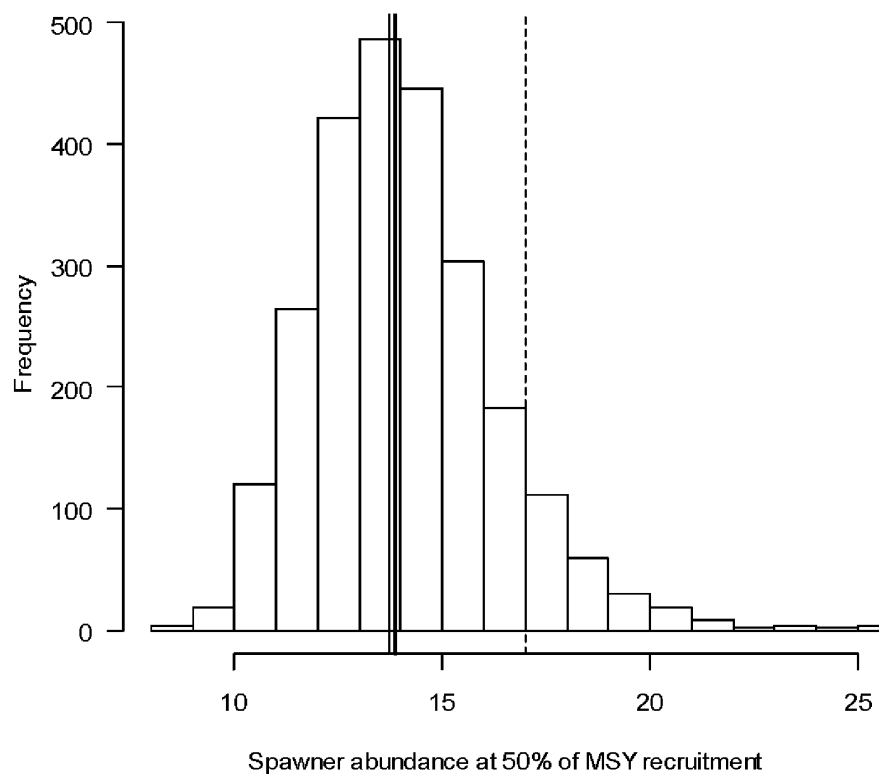


Fig. A 4. Histogram of the posterior distribution of spawner abundances at 50% of *MSY* recruitment (10 000s of fish) for Takla/Trembleur sockeye salmon derived from Bayesian estimation (MCMC sampling) of the stock-recruitment relationship. The thin solid line is the maximum likelihood estimate, the thick solid line is the median value from MCMC samples, and the dashed line is the 90th percentile.

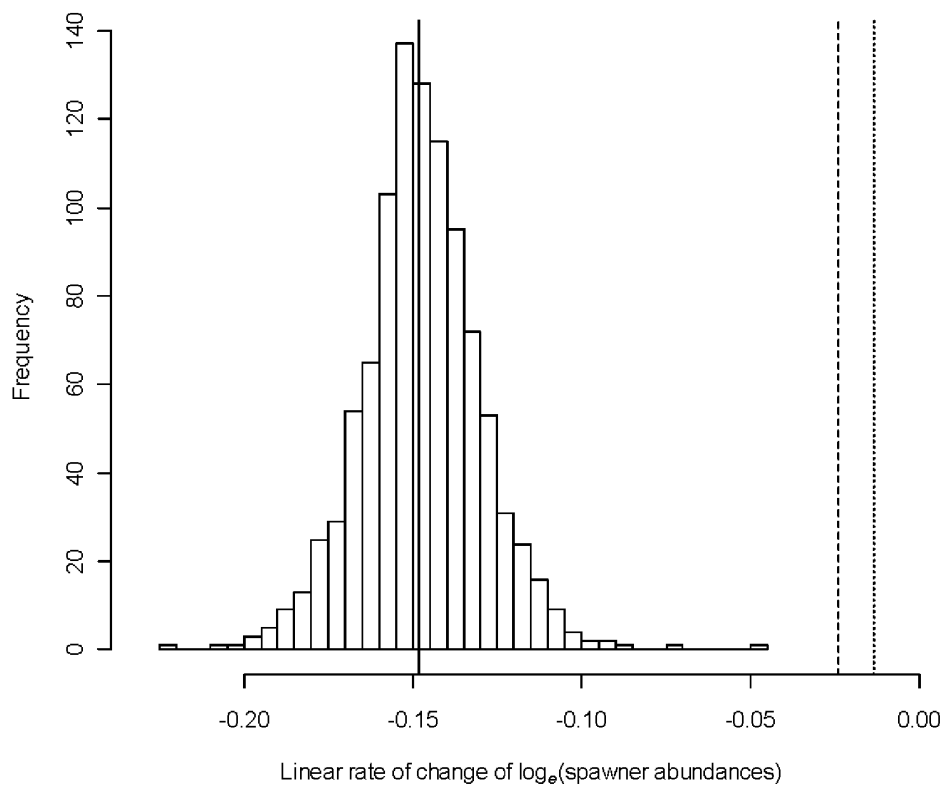


Fig. A 5. Histogram of the posterior distribution of the linear rates of change of smoothed log-transformed spawner abundances. We chose a prior distribution that was uniform over the range shown here ($-0.25 - 0$). The median value (solid vertical line) and maximum likelihood estimate are indistinguishable. The dashed line is the lower benchmark on the linear rate of change of \log_e -transformed spawner abundances and the dotted line is the upper benchmark.

Appendix B

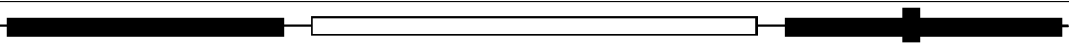
Status of Hecate Strait Lowlands odd-year pink salmon according to various indicators grouped into four classes: spawner abundances, trends in abundance, distribution, and fishing mortality. Status is assessed relative to upper and lower benchmarks. Zone of status (Red, Amber, Green) is identified only for those metrics for which data and benchmarks are available. Abbreviations are described in Table 5 and Table 6 in the text. See also Figs B1-B6 below.

(1) Class of indicator: spawner abundance

Insufficient information to estimate benchmarks based on stock-recruitment relationship or freshwater production
--

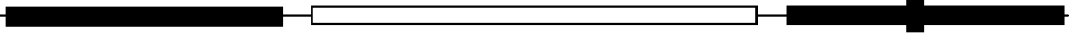
(2) Class of indicator: trends in spawner abundance

Specific metric: Linear rate of change in spawner abundances over previous 10 years (where abundances are log-transformed and smoothed with a four-year running mean)


Lower benchmark	Reference	Upper benchmark	Reference
Linear rate of change = - 0.024 (25% decline over 10 years)	COSEWIC guidelines	Linear rate of change = - 0.014 (15% decline over 10 years)	-
Current status: +0.087			
			

Specific metric: Probability that linear rate of change over 10 years $\geq X$, where X differs between lower and upper benchmarks					
	Lower benchmark	Reference		Upper benchmark	Reference
	Probability that linear rate of change ≤ -0.024 (changes in abundances are $\leq -25\%$) = 0.1	-		Probability that linear rate of change ≤ -0.014 (changes in abundances are $\leq -15\%$) = 0.1	-
Current status: 0.066 for lower benchmark and 0.081 for upper benchmark					

Specific metric: Ratio of geometric mean spawner abundance of current generation to historical mean (1951-2005)					
	Lower benchmark	Reference		Upper benchmark	Reference
	1/4	Fraser River sockeye salmon, Pestal and Cass 2007		1/2	Fraser River sockeye salmon, Pestal and Cass 2007
Current status: 1.42					

Specific metric: Ratio of geometric mean spawner abundance of current generation to the highest generational geometric mean on record					
	Lower benchmark	Reference		Upper benchmark	Reference
	1/4	Fraser River sockeye salmon, Pestal and Cass 2007		1/2	Fraser River sockeye salmon, Pestal and Cass 2007
Current status: 0.5					
					

(3a) Class of indicator: distribution of spawning groups

Specific metric: Proportion of spawning groups with a geometric mean abundance over the last generation of more than 1000 fish					
	Lower benchmark	Reference			
	0.5	Interior Fraser Coho Recovery Team (2006)			
Current status: 0.79 (22/28, of the counting locations that were observed in 2005)					
					

Specific metric: Minimum number of spawning groups that comprise 80% of total abundance, D					
	Lower benchmark	Reference		Upper benchmark	Reference
	Qualitative assessment			Qualitative assessment	
Current status: 11					

Specific metric: Mean inter-generational change in D over last ten years					
	Lower benchmark	Reference		Upper benchmark	Reference
	Qualitative assessment			Qualitative assessment	
Current status: +0.2					

Specific metric: Number of spawning groups with geometric mean abundances > 100 fish in most recent generation					
	Lower benchmark	Reference		Upper benchmark	Reference
	Qualitative assessment			Qualitative assessment	
Current status: 34					

Specific metric: Area under the curve of relationship between ranked order of spawning groups and cumulative proportion of total spawner abundances					
	Lower benchmark	Reference		Upper benchmark	Reference
	Qualitative assessment			Qualitative assessment	
Current status: 0.115					

(3b) Class of indicator: distribution of trends

(5b) Class of indicator: distribution of trends					
Specific metric: Proportion of spawning groups that have changes in abundances over 10 years \leq -25%					
	Lower benchmark	Reference		Upper benchmark	Reference
	Qualitative assessment			Qualitative assessment	
Current status: 0.288					

(3c) Class of indicator: distribution over space and habitat

(5c) Class of indicator: distribution over space and habitat					
Specific metric: spatial extent (area of occupancy)					
	Lower benchmark	Reference		Upper benchmark	Reference
	2 000km ² (when combined with population declines or fluctuations), otherwise < 20km ²	COSEWIC criteria B and D			
Current status: Data from WSP strategy 2. To be determined.					

Specific metric: Change in spatial location of spawners or juveniles in the CU over time; and spatial distribution in trends in spawner abundances					
	Lower benchmark	Reference		Upper benchmark	Reference
	Qualitative assessment	Adapted from McElhany et al. 2006		Qualitative assessment	Adapted from McElhany et al. 2006
Current status: Data from WSP Strategy 2. To be determined.					

Specific metric: Change in the type of habitat used by spawners or juveniles, e.g., change in average stream order					
	Lower benchmark	Reference		Upper benchmark	Reference
	To be determined	McElhany et al. 2006		To be determined	McElhany et al. 2006
Current status: Data from WSP Strategy 2. To be determined.					

(4) Class of indicator: fishing mortality

Insufficient information to assess fishing mortality
--

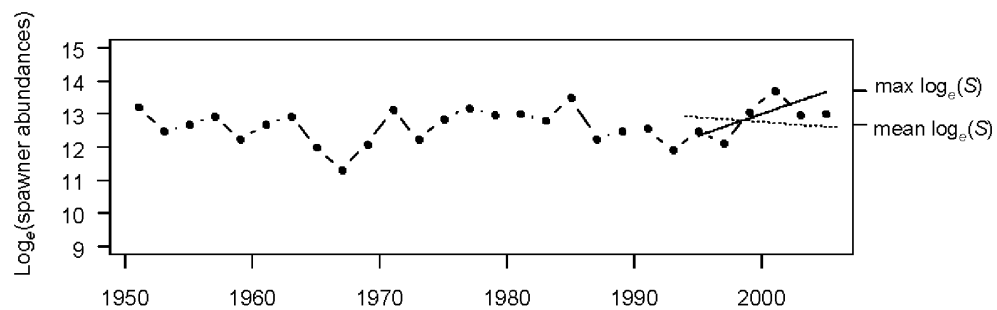


Fig. B 1. Log_e-transformed spawner abundances of Hecate Strait lowlands odd-year pink salmon ($\log_e(S)$; solid circles and broken lines) (1950 through 2005), and the best-fit line to those points for the last three generations (solid line). The dotted line is the decline in $\log_e(S)$ associated with a 25% decline in abundance over 10 years. The maximum and mean smoothed $\log_e(S)$ values over the entire time series are shown on the right axis.

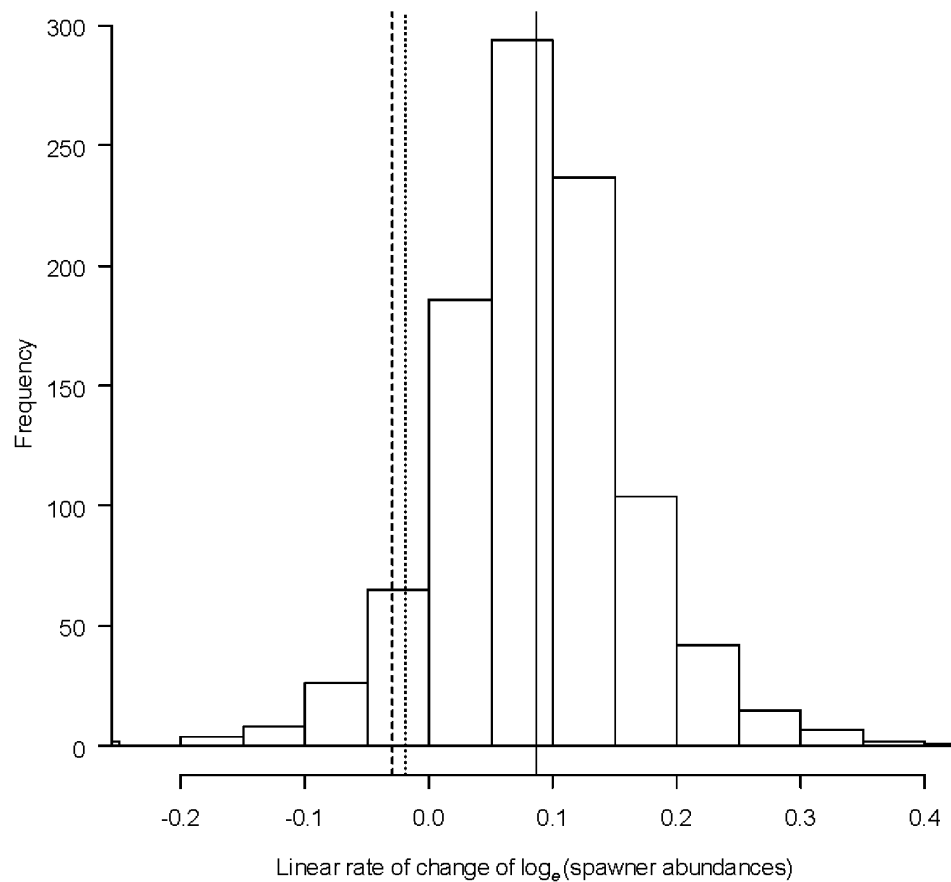


Fig. B 2. Histogram of the posterior distribution of the linear rates of change of log-transformed spawner abundances. We chose a prior distribution that was uniform over the range shown here $(-0.4 + 0.4)$. The median value (solid vertical line) and maximum likelihood estimate are indistinguishable. The dashed line is lower benchmark on the rate of change of \log_e (spawner abundances), and the dotted line is the upper benchmark.

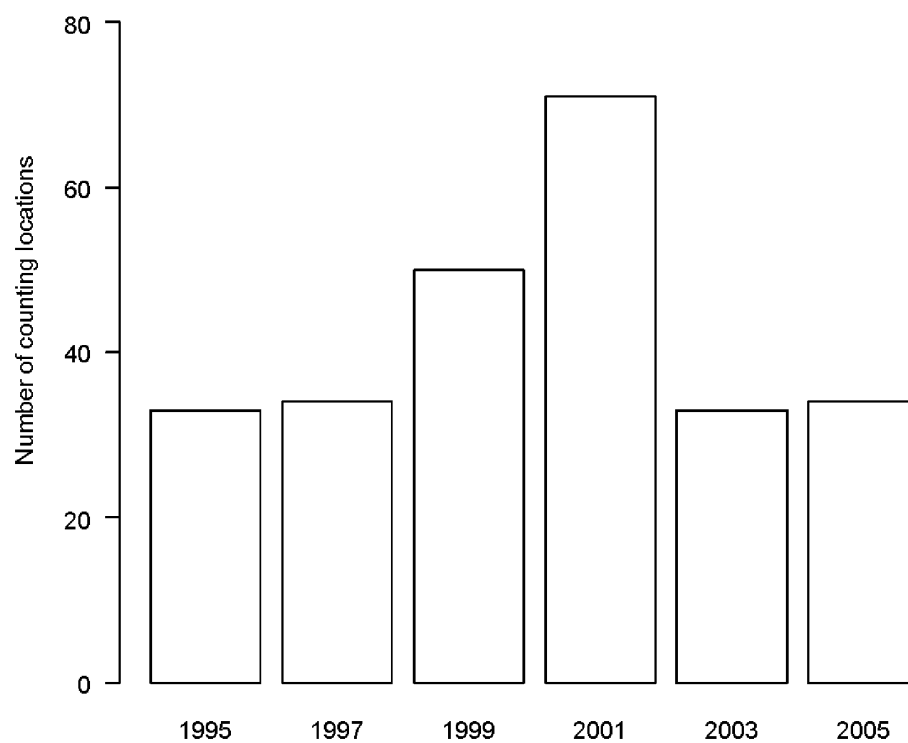


Fig. B 3. Number of counting locations (i.e., spawning groups) with abundances greater than 100 fish, for Hecate Strait Lowlands odd-year pink salmon. Similar trends over time were found when only counting locations with complete time series (i.e., no missing data) were included.

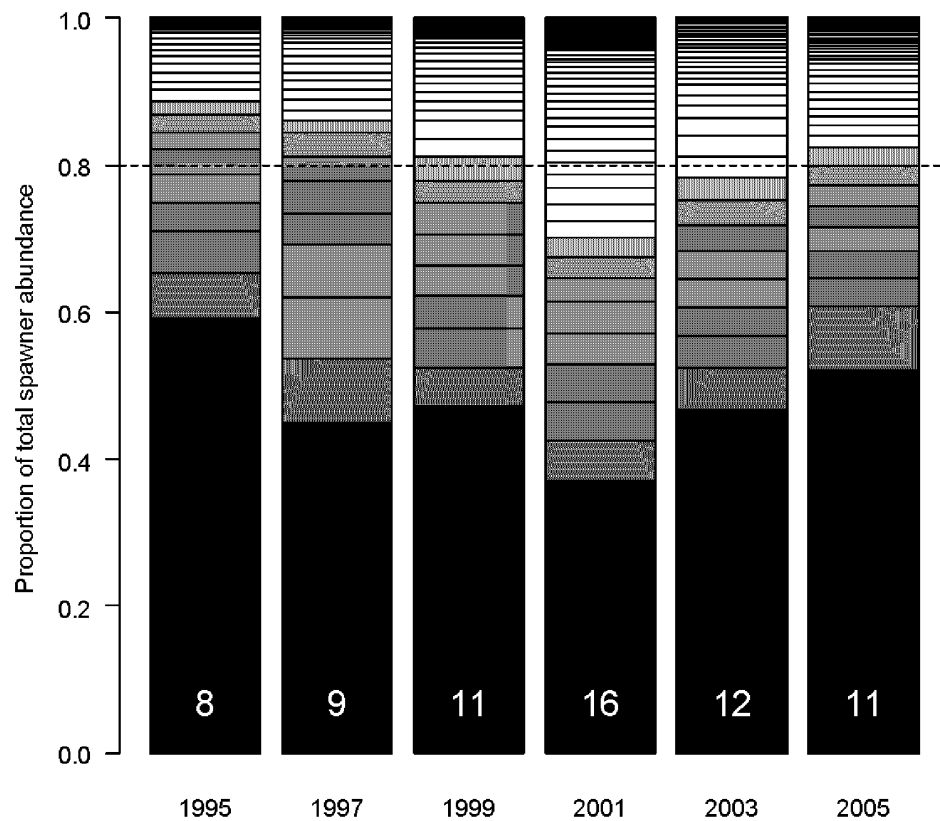


Fig. B 4. Proportion of the total spawner abundances at each counting location (i.e., spawning group), ranked from the highest proportion (bottom) to the lowest (top) for the Hecate Strait Lowlands odd-year pink salmon CU. The numbers inside the bars represent the minimum number of counting locations required to make up 80% of the total abundance in each year.

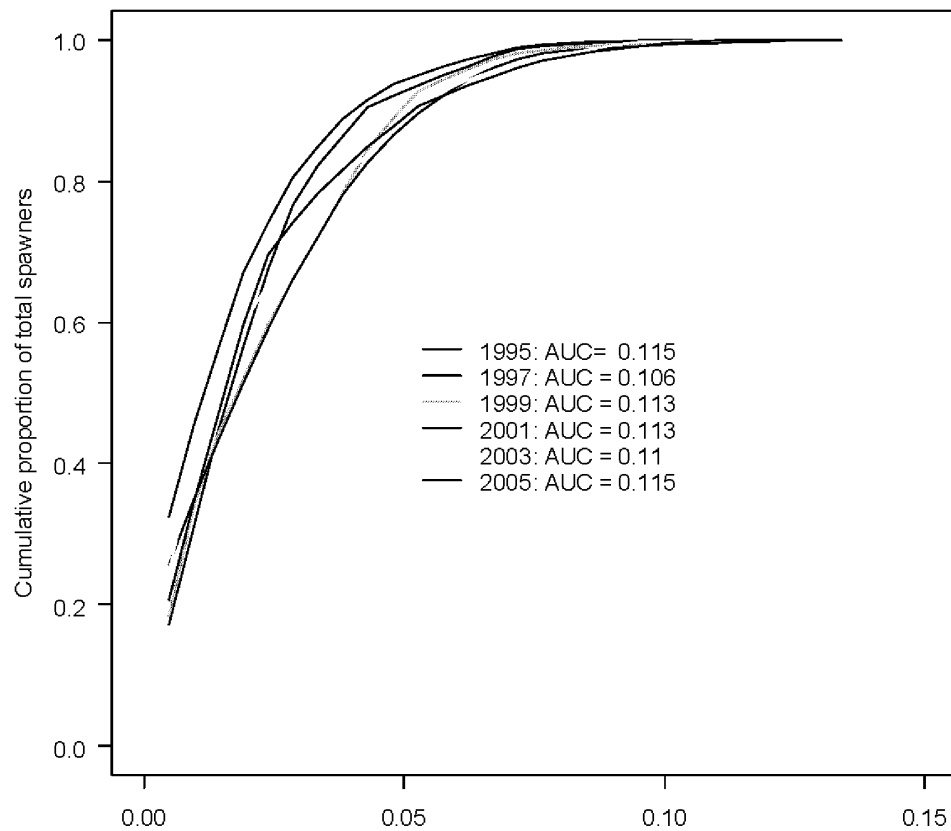


Fig. B 5. Cumulative proportion of total spawners for each spawning group, ranked in decreasing order of abundance for the six most recent generations of spawners in the Hecate Strait Lowlands odd-year pink salmon CU. AUC is area under the curve.

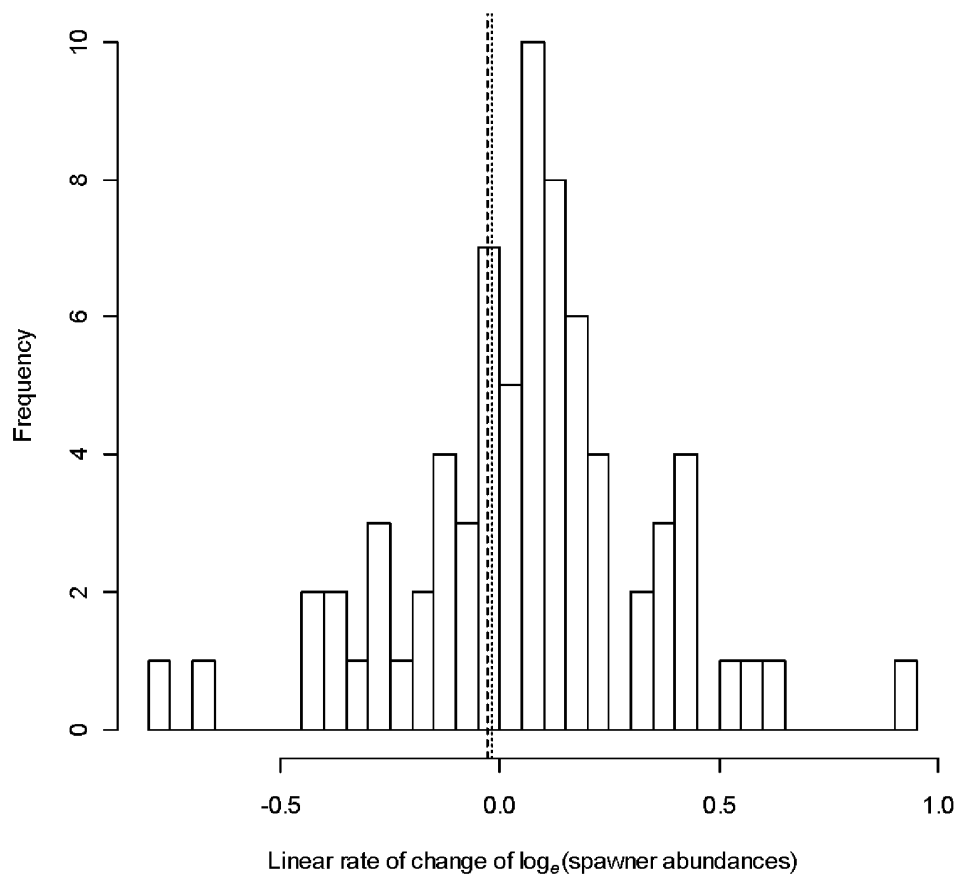


Fig. B 6. Histogram of linear slope of change of log-transformed spawner abundances, for all counting locations (spawning groups) within the Hecate Strait Lowlands odd-year pink salmon CU. Only counting locations with <50% missing data points were included. The linear rate of change associated with 15% and 25% declines in abundances over 10 years are shown with dotted and dashed lines, respectively. 28.8% of counting locations had rates of declines greater than the lower benchmark (i.e., greater than 25% decline).