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HABITAT-BASED ESCAPEMENT BENCHMARKS FOR COHO SALMON IN GEORGIA STRAIT MAINLAND, GEORGIA STRAIT VANCOUVER ISLAND, AND LOWER FRASER RIVER MANAGEMENT UNITS

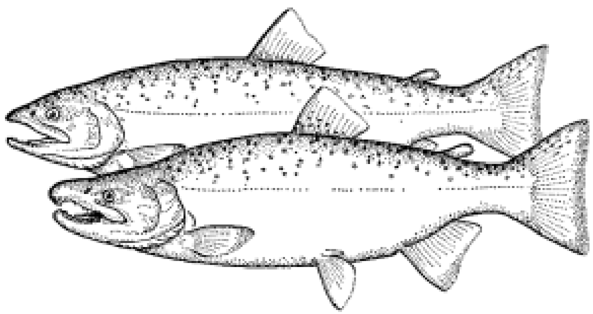

Photo: Coho Salmon line drawing — provided by Fisheries and Oceans Canada, Freshwater Fishes of Canada, 1973 Fisheries Research Board of Canada, Bulletin 184, Catalogue No. FS94-184, Page 158.

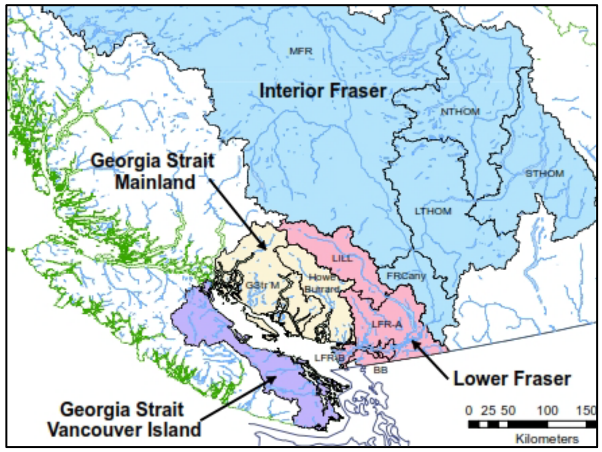

Figure 1. Map of southern BC Coho salmon management units of interest. Noble et al. 2015.

Context:

Objectives of both the Pacific Salmon Treaty (PST) and the Wild Salmon Policy (WSP) require the development of biological benchmarks for assessing population status and monitoring exploitation of Southern BC Coho Salmon. Insufficient data at appropriate temporal and stock-specific scales prevents the use of traditional stock-recruit methods for deriving biological benchmarks for these populations. Instead, novel analytic approaches are required to utilize information from the available data. For populations of Southern BC Coho Salmon, an analysis funded by the Southern Endowment Fund of the Pacific Salmon Commission (PSC) was undertaken by LGL Ltd. of Sidney, BC and Ecometric Research of Vancouver, BC to provide science-based recommendations for escapement and exploitation rate benchmarks.

Fisheries and Oceans Canada (DFO) Fisheries Management Branch has requested that Science Branch provide advice, based on the Contractors' work, for science-based escapement and exploitation rate benchmarks for three PST management units and their component WSP conservation units of Southern BC Coho Salmon. Results of this assessment and advice arising from the Regional Peer Review process will be used to inform the ongoing development of WSP benchmarks, assessment of WSP conservation unit status and PST management reference points.

This Science Advisory Report is from the November 4-5, 2014 and April 14, 2015 regional peer review on Determination of Escapement and Exploitation Rate Benchmarks for the Three Georgia Strait Southern BC Coho Management Units. Additional publications from this meeting will be posted on the Fisheries and Oceans Canada (DFO) Science Advisory Schedule as they become available.

Canada

SUMMARY

- In order to fulfill Pacific Salmon Treaty (PST) obligations and inform the implementation of Strategy 1 of the Wild Salmon Policy (WSP), biologically-based benchmarks to assess the status of PST Management Units (MUs) and WSP Conservation Units (CUs) must be derived for Southern BC Coho Salmon.
- An analysis, funded by the Southern Endowment Fund of the PST, to provide science-based recommendations for escapement and exploitation rate benchmarks for the Strait of Georgia Mainland, Strait of Georgia Vancouver Island and Lower Fraser River Coho salmon MUs (and their component CUs) was undertaken by LGL Ltd of Sidney, BC and Ecometric Research of Vancouver, BC
- The analysis utilizes a habitat-based Coho Salmon carrying capacity model, originally developed for the Nass River watershed, to generate estimates of average smolt production and spawners required to achieve average smolt production for each CU. The habitat-based model was also used to provide a priori information to Bayesian stock-recruit and stock-smolt analyses, which were then used to generate estimates of stock productivity parameters and three common biological benchmarks (Umsy, Smsy and Sgen).
- From the habitat-based model, average estimated smolt production and the number of spawners required to produce the average number of smolts for each CU were calculated respectively as 1,603,226 and 49,422 (East Coast Vancouver Island-Georgia Strait, ECVI-GS); 395,603 and 11,968 (Georgia Strait Mainland, GSM); 751,868 and 22,784 (Howe Sound-Burrard Inlet, HS-BI); 1,484,479 and 46,005 (Lower Fraser River, LFR); 910,977 and 27,605 (Lillooet, LILL); and 608,082 and 18,427 (Boundary Bay, BB). Similarly, estimated average smolt production and required spawners for each MU were calculated respectively as 1,147,471 and 34,752 (GSM); 3,003,538 and 92,037 (LFR); and 1,603,226 and 49,422 (Georgia Strait-Vancouver Island, GS-VI).
- Estimates of average exploitation rates to produce maximum sustainable yield (Umsy) obtained from Logistic Hockey Stick spawner smolt-recruit models (assuming future marine survival rate of 2.5) are roughly 41% for the GSM CU and 35% for the ECVI-GS CU, respectively. There is a high degree of uncertainty in these results (indicated by wide credible intervals associated with the reported averages).
- Results of the spawner smolt-recruit analysis are highly dependent on marine survival estimates (results were provided at three marine survival levels for comparison: 1%, 2.5% and 5%). If assumed future marine survival is reduced from 2.5% to 1%, Umsy drops to 4% and 1% for GSM and ECVI-GS CUs, respectively (from 41% and 35%).
- Potential impact on the results from a number of assumptions and uncertainties in the models were evaluated via sensitivity analyses. Results of the habitat model are highly dependent on the definition of accessible habitat, particularly as it applies to stream order, and to the estimated number of smolts produced per spawner.
- There are varying degrees of uncertainty associated with many of the inputs to both models presented, leading to high uncertainty in the model outputs. Caution should be exercised when interpreting or applying these results.
- Insufficient data for some CUs prevented stock recruit analyses to be completed on four of six CUs (HS-BI, LFR, LILL, and BB), which resulted in no stock recruit analysis results for

the GSM and LFR MUs. For CUs lacking sufficient data to calculate benchmarks, analyses using a high-quality regional data set, similar to the approach used in Korman and Tompkins (2014), would provide a method to generate results for these CUs.

BACKGROUND

The Pacific Salmon Treaty (PST) identifies four Southern BC inside management units (MUs): Interior Fraser (including Thompson), Lower Fraser River (LFR), Strait of Georgia Mainland (GSM), and Strait of Georgia Vancouver Island (GS-VI) (Table 1). The Interior Fraser MU is being assessed under a different review process, leaving three MUs to be analyzed here. The objective of the bilateral Canada/US Coho Salmon management plan is to constrain total fishery exploitation to enable MUs to produce Maximum Sustainable Harvest (MSH) over the long term, while maintaining the genetic and ecological diversity of the component populations and to improve long-term prospects for sustaining healthy fisheries in both countries. The PST requires the development and documented derivation of the escapement goal or exploitation rate that achieves MSH; and exploitation rates for three status categories: Low, Moderate and Abundant for each MU.

In addition to these PST obligations, and as part of implementing Strategy 1 of the Wild Salmon Policy (WSP), Fisheries and Oceans Canada (DFO) is required to identify biological benchmarks to assess the status of WSP Conservation Units (CUs) for Pacific salmon (PST MUs are comprised of multiple WSP CUs). There are six WSP CUs within the three PST MUs of interest here (Table 1). WSP CU benchmarks have not been established for any Southern BC Coho Salmon CUs at this time, and are not an expected outcome of this review process.

Fisheries Management Branch requested that Science Branch provide advice on the appropriateness of the methods for calculating escapement and exploitation rate benchmarks, and the results of these analyses for the Lower Fraser River, Georgia Strait Mainland and Georgia Strait Vancouver Island MUs and their respective component CUs to meet PST and WSP obligations. Results of the assessment and advice arising from this Regional Peer Review process, will also be used to inform the ongoing development of WSP benchmarks, assessments of WSP status at the CU level and determination of PST management reference points.

Table 1. Management units (MUs) and Conservation Units (CUs) of Southern BC Coho Salmon.

Management Unit		Conservation Unit	
Name	Abbreviation	Name	Abbreviation
Georgia Strait Mainland	GSM	Georgia Strait Mainland	GSM
		Howe Sound – Burrard Inlet	HS-BI
Georgia Strait Vancouver Island	GSVI	East Coast Vancouver Island – Georgia Strait	ECVI-GS
Lower Fraser	LFR	Lower Fraser River	LFR
		Lillooet River	LILL
		Boundary Bay	BB

ASSESSMENT

Data & Methods

Habitat Model

The Georgia Strait – East Vancouver Island – Mainland Coho Production Model is a habitat-based model that predicts average smolt abundance for each stream and the number of spawners that are required to produce the average smolt abundance (S_{avg}), using the length of stream available for Coho rearing as the predictor variable. The model first calculates the total length of stream that is accessible for Coho using stream gradient, known barriers and stream order (Strahler 1957). A relationship between smolt yield and stream length was then developed using a log-linear model to predict smolt yield from stream length using smolt production data from a total of 22 streams monitored for wild smolt production in the ECVI-GS (15 streams), GSM (2 streams), HS-BI (2 streams) and LFR (3 stream) CUs. Stream lengths used to generate this predictive model were estimated through GIS and include ditches, tributaries, side channels, manmade habitat, etc. Therefore, these estimates are likely to differ from existing DFO (and other third party) estimates, which could potentially lead to very different smolt yield results. Note also that the model does not directly account for variability in quality of habitat between rivers.

A list of all known Coho bearing streams within each of the six CUs of interest was obtained from DFO's New Salmon Escapement Database (NuSEDS). Smolt data was obtained from DFO biologists and BC Hydro/Metro Vancouver smolt trap studies, where available. All available information on barriers and gradient within each watershed was used to provide consistent delineation of available Coho habitat across all streams. For sensitivity analyses, accessible area was determined for upper gradient limits of 2%, 4%, 6% and 8%. The total accessible stream length within each tributary was calculated from digital TRIM files (1:20,000 scale) using ARCINFO and stratified according to gradient and stream order. The analysis included all accessible lengths for stream orders of 1 or greater.

Stock-Recruit Analysis

Parameter estimates for Beverton-Holt (BH) and logistic hockey stick (LHS) stock-recruitment models were generated using a Bayesian approach, and based on both spawner-adult recruit and spawner-smolt recruit data sets. Uninformative uniform prior distributions were used for the stock productivity (α) and process error (σ) parameters, with limits derived from previous studies or available data. A range of lognormally distributed priors were used for the maximum recruitment parameter (β), with the mean obtained from output of the habitat model and three levels of standard deviation (to represent an informative, moderately informative and uninformative prior). Benchmarks derived from stock-recruit parameters were:

1) the exploitation rate to produce Maximum Sustainable Yield (MSY; U_{msy});

2) escapement to produce MSY (S_{msy}); and

3) the escapement required to recover to S_{msy} in one generation (S_{gen}).

Benchmarks were calculated for both spawner-adult recruit and spawner-smolt recruit parameters. Additionally, benchmarks based on spawner-smolt recruit relationships were computed assuming future marine survival rates of 1%, 2.5% and 5.0%. Posterior distributions of the stock-recruitment parameters were estimated using Markov chain Monte Carlo (MCMC) sampling, and results were summarized based on the means and 95% credible intervals. Models were compared via the Deviance Information Criteria (DIC), which provides a measure to determine the most parsimonious model (providing the most information with the fewest number of parameters) among those being considered (and indicated by the lowest DIC).

Exploitation rate and survival (smolt to adult) data was obtained from DFO biologists. Spawner data was obtained from NuSEDS and subjected to quality control screening and infilling where necessary. Estimates of enhanced contributions were derived from DFO's Salmon Enhancement Program (SEP) data sets.

Sensitivity Analyses

For the habitat model, sensitivity analyses were performed on a number of model parameters to explore the sensitivity of predicted smolt yield and required spawner numbers over a range of values for those parameters. The parameters tested were: gradient barrier criteria, stream order, and smolts produced per spawner, and included assessment of potential interactions among the parameters.

Results

Habitat Model

Coho habitat, as determined by the model, is widely distributed among all streams (Table 1). From a CU perspective, it was estimated that the ECVI-GS CU had the most amount of habitat available (1,765 km), and was also the most productive, capable of producing 1.6 million smolts and 49,000 spawners. From a MU perspective, the LFR MU had the most habitat available (2,572 km); and was the most productive, producing 3.0 million smolts from 92,000 spawners.

Note that this model is not designed for use on a stream-specific basis due to considerable error in the predictions for individual streams. It may be possible, in the absence of entire MU or CU spawner abundance information, to use stream-specific model output to scale abundance for evaluation of escapement levels.

Table 2. Predicted average number of Coho Salmon smolts required to seed available habitat and the required number of spawners to produce these smolts. Spawner confidence intervals are carried forward from smolt estimation confidence limits with no additional variance added to account for other uncertainties (e.g. smolts produced per spawner, fecundity, gradient, stream order, etc.).

MU	CU	Streams (N)	Available Habitat (km)	Total Smolts (1,000s)			Total Spawners (1,000s)		
				Avg	Lower CL	Upper CL	Avg	Lower CL	Upper CL
GSM	GSM	48	367	395.6	304.5	486.7	12.0	9.23	14.8
	HS-BI	46	520	751.9	557.4	946.3	22.8	16.9	28.7
	MU Total*	94	887	1,147.5	997.8	1,297.2	34.8	30.2	39.3
LFR	LFR	93	1370	1,484.5	1,390.6	1,578.4	46.0	42.1	47.8
	LILL	19	721	911.0	567.5	1,254.5	27.6	17.2	38.0
	BB	4	481	608.1	-	-	18.4	-	-
	MU Total*	116	2572	3,003.5	2,821.3	3,185.8	92.0	85.5	96.5
GS-VI	ECVI-GS	103	1765	1,603.2	1,522.2	1,684.3	49.4	46.1	51.0

*MU Totals are not the sum of data from each component CU, but are calculated for each MU separately.

Stock-Recruit Analysis

There was considerable scatter in the stock-recruitment data. Three patterns were apparent:

1) considerable variation in recruitment at low stock size;

2) no apparent carrying capacity limit; and,

3) higher recruitment and spawning stock size in the first half of the period of record when marine survival rates were higher.

These patterns make it difficult to reliably estimate stock-recruitment parameters.

For the most part, differences in stock productivity and carrying capacity estimates between BH and LHS models were relatively minor. The DIC analysis indicates that more emphasis should be placed on results from the BH model; however, stock productivity estimates from the BH model were considerably higher than those from the regional analysis (Korman and Tompkins 2014), suggesting that they are likely too high. Given only modest statistical support for the BH model over the LHS model according to the DIC analysis, results from the LHS model were emphasized. This model predicts that, for the spawner-smolt recruit data set and at an assumed future marine survival rate of 2.5%, average allowable exploitation rates of approximately 35% and 41%, will produce Maximum Sustainable Yield (MSY) for ECVI-GS and GSM CUs, respectively (Table 3). There is a high level of uncertainty in these results (indicated by wide credible intervals associated with the means: [16%, 50%] for ECVI-GS CU and [16%, 60%] for GSM CU, respectively). This is likely owing to the uncertainty in existing estimates of stock productivity, which were ultimately driven by the large scatter in stock-recruit data points. Furthermore, note that actual exploitation rates experienced over the last decade under a Coho fisheries closure are approximately equal to the lower 95% credible interval of U_{msy} estimated here for both CUs (i.e., they have been closer to 16% than the 35-40% means reported here).

Table 3. Average, lower and upper credible limit estimates of U_{msy}, S_{msy} and S_{gen} from a Bayesian spawner-smolt recruit analysis using a Logistic Hockey Stick model for each CU under assumptions of 1%, 2.5% and 5% survival and 0.6 prCV (highly uncertain prior information). Recommended estimates are in bold.

CU	**Assumed Marine Survival**	**U_{msy}**	**LCL**	**UCL**
GSM	1%	**0.04**	0.00	0.26
	2.5%	0.41	0.16	0.60
	5%	0.64	0.47	0.76
ECVI-GS	1%	**0.01**	0.00	0.10
	2.5%	0.35	0.16	0.50
	5%	0.59	0.46	0.70
CU	**Assumed Marine Survival**	**S_{msy}**	**LCL**	**UCL**
GSM	1%	1,000	1,000	1,000
	2.5%	3,100	2,000	6,000
	5%	5,000	3,000	12,000
ECVI-GS	1%	1,500	1,000	8,000
	2.5%	24,800	14,000	37,000
	5%	40,400	25,000	57,000
CU	**Assumed Marine Survival**	**S_{gen}**	**LCL**	**UCL**
GSM	1%	1,200	700	2,000
	2.5%	1,600	600	4,100
	5%	1,300	400	4,400
ECVI-GS	1%	1,800	1,000	6,800
	2.5%	13,900	8,100	20,400
	5%	11,300	5,600	19,200

Sensitivity Analysis

The amount of accessible habitat estimated by the model was robust to gradient, but highly variable under different assumptions of minimum stream order. When tested across gradients of 2% to 8%, habitat availability was found to decrease by a maximum of 17% (HS-BI) from the base case of 8% gradient to 2% gradient. Therefore, any bias due to watershed geomorphology differences is likely to be very small. However, as the minimum stream order included in the analysis was increased from 1 to 4 (resulting in less habitat), the percent of available habitat decreased significantly (between 88% (BB) and 53% (LILL)). The model was similarly sensitive to the number of spawners required to achieve the average number of smolts when gradient and minimum stream order were allowed to vary.

The model was tested for sensitivity to changes in the assumed number of smolts produced per spawner (set initially at 33 smolts/spawner for all CUs). Sensitivity to this assumption was tested for a range of 20 – 100 smolts/spawner and it was found that at the low end of the range (20 smolts/ spawner), the number of spawners would have to be increased by 65% from the base case. At the high end of the range (100 smolts/spawner), a 67% reduction in required spawners from the base case would result.

Sources of Uncertainty

- The habitat-based model assumes that the available empirical smolt data (1983-2010 brood years) reflects the average production of the entire CU or MU, both now and in future.
- The habitat model ignores potential production from Coho Salmon with a non-conventional life history (i.e., fry or autumn migrants). For those systems where non-conventional Coho contribute to total Coho production measured by adult returns, the models would underestimate the required number of spawners to maximize total production. At this time, no data is available to assess this potential contribution.
- Due to lack of data review and quality concerns, no stock-recruit analysis was possible for four of six CUs (and two of three MUs). The spawner smolt-recruit analysis was completed for ECVI-GS and GSM CUs, and GS-VI MU.
- The results are highly influenced by assumed future marine survival rates. In particular, if assumed future marine survival is reduced to 1% (from 2.5%), the average allowable exploitation rate drops to 4% (from 41%, for GSM) and to 1% (from 25%, for ECVI-GS), respectively.
- The analysis assumes that fecundity rates and sex ratios remain constant over differing survival regimes. Estimates of required spawners (based on an assumed average smolts/spawner estimate) would need to be adjusted (upwards) to account for factors such as pre-spawn mortality, decreases in fecundity rates and/or changes in sex ratio, if these are considered significant risks.
- The habitat model explicitly includes variability from the regional smolt data set, but other sources of uncertainty (e.g., exploitation rate estimates for enhanced fish and estimates of marine survival) are not explicitly captured in the model. Sensitivity analyses were used to assess a number of uncertainties not explicitly accounted for in the model.
- The stock recruit analysis utilizes an infilling procedure that assumes covariance among streams within a CU, via two adjustment factors. Each adjustment factor introduces additional uncertainty which is not formally propagated through subsequent steps in the analysis.

- There is uncertainty in indicator streams' escapement, exploitation and survival rate estimates, as well as the degree of representativeness they provide to generating CU or MU-level estimates.

CONCLUSIONS AND ADVICE

- Two models (a Habitat Model and a Stock Recruit Model) were presented for the purpose of providing biological benchmarks for escapement. In addition, the Stock Recruit Model is capable of providing biological benchmarks for exploitation rates. In all, four metrics (habitat-based spawners, U_{msy}, S_{gen}, S_{msy}) were provided for CUs and MUs of Southern BC Coho Salmon, though not all metrics could be calculated for all CUs and MUs. (TOR Objective 1)
- Habitat-based capacity estimates (average smolts and required spawners to produce average smolts) are intended to provide a starting point to assess biological status of CUs and MUs. Additional Coho-specific work to establish WSP biological benchmarks informed by the results from this model will be needed (e.g. similar to existing benchmarks for other species of Pacific salmon).
- Allowable exploitation rate estimates (assuming specific levels of marine survival) were generated by the Stock Recruit Model. These results are not inconsistent with the regional analysis undertaken by Korman and Tompkins (2014), which showed similar rates using high-quality published data obtained at a different spatial scale.
- At this time, there are no MUs for which all of the component CU exploitation rate benchmarks could be calculated. Therefore, no advice was generated on methods to appropriately combine CU-level exploitation rate benchmarks into compatible MU benchmarks (TOR Objective 2).
- For CUs that lack sufficient data to calculate benchmarks, analysis using the high-quality regional data set, similar to Korman and Tompkins (2014), is recommended.
- There are varying degrees of uncertainty associated with many of the inputs to both models presented here, leading to high uncertainty in the model outputs. Caution should be exercised when interpreting or applying these results.
- A number of key assumptions and uncertainties in the data and methods were identified and evaluated through sensitivity analyses. In particular, the models are sensitive to the definition of "accessible habitat", and care must be exercised when setting this model input. Note that within any given watershed, the quantity of accessible habitat (based on a pre-determined definition) can vary from season to season (differentially affecting smolts and spawners), and/or from year to year (e.g. some Order 1 streams may dry up completely in some years or seasons, but not in others).
- The methods presented here are suitable for developing biological benchmarks for escapement and exploitation rates for both Management Units and Conservation Units, provided they can be supported with sufficient data (sufficient in quantity and quality). In order to provide science-based exploitation rate benchmarks for all CUs and MUs of Southern BC Coho Salmon, thorough review of NuSEDS escapement data for Area 13 and the LFR, HS-BI and LILL CUs is necessary to ascertain its quality and suitability for analysis. Further evaluation of the potential for stock recruit analyses of these CUs and their component MUs will not be possible until such a review is complete.
- In order to provide a consistent analytic approach for establishing biological benchmarks across all populations of Pacific salmon, it is recommended that these methods (i.e., using

habitat-based escapement estimates to provide prior information to stock-recruit analyses) be incorporated into the growing suite of analytic "tools".

- Regardless of the approach used to develop biological escapement benchmarks, specific streams (i.e. indicator streams) will need to be identified (and prioritized) for consistent, annual escapement work to ensure there are an appropriate number of indicators in each CU to produce reliable escapement estimates.
- There is a continued need for data assembly and quality review in DFO databases (e.g. NuSEDS) and other data holdings that have not been compiled or archived (e.g. grey literature). Further, steps to improve discoverability of all datasets will facilitate work in this area in the future.

SOURCES OF INFORMATION

This Science Advisory Report is from the November 4-5, 2014 and April 14, 2015 regional peer review on Determination of Escapement and Exploitation Rate Benchmarks for the Three Georgia Strait Southern BC Coho Management Units. Additional publications from this meeting will be posted on the Fisheries and Oceans Canada (DFO) Science Advisory Schedule as they become available.

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Centre for Science Advice
Pacific Region
Fisheries and Oceans Canada
3190 Hammond Bay Road
Nanaimo, BC V9T 6N7

Telephone: 250 756-7208
E-Mail: csap@dfo-mpo.gc.ca
Internet address: www.dfo-mpo.gc.ca/csas-sccs/

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