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

by

C.A.J. Noble[1], J. Korman[2], and R. Bocking[1]

June 2014

1 LGL Limited, 2407 Second St., Sidney, B.C. V8L 3Y8
2 Ecometric Research

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

ACKNOWLEDGMENTS

We would like to acknowledge the contribution of several people to the development of this model. Robin Tamasi and Lucia Ferreira of LGL participated in the development of the GIS components of the model to calculate accessibility from TRIM data. The support for this project by the Pacific Salmon Commission is greatly appreciated. Special thanks to Joel Sawada of DFO for his interest and support in this project. We also thank Steve Baillie (DFO), Pieter Van Wiel (DFO), and Don McCubbin (InStream) for providing the region wide dataset of smolt yields. Thanks also to Jack Cooley (Squamish Steamkeepers), Ian Bruce (Peninsula Streams), Kevin Timothy (Tla'amin Fisheries), Grant McBain (DFO Community advisor, Sechelt), Sid Quinn (Sechelt Fisheries), Nanoose Creek hatchery staff, Capilano Hatchery staff, and Seymour River Hatchery staff; all of whom provided local knowledge regarding the status of barriers to Coho migration.

EXECUTIVE SUMMARY

Identifying biological reference points or benchmarks for management of Coho salmon is a critical component of the Wild Salmon Policy, and key to sustainable fishery management; yet data and budget restrictions limit the use of traditional stock recruit methods to identify benchmarks. Here, we combine a habitat-based model and Bayesian stock-recruit analysis to estimate mean CU smolt productive capacity and the number of spawners required to achieve smolt capacity as well as stock productivity parameters and three benchmarks Umsy, Smsy and Sgen. Stock recruit and benchmark analyses were conducted using both Beverton Holt (BH) and Logistic Hockey Stick (LHS) models and spawner-to-smolt and spawner-to-recruit data sets. Stream length accessible to Coho salmon was determined from terrain resource inventory maps (TRIM) using GIS and maps at 1:20000 scale. Stream order, gradient and known barriers were used to define the accessible length of stream. The number of smolts per kilometre was derived using two models. The first used a log-linear predictive regression of smolt yield and stream length for 13 streams within the CUs of interest. The second used recent decadal smolt yield and stream length for two Coho indicator streams (Little River for EVI-GS and Myrtle Creek for GSM and HS-BI). For reasons herein discussed, the results of the predictive regression model are preferred. Estimated smolt production and the required spawners to fully seed the habitat for each CU were calculated as 1,005,922 and 16,723 (EVI-GS); 227,726 and 4,131 (GSM); and 245,364 and 4,451 (HS-BI). Results of the habitat model are highly dependent on egg-fry and fry-smolt survival estimates, and the results of the stock-recruit analysis are highly dependent on marine survival estimates. We find that Umsy, the most practical benchmark, for the EVI-GS and GSM CUs to be around 0.5, while that of the HS-BI CU was around 0.17.

INTRODUCTION

The need to establish escapement goals (benchmarks) based on stock-specific productive capacity is fundamental to wild stock conservation and sustainability of Coho salmon (*Oncorhyncus kisutch*) fisheries in British Columbia. Action step 1.2 of Canada's Wild Salmon Policy (WSP) states that benchmarks are to be developed for each salmon conservation unit (CU), which will represent biological status and will be based on abundance and distribution of spawners, or proxies thereof (WSP, 2005). Here, we estimate Coho salmon biological escapement benchmarks and productivity parameters based on estimates of stream-specific smolt production capacity, egg to fry and fry to smolt survival estimates, fecundity and available habitat for three CUs and their component Pacific Salmon Commission Management Units (MUs): Georgia Strait Mainland (GSM) (MU: Strait of Georgia Mainland), East Vancouver Island – Georgia Strait (EVI-GS) (MU: Strait of Georgia Vancouver Island), and Howe Sound – Burrard Inlet (HS-BI) (MU: Strait of Georgia Mainland). Hereafter we will refer to CU nomenclature. All data and results are provided at the CU level.

Modern salmon management policies require that salmon escapement goals or reference points be developed, and that they be based on some measure of the ability of the stream (and marine) ecosystem to produce salmon. However, estimating the productive capacity for each Coho stock within a given management unit of interest would be challenging due to technical, financial and data deficiencies. The use of a traditional stock recruit approach at the stock level to estimate productive capacity for Coho salmon is inherently difficult due to a lack of direct estimates of juvenile Coho production, catch estimates and spawner abundance on an annual stock-specific basis. Hence, for virtually all Coho streams in Southern British Columbia, there remains uncertainty regarding the appropriate escapement goals for Coho salmon.

Habitat capacity modelling provides an alternative to spawner-recruit relationships for determining productive capacity for Coho. Numerous authors have investigated relationships between fish abundance in streams (number of spawners, smolt yield, fry density, etc.) and physical habitat variables (e.g., Baranski 1989, Reeves et al. 1989, Holtby et al. 1990, Marshall and Britton 1990, Jowett 1992, Nickelson et al. 1992, Bradford et al. 1997, Rosenfeld et al. 2000, Pess et al. 2002). Faush et al. (1988) reviewed 99 models that predict the abundance of stream fish from habitat variables. Water temperature, flow, depth, velocity, water quality, food availability, channel characteristics, and watershed characteristics have all been considered in models (Jowett 1992). These multi-variate models require intensive amounts of data for specific habitat characteristics and may or may not be suitable beyond specific species, streams or geographic regions. For the majority of the nearly 2,600 spawning populations of Coho salmon in British Columbia (Slaney et al. 1996), these data simply do not exist and would be too costly to collect.

Traditional stock assessment approaches have used either information about the capacity of the environment (e.g. Blackett, 1979) or the observed relationship between stock size and recruitment (e.g. Minard and Meacham, 1987). Both approaches, however, have drawbacks, these being; difficulty of quantifying suitable habitat (environment based), and counting errors, scarcity of data and high environmentally driven variability (stock-recruit) (Adkison and Peterman, 1996). Geiger and Koenings (1991) applied a Bayesian approach to traditional stock-recruit methods that incorporated both environmental and stock recruit data in estimating Chilkoot Lake (Alaska) sockeye salmon stock-recruit relationships. Adkison and Peterman (1996) agree that this approach can be a substantial improvement over traditional stock-recruit methods, however, they caution that failure to include all reasonable stock-recruit relationships in this type of analysis can lead to overestimation in the certainty of results.

Predicting Smolt Abundance from Physical Habitat

Studies have shown that carrying capacity of a stream is related to physical attributes of the stream (Marshall and Britton 1990). Burns (1971), Mason and Chapman (1965) and Chapman (1965) all found that stream surface area provided the best correlation with absolute biomass (all species), production and density, respectively. Lister (1968) found little difference in Coho smolt yield per unit of stream length in five British Columbia streams and concluded that 2,484 smolts per kilometre was a useful biostandard for determining yield. Mason (1974) found that Coho fry biomass could be increased substantially by augmenting the food supply with daily feedings of euphausiids. However, smolt yield did not increase beyond expected natural levels.

Bocking and Peacock (2004) developed a habitat based model to estimate the number of spawners required to seed available habitat and produce the mean number of Coho smolts in

Area 3 (Nass Area) streams. Estimating smolt yield based on the linear distance of available freshwater rearing habitat within a stream or watershed has been suggested by several authors (Holtby et al. 1990, Marshall and Britton 1990, Bradford et al. 1997, Nickelson 1998, Rosenfield et al. 2000 and Bocking et al. 2001). Bocking and Peacock identify a number of key assumptions in their approach: (1) stream length is a valid surrogate for the limiting habitat available to Coho pre-smolts and ultimately limits the amount of smolts produced by the system; (2) the production bottle neck that occurs during the parr-smolt stage of freshwater life is primarily a function of available suitable riverine habitat for pre-smolts; (3) historical mean smolt data is reflective of smolt productive capacity for the region; (4) freshwater survival rates, as measured at an indicator stream, are representative of the region; (5) ocean type Coho play a limited role in productivity; (6) and others related to sex ratio, fecundity and spawning success. Bocking et al. (2005) provide a similar habitat production model for Steelhead in the Nass River and for Coho on Haida Gwaii (Bocking, unpublished).

Through estimating Coho smolt production based on length of available habitat for each of the three CUs and using known or literature values of egg to smolt survival and female fecundity, one can generate estimates of the required number of spawners needed to fully seed the available habitat and yield average smolt production or capacity. The number of spawners required for each system to yield average smolt production is therefore the end goal of the models discussed here.

Study Area

The study area for this work includes all streams where Coho salmon presence is confirmed within the Georgia Strait Mainland, East Coast Vancouver Island – Georgia Strait, and Howe Sound – Burrard Inlet CUs. The Jordan River marks the most south-western boundary, while Menzies and Mohun Creek near Campbell River mark the most north-western boundary. On the Georgia Strait mainland side, the Quatam River marks the northern most boundary, and all streams and rivers south of here to Noons creek (Burrard Inlet) are included (Figure 1). Major watersheds include the Sooke, Cowichan, Qualicum, Englishman, Campbell, Toba, Squamish, Capilano and Seymour Rivers.

There are a total of 227 known Coho streams within our study area. One hundred and five of these are in the East Coast Vancouver Island-Georgia Strait CU, fifty-four are within the Georgia

Strait Mainland CU, and sixty eight are within the Howe Sound-Burrard Inlet CU. Coho escapements vary significantly among all streams, and it is likely that not all Coho-bearing streams are represented in the Fisheries and Oceans database (nuSEDS). Escapement data is generally poor though some systems are fenced or assessed with defensible and repeatable methods and therefore have more rigorous estimates.

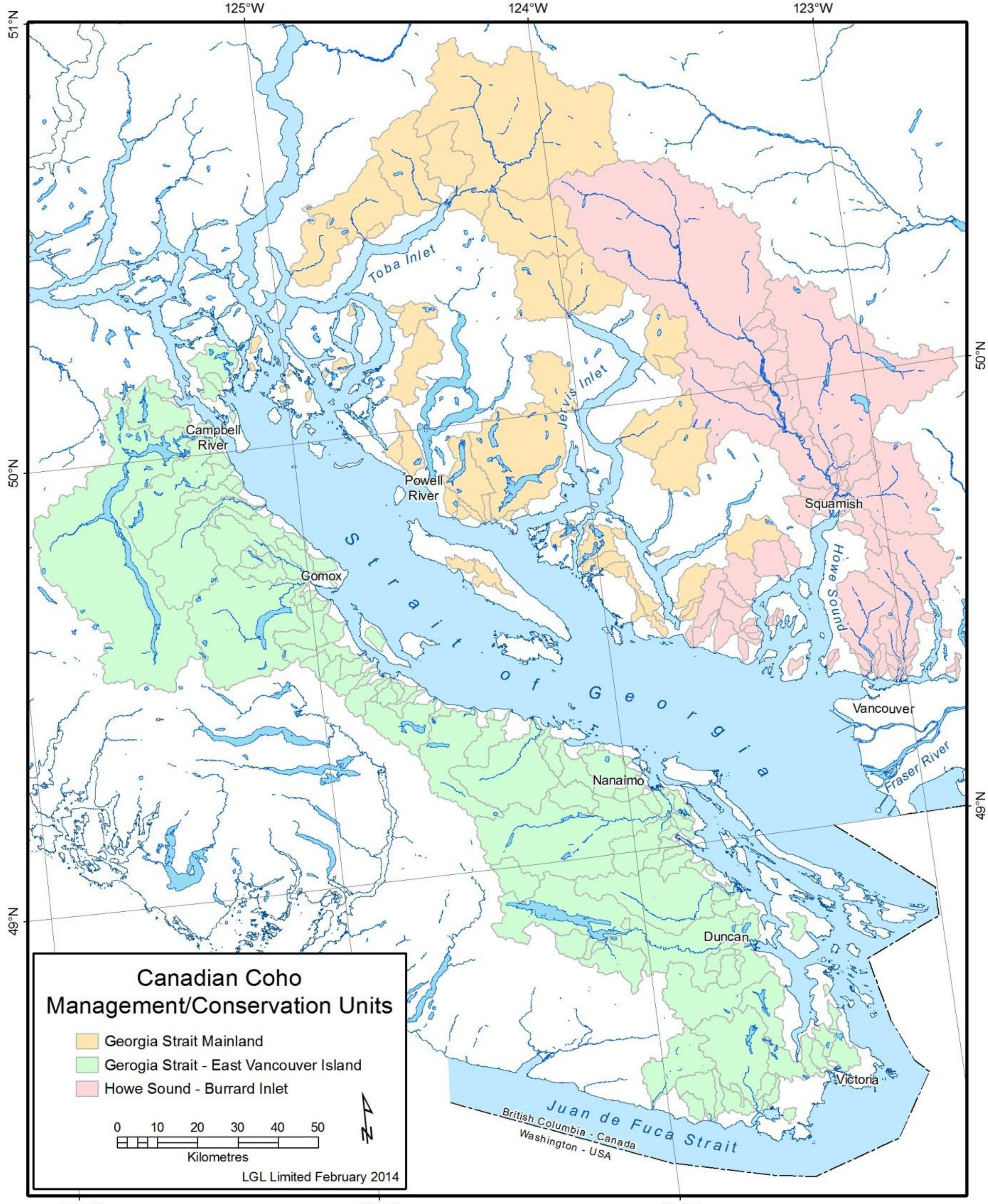
Management of Southern B.C. Coho salmon

Management of Coho fisheries in southern B.C. is formally described and agreed to in the Pacific Salmon Treaty. As of 2002, the fishery has been managed on an abundance based system (ABM) which will continue to 2018. Under the ABM, exploitation of CUs of low abundance are constrained in hopes of facilitating recovery. The Georgia Strait – Mainland, East Vancouver Island – Georgia Strait Mainland, and Interior Fraser CUs are identified as CUs where harvest is constrained (DFO IFMP, 2011), and 2013 Canadian fishery exploitation rates were not to exceed 3% on these CUs. Where abundance and health of wild Coho is high enough to facilitate harvest, fishing mortality limits are developed on an annual basis and fisheries are managed to not exceed the defined limit. For detailed text and formulae on Southern B.C. Coho management, we refer the reader to the PSC website: www.psc.orb/Index.htm.

Within Southern B.C., a number of Coho smolt enumeration programs have occurred since 1995 for the purpose of monitoring both wild smolt output and survival of hatchery planted smolts. The total number of stream years and Pacific Fishery Management Area (PFMA) in which they occurred are: 27 (PFMA 13), 106 (PFMA 14), 12 (PFMA 17), 9 (PFMA 18), 17 (PFMA 15), 10 (PFMA 16), 4 (PFMA 19), and 5 (PFMA 20). Not all streams have been monitored annually, nor have all streams been monitored from the same start year. Wild stocks of Coho salmon in Southern B.C. are supplemented through DFO's salmon enhancement program which is designed to support vulnerable stocks and to provide harvest opportunities through sustainable fisheries. A complete list of enhanced rivers and respective brood releases can be found in the 2011 Southern Salmon IFMP.

Despite the large number of Coho spawning systems within the study area and relatively high number of fenced and enhanced systems, a habitat-based approach to quantifying the productive capacity for Coho production was determined to be the most appropriate approach to establishing escapement reference points for reasons discussed in the introduction. The habitat-based approach to deriving these system specific productivity estimates and total area spawner requirements are described in this paper as the Georgia Strait – East Vancouver Island – Mainland Coho Production Model.

Figure 1. Map of CUs of interest and watersheds where Coho are known to spawn



Coho Production 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 in 227 watersheds in the study area using stream gradient, known barriers and stream order (Strahler 1957). A relationship between smolt yield and stream length was then developed using two different approaches. The first approach (Model 1) used a log-linear model to predict smolt yield from stream length using smolt production data from 13 streams monitored in the EVI-GS (11 streams) and GSM (2 streams) CUs. Stream length used to generate this predictive model was that estimated through GIS and therefore may differ from other estimates (Table 1). In the second approach (Model 2), recent ten-year (2000 – 2010) mean smolt production measures for two non-enhanced streams: Little River (EVI-GS) and Myrtle Creek (GSM) (Table 2) were used and the average smolts produced per kilometre of stream for these systems was applied to all Coho streams on a CU specific basis. Myrtle Creek estimates were applied to HS-BI CUs to generate smolt estimates for Model 2, as no stream estimate specific to the HS-BI CU was available.

Table 1. Average smolt production per km of accessible length for 13 rivers within the EVI-GS and GSM CUs. Data source: Steve Baillie (DFO)

CU	Stream Name	Average # Smolts	Anadromous Length	Avg. per km	N Year
EVI-GS	Black_Creek	57,103	27	1,730	27
	Englishman	44,607	58	1,138	9
	Little	11,767	11	1,154	13
	Millard	2,072	4	691	11
	Morrison	7,106	9	740	9
	Quinsam	57,521	81	1,048	27
	Simms	4,090	13	470	11
	Tsolum	31,808	90	554	7
	Waterloo	1,542	2	811	9
	Willow	9,810	14	868	4
	Woods	1,441	10	288	11
	Average	**20,806**	29	**717**	13
	SE	**6,822**		**120**	
GSM	Myrtle	1,564	8	193	13
	Whittall	869	3	334	4
	Average	**1,216**	6	**216**	9
	SE	**347**		**71**	

Table 2. Average smolt production from 2000 - 2010 for monitored streams

within the EVI-GS and GSM CUs. Average production per km of rivers highlighted in grey was used to generate Model 2 estimates.

CU	Stream_Name	Mean Smolt Production (2000 - 2010)	Length (km)	Average/km	SD on /km
EVI-GS	Black_Creek	54,867	27	2,045	988
	Englishman	45,330	58	775	310
	Little	12,208	11	1,116	153
	Millard	2,357	4	563	971
	Morrison	7,106	9	814	3,695
	Quinsam	51,180	81	629	40
	Simms	4,670	13	359	2,353
	Tsolum	35,397	90	393	9
	Waterloo	1,542	2	866	2,971
	Willow	12,452	14	894	105
	Woods	1,245	10	125	7,685
	Subtotal	228,353	319	715	172
GSM	Myrtle	869	8	107	32
	Whittall	1,948	3	622	429
	Subtotal	2,817	11	250	129

Using estimates of survival by life stage, the model then calculated the number of spawners that would be required to produce the estimated number of smolts. Model estimates of smolt production were compared to empirical data collected for five watersheds where escapement was estimated via “fixed site census”, an escapement method of high precision and accuracy.

The Coho production model carries with it the critical assumption that stream length of stream orders greater than 2 (at 1:20,000 scale) is a valid surrogate measure for the limiting habitat available to Coho pre-smolts and ultimately limits the amount of smolts produced by the system. This assumption is supported by the fact that there is a downstream movement of fry during fall and winter freshets to occupy lower areas of streams as pre-smolts (Cederholm and Reid 1987). A portion of Coho fry migrating downstream may also exit the freshwater environment either passively due to environmental clues (e.g. flooding, freeze-up) or actively due to territorial displacement (Bilby and Bisson 1987, Hartman et al. 1981). The number of smolts emigrating from the stream after one or more years of freshwater residency is therefore assumed to be a function of the number of fry that survive to become parr in their first year of freshwater residency. The limiting factor for maximizing steelhead production is often cited as the availability of suitable habitat at the parr stage (Ptolemy et al. 2004).

The Georgia Strait – East Vancouver Island – Mainland Coho Production Model also assumes then that this production bottleneck occurring during the parr-smolt stage of freshwater life for Coho is primarily a function of available suitable riverine habitat for yearling Coho (hereafter referred to as pre-smolts). To the authors' knowledge, there have been no attempts to quantify any relationship between the amount of late summer or winter rearing habitat available to Coho pre-smolts and stream length. However, Sharma and Hilborn (2001) did find that lower valley slopes, lower stream gradients, and pool and pond densities were correlated with higher smolt densities.

DATA SOURCES AND MODEL INPUTS

Coho Distributions

Fisheries and Oceans Canada provided a list of all Coho bearing streams within each of the three CUs of interest (Figure 1), and a total of 227 streams were identified. Coho streams of Vancouver Island, Howe Sound, Burrard Inlet and the Sunshine Coast are likely well accounted for, while it is possible that streams in and around Jervis and Toba Inlets could support Coho, but have not been included in this model as there is no record of Coho being either present or absent. Therefore, all known Coho producing streams of order 2 - 7 and with Fisheries and Oceans records of escapement were included in the analysis.

Accessible Stream Length

In a particular stream or tributary, available Coho salmon habitat is restricted by both physical limitations (barriers, gradient, discharge, water quality (dissolved oxygen, turbidity, temperature)) and evolutionary distribution factors. Suitable spawning and rearing habitat can remain inaccessible due to waterfalls, debris jams, excessive water velocities, man-made barriers, etc. which may impede fish access seasonally, annually, inter-annually or permanently. However, assessing whether or not an obstruction is a barrier is not easy. Falls that are insurmountable at one time of the year may be passed at other times under different flows (Bjornn and Reiser 1991). Powers and Orsborn (1985) reported that the ability of salmonids to pass over barriers is dependent on the swimming velocity of adult fish, the horizontal and vertical distances to be jumped, and the angle to the top of the barrier. The pool depth to height ratio is also important (Stuart 1962). Bjorn and Reiser (1991) determined a maximum jumping height for Coho of 2.2 m under optimal conditions. Therefore, where a barrier equal to or greater than 2.0 m existed, the habitat model considered this a complete barrier to migration. Furthermore, any gradient in excess of 100% (45°) for longer than 10 metres was also identified as a barrier to Coho migration.

All available information on barriers within each watershed was used to restrict Coho access in systems. The sources of information on barriers included FISS (1991a, b), Aquatic Biophysical Maps (MOE 1977), unpublished information from the Ministry of Water, Land and Air Protection, and data available through the Fisheries Information Summary System (FISS). Where barriers were identified, but were without associated metrics (height, type, etc), all efforts were made by the authors to ascertain the necessary information. This was done through discussions with knowledgeable local first nations individuals (Sliammon, Sechelt), representatives of local stream keeping groups (Squamish, Peninsula Streams, Bowen Island, etc.), hatchery representatives (Qualicum, Nanaimo, Port Moody, Seymour, Chapman Creek, etc.), dam operators/owners, Google Earth and available online documentation. 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. Where lakes were present within the network of accessible stream, the length of centre lines connecting accessible lake tributaries to the lake outlet was included in the total length calculation. This had the net effect of including a portion of the lake something less than the perimeter as suitable habitat for Coho parr.

Gradient

Pess et al. (2002) found that Coho spawner abundance was correlated with stream gradient in the Snohomish River, Washington. Coho have been reported to occur in stream segments with gradients ranging from one to ten percent, with the greatest densities occurring in the lower gradients. Higher gradient areas are dominated by larger substrate and lack the pool habitat favoured by Coho for rearing (Bisson et al. 1982). The Georgia Strait – East Vancouver Island – Mainland Coho Production Model assumed that stream gradients over 8% were not utilized by Coho parr or pre-smolts for rearing and that all gradients below 8% had similar density of Coho. ARCINFO and a gradient analysis program were used to calculate the accessible length of stream within each watershed. For sensitivity analyses, accessible area was determined for upper gradient limits of 2%, 4%, 6% and 8%.

Stream Order

Stream orders were determined using a method developed by Horton (1945) and later modified by Strahler (1957) and were determined from the BC TRIM digital mapping (1:20000 scale). Streams in the study area had stream orders from 1-7. We excluded streams of order 1 due to the ephemeral nature of these streams. The analysis included all accessible lengths for stream orders of 2 or greater, and is schematically illustrated in Figure 2.

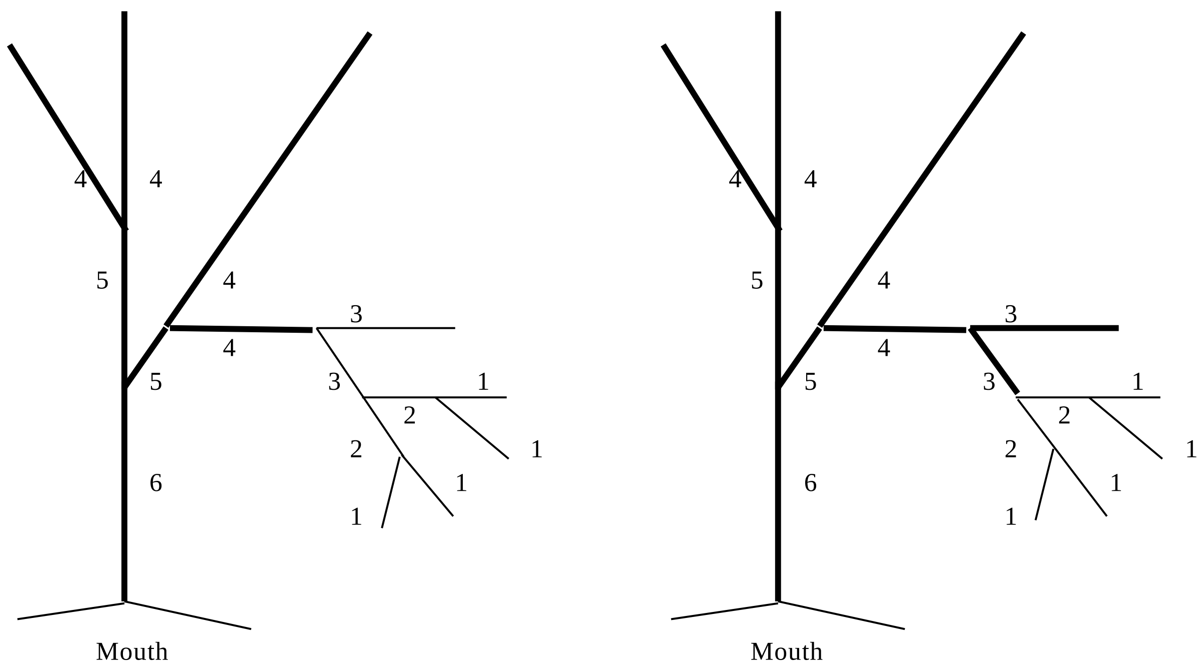


Figure 2. Schematic drawing of stream order, numbers indicate stream order.

Mean Smolt Yield

DFO maintains an extensive data time series of Coho smolt production for 37 different streams in 15 different DFO Statistical Areas around Vancouver Island and the Georgia Strait. Only one of these streams (Carnation Creek) has been monitored annually since 1971, and two have only one observation (Millstream and Mud Bay). To generate mean smolt yield, we selected only streams which had a minimum of 4 annual estimates of wild smolt production and were located in the CUs of interest. A minimum of four years of data was selected in order to both allow a reasonable number of streams to be included, while also generating an average that would be less likely to be driven by one large or small data point. Following our selection process, a total of 13 streams (155 annual estimates) were used in our analyses.

Model 1

The first model for smolt yield used a local geographic data set to determine the smolt yield per kilometre of stream. Annual yield of Coho smolts and the associated accessible stream length (GIS estimate) were compiled for all 13 streams in the study are where data was available (Table 1, Figure 1). The mean Coho smolt yield was calculated for streams with four or more annual estimates. From this data, a predictive regression model was developed (Figure 3). The predictive regression used for the generating Model 1 smolt estimates was:

ln(smolt yield} = 5.7353 + 1.1229 * ln{stream length} equation (1)

R^2 = 0.73

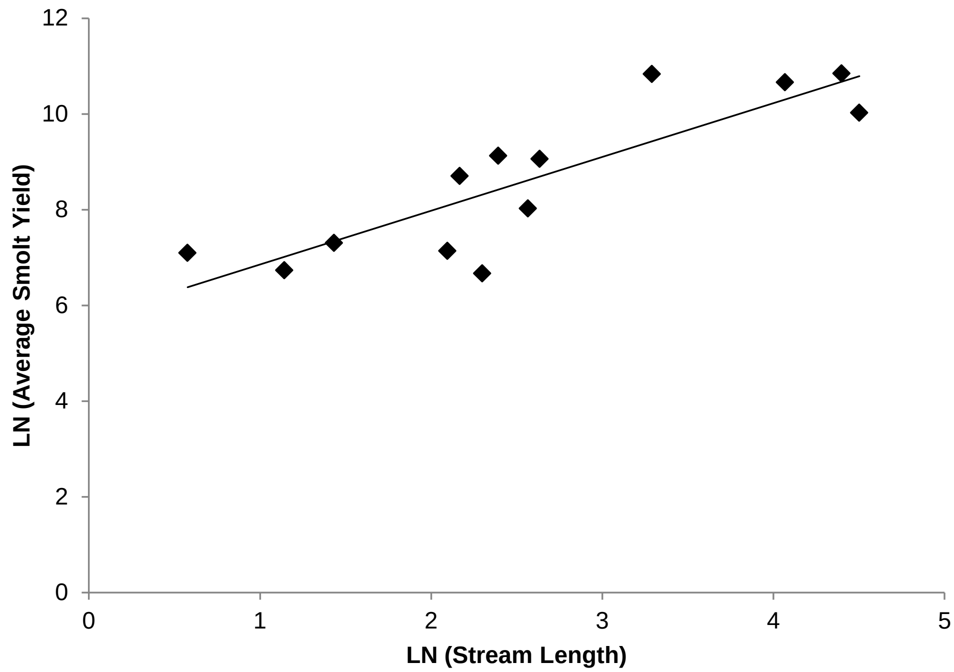


Figure 3. LN average smolt yield as a function of accessible stream length (LN km) for all streams from CUs of interest where data was available.

Predictions of log-transformed smolt yield and the associated variance were then made given the stream length using the well-known predictive regression functions (e.g., Draper and Smith 1981). The arithmetic expectation and variance for smolt yield was next calculated assuming a log-normal distribution using:

$$E[Y] = \exp\{\hat{\mu} + \hat{\sigma}^2 / 2\}$$ equation (2)

and

$$Var(Y) = \exp\{2\hat{\mu} + \hat{\sigma}^2\}(\exp\{\hat{\sigma}^2\} - 1)$$ equation (3)

where $\hat{\mu}$ is the mean and $\hat{\sigma}^2$ is the variance of the logged transformed predictions (Johnson and Kotz 1970). Assuming the stream predictions are independent, the mean for the CU is the sum of the mean of the component streams. Thus, the predicted means were summed for each watershed within each CU, and also for all three CUs. The variance terms for each component stream can be similarly summed to get area-wide variance values. The summed mean and variance estimates can be regarded as normally distributed according to the central limit theorem.

Model 2

The second model for smolt yield used the mean (2000-2010) annual smolt yield per kilometre for Little River (2,914) and Myrtle Creek (107) (Table 2). The 10 year average smolt production of Little River was applied to EVI-GS and the 10 year average from Myrtle Creek was applied to both the GSM and HS-BI CUs as no estimate was available for any stream in the HS-BI CU. Stream specific variability around these estimates was estimated using the observed variability. One other system was available in each CU which could have been used to generate mean production estimates, Black Creek (EVI-GS) and Sakinaw (GSM). Neither estimate was used, however, due to Black Creek having the highest smolt production per kilometre of rivers assessed (Table 2) and uncertainty around quantifying contributions from nearby streams at Sakinaw.

Spawner Requirements

Determining the number of spawners required to produce a given number of smolts involved back calculating from the smolt estimate to spawners using fecundity and egg-fry and fry-smolt survival estimates. Limited data for Coho sex ratios are available for streams of interest, however, the average ratio of adult Coho passing the counting fence at Black Creek from 1989-1997 and 2006-2010 was 0.89 (M/F; Table 3). Sex ratio for the purposes of calculating the number of spawners required in the model was, therefore, assumed to be 0.89.

Table 3. Sex ratio of Coho spawners observed at the Black Creek counting fence, 1989-1997 and 2006-2010 (provided by Pieter Van. Wiel, 2013).

Year	Males	Females	Totals	M/F Ratio
1989	1417	1401	2818	1.01
1990	383	522	905	0.73
1991	1513	1627	3140	0.93
1992	881	793	1674	1.11
1994	316	275	591	1.15
1995	778	831	1609	0.94
1996	82	65	147	1.26
1997	61	60	121	1.02
2006	78	111	189	0.70
2007	1812	2059	3871	0.88
2008	391	500	891	0.78
2009	966	1440	2406	0.67
2010	1052	1292	2344	0.81
Average	**748**	**844**	**1593**	**0.89**

Fecundity

The required number of spawners to fully seed the available habitat was determined for each stream using estimates of fecundity. The number of eggs per female for all three CUs was estimated at 2500, as direct estimates are only available for Nile Creek (2310) and Big Qualicum River (2574 +/- 549) (Groot and Margolis, 1991).

Freshwater Survival

Freshwater survival estimates from egg-fry and fry-smolt for Coho salmon are available for a number of streams in the EVI-GS CU (2), as well as other Vancouver Island streams (4) outside of our CUs of interest (Bradford, 1995, Dave Ewart pers.comm) (Table 4). No freshwater survival estimates are available for mainland streams in our CUs of interest. The required number of spawners to fully seed available habitat in the EVI-GS CU was estimated using CU specific survival estimates of 22.8% (fry-smolt) and 20.0% (egg-fry), while survival estimates for HS-BI and the GSM streams was calculated as the average of all data available for Vancouver Island streams such that survival was 19.6% (fry-smolt) and 21.2% (egg-fry) (Table 4).

Table 4. Egg-fry and fry-smolt survival of Wild Coho, number of years for which data is available, and the source of data for streams of interest.

			Survival		
CU	Stream Name	Years	Egg-Fry	Fry-Smolt	Source
EVI-GS	Oliver Creek	8	20.0%		Bradford et al. 1995
EVI-GS	Quinsam River	27		22.8%	Dave Ewart, pers. comm 2013
Average			**20.0%**	**22.8%**	
Vancouver Island	Carnation	13		16.5%	Bradford et al. 1995
Vancouver Island	Beadnell	4	24.9%		Bradford et al. 1995
Vancouver Island	Carnation	15	19.6%		Bradford et al. 1995
Vancouver Island	Sashin Creek	3	20.4%		Bradford et al. 1995
Average			**21.6%**	**16.5%**	
Grand Average			**21.2%**	**19.6%**	

Sensitivity Analyses

Sensitivity analyses were performed on a number of model parameters to explore the sensitivity of predicted smolt yield and required spawner numbers to those parameters. The parameters tested were gradient barrier criteria, stream order, egg-to-fry survival, fry-to-smolt survival and sex ratio.

Stock-Recruitment Analyses

Data Sources

Escapement data from 1972 – 2012 was used to generate estimates of recruits from 1972 – 2009 with 1972 being the first year for which exploitation rate (ER) data is available (J. Sawada, pers. comm 2013). To estimate recruits (*Rec*) in year *t* we assumed each Coho is 3 years old at escapement and adjusted escapement (*Esc)* according to the following formula:

$$Rec_t = Esc_{t-3}/(1-ER_t)$$

Exploitation rate data is available for four enhanced and one wild stock in the EVI-GS CU, one wild stock in the GSM CU, and no stock from the HS-BI CU. To generate CU specific exploitation rates (ERs), we averaged stock specific exploitation rates for both enhanced and wild stocks of each CU and applied these average exploitation rates to each CU. As no stock specific ER estimates were available for enhanced stocks in the the HS-BI CU, we averaged all available data for enhanced stocks within the EVI-GS and GSM CU. Similarly, for ER estimates of HS-BI wild stocks we averaged ER data from one stock in each of the EVI-GS CU (Black Creek), West Coast Vancouver Island (Carnation Creek) and the Lower Fraser River (Salmon River).

Adult recruit values were converted to smolt recruits for each brood year by dividing the adult recruit values by the marine survival in the return year. Benchmarks developed from the spawner-adult recruit fits make the assumption that the average marine survival over the period of record will hold in the future. Benchmarks based on the spawner-smolt recruit models can be based on any assumed future marine survival rate.

Stock-Recruitment Model Structure

We estimated parameters for Beverton-Holt (BH) and logistic hockey stick (LHS) stock-recruitment models based on both spawner-adult recruit and spawner-smolt recruit data sets. The form of the Beverton-Holt applied here is,

(4) $$\hat{R}_{i,t} = \frac{\alpha_i E_{i,t-3}}{1 + \frac{\alpha_i}{\beta_i} E_{i,t-3}}$$

where, $\hat{R}_{i,t}$ is the predicted number of adult or smolt recruits from conservation unit (CU) 'i' in year 't', $E_{i,t-3}$ is the observed escapement to the CU in year t-3, α_i is the initial slope of the line and is equivalent to the number of recruits produced per spawner at low density (stock productivity), and β_i is the maximum number of recruits that can be produced from the CU (carrying capacity).

The form of the Logistic Hockey Stick model (LHS, Barrowman and Myers 2000) is:

(5) $$R_{i,t} = \alpha_i C \delta_i (1 + e^{\frac{-1}{C}}) \left[\frac{S_{i,t-2}}{C\delta_i} - \log\left(\frac{1 + e^{(S_{i,t-2} - \delta_i)/(C\delta_i)}}{1 + e^{\frac{-1}{C}}} \right) \right]$$

where,

(6) $$\delta_i = \frac{\beta_i}{\alpha_i} \left[C(1 + e^{\frac{-1}{C}}) \left(\frac{1}{C} + \log(1 + e^{\frac{-1}{C}}) \right) \right]^{-1}$$

As for the Beverton-Holt model stock-recruitment models α_i and β_i are estimated. C is a tuning parameter that determines the smoothness at the transition between the initial slope at low stock size and the asymptote at higher stock size. The logistic hockey stick model approaches the hockey stick model as C→0. In this analysis the tuning parameter was held constant at C=1.

We did consider applying the Ricker model. In an earlier analysis of the south coast coho spawner-adult recruit stock-recruitment data we conducted, information theoretic approaches were unable to distinguish between Ricker and Beverton-Holt models owing to the extensive scatter in the data. However, a comparison of Ricker, Beverton-Holt, and Logistic Hockey Stick models based on 17 spawner-to-smolt datasets from the Pacific Northwest indicated that the latter two models had much more support than the Ricker model (Korman and Tompkins 2007) (Figure 4). As this analysis makes the standard assumption that the majority of density dependence for anadromous salmonids occurs in freshwater, the model selection results from Korman and Tompkins apply here, and we therefore did not evaluate the Ricker model. However, we do use information theoretic approaches to compare Beverton-Holt and LHS models to the data from the three southern coho CUs.

Stock-recruitment parameters were estimated by assuming that residuals of log-transformed data were normally distributed. That is, error in recruitment predictions is log-normally distributed. The likelihood of observing $R_{i,t}$ recruits given a set of parameter estimates is computed from,

(7) $$L(R_{i,t} \mid \alpha_i, \beta_i, \sigma_i) = \frac{1}{\sqrt{2\pi\sigma_i^2}} e\left[-\frac{[\log(R_{i,t}) - \log(\hat{R}_{i,t})]^2}{2\sigma_i^2}\right]$$

where, $R_{i,t}$ is the observed number of recruits, $\hat{R}_{i,t}$ is the predicted number of recruits from eqn.'s 4 or 5, and σ_i is the estimated standard deviation of the residuals around the stock-recruitment relationship. σ_i represents the extent of process error as we assume there is no observation error in the data.

Benchmarks derived from stock-recruit parameters were: 1) the harvest rate to produce Maximum Sustainable Yield (Umsy); 2) escapement to produce MSY (Smsy); and 3) the escapement required to recover to Smsy in one generation (Sgen). Benchmarks were computed using both spawner-adult recruit and spawner-smolt recruits stock-recruitment parameters. Benchmarks based on spawner-smolt recruit relationships were computed assuming future marine survival rates of 2.5%, 5.0%, and 10%. Benchmarks based on spawner-adult recruit relationships require no specification of future marine survival rates. However, as the mean of prior distribution of maximum recruitment for the spawner-adult stock-recruitment estimation was based on the average of historical marine survival rates (see below), the benchmarks implicitly assume an equivalent marine survival rate in the future. All benchmarks were estimated by non-linear optimization using the L-BFGS-B algorithm for the optim function of the 'R' statistics package.

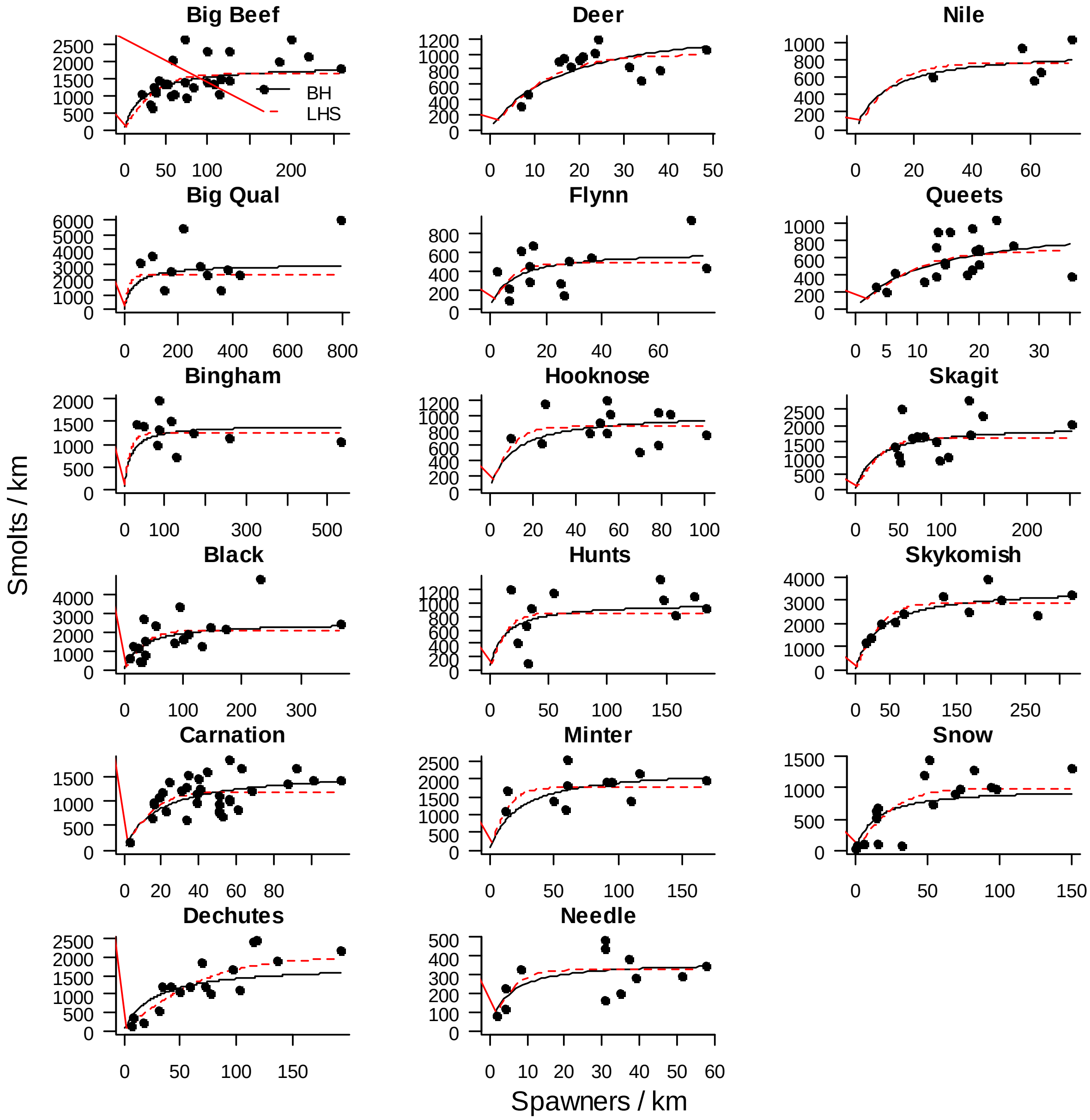


Figure 4. Comparison of fits of Beverton-Holt (BH) and Logistic Hockey Stick (LHS) models to a regional spawner-smolt stock-recruit data set (reproduced from results of Korman and Tompkins 2007). Note these models were fit using a hierarchical Bayesian approach.

Stock-Recruitment Parameter Estimation

Stock-recruitment parameters were estimated using a Bayesian approach where the posterior distributions of parameter estimates ($P(\alpha_i, \beta_i, \sigma_i)$) depend on the prior distributions ($p(\alpha_i, \beta i, \sigma_i)$) and the likelihood of the data given parameter estimates ($L(R_{i,t} \mid \alpha_i, \beta i, \sigma_i)$, eqn. 7),

(8) $$P(\alpha_i, \beta i, \sigma_i) \sim p(\alpha_i, \beta_i, \sigma_i) * (L(R_{i,t} \mid \alpha_i, \beta i, \sigma_i).$$

We used an uninformative uniform prior for stock productivity (α_i for Beverton-Holt model or $e^{\alpha i}$ for Ricker model) with minimum and maximum bounds of 0.05 – amax, where amax= 200 when fitting spawner-smolt recruit relationships, and amax=200*0.065 (13) when fitting spawner-adult recruit relationships. The upper limit of smolt recruit productivity (200) was based on the asymptotic maximum value from the hyper-distribution of stock productivity estimated by Korman and Tompkins (2007) (Figure 5), and 0.065 was the average marine survival for Georgia Strait indicator stocks over the period of record (Figure 6). We used an uninformative uniform prior for process error (σ_i) specified in terms of precision (τ_i), with minimum and maximum bounds of 0.01 and 10, respectively (note that $\sigma_i = \frac{1}{\sqrt{\tau_i}}$).

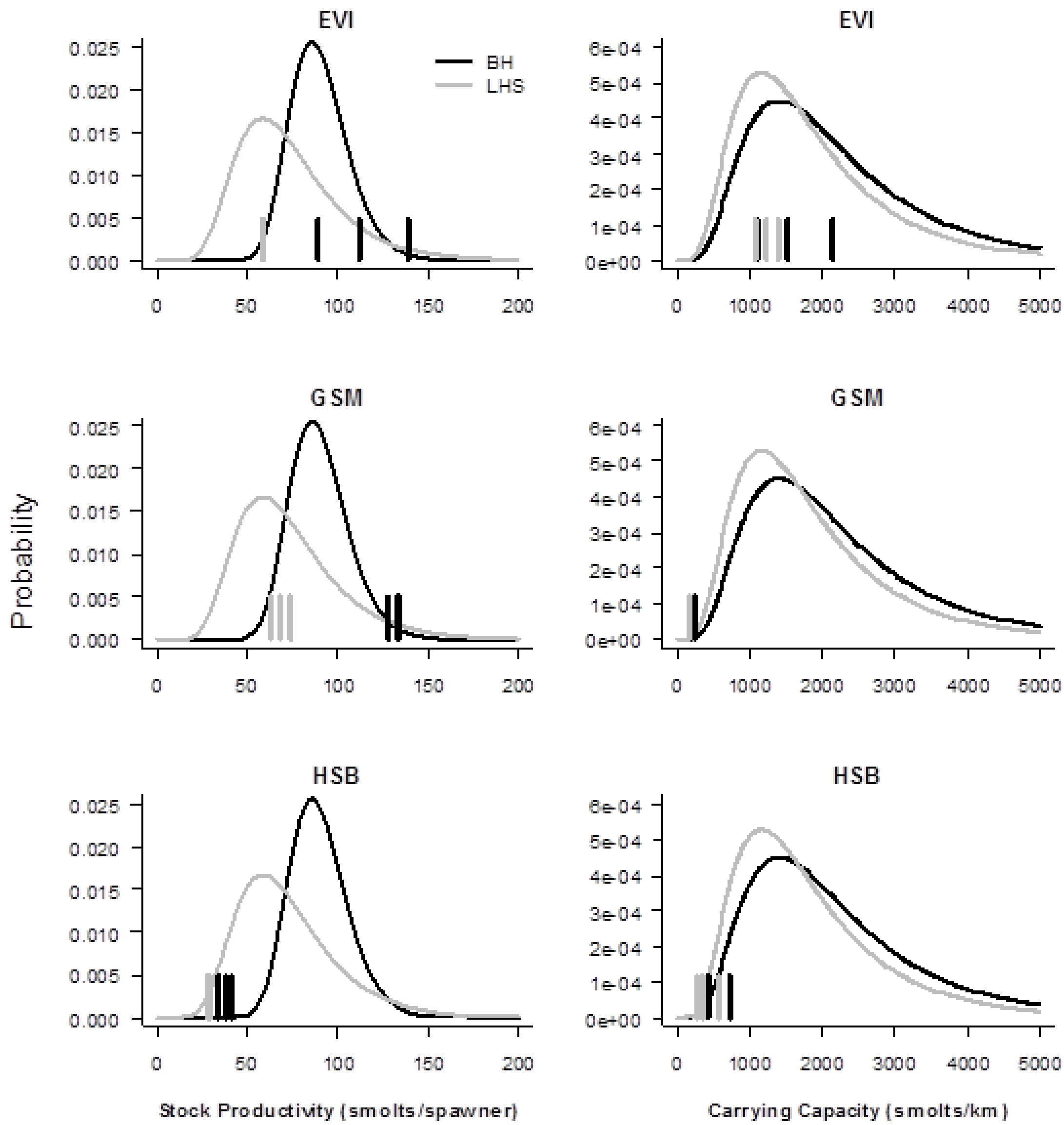


Figure 5. Hyper-distributions of stock productivity and carrying capacity (curved lines) based on a regional analysis of spawner-smolt recruit datasets of Korman and Tompkins (2007) compared to estimates from this study (vertical lines) by CU. For each CU, six estimates are provided (2 stock-recruit model forms * 3 levels of information in the prior for carrying capacity).

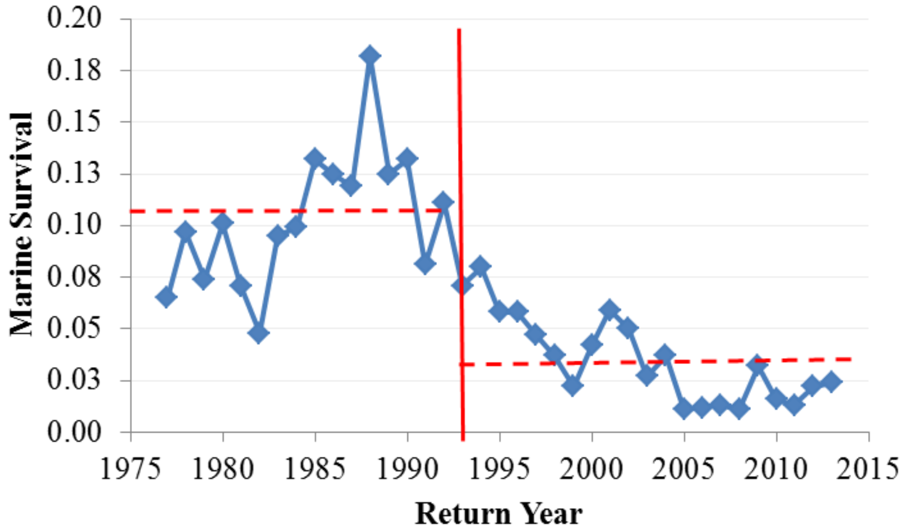


Figure 6. The average smolt-to-adult survival rate across indicator stocks for coho salmon from southern BC. The vertical line represents the approximate year when survival rates began to decline. The horizontal dashed lines represent the average marine survival before and after 1993.

We used a range of lognormal priors for maximum recruitment (β_i) with a mean determined as the product of the maximum number of smolts produced from each CU as determined by accessible stream length (computed from model 1, Table 6) and the historical average marine survival (0.065) when fitting spawner-adult recruit relationships, and simply the maximum number of smolts when fitting spawner-smolt recruit relationships. The standard deviation of the prior distribution for maximum recruitment was set to informative (CV=0.1), moderately informative (CV=0.3), and uninformative (CV=0.6) levels (note CV is approximately equal to the standard deviation for a lognormal distribution).

Posterior distributions of stock-recruitment parameters were estimated using Markov chain Monte Carlo (MCMC) sampling in WinBUGS (Spiegelhalter et al. 1999) version 1.4 called from the 'R' statistical package (R Development Core Team 2009) via the R2WinBUGS library (Sturtz et al. 2005). Three chains with different initial values for stock productivity and maximum recruitment were simulated. A total of 6,000 iterations were completed for each chain with the first 1,000 discarded to remove potential effects of the random parameter values used to initiate the simulations. Posterior distributions were based on saving every 5th sample from the remaining 5,000 iterations for a total sample size of 1,000 for each chain. This sampling approach was sufficient to achieve model convergence in all cases, which was evaluated using the Gelman-Rubin convergence statistic

(Gelman et. al. 2004). Benchmarks were computed for each posterior value, and results were summarized based on the means and the 95% credible interval. The deviance information criteria (DIC, a Bayesian version of AIC) was used to compare Ricker and Beverton-Holt models for each set of information (Spiegelhalter et al. 2002). As information in Bayesian analysis includes the actual data as well as the priors, models were compared for each unique combination of CU (EVI, GSM, HSB) and prior distribution for maximum recruitment (3 CVs). The analysis was conducted for both spawner-adult recruit and spawner-smolt recruit relationships.

MODEL RESULTS

Distribution of Coho Habitat, Accessible Stream Length and Mean Smolt Yield

Coho habitat, as determined by the model, is widely distributed among all streams and is shown in Figure 1, and accessible stream length of the four streams from each CU that contribute the largest percentage of spawners to each CU are provided in Table 5. Estimated accessible lengths for all streams at gradients between 2% and 8% are provided in Appendix Table 1. Stream specific estimates of smolt production and the required number of spawners to fully seed available habitat is available in Appendix Table 1 and Appendix Table 2.

Table 5. Estimates for the 4 top producing streams in each CU and MU by Model number, length of available habitat, the required number of spawners to fully seed habitat and the percent of total escapement each stream represents of each CU.

Model #	CU	MU	Watershed	Stream Length (m)	Smolts Produced	Spawners	Spawner/km	Percent of Total CU spawners	Percent of Available CU Habitat
1	EVI-GS	GS-VI	Puntledge River	87,890	76,130	1,266	14	8%	6%
	EVI-GS	GS-VI	Tsolum River	90,170	78,451	1,304	14	8%	7%
	EVI-GS	GS-VI	Cowichan River	128,360	118,895	1,977	15	12%	10%
	EVI-GS	GS-VI	Nanaimo River	107,270	96,208	1,599	15	10%	8%
	Subtotal			**413,690**	**369,683**	**6,146**	15	**37%**	**31%**
	GSM	GSM	Theodosia River	9,310	5,853	106	11	3%	3%
	GSM	GSM	Quatam River	14,230	9,409	171	12	4%	5%
	GSM	GSM	Little Toba River	30,090	22,001	399	13	10%	10%
	GSM	GSM	Toba River	138,890	130,518	2,368	17	57%	47%
	Subtotal			**192,520**	**167,782**	**3,043**	16	**74%**	**65%**
	HS-BI	GSM	Indian River	9,740	6,155	112	11	3%	3%
	HS-BI	GSM	Seymour River	17,860	12,157	221	12	5%	6%
	HS-BI	GSM	Cheakamus River	25,800	18,457	335	13	8%	9%
	HS-BI	GSM	Squamish River	183,860	182,117	3,304	18	74%	65%
	Subtotal			**237,260**	**218,885**	**3,970**	17	**89%**	**84%**
	TOTAL			**843,470**	**756,351**	**13,160**	16	**67%**	**60%**
2	EVI-GS	GS-VI	Puntledge River	87,890	98,078	1,631	19	7%	6%
	EVI-GS	GS-VI	Tsolum River	90,170	100,622	1,673	19	7%	7%
	EVI-GS	GS-VI	Cowichan River	128,360	143,239	2,381	19	10%	10%
	EVI-GS	GS-VI	Nanaimo River	107,270	119,704	1,990	19	8%	8%
	Subtotal			**413,690**	**461,642**	**7,675**	19	**31%**	**31%**
	GSM	GSM	Theodosia River	9,310	995	18	2	3%	3%
	GSM	GSM	Quatam River	14,230	1,521	28	2	5%	5%
	GSM	GSM	Little Toba River	30,090	3,216	58	2	10%	10%
	GSM	GSM	Toba River	138,890	14,846	269	2	47%	47%
	Subtotal			**192,520**	**20,578**	**373**	2	**65%**	**65%**
	HS-BI	GSM	Indian River	9,740	1,041	19	2	3%	3%
	HS-BI	GSM	Seymour River	17,860	1,909	35	2	6%	6%
	HS-BI	GSM	Cheakamus River	25,800	2,758	50	2	9%	9%
	HS-BI	GSM	Squamish River	183,860	19,652	356	2	65%	65%
	Subtotal			**237,260**	**25,360**	**460**	2	**84%**	**84%**
	TOTAL			**843,470**	**507,581**	**8,508**	10	**60%**	**60%**

Predicted Smolt and Spawner Production

The predicted smolt production by stream for each of the two models is provided in Appendix Table

2. Area totals from both models with confidence limits are summarized in Table 6. Model 1 produced smaller numbers of required spawners for the EVI-GS CU, but larger numbers of required spawners for the GSM and HS-BI CU. Confidence limits on the predicted spawner abundances are also shown in Table 6, but these do not include the considerable uncertainty associated with the survival parameters used to back-calculate required spawners from the predicted smolt yield.

Table 6. Predicted number of Coho smolts required to fully seed available habitat and the required number of spawners to produce said smolts. Percent difference between estimates of Model 1 and 2 are also provided. Spawner CI Limits are carried forward from smolt estimation confidence limits with no variance added to account for uncertainty in survivals and fecundity.

				Smolts			Spawners		
Model #	CU	MU	N	Mean	Upper CI	Lower CI	Mean	Upper CI	Lower CI
1	EVI-GS	GS-VI	103	1,005,922	1,061,254	950,591	16,723	17,643	15,803
	GSM	GSM	46	227,726	279,829	175,623	4,131	5,076	3,186
	HS-BI	GSM	23	245,364	353,005	137,723	4,451	6,403	2,498
	Subtotal		**69**	**473,090**	**518,994**	**427,187**	**25,305**	**29,122**	**21,487**
2	EVI-GS	GS-VI	103	1,481,877	1,489,685	1,474,069	24,636	24,766	24,506
	GSM	GSM	46	31,544	32,917	30,171	572	597	547
	HS-BI	GSM	23	30,288	62,970	60,693	549	596	503
	Total		**172**	**1,543,709**	**62,970**	**60,693**	**25,757**	**25,959**	**25,556**
% Diff (#1/#2)	EVI-GS	GS-VI		68%			68%		
	GSM	GSM		722%			722%		
	HS-BI	GSM		810%			810%		
	Total			31%			98%		

SENSITIVITY ANALYSES

All sensitivity analyses were conducted using output from Model 1.

Accessible Stream Length Determinations

The determination of accessible Coho area is the first point where error can be introduced to the model. In the model, we used known barriers (where available) as the upper limit of Coho accessibility in each watershed. However, for many systems, barriers are unknown or the upper limit is determined by stream gradient. We used a stream gradient of 100% (45^{o}) for greater than 10 m (i.e., a rise of 10 m over 10 m) as a gradient barrier to Coho.

To test model sensitivity to the 8% gradient used as the upper limit of Coho distribution (pres-smolt rearing habitat) and the stream order algorithm used, the model was run using upper gradient limits ranging from <2% to <8%. The model was also run using minimum stream orders ranging from 1 to 3 (see Figure 2). Note that as minimum stream order increases, the amount of habitat available decreases. Decreasing the upper gradient limit for accessibility decreased the estimate of accessible length.

The amount of accessible habitat estimated by the model was robust to gradient, but highly variable under different minimum stream orders. When tested across gradients of 2% to 8%, habitat availability was found to decrease by a maximum of 18% (GSM) from the base case (Table 7). However, as the minimum stream order to include increased (resulting in less habitat), the percent of available habitat decreased between -25% (HS-BI) and -78% (EVI-GS) (Table 7). The model was similarly sensitive to the number of spawners required to fully seed habitat when gradient and minimum stream order were allowed to vary (Table 8).

Sex Ratios

Both Model 1 and 2 generated estimates of the required number of spawners using a male:female ratio of 0.89:1. We assessed the sensitivity of Model 1 results to sex ratios varying from 0.7 to 1.3 (Males:Females). As expected, as the ratio of males increased, the number of spawners required to fully seed available habitat also increased (Table 9).

Table 7. Estimated accessible length (m) over a range of gradient limits and minimum stream orders; grey shading indicates the base case.

CU	Gradient	Minimum Stream Order Included			
		1	2	3	% Difference
	<8%	1,327,950	961,930	745,990	-78%
EVI-GS	<6%	1,300,780	947,390	738,390	-76%
	<4%	1,229,800	903,990	713,960	-72%
	<2%	1,131,590	839,920	670,510	-69%
	% Difference	15%	13%	10%	
GSM	<8%	295,110	217,700	172,830	-71%
	<6%	286,540	212,020	168,940	-70%
	<4%	266,830	198,640	160,650	-66%
	<2%	241,870	179,740	145,500	-66%
	% Difference	18%	17%	16%	
HS-BI	<8%	283,360	236,810	225,780	-26%
	<6%	279,680	233,310	223,000	-25%
	<4%	271,140	225,660	216,170	-25%
	<2%	251,350	208,030	199,480	-26%
	% Difference	11%	12%	12%	

Table 8. Sensitivity of required spawners to gradient and *B* for EVI-GS and GSM and HS-BI CUs. Grey shaded cells indicate the base case scenario.

EVI-GS	Gradient			
B	8	6	4	2
1	0%	-2%	-9%	-17%
2	-31%	-32%	-35%	-41%
3	-49%	-49%	-51%	-55%

GSM	Gradient			
B	8	6	4	2
1	0%	-2%	-8%	-18%
2	-29%	-30%	-35%	-40%
3	-42%	-43%	-46%	-51%

HS-BI	Gradient			
B	8	6	4	2
1	0%	33%	30%	24%
2	24%	23%	22%	14%
3	29%	28%	26%	17%

Table 9. Sensitivity of required spawners as estimated by Model 1 to uncertainty in sex ratio of M:F

CU	Sex Ratio						
	0.7	0.8	0.9	1	1.1	1.2	1.3
EVI-GS	15,042	15,927	16,812	17,696	18,581	19,466	20,351
GSM	3,716	3,934	4,153	4,371	4,590	4,808	5,027
HS-BI	4,003	4,239	4,474	4,710	4,945	5,181	5,416

Freshwater Survival

The model was also tested for sensitivity to the freshwater survival values that were used to calculate the required number of spawners. The EVI-GS CU was modeled with a 22.8% egg-to-fry survival and 20% fry-to-smolt survival, while the GSM and HS-BI CU was modeled with a 19.6% egg-to-fry survival and 21.2% fry-to-smolt survival (Table 10). A range of egg-to-fry and fry-to-smolt survivals was tested. The required number of spawners does not appear to be more sensitive to either fry-to-smolt or egg-to-fry survival, however the required number of spawners increases by many factors when survival decreases below the base case.

Table 10. Sensitivity of required spawners as estimated by Model 1 to uncertainty in egg-fry and fry-smolt survival of EVI-GS (A) and GSM and HS-BI (B). Grey shaded cells indicate the base case scenario.

(A)	Egg-Fry Survival						
Fry-Smolt Survival	2.5%	5%	7.5%	10%	15%	20%	25%
2.5%	7176%	3538%	2325%	1719%	1113%	810%	628%
5%	3538%	1719%	1113%	809%	506%	355%	264%
7.5%	2325%	1113%	708%	506%	304%	203%	143%
10%	1719%	809%	506%	355%	203%	128%	82%
15%	1113%	506%	304%	203%	102%	52%	21%
20%	809%	355%	203%	127%	52%	14%	-9%
22.8%	700%	300%	167%	100%	33%	0%	-20%
25%	628%	264%	143%	82%	21%	-9%	-27%

(B)	Egg-Fry Survival						
Fry-Smolt Survival	2.5%	5%	7.5%	10%	15%	21.2%	25%
2.5%	6568%	3234%	2123%	1567%	1011%	686%	567%
5%	3234%	1567%	1011%	734%	456%	293%	233%
7.5%	2123%	1011%	641%	456%	270%	162%	122%
10%	1567%	734%	456%	317%	178%	96%	67%
15%	1011%	456%	270%	178%	85%	31%	11%
19.6%	749%	324%	183%	112%	41%	0%	-15%
25%	567%	233%	122%	67%	11%	-21%	-33%

Stock-Recruitment Results

Using the product of the historical average of coho marine survival rate of 0.065 and maximum smolt production determined from accessible stream length for each CU(EVI=1,005,922; GSM=227,726; HSB=245,364), the means of the lognormal prior on maximum adult recruitment when fitting spawner-adult recruit relationships were log(65,385), log(14,802), and log(15,949), respectively. The log of the smolt production values (e.g., log(1,005,922) for EVI) was used as the mean when fitting spawner-smolt recruit relationships.

There was considerable scatter in stock-recruitment relationships (Figure 7). Three obvious patterns were apparent: 1) considerable variation in recruitment at low stock size (e.g. HSB); 2) no obvious carrying capacity limit (e.g., EVI); and 3) higher recruitment and spawning stock size in the first half of the period of record when marine survival rates were higher (all CUs). These patterns make it difficult to reliably estimate stock-recruitment parameters. In an earlier analysis of these data, we fitted separate stock recruitment models to data before and after 1990 when there was a rapid decline in marine survival (Figure 6). Unfortunately, this analysis produced nonsensical results (higher productivity estimates during the low marine survival period) because there was not sufficient contrasts in spawning stock size when the data was essentially split in two. This was the motivation to reconstruct the smolt-recruit time series by dividing adult recruitment by the brood year marine survival rate.

For the most part, differences in stock productivity and carrying capacity estimates between Beverton-Holt and Logistic Hockey Stick models were relatively minor. The mean of the prior on carrying capacity based on stream length was lower than what the spawner-adult recruit and spawner-smolt recruit data implied (Figure 5). As a result, carrying capacity estimated by the stock-recruitment analysis increased as the amount of information in the carrying capacity prior was decreased from CV=0.1 to CV=0.6 (Figure 8-Figure 13). In some cases, carrying capacity and stock productivity estimates can be negatively correlated. That is, it can be difficult to distinguish from the data that whether the stock is small and highly productive, or large and less productive. This was the case for EVI for the BH model, where more informative priors on carrying capacity (e.g. CV=0.1) led to higher productivity estimates than less informative ones (see Umsy results for EVI in Table 12). The LHS model did not suffer this issue because productivity and carrying capacity are not as correlated owing to control over the initial slope imposed by the value of C.

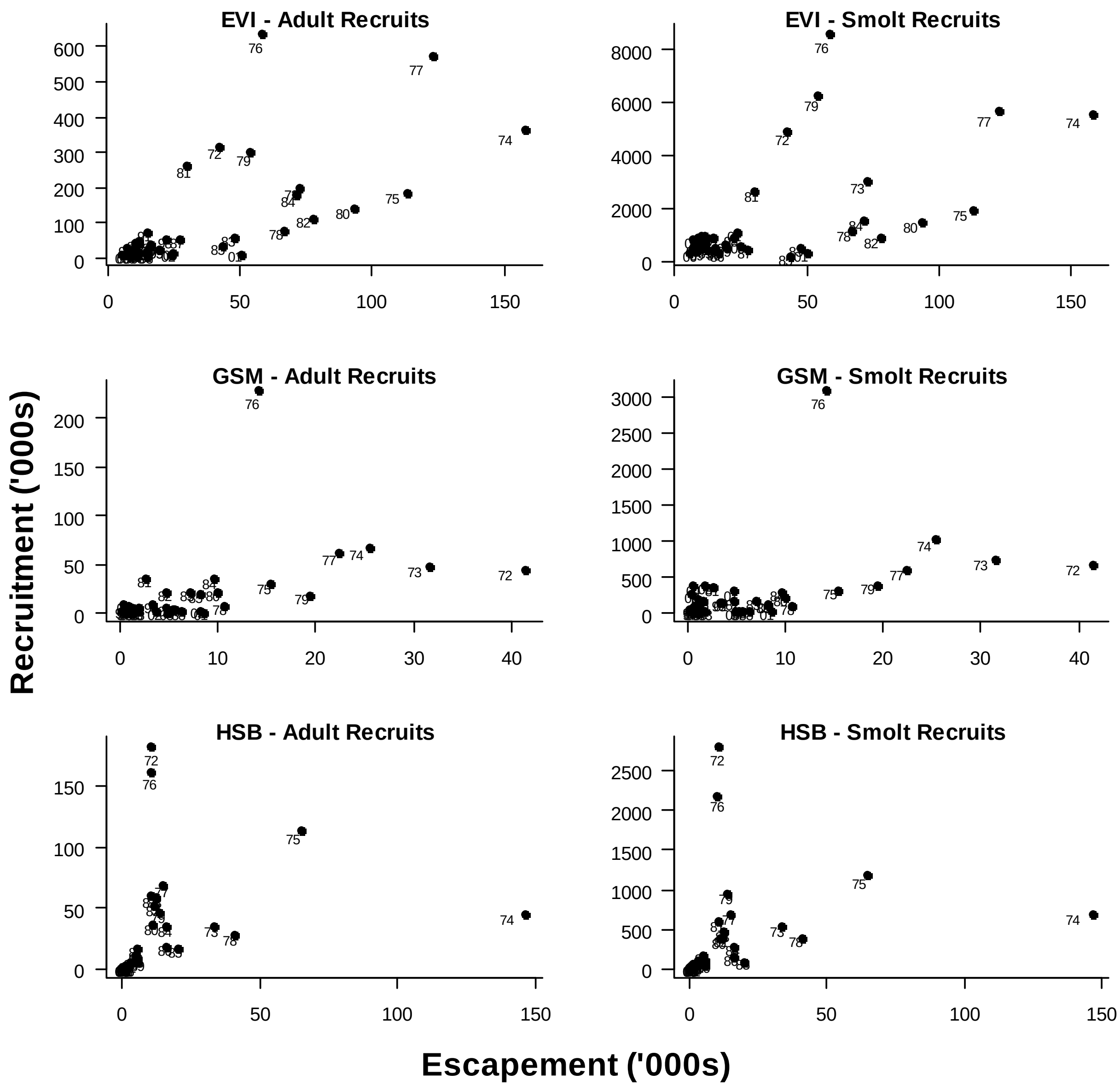


Figure 7. Stock-recruit data for East Coast of Vancouver Island (EVI), Georgia Strait Mainland (GSM), and Howe Sound Burrard (HSB) coho CUs. Recruitment is expressed based on both adult recruits, and smolt recruits, the latter was estimated though back-calculation based on annual marine survival estimates. Labels beside the data points denote the brood year.

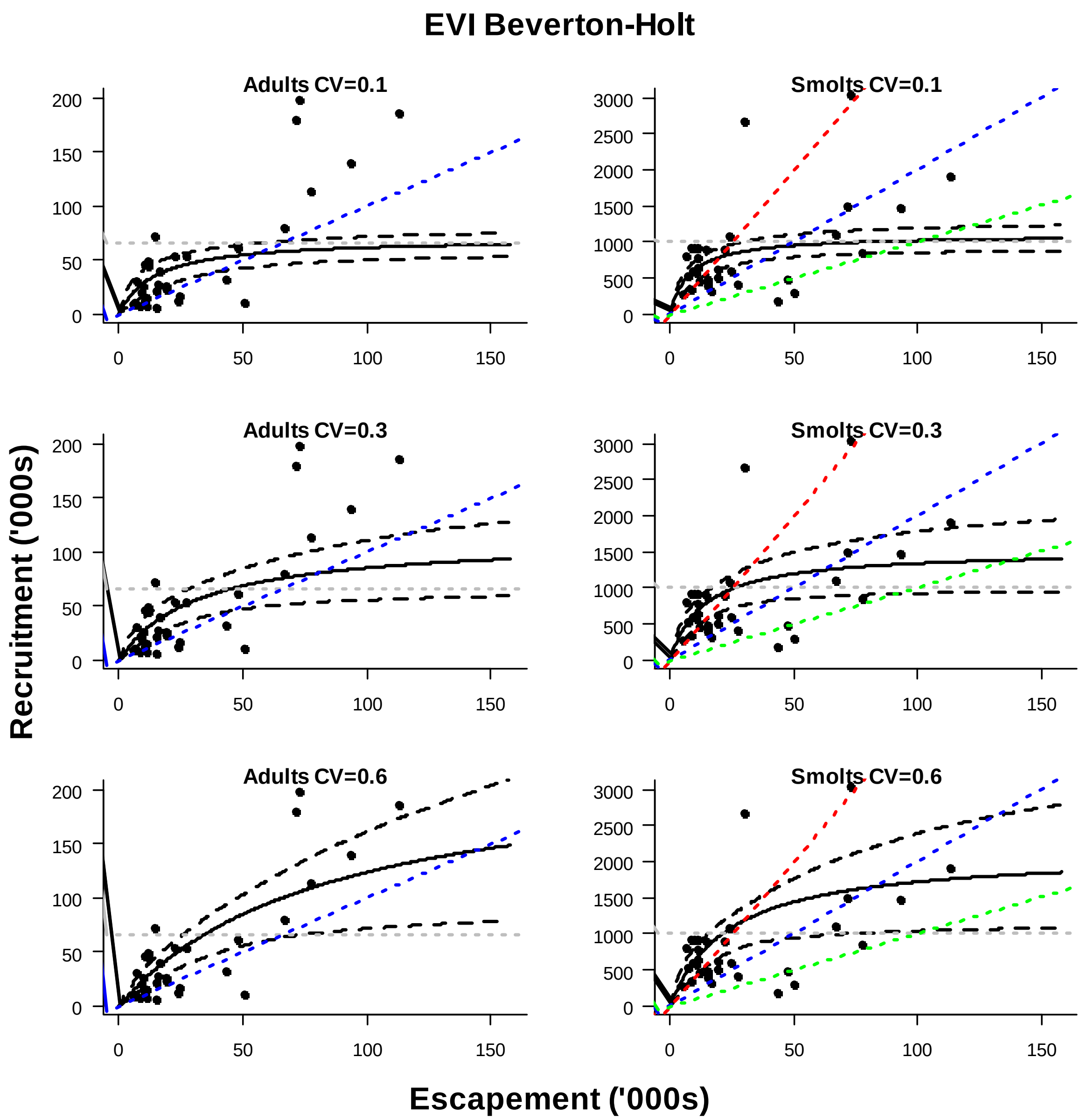


Figure 8. Stock-recruitment relationships for the East Coast of Vancouver Island coho CU based on a Beverton-Holt model fit to spawner-adult recruit (left column) and spawner-smolt recruit (right column) data sets. The solid black line represents the expected relationship based on the mean of parameter estimates from the posterior distributions, and the dashed black lines represent the 95% credible interval. The light gray dashed horizontal line shows the mean of the prior on maximum recruitment. The dashed angled colored lines represent the 1:1 relationship (replacement). For spawner-smolt recruit fits, the slopes of these lines are based on 2.5% (red), 5.0% (blue), and 10% (green) marine survival rates. Each panel presents results for alternate forms of the prior distribution for maximum recruitment as determined by the amount of information in the prior distribution (CV= coefficient of variation). The y-axis maxima were reduced to highlight the estimated stock-recruitment relationships, and larger recruitment estimates are cut-off. See Figure 4 for the full dataset.

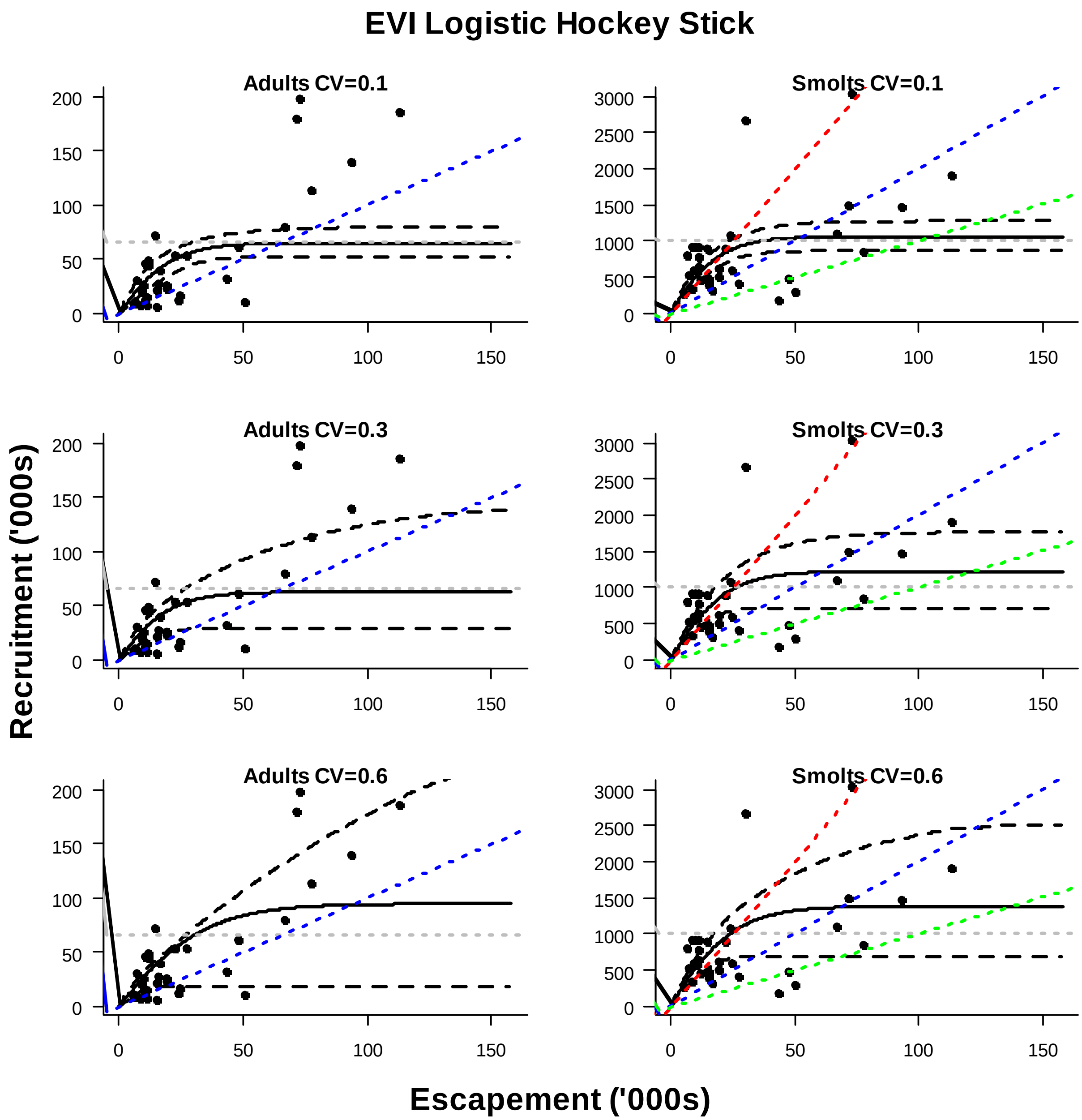


Figure 9. Stock-recruitment relationships for the East Coast of Vancouver Island coho CU based on a Logistic Hockey Stick model fit to spawner-adult recruit (left column) and spawner-smolt recruit (right column) data sets. See caption for Figure 5 for details.

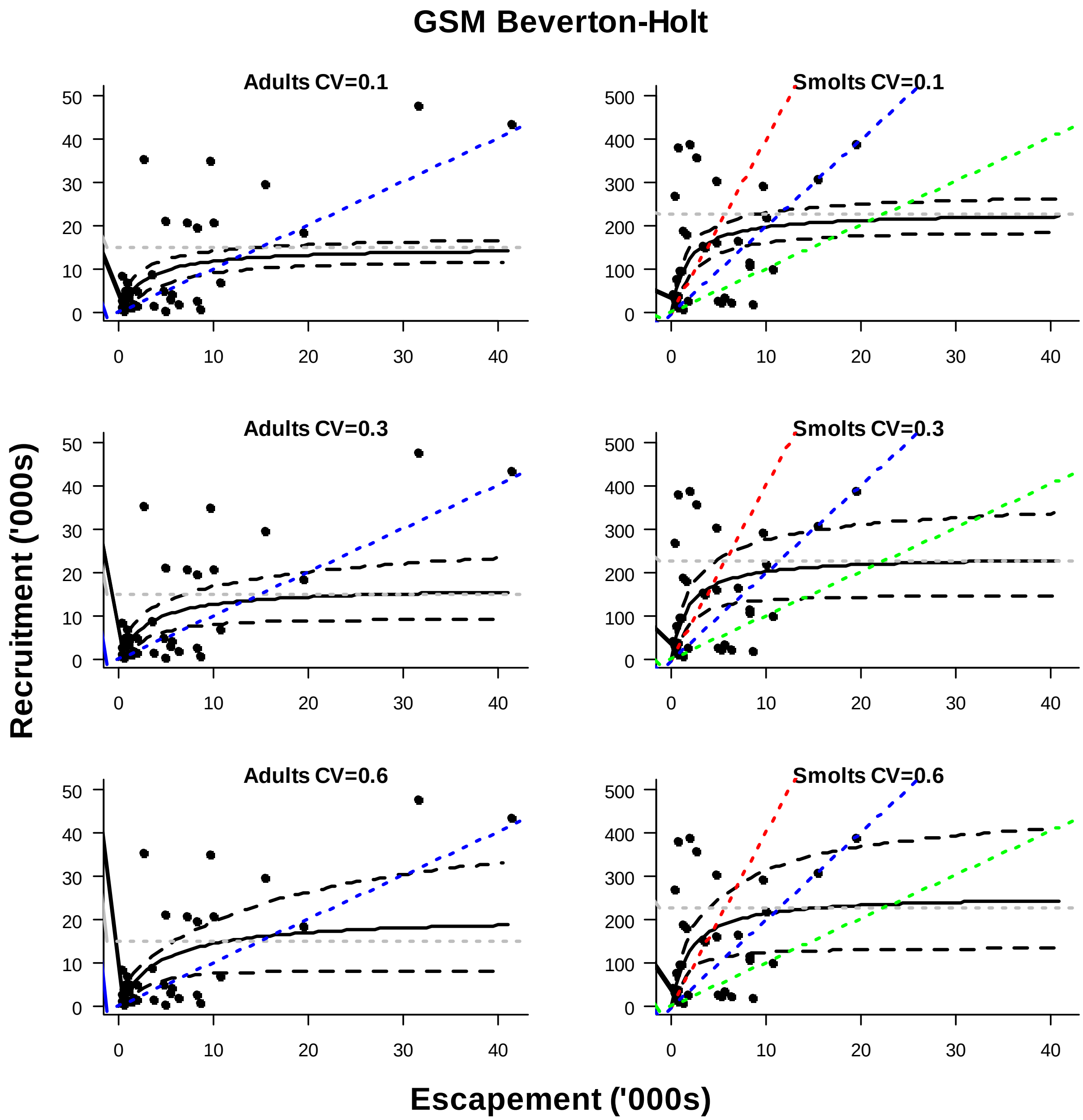


Figure 10. Stock-recruitment relationships for the Georgia Strait Mainland coho CU based on a Beverton-Holt model fit to spawner-adult recruit (left column) and spawner-smolt recruit (right column) data sets. See caption for Figure 4 for details.

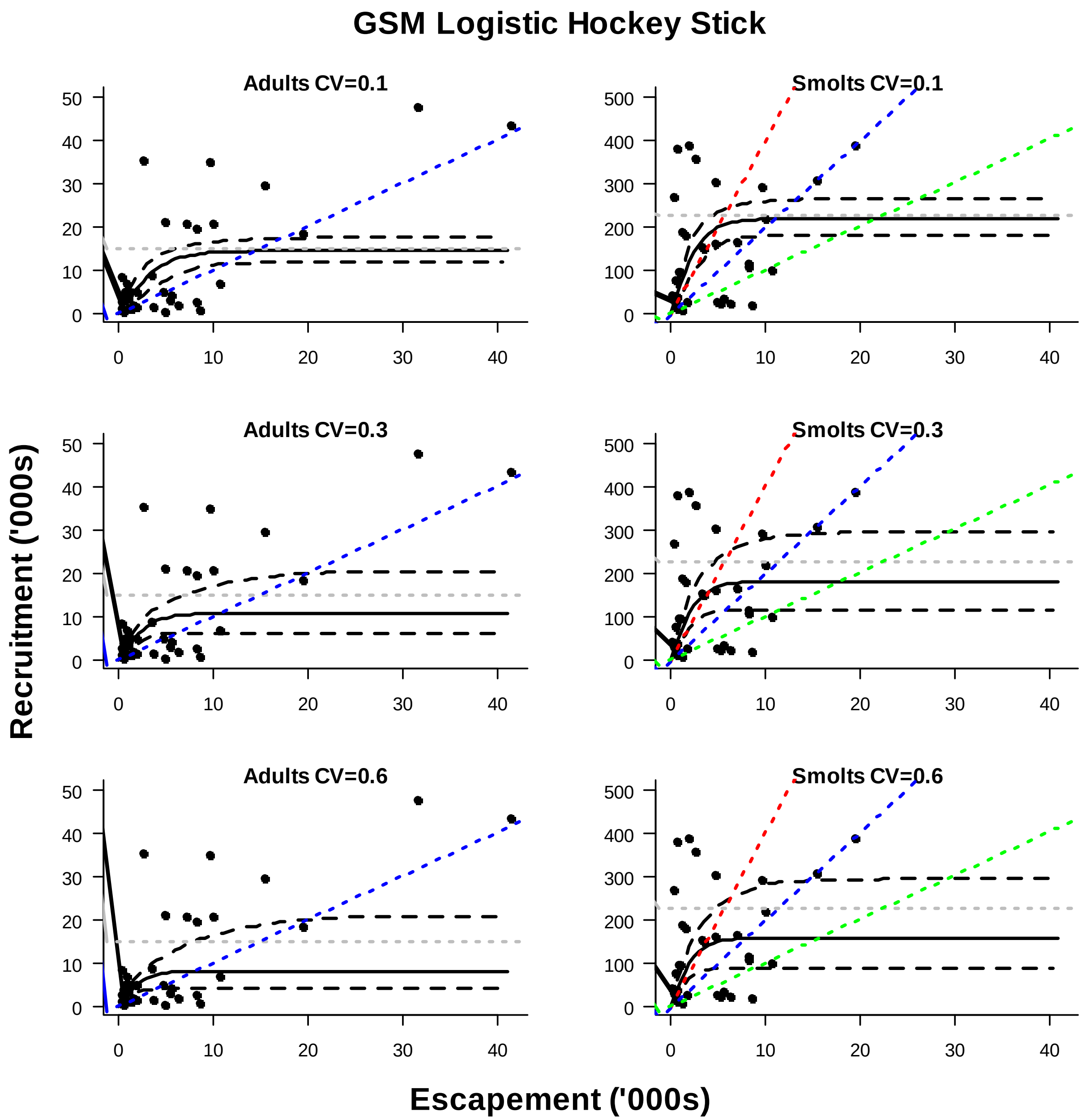


Figure 11. Stock-recruitment relationships for the Georgia Strait Mainland coho CU based on a Logistic Hockey Stick model fit to spawner-adult recruit (left column) and spawner-smolt recruit (right column) data sets. See caption for Figure 4 for details.

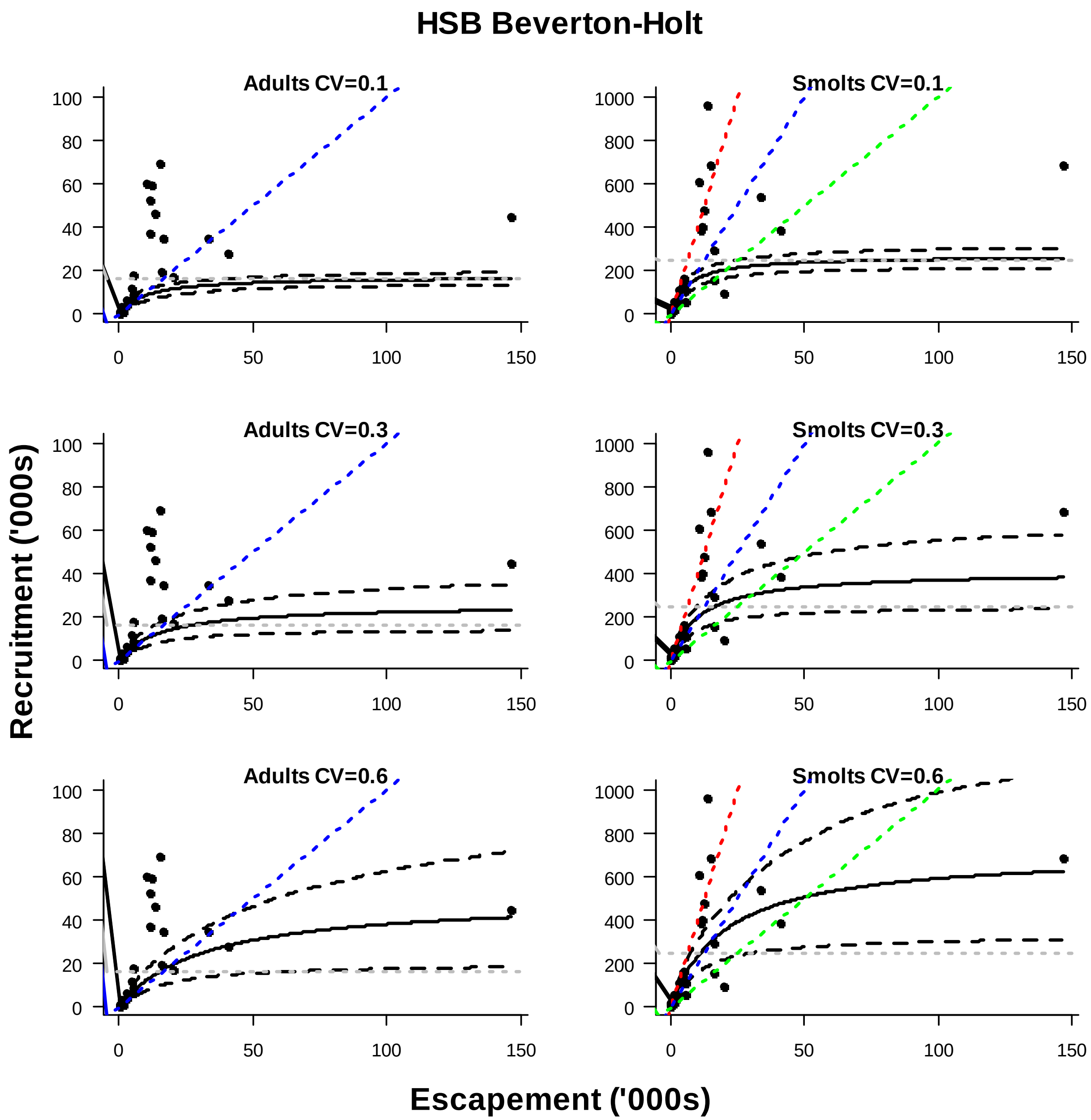


Figure 12. Stock-recruitment relationships for the Howe Sound Burrard coho CU based on a Beverton-Holt model fit to spawner-adult recruit (left column) and spawner-smolt recruit (right column) data sets. See caption for Figure 4 for details.

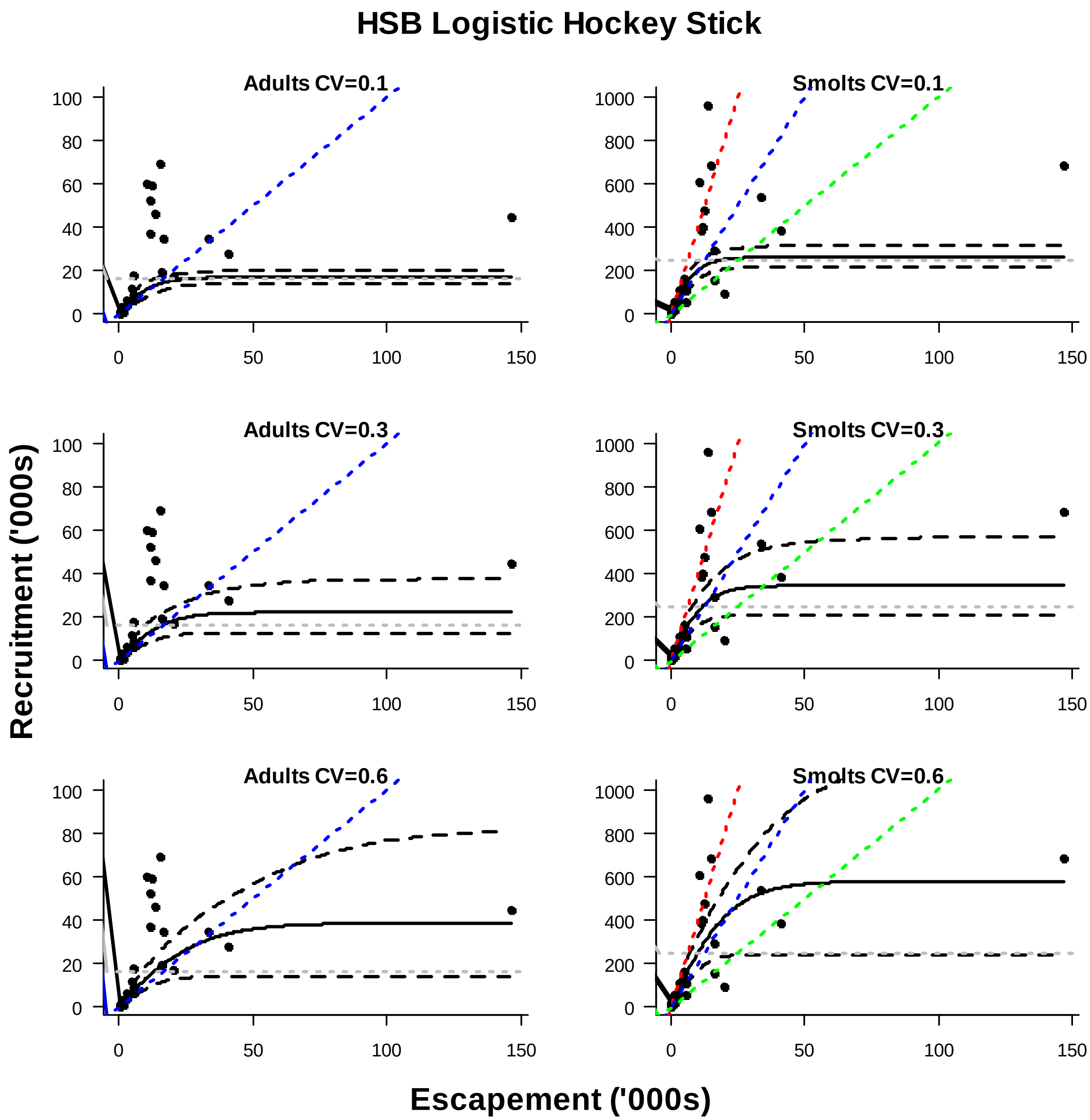


Figure 13. Stock-recruitment relationships for the How Sound Burrard coho CU based on a Logistic Hockey Stick model fit to spawner-adult recruit (left column) and spawner-smolt recruit (right column) data sets. See caption for Figure 4 for details.

Estimates of both stock productivity and carrying capacity determined from the BH and LHS spawner-smolt recruit models for the EVI CU were very consistent with the regional distributions estimated by Korman and Tompkins (2007, Figure 4). Stock productivity based the LHS model was consistent with the regional distribution for GSM, but the estimates based on the BH model were at the top end of the regional distribution. This indicates that the BH model may be overestimating productivity for this CU, or at least that the LHS model is more conservative and consistent with more reliable estimates from the regional analysis. Carrying capacity estimates from GSM and HSB were at the extreme low end of the range from the regional analysis. Estimates of stock productivity for HSB based on the stock-smolt recruit analysis were at the low end of the range of estimates based on the regional analysis.

There was more support for the Logistic Hockey Stick model than for the Beverton-Holt model in most cases (Table 11). DIC values were substantively lower (i.e., better out-of-sample predictive power) for the LHS model for five of six cases for EVI, two cases for GSM, and four cases for HSB. There were no substantive differences in DIC between models for the remaining cases. Thus, there were no cases where there was substantive support for the Beverton-Holt model.

Table 11. Deviance information criteria (DIC) comparing Beverton-Holt (BH) and Logistic Hockey Stick (LHS) models for each conservation unit (CU) and prior distribution of maximum recruitment. Results are presented for spawner-adult recruit and spawner-smolt recruit fits Models with the lower DIC are considered to have better out-of-sample predictive power. Shaded grey cells indicate substantive model support (DIC lower by more than 2 units).

	Recruit		**DIC**		
CU	**Type**	**prCV**	**BH**	**LHS**	**ΔDIC**
EVI	Adult	0.1	410	400	10
		0.3	404	395	9
		0.6	399	389	10
	Smolt	0.1	618	611	7
		0.3	615	612	3
		0.6	613	612	1
GSM	Adult	0.1	271	270	1
		0.3	271	266	5
		0.6	271	264	7
	Smolt	0.1	491	493	-2
		0.3	492	491	1
		0.6	492	491	1
HSB	Adult	0.1	249	242	7
		0.3	245	240	5
		0.6	241	239	2
	Smolt	0.1	454	448	6
		0.3	450	447	3
		0.6	446	446	0

Table 12 summarizes the benchmark statistics for each CU based on BH and LHS models for adult-recruit and smolt-recruit analyses. In this discussion of benchmarks that follows, we focus on trends in Umsy, arguably the most practical benchmark given that: 1) estimates of escapement and recruitment are highly uncertain, thus benchmarks that depend on evaluating status based on abundance are impractical; 2) recruitment forecasts are highly uncertain, so it is impractical to manage harvest towards a fixed escapement goal (e.g., Smsy or Sgen). Umsy can be implemented more effectively since time and area closures can be managed to attain a target harvest rate regardless of stock size. Emphasis should also be placed on LHS-based benchmarks given the results from the DIC analysis.

Umsy for EVI based on BH and LHS models and the adult recruit analysis were around 0.5 and the 95% credible intervals were quite wide (e.g. 0.3-0.7). Increasing the amount of information in the prior on carrying capacity did not appreciably reduce this uncertainty, but it did lead to relatively large (BH) or modest (LHS) reductions in the expected Umsy values. As described above, the habitat-based estimate of capacity was well below that implied by the stock-recruit data. Thus, increasing the amount of information in the habitat-based prior on capacity led to lower predictions of capacity which in turn led to higher productivity, and hence higher values of Umsy. Umsy was very sensitive to the form of the stock-recruitment model for the spawner-smolt recruit analysis for the EVI CU, with much higher values for the BH than LHS models. For example, Umsy was 0.45 for BH (prCV=0.1) at 2.5% marine survival, vs. 0.18 for LHS (prCV=0.1). As expected, increasing the value of future marine survival rates led to increases in the Umsy benchmark. If we assume a 2.5% marine survival is the likely scenario for the future, and use the LHS model given the DIC results (Table 11), the lower credible interval (i.e., a precautionary approach) indicates there is little opportunity to harvest. In fact these low rates (about 0.05) are about 50% lower than realized rates that have occurred over about the last decade due to bycatch.

Umsy estimates for the GSM CU were around 0.5 for both models for the adult recruit analysis, which was very similar to results for EVI (Table 12). EVI and GSM results were also very similar for the smolt recruit BH analysis. Umsy based on the smolt recruit analysis for the LHS model at a low marine survival was a bit higher for GSM (about 0.25) than for EVI (about 0.18). As for EVI, the lower credible interval for Umsy for the GSM CU based on the LHS model at 2.5% marine survival indicates very little opportunity for harvest. Stock productivity estimates for the HSB CU were low for all model types and for both datasets (Figure 5) resulting in much lower Umsy benchmarks compared to other CUs (Table 12). Umsy values based on the adult recruit analysis were about 0.15-0.20 for both models, and the expected values were near 0 for both models under the 2.5% future marine survival scenario.

Table 12. Southern coho benchmarks: Escapement needed to recover to Smsy in one generation (Sgen, in thousands of fish), **e**scapement needed to achieve MSY (Smsy, in thousands of fish), and harvest rate to achieve MSY (Umsy) for EVI, GSM, and HSB coho CUs based on Beverton-Holt (BH) and Logistic Hockeye Stick (LHS) recruitment models. Results are presented for spawner-adult recruit and spawner-smolt recruit fits, where benchmarks for the latter group were computed assuming 2.5%, 5.0%, and 10% marine survival. Model results also differ by the amount of information in the prior (prCV) for maximum recruitment. MU, LCL, and UCL denote the mean of the posterior values and lower and upper 95% credible intervals respectively.

	Recruit	Marine		Umsy			Smsy			Sgen		
Model	**Type**	**Survival**	**prCV**	**MU**	**LCL**	**UCL**	**MU**	**LCL**	**UCL**	**MU**	**LCL**	**UCL**
BH	Adult	0.065	0.1	0.52	0.33	0.7	16.99	13	21	5.4	1.64	9.51
			0.3	0.45	0.29	0.62	26.8	15	43	11.3	3.45	21.43
			0.6	0.38	0.24	0.53	51.39	22	106	26.86	7.76	62.33
	Smolt	0.025	0.1	0.45	0.26	0.55	6.64	5	8	2.67	1.64	3.99
			0.3	0.38	0.17	0.54	8.44	5	12	4.26	1.93	7.25
			0.6	0.3	0.08	0.53	9.82	5	16	6.02	2.19	11.09
		0.05	0.1	0.61	0.48	0.68	12.96	10	16	2.68	1.44	5.3
			0.3	0.56	0.41	0.68	18.43	11	29	5.06	1.65	11.19
			0.6	0.5	0.35	0.66	25.9	13	48.03	9.29	2.12	23.84
		0.1	0.1	0.72	0.63	0.77	21.86	17	28	2.2	1.1	4.82
			0.3	0.69	0.58	0.77	32.55	19	54.03	4.42	1.27	10.93
			0.6	0.65	0.54	0.76	48.65	22	99	8.85	1.61	26.27
LHS	Adult	0.065	0.1	0.52	0.36	0.65	24.8	18	32.00	9.17	4.15	16.53
			0.3	0.51	0.3	0.63	24.29	11	60.00	10.04	3.13	35.12
			0.6	0.47	0.25	0.62	38.88	7	134.03	19.9	2.2	78.57
	Smolt	0.025	0.1	0.18	0.05	0.34	9.31	4	13.00	7.16	3.77	9.24
			0.3	0.17	0.05	0.29	4.29	1	8	3.33	1.06	5.39
			0.6	0.19	0.02	0.32	12.02	3	21.00	9.11	2.88	15.43
		0.05	0.1	0.48	0.38	0.59	21.21	16	26.00	8.59	4.71	12.16
			0.3	0.41	0.33	0.49	14.78	9	22	6.67	3.69	9.93
			0.6	0.48	0.36	0.58	27.63	14	55	11.21	4.91	27.07
		0.1	0.1	0.68	0.62	0.75	30.14	22	37.00	5.86	2.99	8.97
			0.3	0.59	0.52	0.64	29.65	17	43	6.76	3.5	10.73
			0.6	0.68	0.6	0.75	39.33	19	82.03	7.69	3.22	20.13

Table 12 Continued (GSM)

	Recruit	Marine		Umsy			Smsy			Sgen		
Model	Type	Survival	prCV	MU	LCL	UCL	MU	LCL	UCL	MU	LCL	UCL
BH	Adult	0.065	0.1	0.54	0.35	0.7	3.62	3.00	4.00	1.05	0.34	2.01
			0.3	0.53	0.32	0.71	3.99	2.00	7.00	1.26	0.26	2.99
			0.6	0.51	0.29	0.7	4.92	2.00	11.00	1.8	0.25	5.25
	Smolt	0.025	0.1	0.46	0.21	0.61	1.27	1.00	2.00	0.53	0.25	1.08
			0.3	0.44	0.19	0.6	1.37	1.00	2.00	0.6	0.26	1.3
			0.6	0.42	0.17	0.59	1.47	1.00	3.00	0.67	0.26	1.52
		0.05	0.1	0.59	0.44	0.71	2.79	2.00	3.00	0.61	0.26	1.24
			0.3	0.6	0.42	0.7	2.83	2.00	4.03	0.65	0.26	1.6
			0.6	0.59	0.42	0.7	3.05	2.00	6.00	0.75	0.26	2.18
		0.1	0.1	0.72	0.61	0.78	4.62	4.00	6.00	0.49	0.24	1.14
			0.3	0.72	0.6	0.78	4.81	3.00	8.00	0.54	0.19	1.46
			0.6	0.71	0.59	0.78	5.27	3.00	11.00	0.64	0.19	2.07
LHS	Adult	0.065	0.1	0.53	0.31	0.69	5.36	4.00	7.00	1.95	0.73	4.19
			0.3	0.55	0.35	0.68	3.94	2.00	8.00	1.35	0.6	4.14
			0.6	0.52	0.36	0.65	3.07	2.00	8.00	1.11	0.53	3.50
	Smolt	0.025	0.1	0.29	0.05	0.48	2.1	1.00	3.00	1.33	0.85	2.06
			0.3	0.25	0.03	0.44	1.79	1.00	3.00	1.21	0.65	2.06
			0.6	0.22	0	0.40	1.52	1.00	3.00	1.09	0.63	2.00
		0.05	0.1	0.55	0.38	0.68	4	3.00	5.00	1.32	0.63	2.59
			0.3	0.53	0.38	0.65	3.41	2.00	6.00	1.19	0.65	2.50
			0.6	0.5	0.35	0.64	3.04	2.00	6.00	1.12	0.63	2.33
		0.1	0.1	0.73	0.61	0.80	5.42	4.00	8.00	0.86	0.41	1.85
			0.3	0.71	0.62	0.79	4.69	3.00	8.00	0.79	0.41	1.76
			0.6	0.7	0.6	0.78	4.23	3.00	8.00	0.75	0.42	1.60

Table 12 Continued (HS-BI)

	Recruit	Marine		Umsy			Smsy			Sgen		
Model	Type	Survival	prCV	MU	LCL	UCL	MU	LCL	UCL	MU	LCL	UCL
BH	Adult	0.065	0.1	0.2	0	0.43	2.58	1	4.00	1.82	0.89	2.72
			0.3	0.19	0	0.39	3.7	1	8.00	2.65	0.94	4.96
			0.6	0.18	0	0.38	6.91	1	18.00	5.03	0.98	11.87
	Smolt	0.025	0.1	0.03	0	0.26	1	1	1.00	1.24	0.7	1.97
			0.3	0.02	0	0.21	1.02	1	1.00	1.28	0.79	1.92
			0.6	0.01	0	0.14	1.04	1	2.00	1.34	0.9	1.98
		0.05	0.1	0.28	0.08	0.47	2.59	1	4.00	1.6	0.86	2.22
			0.3	0.26	0.07	0.43	3.7	1	6.00	2.43	0.98	4.09
			0.6	0.22	0.05	0.40	5.82	2	12.00	4.09	1.25	8.46
		0.1	0.1	0.49	0.35	0.62	6.5	5	8.00	2.25	1.12	3.50
			0.3	0.47	0.34	0.60	9.99	6	16.00	3.73	1.59	6.80
			0.6	0.45	0.32	0.57	17.3	8	35.00	7.03	2.56	15.28
LHS	Adult	0.065	0.1	0.17	0	0.39	5.25	1	8.00	3.94	1	5.70
			0.3	0.17	0	0.39	6.63	1	14.00	4.99	1	10.06
			0.6	0.16	0	0.38	11.84	1	32.00	8.98	1.01	22.27
	Smolt	0.025	0.1	0	0	0.00	1.01	1	1.00	1.5	1.03	2.10
			0.3	0	0	0.02	1.02	1	1.00	1.47	1.02	2.10
			0.6	0	0	0.00	1.02	1	1.00	1.49	1.04	2.12
		0.05	0.1	0.18	0	0.36	4.37	1	6.00	3.32	1.01	4.53
			0.3	0.19	0	0.36	5.9	1	11.00	4.42	1.03	7.76
			0.6	0.17	0	0.35	9.44	1	23.00	7.26	1.05	16.31
		0.1	0.1	0.48	0.34	0.60	10.3	8	13.00	4.24	2.3	6.66
			0.3	0.48	0.34	0.60	13.56	8	23.00	5.49	2.62	10.73
			0.6	0.47	0.33	0.60	23.18	10	49.00	9.72	3.16	22.05

DISCUSSION

Identification of escapement targets is critical for management of South Coast Coho salmon stocks. The Coho Model described here is the first attempt at defining escapement goals for Coho in this area. The premise of correlation between smolt yield and stream length is well supported in the literature and the use of the large, local smolt data set for Model 1 ensures robustness across stream size and type.

Accessible Stream Length

Digital Terrain Resource Information Management (TRIM) maps at a 1:20,000 scale for Statistical Area 3 were used for this model. TRIM maps are derived from air photo interpretation and are considered to be accurate to within 10 m, 90% of the time (Brown et al. 1996). However, tree vegetation makes capture of all waterways difficult from air photos. In an examination of TRIM mapping with ground surveys, Brown et al. (1996) found that TRIM delineated 80% of the natural channel length in basins with terrain relief. The percentage delineated by TRIM in areas of low relief was 73%. The watersheds included in the model have significant terrain relief, particularly those from the HS-BI and GSM CUs, and TRIM likely captures the majority of the stream network that is accessible to Coho salmon.

Effect of Map Scale

Model 1 was derived using regional data for smolts/km for which stream length was derived from the GIS work that accompanied this analysis. With the exception of Myrtle Creek, the lengths of all rivers used in Model 1 differed from that provided by DFO (Table 13). On average, the length of available habitat was 28% greater via GIS than by DFO estimates. Length of available habitat as calculated via GIS is expected to be larger than that provided by DFO as the GIS estimate includes habitat in all tributaries downstream of all modelled barriers, whereas the methods used to calculate accessible habitat by DFO are based on 40 year old Stream Catalogues, and were not necessarily explicitly measured. Furthermore, the GIS analysis is comprehensive and descriptive in its assessment of accessibility as it accounts for stream gradient and all known barriers of the mainstem and tributaries.

Table 13. Length comparison of watersheds used to generate predictive regression of Model 1, units in Km.

Stream Name	Length (DFO)	Length km (GIS)	% Similar
Waterloo	1.9	1.78	94%
Whittall	2.6	3.13	120%
Millard	3	4.19	140%
Myrtle	8.1	8.13	100%
Morrison	9.6	8.73	91%
Woods	5	9.96	199%
Little	10.2	10.94	107%
Simms	8.7	13	149%
Willow	11.3	13.93	123%
Black_Creek	33	26.83	81%
Englishman	39.2	58.46	149%
Quinsam	54.9	81.33	148%
Tsolum	57.4	90.17	157%
Average	18.8	25.4	128%

Limits to Smolt Production

Coho smolt production appears to be independent of the number of spawners except at low spawner abundances (Bradford et al. 2000, Knight 1980, Holtby and Scrivener 1989). Nickelson et al. (1992) concluded that Coho salmon in Oregon are likely limited by the availability of winter habitat (also Brown and Hartman 1988). Furthermore, several authors have documented the downstream movement of Coho juveniles from upper watershed areas to lower watershed areas in the fall (Brown et al. 1999, Cederholm and Scarlett 1991). This movement is likely in preparation for smolting and perhaps a response to habitat contraction due to drying or freezing. It is these behaviours, which likely enable the prediction of smolt production from available rearing habitat (e.g., stream length) in the higher order streams within a watershed.

Freezing in winter, and low flows in the summer reduces available habitat in some of the watersheds in the model, particularly for the GSM and HS-BI CUs. The life stages of salmonids at the critical times of fall fry, and pre-smolts become the limiting stages to total smolt production. During these times, available habitat to rearing salmonids is contracted and the mainstem and primary tributaries account for a greater proportion of the available and useable habitat. It is this interrelation between critical flow and available habitat that further allows for stream length to be a reasonable predictor of smolt production.

Required Number of Spawners

The applicability of Model 1 for predicting the number of spawners required to produce the average number of smolts carries with it many assumptions. Perhaps foremost, the model assumes that the historical mean smolt data used to derive the model is reflective of current and future smolt productive capacity for the geographic region included. Although this is consistent with the thinking of previous researchers; namely that average smolt production is an appropriate measure of capacity (Marshall and Britton 1990, Bradford et al. 1997, Burns 1971); this assumption should be tested in future research. Similarly, the suitability of Model 2 as a predictor of the required number of spawners depends on the recent decadal average smolt production for Little and Myrtle Creeks being an appropriate measure of capacity for those systems.

Both models evaluated in this paper predict the required number of spawners for smolt production. They ignore potential production from ocean-type Coho that leave the freshwater environment in their first year. For those systems where ocean-type Coho contribute to total Coho production measured by adult returns, the models would underestimate the required number of spawners to maximize total production. Similarly, to the extent that Coho from adjacent streams rear in non-natal streams in the study area, there will be errors in the predicted number of required spawners for those systems. There is very limited to no data available to test either of these assumptions.

A number of additional assumptions were made when determining the number of required spawners to maximize smolt production. These include assumptions about freshwater survival, which were shown to have a significant effect on the model predictions. Currently, freshwater survival is only available from Quinsam River (fry-smolt) and Oliver Creek (egg-fry) for the EVI-GS CU and for Carnation Creek (egg-fry) and Beadnell Creek, Carnation Creek, and Sashin Creek (egg-fry) for the rest of Vancouver Island. No estimates of survival are available for Coho from mainland watersheds. The addition of other Coho indicator stocks from the mainland would greatly enhance understanding of Coho production and survival rates.

Sex ratio was assumed to be 0.89 M to 1.0 F, based on the only sex ratio data available from Black Creek (Vancouver Island). If this is not the case for the majority of streams, then the prediction of the required number of spawners could be biased. If the sex ratio was 1:1, the number of spawners required to fully seed available habitat would increase (Table 9). Egg retention and other factors potentially limiting spawning success were also not factored into the model. If spawning success is significantly less than 100%, then the required number of spawners would be under predicted. While sensitivity to spawning success was not explicitly evaluated, we would expect a similar relationship as seen in Table 9, as decreased female success is functionally similar to increasing the male:female ratio. The relationship between fecundity and the required number of spawners would be expected to be non-linear, with very low fecundities requiring magnitudes more spawners than higher fecundities. .

Notwithstanding the various assumptions and limitations of the models used, we recommend that estimates of the required number of spawners be based on the results of Model 1. There may be considerable error in the predictions for some streams, but on an area basis, the predictions are a major step toward improved fishery management capability for these Coho management units, especially where escapement goals for Coho do not currently exist. The results suggest that appropriate escapement goals should be in the range of 17,000 spawners for East Coast-Vancouver Island, 4,000 for the Georgia Strait-Mainland, and 4,500 for Howe Sound-Burrard Inlet.

Comparison to Empirical smolt and spawner Abundance Data

Estimates of smolt production from both Model 1 and Model 2 were compared to the empirical estimates available for each of the 13 different watersheds where data was available. Predicted smolt production varied between 34% and 438% of empirical estimates for Model 1 (average of 95%), and between 38% and 771% for Model 2 (average of 130%) (Table 14). The larger estimate generated by Model 2 is due to the application of a standard smolt production estimate of 1,116 smolts per kilometre of river for EVI-GS streams. This compares to an average of 621 smolts per kilometre of river generated by the predictive regression of Model 1 and an average of 930 smolts per kilometre from the empirical data.

Table 14. Model 1 and 2 estimates of smolt production compared to available empirical data, and the percent differences. N = number of years of empirical data.

CU	Watershed	Length (km)	Model 1	Model 2	Empirical average	% Difference (Model 1 /Empirical)	% Difference (Model 2 /Emperical)	N
EVI-GS	Black_Creek	26.83	19,300	29,940	57,103	34%	52%	27
EVI-GS	Englishman	58.46	47,309	65,236	44,607	106%	146%	9
EVI-GS	Little	10.94	7,007	12,208	11,767	60%	104%	13
EVI-GS	Millard	4.19	2,426	4,676	2,072	117%	226%	11
EVI-GS	Morrison	8.73	5,449	9,742	7,106	77%	137%	9
EVI-GS	Quinsam	81.33	69,519	90,757	100,762	69%	90%	27
EVI-GS	Simms	13	8,501	14,507	4,090	208%	355%	11
EVI-GS	Tsolum	90.17	78,451	100,622	31,808	247%	316%	7
EVI-GS	Waterloo	1.78	961	1,986	1,542	62%	129%	9
EVI-GS	Willow	13.93	9,187	15,545	9,810	94%	158%	4
EVI-GS	Woods	9.96	6,310	11,114	1,441	438%	771%	11
GSM	Myrtle	8.13	5,034	869	1,564	322%	56%	13
GSM	Whittall	3.13	1,766	335	869	203%	38%	4
	Average	25.4	20,094	27,503	21,118	95%	130%	12

The required number of spawners as estimated via Model 1 were compared to empirical data collected for five watersheds where escapement was estimated via "fixed site census", an escapement method of high precision and accuracy (Table 15). No watersheds from the HS-BI CU were assessed via this method and so we cannot compare spawner estimates from this CU. All "fixed site census" assessments occur at watersheds with low average escapement, and therefore this assessement is not representative of the Model's ability to estimate the required number of spawners for larger systems. The percent difference between the model estimate and nuSEDS averages appear reasonable, but large individual differences are to be expected when applying averages to all streams. In the ten years since the Area 3 Coho Habitat Model (Bocking and Peacock) has been used, empirical estimates of spawner abundance (generated by MCMC AUC methods) on Diskangieq Creek, a tributary of the Nass River, have varied between 17% and 1,495% (average of 291%) of escapement estimated by the Area 3 Habitat Model while escapement to Ansedegan Creek (a nearby Nass River tributary) has varied between 4% and 274% (average of 109%).

Table 15. Estimates of spawners required to fully seed available habitat, as estimated by Model 1, and the average nuSEDS escapement effort for non-enhanced streams.

CU	Watershed	estimated	ΞDS average[1]	% difference
EVI-GS	Woods Creek	105	32	69%
EVI-GS	Colquitz Creek	168	176	-4%
EVI-GS	Craigflower Creek	42	151	-260%
EVI-GS	Simms Creek	141	40	72%
GSM	Myrtle Creek	91	26	72%

[1] In years when fixed site was operated

Stock Recruit analysis and Benchmarks

Estimates of spawner-to-smolt stock productivity from this analysis, which completely determine the most critical benchmark (Umsy), were relatively consistent with those determined from a regional analysis for EVI and GSM CUs. This is comforting, suggesting that Umsy estimates for these provided here are probably not far off the mark. There was a bit more statistical support for the LHS model, which produced lower productivity estimates that were more consistent with regional analysis compared to the BH model. At an assumed future marine survival rate of 2.5%, harvest rates of approximately 18-25% will produce MSY for these CUs. However, there was considerable uncertainty in this benchmark owing to uncertainty in estimates of stock productivity. Harvest rates experienced over the last decade under a coho fisheries closure due to bycatch have exceeded the lower 95% credible interval.

Estimates of carrying capacity based on the stream length smolt model provided in this report are well below those estimated on a per km basis from the regional analysis of Korman and Tompkins (2007). This difference may be due to: 1) a bias towards higher capacity stocks in the regional dataset; 2) underestimates of capacity based on the stream length analysis owing to the assumption that spawning stock size never limited smolt production over the period when smolt abundance was measured. However, this discrepancy did not lead to major differences in the Umsy benchmark. Differences in Umsy based on informative and uninformative priors on carrying capacity were always less than 7% and often less than 5%.

Stock productivity, and hence Umsy, was much lower for the HSB CU than for EVI and GMS

CUs. The low productivity of HSB coho stocks indicate there is no scope for harvest at a future marine survival rate of 2.5%, but a rate of about 15-20% will result in MSY at a future marine survival of 5%. If time-area closures cannot be used to reduce harvest rate on HSB coho stocks relative to other CUs, future harvest rates for south coast coho may be limited by low productivity in the HSB CU.

CONCLUSIONS

1. We recommend that Model 1 estimates of smolt production and required spawners to achieve said smolts should be used to establish CU specific aggregate escapement requirements.
2. We support the use and implementation of Umsy as a benchmark as it is more practical to implement than other benchmarks, and is not abundance based.
3. Much of the data used to derive spawner abundance in the Habitat Based Model is highly uncertain (egg-fry and fry-smolt survival) and the values used have a large impact on the required number of spawners required. An improved and more recent data set could significantly affect the results.

LITERATURE CITED

Adkison, M.D. and R.M. Peterman, 1996. Results of Bayesian methods depend on deaths of implementation: an example of estimating salmon escapement goals. Fisheries Research 25 p. 155 – 170.

Baranski, C. 1989. Coho smolt production in ten Puget Sound streams. Wash. Dep. Fish. Tech. Rep. 99: 29 p.

Barrowman, N.J. and R.A. Myers. 2000. Still more spawner-recruitment curves: the hockey stick and its generalizations. Can. J. Fish. Aquat. Sci. 57: 665-676.

Bilby, R.E. and P.A. Bisson. 1987. Emigration and production of hatchery Coho salmon (*Oncorhynchus kisutch*) stocked in streams draining an old-growth and a clear-cut watershed. Can. J. Fish. Aquat. Sci. 44: 1397-1407.

Bisson, P.A., R.A. Nielsen, R.A. Palmason, and L.E. Gore. 1982. A system of naming habitat types in small streams with examples of habitat utilization by salmonids during low stream flow. In Acquisition and utilization of aquatic habitat information. Edited by N.A. Armatrout. American Fisheries Society, Bethesda, MD. Pp. 62-73.

Blackett, R.F., 1979. Establishment of sockeye and chinook salmon runs at Frazer Lake, Kodiak Island, AK. J. Fish. Res. Board. Can., 36:1265-1277

Bjorn, T.C. and D.W. Reiser. 1991. Habitat requirements of salmonids in streams. American Fisheries Society Special Publication 19: 83-138.

Bocking, R.C., C.K. Parken, and D.Y. Atagi. 2001. Nass River steelhead habitat capability production model and preliminary escapement goals. Unpublished report for Ministry of Water, Land and Air Protection, Smithers, British Columbia.

Bradford, M.J. 1995. Comparative review of Pacific salmon survival rates. Can. J. Fish. Aquat. Sci. 52: 1327-1338.

Bradford, M.J., G.C. Taylor and J.A. Allan. 1997. Empirical review of Coho salmon smolt abundance and the prediction of smolt production at the regional level. Trans. Am. Fish. Soc. 126: 49-64.

Bradford, M.J., R.A. Myers and J.R. Irvine. 2000. Reference points for Coho salmon (*Oncorhynchus kisutch*) harvest rates and escapement goals based on freshwater production. Can. J. Fish. Aquat. Sci. 57: 677-686.

Brown, T.G. and G.F. Hartman. 1988. Contribution of seasonally flooded lands and minor tributaries to Coho (*Oncorhynchus kisutch*) salmon smolt production in Carnation Creek, a small coastal stream in British Columbia. Trans. Am. Fish. Soc. 1217: 546-551.

Brown, T.G., L. Barton, and G. Langford. 1996. The use of a geographic information system to evaluate terrain resource information management (TRIM) maps and to measure land use patterns for Black Creek, Vancouver Island. Can. Manuscr. Rep. Fish. Aquat. Sci. 2395: 34 p.

Brown, T.G., L. Barton, and G. Langford. 1999. Coho salmon habitat within Black Creek, Vancouver Island. Can. Tech. Rep. Fish. Aquat. Sci. 2294: 75 p.

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

Cederholm, C.J. and L.M. Reid. 1987. Impacts of forest management on Coho salmon (*Oncorhynchus kisutch*) populations of the Clearwater River, Washington: project summary, p. 373-398. In E.W. Salo and T.W. Cundy (ed.). Streamside Management: forestry and fisheries interactions. Contribution 57, College of Forest Resources, University of Washington, Seattle, WA.

Cederholm, C.J. and W.J. Scarlett. 1991. The beaded channel: a low-cost technique for enhancing winter habitat of Coho salmon. Amer. Fish. Soc. Symposium 10: 104-108.

Chapman, D.W. 1965. Net production of juvenile Coho salmon in three Oregon streams. Trans. Am. Fish. Soc. 94 (1): 40-52.

DFO. 1991. Stream Summary Catalogue Subdistrict #3. Fish Habitat Inventory and Information Program. North Coast Division, Fisheries Branch, Department of Fisheries and Oceans.

Draper, N.R., and W. Smith. 1981. Applied Regression Analysis (Second Ed.). John Wiley and Sons. 709p

Faush, K.D., C.L. Hawkes, and M.G. Parsons. 1988. Models that predict standing crop of stream fish from habitat variables: 1950-85. USDA For. Serv. Gen. Tech. Rep. PNW-GTR-213, Portland, OR. 52 p.

Fisheries and Oceans Canada. 1998. Draft Wild Salmon Policy. A new direction for Canada's Pacific Salmon Fisheries, policy paper, released for review October 1998. http://www-comm.pac.dfo-mpo.gc.ca/english/newdirections/default.htm (Sept. 2001).

FISS. 1991a. Fish Habitat Inventory and Information Program Stream Summary Catalogue: Subdistrict #3A, Lower Nass. Department of Fisheries and Oceans.

FISS. 1991b. Fish Habitat Inventory and Information Program Stream Summary Catalogue: Subdistrict #3B, Upper Nass. Department of Fisheries and Oceans.

Gelman, A., Carlin, J.B., Stern, H.S., and D.B. Rubin. 2004. Bayesian data analysis, 2nd Edition. Chapman & Hall/CRC, Boca Raton, FL. 668 p.

Hartman, G.F., B.C. Andersen, and J.C. Scrivener. 1981. Seaward movement of Coho salmon (O*ncorhynchus kisutch*) fry in Carnation Creek, an unstable coastal stream in British Columbia. Can. J. Fish. Aquat. Sci. 39:588-597.

Hilborn, R., and C.J. Walters. 1992. Quantitative fisheries stock assessment. Chapman and Hall, New York. 570 p.

Holtby, L.B. and J.C. Scrivener. 1989. Observed and simulated effects of climatic variability, clear-cut logging, and fishing on the numbers of chum salmon (*Oncorhyhnchus keta*) and Coho salmon (*O. kisutch*) returning to Carnation Creek, British Columbia, p. 62-81. In C.D. Levings, L.B. Holtby, and M.A. Henderson [ed.] Proceedings of the National Workshop of Effects of Habitat Alteration on Salmonid Stocks. Can. Spec. Publ. Fish. Aquat. Sci. 105.

Holtby, L.B., B.C. Andersen, and R.K. Kadowaki. 1990. Importance of smolt size and early ocean growth to interannual variability in marine survival of Coho salmon (O*ncorhynchus kisutch*). Can. J. Fish. Aquat. Sci. 47: 2181-2194.

Horton, R. E. 1945. "Erosional Development of Streams and Their Drainage Basins: Hydrophysical Approach to Quantitative Morphology." Bull. Geol. Soc. of America, Vol 56, pp 275-370.

Johnson, N.L., and S. Kotz. 1970. Distributions in Statistic: Continuous Univariate Distributions, Vol 1. John Wiley and Sons, New York. 300p.

Jowett, I.G. 1992. River hydraulics and instream habitat modelling for river biota. In: Mosley, M.P. (Ed.), Waters of New Zealand, Wellington, New Zealand Hydrological Society, 249-263.

Korman, J., and A. Tompkins. 2007. Estimating Regional Distributions of Freshwater Stock Productivity, Carrying Capacity, and Sustainable Harvest Rates for Coho Salmon Using a Hierarchical Bayesian Modelling Approach.

Knight, N.J. 1980. Factors affecting smolt yield of Coho salmon (*Oncoryhnchus kisutch*) in three Oregon streams. M.Sc. thesis, Oregon State University, Corvallis, Oreg.

Lister, D.B. 1968. Use of inaccessible stream areas for Coho salmon production. Fish. Mar. Ser. MS Rep. On File No. 32-5-45: 9 p.

Marshall, D.E. and E.W. Britton. 1990. Carrying capacity of Coho salmon streams. Can. Man. Rep. Fish Aquat. Sci. 2058: 32 p.

Mason, J.C. 1974. A further appraisal of the response to supplemental feeding of juvenile Coho (*O. kisutch*) in an experimental stream. Fish. Mar. Ser. Tech. Rep. 470: 25 p.

Mason, J.C. and D.W. Chapman. 1965. Significance of early emergence, environmental rearing capacity and behavioural ecology of juvenile Coho salmon in stream channels. J. Fish. Res. Bd. Can. 22: 175-190.

Minard, R.E., and Meacham, C.P., 1987. Sockeye salmon management in Bristol Bay, Alaska. In:H.D. Smith, L. Margolis, and C.C. Wook (Editors), Sockeye Salmon Population Biolody and Fugur Management. Can. Spec. Publ. Fish. Aquat. Sci., 96: 336-342.

MOE. 1977. Aquatic Biophysical Maps. Resources Analysis Branch. Ministry of the Environment. Victoria, B.C.

Nickelson, T.E. 1998. A habitat-based assessment of Coho salmon production potential and spawner escapement needs for Oregon coastal streams. Information Reports Number 98-4. Oregon Department of Fish and Wildlife. Portland Oregon.

Nickelson, T.E., J.D. Rodgers, S.L. Johnson, and M. Solazzi. 1992. Seasonal changes in habitat use by juvenile Coho salmon (*Oncorhynchus kisutch*) in Oregon coastal streams. Can. J. Fish. Aquat. Sci. 49: 783-789.

Pess, G.R., D.R. Montgomery, E.A. Steel, R.E. Bilby, B.E. Feist, and H.M. Greenberg. 2002. Landscape characteristics, land use, and Coho salmon (*Oncorhynchus kisutch*) abundance, Snohomish River, Wash., U.S.A. Can. J. Fish. Aquat. Sci. 59: 613-623.

Powers, P.D. and J. F. Orsborn. 1985. Analysis of barriers to upstream fish migration: an investigation of the physical and biological conditions affecting fish passage success at culverts and waterfalls. U.S. Department of Energy, Bonneville Power Administration. Project 82-14 Final Report. Portland, OR.

Ptolemy, R.A., M. Ramsey, and D. Sollitt. 2004. Results of steelhead stock monitoring (1988-2004) in the Bella Coola River and implications for population recovery. Prepared for Ministry of Water, Land and Air Protection, Fish and Wildlife Science and Allocation, Victoria, BC.

R Development Core Team. 2009. R: A Language and Environment for Statistical Computing. Vienna, Austria: R Foundation for Statistical Computing. Available at: http://www.R-project.org.

Reeves, G.H., F.H. Everest, and T.E. Nickelson. 1989. Identification of physical habitats limiting the production of Coho salmon in western Oregon and Washington. U.S. Forest Service General Technical Report PNW-245.

Rosenfeld, J., M. Porter and E. Parkinson. 2000. Habitat factors affecting the abundance and distribution of juvenile cutthroat trout (*Oncorhynchus clarki*) and Coho salmon (*Oncoryhnchus kisutch*). Can. J. Fish. Aquat. Sci. 57: 766-774.

Sharma, R. and R. Hilborn. 2001. Empirical relationships between watershed characteristics and Coho salmon (*Oncorhynchus kisutch*) smolt abundance in 14 western Washington streams. Can. J. Fish. Aquat. Sci. 58: 1453-1463.

Slaney, T.L., K.D. Hyatt, T.G. Northcote, and R.J. Fielden, 1996. Status of Anadromous Salmon and Trout in British Columbia and Yukon. Fisheries, 21(10):20–35.

Spiegelhalter, D.J., Best, N.G., Carlin, B.R., and A. van der Linde. 2002. Bayesian measures of model complexity and fit. J. Roy. Stat. Soc. B 64: 583-616.

Spiegelhalter, D.J., Thomas A., Best, N.G., and Lunn, D. 1999. WinBUGS User Manual: Version 1.4. Cambridge: MRC Biostatistics Unit, 60 pp.

Strahler, A.N. 1957. Quantitative analysis of watershed geomorphology. Trans. Am. Geophys. Union 38: 913-920.

Stuart, T. A. 1962. The leaping behaviour of salmon and trout at falls and obstructions. Department of Agriculture and Fisheries for Scotland, Freshwater and Salmon Fisheries Research Report 28, Edinburgh.

Sturtz, S., Legges U., and Gelman A. 2005. R2WinBGS: a package for running WinBUGS from R. Journal of statistical software 3: 1-16.

APPENDICES

Appendix Table 1. Watershed area, stream order and accessible length for all Coho bearing salmon streams within the EVI-GS, GSM and HS-BI CUs. Streams of order 1 are shown, but are excluded from model calculations per the discussion and therefore show as "NA" and "FALSE".

	Watershed	Area (km^2)	Stream Order	Minimum Stream Order	Accessible length (<8% gradient) (m)	Accessible length (<6% gradient) (m)	Accessible length (<4% gradient) (m)	Accessible length (<2% gradient) (m)
East Vancouver Island - Georgia Strait		*minimum stream order*		*1*				
1	Annie Creek	9.5	1	NA	FALSE	FALSE	FALSE	FALSE
2	Ayum Creek	14.1	3	1	630	570	440	380
3	Beach Creek	3.9	1	NA	FALSE	FALSE	FALSE	FALSE
4	Beck Creek	18.0	2	1	5,400	5,400	5,330	5,330
5	Black Creek	64.6	4	1	26,830	26,830	26,680	26,000
6	Bloods Creek	2.2	1	NA	FALSE	FALSE	FALSE	FALSE
7	Bonell Creek	51.2	4	1	2,820	2,650	2,530	2,370
8	Bonsall Creek	24.4	3	1	12,920	12,810	12,550	12,230
9	Brooklyn Creek	5.4	1	NA	FALSE	FALSE	FALSE	FALSE
10	Bush Creek	28.2	2	1	1,740	1,740	1,740	1,680
11	Campbell River	1460.7	7	1	10,250	10,250	10,250	10,150
12	Casey Creek	8.1	2	1	3,500	3,380	3,140	2,390
13	Charters River	19.4	4	1	700	700	510	420
14	Chase River	29.3	3	1	4,330	4,330	4,180	3,730
15	Chef Creek	8.3	3	1	6,210	6,160	6,050	5,880
16	Chemainus River	355.7	5	1	18,160	18,090	17,980	16,960
17	Clear Creek	71.6	4	1	6,380	6,040	5,980	5,370
18	Colquitz River	47.6	3	1	15,200	14,960	14,230	13,690
19	Cook Creek	19.0	4	1	2,140	2,140	2,140	2,090
20	Cowichan River	671.5	7	1	128,360	124,320	114,120	105,500
21	Cowie Creek	23.3	3	1	1,540	1,540	1,410	1,190
22	Craig Creek	12.0	2	1	4,240	4,180	3,730	3,490
23	Craigflower Creek	22.8	3	1	4,340	4,270	4,140	4,020
24	De Mamiel Creek	32.9	4	1	24,060	23,450	21,110	17,450
25	Departure Creek	4.0	1	NA	FALSE	FALSE	FALSE	FALSE
26	Dove Creek	42.8	3	1	20,360	20,000	18,280	15,350
27	Drew Creek	2.9	1	NA	FALSE	FALSE	FALSE	FALSE
28	Englishman River	316.0	6	1	58,460	58,070	55,560	51,970
29	French Creek	69.7	4	1	10,780	10,780	10,710	10,660
30	Fulford Creek	21.4	3	1	4,910	4,520	4,230	3,620

Appendix Table 1 (cont).

	Watershed	Area (km^2)	Stream Order	Minimum Stream Order	Accessible length (<8% gradient) (m)	Accessible length (<6% gradient) (m)	Accessible length (<4% gradient) (m)	Accessible length (<2% gradient) (m)
East Vancouver Island - Georgia Strait		*minimum stream order*		*1*				
31	Glenora Creek	21.8	4	1	13,830	13,530	12,580	11,120
32	Goldstream River	57.6	4	1	4,840	4,670	4,220	3,440
33	Hart Creek	28.4	3	1	1,530	1,530	1,530	1,530
34	Haslam Creek	125.8	4	1	31,350	30,960	29,780	27,340
35	Headquarters Creek	29.1	3	1	4,680	4,680	4,620	4,270
36	Holden Creek	23.2	3	1	18,170	18,120	17,850	16,840
37	Holland Creek	30.7	3	1	620	510	400	330
38	Jordan River	161.9	5	1	1,370	1,300	1,230	1,160
39	Kelvin Creek	35.7	4	1	8,040	7,790	7,570	7,110
40	Kingfisher Creek	2.8	1	NA	FALSE	FALSE	FALSE	FALSE
41	Kirby Creek	24.5	4	1	2,410	2,340	1,820	1,550
42	Kitty Coleman Creek	12.8	3	1	12,680	12,670	12,140	10,990
43	Knarston Creek	8.2	1	NA	FALSE	FALSE	FALSE	FALSE
44	Koksilah River	247.5	6	1	29,800	29,290	28,150	26,610
45	Lannon Creek	2.7	2	1	990	990	990	940
46	Little George Creek	17.3	2	1	3,540	3,520	3,330	3,180
47	Little Oyster River	38.2	3	1	32,800	32,490	32,030	29,930
48	Little Qualicum River	252.4	4	1	30,350	30,170	29,300	27,990
49	Little River	18.9	3	1	10,940	10,940	10,640	9,940
50	Mckercher Creek	16.3	3	1	5,820	5,120	4,530	3,470
51	Mcnaughton Creek	8.9	3	1	2,490	2,430	2,370	2,250
52	Menzies Creek	23.9	4	1	4,680	4,450	3,930	2,710
53	Mesachie Creek	6.6	3	1	3,990	3,810	3,330	3,170
54	Mill Stream	29.2	3	1	380	380	320	270
55	Millard Creek	7.1	2	1	4,190	4,190	3,930	3,750
56	Millstone River	100.2	4	1	26,690	26,020	24,720	22,660
57	Mohun Creek	129.8	5	1	11,610	10,960	10,510	9,220
58	Morrison Creek	11.1	3	1	8,730	8,530	8,010	6,820
59	Muir Creek	66.0	5	1	2,830	2,760	2,740	2,740
60	Nanaimo River	638.4	7	1	107,270	104,220	95,230	87,440

Appendix Table 1 (cont).

	Watershed	Area (km^2)	Stream Order	Minimum Stream Order	Accessible length (<8% gradient) (m)	Accessible length (<6% gradient) (m)	Accessible length (<4% gradient) (m)	Accessible length (<2% gradient) (m)
East Vancouver Island - Georgia Strait		*minimum stream order*		*1*				
61	Nanoose Creek	34.0	3	1	3,090	3,030	3,030	3,030
62	Napoleon Creek	3.0	2	1	3,690	3,690	3,690	3,640
63	Nile Creek	16.5	3	1	6,180	6,180	6,070	5,960
64	Norrie Creek	6.7	2	1	2,670	2,490	2,140	1,800
65	North Nanaimo River	62.4	4	1	37,180	35,370	32,500	29,300
66	Nunns Creek	6.3	2	1	4,170	4,170	4,110	3,800
67	Oliver Creek	5.0	4	1	3,820	3,460	2,100	1,880
68	Open Bay Creek	12.0	2	1	6,290	6,030	5,010	4,430
69	Oyster River	323.6	6	1	28,530	28,440	28,060	26,380
70	Patricia Creek	5.5	2	1	4,260	4,190	3,790	3,690
71	Porter Creek	4.4	1	NA	FALSE	FALSE	FALSE	FALSE
72	Portuguese Creek	37.0	3	1	32,880	32,730	32,320	31,100
73	Puntledge River	587.7	6	1	87,890	84,890	79,540	68,640
74	Qualicum River	146.2	5	1	13,070	13,070	12,780	12,320
75	Quinsam River	289.5	5	1	81,330	79,790	75,840	70,950
76	Reay Creek	3.2	2	1	1,340	1,270	1,270	1,270
77	Richards Creek	20.8	3	1	17,350	17,190	16,400	14,990
78	Robertson River	99.0	5	1	29,270	28,340	26,010	21,780
79	Rocky Creek	7.2	3	1	450	450	190	-
80	Rosewall Creek	44.1	4	1	4,480	4,360	4,250	4,250
81	Roy Creek	12.6	2	1	3,170	3,110	2,580	2,300
82	Sandhill Creek	11.9	2	1	8,080	7,880	7,260	6,400
83	Sandy Creek	2.5	1	NA	FALSE	FALSE	FALSE	FALSE
84	Shaw Creek	75.6	5	1	4,400	4,320	3,600	3,540
85	Simms Creek	16.3	3	1	13,000	12,670	11,910	10,390
86	Sooke River	282.2	5	1	9,820	9,570	9,240	9,120
87	Stocking Creek	9.8	2	1	430	260	-	-
88	Storie Creek	4.5	2	1	5,700	5,640	5,150	3,800
89	Sutton Creek	43.9	4	1	9,670	9,300	7,930	7,190
90	Tod Creek	24.3	3	1	160	160	50	-

Appendix Table 1 (cont).

	Watershed	Area (km^2)	Stream Order	Minimum Stream Order	Accessible length (<8% gradient) (m)	Accessible length (<6% gradient) (m)	Accessible length (<4% gradient) (m)	Accessible length (<2% gradient) (m)
East Vancouver Island - Georgia Strait		*minimum stream order*		*1*				
91	Trent River	82.0	4	1	9,890	9,890	9,540	9,140
92	Tsable River	54.7	5	1	6,530	6,470	6,470	6,470
93	Tsolum River	157.6	5	1	90,170	89,480	86,690	80,930
94	Tugwell Creek	20.1	4	1	2,270	2,270	1,920	1,810
95	Tyee Creek	12.2	2	1	410	340	290	290
96	Walker Creek	10.1	2	1	2,320	2,230	2,230	2,050
97	Waterloo Creek	7.8	3	1	1,780	1,540	1,540	1,410
98	Wexford Creek	5.9	2	1	910	850	850	850
99	Whitehouse Creek	11.6	2	1	2,290	2,240	2,000	1,900
100	Wildwood Creek	8.8	3	1	100	100	100	60
101	Wilfred Creek	26.3	4	1	4,140	4,080	3,700	3,330
102	Willow Creek	25.6	3	1	13,930	13,800	13,210	12,070
103	Woods Creek	10.9	3	1	9,960	9,890	9,620	8,640
	Subtotal				1,327,950	1,300,780	1,229,800	1,131,590

Appendix Table 1 (cont).

	Watershed	Area (km^2)	Stream Order	Minimum Stream Order	Accessible length (<8% gradient) (m)	Accessible length (<6% gradient) (m)	Accessible length (<4% gradient) (m)	Accessible length (<2% gradient) (m)
Georgia Strait - Mainland		*minimum stream order*		*1*				
106	Anderson Creek	17.9	3	1	3,580	3,580	3,250	2,830
107	Angus Creek	8.6	3	1	1,210	1,160	980	600
108	Bird Cove Creek	2.2	1	NA	FALSE	FALSE	FALSE	FALSE
109	Black Lake Creek	10.4	2	1	320	260	260	260
110	Brem River	233.4	5	1	1,950	1,590	1,370	1,210
111	Brem River Tributary	10.7	3	1	270	160	60	-
112	Brittain River	122.9	5	1	6,630	6,190	6,090	5,500
113	Burnet Creek	9.3	3	1	540	420	180	70
114	Carlson Creek	27.7	3	1	340	340	150	150
115	Carrington Cove Creek	2.1	1	NA	FALSE	FALSE	FALSE	FALSE
116	Cranby Creek	18.6	2	1	1,990	1,930	1,620	1,520
117	Deighton Creek	8.5	2	1	2,220	2,110	1,530	1,240
118	Deserted River	112.6	5	1	8,570	8,110	7,390	6,940
119	Doriston Creek	6.9	2	1	1,140	1,090	1,020	610
120	Forbes Creek	51.0	4	1	1,890	1,580	1,040	990
121	Gray Creek	59.0	5	1	1,410	1,360	1,240	870
122	Hunaechin Creek	155.9	5	1	2,240	2,180	1,920	1,520
123	Jefferd Creek	4.6	1	NA	FALSE	FALSE	FALSE	FALSE
124	Kelly Creek	9.8	1	NA	FALSE	FALSE	FALSE	FALSE
125	Klite River	128.4	5	1	8,770	8,060	6,220	5,370
126	Lang Creek	131.4	4	1	7,060	7,000	6,070	5,720
127	Little Toba River	306.5	5	1	30,090	29,400	26,820	22,230
128	Mixal Lake Creek	8.4	2	1	3,590	3,410	2,980	2,880
129	Mouat Creek	34.1	3	1	1,130	1,070	940	580
130	Myers Creek	21.1	4	1	6,240	6,180	5,840	5,140
131	Myrtle Creek	19.0	2	1	8,130	7,840	7,530	6,840
132	Okeover Creek	18.0	2	1	5,910	5,540	4,210	3,290
133	Pendrell Sound Creek	3.4	3	1	1,740	1,670	1,350	1,280
134	Quatam River	157.3	5	1	14,230	13,880	13,310	9,300
135	Refuge Cove Creek	1.6	2	1	150	150	150	150
136	Ruby Creek	60.7	3	1	1,840	1,680	960	790

Appendix Table 1 (cont).

	Watershed	Area (km^2)	Stream Order	Minimum Stream Order	Accessible length (<8% gradient) (m)	Accessible length (<6% gradient) (m)	Accessible length (<4% gradient) (m)	Accessible length (<2% gradient) (m)
Georgia Strait - Mainland		*minimum stream order*		*1*				
137	Sechelt Creek	84.1	5	1	880	830	830	540
138	Skwawka River	201.6	6	1	7,150	7,120	6,590	6,230
139	Sliammon Creek	58.4	5	1	2,420	2,360	2,080	1,740
140	Snake Bay Creek	4.2	2	1	590	410	360	110
141	Store Creek	3.4	1	NA	FALSE	FALSE	FALSE	FALSE
142	Tahumming River	255.1	5	1	490	490	290	290
143	Theodosia River	133.7	5	1	9,310	9,130	8,600	8,090
144	Toba River	1313.2	6	1	138,890	136,400	133,490	128,750
145	Tsuahdi Creek	23.1	3	1	670	670	670	670
146	Tzoonie River	168.0	6	1	2,490	2,380	2,110	2,000
147	Vancouver River	164.1	5	1	2,950	2,950	2,820	2,180
148	Wakefield Creek	11.8	2	1	170	170	-	-
149	West Creek	20.1	2	1	470	410	410	360
150	Whiterock Pass Creek	7.7	2	1	2,320	2,320	2,040	1,910
151	Whittall Creek	10.0	2	1	3,130	2,960	2,060	1,120
	Subtotal				295,110	286,540	266,830	241,870

Appendix Table 1 (cont).

	Watershed	Area (km^2)	Stream Order	Minimum Stream Order	Accessible length (<8% gradient) (m)	Accessible length (<6% gradient) (m)	Accessible length (<4% gradient) (m)	Accessible length (<2% gradient) (m)
Howe Sound Burrard Inlet		*minimum stream order*		*1*				
155	Ashlu Creek	342.6	5	1	3,810	3,510	3,510	2,950
156	Capilano River	206.9	6	1	5,000	4,920	4,920	4,750
157	Chapman Creek	69.2	5	1	4,010	4,010	3,890	3,450
158	Chaster Creek	10.7	3	1	1,990	1,860	940	310
159	Cheakamus River	1004.3	6	1	25,800	25,120	23,770	21,260
160	Dakota Creek	33.5	5	1	850	640	500	250
161	Hutchinson Creek	4.7	2	1	2,110	1,790	1,150	490
162	Indian River	192.8	5	1	9,740	9,740	9,470	9,060
163	Langdale Creek	8.1	2	1	1,130	720	310	70
164	Loggers Lane Creek	5.6	2	1	380	380	380	380
165	Lynn Creek	50.8	5	1	4,130	4,130	4,130	3,820
166	Mamquam River	33.7	6	1	7,130	7,130	7,090	6,990
167	Mcnab Creek	67.8	5	1	1,690	1,690	1,690	1,530
168	Mcnair Creek	20.3	5	1	730	560	330	-
169	Mill Creek	40.8	4	1	140	140	140	-
170	Ouillet Creek	6.0	3	1	530	470	180	180
171	Rainy River	68.5	5	1	4,880	4,620	3,140	1,410
172	Roberts Creek	29.5	3	1	430	370	190	190
173	Seymour River	177.8	5	1	17,860	17,860	17,840	17,230
174	South Twin Creek	6.0	2	1	250	250	250	140
175	Squamish River	1954.2	7	1	183,860	183,170	181,390	172,130
176	Stawamus River	52.8	4	1	1,530	1,530	1,530	1,020
177	Terminal Creek	9.2	3	1	5,380	5,070	4,400	3,740
	Subtotal				283,360	279,680	271,140	251,350

Appendix Table 2. Stream specific smolt yield estimates and spawners required to produce estimated smolts for each watershed and CU using Model 1 and Model 2

					Smolt and Spawner Estimates			
	Watershed	Area (km^2)	Stream Order	Stream Length (m)	Model 1		Model 2	
		Beta=	*1*	g8	1g8			
East Vancouver Island - Georgia Strait					Smolt	Spawners	Smolt	Spawners
1	Annie Creek	9	1	FALSE	-	-	-	-
2	Ayum Creek	14	3	630	321	5	703	12
3	Beach Creek	4	1	FALSE	-	-	-	-
4	Beck Creek	18	2	5,400	3,204	53	6,026	100
5	Black Creek	65	4	26,830	19,300	321	29,940	498
6	Bloods Creek	2	1	FALSE	-	-	-	-
7	Bonell Creek	51	4	2,820	1,577	26	3,147	52
8	Bonsall Creek	24	3	12,920	8,442	140	14,418	240
9	Brooklyn Creek	5	1	FALSE	-	-	-	-
10	Bush Creek	28	2	1,740	938	16	1,942	32
11	Campbell River	1,461	7	10,250	6,515	108	11,438	190
12	Casey Creek	8	2	3,500	1,994	33	3,906	65
13	Charters River	19	4	700	358	6	781	13
14	Chase River	29	3	4,330	2,515	42	4,832	80
15	Chef Creek	8	3	6,210	3,737	62	6,930	115
16	Chemainus River	356	5	18,160	12,388	206	20,265	337
17	Clear Creek	72	4	6,380	3,850	64	7,120	118
18	Colquitz River	48	3	15,200	10,134	168	16,962	282
19	Cook Creek	19	4	2,140	1,171	19	2,388	40
20	Cowichan River	672	7	128,360	118,895	1,977	143,239	2,381
21	Cowie Creek	23	3	1,540	823	14	1,719	29
22	Craig Creek	12	2	4,240	2,458	41	4,731	79
23	Craigflower Creek	23	3	4,340	2,521	42	4,843	81
24	De Mamiel Creek	33	4	24,060	17,046	283	26,849	446
25	Departure Creek	4	1	FALSE	-	-	-	-
26	Dove Creek	43	3	20,360	14,100	234	22,720	378
27	Drew Creek	3	1	FALSE	-	-	-	-
28	Englishman River	316	6	58,460	47,309	787	65,236	1,085
29	French Creek	70	4	10,780	6,893	115	12,030	200
30	Fulford Creek	21	3	4,910	2,886	48	5,479	91
31	Glenora Creek	22	4	13,830	9,112	151	15,433	257
32	Goldstream River	58	4	4,840	2,841	47	5,401	90
33	Hart Creek	28	3	1,530	818	14	1,707	28
34	Haslam Creek	126	4	31,350	23,059	383	34,984	582
35	Headquarters Creek	29	3	4,680	2,738	46	5,222	87
36	Holden Creek	23	3	18,170	12,395	206	20,276	337
37	Holland Creek	31	3	620	315	5	692	12
38	Jordan River	162	5	1,370	727	12	1,529	25
39	Kelvin Creek	36	4	8,040	4,973	83	8,972	149
40	Kingfisher Creek	3	1	FALSE	-	-	-	-
41	Kirby Creek	25	4	2,410	1,331	22	2,689	45
42	Kitty Coleman Creek	13	3	12,680	8,266	137	14,150	235
43	Knarston Creek	8	1	FALSE	-	-	-	-
44	Koksilah River	247	6	29,800	21,759	362	33,254	553
45	Lannon Creek	3	2	990	515	9	1,105	18
46	Little George Creek	17	2	3,540	2,019	34	3,950	66
47	Little Oyster River	38	3	32,800	24,285	404	36,602	608
48	Little Qualicum River	252	4	30,350	22,219	369	33,868	563
49	Little River	19	3	10,940	7,007	116	12,208	203
50	Mckercher Creek	16	3	5,820	3,479	58	6,495	108

Appendix 2 (cont).

					Smolt and Spawner Estimates			
	Watershed	Area (km^2)	Stream Order	Stream Length (m)	Model 1		Model 2	
		Beta=	*1*	g8	1g8			
East Vancouver Island - Georgia Strait					Smolt	Spawners	Smolt	Spawners
51	Mcnaughton Creek	9	3	2,490	1,379	23	2,779	46
52	Menzies Creek	24	4	4,680	2,738	46	5,222	87
53	Mesachie Creek	7	3	3,990	2,300	38	4,452	74
54	Mill Stream	29	3	380	190	3	424	7
55	Millard Creek	7	2	4,190	2,426	40	4,676	78
56	Millstone River	100	4	26,690	19,185	319	29,784	495
57	Mohun Creek	130	5	11,610	7,489	124	12,956	215
58	Morrison Creek	11	3	8,730	5,449	91	9,742	162
59	Muir Creek	66	5	2,830	1,583	26	3,158	53
60	Nanaimo River	638	7	107,270	96,208	1,599	119,704	1,990
61	Nanoose Creek	34	3	3,090	1,742	29	3,448	57
62	Napoleon Creek	3	2	3,690	2,112	35	4,118	68
63	Nile Creek	16	3	6,180	3,717	62	6,896	115
64	Norrie Creek	7	2	2,670	1,487	25	2,979	50
65	North Nanaimo River	62	4	37,180	28,043	466	41,490	690
66	Nunns Creek	6	2	4,170	2,414	40	4,653	77
67	Oliver Creek	5	4	3,820	2,193	36	4,263	71
68	Open Bay Creek	12	2	6,290	3,790	63	7,019	117
69	Oyster River	324	6	28,530	20,702	344	31,837	529
70	Patricia Creek	5	2	4,260	2,470	41	4,754	79
71	Porter Creek	4	1	FALSE	-	-	-	-
72	Portuguese Creek	37	3	32,880	24,353	405	36,691	610
73	Puntledge River	588	6	87,890	76,130	1,266	98,078	1,631
74	Qualicum River	146	5	13,070	8,552	142	14,585	242
75	Quinsam River	289	5	81,330	69,519	1,156	90,757	1,509
76	Reay Creek	3	2	1,340	710	12	1,495	25
77	Richards Creek	21	3	17,350	11,765	196	19,361	322
78	Robertson River	99	5	29,270	21,317	354	32,663	543
79	Rocky Creek	7	3	450	226	4	502	8
80	Rosewall Creek	44	4	4,480	2,610	43	4,999	83
81	Roy Creek	13	2	3,170	1,791	30	3,537	59
82	Sandhill Creek	12	2	8,080	5,000	83	9,017	150
83	Sandy Creek	3	1	FALSE	-	-	-	-
84	Shaw Creek	76	5	4,400	2,559	43	4,910	82
85	Simms Creek	16	3	13,000	8,501	141	14,507	241
86	Sooke River	282	5	9,820	6,211	103	10,958	182
87	Stocking Creek	10	2	430	216	4	480	8
88	Storie Creek	5	2	5,700	3,400	57	6,361	106
89	Sutton Creek	44	4	9,670	6,106	102	10,791	179
90	Tod Creek	24	3	160	79	1	179	3
91	Trent River	82	4	9,890	6,261	104	11,036	183
92	Tsable River	55	5	6,530	3,950	66	7,287	121
93	Tsolum River	158	5	90,170	78,451	1,304	100,622	1,673
94	Tugwell Creek	20	4	2,270	1,248	21	2,533	42
95	Tyee Creek	12	2	410	205	3	458	8
96	Walker Creek	10	2	2,320	1,278	21	2,589	43
97	Waterloo Creek	8	3	1,780	961	16	1,986	33
98	Wexford Creek	6	2	910	472	8	1,015	17
99	Whitehouse Creek	12	2	2,290	1,260	21	2,555	42
100	Wildwood Creek	9	3	100	49	1	112	2
101	Wilfred Creek	26	4	4,140	2,395	40	4,620	77
102	Willow Creek	26	3	13,930	9,187	153	15,545	258
103	Woods Creek	11	3	9,960	6,310	105	11,114	185
	Subtotal			**1,327,950**	**1,005,922**	16,723	**1,481,877**	**24,636**
				CL	**950,591**	15,803	**1,474,069**	**24,506**
				CL	**1,061,254**	17,643	**1,489,685**	**24,766**

Appendix 2 (cont).

					Smolt and Spawner Estimates			
	Watershed	Area (km^2)	Stream Order	Stream Length (m)	Model 1		Model 2	
		Beta=	1	g8	1g8			
Georgia Strait - Mainland					Smolt	Spawners	Smolt	Spawners
106	Anderson Creek	18	3	3,580	2,044	37	383	7
107	Angus Creek	9	3	1,210	637	12	129	2
108	Bird Cove Creek	2	1	FALSE	-	-	-	-
109	Black Lake Creek	10	2	320	159	3	34	1
110	Brem River	233	5	1,950	1,060	19	208	4
111	Brem River Tributary	11	3	270	134	2	29	1
112	Brittain River	123	5	6,630	4,017	73	709	13
113	Burnet Creek	9	3	540	273	5	58	1
114	Carlson Creek	28	3	340	169	3	36	1
115	Carrington Cove Creek	2	1	FALSE	-	-	-	-
116	Cranby Creek	19	2	1,990	1,083	20	213	4
117	Deighton Creek	9	2	2,220	1,218	22	237	4
118	Deserted River	113	5	8,570	5,338	97	916	17
119	Doriston Creek	7	2	1,140	598	11	122	2
120	Forbes Creek	51	4	1,890	1,025	19	202	4
121	Gray Creek	59	5	1,410	750	14	151	3
122	Hunaechin Creek	156	5	2,240	1,230	22	239	4
123	Jefferd Creek	5	1	FALSE	-	-	-	-
124	Kelly Creek	10	1	FALSE	-	-	-	-
125	Klite River	128	5	8,770	5,476	99	937	17
126	Lang Creek	131	4	7,060	4,306	78	755	14
127	Little Toba River	307	5	30,090	22,001	399	3,216	58
128	Mixal Lake Creek	8	2	3,590	2,050	37	384	7
129	Mouat Creek	34	3	1,130	593	11	121	2
130	Myers Creek	21	4	6,240	3,757	68	667	12
131	Myrtle Creek	19	2	8,130	5,034	91	869	16
132	Okeover Creek	18	2	5,910	3,538	64	632	11
133	Pendrell Sound Creek	3	3	1,740	938	17	186	3
134	Quatam River	157	5	14,230	9,409	171	1,521	28
135	Refuge Cove Creek	2	2	150	74	1	16	0
136	Ruby Creek	61	3	1,840	996	18	197	4
137	Sechelt Creek	84	5	880	455	8	94	2
138	Skwawka River	202	6	7,150	4,366	79	764	14
139	Sliammon Creek	58	5	2,420	1,337	24	259	5
140	Snake Bay Creek	4	2	590	300	5	63	1
141	Store Creek	3	1	FALSE	-	-	-	-
142	Tahumming River	255	5	490	247	4	52	1
143	Theodosia River	134	5	9,310	5,853	106	995	18
144	Toba River	1,313	6	138,890	130,518	2,368	14,846	269
145	Tsuahdi Creek	23	3	670	342	6	72	1
146	Tzoonie River	168	6	2,490	1,379	25	266	5
147	Vancouver River	164	5	2,950	1,656	30	315	6
148	Wakefield Creek	12	2	170	84	2	18	0
149	West Creek	20	2	470	237	4	50	1
150	Whiterock Pass Creek	8	2	2,320	1,278	23	248	4
151	Whittall Creek	10	2	3,130	1,766	32	335	6
	Subtotal			**295,110**	**227,726**	4,131	**31,544**	**572**
				CL	**175,623**	3,186	**30,171**	**547**
				CL	**279,829**	5,076	**32,917**	**597**

Appendix 2 (cont).

					Smolt and Spawner Estimates			
	Watershed	Area (km^2)	Stream Order	Stream Length (m)	Model 1		Model 2	
		Beta=	*1*	g8	1g8			
Howe Sound Burrard Inlet					Smolts	Spawners	Smolts	Spawners
155	Ashlu Creek	343	5	3,810	2,187	40	407	7
156	Capilano River	207	6	5,000	2,944	53	534	10
157	Chapman Creek	69	5	4,010	2,313	42	429	8
158	Chaster Creek	11	3	1,990	1,083	20	213	4
159	Cheakamus River	1,004	6	25,800	18,457	335	2,758	50
160	Dakota Creek	33	5	850	439	8	91	2
161	Hutchinson Creek	5	2	2,110	1,154	21	226	4
162	Indian River	193	5	9,740	6,155	112	1,041	19
163	Langdale Creek	8	2	1,130	593	11	121	2
164	Loggers Lane Creek	6	2	380	190	3	41	1
165	Lynn Creek	51	5	4,130	2,388	43	441	8
166	Mamquam River	34	6	7,130	4,353	79	762	14
167	Mcnab Creek	68	5	1,690	909	16	181	3
168	Mcnair Creek	20	5	730	374	7	78	1
169	Mill Creek	41	4	140	69	1	15	0
170	Ouillet Creek	6	3	530	268	5	57	1
171	Rainy River	68	5	4,880	2,867	52	522	9
172	Roberts Creek	29	3	430	216	4	46	1
173	Seymour River	178	5	17,860	12,157	221	1,909	35
174	South Twin Creek	6	2	250	124	2	27	0
175	Squamish River	1,954	7	183,860	182,117	3,304	19,652	356
176	Stawamus River	53	4	1,530	818	15	164	3
177	Terminal Creek	9	3	5,380	3,191	58	575	10
	Subtotal			**283,360**	**245,364**	4,451	**30,288**	**549**
				CL	**137,723**	2,498	**27,705**	**503**
				CL	**353,005**	6,403	**32,871**	**596**