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Habitat-based methods to estimate escapement goals for data limited Chinook salmon stocks in British Columbia, 2004

Méthode axée sur l'habitat pour estimer les objectifs d'échappée pour les stocks de saumon quinnat de la Colombie-Britannique pour lesquels les données sont rares, 2004

C. K. Parken, R. E. McNicol and J. R. Irvine

Fisheries and Oceans Canada
Science Branch
Pacific Biological Station
Nanaimo, B.C. V9T 6N7

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ABSTRACT

Fisheries and Oceans Canada requires escapement goals for Chinook salmon (*Oncorhynchus tshawytscha*) stocks to evaluate their status and achieve objectives established by international agreements and domestic policy. Unfortunately the data typically needed to establish these 'goals', using stock-recruitment techniques, are expensive to gather and are, for most stocks, lacking. This prompted us to develop the habitat-based approach to generate escapement goals described in this report.

We related productive capacity to freshwater habitat area based on results from a meta-analysis of 25 Chinook stocks. Stocks were distributed between central Alaska and northern Oregon and represented a broad range of environments and life history. We developed an allometric model that predicted Smsy and Srep (spawners required to produced maximum sustained yield and replacement, respectively) from the watershed area and assessed the model's performance. The model adequately predicted the Smsy and Srep for an independent data source and out-performed a current interim method applied to British Columbia (BC) Key Streams. The habitat-based approach adequately predicted Smsy and Srep for seven case study examples, although it overestimated the productive capacity of stocks with relatively small spawning areas.

Our habitat-based model can generate biologically-based escapement goals, rooted in fish-production relationships, for data limited stocks over a broad range of environments. This simple approach requires easily acquirable data and makes few assumptions. However, spawner escapements of known accuracy and reliability are required, which may impede implementation for some systems. The approach is well-suited for most data limited stocks in BC and can be tested and refined as new stock-recruitment data become available. Since the habitat-based method was more accurate than the interim method for BC Key Streams, we recommend applying it for data limited stocks in BC to establish escapement goals until more stock-specific data are available.

RÉSUMÉ

Pêches et Océans Canada a besoin d’objectifs d’échappée pour les stocks de saumon quinnat (*Oncorhynchus tshawytscha*) afin d’évaluer leur état et d’atteindre les objectifs établis par les ententes internationales et les politiques nationales. Malheureusement, les données généralement nécessaires pour fixer ces « objectifs » à l’aide de méthodes traditionnelles stock-recrutement coûtent cher à réunir et, dans la plupart des cas, sont inexistantes. C’est ce qui nous a amenés à mettre au point l’approche axée sur l’habitat pour établir les objectifs d’échappée, décrite dans le présent rapport.

Nous avons établi une relation entre la capacité de production et la superficie de l’habitat en eau douce, d’après des résultats d’une méta-analyse de 25 stocks de quinnats. Ces stocks étaient répartis entre le centre de l’Alaska et le nord de l’Oregon et représentaient un large éventail d’environnement et de cycles biologiques. Nous avons élaboré un modèle allométrique permettant de prédire S_{msy} et S_{rep} (géniteurs requis pour produire le rendement maximal équilibré et le remplacement, respectivement) dans la zone du bassin hydrographique et avons évalué le rendement du modèle. De fait, le modèle a prédit adéquatement S_{msy} et S_{rep} pour une source de données indépendante et a surclassé la méthode provisoire actuellement appliquée aux cours d’eau clés de la Colombie-Britannique (C.-B.). L’approche fondée sur l’habitat a permis de prédire de façon appropriée S_{msy} et S_{rep} pour sept exemples d’études de cas, bien qu’elle ait surestimé la capacité de production des stocks qui ont des frayères relativement restreintes.

Notre modèle axé sur l’habitat permet d’obtenir des objectifs d’échappée reposant sur des facteurs biologiques, issus des relations poissons-production pour les stocks de différents environnements, pour lesquels les données sont rares. Cette méthode simple exige des données faciles à acquérir et pose peu d’hypothèses. Toutefois, il faut des échappées de géniteurs d’une exactitude et d’une fiabilité connues, ce qui peut nuire à son application à certains réseaux. L’approche convient à la plupart des stocks de C.-B. pour lesquels les données sont rares et peut être mise à l’essai et adaptée à mesure que de nouvelles données de stock-recrutement deviennent accessibles. Puisque la méthode axée sur l’habitat s’est révélée plus précise que la méthode provisoire pour les principaux cours d’eau de C.-B., nous recommandons de l’appliquer aux stocks de C.B. pour lesquels les données sont rares pour fixer les objectifs d’échappée, jusqu’à ce que davantage de données sur les différents stocks soient disponibles.

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1 Introduction

Spawner escapement goals are needed to evaluate Chinook salmon *Oncorhynchus tshawytscha* status and set harvest limits. However, the data typically needed to establish escapement goals in Canada are, for the most part, lacking and the resources required to establish biologically-based goals using a conventional spawner-recruit approach for even a small number of stocks are prohibitive. In this report we describe and present findings from an alternate approach that is habitat-based.

Prior to the signing of the 1985 Pacific Salmon Treaty (PST), escapement goals were usually generated by fishery officers familiar with the stocks within their jurisdiction. These goals tended to represent spawner numbers that officers thought fully 'seeded' a system. After the signing of the PST, Canada and the U.S. wanted to set biologically-based escapement goals coastwide as to gauge the effectiveness of changes to the coastwide management of Chinook harvest intended to restore depressed stocks to 'healthy' levels. However, setting target escapements on a stock-by-stock basis proved to be problematic for Canada, as few programs were in place to collect the data necessary to use a conventional spawner-recruit approach. A typical spawner-recruit relationship requires annual estimates of total spawner abundance by age, and brood exploitation rates over a >15 year period. From this relationship, an escapement goal can be derived, such as the escapement that would support maximum sustained yield (S_{msy}), or some fraction thereof. Lacking such data, Canada used a more simplistic approach. Interim escapement goals for each stock or stock aggregate were set as double the average escapement from 1979-1982, years when stock abundances were depressed due to high exploitation rates (goals for some stocks were later revised to double the 1984 escapement; CTC 1998). These goals were meant to be interim in nature, ultimately to be replaced with goals derived from some measure of productive capacity.

With the signing of the 1999 Agreement, specific tasks were laid out for the Chinook Technical Committee (CTC) to complete in order to implement several provisions in the Agreement. Amongst these, the CTC was tasked to "*… evaluate and review existing escapement goals that fishery management agencies have set for Chinook stocks subject to this Chapter for consistency with MSY or other agreed biologically-based escapement goals and, where needed, recommend goals for naturally spawning Chinook stocks that are consistent with the intent of this Chapter.*" (Appendix to Annex IV, Chapter 3, p. 46). Several provisions within the Agreement, including triggers for additional management actions, are explicitly tied to the establishment of escapement goals, as outlined in para. 4 (pg. 32) and para. 9 (p. 36), and detailed in Attachments I-V of the agreement.

The interim goals established in the mid-1980s have proven unrealistically high for many stocks. Furthermore, limited resources have meant that only a small number of Chinook stocks have programs in place to provide the spawner-recruit data necessary to estimate optimal spawner numbers. Currently, Canada has bilaterally-accepted escapement goals for only one of the 11 Canadian stocks or stock groups explicitly identified in the 1999 Agreement. An alternative approach was required for Canada to move forward in establishing valid escapement goals both for domestic management and international Treaty purposes (Appendix D).

Our goal was to develop a habitat-based approach to generate escapement goals for data limited Chinook stocks in British Columbia (BC). We focused on developing a model with general applicability that could be applied inexpensively and quickly, while making sufficiently accurate predictions to suit fisheries management purposes. Since fisheries management strategies are often expressed in the fish-production context (Mace 1994), our objective was to develop models that predict reference points based on the Ricker (1973) fish-production relationship. This biologically-based approach offers sufficient flexibility to calculate reference points for a range of objectives for fisheries management and the Wild Salmon Policy (DFO 2005).

We focused on developing simple models that lacked biological detail, yet described general biological patterns across a range of environmental conditions and Chinook salmon biology. Inasmuch as high precision and accuracy are desirable properties of models, we aimed to develop a method with reasonable accuracy and precision for most domestic and international fisheries management purposes.

2 Model Development

2.1 System Features and Boundaries

Chinook salmon biology is complex when viewed at a fine scale, however important commonalities exist at coarse scales (Healey 1991; Bradford and Taylor 1997; Brannon et al. 2004). Hilborn and Walters (1992) suggested that productivities would typically be similar within a species over much of its range, yet the capacity parameter would depend on the size of the area available and should be quite variable among stocks. Hilborn and Walters' suggestions were supported further after Myers et al. (1999) conducted a meta-analysis of fish productivities, including Chinook salmon, and reported that maximum reproductive rates were relatively constant within a species. The maximum reproductive rates corresponded to the Alpha parameter of the Ricker (1973) spawner-recruitment function. Presumably, Ricker Alpha parameters for Chinook salmon are higher in better quality habitats than in poorer habitats, but over a broad range of habitats the variability may be sufficiently low for effective modeling.

Hilborn and Walters (1992) implied that the capacity parameter, Beta in the Ricker function, would be associated with habitat area, and studies of coho *O. kisutch* and sockeye *O. nerka* salmon indicate that capacity increases with coarse scale measures of habitat area. For example, Marshall and Britton (1990) found much of the variation in juvenile coho capacity in BC was explained by stream length. Later Bradford et al. (1997) expanded Marshall and Britton's analysis to streams ranging from Oregon to Alaska and reported that 70% of the variation in coho smolt abundance was explained by stream length. Bradford et al. (2000) fit hockey stick spawner-recruitment models to various coho salmon data sets and reported that 34% of the variation in smolt carrying capacity was explained by stream length. Among sockeye salmon rearing lakes in British Columbia and Alaska, 65% of the maximum observed juvenile sockeye salmon biomass was explained by lake area (Shortreed et al. 2000). Bradford et al. (1997) and Shortreed et al. (2000) reported that more complex models, with additional variables considering biological details, explained more of the variation in capacity.

To examine if capacity was associated with habitat area for Chinook salmon, we assembled stock-recruitment data for stocks ranging from California to Alaska and conducted a type of meta-analysis by combining results across stocks (Myers and Mertz 1998; Chen and Holtby 2002). The Ricker (1973) stock-recruitment function was used to estimate fish-production parameters, including capacity (Figure 1). We also examined if the number of spawners producing Maximum Sustained Yield (Smsy) and replacement (Srep) on an average annual basis given existing environmental conditions were associated with habitat area. Smsy is a reference point described in the PST and a benchmark for Canada's Wild Salmon Policy, and fishery management thresholds can be expressed as percentages of Srep (e.g. Johnston et al. 2000). Replacement is the point where the replacement line crosses the recruitment curve and forms a stable equilibrium, called capacity, when environmental conditions are stable and the stock is un-fished.

We anticipate minor changes to our results as research is ongoing and some analyses are incomplete (Appendix A). Some parameter values may change after stock-recruitment relationships are updated with new information and adjusted for autocorrelation. As well, time series biases in stock-recruitment parameters resulting from some non-stationary processes probably exist and parameters may not represent future conditions well (CTC 1999). We view habitat model development and implementation as an iterative process of refinement and assessment.

Chinook salmon populations may be limited by the amount of spawning or rearing habitat available (Parken et al. 2002). At a coarse scale, freshwater habitat increases with river network size, unless migration barriers restrict Chinook from accessing habitat. River network size is strongly associated with the watershed area that captures precipitation and contributes water to the channel network that drains it. Thus, rivers increase in size downstream as tributaries increase the drainage area and streamflow, and the watershed is a coarse scale geomorphic unit (Leopold et al. 1992). Accordingly, watershed area is strongly associated with other geomorphologic variables such as mean annual discharge, channel length, width, depth, slope, and velocity along a longitudinal river profile (Leopold et al. 1992). The patterns exist among river basins and vary mainly with climate and controlling geology. Coarse-scale variables of the drainage basin have been used in several habitat models to predict the capacity of stream fish (Fausch et al. 1988).

At fine scales, spawning and rearing habitat suitability curves have been developed to produce fine scale measurements of habitat area (e.g. Gallagher and Gard 1999), yet these approaches can be cost-prohibitive and have yielded mixed results (Shirvell 1989; Williams 2001). Since fine scale habitat data were not available for most systems with stock-recruitment data or all systems where we intended to apply our model, we did not consider this approach further.

Initially, we considered watershed area and mean annual discharge as indicators of habitat area that may limit Chinook numbers. However mean annual discharge data were not available for all stocks with stock-recruitment data or all Chinook bearing systems in BC. Watershed area is a useful surrogate for mean annual discharge (Rodriguez-Iturbe and Rinaldo 1997; Tautz et al. 1992). Our early investigations indicated watershed area explained more variation in capacity than did mean annual discharge. For these reasons, mean annual discharge was not investigated further.

2.1.1 Stock-Recruitment Data Sources

Stock-recruitment data parameters were available from several sources including published and unpublished reports (Tables 1 and 2; Appendix A). For most stocks, stock-recruitment analyses were reported in technical reports or personally communicated: information sources are in the stock summaries (Appendix A).

To provide consistency among data sets and facilitate meta-analysis, we standardized the recruitment and spawner abundance measurement units to the same scale (Myers et al. 2001; Gibson and Myers 2003). Recruitment was the number of adult progeny that would have survived to maturity in the absence of fishing mortality. For stocks experiencing fishing mortality on immature fish, recruitment was estimated as pre-fishery Adult Equivalent (AEQ) abundance. Spawner abundance consisted of the number of 2-ocean age and older fish. Jacks, mainly 1-ocean age precocious males, were usually excluded because their abundance could not be reliably estimated for most stocks, and was not reliably estimated for data-limited stocks in British Columbia (Appendix A).

The relationship between spawners and recruitment was described by the Ricker (1973) function with multiplicative, lognormal error:

(1) $$R_i = \alpha S_i e^{-\beta S_i} \exp(\varepsilon)$$

where R_i was the recruitment in year class i, S_i was the number of spawners that produced them, α was the slope at the origin, β was the capacity parameter, and $\exp(\varepsilon)$ represented the lognormal process error with mean 0 and variance σ^2. For some stocks, survival covariates were included in the Ricker function, and average values were used to calculate parameters corresponding to average conditions (Table 3). Most stock-recruitment relationships were examined with diagnostics described by CTC (1999).

To estimate Smsy and Srep, the stock-recruitment relationship was corrected for process error to estimate average instead of median values (Hilborn 1985). This correction increases $\hat{S}_{msy}$ and $\hat{S}_{rep}$ since the expectation of a lognormal process, an average, exceeds the median (Evans et al. 2000). When sampling variances are available for spawners and recruits, measurement error can be subtracted from the regression mean square error to estimate process error (CTC 1999). However since the necessary sampling variances were only available for a few data sets, we did not subtract measurement error from the regression mean square error. A correction for process error based only on the regression mean square error will over-correct and therefore $S_{msy} \langle \hat{S}_{msy}$ and $S_{rep} \langle \hat{S}_{rep}$; alternatively Smsy and Srep would probably be biased low (e.g. $\hat{S}_{msy} \langle S_{msy}$) if estimates were not adjusted for process error (CTC 1999). As most of the estimates of process error have not been adjusted for measurement error, $\hat{S}_{msy}$ and $\hat{S}_{rep}$ are systematically biased high and in a direction that helps avoid overfishing. Since sampling variances are rarely available for spawners and recruitment, future investigations may examine the sensitivity of Smsy and Srep to different ratios of measurement to process errors and perhaps bias can be reduced by assuming a ratio of these errors.

Although the bootstrap procedure can estimate some of the bias in $\hat{S}_{msy}$ and $\hat{S}_{rep}$ by examining the means of the bootstrap estimates, we did not correct $\hat{S}_{msy}$ and $\hat{S}_{rep}$ for bias because of imprecision in these bias estimates (Efron and Tibshirani 1993). $\hat{S}_{msy}$ and $\hat{S}_{rep}$ contain some uncorrected bias, but are recommended over their bootstrap mean estimates (CTC 1999; Efron and Tibshirani 1993).

2.1.2 Watershed Area Data Sources

Watershed area was used as an index of the habitat area limiting numbers for a Chinook salmon stock (Tables 1 and 2). Watershed area is the drainage area that contributes water to a particular channel or set of channels (Leopold et al. 1992). Horton (1945) and Strahler (1957) defined stream order to characterize river size and drainage basin characteristics. A 1st order stream has no tributaries, and a 2nd order stream forms downstream of the confluence of two 1st order streams, whereas a 3rd order stream forms downstream of the confluence of two 2nd order streams. Stream-type Chinook salmon occur mainly in 3rd order or larger systems at the 1:50,000 scale, however natural barriers on 4th order or larger channels appeared to have a large effect on the available habitat area and the effect of natural barriers on 3rd order systems appeared very minor at the watershed level. Therefore, we excluded watershed areas upstream of barriers on 4th order stream segments for stream-type stocks. Ocean-type Chinook occur mainly in 5th order or larger systems and natural barriers on 5th order or larger channels appeared to have a large effect on the available habitat area. Therefore, we excluded watershed areas upstream of barriers on 5th order stream segments for ocean-type stocks. Drainage areas upstream of man-made barriers were excluded from watershed areas. There may be other conditions where it is appropriate to exclude drainage area, such as when large areas are occupied by glaciers or when aquatic conditions are inhospitable to Chinook salmon. Future investigations may refine the criteria used to discount total watershed area where barriers limit access to habitat.

Migration barriers were determined from sources including published reports, databases, and local knowledge, yet barriers may not be well described for remote watersheds. For BC rivers, the 1:50,000 scale Watershed Atlas and fish wizard, components of the BC Ministry of Sustainable Resource Management's Fishery Inventory Summary System, were used to identify barriers and measure watershed area (http://www.bcfisheries.gov.bc.ca/fishinv/, http://www.bcfisheries.gov.bc.ca/fishinv/fiss.html). For Washington, Oregon, and Idaho rivers, the streamnet database (http://www.streamnet.org/) was queried for fish distribution and published reports were examined. For Alaska rivers, the ADF&G fish distribution database (http://www.habitat.ADFG.state.ak.us/geninfo/anadcat/anadcat.shtml) was examined and staff were consulted about the locations of barriers. Watershed areas were described for systems with stock-recruitment relationships in Appendix B.

2.2 Habitat Model Structure

We assembled stock-recruitment data for 28 stocks ranging from northern California to central Alaska, but excluded three from the model (Figure 2). The Hanford-Above Priest Rapids stock is from unusual habitat conditions and the dynamics of hatchery salmon could not be partitioned from natural salmon for the Klamath (Appendix A). Parameters for Nelson River stock were used for model verification, but we excluded this stock from the model because we concluded the data were of low quality. The 25 stocks in the meta-analysis represent the best available set of stock-recruitment relationships to represent conditions where we intend to generate escapement goals.

A cursory examination of plots for these data indicated an allometric relationship explained much of the variation between habitat area (x) and Srep, Smsy, and the inverse of Beta (y; Figures 3 and 4; Table 4). The allometric model

(2) $$y = ax^{b} \exp(\varepsilon)$$

is log-transformed to

(3) $$\ln y = \ln a + b \ln x + \varepsilon$$

where $\varepsilon \sim \text{Norm}(0, \sigma^2)$ and linear regression was used to estimate $\widehat{\ln a}$, $\hat{b}$, and $\hat{\sigma}^2$, which was the regression mean square error. Predicted values for average conditions were calculated from

(4) $$\hat{y} = x^{\hat{b}} e^{(\widehat{\ln a}) + (\frac{\hat{\sigma}^2}{2})}.$$

In our meta-analysis, the relationship between watershed area and the stock-recruitment reference points was combined for several stocks by linear regression, although other methods can be used to combine results, such as Bayesian methods (Myers et al. 2001). The habitat model is hierarchical in nature because at a primary level, separate stock-recruitment relationships were fit to each of the 25 stocks using linear regression and then Smsy and Srep were calculated. Then at a secondary level, linear regression was used to describe the relationship between the estimated stock-recruitment reference points and habitat area. The approach produced a model describing the best fit between habitat area and stock-recruitment reference points for average habitat conditions and quality and for average productivity of modeled stocks. Using meta-analysis, we developed a multi-stock model that estimated stock-recruitment reference points when only watershed area data are available. The habitat-based approach can contribute prior information when Bayesian methods are used for stocks with little spawner-recruit data and poorly defined stock-recruitment relationships. In this way the meta-analysis can be readily extended to the estimation of biological reference points and provides a basis for evaluating the plausibility of resulting estimates (Gibson and Myers 2003).

With a slope between 0 and 1 for an allometric model, the relative proportion of the habitat area that contributes to capacity decreases as habitat area increases, and on average small watersheds produce more fish per unit area than large watersheds. A small watershed may only have one stream capable of supporting Chinook salmon, but larger watersheds may have several streams, yet some of them or a proportion of the habitat area, may not be capable of producing Chinook salmon.

The allometric structure of the habitat model seems to appropriately describe the relationship between habitat area and capacity. A similar pattern exists for fish yield in lakes with large lakes producing less fish per unit area than small lakes (Rounsefell 1946; Youngs and Heimbuch 1982) and for average coho smolt yield with larger river networks producing less fish per unit length than small river networks (Marshall and Britton 1990; Bradford et al. 1997). Allometric models develop better estimates of the slope parameter than linear models when the frequency distributions of the dependent and independent variables are positively skewed (Figure 3). Also, regression diagnostics indicated assumptions were reasonably met.

2.2.1 Life History

Researchers have suggested different mechanisms contributing to development and expression of Chinook salmon life history (Healey 1991; Brannon et al. 2004; Waples et al. 2004). Brannon et al. (2004) suggested Chinook salmon life history is the biological expression of the incubation and rearing environments that determine spawn timing and juvenile rearing patterns. Stream- and ocean-type Chinook salmon use freshwater and marine habitats differently at several life stages (Healey 1991; Brannon et al. 2004), which probably contributes to different relationships between the stock-recruitment reference points and habitat area. Brannon et al. argued that temperature had the overwhelming environmental influence on the life history expressed by Chinook salmon from California to Alaska, with mean rearing temperature determining ocean- and stream-type forms. Stream-type life history prevails in low mean rearing temperature environments, whereas ocean-type life history prevails in high mean rearing temperature environments. Rearing temperatures are low in most watersheds north of the BC Central Coast, and to the south in high elevation basins in coastal and interior areas. Rearing temperatures are higher along coastal and low elevation interior basins in areas south of the BC Central Coast, and to the north in low elevation coastal watersheds. Some stocks in transition areas have mixed life history.

While developing models to predict Smsy, we found separate models for ocean- and stream-type populations better explained the variation in Smsy because at a similar sized watershed, ocean-type populations usually have higher Smsy than stream-type populations (Table 4; Figure 4). The slope of the relationships was similar (analysis of covariance [ANCOVA]: $F = 2.2$, $P = 0.156$), but intercepts differed (ANCOVA: $F = 20.9$, $P < 0.001$). The habitat model explained 89% of the variation in Smsy for stream-type stocks and 86% for ocean-type stocks and had high indices of resolution power (Prairie 1996). The relationships' residuals formed horizontal bands with no apparent patterns when plotted against the $\log_e$ transformed watershed area and predicted values and allometric models appear adequate for these data (Figure 5). Similar patterns existed for models that predict Srep, with similar slope for stream- and ocean-type models (ANCOVA: $F = 1.8$, $P = 0.196$), but different intercepts (ANCOVA: $F = 29.9$, $P < 0.001$).

Our approach assumed all the error occurs in the dependent variable, and does not fully consider all the uncertainty in the stock-recruitment parameters. The habitat variable contains some uncertainty (Section 3.1), but it was considered very minor with respect to errors in the dependent variable, yet future investigations may consider an errors-in-variables approach. The Smsy habitat model residuals appear normally distributed and homoscedastic (Figures 5 and 6), however the dependent variable variances may be heterogeneous because the precision of the stock-recruitment parameters varies among stocks. The precision of stock-recruitment parameters is affected by the uncertainty in the fitted stock-recruitment relationship described by the regression mean square error. There were no patterns between the regression mean square error from the stock-recruitment relationship and leverage on the habitat model parameters, so precision of stock-recruitment reference points does not appear to strongly influence the habitat model parameters (Figure 7). Also, there were no patterns between regression mean square errors and watershed size for stream- and ocean-type stocks (Figure 8). Future habitat model development may rely on methods that more fully incorporate uncertainty in the stock-recruitment-habitat area relationship, such as hierarchical Bayesian models.

2.2.2 Geography

Inasmuch as it is desirable to represent the full range of habitats in the habitat model, our analysis was limited by the availability of stocks with sufficient stock-recruitment data. Since few BC stocks have sufficient stock-recruitment data, most stocks in the meta-analysis were distributed to the north or south of BC with only one ocean-type stock in the north and one stream-type stock in the south (Figure 2). If one ignores Brannon et al.'s arguments about the relationship between life history and freshwater environment, allometric habitat models can be generated for stocks aggregated by the north and south. The slopes of the relationships were similar (ANCOVA: $F = 0.71$, $P = 0.41$), but intercepts differed (ANCOVA: $F = 13.9$, $P = 0.001$).

To compare the performance of models aggregated by life history and geography, several performance measures were calculated during leave-one-out analyses. A leave-one-out analysis involves omitting a stock then repeating the regression analysis and calculating new habitat model parameters, and then a prediction is made for the omitted stock. The prediction is then compared to the observed value and raw and percent errors are calculated. The process is repeated systematically for all stocks and then the mean absolute percent error (MAPE) and average percent error are calculated to describe accuracy, whereas the root mean square error (RMSE) and root mean square percent error (RMSPE) describe precision (Haeseker et al. 2005). The percent error criteria give equal weighting to high- and low-abundance stocks, whereas the raw error criteria are dominated by stocks with the highest abundance.

The geographically aggregated models explained less variation in Smsy and performed more poorly than models considering life history, which further supports a biological basis for separate habitat models by life-history form (Table 5). Models relying on life history had higher accuracy (lower MAPE) and better precision (lower RMSE and RMSPE) than geographically aggregated models. Among British Columbia coho salmon, Chen and Holtby (2002) reported substantial regional variation in Ricker Alpha and Beta parameters between north and south areas, but the influence of life history was not investigated because it was assumed invariable among the stocks. Although spatially aggregated models can be generated for Chinook salmon, they ignore life history, which appears to be an important biological detail that improves model performance.

2.2.3 Productivity

Productivity is an index of survival across multiple life stages from egg deposition to adult equivalency when there is no density dependent effect (Hilborn and Walters 1992). Productivity contributes to the unexplained variation in the Smsy habitat model because the ratio of Smsy to Srep decreases as productivity increases (Hilborn 1985), but the relationship did not vary significantly between stream- and ocean-type stocks (Table 3; Figure 9; ANCOVA: $F = 0.138$, $P = 0.714$). Therefore at a given watershed size, stocks with higher than average productivity are expected to have a lower than average Smsy, and there is likely a negative relationship between productivity and the residuals from the watershed size habitat model. However, this pattern was less evident among the data, which may be influenced by the small number of stocks examined and uncertainty in productivity estimates (Figure 11).

Productivity ($\hat{\rho}$) was a useful covariate for predicting Smsy of stream-type stocks, accounting for an additional 3% of the variation than watershed area alone, but productivity was not a significant covariate for ocean-type stocks (Table 7).

The allometric model

(5) $$y = ax^b e^{-c\rho} \exp(\varepsilon)$$

is log-transformed to

(6) $$\ln y = \ln a + b \ln x - c\rho + \varepsilon$$

where $\varepsilon \sim \text{Norm}(0, \sigma^2)$ and linear regression was used to estimate $\widehat{\ln a}$, $\hat{b}$, $\hat{c}$, and $\hat{\sigma}^2$, which was the regression mean square error.

Productivity is calculated directly from stock-recruitment data. Some stocks may have sufficient stock-recruitment data to estimate productivity but not a recruitment relationship, such as stocks experiencing chronically high exploitation rates. Productivity may be positively associated with habitat quality, however those data were not available for all stocks to develop predictive relationships. On average, productivity was higher for ocean- than stream-type stocks (Figure 10; one-tailed t = -2.49, P = 0.040). Productivity was not associated with watershed area, latitude, mean annual discharge, water yield or the capacity parameter (all $r^2 < 0.13$; Figure 12). The productivity covariate was not used in the case study examples (Section 4) because neither productivity data nor predictive models were available.

Habitat model parameters could be systematically biased if stocks were selected because they were important and appeared productive, thus the model would not account for the full range of Chinook productivities. To examine if productivities were biased, we tested for departures from normality and symmetry. Productivity was normally distributed for stream- and ocean-type stocks (Kolmogorov-Smirnov Z = 0.431, P = 0.993, and Z = 0.762, P = 0.608, respectively) and symmetric with skewness of less than twice its standard error (Skewness = 0.166, SE = 0.616, and Skewness = 0.245, SE = 0.637, respectively). Although productivity data could not be assessed against the true distribution, the data do not appear systematically biased, since they appear normally distributed and symmetric.

3 Habitat Model Assessment

3.1 Model Sensitivity Analysis

The predictive accuracy of the habitat model depends on the accuracy of the watershed area data. Watershed areas from the 1:50,000 scale Watershed Atlas are polygons described by a series of lines that combine to form an enclosed area described as a ‘hard’ boundary that is considered perfect for the purposes of analysis (MELP 2000). Watershed boundaries were interpreted from 1:50,000 Federal National Topographic Series (NTS) and have a positional accuracy of about 50m. The boundaries are continuous (wall to wall), so when a positional error occurs in a watershed boundary and part of a watershed is excluded, it will be accounted for in the adjacent watershed. Errors in watershed area could originate from the original interpretation of boundaries from the NTS maps and digitization of areas upstream of migration barriers. These factors probably contribute to the overall uncertainty in predictions, but bias is not directional. Watershed areas could be overestimated if barriers are missing from the Watershed Atlas.

To assess the influence of uncertainty associated with measurements of watershed area for modeled stocks, a sensitivity analysis was conducted by introducing known errors into the watershed area data for all modeled stocks and then calculating the bias in the habitat model slope and intercept parameters. Errors were expressed as a percentage of the observed value and varied from -20% to +20%. The slope parameter was unaffected by errors in watershed area (0% bias), whereas the intercept was less sensitive to errors in watershed area for stream-type than ocean-type stocks (Figure 13).

To assess the influence of uncertainty associated with measurements of watershed area, another sensitivity analysis was conducted by introducing known errors into the watershed area of a hypothetical stock and subsequently examining the corresponding error in predictions of Smsy and Srep. Predictions of Smsy and Srep were less sensitive to errors in watershed area for the stream-type models than the ocean-type models (Figure 13). For the ocean-type model, errors in watershed area produced essentially the same proportional size and direction of errors for predicted Smsy and Srep, and the stream-type model produced relatively smaller errors. Thus overestimation of watershed area, caused by missing barriers in the Watershed Atlas, would cause predictions of Smsy and Srep to be overestimated and biased in a direction that helps avoid overfishing. Errors in the interpretation of watershed boundaries from the NTS maps would cause errors in the watershed areas in the Watershed Atlas, however these errors are not directional.

Habitat capacity could vary among watersheds due to habitat quality, however habitat quality data were not always available. Thus, we could not assess the sensitivity of the habitat model to uncertainty in habitat quality and its variability among watersheds. Future investigations could develop and assess the utility of habitat quality indices for improving predictive accuracy.

3.2 Model Verification

To verify if the models performed as intended, we examined model performance against the data used in model development and evaluated if the models adequately represented the patterns in those data. Analyses were based on a leave-one-out method whereby stocks were systematically excluded from the calculation of regression coefficients. Regression diagnostics such as DfBetas, leverage, and Studentized deleted residuals were used to examine the influence of individual stocks on the models. Studentized deleted residuals were the residuals calculated for stocks as they were systematically omitted, and standardized by an estimate of their standard error.

Some stream-type stocks were more influential and exerted more leverage than others on regression coefficients, however none were large outliers and patterns were similar for models predicting Smsy and Srep (Figure 14). The Upper Columbia Spring stock had moderate leverage and influence on regression coefficients, yet the predictive error was small when it was omitted from the model. The model parameters appear precise and stable for the stream-type stocks as indicated by the low coefficients of variation for the slope and intercept parameters from the leave-one-out analysis (Table 8).

For the ocean-type habitat models, the largest and smallest watersheds were the most influential on the model parameters, which indicated more data for stocks with large and small watersheds may help stabilize the regression coefficients by improving the contrast in the data set (Figure 14). Harrison and Situk stocks had large leverage values and when Harrison was omitted from the model there was a large predictive error, whereas the predictive error was small when Situk was omitted. The habitat model parameters appeared more variable and less precise for ocean-type models than stream-type models (Table 8).

The quality of the stock-recruitment parameters varied among stocks (Tables 1 and 2; Appendix A). Stocks with low quality estimates relied on average age compositions and fair quality escapement estimates, whereas stocks with high quality estimates had annual age composition and good quality escapement data. Among stream-type stocks, the Blossom River was the lowest quality, since average age composition was used for several years, expansion factors were developed at another river, and autocorrelation was detected. However, the stock had low influence and leverage on the habitat model parameters and the Studentized deleted residual was small. The stock was retained to develop the model, which can be revised as new information becomes available.

The leave-one-out analysis provided information about the levels of predictive error that may occur when the model is applied to other systems (Table 8). In general, larger predictive errors occurred for stream-type than ocean-type stocks. Predictive errors for Smsy ranged from -54 to +221% for stream-type stocks, and from -59 to +97% for ocean-type stocks, with MAPE of 65 and 35%, respectively. The paired predicted and observed values were centered around the 1:1 line, and the models appear to perform as intended and adequately represent the patterns of the data (Figure 15).

3.3 Model Validation

To examine the validity of model predictions, the habitat model was applied to one stock that was not considered during model development to examine how well the model predictions corroborate with independent stock-recruitment analyses. Escapements at Nelson River, a stream-type stock on the Alaska Peninsula, were estimated with weir and tower counts and visual (helicopter) surveys of areas downstream of the Nelson weir and in the David's River (Nelson et al. 2004). The stock-recruitment parameters for the Nelson are preliminary and assumptions were made about the escapement age composition and accuracy of escapements estimated by visual surveys (Appendix A; R. Clark, pers. comm.). The Nelson River stock was excluded from the habitat model because of poor data quality.

Although the Nelson stock-recruitment parameters were lower quality than modeled stocks, differences between Smsy estimated by the habitat model and stock-recruitment methods were small enough to be acceptable (Table 9). The habitat model predictions of Smsy and Srep were larger (27% and 31%, respectively) than estimates from the stock-recruitment analyses and were within the expected range of errors described by the leave-one-out analysis. The stock-recruitment point estimates were within 90% confidence intervals for the habitat model, indicating the habitat model adequately predicted Smsy and Srep (Reichardt and Gollob 1997). The correspondence seems remarkable when one considers the assumptions of the stock-recruitment analysis and that only a single habitat variable was used for predictions. Errors may be partly attributed to habitat model process error and measurement error in the stock-recruitment estimates, since escapements were visual (aerial) indices with unknown accuracy (not adjusted to total escapement). After considering the sources of uncertainty, Nelson et al. (draft 2004) recommended an escapement goal range based on Smsy estimated from the habitat model.

The habitat model appears to adequately estimate Smsy and Srep for independent stocks, which supports the validity of applying the method to data limited stocks. As additional stock-recruitment parameters become available for new stocks, the process of habitat model performance can be reviewed by repeating the model validation and verification steps and refining the model structure.

3.4 Model Evaluation

To evaluate if the habitat model produces more accurate estimates of Smsy than the interim escapement goal method, both methods were applied to BC rivers with stock-recruitment relationships. Throughout the rebuilding program, sufficient stock-recruitment data were collected by the Cowichan, Kitsumkalum, and Harrison key stream programs. Percent errors were calculated during the leave-one-out analysis for the habitat model to reduce bias, since these stocks were used to calculate habitat model parameters.

During Chinook salmon rebuilding, interim escapement goals were set for most populations as double the recent average escapements (1979-1982 period) primarily based on Starr's (1982) stock-recruitment analysis of one aggregate BC Chinook stock. Most escapements in Starr's analysis were based on visual surveys that likely underestimated the true number of spawners (CTC 1998). Accordingly, the base year was changed to 1984 for the doubling goal of Key Streams to avoid using goals based on visual surveys.

Assuming Smsy estimated by stock-recruitment analysis to be correct, the habitat model estimated more accurately, on average, and precisely than the interim escapement goal method (Table 10). For these stocks, the habitat model consistently under-estimated Smsy whereas the interim escapement goal method consistently overestimated Smsy. The interim escapement goal method does not directly produce estimates of precision, but RMSE and RMSPE criteria indicate the habitat model has higher precision than the interim escapement goal method (Haeseker et al. 2005).

Predictions should be interpreted cautiously for watersheds beyond the size range included in the model and within the size range that was not well-represented by the data. Among stream-type stocks, the largest predictive errors occurred for the King Salmon River, which was the smallest watershed (93 km^2) and the model's representation would be improved with more information for medium (200-1,700 km^2) and large watersheds (> 18,000 km^2). Among ocean-type stocks, the models were most sensitive to the Harrison River, which was the largest watershed (7,611 km^2) and representation could be improved with more information for large watersheds (> 4,500 km^2). Although the smallest ocean-type watershed (Situk, 176 km^2) had low influence on the habitat model parameters and low expected error, representation could be improved with more information for watersheds smaller than 500 km^2.

4 Case Study Application

4.1 Approach Overview

4.1.1 Conditions for Habitat Model Application

Seven case studies demonstrated the habitat-based approach to generate escapement goals for data limited stocks (Figure 16). The approach requires information about life-history, population structure, and watershed area as well as consideration of the characteristics of the habitat model data. For example, the habitat model was developed from naturally occurring and self-sustaining populations, so it would be inappropriate to use the approach for experimentally introduced stocks that are not self-sustaining.

Knowledge of stock-structure helps identify the appropriate stock units and apply the habitat model in a manner consistent with the data it was developed from. The habitat model was sensitive to the stock-structure assumption and can be applied incorrectly if stock structure is considered incorrectly.

Each stock used to develop the habitat model consisted of a single stock unit corresponding to a group of fish in a watershed with common migration times, spawning areas, spawning times, exploitation history, survival, age structure, and correlated spawning abundances. A stock unit may have spawners distributed among spawning sites in several rivers in a watershed, with sufficient migration among sites to function together as a stock unit. Migration among sites may be indicated by coded wire and other tag recoveries or estimates of gene flow.

The habitat model can overestimate Smsy and Srep when applied incorrectly. When a watershed contains a single stock unit with fish spawning in several rivers, an overestimation error will occur when the model is applied to each sub-watershed separately and predictions are summed to estimate Smsy and Srep for the entire stock unit. The appropriate approach for this circumstance is to apply the habitat model to the total watershed area for all the sub-watersheds and make a single prediction.

Also, the habitat model can underestimate Smsy and Srep when applied incorrectly. Underestimation errors occur when a watershed contains multiple stock units and a single prediction is made for the entire watershed. For example, it is inappropriate to generate a single prediction for the Fraser River watershed because it contains multiple stock units (Candy et al. 2002). The appropriate approach in this circumstance is to delineate each stock unit and measure the corresponding watershed area and then make a single prediction for each stock unit. Two of the case study examples, Fraser Spring-Run Age 1.2 and Summer-Run Age 0.3, involve watersheds containing multiple stock units.

The Kitsumkalum watershed is an example of watershed containing two stock units. The summer-run stock spawns downstream of Kitsumkalum Lake and the spring-run stock spawns in the tributaries entering the lake (McNicol 1999). The stocks differ temporally in return timing, spatially by spawning areas, and biologically in age structure. Scale analysis and CWT recoveries support different age structure and separate spawning areas, with little migration between spawning sites. The habitat model includes the summer-run stock and its watershed area corresponds to the area upstream of the Kitsumkalum River confluence with the Skeena River, but excludes areas upstream of barriers on 4th order channels. If a stock-recruitment analysis was available for the spring-run stock, its watershed area would correspond to the tributaries entering the lake.

Watershed areas were measured using the approach described in Section 2.2.2. Total watershed area was determined from the BC watershed atlas database (http://www.bcfisheries.gov.bc.ca/fishinv/) and areas upstream of man-made barriers were excluded. Migration barriers to Chinook salmon distribution were identified from the fish wizard, which uses data from the Fisheries Inventory Summary System (http://www.bcfisheries.gov.bc.ca/fishinv/fiss.html). For ocean-type stocks, areas upstream of natural barriers on 5th order or larger mainstem rivers were excluded, whereas for stream-type stock areas upstream of barriers on 4th order rivers were excluded.

4.1.2 Calculation of Reference Points and Confidence Intervals

Reference points were calculated from equation 4 and confidence intervals were generated with a non-parametric bootstrap procedure. Confidence intervals for stocks with a single watershed area can be calculated following the parametric methods described by Zar (e.g. Section 17.4; 1984). However, we used a bootstrap procedure that included uncertainty associated with adding predictions to generate reference points for stock aggregates.

Confidence intervals were generated from a non-parametric bootstrap procedure involving resampling of regression residuals (Efron and Tibshirani 1993). Residuals were calculated as the difference between observed and predicted values for the reference points of stock *y*:

(7) $$\zeta_y = Y_y - \hat{E}[Y_y]$$

where the observed and predicted reference points are Y_y and $\hat{E}[Y_y]$, respectively. For each bootstrap sample, residuals ζ_y^* were drawn randomly with replacement from an array of *n* residuals calculated from the original regression. A new data set consisting of the original independent variable and simulated dependent variable:

(8) $$\tilde{Y}_y = \zeta_y^* + \hat{E}[Y_y]$$

was generated and $\ln \tilde{\mathrm{a}}$, $\tilde{\mathrm{b}}$, and $\tilde{\sigma}^2$ were estimated by regression. These parameters were substituted into in Equation 4 and new reference points ($\hat{\mathrm{S}}^*_{\mathrm{msy}}$ and $\hat{\mathrm{S}}^*_{\mathrm{rep}}$) were calculated for each stock and stock aggregate. The procedure was repeated 10,000 times creating the distributions $\hat{\mathrm{F}}(\hat{\mathrm{S}}^*_{\mathrm{msy}})$ and $\hat{\mathrm{F}}(\hat{\mathrm{S}}^*_{\mathrm{rep}})$ and confidence limits were calculated with the percentile method (Efron and Tibshirani 1993).

4.1.3 Comparison of Escapement Indices to Reference Points

The predicted reference points may not be appropriate to compare directly with escapement indices because the reference points were for total spawning escapement and escapement indices often represent a fraction of the total escapement (e.g. not all areas were surveyed). However, escapement indices can be standardized to total escapements when their relationship has been examined by conducting concurrent studies and developing expansion factors. The reliability of the expansion factors can be assessed by repeating calibration studies and evaluating the precision of the mean expansion factor. As data standards have not been finalized for expansion factors, their precision was not described for the case study examples. Instead of expanding escapement indices, another approach would be to use the calibration information and adjust the predicted Smsy and Srep to visual index units (e.g. multiply by the inverse expansion factor; Table 14).

Among the stream-type habitat model stocks, reference points were for total escapements estimated from good quality programs (Appendix A). Most total escapements were estimated by direct count (weirs, towers, dams), mark-recapture methods, or escapement indices expanded to estimates of total escapement. Visual escapement indices were expanded to total escapements based on stream-specific expansion factors developed during concurrent programs, except for Blossom River which had an expansion factor from a nearby river.

Among the ocean-type habitat model stocks, reference points were for total escapement estimated from fair quality programs (Appendix A). Most total escapements were estimated from direct count, mark-recapture, or Area-Under-the-Curve (AUC) methods (e.g. redd counts), or from expanded spawner densities measured from weekly visual survey counts of live and dead fish. These methods generally produced lower quality reference points than methods used for stream-type stocks.

4.1.3.1 Escapement Data Sources

Escapement data were obtained from databases maintained by the North Coast, Central Coast, South Coast, Lower Fraser, and BC Interior Area DFO offices and the Secwepemc Fisheries Commission (M. Galesloot, pers. comm.; Appendix C). When partial weir counts occurred at Deadman River, estimates were standardized by the average cumulative timing distribution observed at the nearby Bonaparte River fishway to account for migration during unmonitored periods and estimate total escapement (average of 1992-1997, 2000, 2001, and 2003).

4.2 Case Study Examples

As a means of assessing the validity of the habitat model, estimates of Smsy were generated for several stocks and stock aggregates for which escapement data of reasonable quality was available, including two atypical Chinook systems (Wannock River and Spius Creek).

4.2.1 Stream-type Stocks and Stock Aggregates

4.2.1.1 Area 3 Aggregate

The DFO Statistical Area 3 stock aggregate represents about 25 rivers with escapements monitored in 18 rivers within five watersheds (CTC 2004). On average, the Nass River escapement represented about 90% of the aggregate escapement. Most spawners have stream-type life history in the Nass River watershed (upstream of Gitwinksihlkw), as do stocks in the Ksi Hlginx (Ishkeenickh) River, Kincolith River, Ksi X'anmas (Kwinamass) River, and Kitsault River watersheds, which drain directly into the ocean. These five systems comprise the Area 3 aggregate for this analysis.

The entire Kincolith and Ishkeenickh watersheds were accessible, yet mainstem barriers on 4th order segments of the Kitsault and Kwinamass rivers blocked access to upstream areas (Table 12). Much of the Nass watershed was accessible, but migration barriers prevented access to about 14% of the watershed.

The aggregate escapement consists of visual indices and total escapement estimates. Calibration studies have examined the relationship between visual indices and total escapement at the Nass, Kwinamass, and Kincolith rivers (Appendix C; Winther, unpublished). Within the stock aggregate, most fish spawn in the Nass River watershed (upstream of Gitwinksihlkw) and total escapement has been estimated by mark-recapture methods since 1992. Visual indices were developed through to 1993 and two years of concurrent programs were used to standardize the visual indices to total escapements (Appendix C). At Kwinamass River, mark-recapture programs were performed concurrently with visual surveys in 2002 and 2003, and at Kincolith River weir counts were concurrent with visual surveys in 2002.

Since three of the systems did not have information about the accuracy of visual indices, we used calibration information from nearby rivers with somewhat similar escapement estimation methods and counting condition (Tables 8 and 9). Kincolith and Kwinamass rivers are small clear rivers that reasonably represent visual survey conditions at Ishkeenickh River. Kitsault River was glacially influenced with high turbidity and counts represented fish visible in shallow areas downstream of clear tributaries, so we suspect the standardized visual indices underestimate true spawner numbers.

The predicted Smsy was within the range of escapements for the Nass aggregate and the Nass, Kwinamass, and Kincolith rivers (Figure 17; Table 15). Predictions for Ishkeenickh and Kitsault seem reasonable, however the uncertainty around visual indices make assessments less clear. The stock aggregate escapements appear to be within the 80% confidence interval for Smsy for most years.

4.2.1.2 Fraser Spring-Run Age 1.2 Aggregate

The Fraser spring-run age 1.2 aggregate contains six populations in the lower Thompson River tributaries, Louis Creek of the North Thompson, and Bessette Creek in the South Thompson (CTC 2002). The Bonaparte Indian Band and DFO also monitor escapements at Bonaparte River (Galesloot and McCubbing 2003), but it has not been included in the CTC reports.

Within the Nicola watershed, the Nicola, Spius, and Coldwater stocks were considered separately for the purpose of applying the habitat model, since spawning activity was spatially and temporally separated. CWT recoveries support the pattern of early returning fish spawning in the upper reaches of Spius Creek and Coldwater River, and late returning fish spawning in Nicola River and the lower reaches of Spius Creek and Coldwater River. Spius and Coldwater stocks return and spawn earlier than the Nicola stock (Bailey et al. 2001).

The entire Nicola, Spius, Coldwater and Louis watersheds were accessible, whereas natural barriers in the Deadman and Bonaparte watersheds and several man-made barriers in the Bessette watershed limit salmon distribution (Table 12).

The aggregate escapement consists of visual indices and total escapement estimates (Appendix C). Calibration studies have examined the relationship between visual indices and total escapement at Louis Creek (Galesloot 1999, 2000a, 2000b, 2002, 2003), Nicola (Parken et al. 2003), and Deadman rivers, and expansion factors were applied to other rivers (Table 13).

The predicted Smsy was within the range of escapements for the Fraser Spring-run Age 1.2 aggregate, Nicola, Bonaparte, Deadman and Coldwater rivers (Figures 18 and 19; Table 15). However standardized escapement indices for the other rivers were consistently lower than predicted Smsy. Smsy estimates at Spius Creek, appear biased high and the model may not work well for this stock. At Spius Creek, stream gradients are higher and there appears to be less suitable spawning habitat available than observed in other nearby watersheds of comparable size (Parken et al. 2002). At Bessette Creek, high irrigation demand and water diversions for the City of Vernon contributed to low and intermittent stream flow (Rood and Hamilton 1995), and can limit access to upstream areas. The stock aggregate escapements appear within the 80% confidence interval for Smsy in recent years.

4.2.1.3 Upper Georgia Strait – Klinaklini River

The Klinaklini River is one of five escapement indicator stocks in the upper Strait of Georgia stock aggregate (CTC 2004). The four other stocks were assessed by visual surveys and additional calibration information is needed to standardize the visual indices to total escapement. Much of the Klinaklini watershed is accessible to salmon, but a natural barrier exists on a 5^{th} order tributary (Table 12). Visual indices were developed through to 1998 and two years overlapped with the mark-recapture program and provided calibration information (Appendix C; Sturhahn and Nagtegaal 1999). The predicted Smsy was within the range of escapements (Figure 20; Table 15).

4.2.2 Ocean-type Stocks and Stock Aggregates

4.2.2.1 Lower Georgia Strait - Nanaimo

Within the Lower Georgia Strait stock aggregate, escapements of fall run Chinook salmon were monitored in the Nanaimo and Cowichan rivers (CTC 2004). The Cowichan River escapement goal was estimated by stock-recruitment analysis and is one of the ocean-type habitat model stocks (Tompkins et al. 2005). Escapements in both systems were estimated by visual swim surveys, weir counts, and mark-recapture programs. Since 1995, Nanaimo River escapements were estimated by weir counts or a mark-recapture program when the weir was breached, and visual indices were not standardized to total escapements (Appendix C). The Nanaimo and Cowichan watersheds are 5^{th} order systems on the east coast of Vancouver Island, and man-made barriers occur on two Nanaimo River tributaries (Table 12). The predicted Smsy exceeded the range of recent escapements estimated at Nanaimo River. This is consistent with the pattern of recent low escapements, relative to Smsy, observed for Cowichan River Chinook, another nearby fall stock (Figure 19; Table 15).

4.2.2.2 West Coast Vancouver Island (WCVI) Aggregate

The WCVI aggregate consists of six rivers chosen to provide an index of escapement for wild WCVI stocks (CTC 2004). After 1994, escapement methods improved from infrequent visual surveys of index areas to frequent swim surveys and AUC methods (Appendix C). Survey life was estimated periodically at other systems, and recently more representative survey life was developed at Tranquil River. Tranquil River reasonably represents swim survey conditions on small systems like the 5^{th} order Tahsis, Tahsish, Kaouk, Artlish and Burman rivers, although it remains unclear if the Tranquil River adequately represents conditions in large systems (i.e. 6^{th} order Marble River). The entire Tahsis, Tahsish, Kaouk, Artlish and Burman watersheds were accessible, whereas a natural barrier blocked access on part of the Marble River (Table 12). The predicted Smsy values were within the range of AUC escapement estimates for Marble, Tahsis, Kaouk, Burman, Tahsish and the WCVI aggregate index, while the predicted Smsy exceeded the range of recent escapement estimates at Artlish (Figures 19 and 20; Table 15). The watershed size for Tahsis, Artlish, and Kaouk were smaller than those used to develop the ocean-type habitat-model and predictions should be interpreted cautiously.

4.2.2.3 Fraser Summer-run Age 0.3 Aggregate

The Fraser Summer-run Age 0.3 stock aggregate was the sum of spawners at six locations in the South Thompson watershed and one location in the lower Fraser River (CTC 2002; Appendix C). The South Thompson, Little, and lower Adams locations are close in proximity and were considered to represent a single stock for habitat model purposes, since return and spawning times were similar (Figure 18; Candy et al. 2002). Maria Slough is distant from the spawning systems in the aggregate and appears to be a separate stock. We were less certain that middle and lower Shuswap were separate stocks because of their proximity and they appear genetically clustered (Candy et al. 2002). We considered these separate stocks because they return to freshwater at different times, spawn in different areas at different times, and the correlation between escapement indices was poor ($r^2 = 0.36$).

Visual escapement indices were developed for the South Thompson locations by performing two or three surveys and expanding the peak counts. The visual indices probably underestimate total escapement and were considered less accurate than the methods for the ocean-type habitat model stocks. At the lower Shuswap River, concurrent mark-recapture and visual surveys were performed from 2000 to 2002 and indicated the visual indices were biased low compared to the mark-recapture estimates (Chamberlain and Bailey, unpublished). The lower Shuswap expansion factors were applied to the other South Thompson systems to facilitate comparisons, although counting conditions vary among the South Thompson systems. Visual counts can be influenced by high sockeye salmon densities at lower Adams and lower Shuswap rivers and wind ripples (river surface) at the South Thompson. Furthermore, deep water areas in the South Thompson can be difficult to view during low light or high water conditions and high fish densities at Chase riffle were difficult to count.

The entire Maria Slough watershed was accessible, whereas man-made and natural barriers occurred in the South Thompson watershed (Table 12).

The predicted Smsy was within the range of escapements for the Fraser Summer-run Age 0.3 stocks (Figure 21; Table 15). The escapement estimates were often higher than the predicted Smsy in the Middle and Lower Shuswap rivers, and some years exceeded the predicted Srep at Lower Shuswap. High escapements of hatchery-origin fish to Maria Slough in recent years may have contributed to escapements exceeding the predicted Srep (e.g. 57% hatchery-origin in 2002; R. Cook, unpublished.). The watershed sizes for Maria Slough and the combined South Thompson, Little and Lower Adams Rivers were beyond the range of data included in the habitat model and predictions should be interpreted cautiously.

4.2.2.4 Rivers Inlet – Wannock River

The Wannock River represents an atypical Chinook system. It is a short river (6 km) that drains a large watershed, which encompasses Owikeno Lake, the headwater system to the Wannock. Natural migration barriers occur on two 5th order tributaries to Owikeno Lake (Table 12). The Wannock stock is a fall-run, ocean-type, while several tributaries to Owikeno Lake support small summer-run, stream-type stocks (McNicol 2000).

Wannock River is very turbid year-round and escapements were derived from carcass counts along the spawning area (McNicol 2000). Mark-recapture estimates, from 1991 to 1994 and 2000, indicated the visual indices underestimated total escapement (Winther 1992, 1993, 1995; McNicol 2000; Nelson et al. 2001 Appendix C). The visual indices were considered reasonably consistent indices of abundance for stock assessment. Visual indices were standardized to total escapements by the average expansion factor.

At Wannock River, the predicted Smsy exceeded the range of recent escapement estimates and only two years were within the 80% confidence interval for Smsy (Table 10; Figure 19). The predicted reference points probably have positive bias since the river is short and appears to have less than average amounts of spawning habitat when compared to the other ocean-type habitat model stocks, particularly relative to the size of the watershed. The uncertainty about the accuracy of the predicted reference points may need to be examined further to increase confidence in the estimates.

5 Discussion

We developed a habitat-based approach to generate escapement goals for data limited Chinook stocks in BC. The approach relied on a habitat model that describes a general relationship between capacity and habitat area across a broad range of environmental conditions. Fausch et al. (1988) proposed that models based primarily on drainage basin variables were the most useful for basin-wide planning and analysis in fishery management. Our approach incorporates little biological understanding of the specific mechanisms limiting capacity, but it is supported by statistically-based models fitted to a strong database representing general patterns over a range of environmental conditions and life history. Since management objectives vary among stocks, separate habitat models were developed to predict two reference points on the stock-recruitment curve in case escapement goals other than Smsy are needed. For example, Johnston et al. (2000) described reference points of different fishery management strategies as percentages of capacity for BC steelhead *O. mykiss* stocks.

The habitat-based approach has several favorable qualities that make it well-suited for data limited stocks in BC. The approach has simple structure, makes few assumptions, and does not require a lot of biological or physical habitat data, which contributes to cost- and time-savings over other methods, such as Physical Habitat Simulation or acquiring stock-recruitment data (e.g. Williams 2001). The habitat model predictions are biologically-based and rooted in fish-production relationships measured over a broad range of environments and life histories. The habitat models provided reasonably accurate estimates of Smsy and Srep for stocks with stock-recruitment relationships and it performed better than the interim escapement goal method used for BC key streams. Overall the habitat model predictions of Smsy corresponded well with recent escapements at the case study rivers and appeared high for rivers with unusually small spawning areas for the watershed size, such as at Wannock River and Spius Creek. The approach's performance can be tested and refined as new stock-recruitment information becomes available.

The habitat model has simple structure and lacked biological details, yet it can be applied inexpensively and quickly to Canadian stocks. The approach requires an estimate of the watershed area and the life history, but implementation requires estimates of total escapement, or their relationship to abundance indices, to compare spawner numbers to the predicted reference points. When a stock unit is distributed across multiple rivers, but escapements are not surveyed in all of them, an expansion factor is needed to estimate the total escapement for the entire stock unit. Watershed area can be measured from existing spatial databases and metadata for BC rivers. The cost and timeliness to implement the method depends partly upon the quality of existing escapement estimates and the availability of information describing their accuracy and reliability. When little or no information exists about the relationship between visual escapement indices and total escapements, information from nearby rivers with similar escapement survey methods and conditions was used for the interim. However, the paucity of information relating abundance indices to total escapement is one limitation that may impede the widespread application of the habitat-based approach for BC stocks.

The allometric habitat model structure appears correct and followed the patterns described for coho smolt production and fish yields in lakes. Bradford et al. (1997) reported an allometric relationship between coho smolt production and stream length, which was used by Bocking and Peacock (2004) to generate stock production reference points for Area 3 coho. Rounsefell (1946) reported that total population, annual sport yield, and annual commercial yield of fish had an allometric relationship with lake surface area. The positive allometric association supports Hilborn and Walters' (1992) suggestion that capacity depends on the size of the area used by the stock and would vary among stocks.

The accuracy of the habitat model depends on accurate identification of stock units, since the sum of Smsy predictions for watershed components will exceed the prediction for the entire watershed. Among data limited stock aggregates in BC, the Fraser and Skeena watersheds appear to have most complex circumstances (e.g. Candy et al. 2002). When a stock's spawning distribution is aggregated, yet no barrier limits access to upstream areas, the entire watershed was considered to contribute to the stock's productive capacity. Several BC watersheds containing large lakes have two spatially and temporally separated stocks. Few modeled stocks represent these conditions and data were insufficient to assess the best approach when multiple stock units spawn within a watershed. For the interim, we suggest following the steps in Table 11, where the watershed area includes drainage areas upstream of the river mouth or confluence, but excludes drainage areas upstream of barriers described in Section 2.2.2.

The habitat model developed modest precision estimates of Smsy and Srep and had reasonable accuracy for most fishery management purposes, yet some predictive errors were not trivial. Modest precision estimates, such as coefficients of variation of about 15 to 30% for Smsy, can be expected from predictive models with general applicability. The habitat models had moderate accuracy for Smsy, with MAPE of about 35 and 65% for the ocean- and stream-type models, but on average it overestimated Smsy by about 15 and 40%, respectively. Some predictive errors were substantial, and if the habitat model predictions appear grossly inaccurate then one can apply more accurate methods. Furthermore, fishery management may require more accurate estimates of Smsy or Srep for specific situations, and other more accurate methods may be suitable although they can be more expensive and time demanding.

Habitat capacity and escapement goals can be developed by a variety of simple (e.g. CTC 1998) and complex models (e.g. Lestelle et al. 1996). Simple models often capture a myriad of biological processes into a single equation or variable, whereas complex models intend to better represent reality via more parameters, equations, assumptions, or fine scale data to describe biological processes. An oversimplified model is the two-parameter Ricker (1973) model with Alpha, the slope of the mean recruitment relationship, representing the product of a myriad of short-term survival rates from egg deposition to adult spawners (Walters and Martell 2004). Ludwig and Walters (1989) examined several stock-production models and found that simple models can out-perform complex models when the underlying biological reality is less important than the statistical properties of the estimators and there is a trade-off between accuracy and low model sensitivity to numerical and structural uncertainties. Future habitat model development could examine the performance and trade-offs between simple and complex models.

The watershed area habitat model is a simple model without explicitly modeled mechanisms and relies on few parameters, assumptions, and only coarse-scale habitat data that presumably represent more complex relationships between Chinook production and habitat area. The life stage which limits capacity is generally unknown, so habitat models rely on assumptions about the habitat limiting numbers. The habitat model assumed capacity was limited by the freshwater habitat area associated with watershed area. At fine scales, limiting factors could vary among stocks, life history, and life stages for different brood years, but data were not available for all systems to model these mechanisms. Accordingly, we could not evaluate the performance of models fit separately for stocks limited by spawning, rearing, refuge, or some other habitat compared to models for separate life histories and watershed area. Future research may investigate the life stages and fine scale habitat limiting capacity.

Each approach to generating escapement goals has its own characteristics and limitations and the most appropriate model depends on available data and knowledge of biological processes. BC Chinook stocks have limited data to assess biological processes, thus the habitat model and interim escapement goal methods were developed. When both methods were compared, the habitat model had higher accuracy and precision than the interim escapement goal method. The habitat model requires spawner escapements of known accuracy and reliability, but the interim escapement goal method requires only escapement indices. The habitat model is rooted in fish production relationships ranging from Alaska to Oregon, while the interim escapement goal method is essentially arbitrary and non-biological.

The dynamics of salmon stocks can be quite uncertain, and often simple, naïve models perform better than complex models for predictions of future abundance (Haeseker et al. 2005). Uncertainty arises from random variability in natural systems contributing to variations in growth, survival, distribution, and reproduction as well as relationships between salmon abundance, habitat capacity, and nutrient availability (Montgomery 2004). Also, errors and biases in data collection, choice of model to represent natural systems, and non-stationary environmental conditions due to natural and anthropogenic processes contribute to uncertainty in salmon dynamics and influence the utility of using past patterns to represent the future. Since dynamics are uncertain, fishery planning and implementation may benefit by incorporating the uncertainty of escapement goals into evaluations of the probability of outcomes produced by various management options and strategies.

The habitat model and approach to generating escapement goals has limitations for accurate application. In additions to those described throughout the report, others pertain to the habitat model's predictive accuracy, and numerical and structural uncertainty. The habitat model represents the conditions and characteristics of the data it was developed from and has low degrees of freedom due to small sample size. Modeled stocks (mostly non-Canadian) were not randomly drawn from a sampling frame, therefore the habitat may not represent the full range of habitat conditions for Canadian Chinook salmon stocks. The habitat model described the best fit between habitat area and stock-recruitment reference points for average habitat quality conditions and for average productivity of modeled stocks. Predictions should be carefully examined before implementation because the model may poorly represent other natural or anthropogenic habitat conditions, thus predictive errors will increase as stocks depart from average habitat conditions or depart from average productivities of the modeled stocks. To help avoid developing escapement goals that are too low for unproductive stocks, the ratio of Smsy to Srep can be estimated for a low productivity level (Figure 9) and applied to the habitat model prediction of Srep to estimate Smsy. The habitat model may overestimate Smsy and Srep in watersheds with lower water yield (MAD/Km^2) than the average for modeled stocks because water yield influences drainage density (total length of stream per unit of watershed area; Leopold et al. 1992). For example, few modeled stocks reside in low water yield regions, such as the rainshadow areas of Coast and Cascade Mountain Ranges and most modeled stocks were located in coastal areas with relatively higher water yield. Also, Smsy and Srep may be overestimated for stocks where geology controls the drainage density more than it does for the average watershed used in the habitat model. Watersheds with high geologic control, such as geologically young lava flows, probably have lower drainage density and less river habitat per unit of watershed area than modeled stocks.

Life history is an important phenotypic variable that significantly improved the performance of the habitat model. Most Chinook stocks are dominated by ocean- or stream-type life history, however several transition areas occur in BC which are poorly represented by modeled stocks. For stocks with equal representation of life history types, the pooled life history models may be appropriate but this has not been assessed.

The habitat model parameters are preliminary and will change with iterative habitat model assessment, refinement, and testing. Inclusion of more stocks representing a wider range of habitat conditions may improve the approach's utility. Data for several modeled stocks are being updated and some of the stock-recruitment parameters may be revised with additional brood years, improved data quality, and adjustments for autocorrelation.

In sum, we describe a new habitat-based method to predict the spawning abundance that produces MSY and capacity for Chinook stocks over a broad range of environments. The approach requires easily acquirable data to make predictions. However application requires knowledge of the accuracy and reliability of the escapement estimates which may impede the use of this model for some rivers. The approach is well-suited for data limited stocks in BC and can be tested and refined as new stock-recruitment information becomes available and stock-recruitment relationships are updated with recent data. Although the approach has modest precision and accuracy, the estimates appear suitable for most fishery management and Wild Salmon Policy purposes and may prove useful until more accurate methods are available. The estimates of Smsy and Srep are likely biased in a direction that reduces biological risk and helps avoid overfishing because the method over-corrected for bias in Smsy and Srep and estimates likely exceed true values. The habitat method was more reliable than the interim method when applied to BC Key Streams and was corroborated by results from an independent stock-recruitment analysis. Before accepting Smsy values generated by the habitat-based approach, predictions should be examined and reviewed in the context of other information to ensure they are reasonable. In addition to iterative model assessment and refinement, the next steps could involve a meta-analysis of escapement survey calibration information and development of methods that more fully incorporate uncertainty in the stock-recruitment-habitat area relationship.

6 Summary and Recommendations

- The habitat-based method predicted the spawning abundance that produces MSY (Smsy) and capacity (Srep) with reasonable accuracy for Chinook stocks over a broad range of environments. Since the habitat-based method was more accurate and precise than the interim method for BC Key Streams, we recommend applying the habitat-based method for data limited stocks in BC to establish spawner escapement goals until such time as more stock-specific data are available.

- To better assess the method's performance for Canadian stocks and improve the representation of Canadian environments in the model, it may be worthwhile assembling stock-recruitment data for Canadian stocks for which such data is currently available (e.g. Nass, Nicola, and Nanaimo rivers).

- The reliability of the habitat-based approach should be assessed by testing the model against new stocks as additional stock-recruitment data become available.

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9 Tables

Table 1. Summary of stock-recruitment relationship parameters, reference points, diagnostics, watershed area (WA) and mean annual discharge (MAD) for stream-type stocks used in the meta-analysis (see Appendix A and B for data sources and descriptions). Nelson River stock was excluded from the habitat model (bold text) but used for model verification (see Section 2.2 for explanation).

Stock	Smsy	Srep	Ratio[1]	Alpha	Beta	Sigma[2]	Prod[2]	WA (km^2)	Latitude	MAD	Brood Years		Contrast	Data Quality	Autocorrelation in data series
											Years	n			
Andrew	707	1932	0.37	6.13	0.0009956	0.22	1.81	126	56.669	12.9	1975-1998	24	5.2	good	none detected
Blossom	926	2389	0.39	3.74	0.0006811	0.62	1.32	176	55.403	16.6	1977-1998	22	27.9	fair	detected, but not corrected
Chena	3621	10761	0.34	8.40	0.0002100	0.67	2.13	4515	64.796	38.5	1986-1995	10	4.6	good	none detected
Chickamin	2246	6118	0.37	5.58	0.0003126	0.39	1.72	1696	55.817	218	1977-1998	22	7.1	fair	detected, but not corrected
Keta	1039	2541	0.41	3.34	0.0005250	0.26	1.20	192	55.338	21.3	1977-1998	22	8.7	fair	detected, but not corrected
King Salmon	188	496	0.38	5.04	0.0035370	0.27	1.62	93	58.042	6.4	1971-1991	21	4.1	excellent	none detected
Kitsumkalum	8621	22160	0.39	4.25	0.0000709	0.21	1.45	2255	54.517	123	1984-1997	14	4.4	good	none detected
Klukshu	909	2590	0.35	7.86	0.0008253	0.15	2.06	260	60.116	4.4	1976-1991	16	2.9	excellent	none detected
Salcha	3939	12173	0.32	11.0	0.0002020	0.42	2.40	5620	64.467	45.6	1987-1995	9	5.6	good	none detected
Stikine	17800	41422	0.43	2.71	0.0000273	0.26	1.00	15337	56.564	1609	1977-1998	22	7.3	excellent	none detected
Taku	31678	74919	0.42	2.64	0.0000152	0.33	0.97	15539	58.426	393	1973-1991	19	5.1	good	none detected
U. Columbia-Sp.	49150	138255	0.36	7.38	0.0000150	0.13	2.00	114434	45.644	5320	1939-1969	31	7.9	good	yes, parameters adjusted
Unuk	4090	10700	0.38	3.43	0.0002148	0.23	1.23	3885	56.076	276	1977-1998	22	4.3	fair	none detected
Average			*0.37*				*1.61*					*20*	*7.6*		
SD			*0.03*				*0.46*								
Excluded:															
Nelson	**3337**	**8380**	**0.40**	**4.21**	**0.0001768**	**0.29**	**1.43**	**2077**	**55.906**	**NA**	**1981-1996**	**16**	**3.4**	**poor**	**none detected**

[1]Ratio of Smsy to Srep
[2]Productivity

Table 2. Summary of stock-recruitment relationship parameters, reference points, diagnostics, watershed area (WA) and mean annual discharge (MAD) for ocean-type stocks used in the meta-analysis (see Appendix A and B for data sources and descriptions). Bold text identifies stocks excluded from the habitat model but used for model verification (see Section 2.2 for explanation)..

Stock	Smsy	Srep	Ratio[1]	Alpha	Beta	Sigma[2]	Average Survival	Gamma	Prod[2]	WA (km^2)	Latitude	MAD	Brood Years		Contrast	Data Quality	Autocorrelation in data series
													Years	n			
Chehalis	11735	32030	0.37	5.70	0.0000600	0.36	NA	NA	1.74	4390	46.958	157	1977-1995	20	19.2	fair	none detected
Cowichan	6514	17545	0.37	5.20	0.0001056	0.41	1.023	0.64	1.66	1227	48.767	55.0	1985-2000[3]	14	4.1	good	none detected
Harrison	59255	153460	0.39	4.47	0.0000107	0.30	NA	0.84	1.50	7611	49.217	482	1984-1998	15	7.8	good	none detected
Humptulips	3475	10957	0.32	11.8	0.0002400	0.29	1.050	0.36	2.48	635	47.041	38.1	1977-1995[4]	19	28.8	fair	none detected
Lewis R. Falls	6050	18098	0.33	8.93	0.0001313	0.37	NA	NA	2.19	816	45.851	120	1964-1991	28	6.3	good	none detected
Nehalem	7327	20197	0.36	6.54	0.0000977	0.19	NA	NA	1.88	1728	45.658	76.3	1967-1991	25	12.7	fair	none detected
Queets	3687	10002	0.37	5.91	0.0001890	0.18	1.050	0.50	1.80	1164	47.545	124	1977-1995[4]	19	4.8	fair	none detected
Quillayute	4612	14559	0.32	9.66	0.0001810	0.73	NA	NA	2.27	1313	47.909	53.7	1981-1991	11	4.9	fair	none detected
Siletz	2997	9249	0.32	12.1	0.0002732	0.07	NA	NA	2.49	523	44.904	43.2	1973-1991	19	5.9	fair	yes, corrected by omitting 1967-72
Situk	1014	3089	0.33	8.63	0.0007945	0.33	NA	NA	2.15	176	59.435	8.8	1977-1999	18	4.8	excellent	yes, parameters adjusted
Siuslaw	15161	40318	0.38	4.84	0.0000443	0.42	NA	NA	1.58	2010	44.017	56.9	1965-1991	27	47.5	fair	none detected
Skagit	12842	41093	0.31	7.74	0.0000657	0.27	1.87	0.83	2.70	4198	48.388	470	1971-1998	28	4.8	fair	none detected
Average			0.35						2.03					20	12.9		
SD			0.03						0.38								
Excluded:																	
Columbia HYURB +APR	**43045**	**141671**	**0.30**	**14.8**	**0.0000200**	**0.28**	**NA**	**NA**	**2.69**	**31310**	**46.24**	**3384**	**1964-1991**	**28**	**8**	**excellent**	**yes, parameters adjusted**
Klamath	**40733**	**112298**	**0.36**	**5.92**	**0.0000176**	**0.39**	**NA**	**NA**	**1.78**	**16561**	**41.547**	**507**	**1979-2000**	**22**	**13.9**	**poor**	**not examined**

[1]Ratio of Smsy to Srep
[2]Productivity
[3]Excludes 1986 and 1987.
[4]Excludes 1984.

Table 3. Equations used to describe the relationship between spawners and recruitment and to estimate Smsy, Srep and productivity (ρ).

Parameter	Ricker Function	Ricker Function with survival covariate (M)[B]	Ricker ARMA[C]
Ln (R/S) =	$\ln\alpha - \beta S$	$\ln\alpha - \beta S + \gamma\ln(M)$	$(1-\phi_1)\ln\alpha + \phi_1\ln(R_{t-1}/S_{t-1}) - \beta S_t + \phi_1\beta S_{t-1} + a_t$
$\hat{S}_{MSY}$ [A] =	$1=(1-\hat{\beta}\hat{S}_{MSY})\exp(\hat{\ln}\,a)\exp(-\hat{\beta}\hat{S}_{MSY})\exp(\frac{\hat{\sigma}^2}{2})$	$1=(1-\hat{\beta}\hat{S}_{MSY})\exp(\hat{\ln}\,a)\exp(-\hat{\beta}\hat{S}_{MSY})\overline{M}^{\gamma}\exp(\frac{\hat{\sigma}^2}{2})$	$1=(1-\hat{\beta}\hat{S}_{MSY})\exp(\hat{\ln}\,a)\exp(-\hat{\beta}\hat{S}_{MSY})\exp(\frac{\hat{\sigma}^2}{2(1-\hat{\phi}^2)})$
$\hat{S}_{rep}$ =	$(\hat{\ln}\,\alpha + \frac{\hat{\sigma}^2}{2})\,/\,\hat{\beta}$	$(\hat{\ln}\,\alpha+\gamma\ln(\overline{M})+\frac{\hat{\sigma}^2}{2})\,/\,\hat{\beta}$	$(\hat{\ln}\,\alpha+\frac{\hat{\sigma}^2}{2(1-\hat{\phi}^2)})\,/\,\hat{\beta}$
$\hat{\rho}$	$\hat{\ln}\,\alpha$	$\hat{\ln}\,\alpha+\gamma\ln(\overline{M})$	$\hat{\ln}\,\alpha$

[A]The expected Smsy was estimated by iteratively solving these equations for Smsy.

[B]The average survival covariate was used to estimate the S_{MSY} and S_{Rep}

[C] a_t is an independent error distributed with mean 0 and variance σ_a^2 .

Table 4. Summary of $\hat{\ln}\,a$, $\hat{b}$, $\hat{\sigma}^2$, adjusted R, ANOVA F-test results, and index of resolution power (res. power) for regression habitat-models to predict Smsy, Srep, and inverse Beta of stream- and ocean-type stocks.

	Smsy Habitat Model			**Srep Habitat Model**			**Inverse Beta Model**		
Statistic	**Pooled**	**Stream-type[A]**	**Ocean-type[B]**	**Pooled**	**Stream-type**	**Ocean-type**	**Pooled**	**Stream-type**	**Ocean-type**
$\hat{\ln}\,a$	3.20	2.92	2.20	4.27	3.89	3.52	3.44	3.30	2.11
Standard Error	0.59	0.55	0.81	0.59	0.49	0.77	0.63	0.69	0.91
CV	19%	19%	37%	14%	13%	22%	18%	21%	43%
t-value	5.41	5.36	2.71	7.20	7.90	4.56	5.50	4.79	2.34
p-value	<0.001	<0.001	0.022	<0.001	<0.001	0.001	<0.001	<0.001	0.042
$\hat{b}$	0.712	0.692	0.914	0.704	0.693	0.878	0.726	0.696	0.965
Standard Error	0.08	0.07	0.11	0.08	0.06	0.11	0.08	0.09	0.12
CV	11%	10%	12%	11%	9%	12%	11%	13%	13%
t-value	9.08	9.84	8.21	8.96	10.89	8.27	8.73	7.83	7.77
p-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.001	<0.001
$\hat{\sigma}^2$	0.438	0.293	0.146	0.441	0.240	0.133	0.493	0.468	0.182
Adjusted r^2	0.77	0.89	0.86	0.77	0.91	0.86	0.76	0.83	0.84
ANOVA P-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Res. Power	2.8	4.2	3.8	2.8	4.6	3.8	2.8	2.2	3.6

[A]Using the stream-type regression parameters to estimate the average Smsy (y) from watershed area (x) in equation 3 gives $(\hat{\ln}\,y) = 2.92 + (0.692 * \ln x) + (0.293/2)$.

[B]Using the ocean-type regression parameters to estimate the average Smsy (y) from watershed area (x) in equation 3 gives $(\hat{\ln}\,y) = 2.20 + (0.914 * \ln x) + (0.146/2)$.

Table 5. Summary of $\widehat{\ln a}$, $\hat{b}$, $\hat{\sigma}^2$, adjusted R, and ANOVA F-test results for regression habitat-models to predict Smsy and Srep stocks stratified by north and south areas.

Statistic	Smsy Habitat Model North[A]	Smsy Habitat Model South	Srep Habitat Model North	Srep Habitat Model South
$\widehat{\ln a}$	2.95	4.64	4.01	5.81
Standard Error	0.60	0.83	0.56	0.78
CV	20%	18%	14%	13%
t-value	4.92	5.57	7.18	7.45
p-value	<0.001	<0.001	<0.001	<0.001
$\hat{b}$	0.694	0.579	0.683	0.561
Standard Error	0.08	0.11	0.08	0.10
CV	12%	18%	12%	18%
t-value	8.30	5.50	8.78	5.63
p-value	<0.001	<0.001	<0.001	<0.001
$\hat{\sigma}^2$	0.30	0.26	0.26	0.23
Adjusted r^2	0.85	0.73	0.86	0.74
ANOVA P-value	<0.001	<0.001	<0.001	<0.001

[A]Using the north area regression parameters to estimate Smsy (y) from watershed area (x) in equation 3 gives

$\widehat{(\ln y)} = 2.95 + (0.694 * \ln x) + (0.30/2)$.

Table 6. Performance statistics for the habitat model stratified by life history type and geography.

Statistic	Smsy Habitat Model Stratified by: Life History	Smsy Habitat Model Stratified by: Geography
Adjusted R^2	90%[B]	85%[B]
MAPE[A]	50%	82%
Average Percent Error	26%	57%
Range of Percent Errors	-59 to +221%	-73 to +733%
Average Raw Error	70	12,830
Mean Absolute Raw Error	4,456	18,715
RMSE	10,167	72,711
RMSPE[C]	70%	164%

[A] $MAPE = \dfrac{\sum_n \dfrac{\left|(\hat{Z}_i - Z_i)\right|}{Z_i}}{n}$, where Z represents the stock-recruitment reference point (Smsy or Srep).

[B]From Analysis of Covariance (ANCOVA).

[C] $RMSPE = \sqrt{\dfrac{\sum_n \left(\dfrac{(\hat{Z}_i - Z\ )}{Z_i} \times 100\%\right)^2}{n}}$

Table 7. Summary of $\hat{\ln a}$, $\hat{b}$, $\hat{c}$, $\hat{\sigma}^2$, adjusted r^2, and ANOVA F-test results for regression habitat-models to predict Smsy from watershed area and productivity for stocks aggregated by life history (equation 6).

Statistic	Smsy Habitat Model Stream-type[A]	Ocean-type
$\hat{\ln a}$	3.99	3.28
Standard Error	0.65	1.26
CV	16%	38%
t-value	6.10	2.60
p-value	<0.001	0.029
$\hat{b}$	0.693	0.862
Standard Error	0.06	0.12
CV	9%	14%
t-value	11.6	7.21
p-value	<0.001	<0.001
$\hat{c}$	0.671	0.346
Standard Error	0.29	0.31
CV	43%	89%
t-value	-2.31	-1.11
p-value	0.043	0.295
$\hat{\sigma}^2$	0.21	0.14
Adjusted r^2	0.92	0.86
ANOVA P-value	<0.001	<0.001

[A]Using the stream-type regression parameters to estimate Smsy (y) from watershed area (x) and productivity (ρ) in equation 6 gives $(\hat{\ln y}) = 3.99 + (0.693 * \ln x) - (0.671 * \rho) + (0.21/2)$.

Table 8. Summary statistics for the expected error levels and stability of the habitat model coefficients for leave-one-out assessments of the habitat model performance.

	Smsy Habitat Model		Srep Habitat Model	
Statistic	Stream-type	Ocean-type	Stream-type	Ocean-type
MAPE	65%	35%	56%	32%
Average Percent Error	37%	13%	30%	10%
Range of Percent Errors	-54 to +221%	-59 to +97%	-48 to +215%	-56 to +99%
Average Raw Error	1,333	-1,298	2,927	-3,079
Average Absolute Raw Error	4,982	5,783	10,513	14,584
RMSPE	86%	45%	77%	41%
CV[A] slope ($\hat{b}$)	3%	5%	3%	5%
CV[A] intercept ($\hat{\ln a}$)	6%	14%	4%	8%

[A]Coefficient of Variation.

Table 9. Comparison of estimated Smsy and Srep from a stock-recruitment analysis to predictions from the stream type habitat model for the Nelson River, Alaska.

	Stock-Recruitment Analysis[A]	Stream-type Habitat Model[B]
$\hat{S}_{MSY}$	3,337 (2,972-3,933)[C]	4,233 (3,217-5,183)[C]
$\hat{S}_{rep}$	8,380	10,953

[A]Nelson River data, including David's River tributary, from J. Hasbrouk and R. Clark (pers. comm).
[B]Watershed area was 2,076 (R. Clark, pers. comm.).
[C]The 90% confidence interval.

Table 10. Summary of performance statistics for the habitat model and interim doubling methods for estimating the Smsy of BC Key Streams. The habitat model predicted values were developed during the leave-one-out analysis and errors were expressed with respect to Smsy from the stock-recruitment analyses.

	Habitat Model	Interim Doubling Method
Cowichan	-1%	+54%
Kitsumkalum	-52%	+174%
Harrison	-59%	+308%
MAPE	38%	179%
RMSE	20,315	105,696
RMSPE	46%	207%

Table 11. Sequence of steps to follow in order to estimate stock recruitment parameters for a Chinook stock using the habitat model.

Step	Description
1	Identify the stock unit. Relies on information such as migration times, spawning sites, spawning times, exploitation history, survival, age structure, correlated spawning abundances among sites, and migration of spawners among sites from tag recoveries or genetic analyses.
2	Identify the dominant life history as stream-type or ocean-type.
3	Identify the watershed area corresponding to the stock unit. A watershed is bounded by divides, typically along high points of land and ridges, and by the river mouth. Calculate the total watershed area as the contributing drainage area. • If the stock unit is distributed among multiple rivers within a watershed, then the total watershed area is the sum of the sub-watersheds where spawning occurs. • If the stock unit has an aggregated distribution downstream of a lake, for example, then the total watershed area includes all areas upstream of the outlet of the river, including the sub-watersheds above the lake.
3	Calculate the watershed area upstream of man-made barriers (e.g. dams, diversions) and subtract this area from the total watershed area.
4	Calculate the watershed area upstream of natural barriers that limit access to potentially productive habitats upstream and subtract this area from the total watershed area (Section 2.2.2). For ocean-type stocks used in the habitat model, natural barriers on 5th order and larger rivers appeared to limit access to productive habitats, whereas for stream-type stocks, natural barriers on 4th order and larger rivers appeared to limit access to productive habitats.
5	Calculate the watershed area of inhospitable sub-basins and subtract this from the total watershed area. We suggest following the same stream-order criteria used in step 4 to identify potentially productive habitats.
6	The watershed area used to predict the stock-recruitment reference points is the total watershed area less the areas identified in steps 3, 4, and 5.
7	Use the watershed area from step 6 with the habitat model corresponding to the stock unit's life history and the desired stock recruitment parameter (using equations in Table 4).
8	Confidence limits can be calculated using the parameters in Table 4 and the methods described by Zar (1984; Section 17.4) or by following the bootstrap procedure outlined in Section 4.1.2.

Table 12. Barriers and watershed areas for the Area 3 (Nass), Fraser Spring-run Age 1.2 (FSp 1.2), Upper Georgia Strait (UGS), Lower Georgia Strait (LGS), West Coast Vancouver Island (WCVI), Fraser Summer-run Age 0.3 (FSu 0.3), and Wannock stock aggregates. Bold text indicates watersheds beyond the range of data used to develop the habitat model.

Stock Aggregate	Case Study Stock	Barrier Description	Total Watershed Area	Inaccessible Watershed Area (Km^2)	Watershed Area Used for Model
Area 3	Kincolith	None (3rd order)	222	-	222
Area 3	Ishkeenickh	None (3rd order)	581	-	581
Area 3	Kwinamass	Barrier on mainstem (4th order)	330	127	203
Area 3	Kitsault	Barrier on mainstem (4th order)	461	96	365
Area 3	Nass aggregate	Barrier on Konigus R. (5th order)	-	471	-
Area 3	Nass aggregate	Barrier on Muskaboo R (6th order)	-	619	-
Area 3	Nass aggregate	Barrier on Taylor R. (6th order)	-	755	-
Area 3	Nass aggregate	Barrier on mainstem (6th order)	-	767	-
Area 3	Nass aggregate	Total	19,227	2,612	16,615
FSp 1.2	Nicola	None on 4th order or larger channels	7,211	-	7,211
FSp 1.2	Spius	None on 4th order or larger channels	777	-	777
FSp 1.2	Coldwater	None on 4th order or larger channels	917	-	917
FSp 1.2	Louis	None on 4th order or larger channels	519	-	519
FSp 1.2	Deadman	Barrier on mainstem (5th order)	1,514	624	890
FSp 1.2	Bonaparte	Barrier on Fly C. (5th order)	-	1,238	-
FSp 1.2	Bonaparte	Barrier on Chasm R. (5th order)	-	278	-
FSp 1.2	Bonaparte	Barrier on Clinton R. (5th order)	-	296	-
FSp 1.2	Bonaparte	Total	5,311	1,812	3,499
FSp 1.2	Bessette	Several man-made barriers	795	407	388
UGS	Klinaklini	Barrier on McClinchy Cr. (5th order)	5,852	691	5,161
LGS	Nanaimo	Two man-made barriers	835	249	586
WCVI	**Tahsis**	**None on 5th order or larger channels**	77	-	**77**
WCVI	Burman	None on 5th order or larger channels	242	-	242
WCVI	**Artlish**	**None on 5th order or larger channels**	125	-	**125**
WCVI	Tahsish	None on 5th order or larger channels	277	-	277
WCVI	**Kaouk**	**None on 5th order or larger channels**	115	-	**115**
WCVI	Marble	Barrier on mainstem (5th order)	529	133	396
FSu 0.3	M. Shuswap	Man-made barriers (Bessette, M. Shu.)	3,035	2,419	616
FSu 0.3	L. Shuswap	Man-made barriers (Bessette, M. Shu.)	5,275	2,419	2,856
FSu 0.3	S. Thompson	Man-made barriers (Bessette, M. Shu.)	-	2,419	-
FSu 0.3	S. Thompson	Man-made barrier (Salmon R.)	-	808	-
FSu 0.3	S. Thompson	Barrier on Seymour R. (5th order)	-	810	-
FSu 0.3	**S. Thompson**	**Total**	**17,531**	**4,037**	**13,494**
FSu 0.3	**Maria Sl.**	**None on 5th order or larger channels**	**33**	**-**	**33**
Wannock	Wannock	Barrier on Neechanz (5th order)	-	322	-
Wannock	Wannock	Barrier on Machmell (5th order)	-	440	-
Wannock	Wannock	Total	3,935	762	3,173

Table 13. Descriptions of common characteristics that influence the accuracy of visual escapement indices for the case study stocks. Bold text indicates stocks with expansion factors to convert visual indices to total escapement estimates.

Description of river size and riparian cover	**Water Clarity Conditions**			
	Clear conditions - can see bottom of deep pools	Moderate conditions - can see bottom of shallow spawning areas and occasionally deep pools for counting holding fish	Moderate conditions - can see bottom of shallow spawning areas and rarely deep pools, weather events frequently reduce visibility in spawning areas	Turbid conditions - unique index method (e.g. carcass expansion, index area expansion)
Small system, overhead vegetation, foot survey	**Louis**, Bessette, **Deadman**, Maria, Bonaparte	na	na	na
Small system, overhead vegetation, float/aerial survey	na	**Kwinamass**	na	na
Small system, little overhead vegetation, aerial survey	**Nicola,** Spius, Coldwater	**Kincolith**	na	na
Small system, little overhead vegetation, swim survey	na	Kaouk, Artlish, Burman, Tahsis, Tahsish	Marble	na
Large system, no overhead vegetation, aerial survey	na	**Lower Shuswap**, Middle Shuswap, Lower Adams	South Thompson, Little, Ishkeenickh	Kitsault
Short, wide river, no overhead vegetation, foot survey	na	na	na	**Wannock**
Large system, multiple rivers and spawning areas, often aerial survey	na	na	na	**Klinaklini, Nass**

Na indicates the category did not apply to the case study stocks.

Table 14. Summary of the sources (y) of expansion factors used to adjust visual indices to estimates of total escapement ($\hat{\pi}_y$) and to adjust predicted stock-recruitment reference points to visual index units ($1/\hat{\pi}_y$) for case study systems. Bold Text identifies stocks where current escapement methods produce total escapement estimates.

Stock Aggregate	Stock	Expansion Factor Source (y)	Visual Index Expansion Factor $\hat{\pi}_y$ (years)	Reference Point Expansion Factor ($1/\hat{\pi}_y$)
Area 3	**Nass**	**Nass**	**2.5 (2)**	**0.39**
Area 3	Kincolith	Kincolith	2.0 (1)	0.50
Area 3	Kwinamass	Kwinamass	1.8 (2)	0.54
Area 3	Ishkeenickh	Kwinamass/Kincolith	1.9 (3)	0.53
Area 3	Kitsault	Kwinamass/Kincolith	1.9 (3)	0.53
FSp 1.2	**Nicola**	**Nicola**	**1.2 (9)**	**085**
FSp 1.2	Spius	Nicola	1.2 (9)	085
FSp 1.2	Coldwater	Nicola	1.2 (9)	085
FSp 1.2	**Deadman**	**Deadman**	**1.4 (1)**	**0.72**
FSp 1.2	**Louis**	**Louis**	**1.8 (5)**	**0.55**
FSp 1.2	Bessette	Deadman, Louis	1.8 (6)	0.57
FSp 1.2	**Bonaparte**	**NA**	**NA**	**NA**
UGS	Klinaklini	Klinaklini	4.5 (2)	0.22
LGS	**Nanaimo**	**NA**	**NA**	**NA**
Wannock	Wannock	Wannock	2.3 (5)	0.43
WCVI	**Kaouk**	**NA**	**NA**	**NA**
WCVI	**Artlish**	**NA**	**NA**	**NA**
WCVI	**Burman**	**NA**	**NA**	**NA**
WCVI	**Tahsis**	**NA**	**NA**	**NA**
WCVI	**Tahsish**	**NA**	**NA**	**NA**
WCVI	**Marble**	**NA**	**NA**	**NA**
FSu 0.3	**L. Shuswap**	**L. Shuswap**	**1.7 (2)**	**0.60**
FSu 0.3	M. Shuswap	L. Shuswap	1.7 (2)	0.60
FSu 0.3	L. Adams	L. Shuswap	1.7 (2)	0.60
FSu 0.3	Little	L. Shuswap	1.7 (2)	0.60
FSu 0.3	S. Thompson	L. Shuswap	1.7 (2)	0.60
FSu 0.3	Maria	Deadman, Louis	1.8 (6)	0.57

NA indicates that no expansion factor was available.

Table 15. Predicted spawners to produce MSY (Smsy) with bootstrap percentiles for case study stocks. Bold text identifies summed estimates for stock aggregates. Any difference between the aggregate totals and the sum of component stocks is due to rounding.

Stock Aggregate	**Stock**	$\hat{S}_{MSY}$	**CV[4]**	**Bootstrap Percentiles** 5th	10th	25th	50th	75th	90th	95th
Area 3	Nass	17,900	0.21	12,300	13,300	15,100	17,500	20,200	22,800	24,400
Area 3	Kincolith	900	0.19	600	700	800	900	1,000	1,100	1,200
Area 3	Kwinamass	800	0.20	600	600	700	800	1,000	1,100	1,100
Area 3	Ishkeenickh	1,800	0.16	1,300	1,400	1,500	1,700	1,900	2,100	2,200
Area 3	Kitsault	1,300	0.17	900	1,000	1,100	1,200	1,400	1,500	1,600
Area 3	**Aggregate[5]**	**22,600**	**0.17**	**16,600**	**17,800**	**19,800**	**22,300**	**25,100**	**27,800**	**29,300**
FSp 1.2	Nicola	10,000	0.17	7,300	7,800	8,700	9,800	10,800	12,200	12,900
FSp 1.2	Spius	2,000	0.15	1,500	1,600	1,800	2,000	2,200	2,400	2,600
FSp 1.2	Coldwater	1,100	0.18	800	900	1,000	1,100	1,200	1,400	1,500
FSp 1.2	Deadman	2,400	0.15	1,800	1,900	2,100	2,300	2,600	2,800	2,900
FSp 1.2	Louis	1,600	0.16	1,200	1,300	1,400	1,600	1,800	1,900	2,100
FSp 1.2	Bessette	1,300	0.17	1,000	1,000	1,200	1,300	1,500	1,600	1,700
FSp 1.2	Bonaparte	6,100	0.15	4,600	4,900	5,400	6,000	6,600	7,200	7,600
FSp 1.2	**CTC Aggregate[1,5]**	**18,500**	**0.14**	**14,200**	**14,900**	**16,400**	**18,200**	**20,100**	**21,800**	**22,800**
FSp 1.2	**Total Aggregate[2,5]**	**24,600**	**0.15**	**18,700**	**19,800**	**21,800**	**24,200**	**26,700**	**29,000**	**30,400**
UGS	Klinaklini	8,000	0.16	5,900	6,300	7,000	7,800	8,700	9,600	10,000
LGS	Nanaimo	3,300	0.14	2,600	2,700	2,900	3,200	3,600	3,900	4,100
Wannock.	Wannock	15,300	0.14	12,100	12,700	13,800	15,100	16,700	18,100	19,000
WCVI	Kaouk	700	0.28	500	500	600	700	900	1,100	1,200
WCVI	Artlish	800	0.27	500	600	700	800	1,000	1,100	1,200
WCVI	Burman	1,500	0.21	1,000	1,100	1,200	1,400	1,700	1,900	2,000
WCVI	Tahsis	500	0..32	300	300	400	500	600	800	900
WCVI	Tahsish	1,700	0.20	1,200	1,300	1,400	1,600	1,900	2,100	2,300
WCVI	Marble	2,300	0.17	1,700	1,800	2,000	2,300	2,500	2,800	3,000
WCVI	**Aggregate[5]**	**7,500**	**0.21**	**5,200**	**5,600**	**6,400**	**7,400**	**8,600**	**9,700**	**10,500**
FSu 0.3	L. Shuswap	13,900	0.13	11,100	11,700	12,600	13,700	15,100	16,300	17,100
FSu 0.3	M. Shuswap	3,400	0.14	2,700	2,800	3,100	3,400	3,700	4,000	4,200
FSu 0.3	S. Thompson[3]	57,600	0.26	37,300	40,600	47,500	56,600	67,700	79,300	87,000
FSu 0.3	Maria	200	0.41	100	100	200	200	300	400	500
FSu 0.3	**Aggregate[5]**	**75,200**	**0.22**	**52,600**	**56,400**	**63,900**	**74,100**	**86,100**	**98,800**	**107,000**

[1]Excludes Bonaparte River.
[2]Includes Bonaparte River.
[3]Includes Little and Lower Adams rivers.
[4]Coefficient of variation.
[5]Aggregate totals may vary from the sum of component stocks due to rounding.

Table 16. Predicted spawners at replacement (Srep) with bootstrap percentiles for case study stocks. Bold text identifies summed estimates for stock aggregates. Any difference between the aggregate totals and the sum of component stocks is due to rounding.

Stock Aggregate	Stock	$\hat{S}_{REP}$	CV[4]	Bootstrap Percentiles 5th	10th	25th	50th	75th	90th	95th
Area 3	Nass	46,400	0.18	33,400	35,700	40,200	45,700	51,900	57,500	61,200
Area 3	Kincolith	2,300	0.18	1,700	1,800	2,000	2,300	2,600	2,900	3,000
Area 3	Kwinamass	2,200	0.18	1,600	1,700	1,900	2,200	2,400	2,700	2,900
Area 3	Ishkeenickh	4,500	0.14	3,500	3,700	4,000	4,500	4,900	5,400	5,600
Area 3	Kitsault	3,300	0.16	2,500	2,600	2,900	3,200	3,600	4,000	4,200
Area 3	**Aggregate[5]**	**58,700[5]**	**0.15**	**44,600**	**47,500**	**52,100**	**58,100**	**64,400**	**70,500**	**74,500**
FSp 1.2	Nicola	26,000	0.15	19,700	20,900	23,000	25,600	28,400	31,100	32,700
FSp 1.2	Spius	5,300	0.14	4,100	4,300	4,700	5,200	5,700	6,200	6,500
FSp 1.2	Coldwater	2,900	0.17	2,200	2,300	2,500	2,800	3,200	3,500	3,700
FSp 1.2	Deadman	6,100	0.14	4,800	5,000	5,500	6,000	6,600	7,100	7,500
FSp 1.2	Louis	4,200	0.15	3,200	3,400	3,700	4,100	4,600	5,000	5,200
FSp 1.2	Bessette	3,400	0.16	2,600	2,700	3,000	3,400	3,800	4,100	4,300
FSp 1.2	Bonaparte	15,800	0.14	12,300	13,000	14,100	15,500	17,000	18,400	19,300
FSp 1.2	**CTC Aggregate[1,5]**	**47,900**	**0.13**	**37,800**	**39,800**	**43,200**	**47,400**	**51,600**	**55,700**	**58,300**
FSp 1.2	**Total Aggregate[2,5]**	**63,700**	**0.13**	**50,000**	**52,900**	**57,400**	**62,900**	**68,600**	**74,000**	**77,400**
UGS	Klinaklini	20,600	0.14	15,800	16,800	18,300	20,300	22,400	24,300	25,600
LGS	Nanaimo	9,700	0.13	7,700	8,100	8,800	9,600	10,500	11,300	11,800
Wannock.	Wannock	42,700	0.13	34,000	35,800	38,700	42,300	46,100	49,800	52,100
WCVI	Kaouk	2,300	0.26	1,500	1,700	1,900	2,300	2,700	3,200	3,500
WCVI	Artlish	2,500	0.25	1,600	1,800	2,100	2,500	2,900	3,400	3,700
WCVI	Burman	4,500	0.19	3,200	3,400	3,900	4,400	5,000	5,700	6,100
WCVI	Tahsis	1,600	0.30	1,000	1,100	1,300	1,600	2,000	2,400	2,600
WCVI	Tahsish	5,000	0.18	3,700	3,900	4,400	5,000	5,600	6,300	6,700
WCVI	Marble	6,900	0.16	5,300	5,600	6,100	6,800	7,600	8,300	8,800
WCVI	**Aggregate[5]**	**22,800**	**0.20**	**16,300**	**17,500**	**19,700**	**22,600**	**25,900**	**29,200**	**31,400**
FSu 0.3	L. Shuswap	38,900	0.12	31,200	32,800	35,500	38,500	41,800	45,000	47,000
FSu 0.3	M. Shuswap	10,100	0.13	8,100	8,500	9,200	10,000	10,900	11,800	12,300
FSu 0.3	S. Thompson[3]	152,000	0.24	101,000	110,000	129,000	151,000	177,000	205,000	223,000
FSu 0.3	Maria	800	0.38	400	500	600	800	1,000	1,200	1,400
FSu 0.3	**Aggregate[5]**	**202,000**	**0.20**	**143,000**	**154,000**	**173,000**	**199,000**	**229,000**	**259,000**	**279,000**

[1]Excludes Bonaparte River.
[2]Includes Bonaparte River.
[3]Includes Little and Lower Adams rivers.
[4]Coefficient of variation.
[5]Aggregate totals may vary from the sum of component stocks due to rounding.

10 Figures

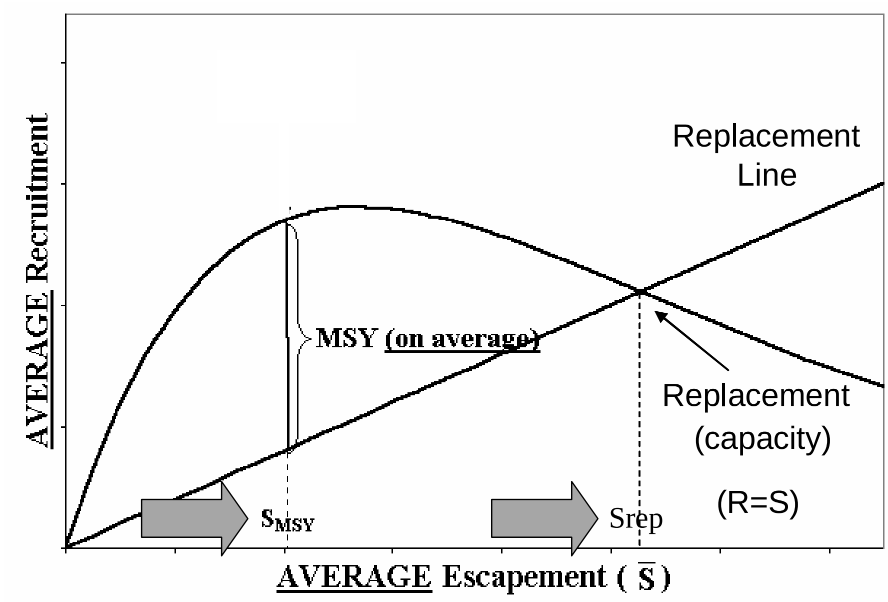

Figure 1. The spawning abundance producing MSY (Smsy) and replacement (Srep) on the Ricker stock-recruitment relationship.

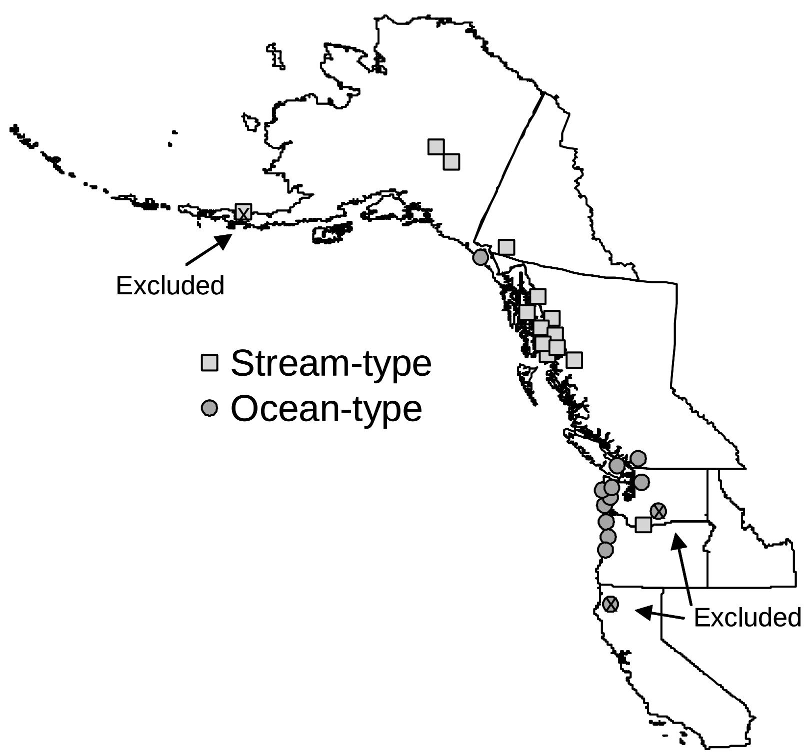

Figure 2. Locations of stocks used in the meta-analysis and stocks for which stock-recruitment data were available, but were excluded (see text for explanation).

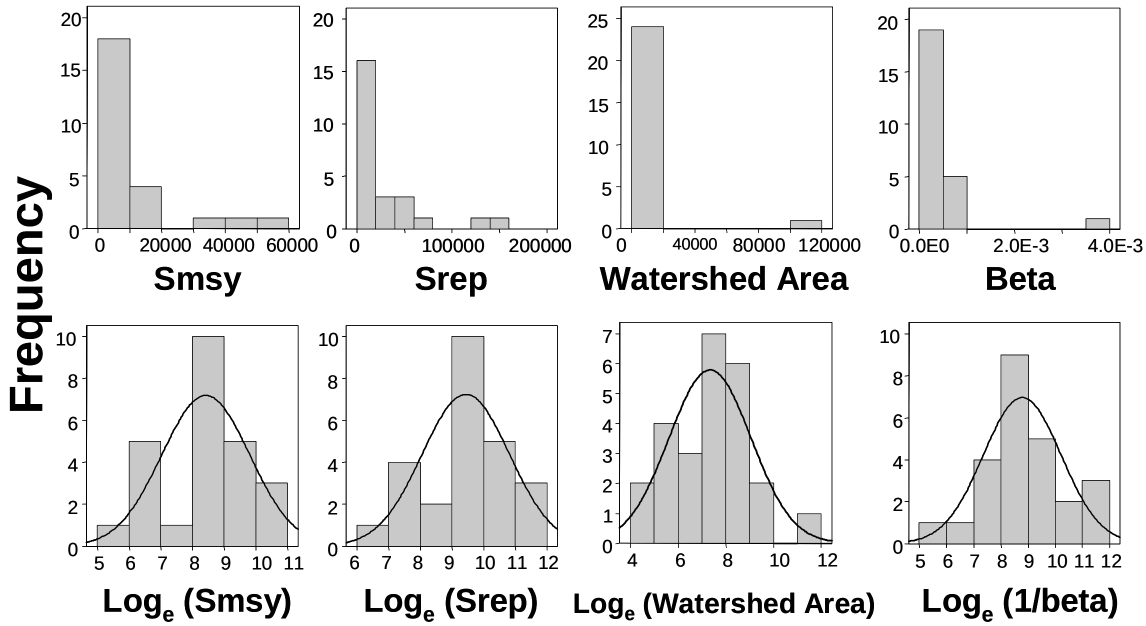

Figure 3. Frequency distributions for untransformed and natural log transformed Smsy, Srep, watershed area, and Ricker Beta data for modeled stocks. Normal curves calculated for transformed data.

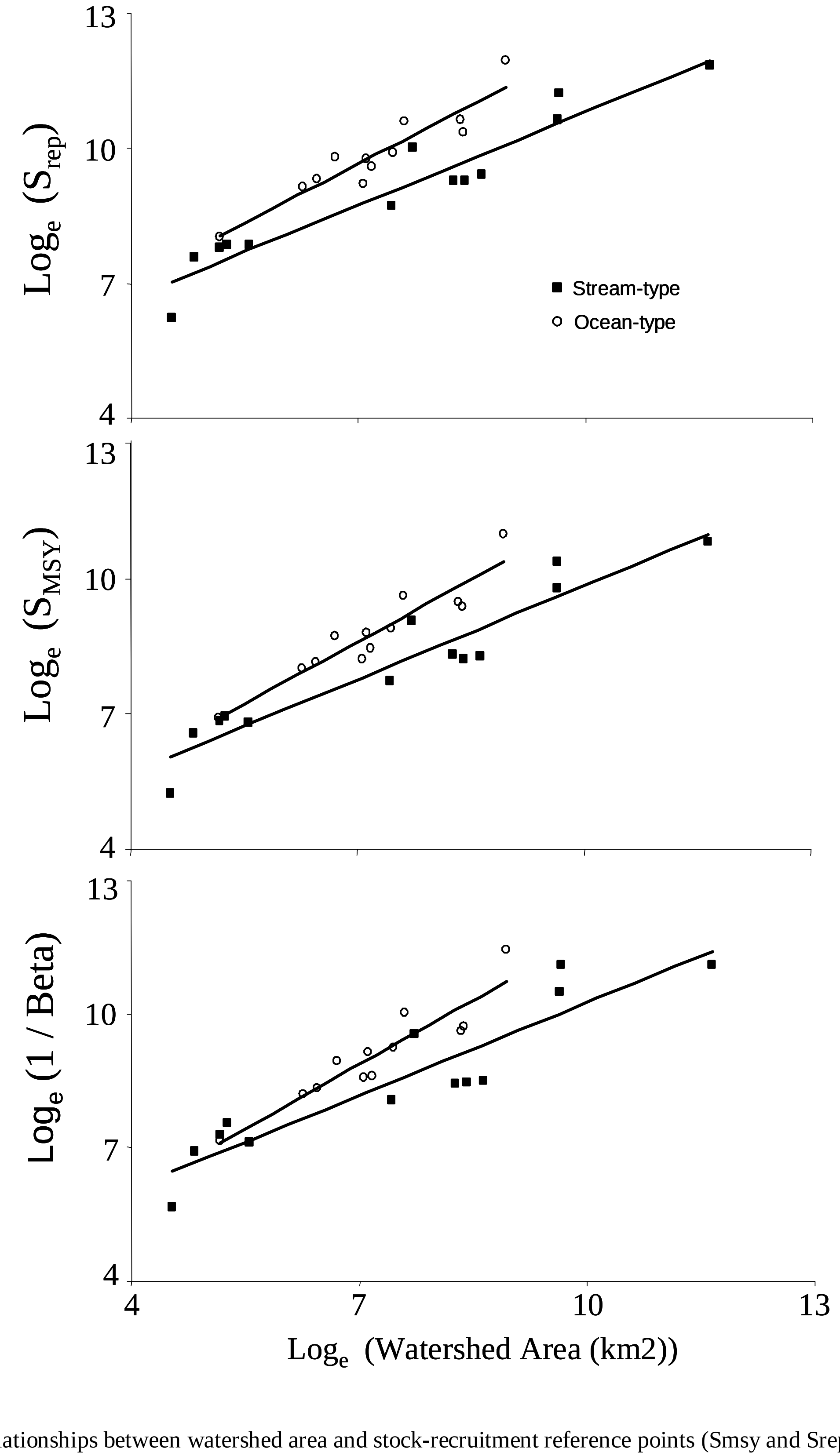

Figure 4. Relationships between watershed area and stock-recruitment reference points (Smsy and Srep) and association with the inverse of the beta parameter for ocean- and stream-type stocks. Regression parameters are in Table 4.

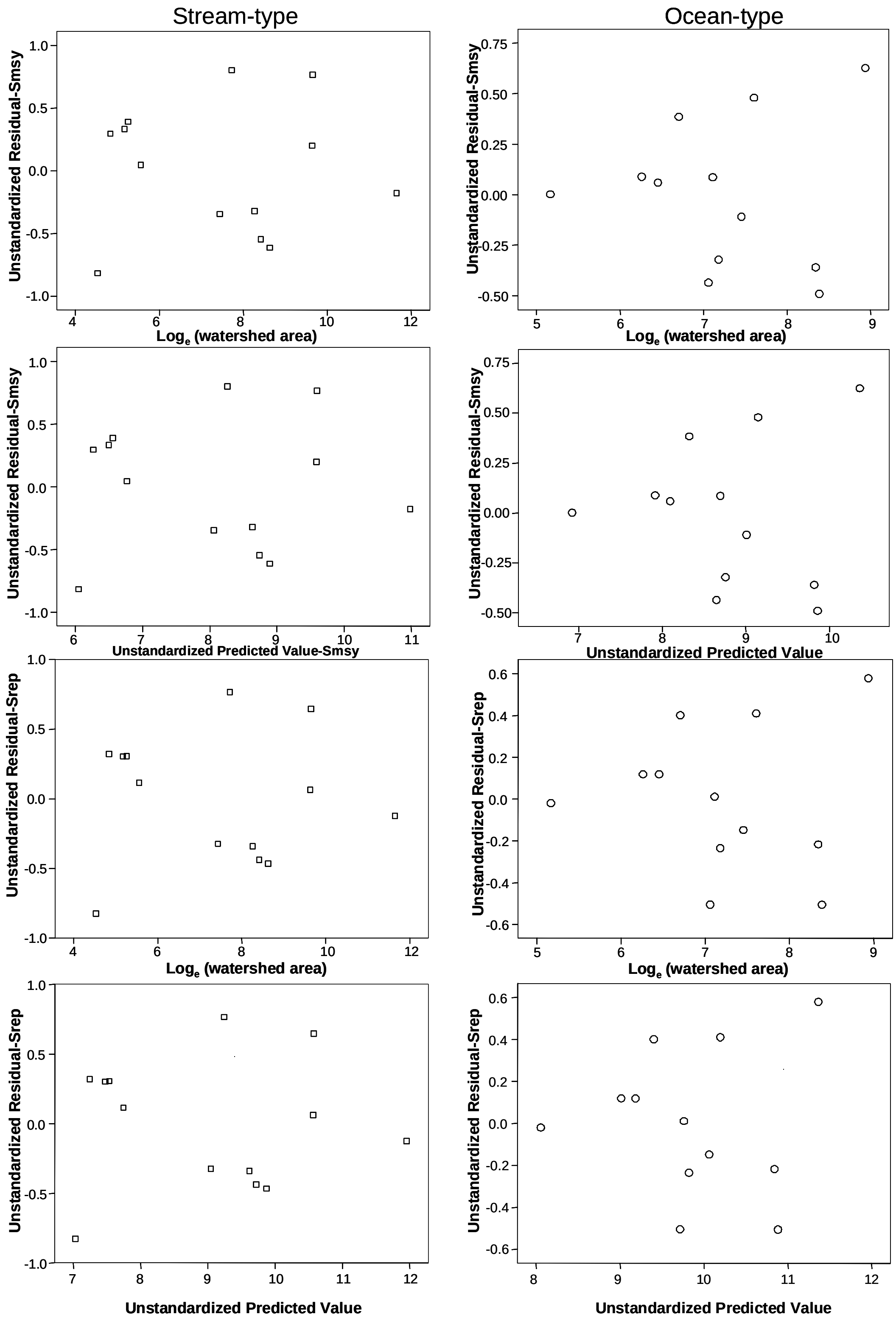

Figure 5. Residuals from the Smsy and Srep habitat models plotted against watershed area and respective predicted values.

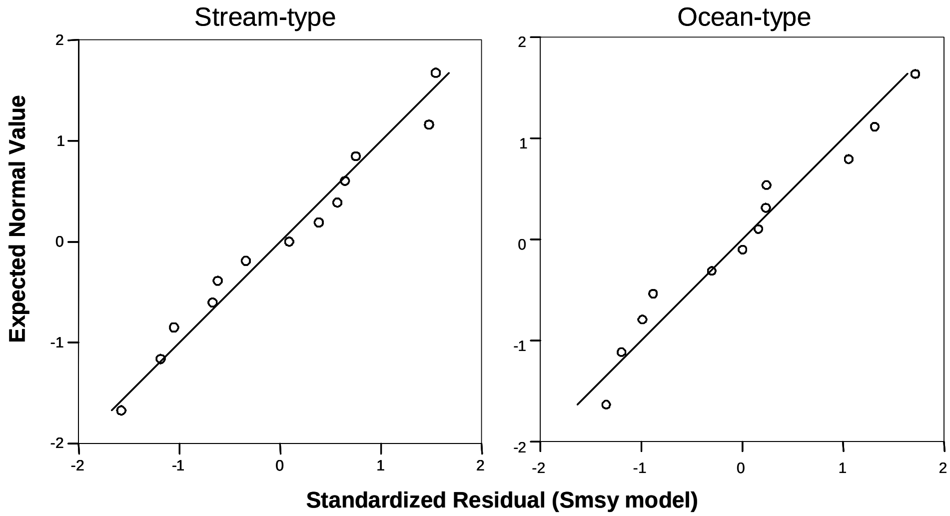

Figure 6. Q-Q plots of standardized residuals from the Smsy habitat models for stream- and ocean-type stocks. Similar patterns were evident for Srep habitat models.

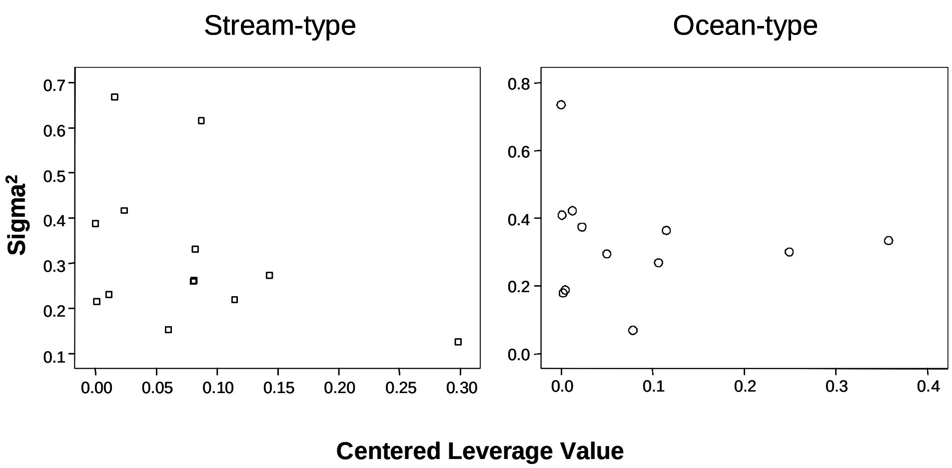

Figure 7. Centered leverage of the Smsy habitat models against the regression mean square error (Sigma^2) from the stock-recruitment relationships.

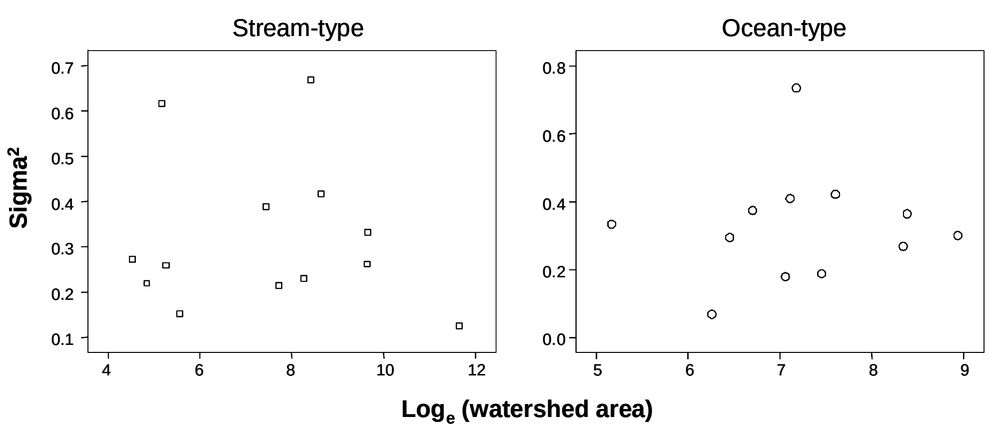

Figure 8. Watershed area versus regression mean square error (Sigma^2) from the stock-recruitment relationships.

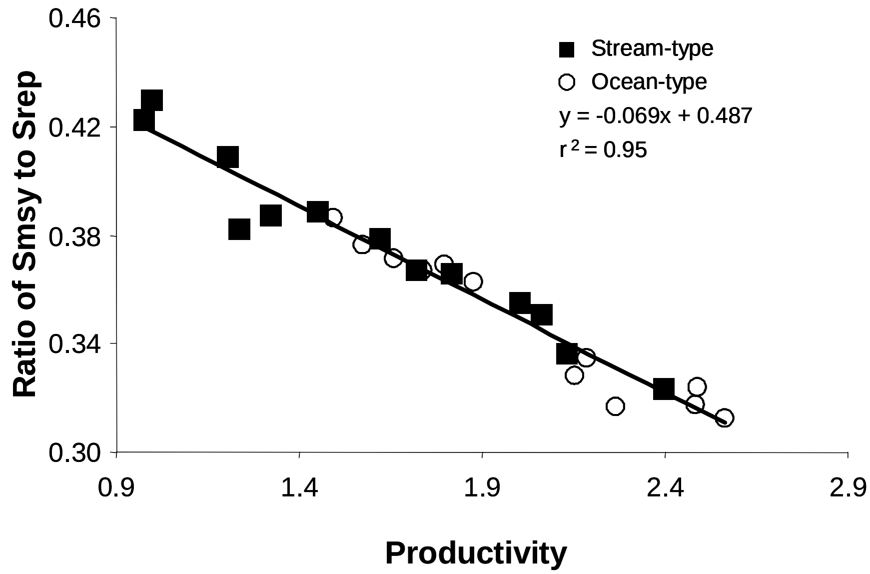

Figure 9. Relationship between productivity and the ratio of Smsy to Srep.
Productivity was defined in Table 3 for Ricker recruitment relationships.

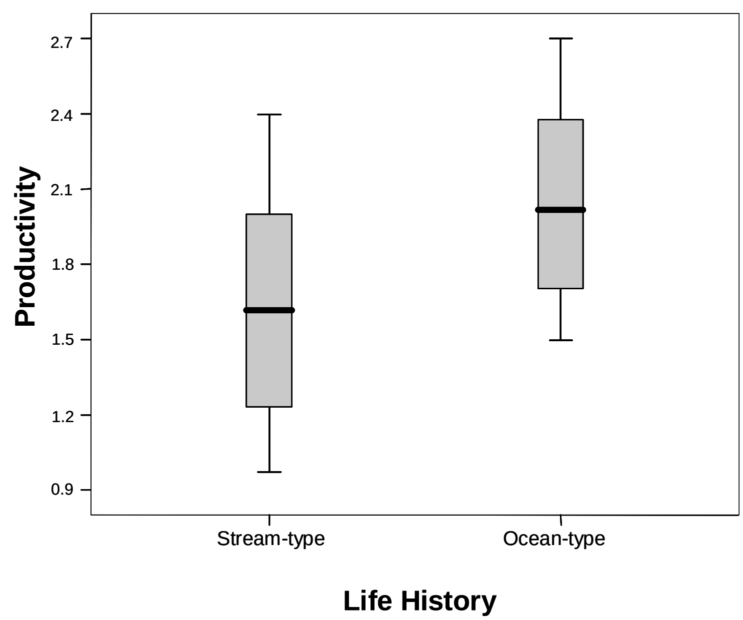

Figure 10. Boxplots of productivity for ocean- and stream-type stocks.
Each boxplot presents the median (solid line), upper and lower quartiles (upper and lower box boundaries), and 10th and 90th percentiles (error bars).

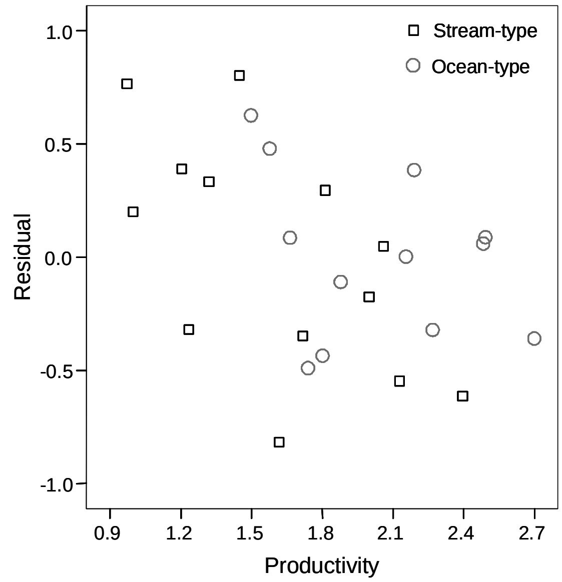

Figure 11. Association between residuals of the Smsy habitat models and productivity of stream- and ocean-type stocks.

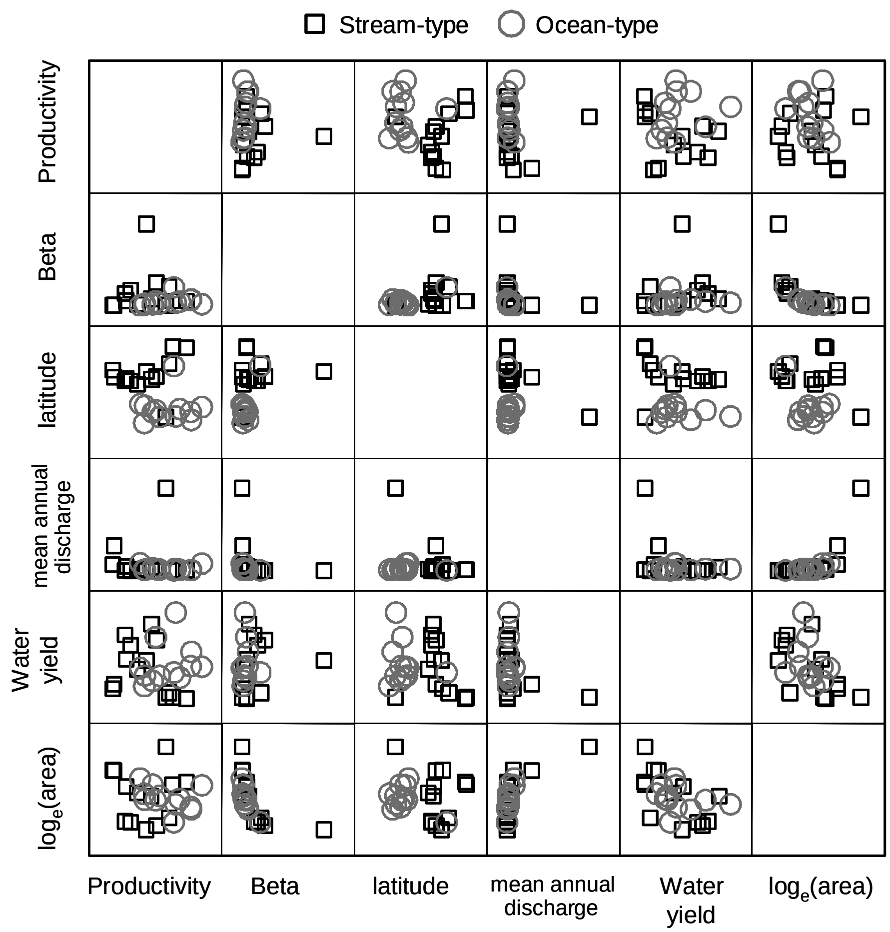

Figure 12. Associations between productivity, capacity parameter (Beta), latitude, mean annual discharge, water yield and watershed area (transformed).

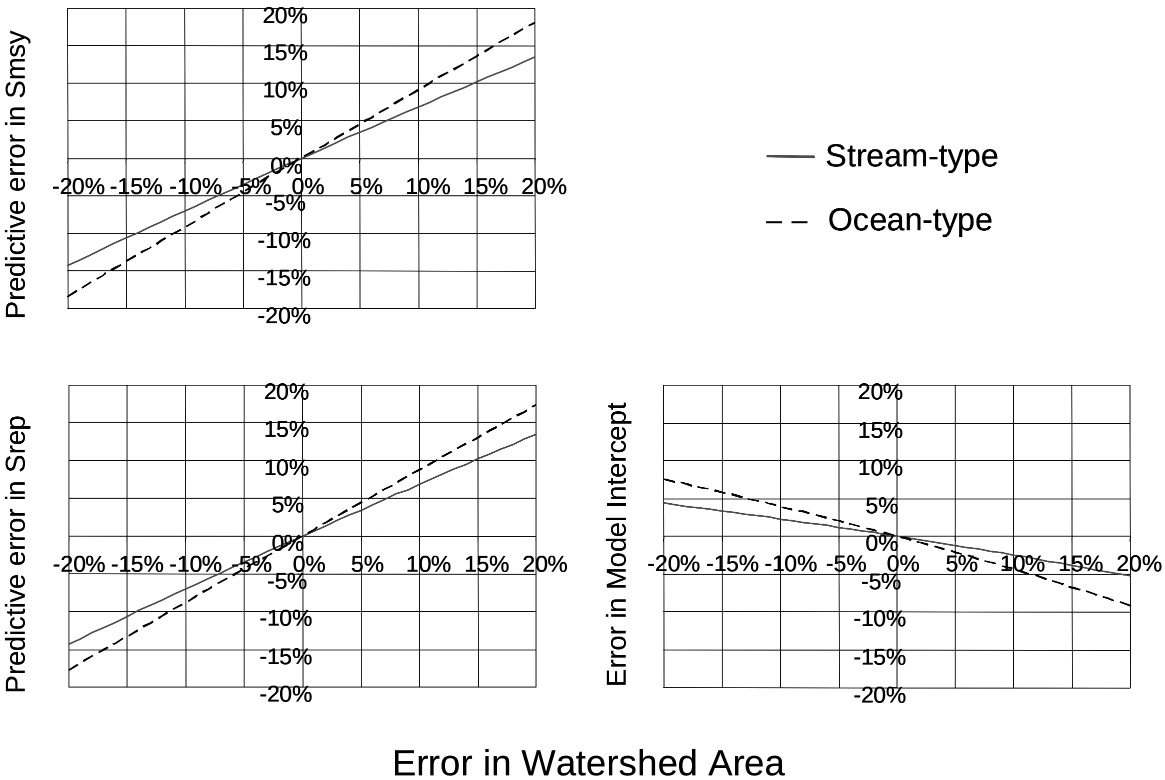

Figure 13. Sensitivity of predictions of Smsy and Srep to errors in watershed area.

For ocean-type stocks in the top panel, a +10% overestimation error of watershed area results in about a +10% overestimation error in Smsy.

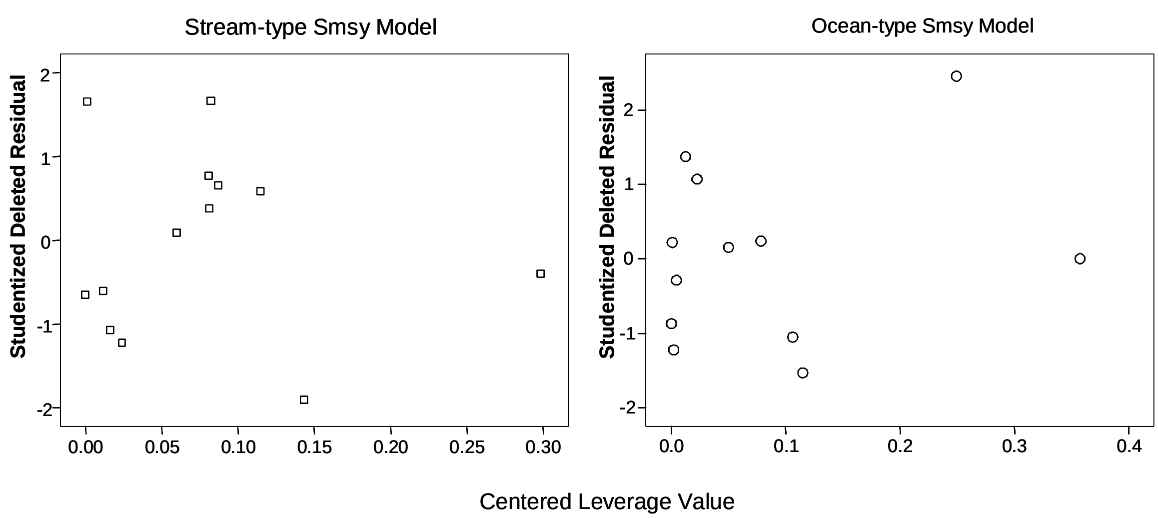

Figure 14. Studentized deleted residuals plotted against leverage for the Smsy habitat models.

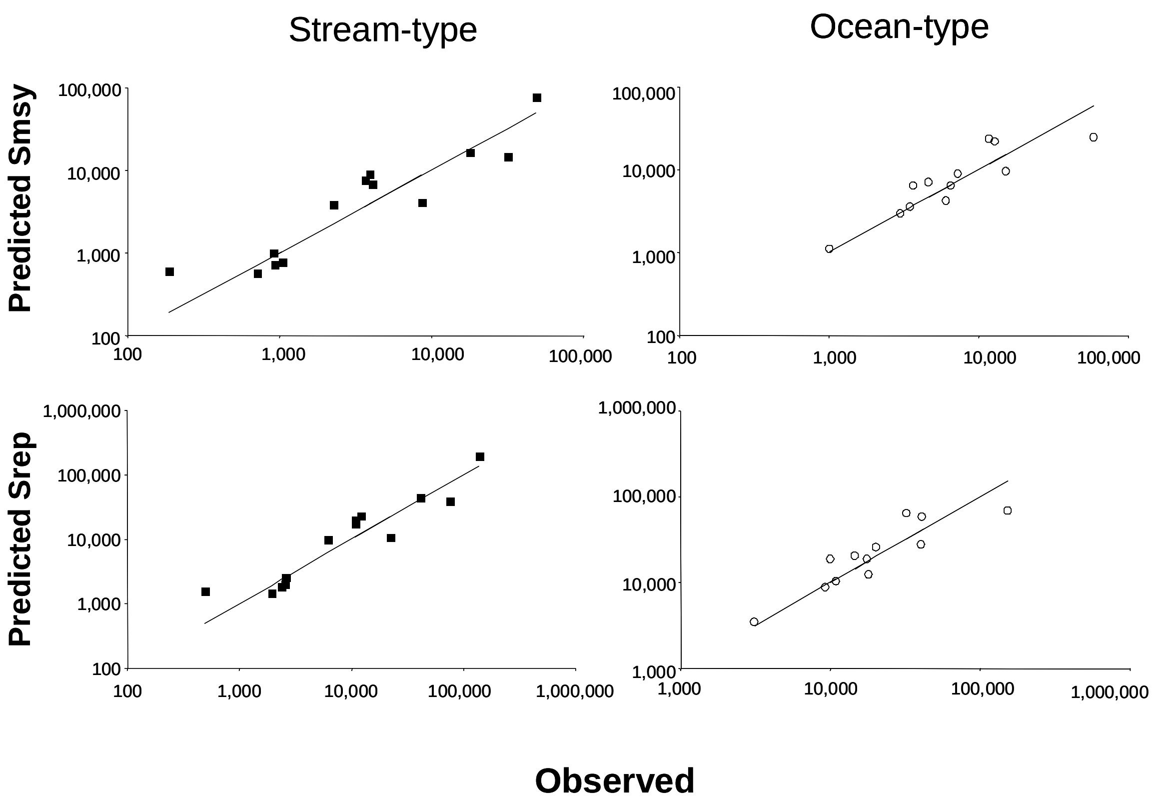

Figure 15. Performance of habitat-based models to predict Smsy and Srep from a leave-one-out analysis. Diagonal line is 1:1, indicating 100% accuracy.

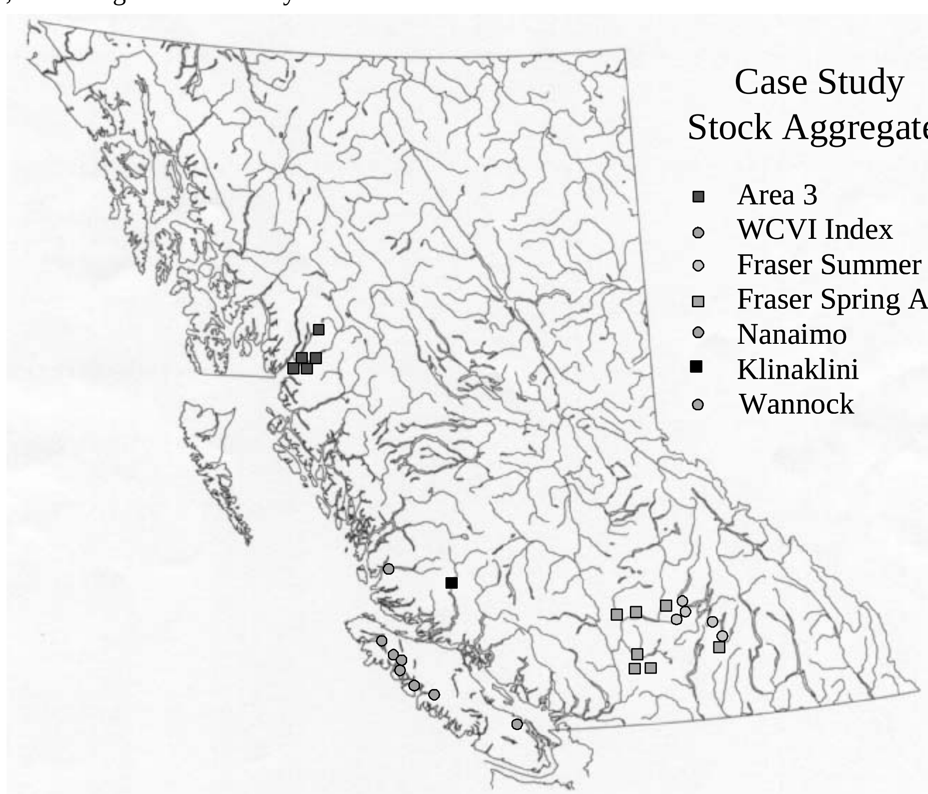

Figure 16. Locations of the case study stocks and stock aggregates.

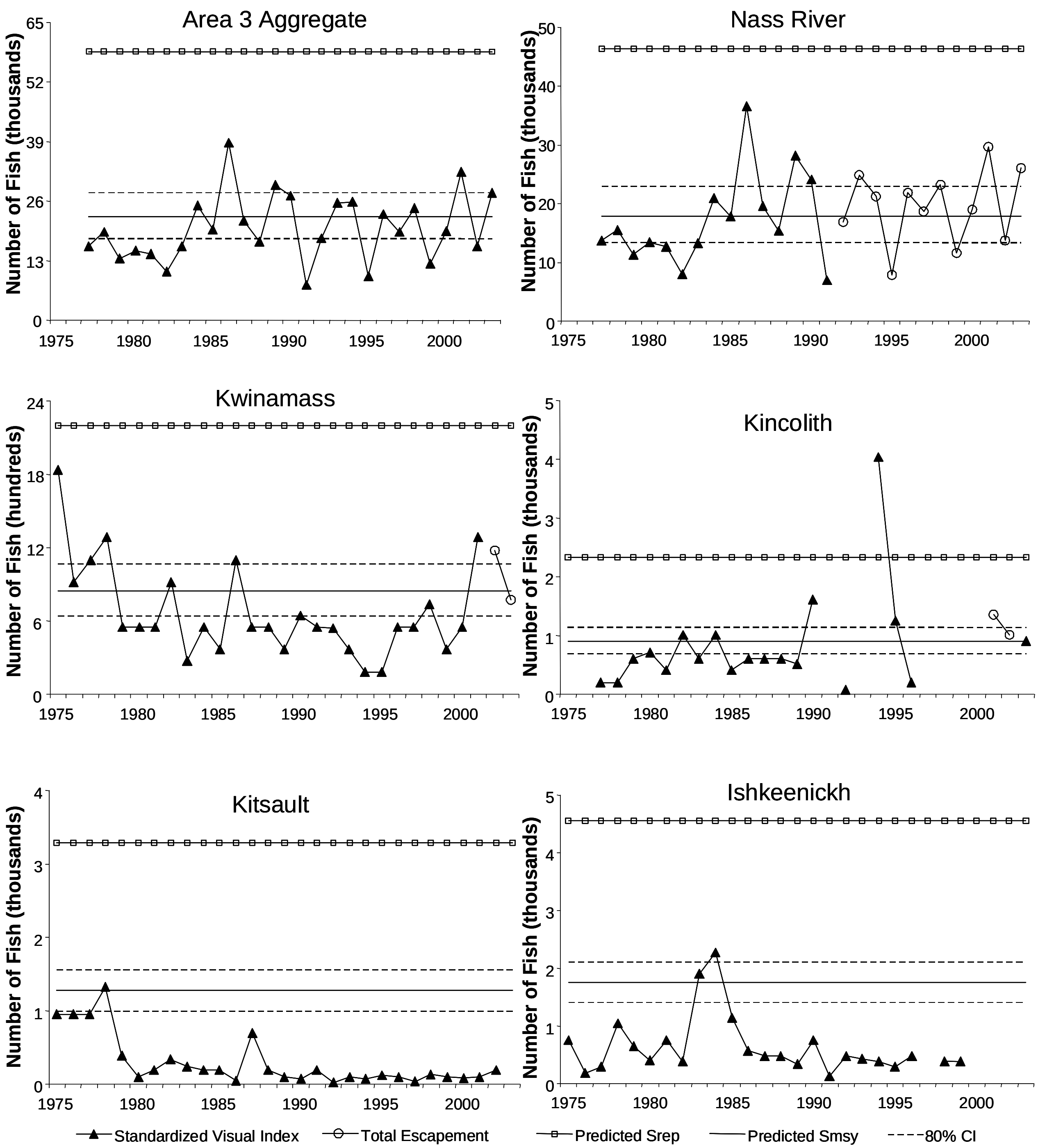

Figure 17. Comparison of habitat model predictions of Smsy and Srep to escapements estimated for the Area 3 stock aggregate and component stocks.

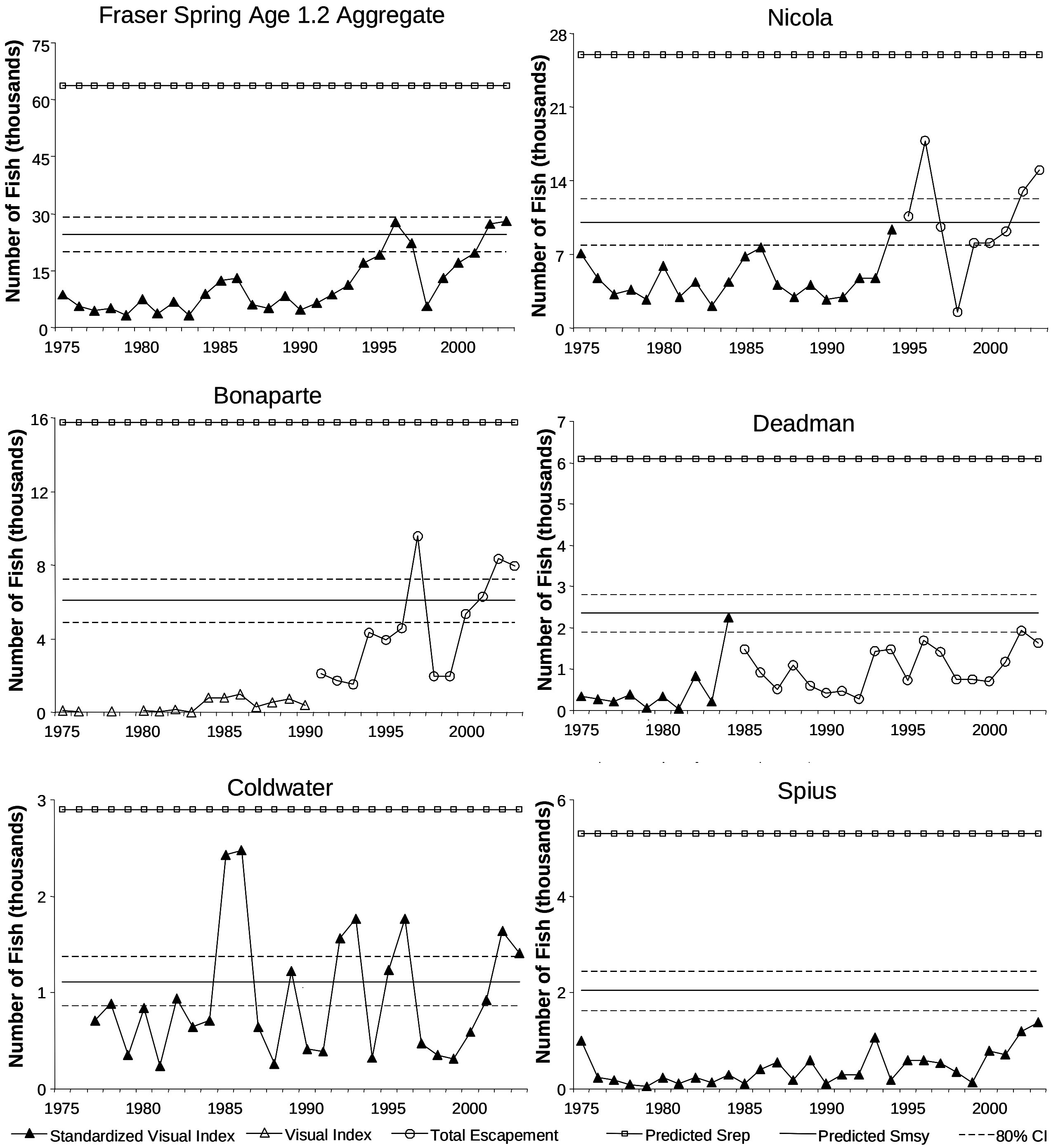

Figure 18. Comparison of habitat model predictions of Smsy and Srep to escapements estimated for the Fraser Spring-run Age 1.2 stock aggregate and component stocks. For Louis and Bessette see Figure 19.

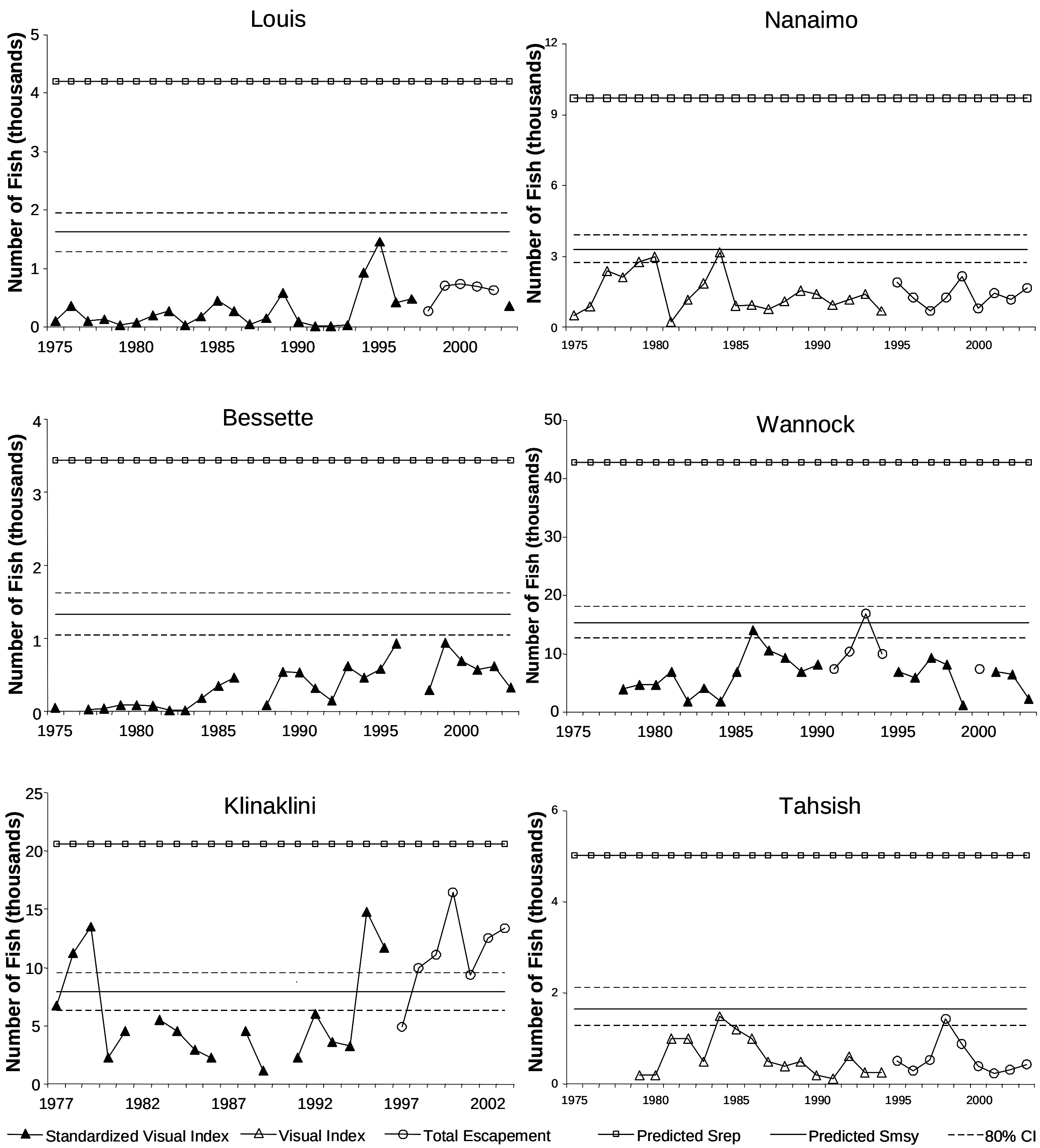

Figure 19. Comparison of habitat model predictions of Smsy and Srep to escapements estimated for the Louis, Bessette, Klinaklini, Nanaimo, Wannock, and Tahsish stocks.

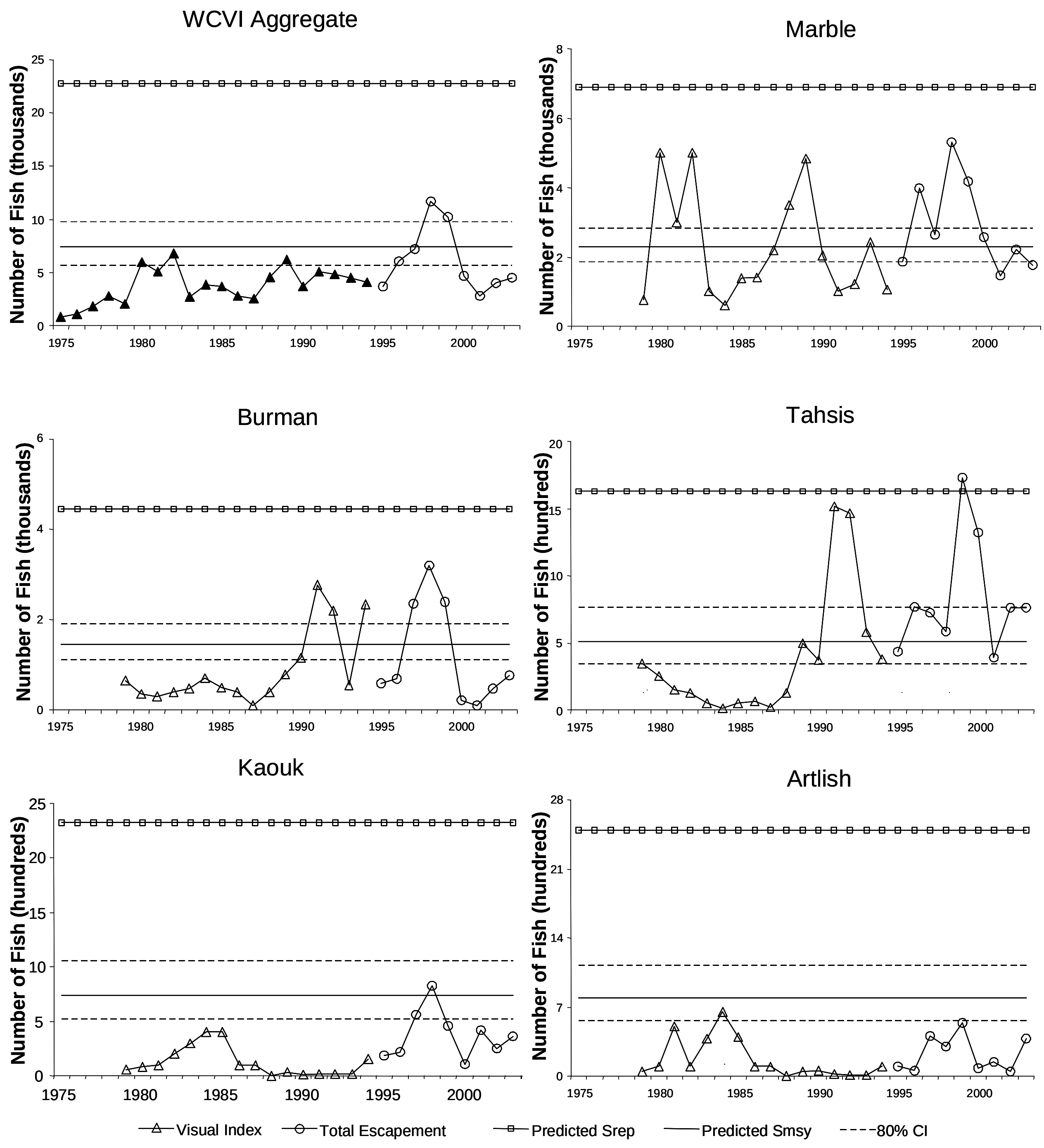

Figure 20. Comparison of habitat model predictions of Smsy and Srep to escapements estimated for the WCVI stock aggregate and component stocks. For Tahsish River see Figure 19.

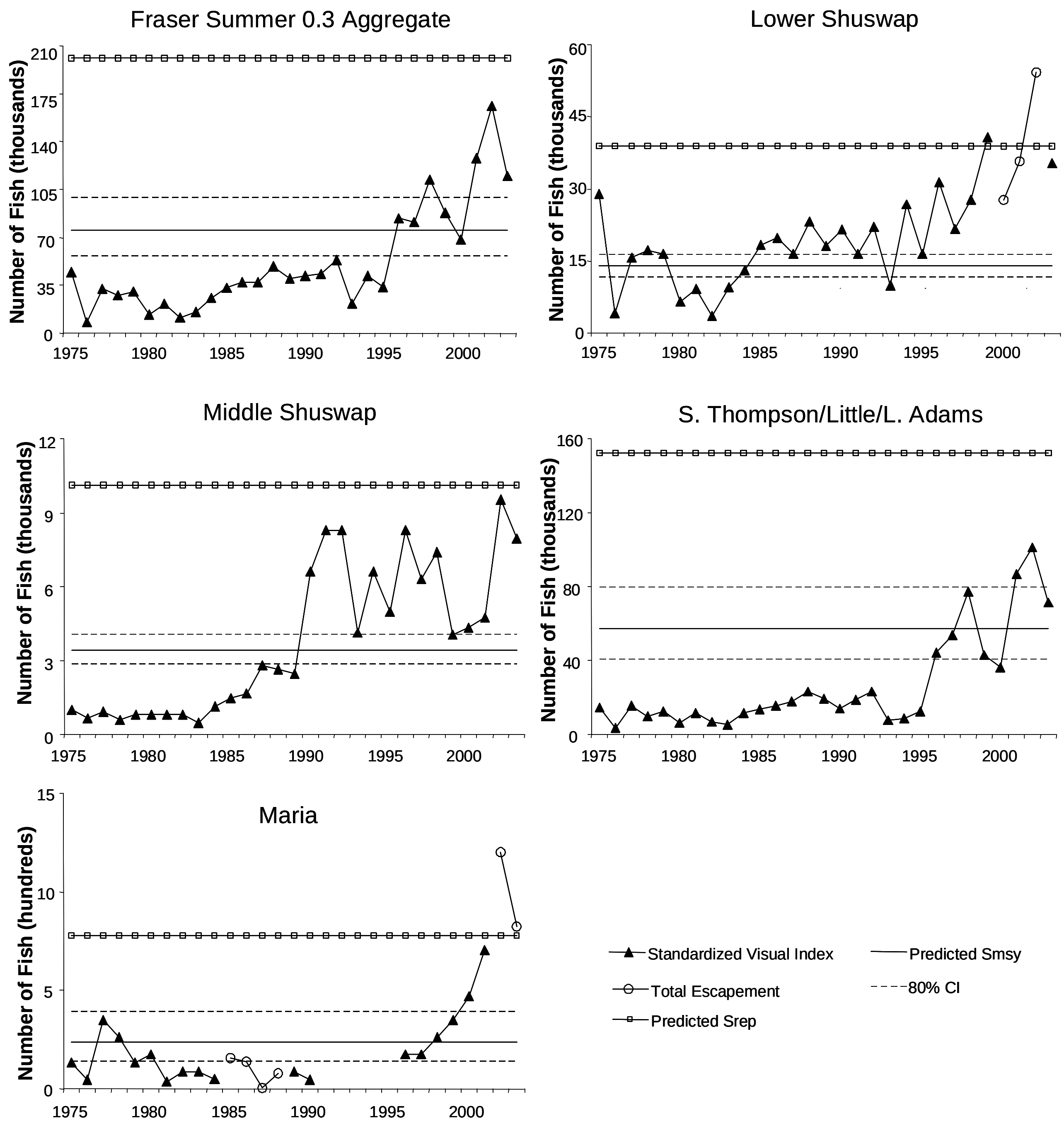

Figure 21. Comparison of habitat model predictions of Smsy and Srep to escapements estimated for the Fraser Summer-run Age 0.3 stock aggregate and component stocks.

11 Appendices

Appendix A. Descriptions of individual stock-recruitment analyses considered in the meta-analysis.

Stream-type stocks

Andrew Creek

Stock-recruitment data and analyses were prepared by Clark et al. (1998) and updated to include additional brood years, updated escapement survey expansion factors, exploitation rate data from Crystal Lake Hatchery, and adjustments for mean square error (MSE; provided by S. McPherson, pers. comm.). Escapements were estimated from weir counts for nine years, and for other years the visual survey (helicopter, fixed wing and/or foot) counts were expanded by a factor developed over four years with a concurrent weir program (McPherson et al. 2003). Age 1.1 (jacks) fish were excluded from the revised expansion factors. The quality of estimated escapements and recruitments is very good, though the preliminary estimates have not been reviewed by ADF&G.

Blossom River

Stock-recruitment data and analyses were prepared by McPherson et al. (2001) and updated to include additional brood years, updated escapement survey expansion factors, exploitation rate data from Unuk River, and recent age structure data (S. McPherson pers. comm.). Age structure data are limited and recent years (1998-2003) were averaged and applied to the time series. Escapements were estimated by mark-recapture for one year. For other years, the visual survey (helicopter) counts were expanded by the Keta River expansion factor developed over three years with a concurrent mark-capture program, which corresponds well with the 1998 and 2004 Unuk River expansion factors. Autocorrelation was detected, but parameters have not yet been corrected, and the residuals have a non-stationary pattern. The quality of estimated escapements and recruitments is fair, though the preliminary estimates have not been reviewed by ADF&G.

Chena River (tributary to Yukon River)

Stock-recruitment data and analyses were prepared by Evenson (2002) and updated to include additional brood years (M. Evenson, pers. comm.). Escapements were estimated from mark-recapture methods for seven years, and tower counts at Moose Creek dam for other years. Age 1.1 fish (jacks) were included in estimates of spawners and recruitment. The quality of estimated escapements is good and of recruitments is fair, since the Yukon River harvest rate was not directly measured and an assumed harvest rate was used to represent harvest on this stock within the Yukon River. Estimated Smsy was insensitive to harvest rate assumptions, but estimated Srep was a little more sensitive. Additional harvest rate information may be available from a 2004 telemetry study.

Chickamin River

Stock-recruitment data and analyses were prepared by McPherson and Carlile (1997) and updated to include additional brood years, updated escapement survey expansion factors, and adjustments for MSE (S. McPherson pers. comm.). Escapements were estimated by mark-recapture methods for five years, and for other years the visual survey (helicopter and foot) counts were expanded by a factor developed during five years with a concurrent mark-capture program (McPherson et al. 2003). Autocorrelation was detected, but parameters have not yet been corrected, and the residuals have a non-stationary pattern. The quality of estimated escapements is excellent and of recruitments is very good, though the preliminary estimates have not been reviewed by ADF&G.

Keta River
Stock-recruitment data and analyses were prepared by McPherson and Carlile (1997) and updated to include additional brood years, updated escapement survey expansion factors, and adjustments for MSE (S. McPherson pers. comm.). Escapements were estimated by mark-recapture methods for three years, and for other years the visual survey (helicopter) counts were expanded by a factor developed over three years with a concurrent mark-capture program (McPherson et al. 2003). Exploitation rate data from the Unuk River were used to estimate recruitments. Autocorrelation was detected, but parameters have not yet been corrected, and the residuals have a non-stationary pattern. The quality of estimated escapements is very good and of recruitments is fair, though the preliminary estimates have not been reviewed by ADF&G.

King Salmon River
Stock-recruitment data and analyses were prepared by McPherson and Clark (2001) and updated to include adjustments for MSE (S. McPherson pers. comm.). Escapements were estimated from weir counts for 10 years, and for other years the visual survey (helicopter and/or foot) counts were expanded by a factor developed over 10 years with a concurrent mark-capture program (McPherson et al. 2003). The quality of estimated escapements is excellent and of recruitments is good.

Kitsumkalum River
Stock-recruitment data and analyses were prepared by McNicol (1999) and updated to include additional brood years and adjustments for MSE (G. Brown, pers. comm.). Escapements were estimated by mark-recapture for 14 years and the quality of estimated escapements and recruitments is good.

Klukshu River
Stock-recruitment data and analyses were prepared by McPherson et al. (1998). Parameters were adjusted for MSE, but not adjusted for measurement error, so Smsy and Srep may be biased high. We intend to adjust parameters for measurement error when time permits. Escapements were estimated by weir counts for 16 years and their quality is excellent. The quality of recruitments is good, though these data are based on the assumption that Klukshu fish represented 55% of the Alsek harvests. Age 1.1 fish were included in estimates of spawners and recruitment. The spawner abundance data have low contrast and all were greater than the estimated Smsy.

Salcha River (tributary to Yukon River)
Stock-recruitment data and analyses were prepared by Evenson (2002) and updated to include additional brood years (M Evenson pers. comm.). Escapements were estimated by mark-recapture methods for seven years and for other years by tower counts. Age 1.1 fish were included in estimates of spawners and recruitment. The quality of estimated escapements is good and of recruitments is fair, since an assumed harvest rate was used to represent harvest on this stock within the Yukon River. Estimated Smsy was insensitive to harvest rate assumptions, but estimated Srep was a little more sensitive. Additional harvest rate information may be available from a 2004 telemetry study.

Stikine River
Stock-recruitment data and analyses were prepared by Bernard et al. (2000) and updated to include additional brood years, updated escapement survey expansion factors, and adjustments for MSE (S. McPherson pers. comm.). Parameters were not adjusted for measurement error and may be biased high. Escapements were estimated by mark-recapture methods for seven years, and for other years the visual survey (helicopter) and Tahltan weir counts were expanded by a factor developed during seven years with a concurrent mark-capture program (McPherson et al. 2003). The quality of estimated escapements is excellent and of recruitments is very good, though the preliminary estimates have not been reviewed by ADF&G.

Taku River
Stock-recruitment data and analyses were prepared by McPherson et al. (2000). Parameters were not adjusted for measurement error and may be biased high; we intend to adjust for parameters measurement error when time permits. Escapements were estimated by mark-recapture methods for five years, and for other years the visual survey (helicopter) counts were expanded by a factor developed over five years with a concurrent mark-capture program (McPherson et al. 2003). The quality of estimated escapements and of recruitments is fair, but the stock-recruit residuals have a non-stationary pattern.

Unuk River
Stock-recruitment data and analyses were prepared by McPherson and Carlile (1997) and updated to include additional brood years, updated escapement survey expansion factors, and adjustments for MSE (S. McPherson pers. comm.). Escapements were estimated by mark-recapture methods for eight years, and for other years the visual survey (helicopter and foot) counts were expanded by a factor developed over five years with a concurrent mark-capture program (McPherson et al. 2003). Age structure data are available for 1982 to 2003 and the average was applied to earlier years. The quality of estimated escapements is excellent and of recruitments is very good; the preliminary estimates have not been reviewed by ADF&G.

Upper Columbia Spring-Run
Stock-recruitment data were summarized by Beamsderfer et al. (1997). Since productivity was significantly lower during the period following the completion of the Snake River dams (post 1969; Schaller et al. 1999), only brood years 1939-1969 were included. Parameters were adjusted for autocorrelation and MSE (G. Brown and L. Godbout, pers. comm.). Escapements were estimated from counts at Bonneville dam and the quality of estimated escapements and of recruitments is good (Schaller et al. 2000).

Stream-type stocks excluded from analysis
Nelson River
Stock-recruitment data were prepared by Nelson et al. (draft 2004) and updated to include additional brood years, spawners in the David's River, and adjusted for MSE (J. Hasbrouck pers. Comm.; G. Brown, pers. comm.). In the Nelson River mainstem, escapements were estimated by weir and/or tower counts for 13 years and combined with visual indices in areas below the weir site, and for three years only visual indices of escapements were available. Weir counts are primarily fielded to count sockeye and therefore do not span the full temporal extent of the Chinook run. In the David's River tributary, escapements were estimated by visual surveys. No calibration information was available to describe the accuracy of the visual survey estimates and visual indices were not adjusted to total escapement. Age composition data for spawners and recruits were based on age composition in a commercial fishery targeting sockeye at the mouth of the Nelson River. Age 1.1 fish were included in estimates of recruitment, but not spawners. The quality of estimated escapements and recruitments was considered poor and the preliminary estimates have not been reviewed by ADF&G.

Ocean-type Stocks
Chehalis River Falls
Stock-recruitment data and analyses were prepared by Goodman (2003a). Escapements were estimated by weekly visual surveys (foot, boat, and helicopter) of redds and expanded by standard expansion factors. The quality of estimated escapements and recruitments is fair.

Cowichan River
Stock-recruitment data and analyses were prepared by Tompkins et al. (2005). Escapements were estimated from weir counts (five years), partial fence counts expanded by an cumulative run curve (four

years), mark-recapture methods (one year), and visual counts (divers) expanded by factors developed during years with concurrent weir and mark-recapture programs. The quality of estimated escapements and recruitments is fair, since some escapement and terminal catch estimates are uncertain. The stock-recruitment relationship included a covariate for marine survival.

Harrison River
Stock-recruitment data and analyses were prepared by Brown et al. (2001) and updated to include additional brood years. Escapements were estimated from mark-recapture methods. The quality of estimated escapements is excellent and recruitments is good. The stock-recruitment relationship included a covariate for marine survival.

Humptulips River
Stock-recruitment data and analyses were prepared by Goodman (2003a). Escapements were estimated by weekly visual surveys (foot, boat, and helicopter) of redds and expanded by standard expansion factors. The quality of estimated escapements and recruitments is fair. The stock-recruitment relationship included a covariate for marine survival.

Lewis River Falls
Stock-recruitment data and analyses were prepared by CTC (1999) and parameters were adjusted for MSE (G. Brown pers. comm.). Escapements were estimated by weekly visual surveys of live and dead fish, and peak counts were expanded by a factor developed during one year with a concurrent mark-capture program. The quality of estimated escapements and recruitments is good.

Nehalem River
Stock-recruitment data and analyses were prepared by Zhou and Williams (1999) and parameters were adjusted for MSE (G. Brown pers. comm.). Escapements were estimated by weekly visual surveys (foot) of live and dead fish, and peak counts per mile were expanded by an average factor developed from several rivers in the north Oregon coast. The quality of estimated escapements is fair and of recruitments is fair. To improve their quality, expansion factors were developed from concurrent visual survey and mark-recapture programs from 1998 to 2002, but stock-recruitment parameters have not yet been updated (White et al. 2003).

Siletz River
Stock-recruitment data and analyses were prepared by Zhou and Williams (2000) and parameters were adjusted for MSE (G. Brown pers. comm.). Escapements were estimated by weekly visual surveys (foot) of live and dead fish, and peak counts per mile were expanded by an average factor developed from several rivers in the north Oregon coast. The quality of estimated escapements is fair and of recruitments is fair.

Situk River
Stock-recruitment data were prepared by McPherson et al. (in prep) and updated to include medium size spawners (age *x*.2) and to adjust parameters for autocorrelation and MSE, though the residuals still have a non-stationary pattern (D. Bernard pers. comm.). Escapements were estimated from weir counts (McPherson et al. 2003). The quality of estimated escapements and recruitments is excellent and the preliminary estimates have not been reviewed by ADF&G.

Siuslaw River
Stock-recruitment data and analyses were prepared by Zhou and Williams (2000) and parameters were adjusted for MSE (G. Brown pers. comm.). Escapements were estimated by weekly visual surveys (foot) of live and dead fish, and peak counts per mile were expanded by an average factor developed from several rivers in the north Oregon coast. The quality of estimated escapements is fair and recruitments is

fair. To improve their quality, expansion factors were developed from concurrent visual survey and mark-recapture programs from 1998 to 2002, but stock-recruitment parameters have not yet been updated (Weeks et al. 2003).

Skagit River

Stock-recruitment analyses were prepared by N. Sands (pers. comm.). Escapements were estimated by weekly or biweekly visual surveys (helicopter and foot) of redds by the area-under-the-curve method (Smith and Castle 1994). Estimation of survey life and expansion factors were developed by Orrell (1976 cited in Smith and Castle 1994). The quality of estimated escapements and recruitments is good and the stock-recruitment relationship included covariates for marine survival and river discharge.

Quillayute

Stock-recruitment parameters were provided by P. Goodman (pers. comm.). Escapements were estimated by weekly visual surveys (foot, boat, and helicopter) of redds and expanded by standard expansion factors. The quality of estimated escapements and recruitments is fair.

Queets

Stock-recruitment data and analyses were prepared by Goodman (2003b). Escapements were estimated by weekly visual surveys (foot, boat, and helicopter) of redds and expanded by standard expansion factors. The quality of estimated escapements and recruitments is fair. The stock-recruitment relationship included a covariate for marine survival.

Ocean-type stocks excluded from analysis

Columbia Hanford-Yakima-Upriver Bright and Above Priest Rapids Dam (HYURB-APR)

Stock-recruitment data and analyses were prepared by Langness and Reidinger (2003). The stock was excluded because the construction of mainstem dams and reservoirs has resulted in substantial suitable spawning and rearing habitat area being flooded. Consequently, watershed area would likely grossly overestimate spawner capacity for this system. For this reason, this system was not considered representative of habitat conditions experienced by data-limited Canadian stocks.

Klamath

Stock-recruitment data and analyses were prepared by Mohr and Prager (draft 1999), Prager and Mohr (2001), and updated to include recent brood years, adjust spawner estimates to age 0.2 and older fish, adjust recruitment estimates to pre-fishery AEQ values, and adjust parameters for MSE (M. Mohr pers. comm.). The stock was excluded because the dynamics of hatchery salmon could not be separated from natural salmon and assumptions of their age structure. A constant factor was used to divide the stock into natural and hatchery components, and during years with high returns to hatcheries, hatchery gates were closed forcing hatchery-origin fish to spawn naturally. Also, the age structure of hatchery and natural area spawners was not available prior to 1991. Data quality is good after 1991, and as more data become available the influence of age structure and hatchery contribution assumptions can be assessed.

Appendix B. Descriptions of watershed area estimation for habitat model stocks.
Among the 27 stocks with stock-recruitment relationships, 18 were considered entirely accessible (Table B.1). Watershed area data were available from several sources including Water Survey of Canada (WSC) and United States Geological Service (USGS) river discharge stations, BC stream atlas database, published reports, and agency staff.

Appendix Table B.1. Watershed areas for stocks with stock-recruitment relationships.

River	Type of Barrier	Watershed Area	Watershed Area Source
Andrew	None identified	126	Kevin Brownlee, ADF&G pers. comm
Blossom	None identified	176	USGS 15011894
Chickamin	None identified	1,696	Kevin Brownlee, ADF&G pers. comm
Cowichan	None identified	1,227	WALP Watershed Atlas
Humptulips	None identified	635	Seiler 1989
Keta	None identified	193	USGS 15011880
King Salmon	None identified	93	Kevin Brownlee, ADF&G pers. comm
Kitsumkalum	None identified	2,255	WALP Watershed Atlas
Klukshu	None identified	260	McPherson et al. 1998
Nehalem	None identified	1,728	USGS 14301000
Queets	None identified	1,164	Abbe and Montgomery 1996
Quillayute	None identified	1,313	USGS 12043015 & 12042500
Salcha	None identified	5,620	USGS 15484000
Siletz	None identified	524	Zhou and Williams 2000
Situk	None identified	176	Kevin Brownlee, ADF&G pers. comm
Siuslaw	None identified	2,010	Kenaston et al. 2001
Unuk	None identified	3,885	Pahlke 2001
Chehalis	Man-made	4,390	Several described in text
Lewis	Man-made	825	Several described in text
Chena	Inhospitable sub-basin	4,515	USGS 15511000 & Matt Evenson, ADF&G, pers. comm.
Harrison	Natural	8,438	WLAP Watershed Atlas
Taku	Natural	15,539	Several described in text
Stikine	Natural	15,337	Several described in text
Skagit	Man-made	4,198	Several described in text
Upper Columbia Spring	Man-made and natural	114,434	Several described in text
Klamath	Man-made	16,561	Several described in text
HYURB-APR	Man-made and natural	31,310	Several described in text

Several watersheds had man-made barriers to migration. At the Chehalis River watershed (4,610 Km^2; USGS 12035100), Skookumchuck Dam blocked migration to upstream areas (290 Km^2; USGS 12026400). At the Lewis River watershed (2,709 Km^2; http://vulcan.wr.usgs.gov/Volcanoes/MSH/Hydrology/Drainages/Lewis/framework.html), Merwin Dam blocked access to upstream areas (1,893 Km^2; USGS 14220500). At the Skagit River watershed (8,011 Km^2; USGS 12200500), Gorge Dam at Newhalem (3,043 Km^2; USGS 12178000) and the Lower Baker Dam at Concrete (769 Km^2; USGS 12193500) blocked access to upstream areas.

The construction of dams and irrigation practices limited the areas accessible to salmon to about 53% of the Klamath watershed (NRC 2003; 31,339 Km^2; USGS 11530500). Iron Gate Dam (11,992 Km^2; USGS 11516530), Lewiston Dam (1,862 Km^2; USGS 1152500), and Dwinnel Dam (311 Km^2) blocked access to upstream areas. In addition, numerous small dams block the movement of salmon and irrigation practices contribute to the complete dewatering of tributaries in the Shasta and Scott watersheds (~694 Km^2).

Several watersheds had natural barriers to migration or sub-basins with inhospitable conditions for Chinook production. Within the Harrison River watershed (8,438 Km^2; BC stream atlas), a falls on Green River, a 5^{th} order river, blocked access to upstream areas (827 Km^2; BC stream atlas). At the Taku River watershed (17,094 Km^2; USGS 15041200), a falls on Nakina River, a 7^{th} order river, blocked migration to upstream areas (1,555 Km^2; BC stream atlas). At Chena River, Chinook were not distributed in the Little Chena River (ADF&G Fish Distribution Database), presumably because it was inhospitable, and its watershed area was excluded.

About 70% of the Stikine River watershed (51,593 Km^2; USGS 15248000) was inaccessible. A velocity barrier on the mainstem Stikine River, an 8^{th} order system, blocks access to upstream areas (21,164 Km^2; BC stream atlas). A velocity barrier on the mainstem Iskut River, a 7^{th} order system, blocks access to upstream areas (7,360 Km^2; BC stream atlas). Among 6^{th} order systems, natural migration barriers occur on Tuya (3,576 Km^2; BC stream atlas), Mess (2,306 Km^2; BC stream atlas), Klastline systems (1,851 Km^2; BC stream atlas).

For the Columbia River spring-run aggregate, about 82% of the watershed upstream of Bonneville Dams was inaccessible due to natural and man-made barriers, and other anthropogenic actions. The total area upstream of Bonneville Dam was estimated from the area upstream of The Dalles Dam and the Wind, Hood, and Klickitat watersheds located between Bonneville and The Dalles dams (Table B.2). Salmon distribution was limited by natural barriers, dams, or water diversions on several systems (Table B.3).

For other Columbia systems, migration barriers or other anthropogenic conditions contributed to the extirpation of spring-run Chinook salmon during the period corresponding to the stock-recruitment analyses (Nelson et al. 1991; Myers et al. 1998 ICBTR draft 2003). Three Mile Dam blocked access to the Umatilla River and several irrigation dams blocked access in the Walla Walla River. In the Clearwater River, spring Chinook distribution was blocked by the Lewiston Dam in 1927. Mining activities contributed to Chinook extirpation at Panther Creek and East Fork South Fork Salmon River (Reiser et al. 2000; ICBTR draft 2003). Little is known about the historic distribution and abundance of spring-run Chinook salmon in the Okanogan watershed, but the stock status was certainly influenced by the Grand Coulee Fish Maintenance Project (GCFMP; Ford et al. 2001). From 1939 to 1943, all spring-run Chinook salmon were intercepted at Rock Island Dam and transferred to the Wenatchee, Entiat, or Methow rivers or hatcheries, and no adults or juveniles were transferred to the Okanogan watershed.

The Columbia HYURB-APR stock returns to the Columbia River mainstem and upstream of Pasco, Washington (269,539 Km^2; USGS 12514000), yet only about 12% of this area appears accessible. The same natural and man-made barriers that influence the distribution of spring-run Chinook salmon were used to estimate the HYURB-APR distribution, except for the Okanogan watershed. Summer-run Chinook salmon either re-colonized or were re-introduced to the Okanogan River, but were not re-introduced into Canada. Accordingly, the Okanogan watershed upstream of Oroville, Washington was considered inaccessible during the period corresponding to the stock-recruitment time series (8,114Km^2; USGS 12439100). Dams on the Similkameen River (9,272 Km^2; USGS 12442500) and Salmon Creek (313 Km^2; http://www.usbr.gov/dataweb/dams/index.html) block migration.

Appendix Table B.2. Summary of the accessible and inaccessible watershed areas for the Columbia Spring stock.

Watershed	Area (Km^2)	Source
Columbia River above The Dalles Dam	613,827	USGS 14105700
Wind River	583	USGS 14128500
Hood River	852	USGS 14105700
Klickitat River	3,359	USGS 14105700
Total above Bonneville Dam	**618,621**	
Total Inaccessible Areas due to natural barriers	32,041	(Table B.3)
Total Inaccessible Areas due to dams	412,838	(Table B.3)
Total Inaccessible Areas due to anthropogenic extirpations	59,308	(Table B.3)
Total Accessible Areas	**114,434**	

Appendix Table B.3. Description of migration barriers and corresponding inaccessible watershed areas for Columbia Spring-run distribution.

Watershed	Barrier type	Description	Inaccessible Watershed Area	Source
Columbia	Dam	Chief Joseph	196,062	USGS 12438000
Deschutes	Dam	Pelton	20,565	USGS 14093500
Deschutes	Dam	Shitike Diversion	269	USGS 14093000
Big White Salmon	Dam	Condit	1,000	USGS 14123500
Foster Creek	Dam	Irrigation Diversion	712	PGG 2003
Wenatchee	Dam	Dryden Dam	552	USGS 12458500
Yakima	Dam	Tieton River	484	USGS 12491500
Yakima	Dam	Cle Elum River	526	USGS 12479000
Yakima	Dam	Kachess River	165	USGS 12479000
Yakima	Dam	Near Martin	142	USGS 12474500
Yakima	Dam	Ahtanum Creek	448	USGS 12502500
Yakima	Dam	Manatash Creek	192	USGS 12483500
Yakima	Dam	Taneum Creek	193	USGS 12483500
Yakima	Dam	Cowiche Creek	311	YRBPU 2001
Yakima	Dam	Naneum Creek	180	USGS 12483800
Yakima	Dam	Wilson Creek	989	YRBPU 2001
Snake	Dam	Hells Canyon	189,846	USGS 13290450
Grande Ronde	Dam	Looking Glass	203	USGS 13324300
Sub-total Inaccessible			**412,838**	
Chelan	Natural barrier	-	2,393	USGS 12452500
Crab	Natural barrier	-	12,535	USGS 12472600
Esquatzel Coulee	Natural barrier	-	2,067	USGS 12513650
Moses Coulee	Natural barrier	-	2,398	USGS HUC 17020012
Willow	Natural barrier	-	2,201	USGS 14036000
Wind	Natural barrier	Shipherd Falls	583	USGS 14128500
White River (Deschutes)	Natural barrier	-	1,080	USGS 14101500
Hay Creek (Deschutes)	Natural barrier	-	202	USGS 14109500
Little White Salmon	Natural barrier	-	347	USGS 14125500
Palouse	Natural barrier	Palouse Falls	8,234	USGS 13351000 & 13352500
Sub-total Inaccessible			**32,041**	
Umatilla	extirpation	3 Mile Dam	6,579	Streamnet
Walla Walla	extirpation	Irrigation dams	4,558	USGS 14019000
Clearwater	extirpation	Lewiston Dam	24,968	USGS 13343000
Panther	extirpation	Mining activities	1,323	Reiser et al. 2000
East Fork S. F. Salmon	extirpation	Mining activities	542	
Okanogan	extirpation	GCFMP	21,290	USGS 12447300
Sub-total Inaccessible			**59,309**	

Appendix C. Summary of visual indices (VI), total escapements (TE), and standardized visual indices (SVI) for case study stocks.

Appendix table C.1. Summary of visual indices (VI), total escapements (TE), and standardized visual indices (SVI) for the Klinaklini, Nanaimo, and Wannock stocks.

	Klinaklini			Nanaimo		Wannock		
Year	VI	TE	SVI	VI	TE	VI	TE	SVI
1975	1,500	na	6,742	475	na	na	na	na
1976	2,500	na	11,237	880	na	na	na	na
1977	3,000	na	13,484	2,380	na	na	na	na
1978	500	na	2,247	2,125	na	1,700	na	4,256
1979	1,000	na	4,495	2,741	na	2,000	na	5,007
1980	na	na	na	2,982	na	2,000	na	5,007
1981	1,220	na	5,484	225	na	3,000	na	7,511
1982	1,000	na	4,495	1,152	na	750	na	1,878
1983	650	na	2,922	1,840	na	1,750	na	4,381
1984	500	na	2,247	3,178	na	750	na	1,878
1985	na	na	na	914	na	3,000	na	7,511
1986	1,000	na	4,495	958	na	6,000	na	15,022
1987	250	na	1,124	757	na	4,500	na	11,266
1988	na	na	na	1,079	na	4,000	na	10,015
1989	500	na	2,247	1,552	na	3,000	na	7,511
1990	1,350	na	6,068	1,397	na	3,500	na	8,763
1991	805	na	3,618	935	na	2,000	7,328	na
1992	720	na	3,236	1,177	na	7,500	10,332	na
1993	3,290	na	14,788	1,378	na	8,000	16,895	na
1994	2,600	na	11,686	680	na	3,500	10,014	na
1995	2,100	4,906	na	na	1,903	3,000	na	7,511
1996	1,500	9,980	na	na	1,247	2,500	na	6,259
1997	na	11,068	na	na	690	4,000	na	10,015
1998	na	16,429	na	na	1,262	3,500	na	8,763
1999	na	9,355	na	na	2,162	500	na	1,252
2000	na	12,529	na	na	780	4,500	7,443	na
2001	na	13,365	na	na	1,442	3,000	na	7,511
2002	na	na	na	na	1,158	2,800	na	7,010
2003	na	na	na	na	1,674	1,000	na	2,504

na indicates that no estimate was available.

Appendix table C.2. Summary of visual indices (VI), total escapements (TE), and standardized visual indices (SVI) for the Area 3 stock aggregate.

	Stock Aggregate	Nass		Kincolith			Kwinamass			Ishkeenickh		Kitsault	
Year	SVI	SVI	TE	VI	TE	SVI	VI	TE	SVI	VI	SVI	VI	SVI
1977	16,226	13,688	na	100	na	202	600	na	1,102	150	285	500	949
1978	19,345	15,485	na	100	na	202	700	na	1,286	550	1,044	700	1,328
1979	13,435	11,253	na	300	na	606	300	na	551	340	645	200	380
1980	15,228	13,476	na	350	na	707	300	na	551	210	399	50	95
1981	14,529	12,625	na	200	na	404	300	na	551	400	759	100	190
1982	10,599	7,959	na	500	na	1,010	500	na	918	200	380	175	332
1983	16,278	13,252	na	300	na	606	150	na	276	1,000	1,898	130	247
1984	24,995	20,967	na	500	na	1,010	300	na	551	1,200	2,277	100	190
1985	19,882	17,782	na	200	na	404	200	na	367	600	1,139	100	190
1986	38,848	36,523	na	300	na	606	600	na	1,102	300	569	25	47
1987	21,874	19,540	na	300	na	606	300	na	551	250	474	370	702
1988	17,166	15,345	na	300	na	606	300	na	551	250	474	100	190
1989	29,432	28,133	na	250	na	505	200	na	367	175	332	50	95
1990	27,145	24,051	na	800	na	1,616	350	na	643	400	759	40	76
1991	7,774	6,907	na	UNK	na	na	300	na	551	67	127	100	190
1992	17,924	na	16,808	40	na	81	295	na	542	250	474	10	19
1993	25,705	na	24,814	UNK	na	na	200	na	367	226	429	50	95
1994	25,848	na	21,169	2,000	na	4,040	100	na	184	200	380	40	76
1995	9,680	na	7,844	616	na	1,244	100	na	184	150	285	65	123
1996	23,164	na	21,842	100	na	202	300	na	551	250	474	50	95
1997	19,291	na	18,702	UNK	na	na	300	na	551	na	na	20	38
1998	24,460	na	23,213	N/I	na	na	400	na	735	200	380	70	133
1999	12,386	na	11,544	UNK	na	na	200	na	367	200	380	50	95
2000	19,548	na	18,912	UNK	na	na	300	na	551	na	na	45	85
2001	32,418	na	29,687	na	1,350	na	700	na	1,286	na	na	50	95
2002	16,149	na	13,773	500	1,010	na	600	1,176	na	na	na	100	190
2003	27,767	na	26,087	450	na	909	450	771	na	na	na	na	na

na indicates that no estimate was available.

Appendix table C.3. Summary of visual indices (VI), total escapements (TE), and standardized visual indices (SVI) for the Fraser Spring-run Age 1.2 stock aggregate.

	Stock Aggregate	Nicola			Bonaparte		Spius		Coldwater		Deadman			Louis			Bessette	
Year	SVI	VI	TE	SVI	VI	TE	VI	SVI	VI	SVI	VI	TE	SVI	VI	TE	SVI	VI	SVI
1975	8,656	6,000	na	7,065	100	na	850	1,001	na[1]	na	250	na	348	54	na	99	25	44
1976	5,619	4,000	na	4,710	30	na	200	235	na[1]	na	200	na	278	200	na	366	na	na
1977	4,407	2,700	na	3,179	na	na	150	177	600	706	150	na	209	60	na	110	15	26
1978	5,239	3,100	na	3,650	50	na	80	94	750	883	280	na	390	75	na	137	20	35
1979	3,314	2,300	na	2,708	na	na	50	59	300	353	50	na	70	20	na	37	50	88
1980	7,552	5,000	na	5,887	75	na	200	235	710	836	250	na	348	45	na	82	50	88
1981	3,628	2,500	na	2,944	25	na	100	118	200	235	25	na	35	110	na	201	40	70
1982	6,870	3,750	na	4,416	150	na	200	235	800	942	600	na	835	150	na	274	10	18
1983	3,183	1,800	na	2,119	20	na	102	120	547	644	162	na	225	20	na	37	10	18
1984	8,783	3,700	na	4,357	800	na	256	301	598	704	1,626	na	2,262	100	na	183	100	176
1985	12,465	5,800	na	6,829	800	na	100	118	2,061	2,427	1,066	1,483	na	250	na	457	200	351
1986	13,185	6,500	na	7,654	993	na	350	412	2,100	2,473	945	923	na	150	na	274	260	457
1987	6,173	3,500	na	4,121	275	na	475	559	550	648	499	524	na	25	na	46	na	na
1988	5,230	2,490	na	2,932	525	na	150	177	220	259	1,013	1,103	na	80	na	146	50	88
1989	8,389	3,500	na	4,121	724	na	500	589	1,040	1,225	571	592	na	325	na	594	310	544
1990	4,673	2,300	na	2,708	380	na	100	118	350	412	225	437	na	50	na	91	300	527
1991	6,521	2,500	na	2,944	na	2,100	248	292	325	383	232	468	na	10	na	18	180	316
1992	8,759	4,028	na	4,743	na	1,732	250	294	1,332	1,568	241	270	na	6	na	11	80	140
1993	11,121	4,000	na	4,710	na	1,500	900	1,060	1,500	1,766	1,200	1,434	na	20	na	37	350	615
1994	17,052	7,970	na	9,385	na	4,301	150	177	275	324	1,591	1,476	na	510	na	933	260	457
1995	19,149	6,500	10,624	na	na	3,936	500	589	1,050	1,236	540	721	na	800	na	1,463	330	580
1996	27,757	16,400	17,777	na	na	4,588	500	589	1,500	1,766	1,506	1,695	na	na	na	420	525	922
1997	22,100	7,614	9,612	na	na	9,584	450	530	400	471	934	1,423	na	na	na	480	na	na
1998	5,537	1,211	1,547	na	na	1,966	300	353	300	353	665	760	na	na	268	na	165	290
1999	12,969	7,495	8,130	na	na	1,987	109	128	267	314	350	757	na	na	715	na	534	938
2000	16,967	8,808	8,108	na	na	5,357	668	787	497	585	787	711	na	na	733	na	391	687
2001	19,570	7,771	9,205	na	na	6,285	603	710	781	920	780	1,183	na	na	700	na	323	567
2002	27,247	11,628	13,024	na	na	8,368	869	1,023	1,394	1,641	1,940	1,940	na	na	636	na	350	615
2003	28,042	14,574	15,000	na	na	7,928	1,170	1,378	1,195	1,407	N/A	1,639	na	198	na	362	187	328

[1]1975 and 1976 Coldwater escapement estimates were added to Nicola River, since survey dates corresponded to the late-run spawners.
na indicates that no estimate was available.

Appendix table C.4. Summary of visual indices (VI) and total escapements (TE) for the WCVI stock aggregate.

	Stock Aggregate	Kaouk		Artlish		Burman		Tahsish		Tahsish		Marble	
Year	VI	VI	TE	VI	TE	VI	TE	VI	TE	VI	TE	VI	TE
1979	2,048	60	na	40	na	650	na	348	na	200	na	750	na
1980	5,974	80	na	100	na	345	na	249	na	200	na	5,000	na
1981	5,050	100	na	500	na	300	na	150	na	1,000	na	3,000	na
1982	6,813	200	na	100	na	388	na	125	na	1,000	na	5,000	na
1983	2,700	300	na	375	na	475	na	50	na	500	na	1,000	na
1984	3,862	400	na	650	na	700	na	12	na	1,500	na	600	na
1985	3,940	400	na	400	na	500	na	50	na	1,200	na	1,390	na
1986	3,070	100	na	100	na	400	na	60	na	1,000	na	1,410	na
1987	3,020	100	na	100	na	100	na	20	na	500	na	2,200	na
1988	4,425	na	na	na	na	400	na	125	na	400	na	3,500	na
1989	6,669	30	na	40	na	780	na	500	na	500	na	4,819	na
1990	3,825	10	na	50	na	1,165	na	370	na	200	na	2,030	na
1991	5,442	20	na	20	na	2,767	na	1,515	na	120	na	1,000	na
1992	5,502	20	na	10	na	2,198	na	1,463	na	600	na	1,211	na
1993	3,822	20	na	10	na	550	na	578	na	250	na	2,414	na
1994	4,260	150	na	100	na	2,330	na	380	na	250	na	1,050	na
1995	3,692	na	186	na	99	na	594	na	437	na	510	na	1,866
1996	5,996	na	220	na	53	na	693	na	770	na	290	na	3,970
1997	7,197	na	558	na	402	na	2,354	na	722	na	523	na	2,638
1998	11,643	na	824	na	300	na	3,205	na	587	na	1,430	na	5,297
1999	10,186	na	453	na	539	na	2,399	na	1,731	na	879	na	4,185
2000	4,675	na	105	na	75	na	212	na	1,320	na	391	na	2,572
2001	2,737	na	415	na	139	na	107	na	389	na	237	na	1,450
2002	4,036	na	251	na	41	na	472	na	758	na	308	na	2,206
2003	4,456	na	358	na	379	na	768	na	762	na	440	na	1,749

na indicates that no estimate was available.

Appendix table C.5. Summary of visual indices (VI), total escapements (TE), and standardized visual indices (SVI) for the Fraser Summer-run Age 0.3 stock aggregate.

	Stock Aggregate	Lower Shuswap			Middle Shuswap		Lower Adams[1]		Little		South Thompson		Maria		
Year	SVI	VI	TE	SVI	VI	SVI	VI	SVI	VI	SVI	VI	SVI	VI	TE	SVI
1975	44,438	17,500	na	28,932	600	992	1,300	2,149	400	661	7,000	11,573	75	na	132
1976	8,145	2,500	na	4,133	400	661	400	661	100	165	1,500	2,480	25	na	44
1977	32,424	9,500	na	15,706	550	909	1,750	2,893	600	992	7,000	11,573	200	na	351
1978	27,624	10,400	na	17,194	350	579	2,200	3,637	100	165	3,500	5,786	150	na	263
1979	30,221	10,000	na	16,532	500	827	1,000	1,653	700	1,157	6,000	9,919	75	na	132
1980	13,815	4,000	na	6,613	500	827	350	579	400	661	3,000	4,960	100	na	176
1981	21,693	5,500	na	9,093	500	827	700	1,157	400	661	6,000	9,919	20	na	35
1982	11,330	2,200	na	3,637	500	827	500	827	100	165	3,500	5,786	50	na	88
1983	15,711	5,800	na	9,589	300	496	250	413	100	165	3,000	4,960	50	na	88
1984	25,665	7,892	na	13,047	700	1,157	650	1,075	250	413	6,000	9,919	30	na	53
1985	33,509	11,125	na	18,392	900	1,488	750	1,240	400	661	7,000	11,573	200	155	na
1986	37,090	12,000	na	19,839	1,000	1,653	2,500	4,133	350	579	6,500	10,746	110	140	na
1987	37,037	10,000	na	16,532	1,700	2,811	2,000	3,306	200	331	8,500	14,053	4	4	na
1988	48,847	14,000	na	23,145	1,600	2,645	1,500	2,480	400	661	12,000	19,839	67	77	na
1989	40,013	11,000	na	18,186	1,500	2,480	1,250	2,067	400	661	10,000	16,532	50	na	88
1990	42,036	13,000	na	21,492	4,000	6,613	2,000	3,306	400	661	6,000	9,919	25	na	44
1991	43,397	10,000	na	16,532	5,000	8,266	3,000	4,960	250	413	8,000	13,226	na	na	na
1992	53,234	13,300	na	21,988	5,000	8,266	1,300	2,149	600	992	12,000	19,839	na	na	na
1993	21,988	6,000	na	9,919	2,500	4,133	800	1,323	n/r	na	4,000	6,613	na	na	na
1994	41,910	16,150	na	26,700	4,000	6,613	1,800	2,976	400	661	3,000	4,960	na	na	na
1995	33,974	10,000	na	16,532	3,000	4,960	1,900	3,141	150	248	5,500	9,093	na	na	na
1996	84,160	19,000	na	31,412	5,000	8,266	2,200	3,637	3,000	4,960	21,600	35,710	100	na	176
1997	81,432	13,100	na	21,657	3,800	6,282	3,400	5,621	1,850	3,058	27,000	44,637	100	na	176
1998	112,490	16,704	na	27,616	4,474	7,397	4,182	6,914	1,246	2,060	41,277	68,241	150	na	263
1999	87,979	24,698	na	40,832	2,441	4,036	2,029	3,354	1,163	1,923	22,675	37,487	198	na	348
2000	68,624	20,409	27,676	na	2,617	4,327	2,266	3,746	2,043	3,378	17,560	29,031	266	na	467
2001	128,052	18,349	35,788	na	2,868	4,741	5,890	9,738	9,885	16,342	36,740	60,740	400	na	702
2002	166,087	19,475	54,219	na	5,775	9,547	3,674[1]	10,229	3,680	6,084	51,298	84,808	1,200	1,200	na
2003	115,460	21,380	na	35,346	4,799	7,934	2,496	4,126	2,488	4,113	38,178	63,117	823	823	na

[1]The 2002 Lower Adams visual index was expanded by the 2002 Lower Shuswap expansion factor because of unusually high sockeye escapement.
na indicates that no estimate was available.

Appendix D. Request for working paper.

PSARC Request for Working Paper[1]

Date Submitted: October 5, 2004

Individual or group requesting advice: Salmon Working Group – Pacific Region

Proposed PSARC Presentation Date: October 2004

Subject of Paper (title if developed):
A habitat-based method to generate abundance-based reference points for Chinook salmon

Science Lead Author: Chuck Parken
Rick McNicol / Jim Irvine – co-authors

Resource Management Lead Author: N/A

Rationale for request:

Stock-recruit life history information for Chinook salmon stocks is limited for many river systems in British Columbia. This lack of information is particularly prevalent with respect to many stocks in the Fraser River watershed. As a result of this lack of information, escapement goals for purposes of enhancing effective management of Chinook stocks are lacking. The subject paper will outline a proposed method to establish Chinook escapement goals using spawning capacity of stream habitat. Establishing an escapement goal will provide a foundation from which effective fish management strategies can be developed to insure long term sustainability of Chinook stocks while providing harvest opportunities within these stocks for various user groups

The importance of establishing defensible escapement goals for Canadian Chinook stocks is also of primary importance to the Pacific Salmon Treaty (PST). The PST outlines tasks for the Chinook Technical Committee, which include establishing MSY or other biologically-based escapement goals. Chinook escapement goals are used in the management of ISBM fisheries (Appendix to Annex IV, Chapter 3, para. 4, p. 35), as well as triggers for additional management actions for both ISBM and AABM fisheries (Para. 9, p. 39). Escapement goals for the Canadian CTC escapement indicator stocks have been identified as high priority on several occasions, and currently only 1 of 12 Canadian escapement indicator stocks has an escapement goal.

The development of a reliable and defensible tool for setting Chinook escapement goals is required for both international and domestic fisheries management.

Objective of Working Paper including assessment of environment/climate impacts:

- The objective of the working paper will be to explore the feasibility of developing a habitat-based approach to estimating the optimal spawning escapements based on the size of the watershed used by the stock. The habitat based model should be designed in such a way so that abundance based reference points can be predicted from a single or multiple number of habitat variables. In accordance with the PST, the model should attempt to predict Smsy and Capacity from an appropriate stock-recruitment curve for Chinook (i.e. Ricker or Beverton-Holt).

- At this time the ability to incorporate known or forecasted environmental or climatic impacts into the setting of habitat based Chinook escapements goals is beyond the scope of the paper.

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Question(s) to be addressed in the Working Paper:

- The paper will attempt to develop a tool to help generate escapement goals for Canadian CTC escapement indicator stocks to implement parts of the PST. This tool could also be used to develop reference points for domestic management.

- The working paper will describe the method, the data it was developed from, how to apply the model, expected error rates, accuracy, and reliability. If feasible, the model, should be applied to the Canadian CTC escapement indicator stocks as a case study to assist in its evaluation, and the predictions would be compared to the Interim Goals (circa 1985). The working paper should also compare the habitat-based and interim escapement goal methods for the Key streams to see which method performs better. This comparison will help evaluate which method performs best for developing escapement goals for PST implementation based on available information.

Stakeholders Affected:

The development and acceptance of more realistic escapement goals for Chinook salmon may have an impact on level and intensity of a variety of fisheries. Depending on the status of specific stock groups, in relation to the new escapement goals, fisheries may be reduced or expanded to meet Departmental or PST objectives. The stakeholders affected through the adoption of new reference points would be those in the Commercial, Recreational and First Nations fisheries, as well as environmental groups. The Canadian public will benefit from improved fisheries management.

How Advice May Impact the Development of a Fishing Plan:

Advice on appropriate escapement targets for Chinook salmon, where such information is lacking, will form the basis for developing harvest opportunities for First Nations, recreational, and commercial fisheries. Fishing plans will be developed with the objective of achieving Chinook salmon escapement goals for systems where these goals are in place.

Timing Issues Related to When Advice is Necessary:

Development of Chinook salmon fishing plans for the 2005 fishing season will commence in late 2004. Advice on appropriate escapement goals for Chinook salmon is required by end of January 2005 for use in completing development of fishing plans which is expected to be complete by mid May 2005.

Initiating sector approval:

Regional Director: ________________________; Date:________________________