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An Evaluation of the Percentile Approach for Establishing Sustainable Escapement Goals in Lieu of Stock Productivity Information

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Abstract

Stock-recruitment analysis is the typical method used to establish biological escapement goals (BEGs) that provide the greatest potential for maximum sustainable yield (S_{MSY}) of Pacific salmon stocks in Alaska. For

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stocks where the necessary stock-specific information is lacking, there are no published methods for estimation of proxies for S_{MSY} to aid in the development of sustainable escapement goals (SEGs). One such proxy for S_{MSY} was developed in an unpublished report by Bue and Hasbrouck in 2001 and is now commonly called the Percentile Approach. We evaluated the Percentile Approach and recommended changes to the approach based on outcomes of our analyses. All of the analyses indicate that the four tiers of the Percentile Approach are likely sub-optimal as proxies for determining a range of escapements around S_{MSY}. The upper bounds of SEGs developed with this approach may actually be unsustainable in that they may specify a spawning escapement that is close to or exceeds the carrying capacity of the stock. The lower bound percentile of SEG Tier 1 (25%) also appears somewhat higher than necessary. Escapements in the lower 60 to 65 percentiles are optimal across a wide range of productivities, serial correlation in escapements, and measurement error in escapements. We recommend that the current four-tier Percentile Approach be replaced with the following three tiers for stocks with low to moderate (less than 0.40) average harvest rates:

- Tier 1: high contrast (>8) and high measurement error (aerial and foot surveys) with low to moderate average harvest rates (<0.40), the 20th to 60th percentiles
- Tier 2: high contrast (>8) and low measurement error (weirs, towers) with low to moderate average harvest rates (<0.40), the 15th to 65th percentiles
- Tier 3: low contrast (8 or less) and high or low measurement error with low to moderate average harvest rates (<0.40), the 5th to 65th percentiles

Use of the Percentile Approach is not recommended for the following situations:

- average harvest rates of 0.40 and greater
- very low contrast (4 or less) and high measurement error (aerial or foot surveys)

Introduction

Background

Pacific salmon stocks in Alaska are managed for escapement in terminal fisheries, where fish that escape harvest subsequently spawn to perpetuate the stock. Escapement refers to the annual estimated number of spawning salmon, enumerated after harvest. Stock-recruitment analysis (e.g., Quinn and Deriso 1999) is the typical method used to estimate stock productivity and carrying capacity, and to establish biological escapement goals (BEGs) that provide the greatest potential for maximum sustainable yield of Pacific salmon stocks in Alaska, consistent with the policy for statewide salmon escapement goals (Title 5 of the Alaska Administrative Code [AAC], Chapter 39, Section 223). Stock-specific information on harvest, escapement, and age composition over a series of years is necessary to conduct these analyses. Central to this recipe for escapement goal development is the calculation of a reliable estimate of escapement that produces maximum sustainable yield, or S_{MSY}.

For Pacific salmon stocks where the necessary stock-specific information is lacking, there are no published methods for estimation of proxies for S_{MSY} to aid in the development of sustainable escapement goals (SEGs). Development of a proxy for S_{MSY} is a reasonable methodological approach because SEGs are defined in regulation as providing for sustainable yields over a 5-10 year period rather than maximum sustainable yields, so that a reliable estimate of S_{MSY} is not required. SEGs must also be scientifically defensible and consider uncertainty. One such proxy for S_{MSY} was developed in an unpublished report by Bue and Hasbrouck in 2001 (Otis 2001) and is now commonly called the Percentile Approach. This approach is currently being used to develop SEGs statewide and was the principal method used for development of 140 of the 300 escapement goals established and in use throughout Alaska during 2012 (Munro and Volk 2013).

The Percentile Approach is based on the very simple principle that a range of observed escapements, or an index of escapements that have been sustained over a period of time, represent an SEG for a stock that has been fished and likely sustained some unknown level of yields over that same time period. Moreover, for a moderately fished stock, maintaining levels of escapement within a range of percentiles of previously observed escapements can be considered a proxy for maintaining escapements within a range that encompasses a desired management objective such as S_{MSY}. Bue and Hasbrouck considered the contrast in observed escapements (maximum escapement divided by the minimum escapement) and supposed rate of harvest in prescribing four ranges of percentiles of observed escapements to apply in developing the SEG (Otis 2001). We have rearranged their four percentile ranges and named them as tiers as follows:

- Tier 1: high escapement contrast (greater than 8) and at least moderate harvest rate, the central 50-percentile range (25th to 75th percentiles)
- Tier 2: medium escapement contrast (4 to 8) and at most low harvest rate, the 15th percentile to the 75th percentile

- Tier 3: medium escapement contrast (4 to 8), the central 70-percentile range (15th to 85th percentiles)
- Tier 4: low escapement contrast (less than 4), the 15th percentile to maximum observed escapement (100th percentile).

Bue and Hasbrouck developed the four Percentile Approach tiers from the statistical principle that the central 70-percentile range of escapements (i.e., the 15th to 85th percentiles of Tier 3) is the nonparametric analog of ±1 standard deviation from the average escapement (or the central 67-percentile of the observations) and that a nonparametric approach would avoid the parametric problem of outliers in the form of very large escapements that would likely not produce sustainable yields. They also reasoned that as escapement contrast and harvest rate increases, the range of escapements thought to produce sustainable yields should narrow (Tiers 1 and 2). For situations of very low escapement contrast, they reasoned that a wider range of escapements should be allowed (Tier 4). Bue and Hasbrouck confirmed the utility of these tiers by observing favorable comparisons of SEG escapement ranges derived from the Percentile Approach with the estimated BEG ranges for 11 selected stocks. The specific stocks examined were two sockeye and two Chinook salmon stocks from Upper Cook Inlet, and seven sockeye salmon stocks from Bristol Bay.

Rationale for evaluation

This evaluation was initiated due to the popularity and simplicity of the Percentile Approach as a proxy for S_{MSY} in the development of SEGs and concerns about scientific defensibility that arose as the approach was implemented throughout Alaska. As currently defined in the policy for the management of sustainable salmon fisheries (5 AAC 39.222(f)(36)), an SEG must be scientifically defensible, provide for sustainable yields, and consider uncertainty.

One tenet of scientifically defensibility is that the science must be peer reviewed and accepted by the scientific community. Another tenet is that the science must comport with broadly accepted and peer-reviewed scientific principles and the theory of sustained yield. Lastly, the science must be robust to uncertainty with respect to the measurement of escapements and the underlying dynamics of the stock. Although Bue and Hasbrouck reasoned that the tiers should provide for sustainable yields and defended their choice of percentiles by comparing results with BEG ranges from stocks that had information on productivity, their work is largely based on statistical (non-biological) considerations and remains unpublished, without the benefit of scientific peer review. Moreover, upper bounds of SEG ranges developed from this approach may be unsustainably high, especially when harvest rates are low (<25%). The tiers and recommended percentiles also do not consider data quality in terms of error in the measurement of escapements or the minimum number of years of escapements in the time series; nor do they consider the potential for serial correlation of escapements in the time series. Lastly, there are now many more data sets in Alaska with information on productivity (and S_{MSY}) that could be used to compare BEGs with SEGs developed with the Percentile Approach.

We attempt to resolve these concerns and provide a scientific evaluation of the Percentile Approach, with recommendations for applying this method in the future. Three methods of analysis are utilized to investigate the theoretical, statistical, and empirical aspects of the Percentile Approach as a proxy for S_{MSY}.

Methods

Theoretical analysis

The Percentile Approach was evaluated with respect to the theoretical range of escapements expected under a range of productivities, harvest rates, and process and measurement errors. The production relationship used for this analysis was the familiar version of the Ricker model (Ricker 1975) that is typically used in escapement goal analyses in Alaska (Clark et al. 2009):

$$R = S \exp [\ln(\alpha) - \beta S] \tag{1}$$

where R is the production of adult salmon from the escapement S of adult salmon in the previous generation, α is a parameter governing productivity of the stock, and β is a scale parameter. For this analysis we are considering a multitude of possible stocks of the same carrying capacity but with differing productivity. To accomplish this, carrying capacity $[\frac{\ln(\alpha)}{\beta}]$ is rescaled to a value of 1 so that $\beta = \ln(\alpha)$ and the relationship is recast as:

$$R = S \exp [\ln(\alpha) - \ln(\alpha)S] \tag{2}$$

For any fixed rate of harvest u, the equilibrium (i.e., average) spawning level $\overline{S}$ can then be calculated (adapted from Ricker 1975):

$$\overline{S} = \frac{[\ln(\alpha) - \ln(\frac{1}{(1-u)})]}{\ln(\alpha)} \tag{3}$$

Multiplicative process error [α^2_ε where, $\varepsilon \sim N(0, \alpha^2_\varepsilon)$] makes the relationship in Equation 2 stochastic, with expectation:

$$E[R \mid S] = S\exp[\ln(\alpha) - \ln(\alpha)S]\exp(\frac{\sigma_\varepsilon^2}{2}) \tag{4}$$

The theoretical frequency distribution around equilibrium spawning escapement is determined by the fixed rate of harvest, the process error of the stock-recruitment relationship, and, if escapements are estimated or indexed, by measurement error. Under a fixed rate of harvest, observed S over time can reasonably be expected to be lognormally distributed with mean $\bar{S}$ and variance , with $\bar{S}$ dependent on the rate of harvest *u* (from Equation 3). If *S* is measured with error, then observed S would be lognormally distributed with mean $\bar{S}$ and variance $\sigma^2_\varepsilon = \sigma^2_S$ where σ^2_S governs sampling error associated with individual spawning escapement estimates.

Because log-productivity of salmon stocks in Alaska typically varies from 1 to 2, ln(α) was fixed at those two values in the analysis to represent the range of productivities that could occur. Harvest rate was fixed at three levels ($u = 0.15$, 0.25, and 0.40) in the analysis to represent a range of low to moderate average harvest rates that would typically be encountered in stock assessments where an SEG range would be applied.

A hypothetical distribution of resultant escapements from both of these levels of log-productivity was expressed as the maximum value of two lognormal distributions of escapements, each with differing $\bar{S}$ due to the fixed harvest rate (Equation 3) and each with similar process and measurement error variances. For this analysis, process error was fixed at $\sigma_\varepsilon = 0.6$, which is typical for many salmon stocks. Measurement error was also fixed at two arbitrary levels ($\sigma_S = 0.05$ or 0.50) to represent a range of possible assessments where spawning escapement is counted or precisely estimated (e.g., weirs or towers) or where spawning escapement is indexed or less precisely estimated (e.g., aerial or foot surveys). These levels represent a 100-fold increase in squared measurement error that are likely to occur between attempted counts of individual fish at weirs and visual counts of fish sighted during a single aerial survey assumed to occur during the peak of spawning.

The cumulative distribution of the maximum values of the two lognormal distributions was used to calculate percentiles representing specific levels of spawning abundance corresponding to a desired range around S_{MSY}. The range around S_{MSY} was the smallest escapement that produces 90% of maximum sustainable yield (MSY) at the lower bound (or L90) and the largest escapement that produces 70% of MSY at the upper bound (or U70). This range represents a conservative approach to development of an SEG, where low escapements that might cause overfishing are avoided at the lower bound and larger escapements that might be informative to better understanding future production are encouraged at the upper bound. A range based on the strict 90% of MSY boundaries (i.e., L90 to U90), as is typically estimated and used in BEG analyses, was considered but rejected as too narrow for development of a SEG when information on productivity of the stock is lacking.

To ensure that the Percentile Approach is conservative with respect to our limited knowledge of stock-specific productivity, a maximum harvest rate of 0.40 was chosen because it represents the highest harvest rate that would result in observed escapements near or above S_{MSY}, even if productivity was low (i.e., $\ln(\alpha) \approx 1$ and $u_{MSY} \approx 0.40$). While harvest rates greater than 0.40 can be optimal with respect to producing MSY for a particular stock, stock-specific knowledge of productivity would be needed to develop an escapement goal range that prevents overfishing.

Simulation analysis

While a theoretical analysis will provide insights into the likely range of percentiles that can be used as proxies for S_{MSY}, many aspects of salmon stock dynamics and fisheries are not fixed and may vary over the time period of spawning escapement data collection. A combined escapement-to-recruitment and recruitment-to-escapement Monte Carlo simulation model was constructed to examine the robustness of the Percentile Approach to these additional uncertainties.

Similar to the theoretical analysis, log-productivity was set at three levels (1, 1.5, and 2 after accounting for process error and serial correlation) to represent the range and typical value for this parameter. Rather than forcing each production model through the same carrying capacity, as was done for the theoretical analysis, the scale parameter was held constant in this analysis at $\beta = 1$ to reflect the dynamics of a single stock with varying productivity. For the escapement-to-recruitment component of the model, a more complex stochastic model of Ricker stock-recruitment was used. This model allows for lag-1 serial correlation among deviations from expected production over time (Noakes et al. 1987):

$$E[R_y \mid S_y] = S_y \exp[\ln(\alpha) - \beta S_y + \phi v_{y-1}] \exp(\frac{\alpha^2_{\varepsilon_y}}{2}) \tag{5}$$

where y is a subscript denoting the brood year, ϕ is the lag-1 correlation coefficient, and v_{y-1} is the log-scale residual in the previous brood year:

$$v_{y-1} = \ln(R_{y-1}) - \ln(S_{y-1}) - \ln(\alpha) + \beta S_{y-1} \tag{6}$$

The serial correlation coefficient was set at two levels (0.00 and 0.50) to reflect no and moderate lag-1 serial correlation, representing a range of serial correlation in production typically observed in Alaska salmon stocks. While we suggest no causal mechanism for the existence of lag-1 positive serial correlations, there is good empirical support for using this form of deviations in production from a standard Ricker model. Clark et al. 2014 found that non-negative lag-1 serial correlation occurred in 65 of 66 Alaska salmon stocks examined (range of 0.00 to 0.85) with the same form of Ricker model as used herein.

The recruitment-to-escapement component of the model was accomplished by fishing at five different average harvest rates ($u = 0.10$, 0.18, 0.26, 0.33, and 0.39) corresponding to instantaneous rates of harvest of 0.10 to 0.50 (F) in increments of 0.10. Results from these five average rates of harvest were also grouped into low (0.10 and 0.18) and moderate (0.26, 0.33, and 0.39) levels of harvest. Annual variation in average harvest rate in the absence of a constraining escapement goal was modeled as a lognormal process with σF fixed at 0.3. Resultant escapements were estimated as:

$$S_y = R_y \exp(-F) \exp(\sigma_F), \tag{7}$$

which then produce the next generation ($y + 1$) of recruitment in the escapement-to-recruitment relationship (Equation 5).

As in the theoretical analysis, process error (σ_ε) was fixed at 0.6 and measurement error (σ_S) was set at two values (0.05 and 0.50) to reflect the range in precision of estimation of escapement seen in various types of assessments. Each realization of the model was a run of 100 brood years, with time series of 10 and 30 years of escapements extracted from the end of the 100 years and used to develop a SEG based on the Percentile Approach. One thousand realizations were performed for each combination of parameter values.

Percentiles of the time series of simulated escapements were estimated, and all possible ranges of percentiles, from the minimum to maximum in increments of 5%, were calculated with the following restrictions: no percentile range (upper percentile-lower percentile) was narrower than 25%, the lower bound percentile was no greater than the 60th percentile, and the upper bound percentile was no lower than the 40th percentile. Included in these ranges of percentiles are the four current SEG tiers. Each potential SEG range was rated against the L90 to U70 range around S_{MSY} with the following formula:

$$Rating = \left| \frac{(P_L - L90)}{L90} \right| + \left| \frac{(P_U - U70)}{U70} \right|, \tag{8}$$

where PL is the escapement value of the lower percentile of the range, PU is the escapement value of the upper percentile of the range, and L90 and U70 are the lower and upper bounds around S_{MSY} as previously defined. Smaller values of *Rating* imply a better match to the L90-U70 interval around S_{MSY}, and a *Rating* of zero is a perfect match of the L90-U70 interval around S_{MSY}.

*Rating*s of each percentile range were summarized by averaging the 1,000 realizations of the model for each combination of parameter value, low and moderate harvest rates, level of contrast, and number of years of escapements. Summaries of the percentile range with the lowest (Best) *Rating* and of each of the current SEG tiers were also categorized by level of contrast (greater than 8 and 8 or less), measurement error (low or high), and number of years of escapements (10 and 30 years).

Uncertainty in determining the Best *Rating* was examined by plotting the Best upper bound percentile against the Best lower bound percentile for each of the 1,000 realizations of the model for each combination of log-productivity, serial correlation, measurement error, harvest rate, level of contrast, and number of years of escapements simulated.

Performance of the current Percentile Approach tiers was evaluated against those recommended herein by comparing expected yields derived when the recommended escapement goals from each tier system were managed for exactly. Average expected yields were calculated as a percentage of MSY at the lower bound, midpoint, and upper bound of the applicable tier of the current Percentile Approach and compared to average expected yields relative to MSY at the bounds and midpoint of the applicable revised tier based on recommendations made herein. Comparisons were also made by plotting the percentile range with the Best *Rating* and the expected yields as a percentage of MSY at the lower and upper bounds of the recommended SEG tier for each combination of log-productivity, serial correlation, measurement error, harvest rate, level of contrast, and number of years of escapements simulated.

Empirical meta-analysis

Lastly, the Percentile Approach was evaluated by comparing various percentile escapement intervals to S_{MSY} escapement intervals estimated from a standardized stock recruit analysis. Bue and Hasbrouck performed a similar comparison on 11 stocks in their initial formulation of the Percentile Approach.

We utilized information from a previous analysis (Clark et al. 2014) where a linearized form of the Ricker stock-recruitment model (Equation 5) was to fit 76 stock-recruitment data sets from throughout Alaska using a standard linear regression approach (Ricker 1975). These data included historical stock-recruitment observations for seven pink salmon, seven coho salmon, 43 sockeye salmon, six chum salmon stocks, and 13 Chinook salmon stocks. Ten data sets (all sockeye salmon stocks) were eliminated from their analysis due to inadequate statistical fits to the Ricker model (i.e., scale parameter β not significantly different from zero at an alpha level of 0.05) resulting in 66 stocks with reasonable estimates of S_{MSY}, L90, and U70.

As in the simulation analysis, percentiles of the time series of observed escapements were estimated, and all possible ranges of percentiles, from the minimum to maximum in increments of 5% were calculated with the restrictions that no percentile range (upper percentile-lower percentile) was narrower than 25%, the lower bound percentile was no greater than the 60th percentile, and the upper bound percentile was no lower than the 40th percentile. Included in these ranges of percentiles are the four current SEG tiers. Each potential SEG range was rated against the L90 to U70 range around S_{MSY} by calculating the *Rating* (Equation 8). Summaries of the percentile range with the Best *Rating* and of each of the current SEG tiers were also categorized by species, level of contrast (greater than 8 and 8 or less), and low to moderate and high harvest rates (less than 0.4 and 0.4 and greater).

Results

Theoretical analysis

Theoretical values for percentiles that encompass an L90-U70 range around S_{MSY} ranged from 1% to 24% for the lower bound, and from 28% to 74% for the upper bound, depending on the value of log-productivity, measurement error, and harvest rate (Tables 1 and 2). When results for both values of log-productivity were combined to represent a lack of productivity information, reasonable percentile-based SEG ranges varied from 2-40% to 10-74% for low measurement error situations and from 5-42% to 17-69% for high measurement error situations. Results from this analysis approached that of Tier 1 and Tier 2 SEGs (25-75% and 15-75%) with a harvest rate of 0.40 and low log-productivity. Graphical representation of the theoretical analysis for a fixed harvest rate of 0.25 and low measurement error is shown in Fig. 1.

Simulation analysis

None of the four SEG tiers had the Best percentile *Rating* for all possible scenarios of the low measurement error ($\sigma_S = 0.05$) series of simulations. Best percentile *Rating* ranged from Min-50% to 20-70%, with low contrast (8 or less) scenarios favoring minimum and 5th percentiles for lower bounds, regardless of the number of years of escapements or presence of serially correlated escapements. Conversely, Best lower bound percentiles of 10 and 15% were common in the high contrast (greater than 8) scenarios. Best upper bound percentiles varied from 50 to 70%, positively related to the change in rate of harvest from low to moderate.

Similarly, none of the four SEG tiers had the Best percentile *Rating* for all possible scenarios of the high measurement error ($\sigma_S = 0.50$) series of simulations. Best percentile *Rating* ranged from Min-50% to

Table 1. Definitions of variables used in tables.

Variable	Definition
ln(α)	The log-productivity parameter of the Ricker stock-recruitment model
σ_ε	The standard error of the multiplicative process error
σ_S	The standard error of simulated escapements
L90	The largest escapement that is less than S_{MSY} and produces at least 90% of MSY
U70	The smallest escapement that is greater than S_{MSY} and produces at least 70% of MSY
S_{MSY}	Spawners that produce MSY
u	Harvest rate
$\bar{S}$	Average escapement
ϕ	The lag-1 correlation coefficient of the Ricker model with lagged serial correlation in expected production over time
σ_F	The standard error of simulated instantaneous harvest rates
Contrast	The maximum escapement divided by the minimum escapement
Years	Years of simulated escapements
n	Number of years of information in the brood table
Best	Lowest Rating
Rating	Absolute relative difference between the L90 and P_L plus the absolute relative difference between U70 and P_U
25–75	Rating of the Tier 1 percentiles of Bue and Hasbrouck (Otis 2001)
15–75	Rating of the Tier 2 percentiles of Bue and Hasbrouck (Otis 2001)
15–85	Rating of the Tier 3 percentiles of Bue and Hasbrouck (Otis 2001)
15–Max	Rating of the Tier 4 percentiles of Bue and Hasbrouck (Otis 2001)
LB	The lower bound of either the current or recommended percentile range
Mid	The midpoint of either the current or recommended percentile range
UB	The upper bound of either the current or recommended percentile range
P_L	The escapement at the lower bound percentile
P_U	The escapement at the upper bound percentile

Table 2. **Parameter values and lower and upper percentiles calculated from the theoretical analysis.**

$\ln(\alpha)$	σ_ε	σ_S	L90	S_{MSY}	U70	u	$\bar{S}$	Lower percentile	Upper percentile
1	0.60	0.05	0.28	0.43	0.72	0.15	0.84	4%	40%
						0.25	0.71	6%	51%
						0.40	0.49	18%	74%
1	0.60	0.50	0.28	0.43	0.72	0.15	0.84	8%	42%
						0.25	0.71	12%	51%
						0.40	0.49	24%	69%
2	0.60	0.05	0.23	0.36	0.65	0.15	0.92	1%	28%
						0.25	0.86	1%	33%
						0.40	0.74	3%	41%
2	0.60	0.50	0.23	0.36	0.65	0.15	0.92	4%	33%
						0.25	0.86	5%	36%
						0.40	0.74	7%	43%
Both	0.60	0.05	0.23		0.72	0.15		2%	40%
						0.25		3%	51%
						0.40		10%	74%
Both	0.60	0.50	0.23		0.72	0.15		5%	42%
						0.25		7%	51%
						0.40		17%	69%

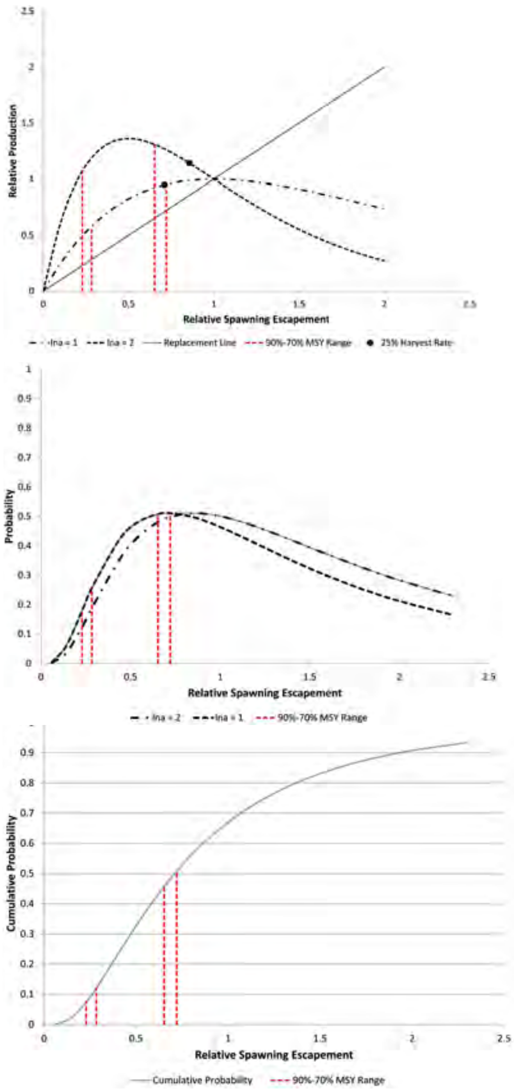

Figure 1. Top: Two hypothetical stock-recruitment relationships (dashed curves), the L90 and U70 lines (vertical dashed lines) for each relationship, and equilibrium points (black circles) based on a fixed harvest rate of 0.25. Middle: two hypothetical lognormal distributions (dashed curves) around the two equilibrium spawning escapements from the top graph and the same L90 and U70 lines from the top graph. Lower: the combined cumulative distribution (solid curve) of the two theoretical lognormal distributions in middle graph and the same L90 and U70 lines (vertical dashed lines) from the top graph. Results are for the low measurement error scenario ($\sigma_S = 0.05$).

25-65%, with low contrast (8 or less) scenarios favoring minimum and 5th percentiles for lower bounds regardless of the presence of serially correlated escapements. No results were available for scenarios of low contrast and 30 years of data due to the effect of high measurement error on the apparent contrast in escapements over time. Best lower bound percentiles of 10 and 15% were common in the high contrast (greater than 8) scenarios with 10 years of escapements, but increased to 15 to 25% as the time series of escapements increased to 30 years. Best upper bound percentiles varied from 50 to 70%, positively related to the change in rate of harvest from low to moderate.

Measurement error and contrast emerged as the most influential variables in determining Best percentiles from the simulations (Table 3). Percentile ranges of 15–65% for low measurement error and 20-60% for high measurement error when contrast was high did not differ appreciably with differences in harvest rate, presence of serial correlation, and the range in number of years of escapements. For situations of low contrast, a percentile range of 5–65% remained fairly stable despite variations in measurement error and presence of serial correlation. Differences in length of time series and lack or presence of lag-1 serial correlation did not appreciably change the Best percentiles within each measurement error level and contrast level.

Best lower and upper percentiles were highly variable between realizations of a simulation, reflecting the variability in contrast in the simulated escapements relative to S_{MSY} and the harvest rate relative to the harvest rate at MSY for a given log-productivity. Highest levels of variability were observed for low log-productivity and low contrast scenarios (Fig. 2A). Conversely, lower levels of variability occurred for higher log-productivity and high contrast scenarios (Fig. 2B).

Empirical meta-analysis

Thirty of the 66 stocks in the meta-analysis had average harvest rates less than 0.40 (Table 4), with a range of average harvest rates from 0.06 to 0.39. For these 30 stocks, percentile ranges that best matched the L90–U70 range around S_{MSY} (i.e., Best *Rating*) ranged from Min–45% to 40–85%. Of these 30 stocks, 24 of them had contrast greater than 8, and six had contrast of 8 or less. The 24 stocks with high contrast and low to moderate harvest rates had Best percentile ranges of 40–75% for four pink salmon stocks, 15–45% for five Chinook salmon stocks, 20–55% for eight sockeye salmon stocks, 20–65% for six chum salmon stocks and 35–60% for one coho salmon stock (Table 4). Average *Rating* for these Best percentile ranges varied from 0.09 to 0.57, whereas average *Rating* for the four SEG tiers varied from 0.46 to 1.15 (Tier 1), 0.57 to 0.94 (Tier 2), 0.72 to 1.31 (Tier 3), and 2.19 to 2.31 (Tier 4).

The six stocks that had contrast of 8 or lower and low to moderate harvest rate had a Best percentile range of Min-45% for two Chinook

Table 3. Summary of simulation analysis results. Results in bold are the recommendations for updated SEG tiers.

σ_s	ϕ	**u**	**Contrast**	**Years**	**Best**	***Rating***	**25–75**	**15–75**	**15–85**	**15–Max**
0.05	Both	0.10–0.39	>8	10	15–60	0.81	0.99	0.90	1.14	2.29
0.50					15–60	0.83	1.12	1.02	1.37	2.96
0.05	**Both**	**0.10–0.39**	**>8**	**30**	**15–65**	**0.67**	**0.85**	**0.74**	**0.98**	**2.69**
0.50					**20–60**	**0.68**	**0.90**	**0.84**	**1.21**	**4.05**
0.05	Both	0.10–0.39	≤8	10	5–70	0.72	1.14	0.96	1.09	1.49
0.50					5–60	0.73	1.17	0.99	1.16	1.62
0.05	Both	0.10–0.39	≤8	30	Min–55	0.33	0.98	0.73	0.95	1.71
0.50					ND	ND	ND	ND	ND	ND
Both	0.0	0.10–0.39	>8	10	15–60	0.71	0.97	0.86	1.18	2.61
	0.5				15–65	0.93	1.14	1.06	1.33	2.64
Both	0.0	0.10–0.39	>8	30	15–65	0.58	0.82	0.71	1.03	3.25
	0.5				20–60	0.77	0.92	0.87	1.16	3.49
Both	0.0	0.10–0.39	≤8	10	5–65	0.69	1.11	0.92	1.07	1.51
	0.5				Min–65	0.77	1.21	1.03	1.18	1.60
Both	0.0	0.10–0.39	≤8	30	ND	ND	ND	ND	ND	ND
	0.5				ND	ND	ND	ND	ND	ND
Both	Both	0.10–0.18	>8	10	10–55	0.73	1.17	1.01	1.41	3.09
		0.26–0.39			15–65	0.85	0.97	0.92	1.14	2.32
Both	Both	0.10–0.18	>8	30	15–55	0.54	0.99	0.83	1.25	3.94
		0.26–0.39			20–70	0.71	0.79	0.77	0.99	2.99
Both	Both	0.10–0.18	≤8	10	Min–55	0.63	1.35	1.11	1.32	1.86
		0.26–0.39			5–70	0.74	1.02	0.88	0.99	1.35
Both	Both	0.10–0.18	≤8	30	ND	ND	ND	ND	ND	ND
		0.26–0.39			ND	ND	ND	ND	ND	ND
Both	Both	0.10–0.39	>8	10	15–60	0.82	1.05	0.96	1.25	2.62
				30	20–65	0.67	0.87	0.79	1.09	3.37
Both	**Both**	**0.10–0.39**	**≤8**	**10**	**5–65**	**0.73**	**1.16**	**0.97**	**1.12**	**1.55**
				30	ND	ND	ND	ND	ND	ND

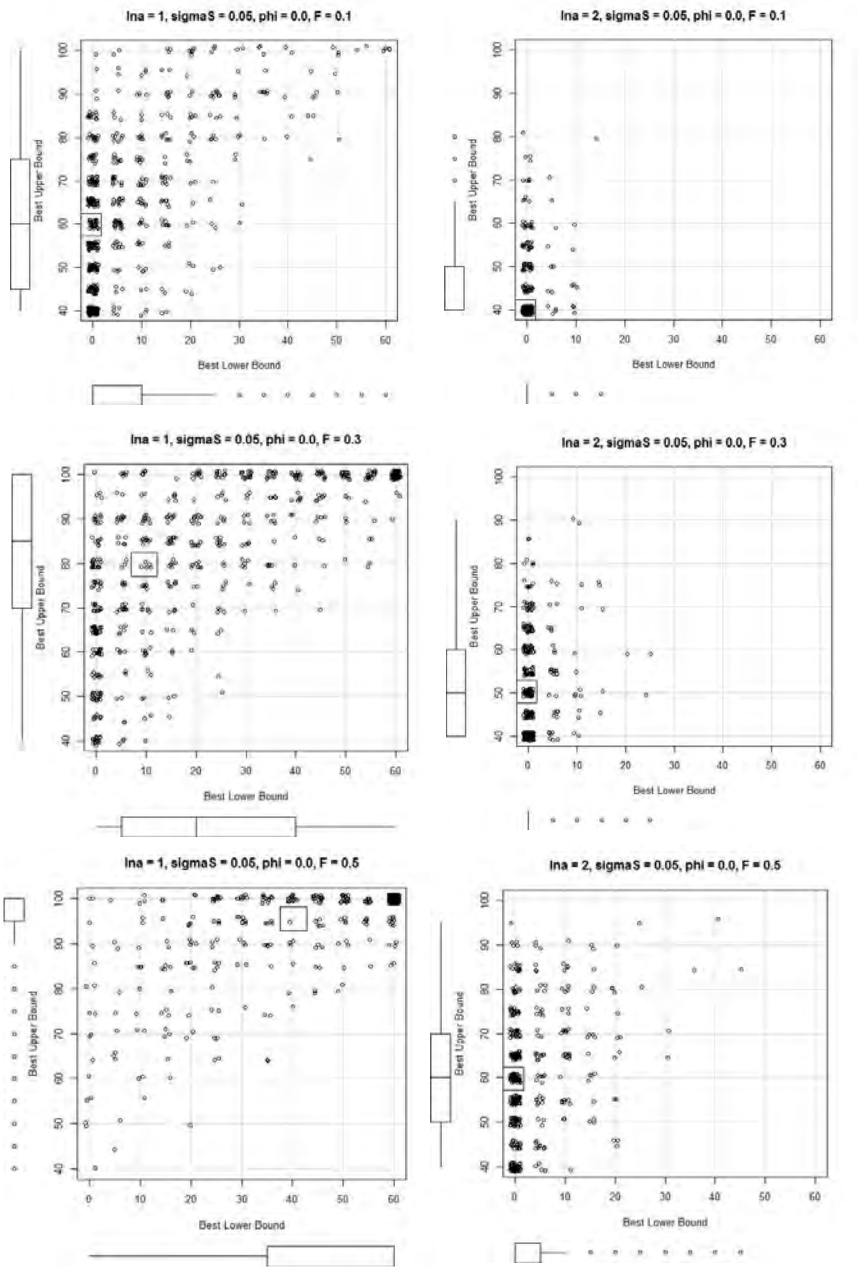

Figure 2A. Scatter plots of simulated Best upper against Best lower percentile based on lowest *Rating* for two log-productivities and three harvest rates; with low measurement error, no serial correlation, and low contrast for 10 years of escapements. Squares indicate the average Best percentile range.

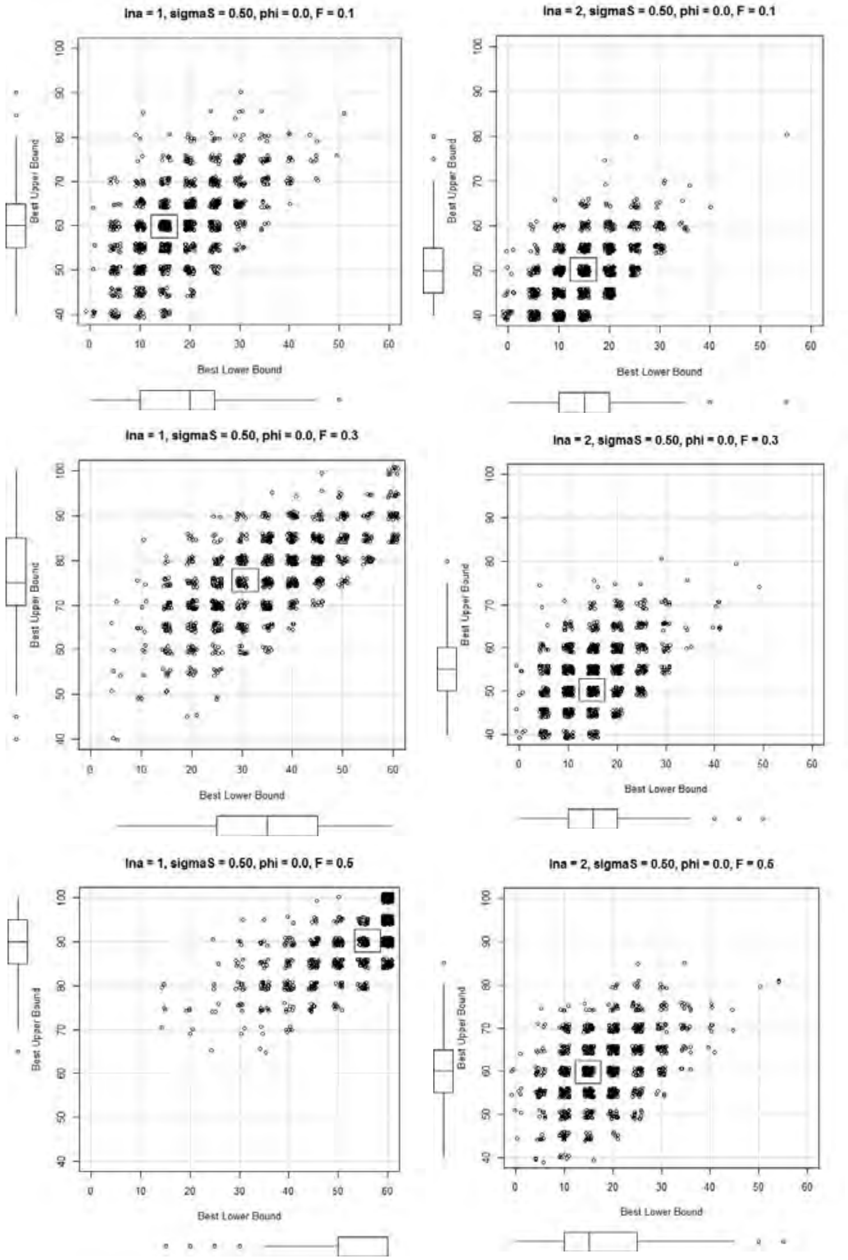

Figure 2B. Scatter plots of simulated Best upper against Best lower percentile based on the lowest *Rating* for two log-productivities and three harvest rates; with high measurement error, no serial correlation, and high contrast for 30 years of escapements. Squares indicate the average Best percentile range.

salmon stocks and four sockeye salmon stocks (Table 4). Average *Rating* for these Best percentile ranges varied from 0.16 to 0.31, whereas average *Rating* for the four SEG tiers varied from 1.09 to 1.12 (Tier 1), 0.94 to 1.01 (Tier 2), 0.66 to 1.16 (Tier 3), and 1.77 to 2.12 (Tier 4).

Thirty-six of the 66 stocks in the meta-analysis had average harvest rates of 0.40 or more (Table 4), with a range of average harvest rate from 0.40 to 0.69. For these 36 stocks, percentile ranges that best matched the L90-U70 range around S_{MSY} (i.e., Best *Rating*) ranged from Min–45% to 40–Max%. Of these 36 stocks, 21 of them had contrast greater than 8, and 15 had contrast of 8 or less. The 21 stocks with high contrast and high harvest rates had Best percentile ranges of 10–50% for 1 Chinook salmon stock, 15–65% for two coho salmon stocks, 35–75% for 15 sockeye salmon stocks, and 40–85% for three pink salmon stocks (Table 4). Average *Rating* for these Best percentile ranges varied from 0.00 to 0.44, whereas average *Rating* for the four SEG tiers varied from 0.44 to 0.58 (Tier 1), 0.51 to 0.61 (Tier 2), 0.61 to 0.67 (Tier 3), and 1.51 to 1.68 (Tier 4).

The 15 stocks that had contrast of 8 or lower and high harvest rate had a Best percentile range of 5–45% for five Chinook salmon stocks, 20–65% for six sockeye salmon stocks, and 40–75% for four coho salmon stocks (Table 4). Average *Rating* for these Best percentile ranges varied from 0.18 to 0.29, whereas average *Rating* for the four SEG tiers varied from 0.21 to 0.91 (Tier 1), 0.27 to 0.75 (Tier 2), 0.28 to 1.02 (Tier 3), and 0.85 to 1.66 (Tier 4).

There appeared to be little to no relationship between average harvest rate and Best lower bound percentile and a weak positive relationship between average harvest rate and the Best upper bound percentile for all 66 stocks (Fig. 3). Percentiles from minimum to 40th were selected as Best lower bounds across a wide range of average harvest rates. With only two exceptions (both pink salmon stocks), Best upper bound percentiles of 75% and greater were selected only at average harvest rates greater than 0.30.

Discussion

All three of the analyses indicate that the four tiers of the Percentile Approach currently used are likely suboptimal as proxies for determining a range of escapements around S_{MSY} in lieu of information about productivity of salmon stocks. While there were differences among the three analyses, in general escapements in the lower 60 to 65 percentiles are optimal across a wide range of productivities, serial correlation in escapements, and measurement error in escapements, particularly in situations of low to moderate harvest rates.

SEGs based on the current Percentile Approach, especially the upper bounds, may actually be unsustainable in that they may specify

Table 4. Summary of empirical information and percentile ranges obtained by applying the Percentile Approach to 66 Pacific salmon stocks in Alaska.

Number of stocks	Species	Contrast	*u*	Best	*Rating*	25–75	15–75	15–85	15–Max
5	Chinook	>8	<0.40	15–45	0.37	1.15	0.86	1.07	2.28
1			≥0.40	10–50	0.00	0.58	0.51	0.61	1.68
2		≤8	<0.40	Min-45	0.16	1.09	0.94	1.16	1.77
5			≥0.40	5–45	0.29	0.91	0.75	1.02	1.66
6	Chum	>8	<0.40	20–65	0.38	0.46	0.57	0.72	2.20
1	Coho	>8	<0.40	35–60	0.09	0.61	0.72	0.82	2.19
2			≥0.40	15–65	0.44	0.53	0.51	0.67	1.59
4		≤8	≥0.40	40–75	0.18	0.21	0.27	0.28	0.85
4	Pink	>8	<0.40	40–75	0.57	0.79	0.82	1.03	2.29
3			≥0.40	40–85	0.32	0.49	0.61	0.66	1.51
8	Sockeye	>8	<0.40	20–55	0.44	0.86	0.94	1.31	2.31
15			≥0.40	35–75	0.38	0.44	0.59	0.66	1.55
4		≤8	<0.40	Min–45	0.31	1.15	1.01	1.18	2.12
6			≥0.40	20–65	0.26	0.33	0.30	0.36	1.04
24	All	>8	<0.40	20–55	0.54	0.79	0.82	1.03	2.29
21			≥0.40	40–75	0.47	0.49	0.61	0.66	1.51
6		≤8	<0.40	Min–45	0.26	1.13	0.89	1.17	2.00
15			≥0.40	15–55	0.39	0.49	0.44	0.56	1.20

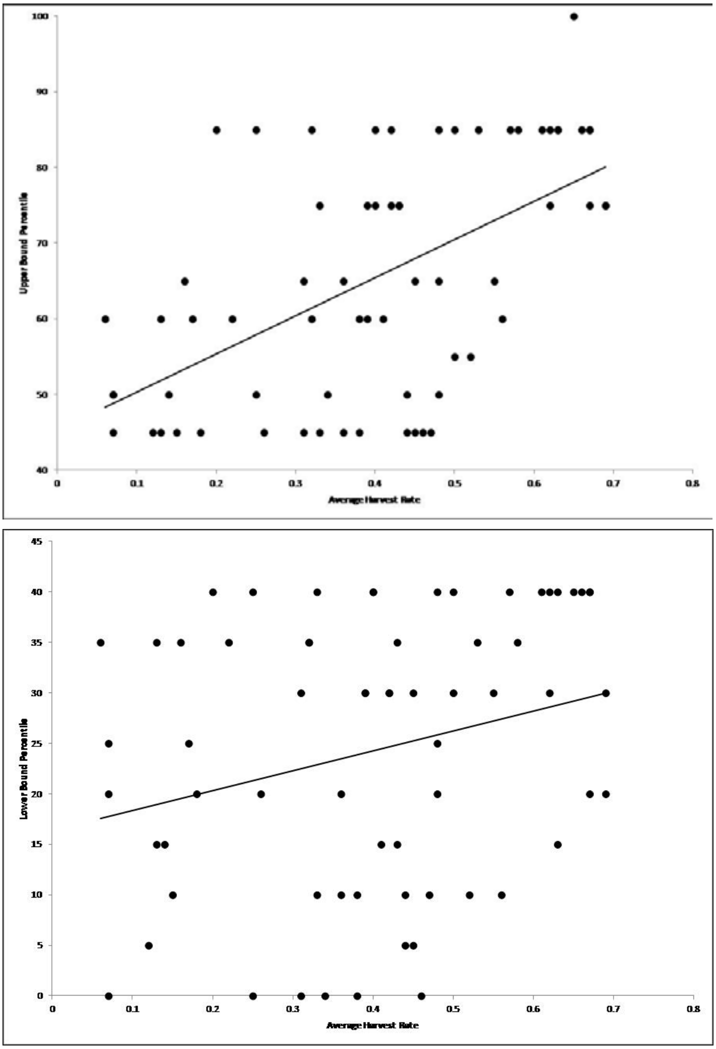

Figure 3. Best lower bound (lower panel) or upper bound (upper panel) percentile plotted against average harvest rate for 66 Pacific salmon stocks in the empirical meta-analysis. Solid lines are simple least-squared linear regressions.

a spawning escapement that is close to or exceeds the carrying capacity of the stock where there is the expectation of no sustainable yields. For example, from the theoretical analysis, at a harvest rate of 0.25, escapements greater than the 70 percentile have a high probability of exceeding carrying capacity (Fig. 1, top graph). At a harvest rate of 0.40, this percentile increases to 80% so that the upper bound of SEG Tiers 3 (85%) and 4 (100%) are most likely unsustainable even in cases of moderate harvest rates. Simulation results corroborate the same general indication that optimal Best upper bound percentiles occur most often at 55 to 65%, not 75% and higher (Table 3). While 28 of the 66 stocks in the meta-analysis have a Best upper bound percentile that exceeds 65% (Table 4), the average harvest rate of these 28 stocks is 0.52, much higher than would be recommended for use of the Percentile Approach. Of the 30 stocks with average harvest rates less than 0.40, only five have upper bound percentiles greater than 65% (two chum salmon and three pink salmon stocks) and these five stocks have a much lower average log-productivity [$\ln(\alpha) = 1.19$] than the other 25 stocks [$\ln(\alpha) = 1.66$].

The lower bound percentile of SEG Tier 1 (25%) appears somewhat higher than necessary given the results of these analyses. The theoretical analysis indicates that lower bound percentiles of 17% or less are Best across a range of productivities (Table 2). Similarly, simulation analyses indicate that lower bound percentiles of 5 to 20% are Best across a wide range of harvest rates, depending primarily on the level of measurement error and contrast (Table 3). The meta-analysis indicates that overall Best lower bound percentiles typically range from the minimum to 20% for stocks with harvest rates of 0.40 or less (Table 4). Twenty-nine of the 66 stocks had a Best lower bound percentile of 20% or less, and of the 30 stocks with average harvest rates of less than 0.40, 16 had a Best lower bound percent of 20% or less.

Although 37 of the 66 stocks in the meta-analysis had a Best lower bound percentile of 25% or more, 23 of these stocks had harvest rates of 0.40 or greater (Table 4). Average harvest rate of stocks with a lower bound percentile less than 25% was 0.36, and for stocks with a 25% or higher lower bound percentile it was 0.43. Of the 14 stocks with a lower bound percentile of 25% or more and average harvest rates less than 0.40, average process error (residual error plus error due to lag-1 serial correlation) was the highest (0.44) of all the stocks in the meta-analysis (0.26) and higher than the highest value used in the simulation analysis (0.24). This means that for some stocks with low to moderate harvest rates, there may be extreme density-independent variation in escapements that would cause the optimal lower bound percentile to be higher than 25%, especially for stocks with low log-productivity [$\ln(\alpha) \approx 1$].

While the analyses presented provide consistent and reasonable outcomes with respect to the current Percentile Approach, several aspects of salmon population dynamics were ignored or greatly simplified to facilitate the analyses. For example, only one form of stock-recruitment function (Ricker) was presented in the analyses where others could be considered (e.g., Beverton-Holt [Beverton and Holt 1957] or hockey-stick [Barrowman and Myers 2000] forms). Other forms of stock-recruitment function were not used because they have been shown to not fit salmon production data in Alaska very well and would likely have resulted in lower values for best percentiles given the asymptotic shape of these other forms of stock-recruitment function. Choice of the Ricker model was one made primarily out of practical rather than biological considerations. The Ricker model has been shown to statistically fit Alaska salmon data well, can accommodate overcompensation that has been shown to occur in Alaska salmon stocks, and is conservative with respect to the estimate of S_{MSY} when compared to asymptotic models (Fleischman et al. 2012).

Other or additional criteria beyond the Best *Rating* compared to an L90 and U70 range around S_{MSY} could have been employed for determining the recommended percentiles for a SEG range. For example, another potential measure of the adequacy of an escapement goal range is that the lower bound has a low probability of enabling long-term problems with population viability (e.g., lower bound of escapement goal set at a very small percentage of carrying capacity). Use of the L90 criterion for evaluating the lower bound of the Percentile Approach and restricting the maximum harvest rate of this approach to 0.40 ensured that these potential problems were minimized.

A simple age composition was used in the theoretical and simulation analyses, with one age at maturity. Different species of salmon have differing age composition and differing rates of maturation at age, so it was difficult to choose one over the other in analyses that could potentially apply to any species of salmon. Several differing age compositions were contemplated in constructing the simulation analysis, but these were rejected in favor of a single age at maturation. The inclusion of more complex age composition and maturation rates into the simulation analyses, which tend to moderate the amount of contrast in escapements, would have universally resulted in slightly lower values for Best percentiles than those reported herein, so that the results of this study are somewhat conservative with respect to recommended percentiles for species of salmon with multiple ages and differing rates of maturation.

Values of the parameters of interest in the simulation study were limited to log-productivities of 1 to 2, lag-1 serial correlation of 0.00 or 0.50, and log-scale process error of 0.6, although a survey of these parameters from the meta-analysis confirms that these are the most commonly estimated values for these parameters. We also did not focus attention on scenarios of very low contrast (<4) as they are fairly rare in salmon escapement data sets from Alaska, especially in situations of high measurement error (Munro and Volk 2013). We ignored measurement error in estimation of stock-recruitment parameters for data sets in the meta-analysis as these data were not consistently available for all 66 stocks.

Recommendations

Based on the analyses and our discussion above, we recommend that the current four-tier Percentile Approach be replaced with the following three tiers for stocks with low to moderate (less than 0.40) average harvest rates:

- Tier 1: high contrast (>8) and high measurement error (aerial and foot surveys) with low to moderate average harvest rates (<0.40), the 20th to 60th percentiles
- Tier 2: high contrast (>8) and low measurement error (weirs, towers) with low to moderate average harvest rates (<0.40), the 15th to 65th percentiles
- Tier 3: low contrast (8 or less) and high or low measurement error with low to moderate average harvest rates (<0.40), the 5th to 65th percentiles

The lower bound percentiles of these three tiers can also be used in developing lower-bound SEGs for stocks with low to moderate average harvest rates.

These recommended tiers appear to represent reasonable proxies for S_{MSY}. When the recommended tiers were applied to the simulation analyses as SEG ranges for management, expected yields with respect to MSY improved over those derived from the current Percentile Approach. In particular, performance in terms of expected yields relative to MSY decreased slightly at the lower bound but increased markedly at the midpoint and upper bounds of escapement goals derived from the recommended tiers (Table 5). Reasonable and sustainable levels of expected yield were projected for a wide range of log-productivity, serial correlation, and harvest rates, given the recommended tiers based on the amount of measurement error and contrast in observed escapements (Fig. 4). It should be noted that these results are expectations across a large number of simulated stocks. As such, implementation of the percentile method on an individual stock would be subject to greater variability in performance.

With some exceptions, when applied to 30 stocks in the meta-analysis with average harvest rates less than 0.40, the recommended tiers provided reasonable and sustainable proxies for a range around S_{MSY} (Fig. 5). Notable exceptions are Kodiak Mainland and NSE Outside pink salmon stocks, where the escapement range calculated from the recommended tier does not overlap with the L90-U70 range around S_{MSY} and could potentially result in overfishing. These two stocks have fairly low log-productivities (0.80 and 1.22) and very high levels of contrast (>200), likely caused by high levels of measurement error in estimation of escapements, situations that can cause estimates of S_{MSY} (and therefore the L90–U70 range) to be biased high (Su and Peterman 2012). We do not believe that species-specific recommendations of optimal percentiles (e.g., for pink salmon stocks) are warranted, as the primary factors in determining whether observed escapements encompass, exceed, or are beneath S_{MSY} are the rate of harvest and the productivity of the stock.

Use of the Percentile Approach is not recommended for the following situations:

- average harvest rates of 0.40 and greater, or
- very low contrast (4 or less) and high measurement error (aerial or foot surveys).

Stocks with average harvest rates of 0.40 and greater should undergo improvements in stock assessment so that run reconstruction and production modeling can be achieved to determine an appropriate SEG or BEG. In situations of high harvest rates, Clark et al. (2009) showed that comparison of the observed average harvest rate against the estimated harvest rate at MSY is a diagnostic for the adequacy of the current escapement goal (e.g., observed u >> uMSY indicates that the current escapement goal is too low). Although not recommended, if the Percentile Approach is used in this situation, we suggest that the lower bound be set no lower than the 25th percentile to avoid potential overfishing and the upper bound be set at the 75th percentile or greater, regardless of the level of measurement error.

Conditions of very low contrast (4 or less) over long time spans (more than 10 years) when escapements are measured imprecisely (i.e., indexed) indicate a high potential for bias due to depensatory counting or other density-related effects that limit the utility of these data for informing an escapement goal developed by any method. In general, indexed escapements should be verified against independent estimates of total abundance to ensure that the index of escapement scales consistently with abundance.

Table 5. Expected yield as a percentage of MSY at the lower bound (LB), midpoint (Mid) and upper bound (UB) of the appropriate current or recommended SEG tier from the simulation analysis.

					Current tier			Recommended tier		
σ_s	ϕ	**Contrast**	**Years**	u	**LB**	**Mid**	**UB**	**LB**	**Mid**	**UB**
0.05	0.0	>8	10	0.10–0.18	90	68	8	84	85	46
				0.23–0.39	81	81	50	73	87	70
				0.10–0.39	84	76	33	78	86	60
	0.5	>8	10	0.10–0.18	81	59	1	75	77	37
				0.23–0.39	73	67	31	66	76	54
				0.10–0.39	76	64	19	70	77	47
	0.0	≤8	10	0.10–0.18	93	59	−8	92	82	40
				0.23–0.39	87	72	22	83	88	68
				0.10–0.39	90	67	10	87	85	57
	0.5	≤8	10	0.10–0.18	89	52	−13	90	75	33
				0.23–0.39	83	58	3	81	79	53
				0.10–0.39	86	56	−3	85	78	45
0.05	0.0	>8	30	0.10–0.18	95	70	10	89	88	46
				0.23–0.39	86	84	54	77	90	74
				0.10–0.39	90	78	36	82	89	63
	0.5	>8	30	0.10–0.18	86	72	15	78	86	50
				0.23–0.39	71	79	51	61	82	69
				0.10–0.39	77	76	37	68	84	62
	0.0	≤8	30	0.10–0.18	96	78	20	91	91	53
				0.23–0.39	93	81	23	86	96	74
				0.10–0.39	95	79	21	88	94	65
	0.5	≤8	30	0.10–0.18	98	68	7	95	85	39
				0.23–0.39	98	64	−6	94	90	55
				0.10–0.39	98	66	0	94	88	48
0.50	0.0	>8	10	0.10–0.18	90	65	8	89	84	55
				0.23–0.39	84	80	51	82	87	75
				0.10–0.39	86	74	33	85	86	67
	0.5	>8	10	0.10–0.18	80	61	8	79	76	51
				0.23–0.39	70	70	41	68	75	64
				0.10–0.39	74	66	28	73	75	59
	0.0	≤8	10	0.10–0.18	93	61	1	93	81	40
				0.23–0.39	87	73	26	83	87	69
				0.10–0.39	90	68	16	87	85	57
	0.5	≤8	10	0.10–0.18	88	60	6	88	78	42
				0.23–0.39	80	63	16	77	79	60
				0.10–0.39	84	62	12	82	79	53
0.50	0.0	>8	30	0.10–0.18	95	69	9	94	88	59
				0.23–0.39	86	84	54	83	90	79
				0.10–0.39	90	78	36	87	89	71
	0.5	>8	30	0.10–0.18	86	71	14	84	86	61
				0.23–0.39	71	79	50	67	81	74
				0.10–0.39	77	75	36	74	83	69
	0.0	≤8	30	0.10–0.18	ND	ND	ND	ND	ND	ND
				0.23–0.39	ND	ND	ND	ND	ND	ND
				0.10–0.39	ND	ND	ND	ND	ND	ND
	0.5	≤8	30	0.10–0.18	ND	ND	ND	ND	ND	ND
				0.23–0.39	ND	ND	ND	ND	ND	ND
				0.10–0.39	ND	ND	ND	ND	ND	ND

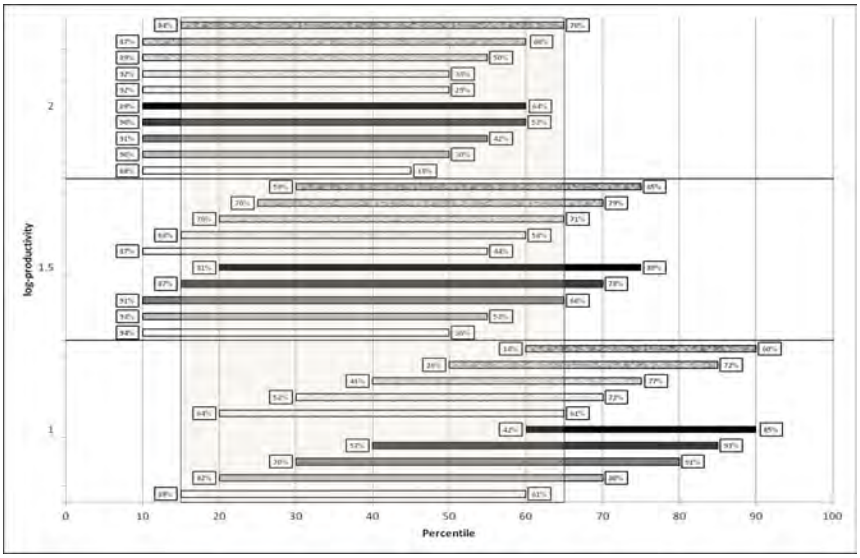

Figure 4A. Plots of average Best percentiles (bars) and expected yields as a percentage of MSY (values in boxes) for three levels of log-productivity when the recommended 15th-65th percentiles (shaded area) are managed for. Shading represents low (lightest) to moderate (darkest) harvest rate, and fill represents no (solid) to moderate (stippled) serial correlation for simulations with low measurement error and high contrast, with 30 years of escapements.

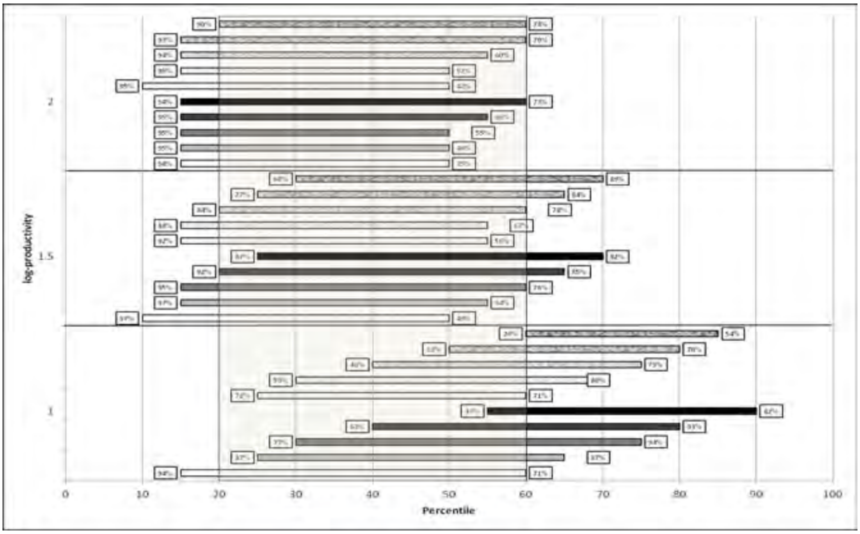

Figure 4B. **Plots of average Best percentiles (bars) and expected yields as a percentage of MSY (values in boxes) for three levels of log-productivity when the recommended 20th-60th percentiles (shaded area) are managed for. Shading represents low (lightest) to moderate (darkest) harvest rate, and fill represents no (solid) to moderate (stippled) serial correlation for simulations with high measurement error and high contrast, with 30 years of escapements.**

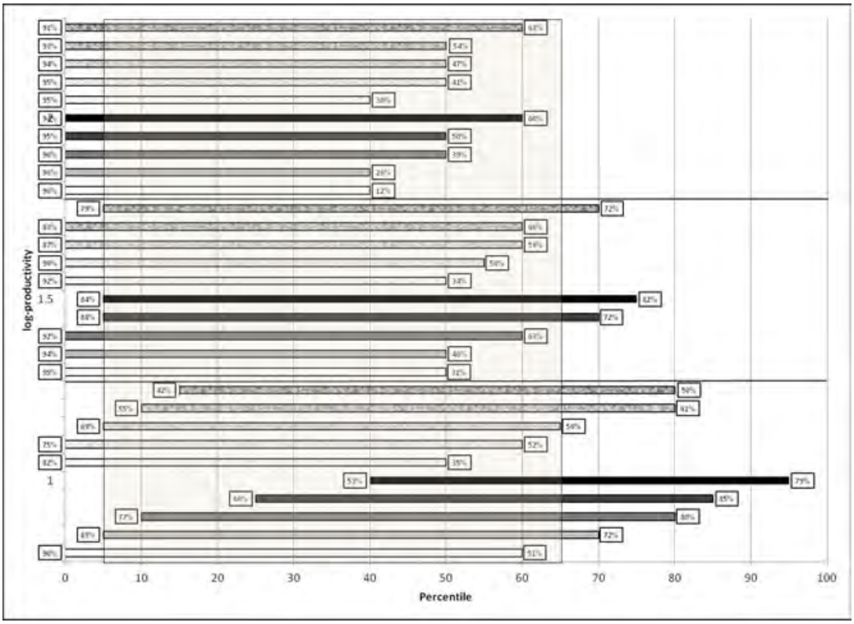

Figure 4C. Plots of average Best percentiles (bars) and expected yields as a percentage of MSY (values in boxes) for three levels of log-productivity when the recommended 5th-65th percentiles (shaded area) are managed for. Shading represents low (lightest) to moderate (darkest) harvest rate, and fill represents no (solid) to moderate (stippled) serial correlation for simulations with low measurement error and low contrast, with 10 years of escapements.

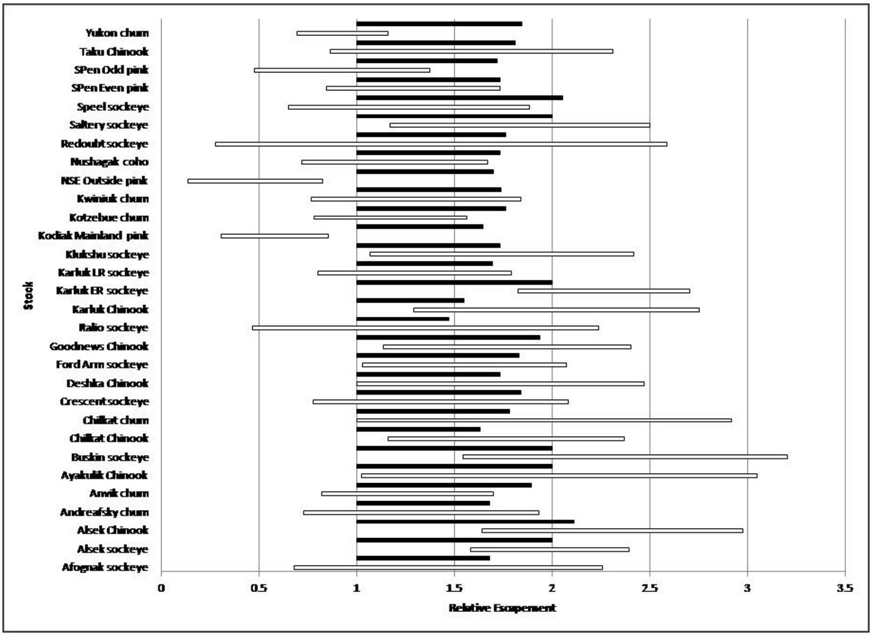

Figure 5. **Comparison of relative escapements (L90 = 1) calculated for the L90–U70 range around S_{MSY} (solid bars) and for the tier level from the recommended Percentile Approach (open bars) for the 30 salmon stocks in the meta-analysis with harvest rates of less than 0.40. NSE = northern Southeast.**

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Many of the variables examined in these analyses were chosen based on questions asked and comments made by members of the Statewide Escapement Goal Panel (Tim Baker, Dan Bergstrom, Bob Chadwick, Jan Conitz, Bill Davidson, Jack Erickson, Matt Evenson, Lowell Fair, Dan Gray, Steve Heinl, Katie Howard, Ed Jones, Nick Sagalkin, Tom Taube, Eric Volk, and Jeff Wadle) during the May 2013 meeting of the panel on this topic. We also thank the panel members and David Bernard for their insightful reviews of an earlier version of this manuscript. We especially thank Richard Yanusz, Lowell Fair, and David Bernard for participating in various discussions of the Percentile Approach over the past decade.

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