Evaluation of sockeye salmon production to Upper Station & Frazer Lake, Kodiak A.

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RC 035

Executive summary:

1. Sockeye salmon returning to Frazer Lake and the Olga Lakes (Upper Station) on Kodiak Island, Alaska, support valuable commercial fisheries that harvest fish in the estuaries of Olga Bay. Sockeye salmon production in these systems has declined over the past two decades, prompting concern that escapements have not been adequate to maximize yield from these systems.
2. Using data from brood tables compiled by the Alaska Department of Fish & Game we fit Ricker stock-recruit models to estimate the relationships between escapement and subsequent returns for the Frazer system, and the early and late runs of Upper Station. From the best-fit models, we estimated the Maximum Sustainable Yield (MSY) that could be produced from each of the systems, and the escapement that would produce MSY over the long-term (S_{msy}). Each of these parameters was estimated with uncertainties expressed as 50% and 95% credible intervals.
3. Because salmon stocks often show high productivity during some time periods and low productivity during other times, we fit a model for each of the stocks that allowed for low- and high-productivity time periods (referred to as 'regimes'), each defined by different parameters of the stock-recruit relationship. Subsequently we estimated the MSY and S_{msy} for the low- and high-productivity regimes for each stock, and assessed whether there was a general tendency for the stocks be characterized by one or the other of the regimes in the last decade.
4. Productivity of sockeye salmon from the Frazer Lake system was the most stable of the three stocks considered, showing only modest differences in MSY and S_{msy} between the low and high productivity regimes. Current escapement goals match well with our estimates of S_{msy} for this system. While run sizes were highest for a few years around 1990, there is no clear indication that there has been a long-term decline in the productivity of this system. Further, recent escapements appear to have been appropriate for achieving MSY.
5. √ The run sizes of the <u>early</u> stock to Upper Station have been relatively low since the mid-2000s and this system has been in a low productivity regime since about the 2000 brood year. Current escapement goals match well with our estimates of S_{msy} for the high productivity regime, but they appear to be too low for the current low-productivity regime. Average escapements during the last ten years were substantially lower than the levels our analyses suggest they should be in order to maximize long-term yield to the fishery.
6. The total size of the <u>late</u> run to Upper Station has declined steadily since the mid-1980s and we estimate that this stock has been in a low productivity regime since the brood year that spawned in the mid-1990s. While escapements to the system during the last 10 years match well with our estimates of S_{msy} for the high productivity regime, they are on the low end of our estimates for the low productivity regime. While subject to considerable uncertainty, our analyses indicate that the current lower bound on the

escapement goal might also be too low if the goal is to maximize long-term yield from this system.

7. The mixed stock nature of the Frazer / early Upper Station fisheries poses a challenge to management of this system. Efforts to reduce harvest on the early Upper Station run while enabling efficient harvest of the larger Frazer run will likely require more spatial separation of the harvest. While allowing recovery of the early run to Upper Station would produce only a modest increase in overall production from this system (unless is returns to a high productivity regime where additional yield will be substantial), maintaining run diversity in the overall stock complex may have tangible long-term benefits to the sustainability of this fishery.

Parts of this report were left out due to 10 page limit. They would provide scientific insight but these pages encompass the majority of findings by Daniel Schindler and his team.

B.Underwood

Background

Sockeye salmon returning to Frazer Lake and the South Olga Lakes (referred to as Upper Station in this report) on Kodiak Island, Alaska, are harvested in a gillnet fishery operating in Olga Bay. Recent declines in run size have prompted concerns that escapements are not sufficient to maximize sustainable commercial fishery yield from these systems. Further, there is concern about the status of the Upper Station early run as its timing overlaps with the larger Frazer Lake stock, and interception of Upper Station fish is likely common in the Frazer Lake fishery.

The purpose of this analysis was to evaluate the spawner-recruit relationships for sockeye salmon runs to Frazer Lake and two runs to the Upper Station (early and late) to determine whether current escapements are appropriate for maximizing sustainable yield from these systems. By fitting Ricker spawner-recruit models to available data providing by the Alaska Department of Fish & Game (ADFG), we estimated the maximum sustainable yield (MSY) that could be produced by these systems, and the spawning stock size (escapement) needed to produce maximum sustainable yield (S_{msy}). See Figure 1 for explanation of these terms. Because these parameters are estimated with a high degree of uncertainty, we also expressed the uncertainty in each of the management-relevant parameters as 50% and 95% credible intervals; parameters that are estimated with more certainty will have narrower credible intervals.

We also evaluated changes in the productivity of these stocks over time using a time-varying spawner-recruit model that allows production to be modeled as a series of periodic shifts between high and low productivity regimes. Regimes shifts may result from a range of different environmental processes but are typically related to changes in ocean conditions such as the Pacific Decadal Oscillation (PDO, Mantua et al. 1997). Under this formulation, the standard stock-recruit model takes on two possible values of the parameter (alpha, α) describing the slope of the line between returns and escapement at low escapement values. See Figure 1. Using this model we evaluated differences in S_{msy} and MSY between these production regimes, and the history of regime occupancy for each stock. When a stock is in a high productivity regime, the value of α is higher which increases values of MSY but reduces the value of S_{msy}. Thus, under a high productivity regime, MSY is achieved with lower escapements than when the system is in a low productivity regime.

We also used information about pre-fishing stock sizes from analysis of nitrogen isotopes in lake sediments (Schindler et al. 2005, Rogers et al. 2013) to inform unfished equilibrium stock size parameters, which are otherwise difficult to estimate. This is the best available information for estimating fish abundance prior to industrialized fishing.

Overview of Methods and Definitions.

We used a standard approach for assessing the productivity and management reference points for sockeye salmon in the Frazer Lake and Upper Station systems. This approach involves statistically fitting a 'Ricker stock-recruit' relationship to existing data to quantify the expected number of sockeye salmon that will be produced (return) by a specific escapement abundance.

Results

There was evidence for alternative productivity regimes in all three stocks, but differences between the high and low productivity regimes in the Frazer Lake stock were small. In the Upper Station stocks, differences between the high and low productivity regimes were substantial. The timing of regime transitions did not occur at the same times for the three stocks. However, all stocks currently appear to be in a low productivity regime even though they seemed to have entered this low productivity period at different times in the past.

For all stocks, the spawning stock size estimated to produce maximum sustainable yield (S_{msy}) for the low productivity regime is higher than that estimated for the high productivity regime. Conversely, estimated maximum sustainable yield (MSY) is lower in the low productivity regime than in the high productivity regime (Table 1). These differences are most pronounced in the Upper Station stocks and were negligible in the Frazer stock.

Table 1: Summary of model estimates for the escapement that will produce MSY (S_{msy}) and the maximum sustainable yield (MSY) for Upper Station and Frazer Lake sockeye salmon stocks. Also included here are model estimates assuming that Upper Station has a single stock of sockeye salmon, characterized by one (combined) brood table. Uncertainties are expressed as 95% credible intervals (CI). All numbers are expressed as thousands of fish.

Stock	Productivity regime	S_{msy} median (1000s)	S_{msy} 95% CI (1000s)	MSY median (1000s)	MSY 95% CI (1000s)
Frazer	Low	147	110-301	286	132-510
	High	118	27-174	470	272-2,285
Upper Station (early run)	Low	121	58-751	38	14-119
	High	73	38-139	111	60-261
Upper Station (late run)	Low	184	133-273	186	90-361
	High	139	94-184	479	274-1,049
Upper Station (combined)	Low	209	160-354	223	93-398
	High	170	105-221	422	243-1,429

Frazer Lake stock

Since 1975, sockeye salmon runs to Frazer Lake have averaged 425,000 fish but have varied from as low as 100,000 to as high as 1.3 million fish (Figure 2, All data figures are given at end of report starting on page 17). There was a notable period of large runs in the late 1980's and early 1990's. The average over the last 10 years, 333,000, was lower than the long-term average. Escapement to Frazer Lake has been very consistent, averaging 181,000 fish since 1975. Over the last 10 years, escapement has averaged 135,000 fish (Figure 2). Escapement in most years has been within the escapement goal ranges set by ADFG (Note: escapement goals have varied over time as shown in Figure 2).

Productivity in the Frazer Stock, as indicated by the parameter alpha (α), has shifted slightly over time (Figure 3). However, the low and high productivity regimes have similar relationships between return and escapement (Figure 3, top panel). While there is considerable uncertainty, there may have been a slight increase in productivity through the 1980's, which corresponds to the large return years in the late 1980's (Figure 3, bottom panel). Yet, productivity in recent years corresponds most closely to the low productivity regime. There is only weak evidence for overcompensation in this stock as some of the highest escapements have produced very low returns. However, two very large escapements also produced 2 of the top 5 returns (Figure 3, top panel). It should be noted however, that the spawner-recruit model fits these extreme low productivity points while not being able to capture the brood years with extremely high returns.

Median estimates for S_{msy} for the Frazer stock are 147,000 and 118,000 in the low and high productivity regimes, respectively (Table 1, Figure 4). The average escapement over the last 10 years, 135,000 fish, is very close to the predicted median values for the low productivity regime. It is also well within the 95% credible interval for the high productivity regime. Only 6 of the last 30 years have had escapements that fall outside of the 95% credible interval for the low productivity regime. All 6 were below the lower estimate of 110,000 fish. Additionally, the lower escapement goal bound of 75,000 is well below the 95% credible interval for the low productivity regime and near the bottom of the 95% credible interval for the high productivity regime (Figure 4). Generally, escapement to this system has been very close to our model predicted S_{msy}, but small escapements should probably be avoided as they are more likely to lead to reduced yield independent of the production regime.

Harvests from the Frazer stock are similar to the model estimates for MSY (Figure 4). Harvest over the last 10 years has averaged 198,000 fish. This value is about 100,000 fish lower than the median estimated MSY for the low productivity regime but is well within the 95% credible interval. MSY for the high productivity regime is estimated to be about 200,000 fish higher (Table 1, Figure 4).

Upper Station - early run stock

Since 1977, the early run to Upper Station has averaged 104,000 fish with a low of 32,000 and a high of 269,000 fish (Figure 5). Between 1980 and 2005, runs were quite variable but years with greater than 100,000 were common. Over the last 10 years run sizes have been consistently small, averaging only 58,000 fish (Figure 5). Escapement for this run has averaged 53,000 fish over the period of record, but has only averaged 35,000 fish over the last 10 years. Since formal escapement goals for this stock were implemented in 1988, escapements have regularly failed to reach the lower bound of the escapement goal (Figure 5). Overall, less than 30% of escapements reached the lower bound of the escapement goal. More recently, escapement has surpassed the lower bound of the escapement goal in only 2 of the last 10 years.

There is strong evidence for substantially different productivity regimes over time for the Upper Station early run (Figure 6). Productivity was generally high in mid-1980's to 2000, although variable. Recently (i.e. since the 2000 brood year) productivity has been consistently low (Figure 6, bottom panel).

Median model estimates for S_{msy} for the Upper Station early run are 121,000 and 73,000, in the low and high productivity regimes, respectively (Table 1, Figure 7). The average escapement over the last 10 years of 35,000 fish is well below the median estimates and falls below the 95% credible interval for either productivity regime (Figure 7). The lower bound of the current escapement goal of 43,000 fish is below our model 95% credible interval for the low productivity regime (58,000 fish). It is also near the bottom of the 95% credible interval for the high productivity regime (38,000 fish). The upper bound of the current escapement goal of 93,000 fish captures the uncertainty in the high productivity regime. However, this goal is still below the median estimate for S_{msy} in the low productivity regime (Figure 7). These results suggest that yield from this system would benefit from increased escapement, as it appears to be over-exploited at present. Importantly, there is very little evidence for overcompensation in this stock and the biological risks of over-escapement are minimal (Figure 6, top panel).

Median estimates for MSY for the Upper Station early run are 38,000 and 111,000 fish in the low and high productivity regimes respectively (Table 1, Figure 7). The average harvest over the last 10 years of 24,000 fish is below the median estimated MSY for the low productivity regime and is near the lower bound of the 95% credible interval. Based on trends in productivity of this stock, MSY in recent years is less than half of the MSY common in the mid 1980's. While the system appears to be over-exploited in recent years, the additional yield to be gained is relatively small as the median MSY is 38,000 and 111,000, in the low and high productivity regimes, respectively.

Upper Station - late run stock

Since 1977, Upper Station late runs have averaged 446,000 fish and ranged from 115,000 to as many as 1.4 million fish (Figure 8). Similar to the Upper Station early run, this stock had large returns in the mid 1980's to late 1990's, but has declined in recent years. Run sizes for this stock over the last 10 years has averaged 231,000 fish, about half of the long-term average (Figure 8). Escapement has been relatively consistent over the period of record, averaging 181,000 fish. Escapement over the last 10 years averaged 148,000 fish. Escapements have generally ended up within the escapement goals for this system with a few exceptions. These have generally been escapements above the upper escapement target, mostly occurring in the 1980's and 1990's (Figure 8).

There is strong evidence for substantially different productivity regimes in the Upper Station late run stock (Figure 9). Productivity switched to the high productivity regime in the late 1970's and remained there through the early 1990's. This shift likely corresponds to a shift in the

Pacific Decadal Oscillation, which has been shown to have high correlation with Alaskan salmon production (Mantua et al. 1997). Since the late 1990's, the Upper Station late run has remained in the low productivity state (Figure 9, bottom panel). The largest returns were generally produced from broods where there were high returns of 0-check fish that occurred during the high productivity regimes we detected here. See more discussion of this on page 11.

Median model estimates for S_{msy} for the Upper Station late run were 184,000 and 139,000 fish for the low and high productivity regimes respectively (Table 1, Figure 10). The average escapement over the last 10 years of 148,000 fish is below the median S_{msy} for the low productivity regime but within the 95% credible interval (Figure 10). The lower escapement goal of 120,000 fish is also below the 95% credible interval for the low productivity regime. Generally, observed escapements and escapement targets are near S_{msy} and centered within the 95% credible interval for the high productivity regime. As with the Upper Station early run, there is no evidence for over-compensation in the late run Upper Station stock over the range of observed escapements (Figure 9, top panel). The three largest escapements of greater than 300,000 fish produced three of the four largest returns.

Median estimates of MSY for the Upper Station late run are 186,000 and 479,000 fish in the low and high productivity regimes respectively (Table 1, Figure 10). The average harvest over the last 10 years of 83,000 fish is below the median MSY for the low productivity regime of 186,000 fish, but is within the 95% credible interval. Based on trends in productivity, MSY in the low productivity regime present in recent years is less than half of the MSY of the high productivity regime present throughout the 1980's and 1990's (Figure 10).

By combining the brood tables from the two Upper Station runs into a single brood table (i.e. treating it as a single stock), results from the analyses presented here were not substantially different than treating the fish as two independent stocks (Table 1).

Discussion

In this report we evaluated the spawner-recruit relationships and productivity over time for the Frazer Lake, and Upper Station early and late sockeye salmon runs. The Upper Station stocks appear to have gone through multiple productivity regimes, occupying more productive regimes in the 1980's and 1990's but occupying low productivity states over the last decade. The Frazer stock appears to be more stable as there is only a small difference in productivity between the high and the low regimes. It is important to note that in all three cases the future probability of occupying either the low or high productivity states are about equal. Therefore, when evaluating escapement policies it may be important to consider the possibility of future regime changes. In other words, even though all three stocks are currently in a low productivity regime, there is no evidence to suggest they will be permanently in this state.

There is some indication that the Upper Station early run is currently overexploited. Since run timing for the Upper Station early run overlaps with the Frazer Lake run, it may be possible to improve yield from the Upper Station early run by being more spatially restrictive in the management of the Frazer Lake stock. There are several factors that need to be considered when balancing tradeoffs of these options. Increasing escapement to the Upper Station early run may come at the expense of forgone harvest and over-escapement to the Frazer Lake stock (due to increased passage through the fishery). However, based on the data we examined here, there is little evidence of strong overcompensation in the Frazer Lake stock so the risks to future returns of over-escaping to the Frazer Lake stock are likely small. Yet, due to the small potential gain in the yield of the Upper Station early run, further analysis of the relative losses and gains from each stock is necessary to rigorously assess this tradeoff. Another important consideration, and argument for increasing the Upper Station early run, is the clear benefits of maintaining run diversity (Hilborn et al. 2003). The changes between regimes is not synchronous across the three stocks therefore improving the early run could increase the reliability of the system.

In the analyses presented here we have not accounted for the effects of interceptions of fish from these three stocks that is certainly occurring outside of Olga Bay. Interceptions that occur outside of the fishing district are currently not accounted for in the brood tables we analyzed here. It is important to note that if these interceptions were to be accounted for, then our estimates of the productivity of these stocks would be higher than we have reported here. Increased productivity will tend to cause a shift in S_{msy} towards lower values. However, the degree to which S_{msy} would be shifted relative to what we have reported here depends on several variables. Among these variables are: 1) the overall interception rates, 2) the degree to which the interception rate depends on run strength of these stocks versus that for neighboring stocks that these fish are exploited with, and 3) any long-term changes in interception rates. At present, the data do not exist to inform any of the assumptions that would be needed to assess the effects of interceptions on the population dynamics and management reference points for these stocks. Ongoing genetics studies to identify stock of origin of fish caught in fisheries outside of Olga Bay could be formally incorporated into analyses such as those we have done here as the data become available. We have not analyzed any possible interception scenarios through our models in this report because we simply do not have the information needed to bound such scenarios.

An interesting aspect of the Upper Station late run stock is in the contribution of '0-check' fish to the returns. These are fish that typically do not spend a full summer (and winter) in lakes before migrating to the marine environment. In all likelihood, these fish migrate to Olga Bay to feed during their first summer and possibly overwinter in the estuaries before migrating further to sea. In the Upper Station late run, 0-check fish have represented as much as 70% of the total return, and have averaged 16% over the period of record. There is a very strong relationship between the total return and the contribution of 0-check fish. Most of the high productivity regimes in the Upper Station late run stock were characterized by large contributions of 0-check fish returning from broods that were spawned between about 1980 -1993. 0-check fish averaged ~30% of the total return during this time period. Interestingly, there is essentially no relationship between escapement and the proportion of 0-check fish in the returns. Taken together, these observations suggest that the largest runs to the Upper Station late stock were produced by exceptionally large returns of 0-check smolts, but that escapement densities had little effect on the expression of 0-check fish in the stock. Instead, it is likely that the estuaries were exceptionally productive habitat and supported high survival of 0-check fish during those years. The early run to Upper Station has only negligible contributions of 0-check fish to the returns so their effect on population dynamics is likely very small.

The contributions of jacks (male fish that spend only one year in the ocean) to runs of the Frazer Lake stock has become a major concern to fishermen and managers. We are currently working on a collaborative project with ADFG to explore some of the causes of the large contributions of jacks to current runs. At this point, our analyses are very preliminary and have not been included in this report; however, we offer some qualitative observations here. First, the prevalence of jacks to the Frazer Lake sockeye stock has always been relatively high compared to other sockeye salmon stocks in Alaska. Over the period of record, jacks have contributed an average of 7% of returns to brood years, with a range from 1 – 19%. These proportions are about 10 times higher than observed in other Alaska sockeye systems such as in Bristol Bay. Since 1990, returns to brood years have averaged over 10% jacks. These high proportions of jacks in the brood year returns have translated into exceptionally high contributions of jacks to annual runs because of the development of strongly cyclic population dynamics over the last two decades. A stock that is strongly cycling will have very high contributions of jacks to the run in any year prior to a peak year dominated by 2-ocean fish. These dynamics appear to have developed in the Frazer Lake stock.

While we have not performed any specific analyses to quantify the potential effects of current efforts to cull jacks from spawning populations, we can offer some general insights into whether this activity is likely to alter the population dynamics. First, it is clear that the proportion of jacks has increased for brood years that spawned since 1990 in Frazer Lake. A similar increase in the proportion of jacks has occurred in the returns to Upper Station (though the proportions are somewhat lower). That all of these stocks are showing an increase in the contribution of jacks to brood year returns suggests a response to some regional phenomenon. Second, the heritability of the traits associated with jacking is generally low, meaning that this is a genetic trait that is typically not strongly under strong evolutionary selection. Thus, culling jacks from the spawning grounds is not likely to reduce their contributions to the population. Based on information we have currently in-hand, it appears that the high proportion of jacks in these runs is mostly a function of the cyclic population dynamics in the stock. We cannot offer a single explanation for why the jack proportion by brood year is so high in all these stocks, and why there has been an increase during the last two decades.

Future work should include an explicit accounting of the tradeoffs involved in harvesting these three stocks, while simulating future productivity regime occupancy and resulting changes in expected production. Additionally, robust estimates of S_{msy} and MSY moving into the future should account for the relative probabilities of low and high productivity regimes. Additionally, if interceptions in other fisheries are high, genetics should be used to estimate the exploitation rates, as this is likely to bias the model estimates of productivity, MSY, and S_{msy}. Understanding the causes of the cyclic population dynamics in the Frazer Lake stock may provide insights to management about how to reduce the proportion of jacks in the runs. Why the proportion of jacks to brood year returns has increased in the last two decades is also worthy of further investigation, though it seems that culling of jacks on the spawning grounds is unlikely to change this pattern.

Methods:

To estimate S_{msy} and MSY we fit spawner-recruitment relationships to brood table data for the Frazer Lake (brood years 1966-2007) and Upper Station (brood years 1970-2007) stocks. A Ricker model was used to represent the spawner-recruit relationship, assuming log-normally distributed errors.

$$R_t = S_t * \exp\left(\alpha\left[1 - \frac{S_t}{\beta}\right]\right) * \exp(\varepsilon)$$

$$\varepsilon \sim N(0, \sigma)$$

St is the number of individuals spawning in year t, and Rt is the recruitment or adult production from spawning in brood year t, returning anywhere from 2 to 8 years later. Estimated parameters include the maximal productivity in the absence of density-dependent compensation (α), the equilibrium population size (β), and the standard deviation for the lognormal error distribution (σ). Parameters were estimated using Bayesian methods for two reasons: 1) a Bayesian analysis allows the uncertainty in parameter estimates (α, β, σ) and estimates of derived quantities of interest (S_{msy} and MSY) to be directly quantified, and 2) Bayesian methods allow incorporation of prior information (Gelman et al. 2004) about the parameter describing equilibrium stock size (β), which is often poorly defined by the available time series of data.

Given the difficulty in estimating equilibrium stock size from brood table data given the limited contrast in observed spawning abundances, we placed priors on equilibrium stock sizes for the Frazer and Upper Station stocks. These priors are based on paleolimnological estimates of historical salmon abundance (Schindler et al. 2005, Cunningham et al. 2015). Historical salmon abundances from 1750 – present were reconstructed from nitrogen stable isotope ratios in lake sediments around Alaska (Rogers et al. 2013). We used the average of the top twenty percent of salmon abundances between 1750 and 1890 for 11 lakes across Southwest Alaska as a proxy for equilibrium stock size. There is a strong correlation between lake area (km^2) and the historical equilibrium stock size ($R^2 = 0.91$) across these lakes. We used normal priors on equilibrium stock sizes in this report with means derived from this regression and each systems respective lake