EXECUTIVE SUMMARY:

Project 6: Data synthesis and cumulative impact analysis

Purpose of This Study and Methods Used

The overall goal of this study was to synthesize the results of Cohen Commission research projects into an assessment of the cumulative impacts of various factors potentially affecting the Fraser River sockeye fishery over the recent period of declining productivity. Salmon biologists calculate *total productivity* as the number of mature adults produced per spawner[1]. Over the last two decades, there has been a general decline in both Fraser sockeye productivity and the rate of survival of returning adults from the estuary to the spawning ground. However, some Fraser sockeye stocks have not shown productivity declines (i.e., Harrison and Late Shuswap) and some years (e.g, 2010) have shown notable increases in productivity.

We organized our work around five objectives: a workshop involving all Cohen Commission researchers; synthesis and integration of data on stock productivity and potential explanatory factors acquired from these researchers; integrative analyses of cumulative impacts based on the ten technical reports completed to date for the Commission (the aquaculture report is still in progress); quantitative analyses of cumulative impacts based on the available data; and completion of this report.

Prior to considering potential causes of declining productivity, we first summarized the observed patterns of change in various attributes of the Fraser sockeye fishery. We then systematically analyzed potential causes of these patterns, using a framework adapted from the literature on cumulative effects/impacts and retrospective ecological risk assessment. This framework considered the cumulative impacts of all of the factors potentially affecting each of five life history stages, as well as possible interactions across life history stages. We explicitly recognize that combinations of factors are likely responsible for observed effects, and that these combinations will vary in complex, usually unknown ways across years and stocks. The intent of this analysis is to make the best use of the available evidence to improve our understanding of changes to Fraser sockeye populations over the last two decades.

Within each life stage, we considered whether each of the hypothesized stressors:

1. could affect sockeye survival through a plausible mechanism;
2. has generally exposed Fraser sockeye to increased stress over the period of productivity declines;

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[1] Mature adults (or recruits) are estimated as the number of fish returning to the coast *before* the onset of fishing. This estimate is derived by working backwards from the numbers of adults that eventually reached the spawning ground, plus any en-route mortality between the mouth of the Fraser and the spawning ground, plus harvest. Biologists also estimate *juvenile productivity* (fry or smolts per spawner), and *post-juvenile* productivity (mature adults per fry or spawner).

3. is correlated with variations in sockeye productivity (i.e. over space, time and stocks); and,
4. has other corroborating evidence from cause-effect studies.

Based on the available evidence, we then came to a conclusion whether the factor was *unlikely* (representing the lowest level of confidence), *possible, likely,* or *very likely* (representing the highest level of confidence) to have been a **primary driving factor** behind the overall pattern of declining productivity in Fraser sockeye. Factors that were unlikely to have been primary drivers to the overall pattern may still have contributed to changes within particular stocks and years. In some cases, major data gaps led us to the outcome that *no conclusion was possible.* Our synthesis of evidence from the Cohen Commission technical reports was supported by our own statistical analyses to determine the relative ability of various factors (representing different combinations of stressors) to explain changing patterns of productivity in Fraser sockeye.

The Pattern We Seek To Explain

Based on the Cohen Commission's technical reports (Peterman and Dorner 2011, Hinch and Martins 2011), we can describe five key attributes of change in Fraser and non-Fraser sockeye populations:

1. Within the Fraser watershed, 17 of 19 sockeye stocks have shown declines in productivity over the last two decades (the two exceptions are Harrison and Late Shuswap sockeye).
2. Most of 45 non-Fraser sockeye stocks that were examined show a similar recent decrease in productivity. Thus, declining productivity has occurred over a much larger area than just the Fraser River system and is not unique to it.
3. Of the nine Fraser sockeye stocks with data on juvenile abundance, only Gates sockeye have showed declines in juvenile productivity (i.e., from spawners to juveniles) but 7 of the 9 stocks showed consistent reductions in post-juvenile productivity (i.e., from juveniles to returning adult recruits).
4. There have been three separate phases of decline in productivity since 1950. The first started in the 1970s, the second in the mid-1980s, and then the most recent one in the late 1990s or early 2000s, with individual stocks showing these trends to various extents.
5. Over the last two decades there has been an increasing amount of en-route mortality of returning Fraser sockeye spawners (i.e., mortality between the Mission enumeration site and the spawning ground). This results in reduced harvest, as fishery managers do their best to ensure enough spawners return to the spawning ground in spite of considerable mortality along the way.

Conclusions Regarding Potential Causes of This Pattern

We present our conclusions for each life history stage, recognizing that there are interactions both within and between life history stages. These results do not consider aquaculture (report in progress) or other factors not considered by the Cohen Commission (except for a brief consideration of interactions between sockeye and pink salmon).

Stage 1: Incubation, Emergence and Freshwater Rearing

With the exception of **climate change**, which we consider to be a *possible* factor, and **pathogens** (for which *no conclusion is possible* due to data gaps), it is *unlikely* that the other factors considered for this stage, taken cumulatively, were the *primary* drivers behind long term declines in sockeye productivity across the Fraser Basin. These factors included **forestry**, **mining**, **large hydro**, **small hydro, urbanization, agriculture, water use, contaminants, density dependent mortality, predators,** and effects of **Lower Fraser land use** on spawning and rearing habitats. We feel reasonably confident in this conclusion because juvenile productivity (which integrates all stressors in this life history stage except over-wintering in nursery lakes) has not declined over time in eight of the nine Fraser sockeye stocks where it has been measured. We would be even more confident if more stocks had *smolt* enumeration rather than *fry* estimates (only Chilko and Cultus stocks have smolt estimates). Though not primary drivers of the Fraser sockeye situation, each of these factors may still have had some effects on some Fraser stocks in some years (the data are insufficient to reject that possibility). We suspect, based on qualitative arguments alone, that **habitat** and **contaminant** influences on Life Stage 1 were also not the *primary* drivers responsible for productivity declines occurring to most non-Fraser stocks assessed by Peterman and Dorner (2011). However, given the absence of any exposure data and correlation analyses for non-Fraser stocks, it is not possible to make conclusions on the relative likelihoods of factors causing their declining productivities. None of the factors considered for Stage 1 are likely to have been much worse in 2005 and 2006 for Fraser sockeye stocks, sufficient to have significantly decreased egg-to-smolt survival in the salmon that returned in 2009. Similarly, none of these factors are likely to have been much better in 2006 and 2007, sufficient to have substantially improved egg-to-smolt survival in the salmon that returned in 2010.

Stage 2: Smolt Outmigration

We analyzed the same factors for Stage 2 as for Stage 1 and came to the same conclusions. There are however three key differences in our analyses for these two stages. First, regardless of differences in their spawning and rearing habitats, all sockeye stocks pass through the highly developed Lower Fraser region. Second, migrating smolts are exposed to the above-described stressors for a much shorter time than are eggs and fry, which reduces the likelihood of effects. Third, since smolt migration occurs subsequent to enumeration of fry and smolts in rearing lakes, we have no analyses relating survival rates to potential stressors during this life history stage. Thus our conclusions have a lower level of confidence than for Stage 1. While there are some survival estimates for acoustically tagged smolts, these data (which only cover a few stocks) were not analyzed by any of the Cohen Commission technical studies. None of the factors considered for Stage 2 is likely to have been much worse in 2007 for downstream migrating smolts (affecting the 2009 returns), or to have been much better in 2008 (affecting the 2010 returns).

Stage 3: Coastal Migration and Migration to Rearing Areas

There are almost no data on exposure for **pathogens** making *no conclusion possible.* The evidence presented suggests that sockeye salmon in the Strait of Georgia have little direct exposure to **human activities and development**[2], leading to a conclusion that it is *unlikely* that these factors have contributed to the decline of Fraser River sockeye salmon. Sockeye salmon have been exposed to predators, marine conditions, and climate change during this early marine phase. However, there has been no evidence presented on any correlations between key predators and sockeye salmon survival. Some important predators appear to be increasing in abundance, and some potentially important alternate prey appear to be decreasing, but many other known predators are decreasing or remaining stable. It therefore remains *possible* that **predators** have contributed to the observed declines in sockeye salmon. Based on plausible mechanisms, exposure, consistency with observed sockeye productivity changes, and other evidence, **marine conditions** and **climate change** are considered *likely* contributors to the long-term decline of Fraser River sockeye salmon. It is also *very likely* that poor **marine conditions** during the coastal migration life stage in 2007 contributed to the poor returns observed in 2009. Marine conditions were much better in 2008 (much cooler temperatures), which benefited returns in 2010. **Aquaculture** was not considered in our report as the Commission Technical reports on this potential stressor were not available, but will be considered in an addendum to this report.

Stage 4: Growth in North Pacific and Return to Fraser

Our conclusions on this life history stage are similar to those for Stage 3, though we conclude that **marine conditions** and **climate change** remain *possible* contributors to the long-term decline of Fraser River sockeye salmon (whereas in Stage 3, we considered them to be likely contributors).

Stage 5: Migration back to Spawn

While the timing of increased **en-route mortality** coincides generally with the Fraser sockeye situation, the Fraser sockeye productivity indices already account for en-route mortality (i.e., recruits = spawners + harvest + en-route mortality). Therefore, there is no point in examining correlations between en-route mortality and life cycle or post-juvenile productivity indices within the same generation. The only possible effects on productivity are inter-generational effects, for which the evidence is limited and equivocal. We therefore conclude that it is *unlikely* that en-

[2] "Human activities and development" refers specifically to those activities and developments considered within Technical Report #12 (Fraser River Sockeye Habitat Use in the Lower Fraser and Strait of Georgia), which do not include salmon farms. Exposure to salmon farms will be covered in the technical report on aquaculture, which is currently in progress. The present report does not provide any conclusions regarding salmon farms.

route mortality (or pre-spawn mortality[3], which has only increased for Late Run sockeye) are a primary factor in declining indices of Fraser sockeye productivity. However, en-route mortality has *definitely* had a significant impact on the *sockeye fishery* and the *numbers of adult fish reaching the spawning ground*, particularly for the Early and Late runs. **Pre-spawn mortality**, **habitat changes**, and **contaminants** are *unlikely* to be responsible for the overall pattern of declining sockeye productivity. *No conclusion is possible* regarding **pathogens** due to insufficient data. None of the factors assessed for this life history stage are likely to have shown significant changes between 2009 and 2010.

The above conclusions are based on qualitative and quantitative analyses of existing information. There are two important caveats on these conclusions. First, there are major gaps in both our fundamental understanding of how various factors interact to affect Fraser River sockeye salmon, and in the data available to quantify those factors. Second, all Cohen Commission researchers have had a limited amount of time to analyze existing information; future data syntheses and analyses may provide deeper and different insights. Below, we summarize our recommendations for research, monitoring and synthesis activities.

Recommendations for Research, Monitoring and Synthesis

Researchers at the Cohen Commission workshop agreed with the PSC report (Peterman et al. 2010) that the 2009 and long-term declines in sockeye productivity were likely due to the effects of multiple stressors and factors, and that a strong emphasis should be placed on studying the entire life cycle of sockeye salmon along with their potential stressors. Unlike the PSC report, participants felt that research efforts should be expanded outside the Strait of Georgia as a priority area, as well as increasing efforts inside the Strait.

Section 5.2 of this report describes 23 recommended research and monitoring activities, organized by life history stage, based on four sources: the PSC report (Peterman et al. 2010), the Cohen Commission's research workshop, the Commission's Technical reports, and this cumulative effects assessment. We have highlighted 12 of these 23 recommendations as particularly high priority, but the others are also essential to provide the information needed to properly manage Fraser sockeye. The three dominant themes are: 1) coordinated, multi-agency collection of data on sockeye stock abundance, survival and stressors for each life history stage; 2) development of an integrated database and cumulative assessments both within and across multiple life history stages; and 3) transparent dissemination of information annually to scientists and non-scientists. Since the early marine environment appears to be a major potential source of declining productivity, it is particularly important to improve information on potential stressors affecting sockeye along their migratory path from the mouth of the Fraser River through Queen Charlotte Sound, including food, predators, pathogens, and physical, chemical, and biological ocean conditions. Further efforts to prioritize, sequence and refine our

[3] Pre-spawn mortality is defined as females that have arrived on spawning grounds but die with most of their eggs retained in their body.

recommendations will require a careful consideration of several factors: the ultimate uses of the information; given those uses, the appropriate space and time scales and required/achievable levels of accuracy and precision; and the most cost-effective, well-integrated designs for the overall monitoring and research program.