Investigating Freshwater and Ocean Effects on Pacific Lamprey and Pacific Eulachon of the Columbia River Basin: Projections within the Context of Climate Change

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Executive Summary

In this report we utilized statistical models and G.I.S-based approaches to analyze available life cycle, abundance and distribution data from the last 80 years on Pacific lamprey (Entosphenus tridentatus) and Pacific eulachon (Thaleichthys pacificus, and determine how climate change may potentially impact these species in the Columbia River basin. Both species have experienced substantial declines in this basin, and are in urgent need of protection and restoration. While data on these species have incomplete spatial and temporal coverage in this region, some inferences can be derived on possible adverse effects of climate change and subsequent impacts on persistence and resilience of populations. The quantified impacts indicate that the predicted higher late fall and winter stream flows are likely to have a negative impact on Pacific lamprey and possibly a positive impact on Pacific eulachon, though this could be negative for eulachon if the increased flow does not coincide with the spring oceanic upwelling transition. Higher ocean temperatures and reduced upwelling are likely to have negative impacts on the oceanic life cycle phases of both species. The current status and distribution of Pacific lamprey during its freshwater lifecycle is likely to be negatively impacted by climate change effects (e.g. changes to seasonal stream flow and higher summer water temperature) to a greater degree in interior snow dominant parts of the basin, areas where lamprey are already severely imperilled.

Datasets examined

We examined the following information:

1) Fish abundance and distribution either through direct measures of abundance (larval surveys or dam counts) or estimated catches (with the assumption that they were directly proportional to abundance).
2) Freshwater flow and temperature measurements from various locations in the available tributary habitat of the fish species, in relation to relevant life cycle aspects.
3) Ocean condition measurements, in relation to relevant life cycle aspects.
4) Projected future climate change scenarios for freshwater flow and temperature, and ocean conditions, considering how they may affect overall abundance and distribution.

Major Conclusions

Our major conclusions were as follows:

1) Both Pacific lamprey and Pacific eulachon will be adversely affected under climate change projections by poorer ocean conditions for growth, namely lower than average upwelling conditions and higher than average sea surface temperatures (correlating with positive phases of the Pacific Decadal Oscillation).
2) Limited data reduced our confidence in characterizing long-term abundances of both species. Nevertheless, projected higher peak flows in the winter months can be directly linked to poor survival and consequentially lower abundance of Pacific lamprey on some

systems on the Willamette River. Possible causal mechanisms include higher flow events moving larval and juvenile stage lamprey out of the lower tributaries into the mainstem areas, making them more vulnerable to predation, thereby reducing survival and consequential abundance.

3) Pacific eulachon abundance was found to be dependent on higher spring flows that appeared to be correlated with higher survival in a similar manner as Columbia River stream- type Chinook. However, abundance could possibly be confounded with better than average ocean conditions that are critical to the overall survival and abundance of eulachon. It is more than likely that both factors are related to overall increases in abundance, as good freshwater years are normally correlated with good ocean years and vice versa.
4) Projected climate change effects to seasonal flow and summer water temperatures will likely reduce the available tributary spawning and rearing habitat, and limit upstream migration of adult Pacific lamprey to the greatest degree in areas where they are already highly impacted by passage through Snake River and interior Columbia Basin hydropower dams and reservoirs. Areas where lamprey abundance is documented to be greater, including the Willamette Basin and the lower Columbia basin tributaries, will likely experience less severe future climate change impacts, and may represent strongholds for restoring populations.
5) For Pacific eulachon, peak early spring stream flows in spawning areas may likely increase under climate change, possibly extending the spawning season and assisting outmigrating juveniles. However, under climate change projections, these peak flows will likely occur earlier, which may cause a mismatch with optimal upwelling conditions needed in the ocean for juvenile growth. Warmer water temperatures in the Columbia River mainstem may also trigger an earlier in-migration of adults for spawning.

Recommendations

Our work was limited to available but insufficient datasets to achieve a comprehensive and detailed analysis. As such many recommendations follow to improve future analyses. These recommendations are split into two tiers (Tier 1, a primary focus and Tier 2, a secondary focus).

Tier 1 recommendations:

1. While it is indicative that both Pacific lamprey and Pacific eulachon have shown dramatic declines in abundance and distribution, the particulars of both species, i.e. age class and year class strength and declines over time, are lacking. Hence, acquiring a more comprehensive database to make these inferences is important. The primary report recommendations are:

    a. Better time series data on abundance should be collected on Pacific lamprey and Pacific eulachon. A 20-25 year horizon is needed for Pacific lamprey, and a 10-15 year horizon for Pacific eulachon is necessary because the freshwater and ocean life cycle for one brood of lamprey could extend anywhere from 7 to 15 years, and extends 2-3 years for eulachon. The recommended time series would ensure multiple complete life-cycle replicates.

b. For Pacific eulachon, consider reinstating shrimp by-catch information by establishing a test fishery, in order to relate this information to eulachon abundance so it can be managed in a pre-season context.
c. For both Pacific eulachon and Pacific lamprey, expand collection of measures of larval and juvenile abundance. This is currently is done with larval surveys for eulachon, but could be expanded. A critical but missing piece of information is the age-structure of the larval and juvenile life-cycle stages for Pacific lamprey, which would be useful to assess survival across ages. Extensive multi-year surveys should be conducted for larval and juvenile lamprey, including collections at dams, irrigation facilities and tributary monitoring sites. Once these data were available, a better idea on population trajectories could be made by using a life cycle model.
d. Develop consistent and measurable monitoring and evaluation of all life cycle aspects to better understand the dynamics of these populations (i.e. spawning abundance, juvenile abundance and some tagging and recovery efforts in the oceans), with sustained implementation.
e. No additional data collection programs may be required for environmental conditions, including stream temperature and flow, as current efforts to date are adequate for this modelling. However, it should be insured that the programs that collect these data are maintained into the future, as well as modelling efforts that project future climate change impacts to these conditions.

Tier 2 recommendations:

a. Support greater research into the thermal tolerance of Pacific lamprey and Pacific eulachon in the freshwater environment, including upper and lower lethal limits. Improve other biological data about both species (such as predator-prey interactions, juvenile rearing area, dissolved oxygen level effects, spawning distribution, and habitat/food web quality preferences) that is lacking for both species so that we improve the information base where bottlenecks exist.
b. Conduct more adequate ocean monitoring and sampling for the adult life cycle stages of both species.
c. Expand research on the current and potential impacts of non-native predators of Pacific lamprey and Pacific eulachon
d. Possibly build a more refined version of the lamprey life cycle model presented in Appendix A

Summary of Impacts to Pacific Lamprey

Figure ES1 summarizes seasonal impacts of climate change on the life cycles of Pacific lamprey in the Columbia River Basin. Inferences on how climate change could adversely affect life cycle trajectories were a product of our research but should not be considered comprehensive because there are other possible effects that were not considered. The graphic portrays both the climate change impact and their likely biological significance on the species, as separated into freshwater and ocean life cycles.

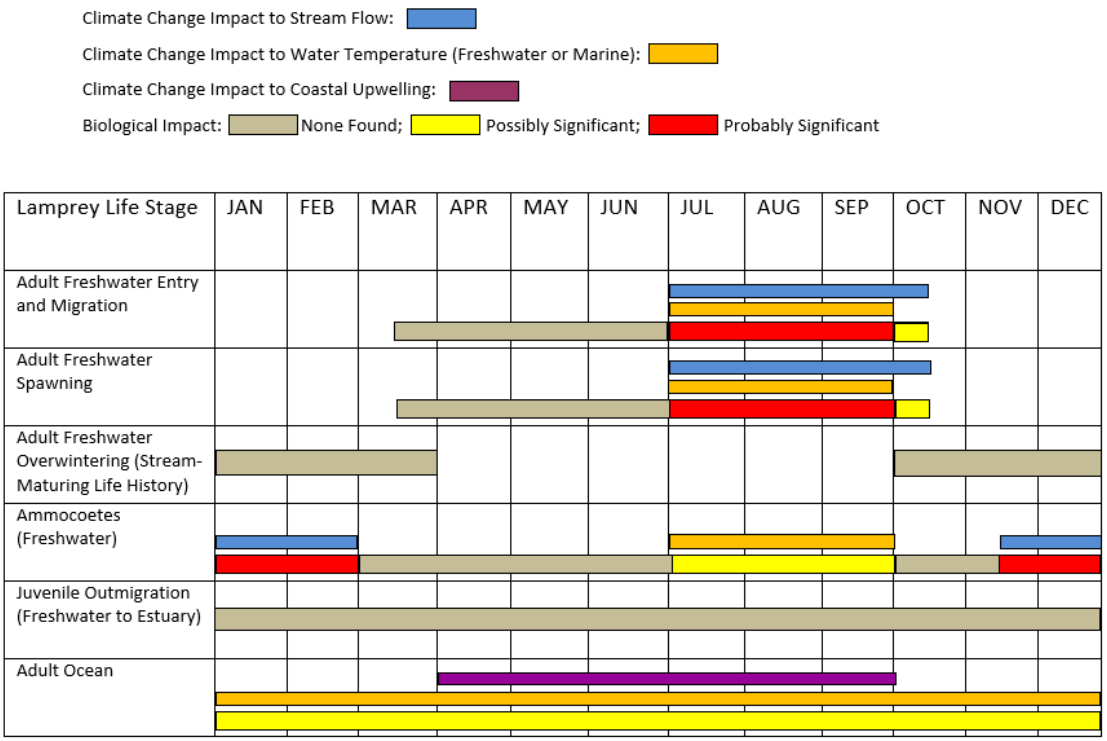

Figure ES1: Pacific Lamprey Life History Stages and Assessed Potential Impacts of Climate Change

The climate change effects referred to above in Figure ES1 include:

1) During the adult freshwater entry and migration period (early summer), impediments to upstream migration will be expected to increase because of lower stream flows and warmer water temperatures in the mainstem migratory corridors and tributaries.
2) During adult spawning (late summer), high water temperatures and lower stream flows will be expected to reduce spawning areas in the tributaries.
3) Larval and juvenile lamprey in the freshwater environment are expected to be negatively impacted by higher flooding during the late fall and winter, and may be "washed out" of their natal habitats.
4) Increases in predation on larval and juvenile lamprey in watersheds exhibiting high summer stream temperatures.
5) During the adult ocean immature phase, changes to ocean upwelling conditions may impact marine food webs and hinder growth of the fish.
6) During the adult ocean mature phase, increases to sea surface temperatures and impacts to the food web from changes to ocean upwelling conditions may hinder the survival of the fish.

In general, dam and reservoir passage and passage through numerous irrigation systems cause significant existing impact to lamprey, favoring lower Columbia River populations that do not need to navigate as many dams as upriver lamprey populations. Ongoing mitigating efforts such as providing safer passage routes and translocation of adult lamprey to upper basin areas are top priorities for lamprey restoration.

Summary of Impacts to Pacific Eulachon

Figure ES2 summarizes seasonal impacts of climate change on the life cycles of Pacific eulachon in the Columbia River Basin. Inferences on how climate change could adversely affect life cycle trajectories were a product of our research but should not be considered comprehensive because there are other possible effects that were not considered. The graphic portrays both the climate change impacts and their likely biological significance on the various life cycles of the species.

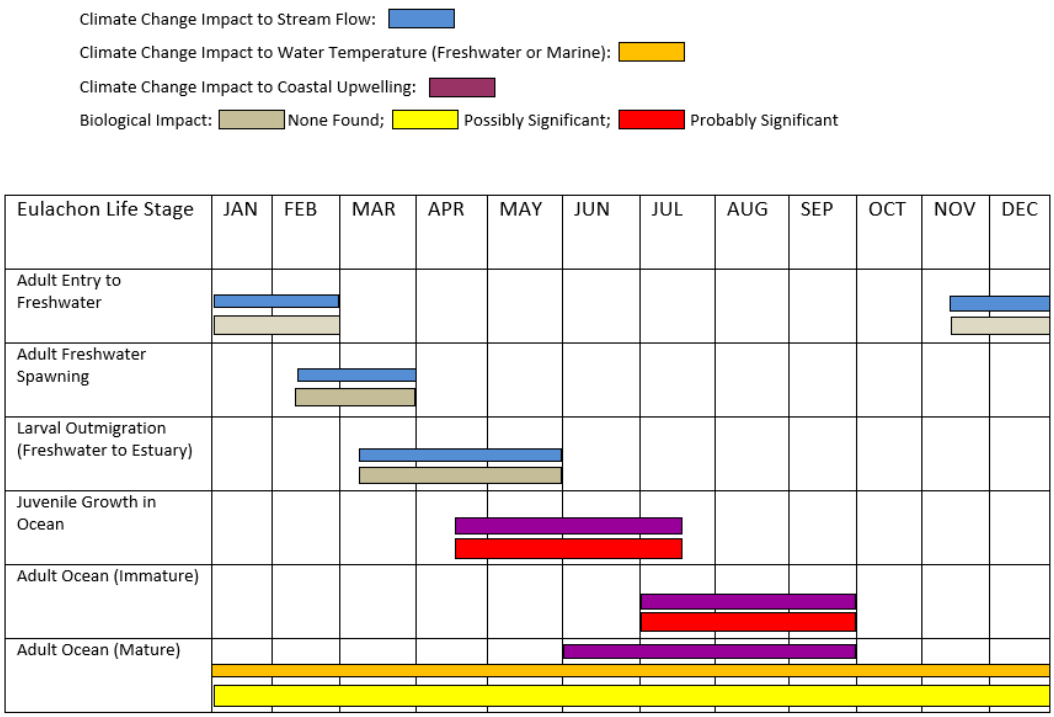

Figure ES2: Pacific Eulachon Life History Stages and Assessed Potential Impacts of Climate Change

The climate change effects referred to above in Figure ES2 include:

1) No likely detriment to fish populations indicated by increases to tributary stream flow during the inmigration and spawning phases.
2) No likely detriment to fish populations indicated by increases to tributary stream flow during the outmigration of juveniles to the estuary.
3) Changes in timing of the freshet of the tributaries and Columbia River (likely to an earlier occurrence) possibly having a significant negative effect on the growth of juveniles in the nearshore environment if it is not timed to match the period of marine nutrient upwelling.
4) A strong correlation between ocean conditions, with a negative impact on adult growth and survival in the marine environment if climate change effects include warmer ocean temperatures and/or disrupted ocean upwelling conditions.

Overall, the life cycle of Pacific eulachon is thought to be not very adaptable, leaving populations susceptible to changes, especially in ocean conditions. A high variability in returns has occurred historically, however, with periodic declines followed by restored abundance, coinciding with improved ocean conditions.

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1 Introduction

Both Pacific eulachon (*Thaleichthys pacificus*) and Pacific lamprey (*Entosphenus tridentatus*) have had an important cultural significance for the Native American tribes of the Pacific Northwest region of North America for millennia. In British Columbia and parts of the Columbia River Basin, Pacific eulachon were used as grease fish for trade between tribal communities for thousands of years prior to the settlement of the west coast by European-Americans (Hay, et al. 1997), and continue to be harvested by tribal members. Pacific lamprey are an important source of nutrients for the tribes of the Columbia River Basin, and a traditional harvest species (CRITFC 2011). Both species have experienced precipitous declines in abundance and distribution in the Columbia River Basin during the last several decades, and efforts are currently underway to restore and protect them (Gustafson, et al. 2010, CRITFC 2011). The myriad potential impacts of climate change present additional concerns for these species, which are vulnerable throughout both the freshwater and marine phases of their life cycles to environmental conditions.

A set of related exploratory analyses were conducted here, examining both freshwater and oceanic impacts on both species, with an emphasis on potential climate change effects. Our methods of analysis included statistical models using empirical data, and G.I.S-based approaches coupled with regional climate change projections. We analyzed available life cycle, abundance and distribution data from the past 80 years, to explore relationships between freshwater and marine conditions and species persistence. To establish these relationships to environmental conditions, we examined historic and hypothetical data in the Columbia Basin, and drew inferences for the greater Pacific Northwest based on these relationships. We also summarized climate change projections on the seasonal hydrology and water temperature of freshwater basins where these species spawn and rear, to assess how climate change may affect their abundance and distribution in the future.

1.1 Overall Background

Pacific lamprey (hereafter, referred to as 'lamprey') and Pacific eulachon (hereafter, referred to as 'eulachon') are important cultural food sources of Pacific Northwest Native Americans. These fish are already limited by a number of factors (habitat changes, poor ocean conditions, migration timing changes, and impeded passage through regional dams and irrigation facilities) and are being considered for additional protections by management agencies (eulachon are already listed as threatened under the Endangered Species Act). Under a changing climate, these fish are likely to be impacted both by changes to ocean conditions and food availability and freshwater habitat because of their life histories, which include both environments. Little research today has assessed the magnitude or nature of these impacts on these two species, despite their importance to tribes and the ecosystems where they reside. This report is intended to be an initial step to assess how these factors may affect the life cycle and abundance dynamics of these populations. For this report, we assessed the Columbia River Basin (Figure 1) runs of lamprey and eulachon, focusing on this area because of its importance to regional tribes and the perilous status of these species there. Eulachon are believed to be restricted to the

lower parts of the Columbia Basin (below Bonneville Dam), and lamprey are believed to be restricted to accessible areas of the basin in the states of Washington, Oregon, and Idaho.

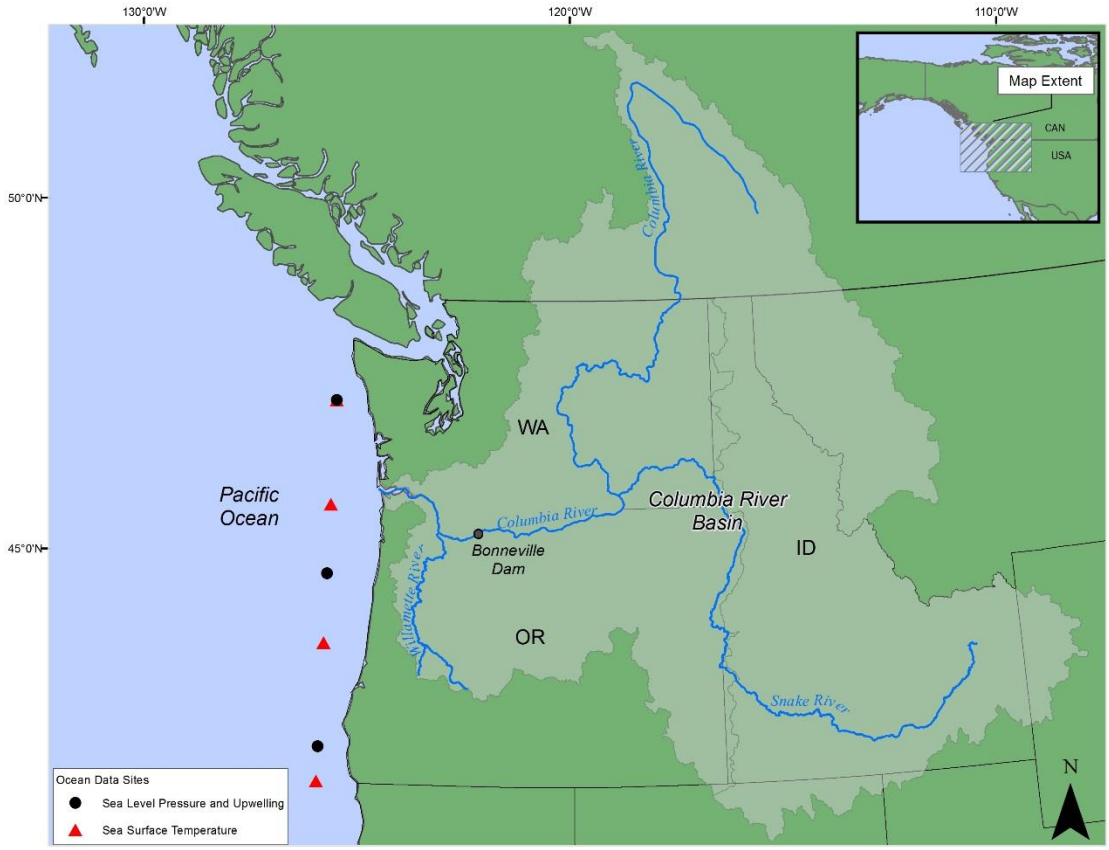

Figure 1: Map of the Columbia River Basin Study Area and Sea Surface Data Collection Locations.

From southeast Alaska to northern California, juvenile salmonids, eulachon and lamprey all seasonally leave the freshwater environment to enter an ocean typically when it is either in or near a state of transition from winter to spring conditions (Quinn 2005, Sharma et. al. 2013), although there is evidence that juvenile lamprey enter the Columbia River Estuary earlier, during the late fall and winter months (Weitkamp, et al. 2015). Depending on the timing of this spring transition, out-migrants may encounter spring-like conditions characterized by a coastal ocean that has experienced significant upwelling that supports nutrient enrichment and elevated primary productivity, or winter-like conditions characterized by downwelling that favours low nutrients and low primary productivity, or the transition between the two (Bakun 1996). While juvenile Chinook salmon spend a large amount of time on the coastal shelf immediately after ocean entry either migrating along the coast or staying close to their natal rivers (Trudel, et al. 2009), not much is known about the locations of eulachon or lamprey during their ocean phases (Hay, et al. 1997, Clemens, et al. 2013). This early marine life history phase has been shown to be extremely important with many studies linking inter-annual variations in different aspects of ocean conditions such as upwelling and water temperature with indicators of *Oncorhynchus* spp. marine survival (Sharma, et. al. 2013, Trudel, et al. 2009, Logerwell, et al. 2003; Peterson

and Schwing 2003; Lawson, et al. 2004; Peterson, et al. 2006). We hypothesize that this will be equally important for lamprey and eulachon, as evidence of strong upwelling has coincided with higher than average survival for numerous species (Bakun 1996). Early studies of the Fraser River basin population (Hay, et al. 1997) show that these conditions are important for survival of eulachon and this project furthers this analysis with a focus on the Columbia River basin population

Marine conditions were assessed primarily through Sea Surface Temperature (SST), Coastal Upwelling (UPI) and Sea Level Pressure (SLP) data to assess early life-stage survivals. In addition, indices of abundance that are estimated through trawl surveys or other by-catch surveys were examined in relation to external indicators of abundance through correlational analysis, lagged time-series models, and likelihood profile analysis.

1.1.1 Specifics of Lamprey Life History

Figure 2 depicts the general life cycle of lamprey. The Freshwater stage of lamprey can vary from three to eight years from larvae to juvenile development. After outmigration, the adults spend on average four years in the marine environment, primarily as parasites, before maturing and spawning in the freshwater environment. In the marine environment, adult lamprey are adept as a parasites on a number of different fish species, and their overall abundance is likely limited by the availability of their prey species within a large range (Murauskas, et al. 2013).

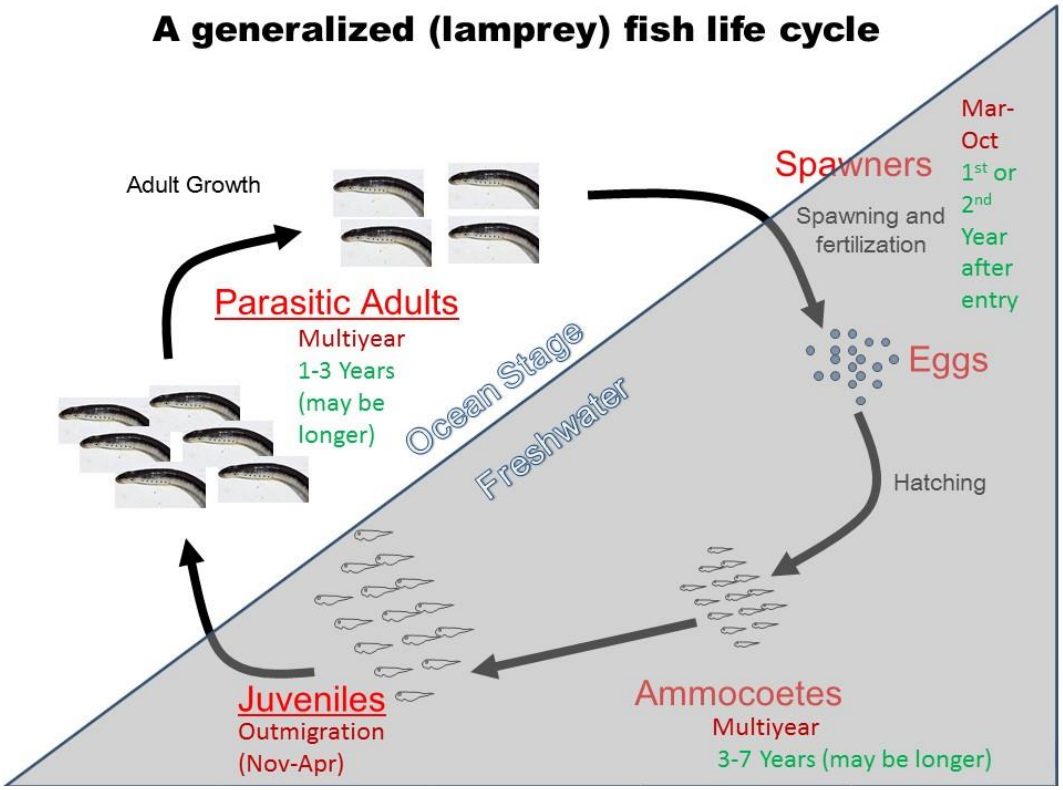

Figure 2: Lamprey Life History

Like salmon, lamprey rely on cool, well-flowing tributaries for migration, spawning, and larval development. Along their spawning migration, they are faced with several potential obstacles, including passage through dams, predators, and stream conditions, which may slow, stop, or restrict their migration. Clemens, et al. (2013) suggested two different life histories for Columbia Basin lamprey: Ocean-maturing fish are thought to spawn within several weeks of their spring arrival into freshwater, while stream-maturing fish may enter freshwater in the spring, migrate up tributaries over the summer, and then overwinter under stones and rocks before a final migration to their spawning sites during the following spring. Similar behaviour was detected in a Smith River radio/pit tagging study, where some lamprey migrate upstream normally in the months of April to June, and then reside in freshwater over a nine month period before spawning in the following year.

The upstream migration of adult lamprey in the Columbia River is correlated to water temperatures and discharge, with earlier migrations occurring during years with warmer water temperatures and lower discharge (Keefer, et al. 2009). Clemens, et al. (2012) found that migrating adults studied in the Willamette River (a principal tributary of the lower Columbia River) generally migrate most during the late spring (May and June) and cease migration in the late summer (August and September). Counts of adult lampreys passing through Bonneville Dam to upper parts of the Columbia Basin Adults occur between early May and late September, with peak passage in July (Weitkamp, et al. 2015). Passage through existing dams, reservoirs, and irrigation systems presents significant obstacles to lamprey, posing the greatest difficulty to runs that are migrating further into the Columbia Basin (and hence through more passage obstacles) (CRITFC 2011).

In the Willamette River, adult lamprey appear to generally stop migrating upstream when water temperatures exceed 20 °C, except to get above large barriers, such as mainstem dams or Willamette Falls (Clemens, et al. 2010, Starcevich, et al. 2014). Clemens, et al. (2009) found that steam temperatures above 20 °C cause a number of detrimental effects in lamprey adults including smaller body sizes, faster sexual maturation, earlier death (from *A. salmonicida* infection), and a quicker metabolism and increased activity. Smaller fish that matured earlier consequently were lacking in energy reserves needed for reproduction as well as migration. High summer temperatures also may serve as thermal barriers, causing adults to hold at lower locations, and possibly spawn there (Clemens, et al. 2013). Higher tributary water temperatures likely favour ocean-maturing runs over stream-maturing runs of lamprey (Clemens, et al. *In Press*). High spring/summer stream flows aid upstream migration, and when lacking, may cause adults to hold and spawn lower in tributaries (Clemens, et al. 2012). Little research has been done to date to establish how high summer water temperatures and low flows may combine to deter adult lamprey migration, but these two factors likely are significant in combination (Clemens, et al. *In Press*).

Lamprey spawn in shallow rivers with gravel substrates and moderate flows (Clemens, et al. 2013) during the spring and summer months. Schultz, et al. (2014) found that larval lamprey (ammocoetes) in the tributaries of the Willamette Basin occur in higher densities in lower

velocity habitats, such as off-channel areas and pools, and estimated that 1 m^2 of low-velocity habitat is equal to 11 m^2 of riffle habitat for larval lamprey abundance. Lamprey ammocoetes were found in most abundance in habitats with medium fine sand substrate, and these habitats likely most benefit by natural river flows and regular distribution of sediment (Sheoships 2014). Pacific lamprey ammocoetes spend 3-7 years in riverine sediment before metamorphosing into juveniles (macropthalmia) for their downstream migration (Weitkamp, et al. 2015), and thus may be strongly influenced by stream conditions such as stream flow, including winter flooding, and water temperature.

In the Columbia River tributaries, juveniles generally metamorphose during the fall. Predation by non-native fish, including Smallmouth bass (*Micropterus dolomieu*), is thought to have significant impacts on larval and juvenile lamprey (Ralph Lampman, Yakama Nation Pacific Lamprey Biologist, pers. comm.) Outmigration of juveniles from tributaries to the lower Columbia River is correlated with high discharge events, typically manifesting as two pulses, one in the late fall (November-December) and another in the early spring (March-April) (Brian McIlraith, Pacific Lamprey Project Lead, Columbia River Inter-Tribal Fish Commission, pers. comm.)

The entire life cycle of lamprey can be anywhere from eight to fifteen years, and they are vulnerable to both freshwater and ocean impacts, though the larger portion of the larval and juvenile life-cycle stages were hypothesized to be highly vulnerable to stream flows and water temperature (Schultz, et al. 2014, Sheoships 2014). Because data on juvenile migration and abundance are for the most part lacking in the Columbia River Basin (Mesa, et al. 2015), these hypotheses are valuable predictors of their behaviour and survival.

1.1.2 Specifics of Eulachon Life History

Eulachon historically extended from southeast Alaska to the Sacramento River (Pickard and Marmoreck 2007). The documentation of historic trading routes for eulachon grease between coastal and interior indigenous tribes (Collison 1941) supports the notion that the fish were never distributed in the upper basin, and naturally spawn in lower rivers. Current research indicates that 90% of these historic runs have vanished in the past century primarily due to human induced impacts (Pickard and Marmoreck 2007).

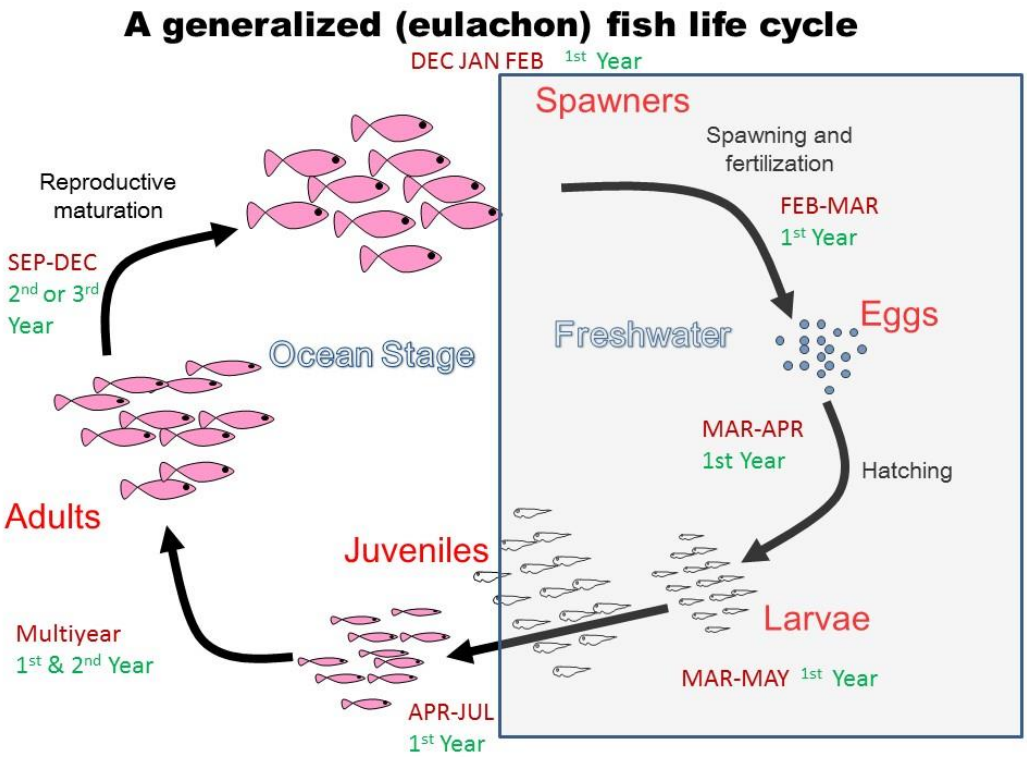

Figure 3: Eulachon Life History

Figure 3 depicts the general life cycle of the Eulachon. Adult eulachon typically return from the Pacific Ocean to the Columbia River during early-mid January (Moody 2008). Adults can remain in the Columbia River estuary "for weeks before peak spawning" as they wait for suitable water temperatures to occur (Zamon 2015). Eulachon migrate to their spawning grounds in the Lower Columbia after water temperatures increase to above 4.4 degrees Celsius (Bargmann 2000). Columbia River runs of spawning eulachon typically reach peak abundance during February (Moody 2008). Adults normally spawn in spring freshets in March in the lower rivers next to the ocean, and also in the lower estuary (Langness 2015). Spawning usually occurs at night before a high tide event. Broadcast spawning is the normal approach used and eggs attach to any form of substrate or other eggs.

Eulachon eggs hatch about a month after they are laid, and as soon as the larvae hatch, they are swept downstream with the river currents (Hinrichsen 1998). Peak eulachon larval densities (eggs and larvae per cubic meter of water) in the Columbia River typically occur in late March (Langness 2015). In the estuary and marine environment, juvenile eulachon experience large predation from fish such as hake, sturgeon, other trout and sea lions and harlequin ducks. The arrival of juvenile eulachon in the Pacific Ocean is timed to match an "environment marvellously rich with food", when spring currents promote nutrient upwelling, and zooplankton, an abundant food source for young eulachon normally increase in abundance off coastal waters (Hinrichsen 1998). Critical marine growth for eulachon occurs between April and June (Zamon 2015). Adult eulachon typically reside in the Pacific Ocean waters offshore to about an extent of

100 kilometres and mature in 2-3 years to return to spawn. They may spawn multiple times, and normally leave the river after spawning.

Eulachon runs off the coast of British Columbia, Washington, Oregon, and California have exhibited great variability in year-to-year abundance, with the largest historic runs returning to the Columbia River (Gustafson, et al. 2010). The Columbia River run sizes were severely depressed during between 2004 and 2010, but exhibited relatively strong returns from 2013 to 2015 (Langness 2015), perhaps reflecting improved ocean conditions during that period.

2 Material and Methods

2.1 Data Available and Analysed

This section describes the data sets that were obtained and used for our analyses.

2.1.1 Lamprey Data

Data sets examined were from multiple sources, but covered the following aspects for abundance: (1) Daytime counts of adult lamprey passage through Bonneville and The Dalles Dams and catch data from Willamette Falls were the primary sources of estimates of abundance. Counts at Bonneville Dam do not include night passage and passage through alternative routes, so are conservatively considered as an index of abundance in absence of more complete data; (2) Juvenile data were examined (Clemens 2013, and Gabe Sheoships, Oregon State University, pers. comm.), though discarded as they could not be correlated to spawning abundance and in any particular year; (3) Separate flow data on the Willamette and at Bonneville Dam (USGS 2015) were used to discern any relationships with abundance, as well as relating it to climate indices at the appropriate spatial scale. Some cyclical patterns in abundance are evident from this data, though reasons for these peaks and troughs are not understood (Figure 4).

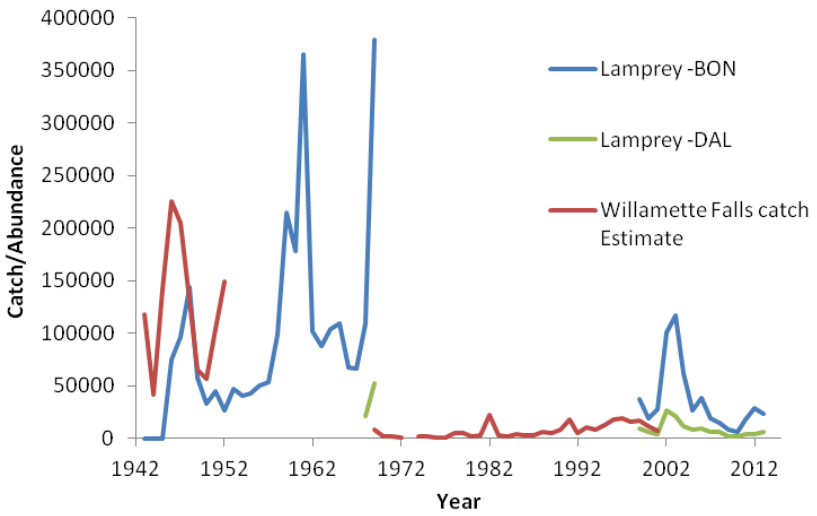

Figure 4: Lamprey Adult Abundance (Willamette Falls Catch and Counts at Bonneville and the Dalles Dams)

2.1.2 Eulachon Data

Different sources of data were collected to relate the abundance of eulachon to environmental conditions. The primary source was a survey done by NOAA based on its observer program to serve as an indicator of ocean abundance (Ward, et al. 2015, Figure 5a), and in-river estimates based on surveys and calculations done on larval abundance (Langness, et al. 2015, Figure 5b). In addition to these, there were longer time series of catches available on both the Columbia and Fraser Rivers (Figure 6b), and a longer series based from the 2011 Joint Staff Report (ODFW and WDFW 2011) (Figure 6a).

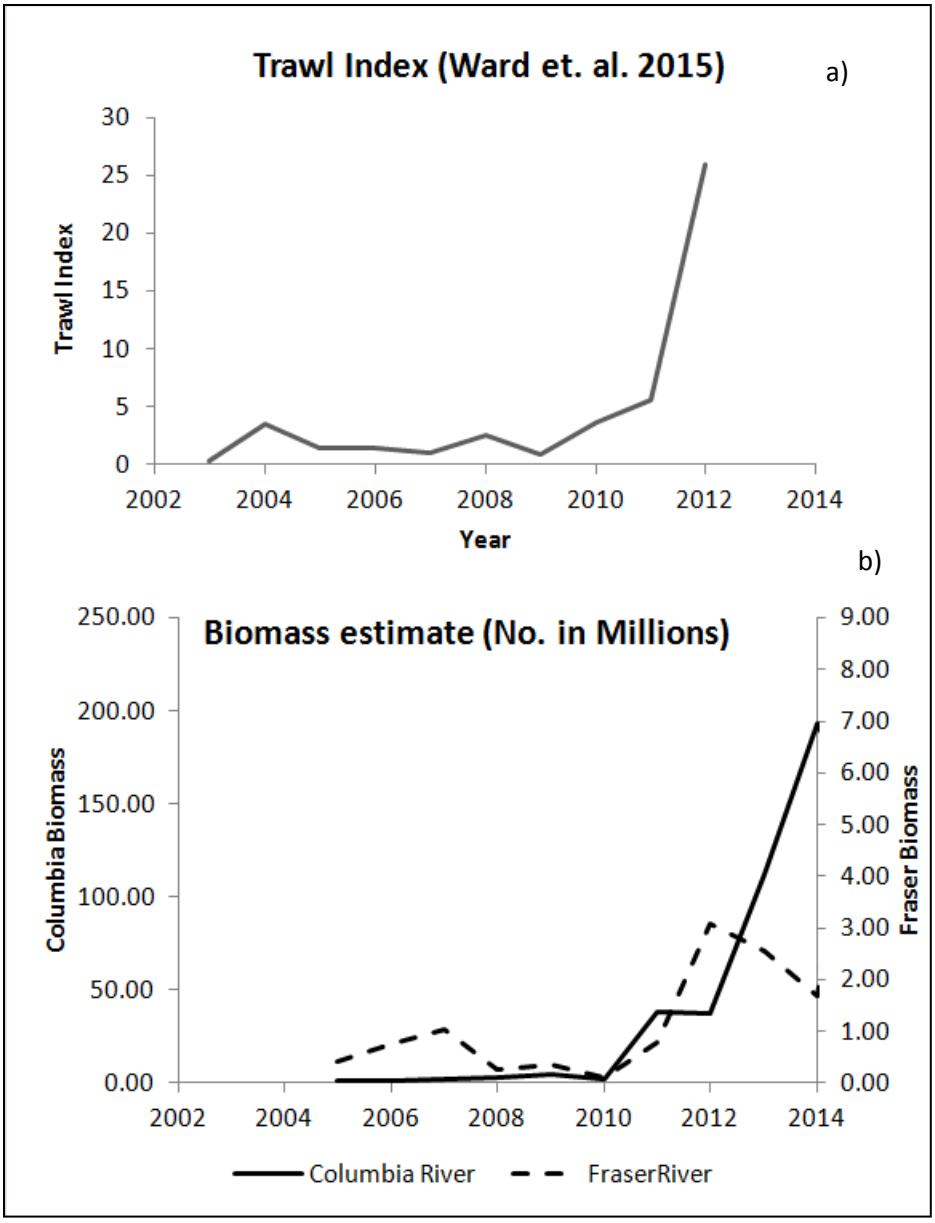

Figure 5: (a) Estimates from Ward, et al. (2015) of Eulachon Trawl Bycatch Index, and (b) Eulachon Larval Spawning Biomass Index (assumes 1:1 ratio of males to females over time for Fraser and Columbia Rivers)

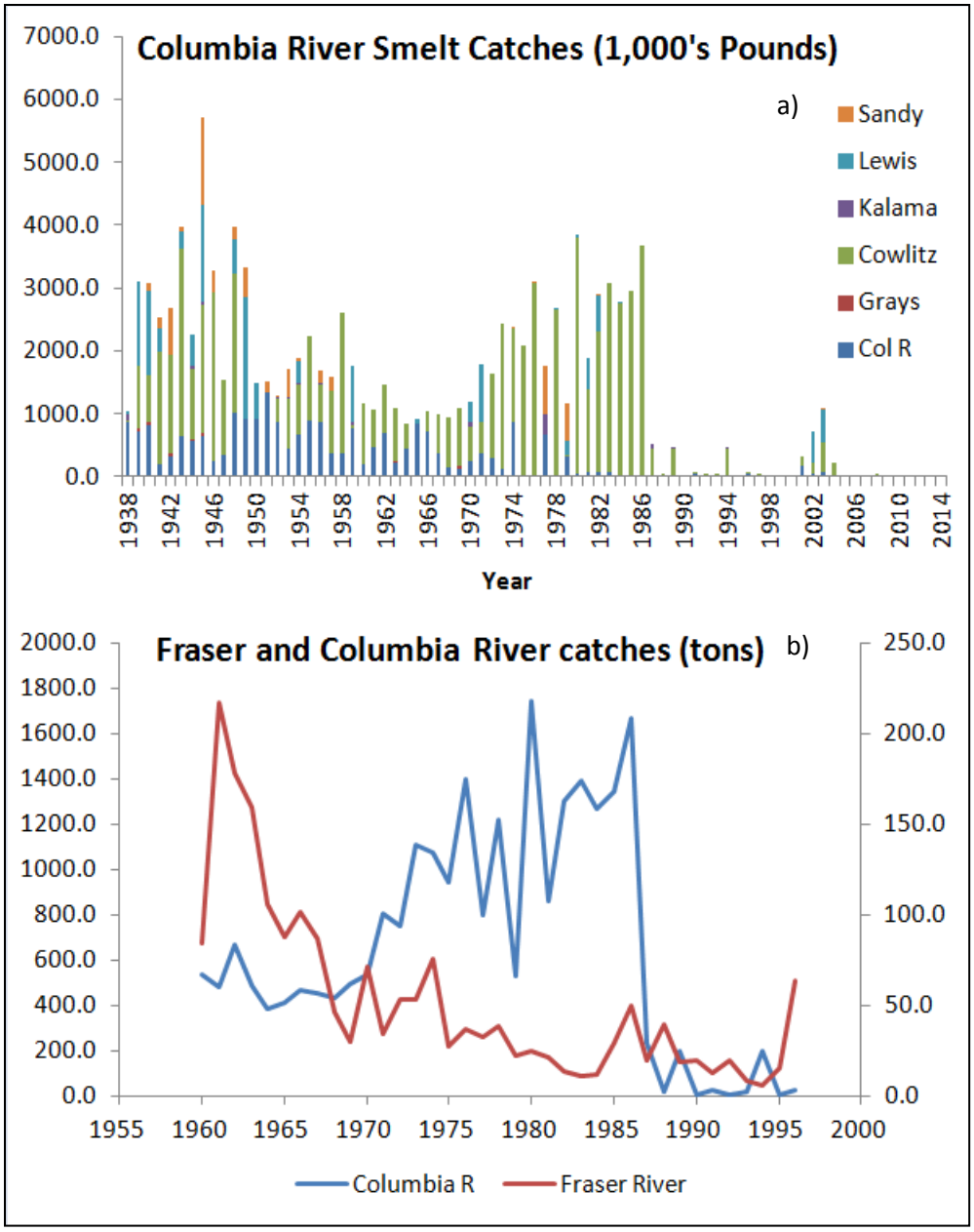

Figure 6: (a) Long Time Series of Eulachon Catches by Columbia Tributary, and (b) Columbia River - Fraser River Comparison of Eulachon Catch 1960-1996 (taken from Hay, et al. 1997)

2.1.3 Freshwater Flow and Temperature Data

Historic flow records were obtained for tributaries of the Willamette Basin, the lower Columbia River tributaries, and the Columbia River from the US Geological Survey Water Resources Program (USGS 2015). Historic water temperature data were obtained for the tributaries of the Columbia River Basin from the NorWeST database, a collection of the Boise Aquatic Sciences Laboratory of the US National Forest (2015), and for the Columbia River below Bonneville from the Columbia Basin Research Project (DART 2015).

Projected changes to monthly runoff by 4th-Field Hydrologic Unit (HUC) for future climate change scenarios were obtained from the University of Washington Climate Impacts Group (UWCIG) (Littell, et al. 2011; UWCIG 2011). The UWCIG produced these data as part of the Western Wildland Environmental Threat Assessment (WWETAC), a project of a consortium of federal agencies responsible for managing federal land in the West. For this assessment, the UWCIG selected the ten global climate models with the best performance at predicting historical temperature and precipitation trends, and combined them into an ensemble product. The UWCIG downscaled the outputs of these models to generate relative changes to monthly climate by HUC for two future time periods: 2030-2059 (2040s) and 2060-2099 (2080s). The UWCIG ran the Variable Infiltration Capacity (VIC) model with these data to simulate changes to hydrologic discharge in each basin under the climate change scenarios. For projected flows on the Lower Columbia River (at Vancouver, WA), we obtained data from the UWCIG's 2010 Climate Change Scenarios, a similar set of forecasts based on a slightly different set of ensemble climate change models and consequent VIC hydrologic model runs, which are specific to gaged locations (UWCIG 2010). These hydrologic projections simulate naturalized flow (i.e. unregulated flow, prior to regulation by the hydropower system).

The climate change projections are derived from the 2008 Coupled Model Intercomparison Project (CMIP3) and include two sets of scenario families, A1B and B1, to reflect higher and lower end projected emissions of greenhouse gases during the 21st century, and consequently higher and lower rates of air temperature increases from gas concentrations in the atmosphere. The A1B scenario family lies higher on the spectrum of projected changes to emissions, and assumes "very high economic growth, global population peaking mid-century and then declining, and energy needs being met by a balance of fossil fuels and alternative technologies." (UWCIG 2010). The B1 Scenario family lies near the low end of the spectrum, and "assumes global population growth peaks by mid-century and then declines, a rapid economic shift towards service and information economies, and the introduction of clean and resource-efficient technologies." Trajectories from the more recent set of global climate models (CMIP5), which have not yet been statistically and dynamically downscaled for the Pacific Northwest hydrology, suggest that the current projection, relative concentration pathway (RCP) 8.5, will result in higher summer temperatures than the A1B scenario projections considered in this report (Rupp et al 2013, IPCC 2013).

We obtained projected changes to summer water temperatures under future climate change scenarios from the NorWeST database (Boise Aquatic Sciences Lab 2015). Isaak, et al. (2015) developed spatial statistical network models of summer water temperatures using historic measurements collected in the NorWeST database and a series of other climatic and geomorphic data. They used these models to produce simulated August mean water temperatures throughout the Pacific Northwest for a range of historic years (1993-2011), and for the future climate change scenarios used by the UWCIG and WWETAC (Littell, et al. 2011; UWCIG 2011). We obtained projected changes to air temperature under future climate change

scenarios from the UWCIG/WWETAC assessment (UWCIG 2011) and used these to estimate winter water temperatures in the Lower Columbia River under future climate change scenarios.

2.1.4 Ocean Environmental Data

We used sea surface temperature from April to July (SSTAMJJU), ocean upwelling indices from April to July (UpwellAMJJU), and sea level pressure (SLPAMJJU) for April to July. SSTAMJJU was calculated as the mean monthly sea surface temperature from April to July (the primary months of ocean entry for the juveniles affecting both lamprey and eulachon) in the years following spawning (one year for eulachon and 6-8 years for lamprey), obtained from Comprehensive Ocean Atmospheric Data Set (COADS) (http://iridl.ldeo.columbia.edu/SOURCES/.NOAA/.NCDC/.ERSST/.version2/.SST/) and standardized using an approach detailed by Smith and Reynolds (2004). Stations are located along the coastal shelf from 42 °N to 48 °N. Some SST for the region of interest was taken from the National Data Buoy Center (NDBC, http://www.ndbc.noaa.gov/historical_data.shtml) for US waters. However, US coastal Buoy data for SST had poor spatial coverage and were not available for the entire time period for most areas analysed. Hence, we used COADS (http://iridl.ldeo.columbia.edu/SOURCES/.NOAA/.NCDC/.ERSST/.version2/.SST/) which had adequate coverage and resolution for the stocks analysed here.

Similarly, UpwellAMJJU was calculated as the monthly mean upwelling indices from April to July in a particular year, obtained from the Pacific Fisheries Environmental Laboratory (PFEL: http://www.pfeg.noaa.gov/pfel/, Schwing, et al. 1996).

2.2 Methods Used for Lamprey Analysis

A range of methods (described below) were used including empirical analysis, model based methods, and GIS methods to evaluate future climate change impacts were used for the lamprey analyses. There are large sources of uncertainty in the data, as stage specific data is largely unavailable, and it is unlikely that the exploratory analysis using large scale data will discern any climate signals, and hence an alternative-model sensitivity analysis is also presented to illustrate the concept of how changes influenced by climate change are likely to influence the dynamics of lamprey populations.

A Summary of Methods used for the Lamprey Analysis

Methods were employed here to study the potential effects of climate change on Pacific lamprey in the Columbia River basin. These included several different approaches, to evaluate different stages of the lamprey life cycle.

Exploratory analysis was the first step used to determine if there were any lag or periodicity signals in the time series data used examining simple ARIMA (Autoregressive Integrated Moving Average) models. Empirical relationships (section 2.2.1) were established between indices of lamprey abundance, freshwater conditions and ocean conditions in the N.E. Pacific Ocean, including a

measure of spring upwelling of the nutrient-rich California current, and sea surface temperature, and seasonal freshwater flow from tributaries where lamprey spawn and rear. These relationships test different historical periods and variables to establish statistical links between different conditions and measures of abundance (in this case dam passage and harvest counts of adult lamprey). The results of this method are presented in sections 3.1.1 – 3.1.6.

An evaluation of likely freshwater impacts from climate change on lamprey spawning and rearing habitat with a GIS-based approach is presented in section 2.2.6. For this method, we overlaid current rankings of lamprey status on a hypothetical stream-based distribution, and then evaluated future climate change impacts to seasonal stream flow and summer water temperature on this distribution, considering likely effects on the lamprey life cycle. The results of this method are presented in section 3.1.8.

Additionally, a life cycle model approach (sections 2.2.2-2.2.5) for lamprey was developed with hypothetical variables. Its purpose is to estimate changes to lamprey abundance and survival over time in response to changing environmental (both freshwater and marine), conditions. This model includes a conceptual spawner recruit component, which estimates the number of "recruits" or larvae that are still alive after a certain time from a single spawner, depending on fecundity, and habitat conditions affecting carrying capacity and survival of eggs. The full life cycle of the lamprey is modelled, including larval, juvenile, and adult ocean, migration, and spawning phases. While data was inadequate to simulate past, current, or future conditions, this hypothetical model presents a means to do so when adequate data is collected and used as inputs. The model is presented in Appendix A.

2.2.1 Empirical Relationships between Environmental Conditions and Lamprey Survival

We constructed linear regressions between abundance and ocean variables from the geographical stations closest to the river mouth in the year preceding returns with lag of one to two years for ocean conditions, and 5-10 years for lamprey freshwater conditions affecting abundance. This was used primarily to examine the relationship between freshwater/ocean conditions and abundance. The linear regressions are expressed as:

(1) $$A_{\mathrm{R,t,s}} = \alpha + \beta V_{t-x,s} + \varepsilon_s$$

where $A_{R,t,s}$ is abundance for lamprey either at Willamette or Bonneville (s) at time (t), $V_{t-x,s}$ is the independent ocean variable (SST, UPI, SLP etc.), or flow lagged at intervals (x) of 1-2 years for ocean conditions and x=5-10 years for freshwater conditions at time t-x, α is a constant, β is the slope parameter of the variable ($V_{t,s}$) and ε is the normal additive error.

Likelihood profiles (Hilborn and Mangel 1997, Sharma and Hilborn 2001) were generated on the slope parameter using equation 2:

(2) $$L(A_{R,t,s} \mid \alpha, \beta) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left[-\frac{\left(A_{R,t,s} - \hat{A}_{R,t,s})\right)^2}{2\sigma^2} \right]$$

Because on a local scale the physical variables (upwelling, and SST) are highly correlated, the analysis was performed only with SST for ocean indicators. Rather than using a traditional approach of statistical inference, i.e. testing for significance of a particular variable (in this case the value of the β parameter in equation 3.5), a likelihood profile analysis on SST was performed (Hilborn and Mangel 1997) to quantify the uncertainty of the effect.

2.2.2 Life-Cycle Model-based Methods

While a conceptual life-cycle model for lamprey is presented here, there was insufficient time to fully develop this part of the project, and it may be pursued at a later stage. Some results of this are shown in Appendix 1, of the report.

2.2.3 The Conceptual Model Developing a Stage-Based Recruitment Relationship

The basic model of population dynamics is an adapted Beverton-Holt model spawner recruit model (Beverton and Holt 1957) applied to lamprey (Hilborn and Walters 1992). The model can be easily extended to other populations as well. The basic structure of the model is:

(3) $$R_{t+1} = \frac{aS_t}{b + S_t}$$

where R_{t+1} is the recruits in time t+1, S_t is the spawners in time t, and *a* and *b* are parameters of the model. Harvest rate (u_t) is incorporated as follows:

(4) $$N_{i+1,t+1} = \frac{aN_{i,t}}{b + N_{i,t}}(1 - u_{t+1})$$

where $N_{i,t}$ is the number of individuals in stage i at time t. In this case, the subscript t refers to the generation of lamprey, ignoring the fact that many lamprey return to spawn at different ages. Mousalli and Hilborn (1986) used a sequence of Beverton-Holt models to represent the different life history stages of salmon and Sharma, et al. (2005) further modified the above models to directly relate the model parameters to habitat quality and quantity. The approach is an extension of Moussali and Hilborn's model (1986) shown below:

(5)
$$N_{i+1,t+1} = \frac{N_{i,t}}{\frac{1}{p_{i,t}} + \frac{1}{c_{i,t}} N_{i,t}}$$

where $N_{i,t}$ is the number of individuals alive at the beginning of life history stage *i* at time *t*, p_i is the "productivity" at stage *i* (the maximum survival rate from stage *i* to *i +1*) and c_i is the "capacity" (the maximum number of individuals that will survive from stage *i* at time *t* to stage *i+1* at time *t+1*).

This model (Figure7) can be used to represent a n-stage life history model; or in the case of lamprey here, a four-stage freshwater life cycle model that tracks spawners ($N_{1,t}$) and larvae ($N_{2,t+1}$), early ocean ($N_{3,t+x}$), and adults ($N_{4,t+y}$). The larval component can easily be broken into numerous stages as lamprey can remain inactive for up to seven years as ammocoetes in the freshwater, allowing for both ocean survival rate (o_{t+x}), and harvest (u_{t+x}), to change over time.

The timestep subscript is a calendar year for the life-cycle starting with spawners N_1, at a particular year t. The juvenile life cycle occurs in t+1 and then can extend to upto 7 years in freshwater, and the adult's life cycle stage occurs for t+y years again which can extend upto 7 years, and the adults mature in year t+y during which they are either harvested or return to the home streams to spawn (we assume some homing patetrns here, which may not be apparent for lamprey). Immature fish are modeled to stay another year in the ocean. For modeling, we assume known proportions of the population maturing in year t+2, t+3, t+4, t+5, t+6 and t+7). These parameters will of course be influenced by ocean conditions and we also assume known estimates of survival from one age class to the next in the ocean.

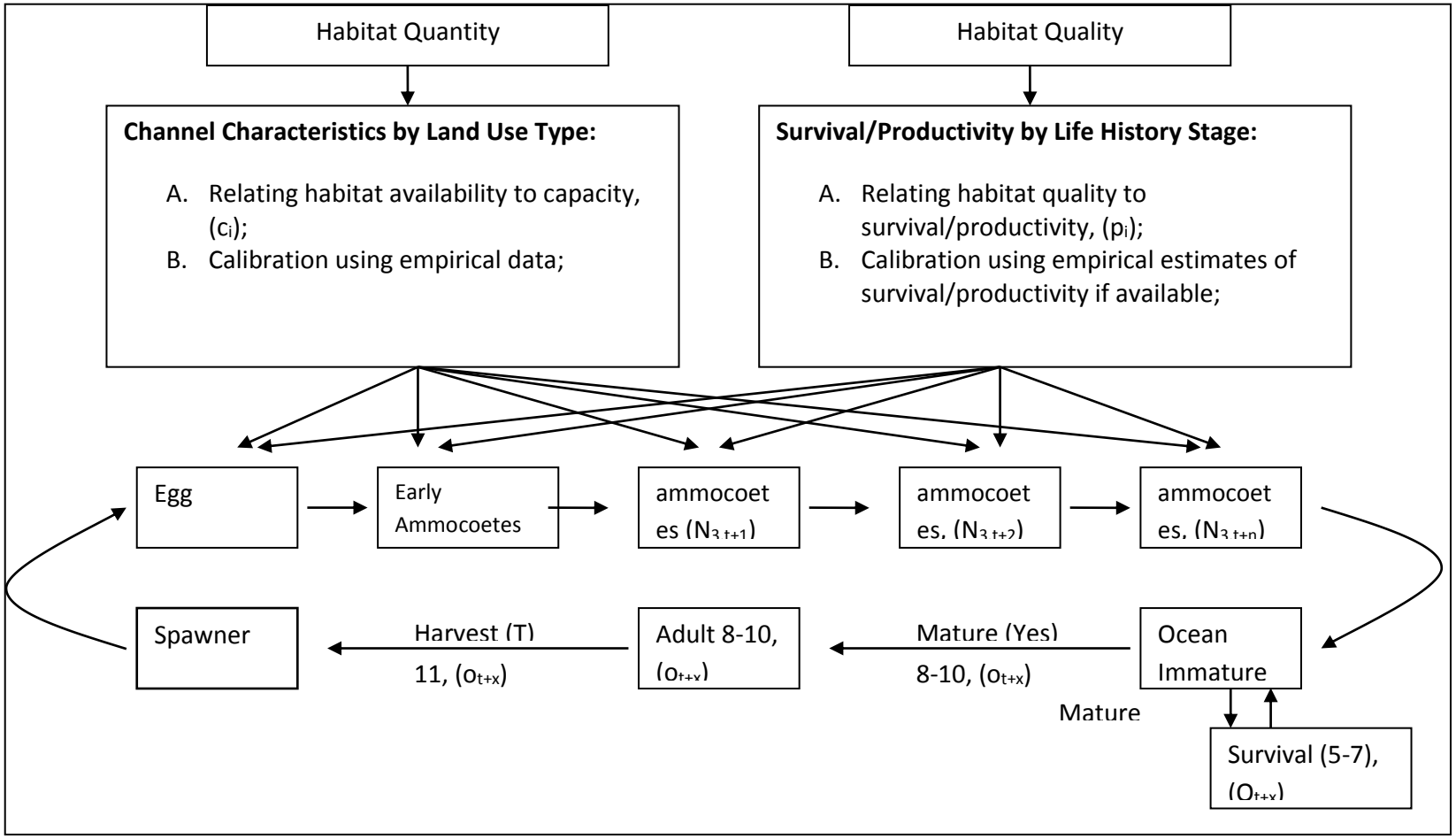

Figure 7: Schematic Illustrating how the Model Develops Relationships between Habitat Quantity (capacity) and Quality (survival/productivity) to Stage-based Abundance and Productivity and Population Growth Rate.

For the above notation and for the lamprey life-cycle, p_1 is fecundity per spawner, c_1 is the carrying capacity for eggs, p_2 is the survival from egg to juveniles at low densities, c_2 is the maximum juvenile production as determined by the total amount of rearing area available, p_3 is the maximum juvenile to early survival, c_3 is the maximum production of adults, assuming the ocean is not density dependent, this will be driven by p_3.

2.2.4 Ocean Immature Adult Life Cycle Stages

Lamprey are assumed to mature after spending 1, 2, 3, 4, 5, 6 or 7 years respectively in the ocean. As such, the subsequent stages are now broken into a yearly time step (i.e. y years spent in ocean translate to N_4, to N_{10} respectively).

(6)
$$N_{4,t+2} = \frac{N_{3,t+n}}{\frac{1}{Z_{t+n}} + \frac{1}{c_{3,t+n}} N_{3,t+n}}$$

N_4 is the number of individuals that make it from the ammocoetes life-stage in the Columbia to the ocean life cycle stage at the same age. The effect of c_3 is assumed to be negligible, and the Dam (Z) survival is the only effect on the outmigrating smolts. For simplification purposes, we multiply equation (3) above from the ammocoetes life cycle stage, N_5 by the the passage survival (Z).

Since ocean fisheries are negligible on lamprey, we assume only NM (o_{t+3}) from age 1 (N_7) ocean to age 2 ocean (N_8) or 2+ to 3+ in real age, and c_5 is the ocean capacity for age 2+ fish. We assume sequential Maturation followed by Natural Mortality for all subsequent ages in the ocean.

For ocean age 2, N_5 we have:

(7)
$$N_{5,t+n+1} = \frac{N_{4,t+n}}{\frac{1}{o_{t+n+1}} + \left(\frac{1}{c_{7,t+n}} N_{4,t+n} \right)}$$

For ocean age 3, N_6 we have:

(8)
$$N_{6,t+n+2} = \frac{N_{5,t+n+1}(1 - M_5)}{\frac{1}{o_{t+n+2}} + \left(\frac{1}{c_{5,t+n+1}} N_{5,t+n+1}(1 - M_5) \right)}$$

For ocean age 4, N_7 we have:

(9) $$N_{7,t+n+3} = \frac{N_{6,t+n+2}(1-M_6)}{\frac{1}{o_{t+n+3}} + \left(\frac{1}{c_{6,t+n+2}} N_{6,t+n+2}(1-M_6)\right)}$$

Following year classes are similar for the ocean immatures.

2.2.5 Mature Terminal Adult Life Cycle Stages.

Most of the fisheries take place in river for spring Chinook salmon and steelhead. The vulnerability of cohorts by age is determined in the following manner:

(10) $$N^T_{5,t+n+1} = \left(\frac{N_{4,t+n}}{\frac{1}{o_{t+n+1}} + \left(\frac{1}{c_{4,t+n}} N_{4,t+n}\right)}\right) M_4$$

(11) $$N^T_{6,t+n+2} = \left(\frac{N_{5,t+n+1}(1-M_4)}{\frac{1}{o_{t+n+2}} + \left(\frac{1}{c_{5,t+n+1}} N_{5,t+n+1}(1-M_4)\right)}\right) M_5$$

(12) $$N^T_{7,t+n+3} = \left(\frac{N_{6,t+n+2}(1-M_5)}{\frac{1}{o_{t+n+3}} + \left(\frac{1}{c_{6,t+n+2}} N_{6,t+n+2}(1-M_5)\right)}\right) M_6$$

And so on till the last age, i.e 10 where we have all the fish remaining mature, so age 7 mature fish in year t+n+6, would be:

(13) $$N^T_{10,t+n+6} = \left(\frac{N_{9,t+n+5}(1-M_9)}{\frac{1}{o_{t+n+6}} + \left(\frac{1}{c_{6,t+n+5}} N_{9,t+n+5}(1-M_9)\right)}\right)$$

Accounting for harvest by age, we have the remaining spawners by age shown in eq (12).

(14) $$N_x^T = N_x^T(1-u_x)$$

where x is the year that the terminal get mature which could be anywhere from 8-15 years after they spawned. The results of the empirical and life cycle model analyses are presented in sections 3.1.1 to 3.1.6.

An example application of the life cycle model described in sections 2.2.2-2.2.5 is presented in Appendix A.

2.2.6 Freshwater Climate Change Scenarios Analysis

In order to assess potential climate change effects on the tributary habitat of lamprey, it was first necessary to estimate their distribution throughout the Columbia River Basin. We used the results of an assessment by the US Fish and Wildlife Service, (Luzier, et al. 2011, USGS 2014), which analysed the current status of lamprey in each 4th-field Hydrologic Unit (HUC) with a modification of the systematic ranking method termed the NatureServe Conservation approach. This approach uses available information on population abundance, distribution, and population trend to assess the status of an aquatic migratory species and its vulnerability of extirpation. Through this approach, they categorized lamprey in each HUC into one of nine conservation ranks:

Historic (Extirpated), NA - Not Applicable, S1 – Critically Imperilled, S1-S2, S2 – Imperilled, S3 – Vulnerable, S4 – Apparently Secure, and SH- Possibly Extinct, and SX - Presumed Extinct. In the Columbia Basin, all rankings were present except for S3 and S4. We then established a hypothetical stream-based distribution of lamprey within each HUC, using information from two sources:

(1) In Oregon State, we used fish habitat distribution established by the Oregon Department of Fish and Wildlife (2012), which was constructed from knowledge of suitable freshwater habitat and field observations of lamprey in Oregon streams and rivers;

(2) In Washington and Idaho, stream-based lamprey distribution was not available, so we instead used the current generalized fish distribution of steelhead (StreamNet 2012). Where accessible, lamprey are thought to inhabit the streams that salmon and steelhead do, and are able to migrate upstream at least as far upstream as steelhead (Brian McIlraith, personal communication, July 29, 2014). This also corresponds with the approach used by Luzier, et al. (2011) to estimate historical lamprey distribution where it is unknown.

We overlaid the NatureServe rankings on the stream-based data, eliminating distribution from hydrologic units where lamprey were classified as “Presumed Extinct”, “NA”, or “Historical”, to arrive at a hypothetical current lamprey distribution and status within the tributaries of the Columbia River Basin (Table 1 and Figure8) The majority of the distribution (78.7%) is classified as “possibly extinct” or “critically imperilled”, reflecting the severe impact that dams on the mainstem Columbia and Snake Rivers have had on lamprey populations of Central Idaho and the Upper Columbia Basin (Moser and

Close 2003). The Lower Columbia and Willamette hydrologic units are mostly classified as “imperilled”, reflecting the relative strength of their populations. This geographic distribution of ranks matches the patterns of abundance found by Mesa, et al. (2015) of higher numbers of juveniles in the lower Columbia tributaries.

Table 1: Sum of Stream Length of Hypothetical Lamprey Distribution by NatureServe Rank

NatureServe Rank	Km (%)
S1 - Critically Imperilled	6110 (42.8%)
S1 - S2	550 (3.9%)
S2 – Imperilled	2499 (17.5%)
SH - Possibly Extinct	5125 (35.9%)

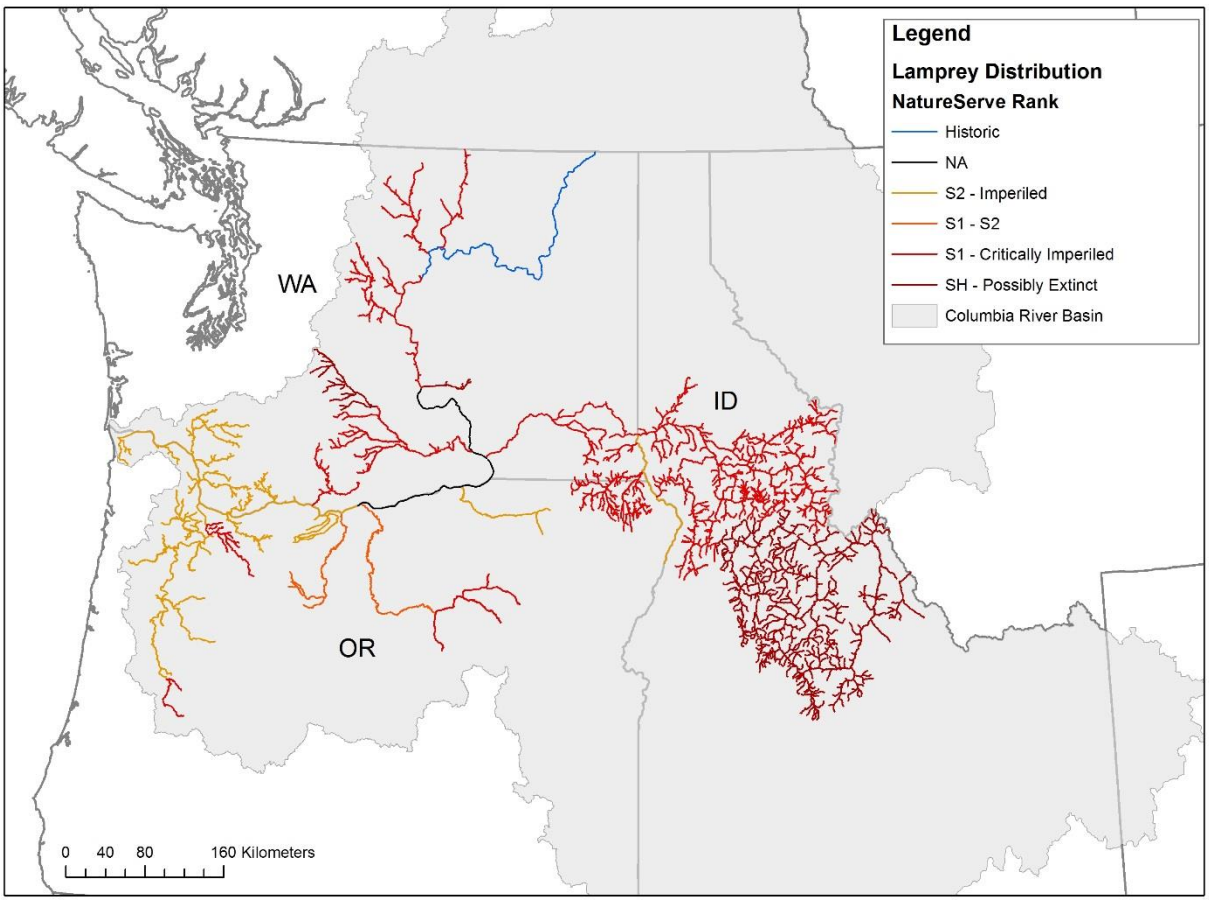

Figure 8: Hypothetical Current Lamprey Distribution and Status in the Columbia River Basin

Next, we obtained two data sets of projected changes to stream flow and stream temperature for future climate change scenarios to apply to the hypothetical lamprey distribution. Stream temperature model information was obtained from the NorWeST project for a historical period (1993-2011) and two future climate change scenarios (2030-2059) and (2070-2099). These scenarios were derived from an ensemble suite of model outputs from the A1B family. Projected changes to stream discharge (flow) by 4th field hydrologic unit for a historical period (1916-2006) and the same A1B future climate change scenario ensembles were obtained from the University of Washington CIG (for more details on both sets of data, please see section 2.1.1). We overlaid the stream temperature information directly on the stream-based lamprey distribution, while the flow model information was overlaid by hydrologic unit onto the lamprey distribution. The resulting layer showed hypothetical stream-based lamprey distribution with the NatureServe status ranks and projected changes to stream flow and temperature for future climate change scenarios.

Lacking detailed information about lamprey habitat constraints, we used a relative approach to assess the potential change to three factors identified as limiting to lamprey in the literature (see section 1.1.1):

(1) Increases in Winter (Dec-Feb) stream flows under future climate change scenarios, which may increase flooding and alter the preferred low-velocity habitats of larval lamprey, as well as potentially impacting stream-maturing adults;
(2) Decreases in late spring/early summer (May-Jul) stream flows under future climate change scenarios, which may inhibit the upstream migration of adults to their spawning grounds;
(3) Increases to summer water temperatures, which may inhibit the upstream migration of adults to their spawning grounds and stress these fish when holding in place, and also will likely favor the spread of non-native predators of larvae and juveniles such as Smallmouth bass (Lawrence, et al. 2014). Mean August water temperature is the only metric available with modelled climate change projections throughout the region, so this metric was used as a proxy for overall relative increases to summer water temperatures.

We analysed these three factors for change between the historical periods and the future climate change scenarios for all streams with hypothetical lamprey distribution. The results of this analysis are presented in detail under section 3.1.8.

2.3 Methods used for Eulachon Analysis

Various methods were used in the Eulachon analyses and described in detail below. These included empirical analysis of historic abundance data and freshwater and ocean conditions, and an examination of future projections from climate change on freshwater stream flow and temperature.

A Summary of Methods used for the Eulachon Analysis

Methods were employed here to study the potential effects of climate change on Pacific eulachon in the Columbia River basin. These included several different approaches, to evaluate different stages of the eulachon life cycle. Initially, we examined the eulachon time series data to determine if any lags are estimable from the data using simple ARIMA models. The second step was to establish empirical relationships (sections 2.3.1-2.3.2) between indices of eulachon abundance, and environmental conditions, including sea surface temperature, which was found to be highly correlated with other marine conditions (spring upwelling of the nutrient-rich California current and sea level pressure), and seasonal stream flow from tributaries where eulachon spawn. These relationships test time series over the historical record to establish statistical links between different environmental conditions and measures of abundance (in this case, estimates of biomass of returning adults and bycatch estimates from the shrimp fishery). The results of this method are presented in sections 3.2.1, 3.2.3, and 3.2.4.

A newly developed stock assessment method was developed for this paper (section 2.3.3). This method employs a simple population dynamics model, using available catch data of eulachon. It systematically examines a range of parameters (environmental conditions including flow and ocean conditions) to select those that are correlated to catch estimates. It then creates stochastic simulations with these parameters to explore potential sustainable harvest levels by estimating two parameters in a biomass dynamic model. The results of this method are presented in sections 3.2.2.

We also evaluated (section 2.3.4) future projected climate change conditions, including seasonal flow and winter water temperature, in the tributaries where eulachon spawn and the lower Columbia River. The results from this examination allow speculation as to how conditions may change in the future during the freshwater life cycle stages of eulachon. The results of this method are presented in section 3.2.5.

2.3.1 Empirical: Relationship with the Environment

As with lamprey in the previous section, an empirical approach was developed to test abundance as a function of ocean and freshwater conditions. In addition to that, the trawl bycatch index was examined to assess if there were any signal in catch rates/estimated biomass as a function of the index.

We constructed linear regressions between abundance and ocean variables (including SST) from the geographical stations closest to the river mouth in the year preceding returns with lag of one to two years for ocean conditions, and two to three years for lamprey freshwater conditions affecting abundance, based on life history characteristics as multiple spawners are smaller than the first time spawners. This was used primarily to examine the relationship between freshwater/ocean conditions and abundance. The linear regressions are expressed as:

(15) $$A_{\mathrm{R,t,s}} = \alpha + \beta V_{t-x,s} + \varepsilon_s$$

where $A_{R,t,s}$ is abundance for eulachon as expressed through the estimated biomass either at the Columbia or Fraser Rivers (s) at time (t), $V_{t-x,s}$ is the independent ocean variable (SST, UPI, SLP etc.), or flow lagged at intervals (x) of 1-2 years for ocean conditions and x=2-3 years for freshwater conditions at time t-x, α is a constant, β is the slope parameter of the variable ($V_{t,s}$) and ε is the normal additive error. Instead of using abundance as estimated through the larval surveys, we could also use catch to assess if there is any effect of these variables on catch rates in different rivers as shown in Figure 9 (namely the Grays, Cowlitz, Kalama, Lewis, and Sandy Rivers and the mainstem of the Columbia River).

Likelihood profiles (Hilborn and Mangel 1997, Sharma and Hilborn 2001) were generated on the slope parameter using equation 2 in the previous section (or eq. 16 below):

(16) $$L(A_{R,t,s} \mid \alpha, \beta) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left[-\frac{\left(A_{R,t,s} - \hat{A}_{R,t,s}\right)^2}{2\sigma^2} \right]$$

Because on a local scale the physical variables (upwelling, and SST) are highly correlated, the analysis was performed only with SST for ocean indicators, and flow for freshwater indicators. Rather than using a traditional approach of statistical inference, i.e. testing for significance of a particular variable (in this case the value of the β parameter in equation 3.5), a likelihood profile analysis on SST was performed (Hilborn and Mangel 1997) to quantify the uncertainty of the effect.

2.3.2 Empirical: Relationship with the Bycatch Indicator

Based on data collected in the trawl index (Ward, et al. 2015), we examined a lagged model to see whether there were any relationships in abundance or catch rates based on this as an indicator, i.e. equation 17.

(17) $$A_{\mathrm{R,t,s}} = \alpha + \beta CPUE_{t-1,s} + \varepsilon_s$$

where CPUE is estimated as the standardized index of abundance that is estimated by Ward, et al. (2015). Uncertainty would be examined and sensitivity to abundance or catch rates as function of change in the abundance using likelihood profile analysis (eq. 16 & 2).

The results for the empirical analysis of eulachon are presented in sections 3.2.1, 3.2.2, and 3.2.4.

2.3.3 Catch MSY to Estimate Target Yield

We use a newly developed stock assessment method in this paper. This method is based on catch data and does not require fishing effort or CPUE data. The method involves several steps. It applies a simple population dynamics model, starts with wide prior ranges for the key parameters, and includes the available catch data in the model. Then the model systematically searches through possible parameter spaces and retains feasible parameter values. Mathematically and biologically unfeasible values are excluded from the large pool of data. We progressively derive basic parameters, and carry out stochastic simulations using these base parameters to get biomass trajectories and additional parameters. Finally, we project to future biomass to explore alternative harvest policies.

We use following Graham-Schaefer surplus production model (Schaefer 1954):

(18) $$B_{t+1} = B_t + rB_t\left(1 - \frac{B_t}{B_0}\right) - C_t$$

Where B_t is biomass in time step *t*, *r* is the population growth rate, B_0 is the virgin biomass equal to carrying capacity K, and C is the known catch.

This simple model has two unknown parameters, r and K. We set reasonably wide prior range, for example, *K* between C_{max} and 500 * C_{max}. We used the approach proposed in Martell and Froese (2012) for "resiliency" estimates that ties to the productivity parameter r (low resiliency levels indicated r between 0.05-0.5, medium resiliency indicated a r between 0.2-1, and high between 0.5-1.5). These were compared to values obtained in the literature and alternative methods.

We run model (1) to find all mathematically feasible *r* values by searching through a wide range of K values for all depletion levels. If the feasible choice of r and k chosen meets the intermediate (0.1 and 1 level of depletion in 1980), and last point depletion levels (the range specified was 0.3-0.7 level of depletion for these billfish stocks) it is kept. The summary of all runs which meet these criteria are then used, and geometric mean values are reported to be the better representation of yield targets (Martell and Froese 2012). Biological parameters, including K, r, MSY, are derived from the retained pool of [r, K] values. The geometric mean values of these are then used to assess the stock dynamics over time and reported using a phase plot. The results of these analyses are presented in section 3.2.2.

2.3.4 Freshwater Climate Change Scenarios Analysis

In the Pacific Northwest, eulachon are found in a variety of types of streams, but virtually all have extensive spring freshets, characteristic of drainages with headwaters "occurring in glacier or snow pack areas". The timing of egg hatching in these streams coincides with the peak spring river discharge (Hay and McCarter 2000). During the period between 1994 and 2007, eulachon abundance declined in many west-coast rivers, and reductions in the spring freshets in these rivers may be a primary cause of this decline (Schweigert, et al. 2007). In the majority of rivers, eulachon spawn "well before" the spring freshet near the seasonal flow minimum, and this timing "typically results in egg hatch coinciding with peak spring river discharge" (Gustafson, et al. 2010). There is evidence that milder weather in recent years has encouraged eulachon to enter rivers and peak earlier in the winter than in the past (Moody 2008). Warmer winter temperatures from climate change in the Pacific Northwest will almost certainly lead to reduced snowpack as more precipitation falls as rain and less as snow in mountainous headwaters. This will cause a disruption in seasonal discharge patterns from these streams, with more runoff likely occurring in the late fall and winter, and an earlier spring freshet (Elsner, et al. 2010). In the National Marine Fisheries Service Eulachon Status Review, Gustafson, et al. (2010) hypothesized that this change in timing may lead to eulachon spawning earlier or being flushed out of rivers earlier, and that this may lead to a mismatch with marine upwelling periods in the eastern Pacific. Because of this impact, the projected that climate change effects on freshwater habitat will present a moderate-to-high threat for future eulachon runs in the Columbia River. Juvenile eulachon in the Columbia River estuary would be aided by a synchronization of Columbia River flows (the spring freshet) with the upwelling of the California current (Anderson 2015).

Storch, et al. (2014) described eulachon spawning distribution in the lower Columbia River as follows:

Elochoman (rkm 4), Cowlitz (rkm 3-29), Kalama (rkm 0.3-2), Lewis (rkm 1-9), Grays (rkm7-9), Sandy, Skamokawa (rkm 0.3-5). We mapped this distribution in a geographic information system (GIS), as shown in Figure 9. Relative abundance of the Columbia River run by each tributary is not known, but during 2015, the Cowlitz River Tribe estimated from their research that the Cowlitz River migrants comprised 34% of the total Columbia River escapement (Reynolds 2015).

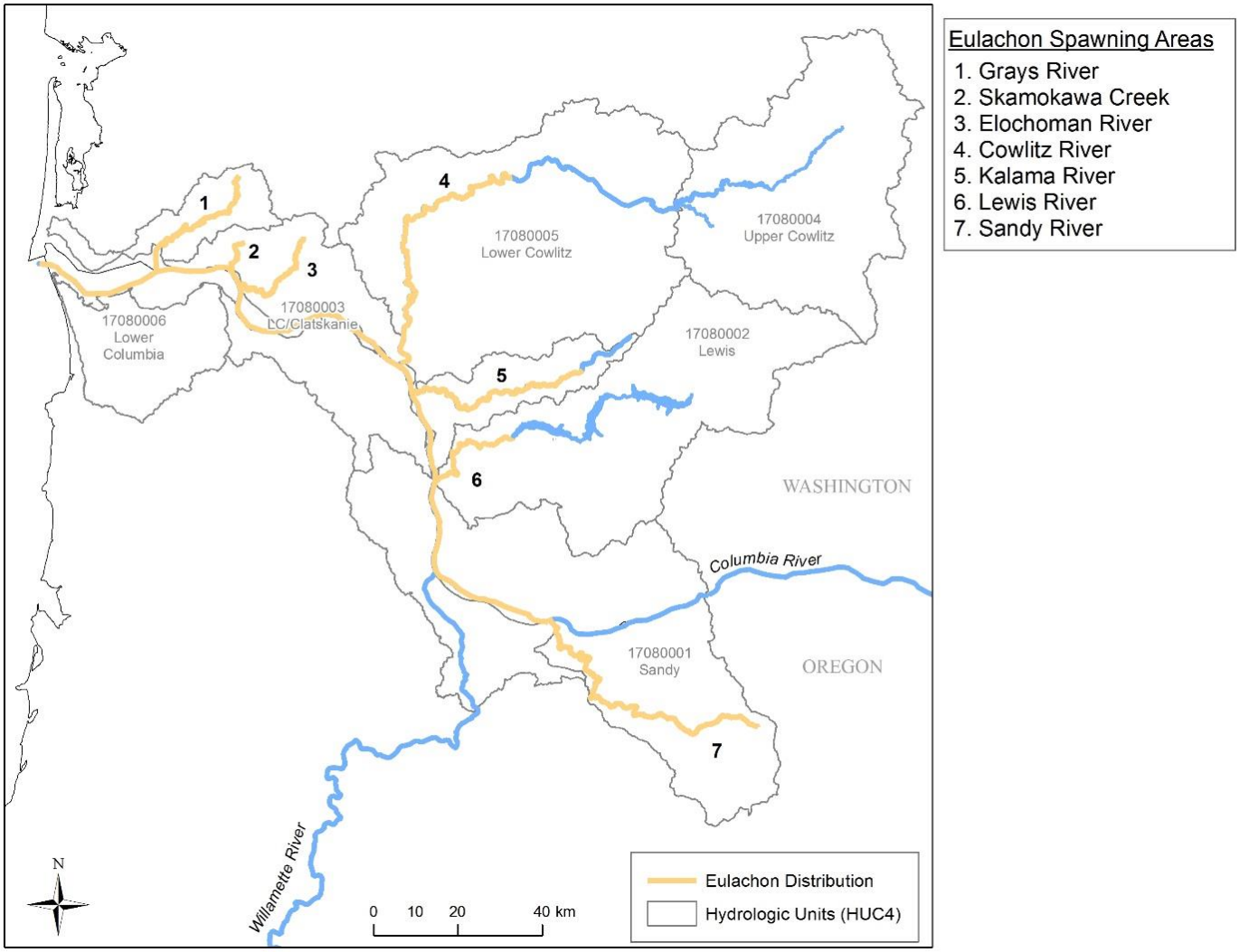

Figure 9: Eulachon Distribution in the Lower Columbia River

For the freshwater eulachon assessment, we examined monthly runoff for historic and modelled future climate change scenarios (described in section 2.1.1.3) in each hydrologic unit with eulachon spawning areas, as well as historic and projected changes to flow and water temperature in the Columbia River. The results of these analyses are presented in section 3.2.5.

3 Results

3.1 Lamprey Empirical Analysis

The results presented here encompass five different analyses for lamprey: (i) A time series approach to assess whether there are any lag-based patterns in abundance (as related by catch numbers); ii) A lagged correlational analysis to assess the effects of flow on abundance (as estimated by catches); iii) A similar analysis to ii) using ocean data; iv) An examination of a hypothesis on future freshwater and ocean conditions and how they affect abundance; and v) An analysis of potential spatial distribution changes to lamprey using GIS-based approaches to examine hypothetical shifts in freshwater conditions under future climate change scenarios.

3.1.1 Time Series Analysis

Data were examined to test if there was any cyclical pattern using the auto-correlation functions. Spectral analysis was used to also determine any periodicity in the observed patterns. As data were not continuous, we chose to only use the latter part (post 1975 for Willamette catch series), and between 1947-1970 for the Columbia Bonneville count in determining the temporal scale to be used in the analysis, followed by another analysis from 2000-2014 on the Bonneville dam count data.

3.1.2 Willamette Catch Data

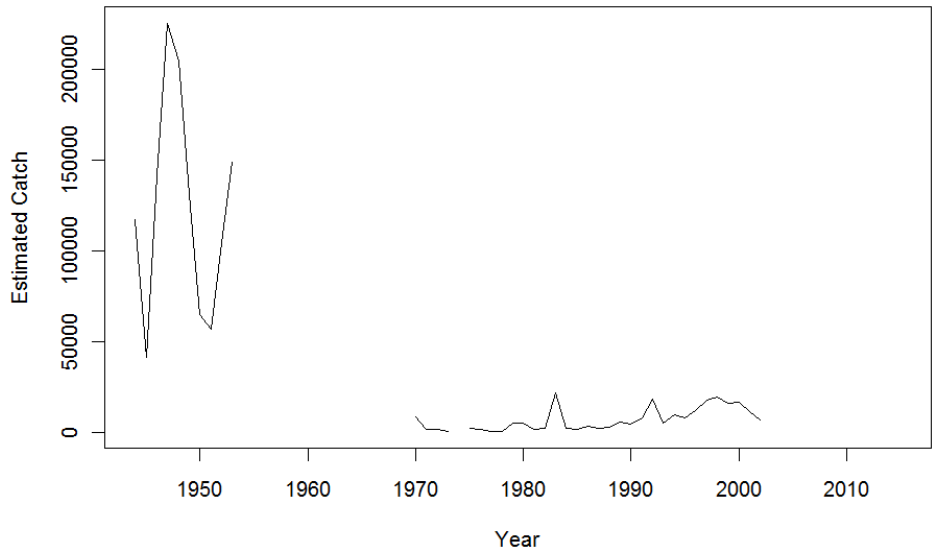

Figure 10: Estimated Counts of Willamette Falls Lamprey Catch (1938-2001)

It is apparent from the data presented in Figure 10 that the total catch of lamprey on the Willamette River declined drastically following the Willamette tributary dam constructions between the 1940's and 1960's. The early year data sets averaged 123,750 lamprey versus the latter years, which averaged around 8,800 lamprey, over a 90% drop in catch. If catch is proportional to abundance, which is likely in this case, then this indicates a dramatic decline in overall biomass as well.

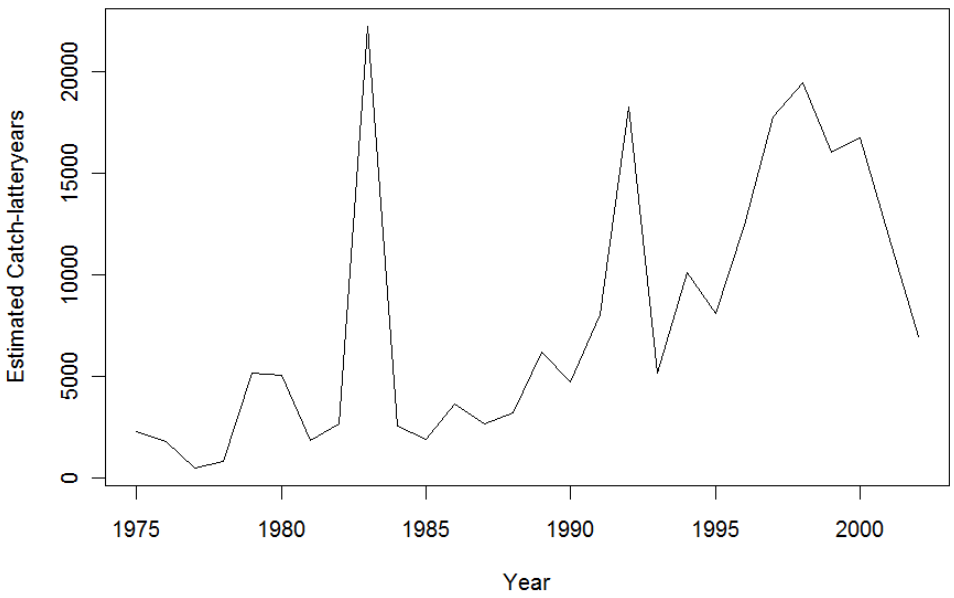

Figure 11: Data on Estimated Willamette Catch Series (1975-2001)

To examine periodicity and any sort of correlation over time, we used the latter series (after 1975, Figure 11) and examined if there were any periodicity as well as whether a 3rd order ARIMA model would be useful in predicting the decline. Four plots are shown in Figure 12 below, examining lag auto-correlated process, partially lagged auto-correlated process, and two plots indicating whether there is a spectral density with a periodogram at a certain lagged interval, and whether the process fits into a lagged model process. The plots indicate that the highest lag is at a time lag of 1, and the model with 3 terms shows a significant effect of this. However, this is not surprising, and we thus examined environmental data from the ocean at a lag of one year to understand if any process may be driving abundance in that manner, and examined 8-12 year lags as well for freshwater effects on the overall abundance.

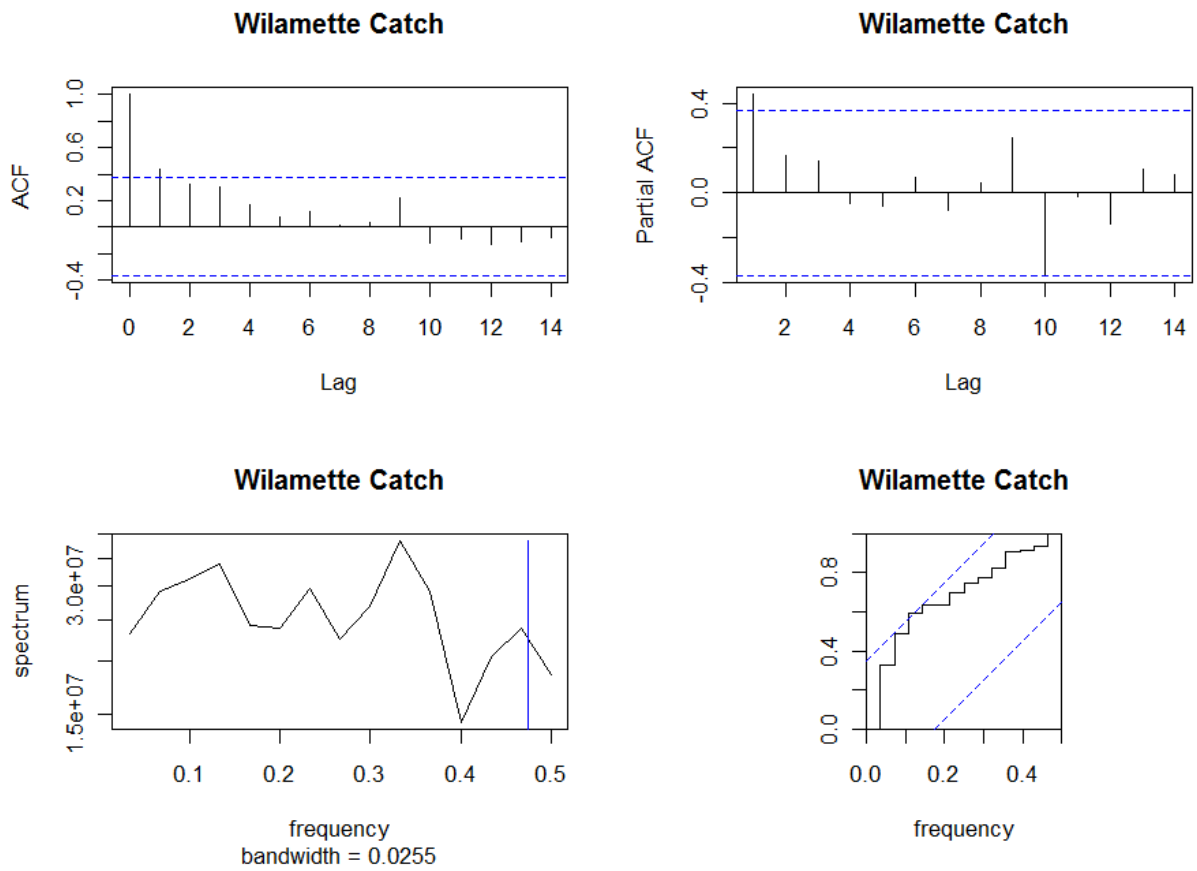

Figure 12: Plots of Autocorrelation (Full and Partial), Spectral Density, and CPgram (26 year data series)

Lag one and lag 3 models were examined on the dataset without transformation, and the lag one ARIMA model indicates that there is significant indicator at a one year time lag that affects abundance. Diagnostics of the lag one model are shown in Figure 13, both the intercept, and the lag-1 coefficient were significant (Table 2). The lag 3 model with 3 terms was not significant and was thus abandoned.

Table 2: Parameter Values of the Lag One ARIMA Model

	AR 1 term	Intercept
Estimate	0.435	7634.45
SE	0.167	1862.5

σ^2 estimated as 32610801: log likelihood = -282.04, aic = 570.07

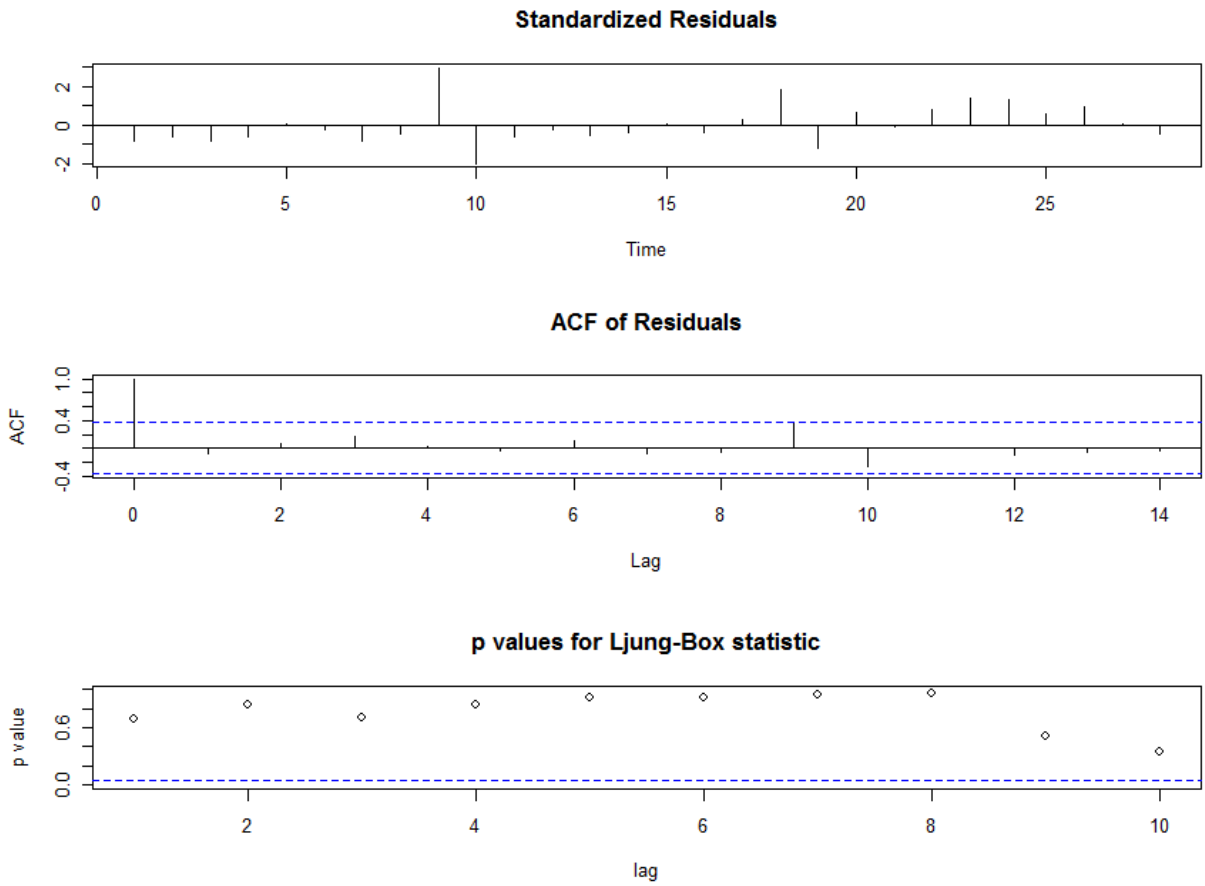

Figure 13: ARIMA Lag-1 Model Diagnostics

3.1.3 Bonneville Count Data

We examined Bonneville count data in a similar manner as to the Willamette catch data. As in the case of the Willamette data, the dam count data was incomplete for a large number of years (Figure 14). As with the Willamette data, we focused on different periods of continuous data to assess any periodicity or lags. Two periods were chosen to examine: (i) 1947-1970 and (ii) 2001 to 2014.

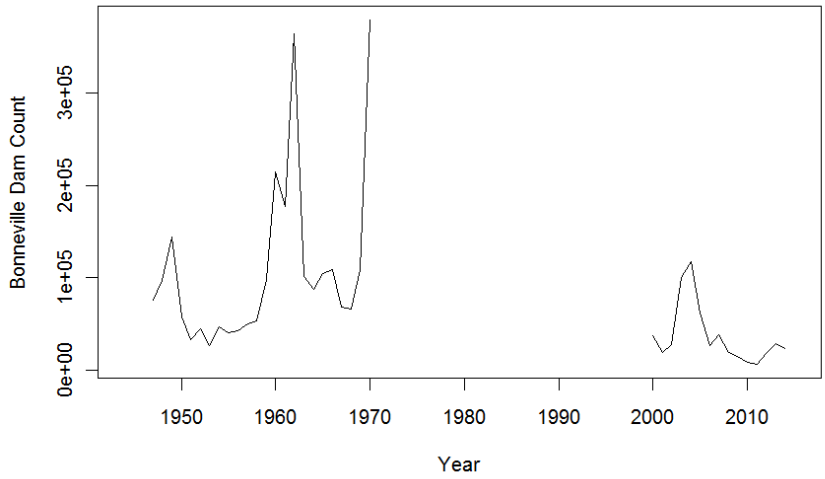

Figure 14: Lamprey Bonneville Dam Count (1947-Present)

The first period examined was from 1937-1970 (Figure 15).

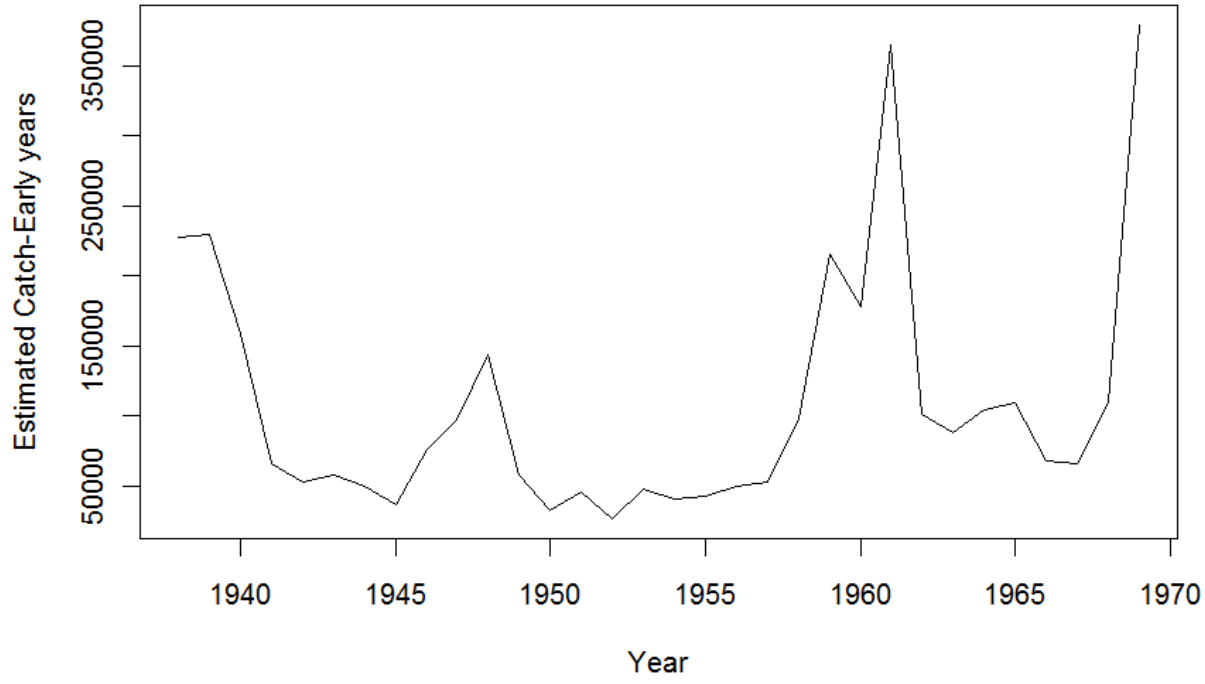

Figure 15: Dam count data on Bonneville dam prior to 1970.

Data indicates some periodicity (Figure 16), and examining it with auto-correlation and partial auto-correlation functions, as well as spectrums and periodograms (Figure 17), there appears to be some periodicity every one and 6 years, which is tested with ARIMIA models (residual patterns examined in Figure 18).

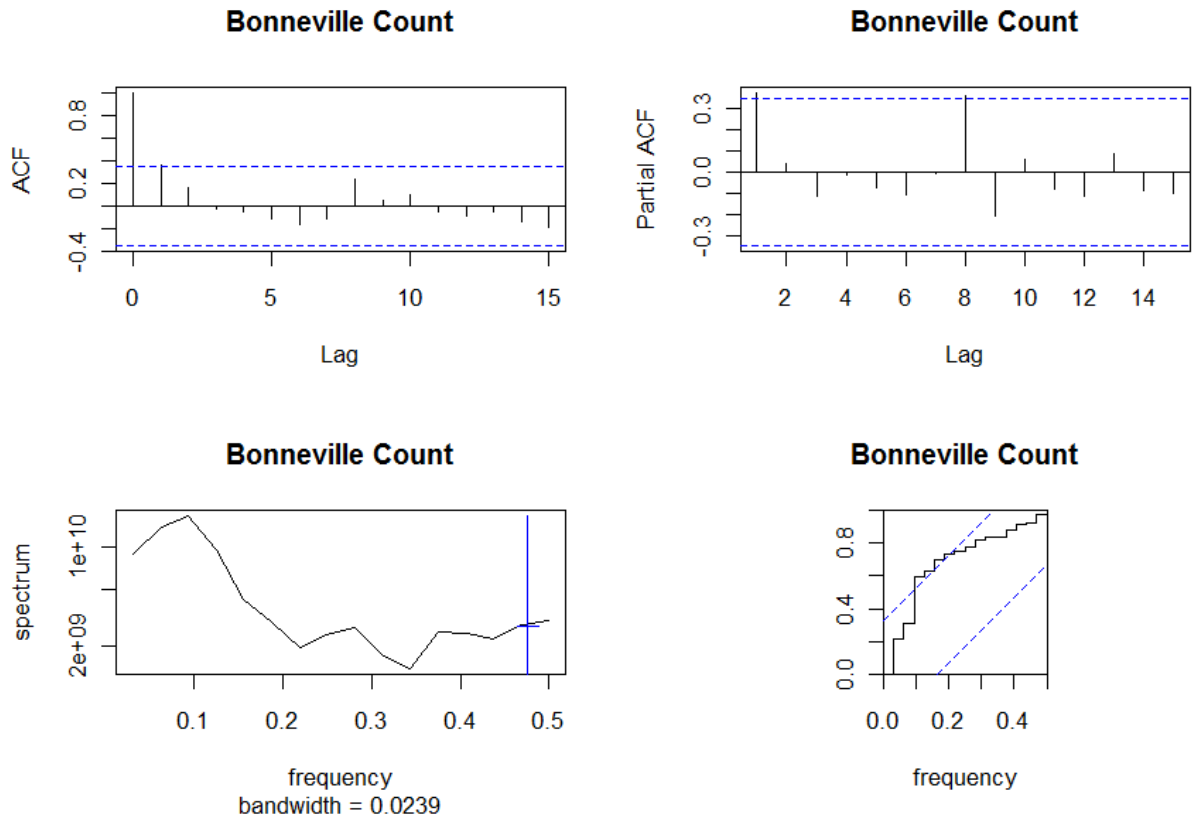

Figure 16: Plots of Correlation (full and partial), Fourier Analysis, and CPGram Analysis for Lamprey Time Series Data on Bonneville dam prior to 1970's

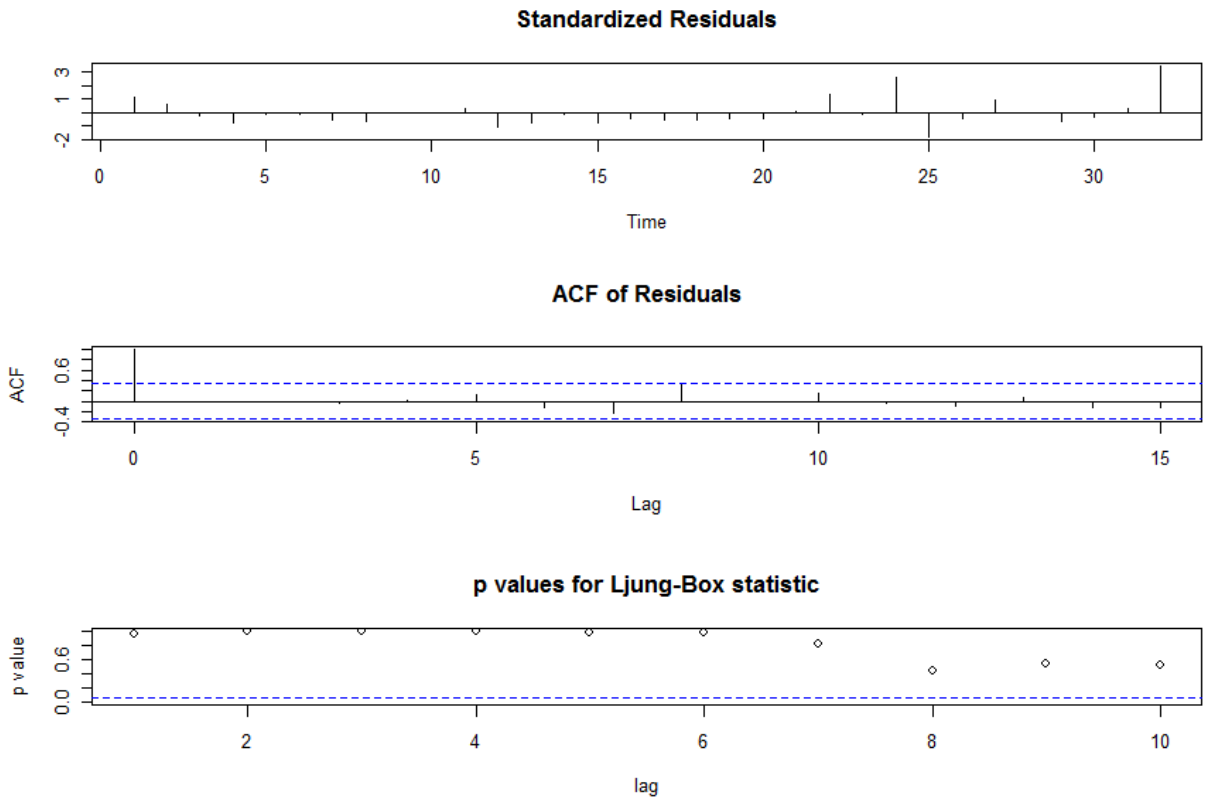

Figure 17: Time Series Model Diagnostics Used on the early Bonneville dam count data

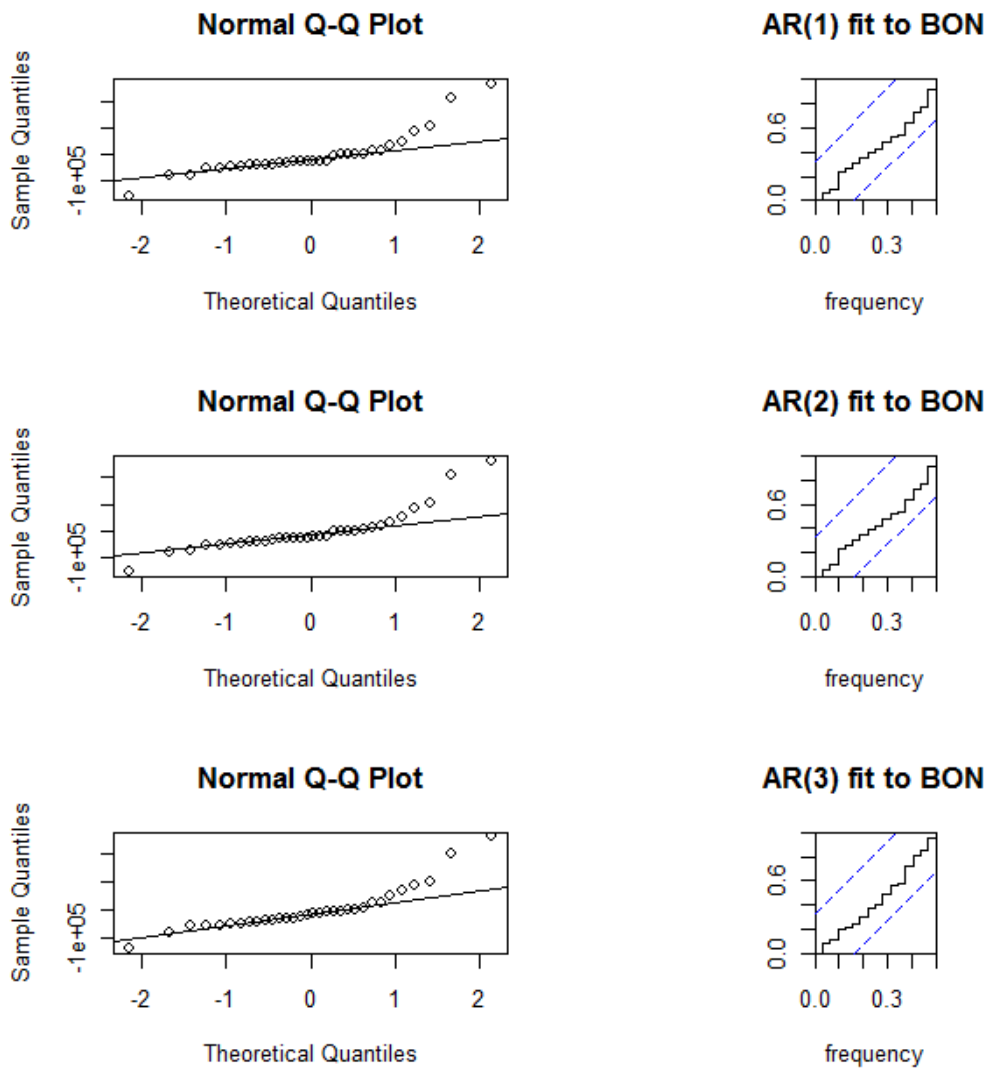

Figure 18: Comparison of Residuals for ARIMA Models Used (1, 2, and 3 year lag terms) and Overall Fit for the Arima models fit to the earlier period lamprey Bonneville dam count data.

As assessed in the previous case, a lag-1 time series model is the most parsimonious choice of models to use in analysis. The cpgrams have no values out of the statistical envelope. In the ARIMA 2, and 3 models the additional terms are non-significant and thus the model chose was the ARIMA -1 model with the following parameter values (Table 3).

Table 3: Parameter Values of the Lag One ARIMA Model

	AR 1 term	Intercept
Estimate	0.55	122463
SE	0.19	31245

σ^2 estimated as 6.083e+09: log likelihood = -406.05, aic = 818.1

3.1.4 Effects of Flow on Willamette Catch Levels

Based on the analysis shown in the times series data, we know that processes that affect lamprey abundance possibly occur at a lag of one year. However, freshwater impacts would only be noticeable in lags of 2-8 years or more as the life-cycle affected is an earlier one (Figure 2). Thus, we examined flow conditions (average flows) related to abundance (catch or dam counts) using the methods described in equations 1-3 above assuming that conditions during outmigration into the ocean primarily affect their survival.

We examined stream conditions from numerous areas of the Willamette River Basin (mainstem and tributaries including the Clackamas, Santiam and Tualatin Rivers) from late fall to spring when the ammocoetes may be washed out during maximum flow events. Figure 19 shows the location of stream gages used in this analysis, as well as the major tributaries of the Willamette Basin where lamprey spawning is known to occur. We examined average flows using a lag of 2 to 8 years to see if there was any effect on catches at Willamette Falls (assuming that catch rates are proportional to overall abundance). The months examined were November, December, January, February, March, April and the average of NOV-JAN and JAN-MAR to test if there were any effects of these events.

Note: We discounted the Bonneville count data as the data was not collected systematically over time, and flow data was not available below Bonneville with a USGS gauge collected consistently. In addition, the results are system specific and while similar results probably are evident on other systems, the approaches presented here are a framework for evaluating the effects of flow and ocean conditions on systems in the PNW. Results will vary by system and ideally, stage specific data and age-based information would make this analysis easier to conduct and provide system specific inference.

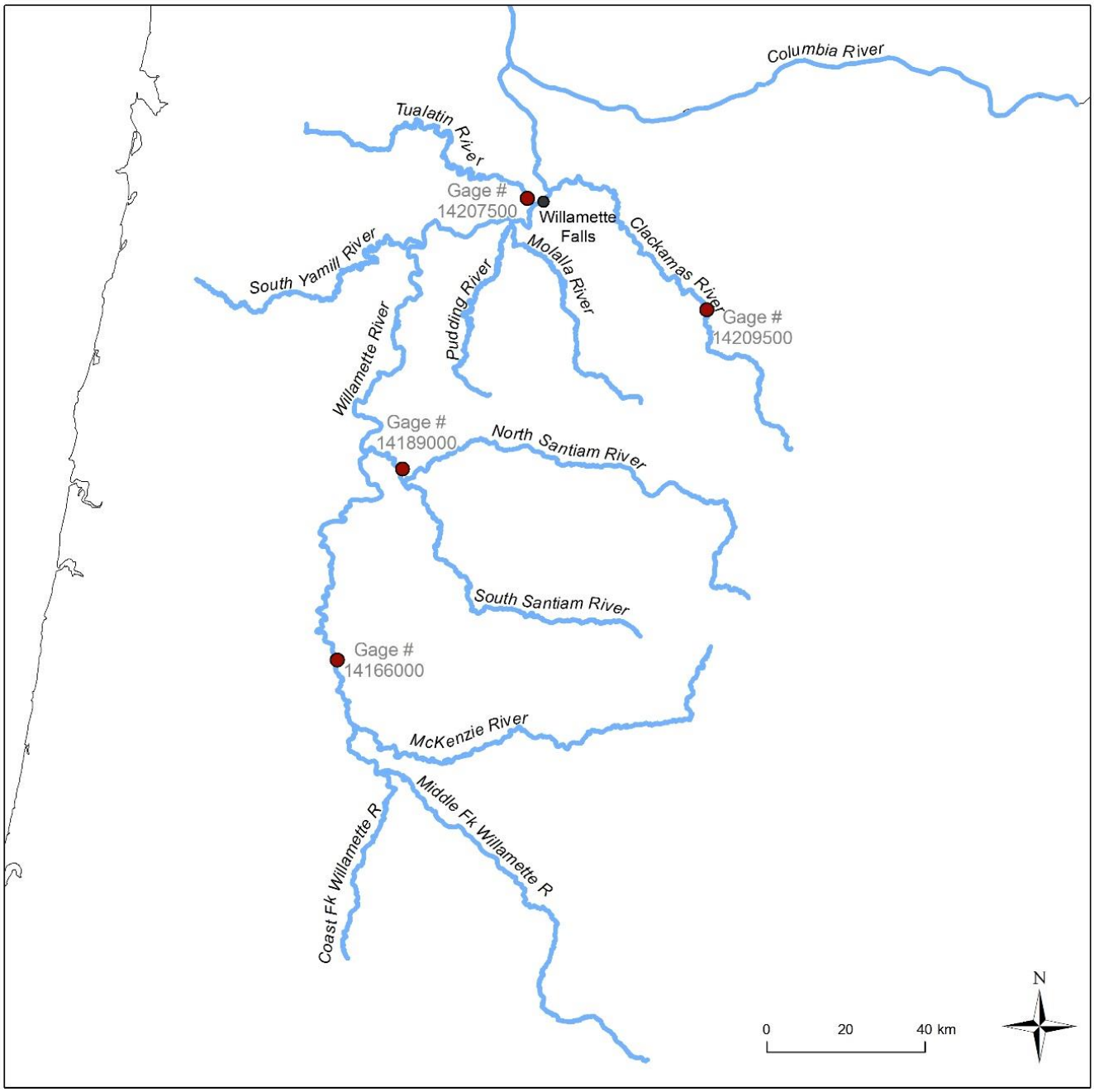

Figure 19: Major Lamprey-bearing Tributaries and Stream Gage Locations of the Willamette River Basin

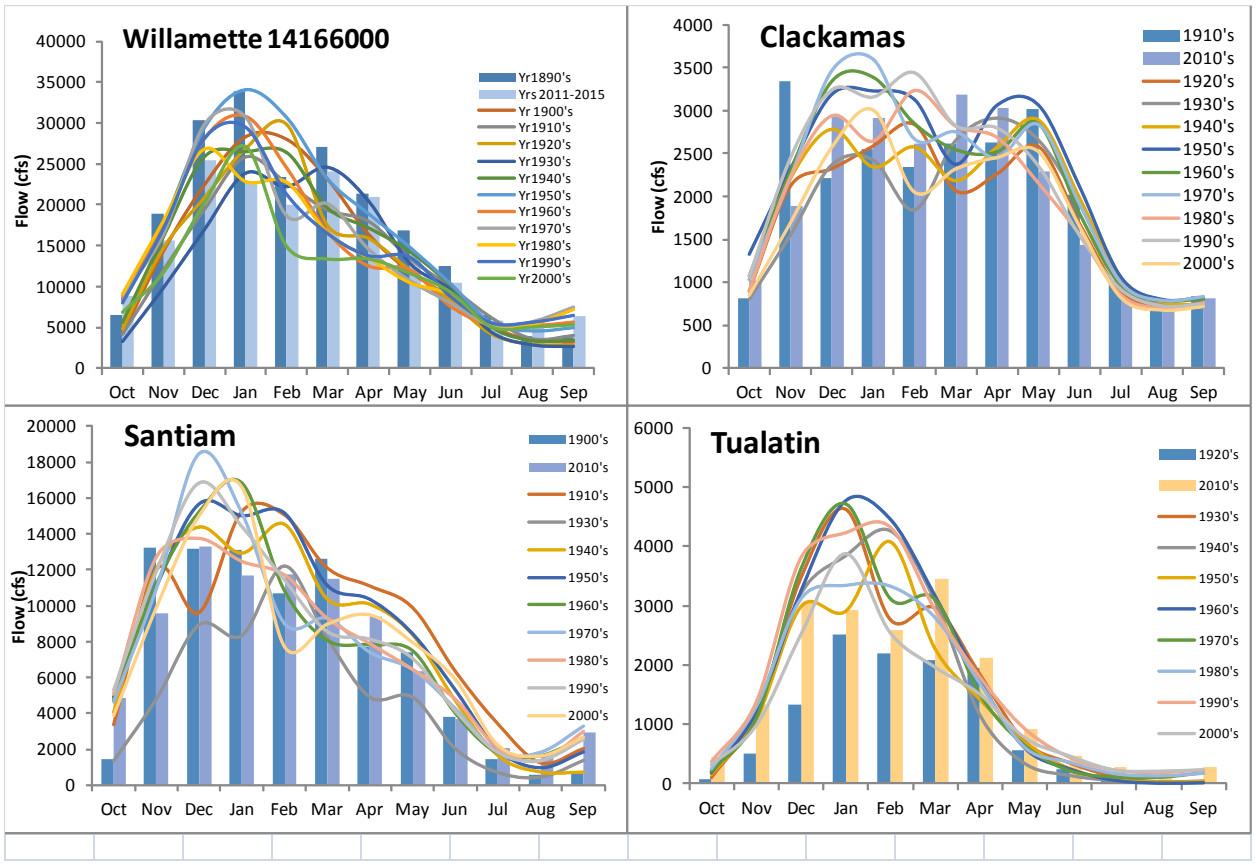

Figure 20: Flow data averaged over 10 year periods for different gauges on the Willamette River basin.

The histograms in Figure 20 show the differences over the earliest and latest periods on record. USGS Gage #s used in this analysis are 14209500 (Clackamas), 14207500 (Tualatin), and 14189000 (Santiam) and 1416600 (Willamette). It is evident from the gauges examined that there has been a shift over time of peak flows occurring later in the fall (October to November) and earlier in the spring (April to March).

3.1.4.1 Average flow effects (lag 6, 7 and 8)

Numerous correlational and lag time series analysis was performed on abundance data (Willamette catches), and average winter and spring flows from November through March to determine the appropriate time scale relating the freshwater effects to hypothesized abundance as expressed by catches. The hypothesis being examined was that these data lagged by 6, 7 and 8 years (primary years that lamprey migrate) after spawning, were important in determining overall abundance. However, there seems to be little or no relationship with overall catch estimates (Figure 21-23 and Table 4). This is not surprising as we have very little information on age structure of the return, and thus can't discern what the recruitment pattern maybe.

The only relationship that had some effect was the average winter flow conditions from November-January (variable named WILNOVJANJUN) of the calendar year that was related negatively to overall catch levels at the falls. This could be a spurious relationship as it is believed that more flow would imply

better survival, unless there is some optimal flow beyond which the ammocoetes/juvenile larvae experience higher mortality (Figure 24 and 25 and Table 5). Essentially, the higher flow in fall could either affect spawning success, or wash out some of the rearing beds with juvenile ammocoetes. It is likely that the latter is more plausible hypothesis though as a mechanism for this phenomena.

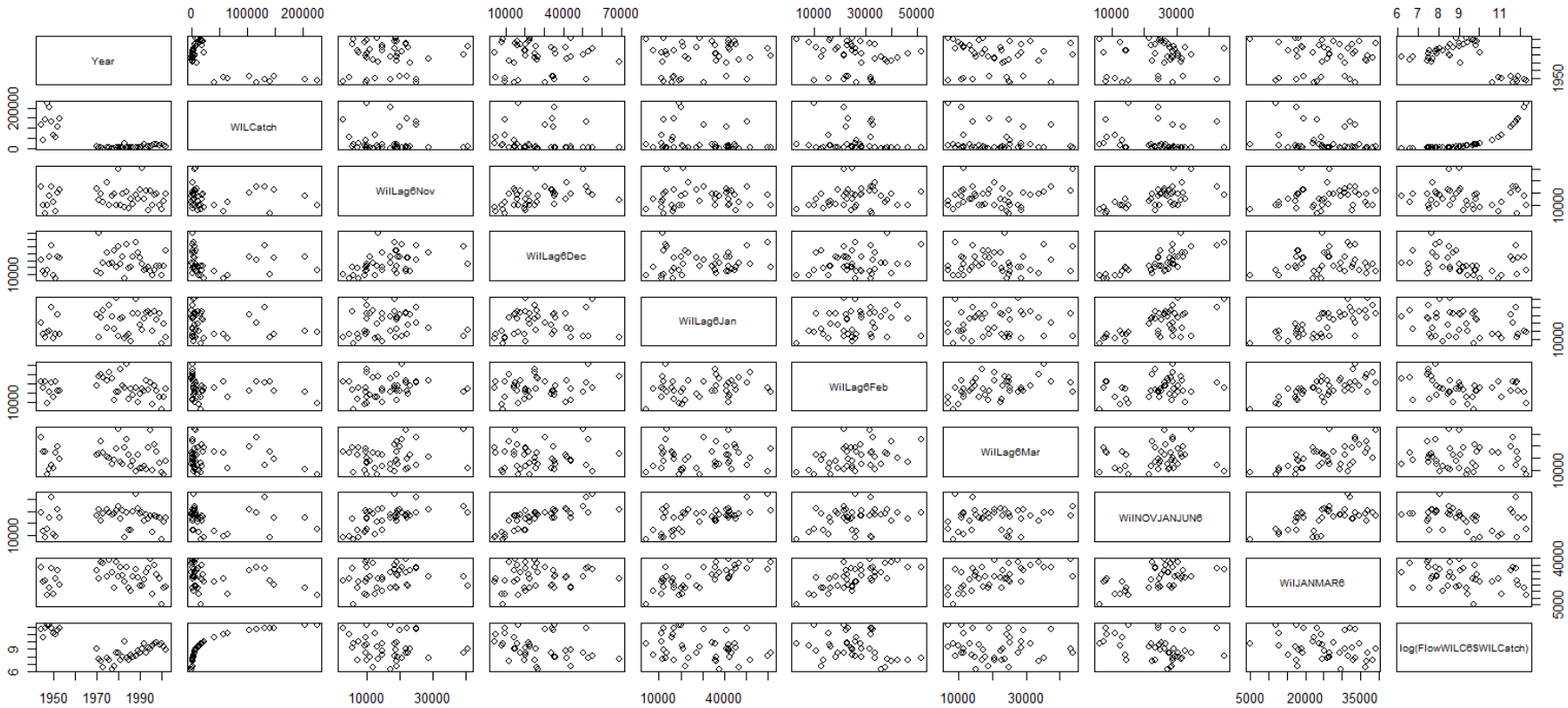

Figure 21: Lag 6 Plot of Monthly Flow Effects on Willamette Lamprey Counts using Gauge 14166000.

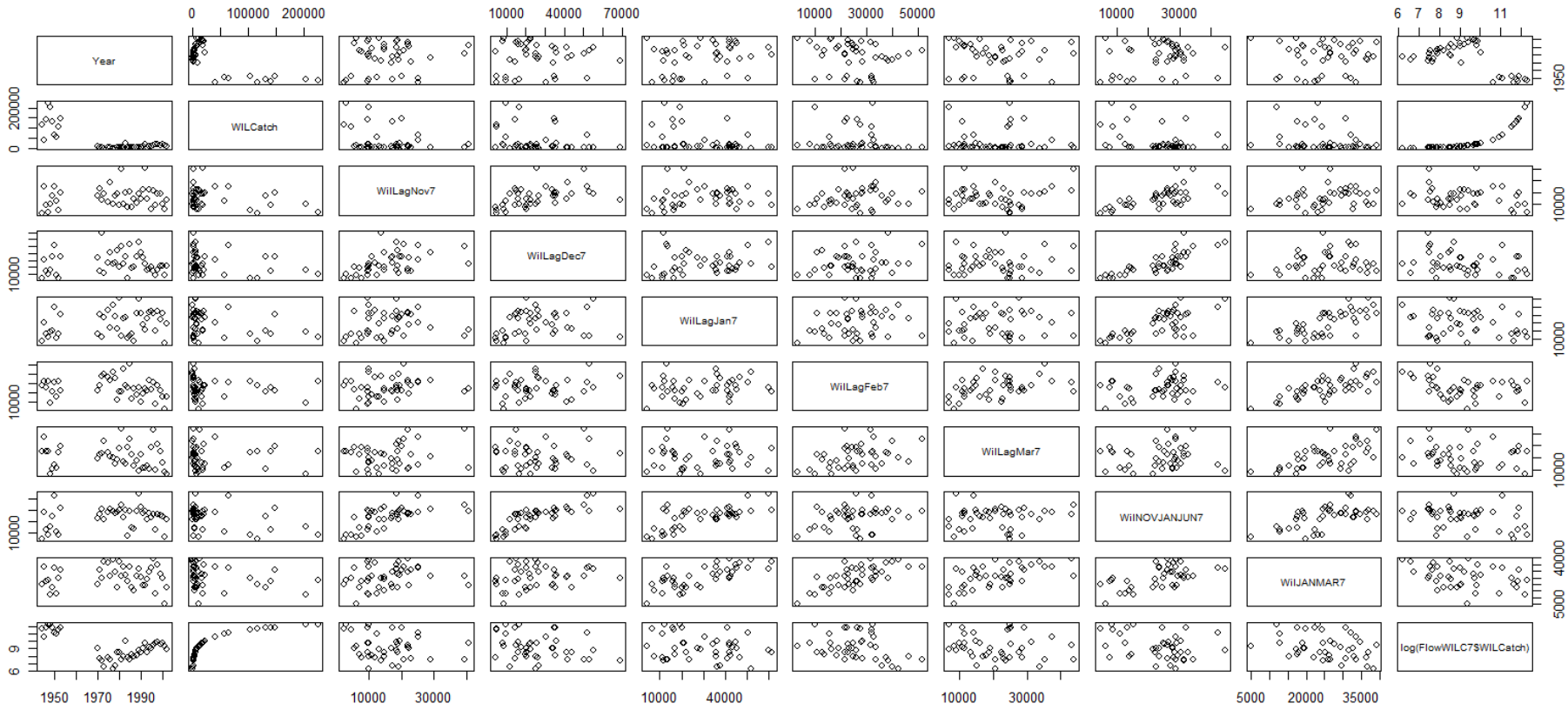

Figure 22: Lag 7 Plot of Monthly Flow Effects on Willamette Lamprey Counts using Gauge 14166000

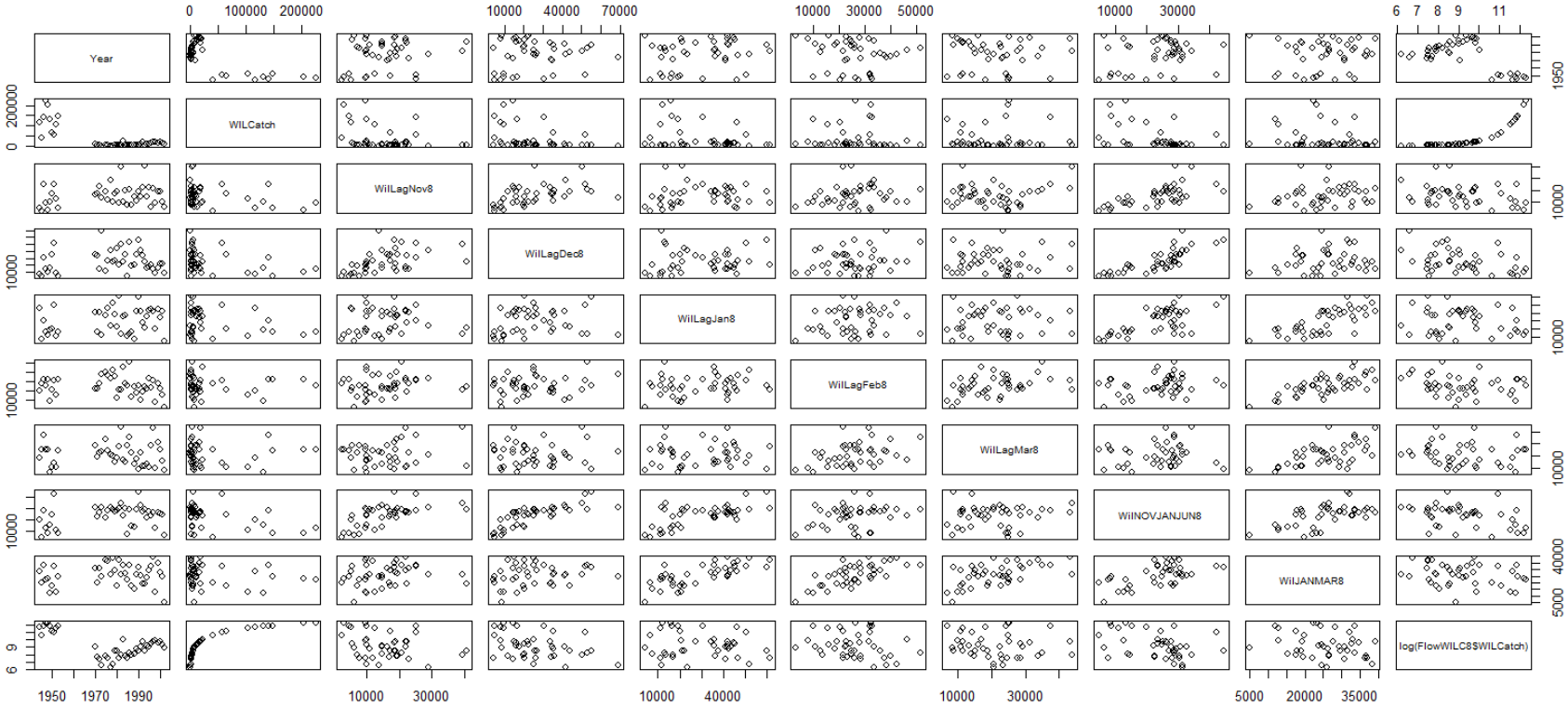

Figure 23: Lag 8 Plot of Monthly Flow Effects on Willamette Lamprey Counts using Gauge 14166000

Table 4: Covariance Matrix of Willamette River Winter (Gauge 14166000) and Spring Flows with the Willamette Falls Lamprey Count

	WILCatch	*VilLag6Nov*	*VilLagNov7*	*VilLagNov8*	*VilLag6Dec*	*VilLagDec7*	*VilLagDec8*	*VilLag6Jan*	*WilLagJan7*	*VilLagJan8*	*VilLag6Feb*	*VilLagFeb7*	*VilLagFeb8*	*VilLag6Ma*	*VilLagMar7*	*VilLagMar8*	*NOVJANJU*
WILCatch	1.00																
WilLag6Nov	-0.06	1.00															
WilLagNov7	-0.29	-0.22	1.00														
WilLagNov8	-0.31	0.10	-0.17	1.00													
WilLag6Dec	-0.05	0.46	-0.12	-0.13	1.00												
WilLagDec7	-0.24	-0.01	0.49	-0.07	-0.08	1.00											
WilLagDec8	-0.33	0.08	0.03	0.50	0.02	-0.04	1.00										
WilLag6Jan	-0.20	0.04	0.11	0.14	0.09	0.15	-0.04	1.00									
WilLagJan7	-0.29	0.22	0.12	0.16	0.20	0.17	0.18	-0.02	1.00								
WilLagJan8	-0.26	-0.01	0.16	0.08	-0.26	0.16	0.14	0.12	-0.06	1.00							
WilLag6Feb	-0.15	0.16	0.09	0.29	0.22	-0.03	0.17	0.20	-0.22	0.09	1.00						
WilLagFeb7	-0.10	-0.11	0.15	0.09	-0.01	0.21	-0.03	0.01	0.19	-0.22	0.13	1.00					
WilLagFeb8	-0.03	-0.30	-0.08	0.16	-0.26	0.03	0.22	-0.09	0.01	0.17	0.18	0.13	1.00				
WilLag6Mar	-0.14	0.18	-0.19	0.02	0.05	-0.08	-0.08	0.07	0.02	0.15	0.40	0.17	0.10	1.00			
WilLagMar7	-0.06	-0.09	0.17	-0.20	-0.09	0.04	-0.10	-0.12	0.04	0.03	0.19	0.41	0.16	0.25	1.00		
WilLagMar8	0.01	-0.13	-0.08	0.16	-0.19	-0.04	0.04	-0.14	-0.16	0.03	0.01	0.19	0.39	-0.06	0.24	1.00	
WilNOVJANJUN6	-0.16	0.61	-0.07	0.04	0.77	0.04	0.01	0.64	0.17	-0.08	0.29	-0.04	-0.29	0.13	-0.15	-0.23	1.00
WilNOVJANJUN7	-0.38	0.05	0.64	-0.01	0.03	0.79	0.09	0.11	0.68	0.10	-0.11	0.27	0.00	-0.09	0.10	-0.13	0.09
WilNOVJANJUN8	-0.43	0.07	0.05	0.63	-0.17	0.04	0.79	0.09	0.12	0.66	0.24	-0.11	0.27	0.04	-0.10	0.09	-0.03
WilJANMAR6	-0.24	0.17	0.04	0.22	0.17	0.05	0.02	0.74	-0.10	0.17	0.71	0.13	0.06	0.61	0.10	-0.11	0.57
WilJANMAR7	-0.25	0.05	0.21	0.06	0.08	0.22	0.06	-0.06	0.73	-0.12	-0.01	0.71	0.12	0.18	0.59	0.07	0.03
WilJANMAR8	-0.18	-0.19	0.04	0.18	-0.35	0.10	0.20	-0.02	-0.10	0.74	0.14	-0.01	0.69	0.11	0.18	0.58	-0.27

Variable shown in the above Table 4 and Figures 21-23 are the catches as expressed as Willamette catch, and flows November through March, with average flows with average flows on the mainstem Willamette from November to January, and January to March. Numbers indicate the number of years in a lag (for example, '6' represents a 6-year lag). Correlations greater that 0.4 or -0.4 are highlighted showing some correlations across independent variables, though the main variable of interest in WILCatch and how that relates to each of these variables. Note, for consistency the variable names were left the same, but are measured with different flow gauges (Clackamas, Santiam, and Tualatin Rivers in subsequent Tables and graphs for the same months, i.e. November through March, and with same lags 6, 7 and 8 year lags)

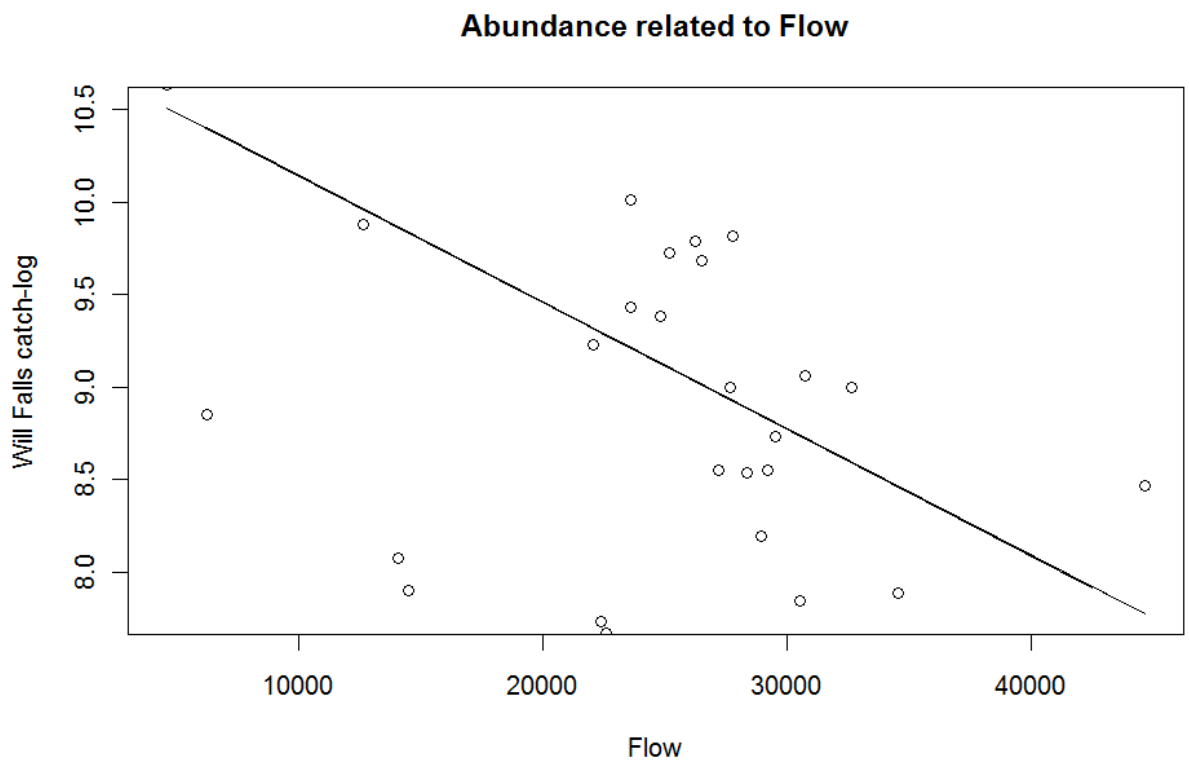

Figure 24: Model Fit of a Linear Model of Average Flow (Nov-Jan using Gauge 14166000) with a Lag 8 Year and its Relation to Log-Scale Willamette Falls Lamprey Catch Levels

Table 5: ANOVA of Linear Model Predicting Willamette Falls Lamprey Catch Based on Flow Levels from Mainstem Willamette using gauge 14166000

Parameters	DF	SSQ	MSE	F-value	Pr(>F)
Flow (Nov-Jan)t-8	1	16.679	16.6789	7.099	0.01106 *
Residuals	40	93.978	2.3495		

'*' 0.05 '

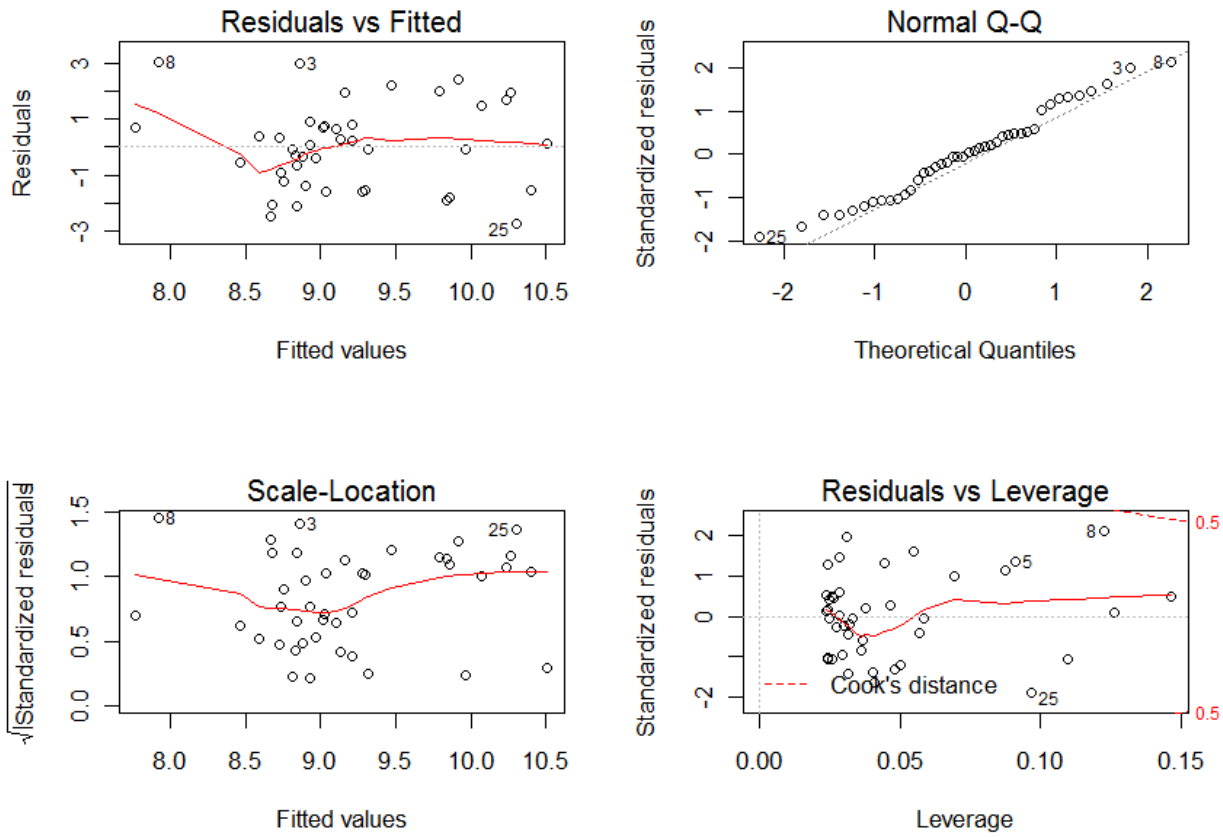

Figure 25: Diagnostics of a Linear Model of Average Flow (Nov-Jan) from Willamette mainstem, gauge 14166000, related to Willamette Falls Lamprey Catch Levels

Similar relationships were examined on the Clackamas (Figures 26-28). Table 6 indicates the significant results indicating again an inverse relationship with flow, thereby implying a higher mortality, once a threshold flow is exceeded. The most significant of these is the lag 7 flow in February, followed closely by the lag 6 and lag 8 flows for the same month (February). Other significant relationships are, the average flows from Jan through March for each of the lags.

Similar models to those shown in Figure 24 and 25 and Table 5 above can be developed for each indicator and then examined in detail.

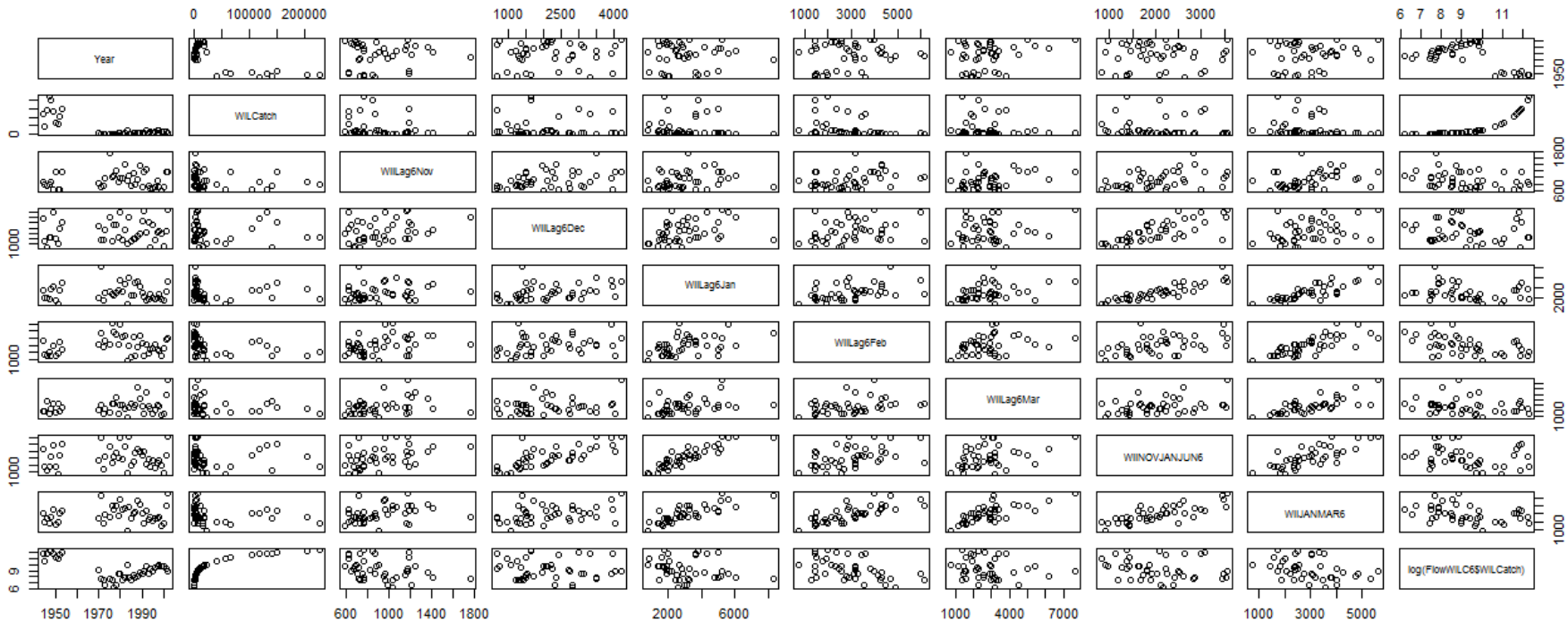

Figure 26: Lag 6 Plot of Monthly Clackamas River Flow Effects on Willamette Falls Lamprey Counts

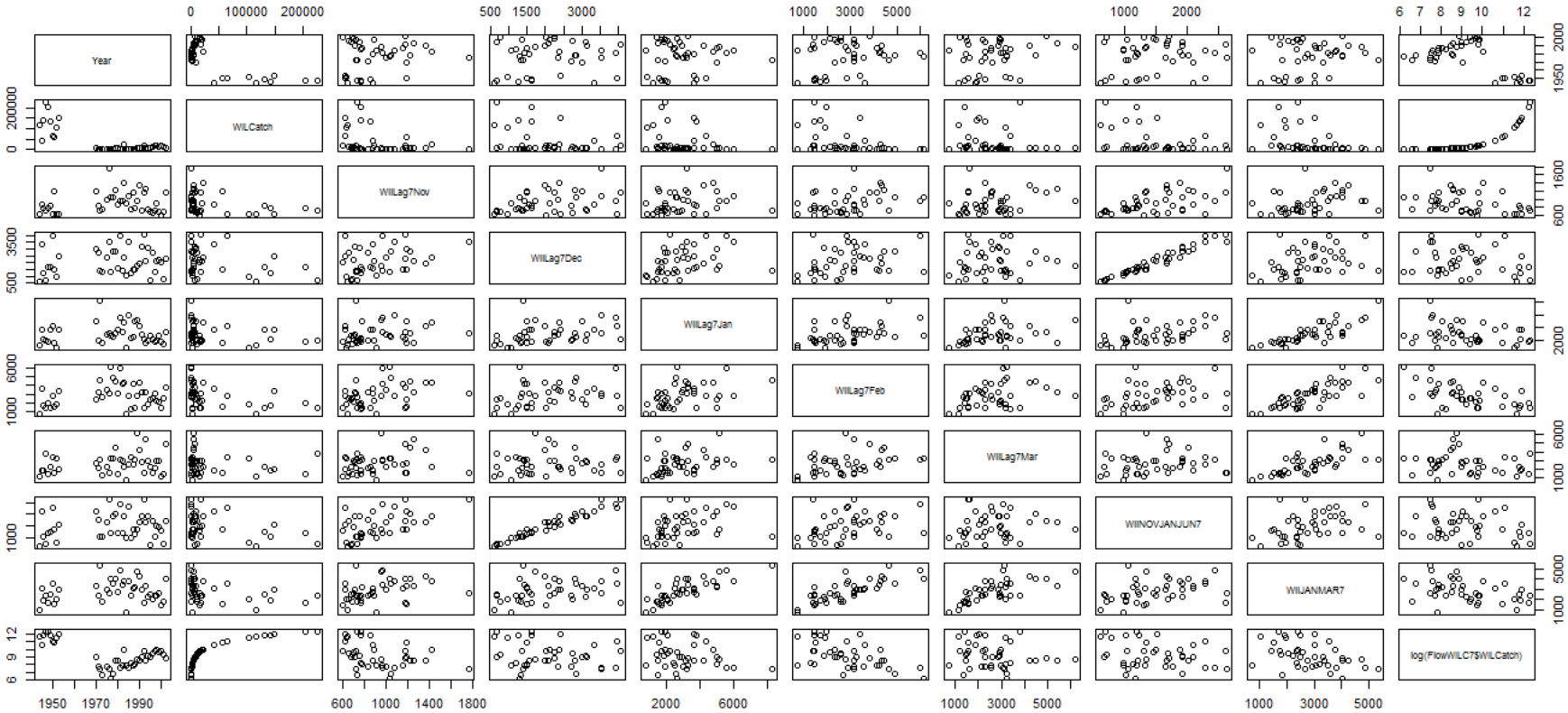

Figure 27: Lag 7 Plot of Monthly Clackamas River Flow Effects on Willamette Falls Lamprey Counts

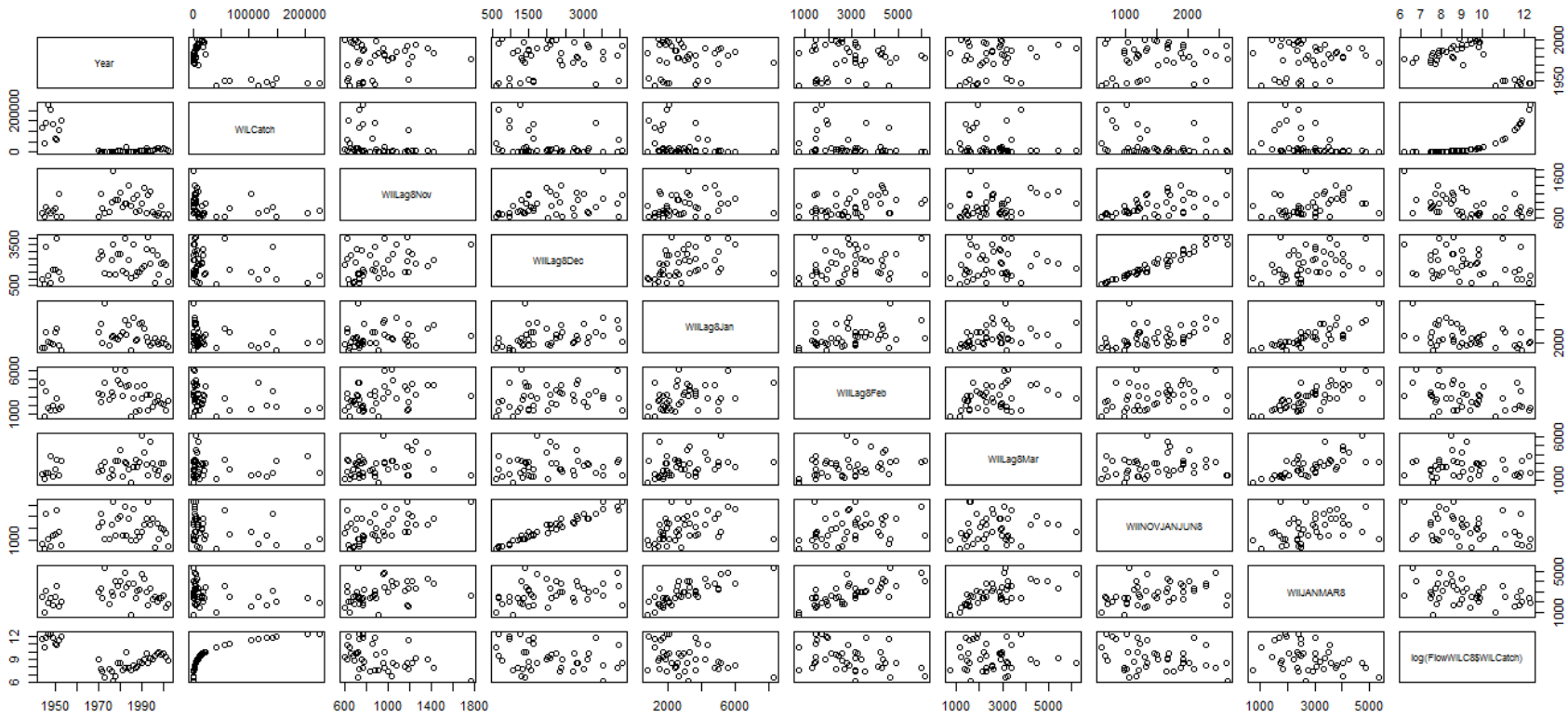

Figure 28: Lag 8 Plot of Monthly Clackamas River Flow Effects on Willamette Falls Lamprey Counts

Table 6: Covariance Matrix of Clackamas River Winter and Spring Flows and Willamette Falls Lamprey Count

	ln(WILC)	VilLag6Nov	WilLag6Dec	VilLag6Jan	VilLag6Feb	VilLag6Mar	NOVJANJU	ilJANMAR	VilLag7Nov	WilLag7Dec	VilLag7Jan	VilLag7Feb	VilLag7Mar	NOVJANJU	ilJANMAR	VilLag8Nov	WilLag8Dec	VilLag8Jan	VilLag8Feb	VilLag8Mar	NOVJANJU	ilJANMAR
ln(WILC)	1.00																					
WilLag6Nov	-0.31	1.00																				
WilLag6Dec	-0.09	0.35	1.00																			
WilLag6Jan	-0.21	0.20	0.36	1.00																		
WilLag6Feb	-0.49	0.35	0.28	0.45	1.00																	
WilLag6Mar	-0.18	0.25	0.20	0.36	0.33	1.00																
WilNOVJANJUN6	-0.22	0.41	0.74	0.89	0.48	0.37	1.00															
WilJANMAR6	-0.37	0.34	0.37	0.81	0.75	0.73	0.78	1.00														
WilLag7Nov	-0.36	0.12	0.01	-0.05	0.21	0.22	-0.02	0.15	1.00													
WilLag7Dec	-0.16	0.15	-0.21	-0.16	-0.04	0.03	-0.19	-0.08	0.34	1.00												
WilLag7Jan	-0.26	0.10	-0.10	-0.08	0.00	0.01	-0.09	-0.04	0.20	0.34	1.00											
WilLag7Feb	-0.54	0.24	0.06	0.04	0.24	-0.01	0.08	0.11	0.37	0.30	0.46	1.00										
WilLag7Mar	-0.17	0.12	0.12	0.01	0.04	0.19	0.07	0.10	0.23	0.07	0.32	0.35	1.00									
WilNOVJANJUN7	-0.22	0.16	-0.18	-0.15	0.01	0.08	-0.17	-0.03	0.55	0.97	0.35	0.35	0.12	1.00								
WilJANMAR7	-0.42	0.19	0.02	-0.02	0.11	0.07	0.01	0.07	0.34	0.32	0.82	0.78	0.69	0.37	1.00							
WilLag8Nov	-0.43	0.04	0.17	0.27	0.27	-0.04	0.27	0.22	0.11	-0.02	-0.07	0.21	0.18	0.01	0.12	1.00						
WilLag8Dec	-0.24	-0.03	-0.07	-0.11	0.20	-0.03	-0.12	0.01	0.17	-0.17	-0.13	0.00	0.06	-0.11	-0.04	0.35	1.00					
WilLag8Jan	-0.38	0.21	-0.04	0.11	0.28	-0.05	0.08	0.14	0.12	-0.07	-0.06	0.04	0.03	-0.03	0.00	0.21	0.36	1.00				
WilLag8Feb	-0.37	0.29	0.20	0.12	0.37	0.02	0.21	0.21	0.18	-0.03	-0.02	0.16	-0.12	0.02	0.01	0.33	0.25	0.41	1.00			
WilLag8Mar	-0.06	-0.07	0.00	0.08	0.02	-0.14	0.05	-0.01	0.09	0.04	-0.04	0.03	0.05	0.06	0.01	0.20	0.09	0.34	0.30	1.00		
WilNOVJANJUN8	-0.31	-0.02	-0.03	-0.04	0.24	-0.04	-0.04	0.06	0.18	-0.16	-0.13	0.05	0.09	-0.10	-0.01	0.55	0.98	0.37	0.30	0.13	1.00	
WilJANMAR8	-0.38	0.21	0.06	0.14	0.31	-0.07	0.15	0.16	0.18	-0.03	-0.05	0.10	-0.02	0.01	0.01	0.33	0.33	0.82	0.75	0.68	0.37	1.00

Variable shown above (Table 6¸ and Figures 26-28) are the catches as expressed as Willamette catch, and flows November through March, with average flows with average flows on the Clackamas from November to January, and January to March. Numbers indicate lags (for example, '6' represents a 6-year lag). Correlations greater that 0.4 or -0.4 are highlighted showing some correlations across independent variables, though the main variable of interest in WILCatch and how that relates to each of these variables.

Similar exercises were examined on the Santiam (Table 7), e which also indicates that the catch levels are proportional to January flow in a lag 7 and lag 8 relationship. Similar results are shown for pairs across the Santiam flows (Figure 29-31 and Table 7) and Tualatin (Figure 32-34 and Table 8). Lag 2- 5's were also examined for each system and their overall relationships to abundance.

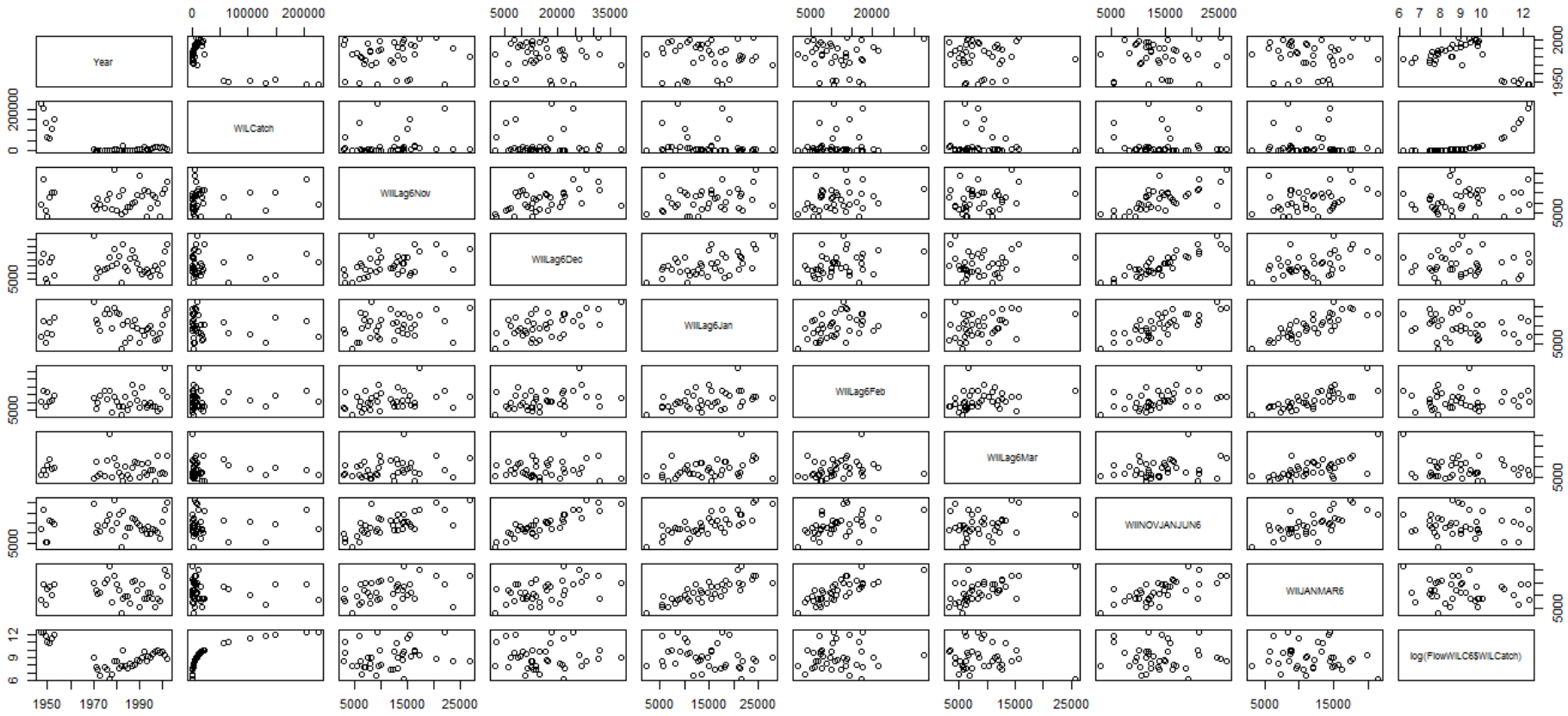

Figure 29: Lag 6 Plot of Monthly Santiam River Flow Effects on Willamette Falls Lamprey Counts

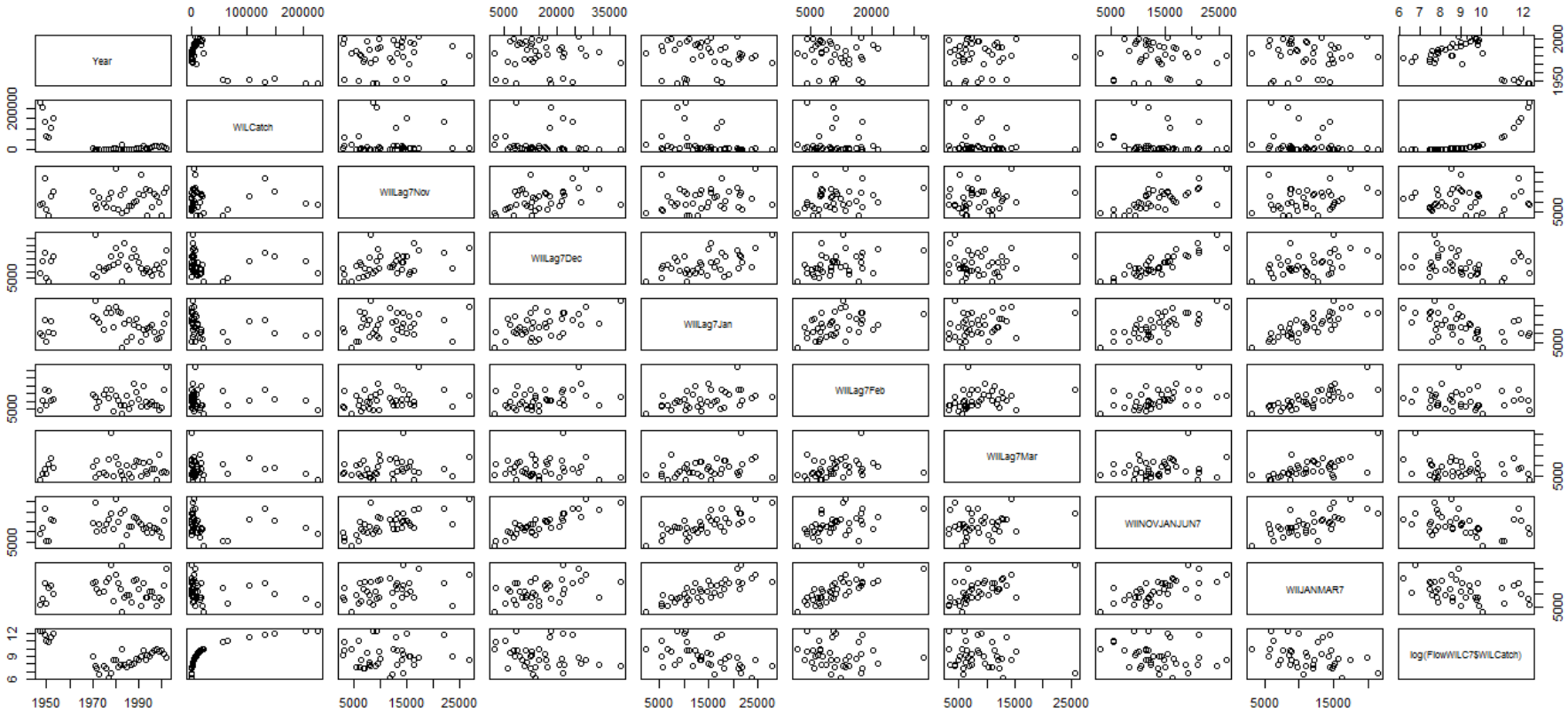

Figure 30: Lag 7 Plot of Monthly Santiam River Flow Effects on Willamette Falls Lamprey Counts

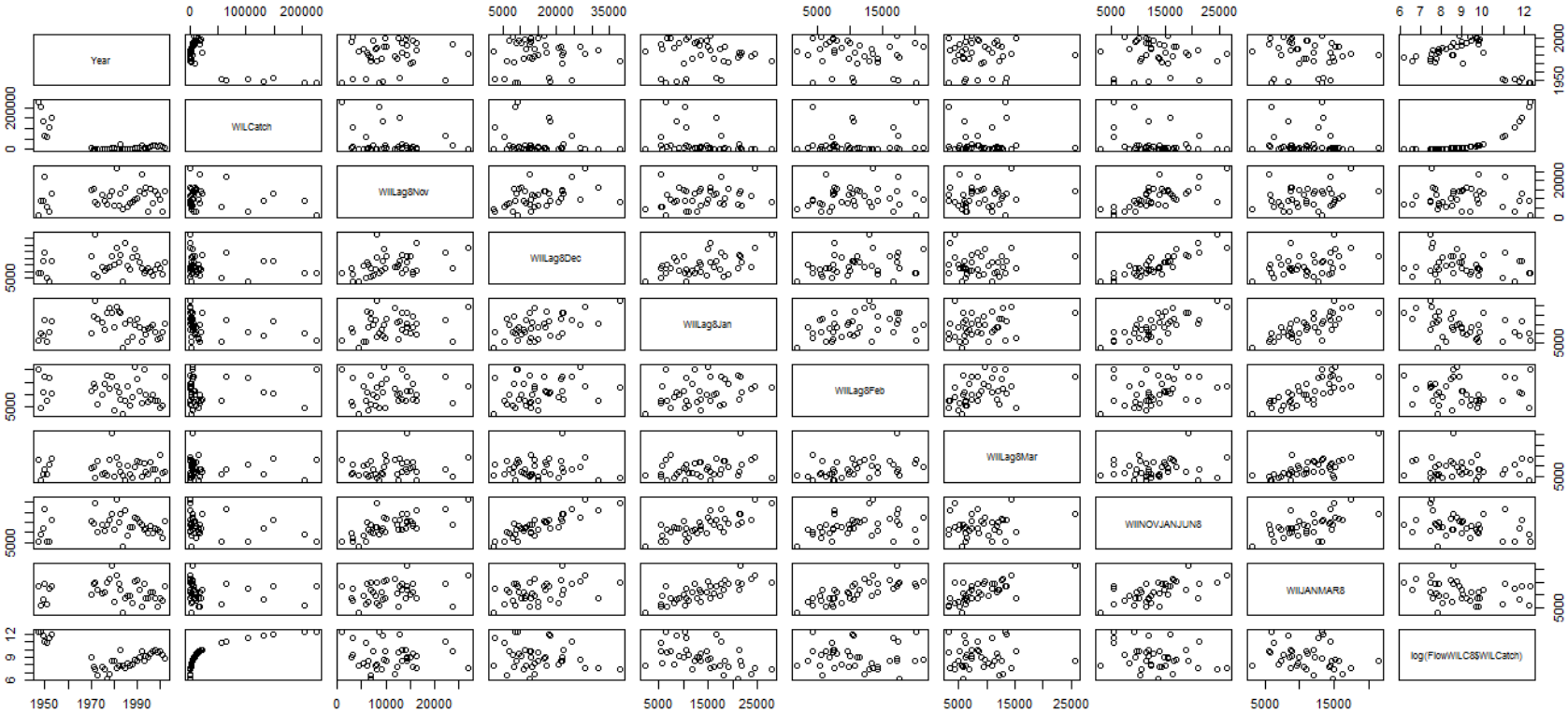

Figure 31: Lag 8 Plot of Monthly Santiam River Flow Effects on Willamette Falls Lamprey Counts

Table 7: Covariance Matrix of Santiam River Winter and Spring Flows and Willamette Falls Lamprey Count

	ln(WILC)	*WilLag6Nov*	*WilLag6Dec*	*WilLag6Jan*	*WilLag6Feb*	*WilLag6Mar*	*WilNOVJANJU*	*WilJANMAR*	*WilLag7Nov*	*WilLag7Dec*	*WilLag7Jan*	*WilLag7Feb*	*WilLag7Mar*	*WilNOVJANJU*	*WilJANMAR*	*WilLag8Nov*	*WilLag8Dec*	*WilLag8Jan*	*WilLag8Feb*	*WilLag8Mar*	*WilNOVJANJU*	*WilJANMAR*
ln(WILC)	1.00																					
WilLag6Nov	0.17	1.00																				
WilLag6Dec	-0.02	0.46	1.00																			
WilLag6Jan	-0.23	0.27	0.56	1.00																		
WilLag6Feb	0.06	0.28	0.36	0.42	1.00																	
WilLag6Mar	-0.16	0.22	0.08	0.33	0.24	1.00																
WilNOVJAN	-0.04	0.69	0.89	0.77	0.44	0.25	1.00															
WilJANMAR	-0.15	0.35	0.48	0.82	0.77	0.63	0.69	1.00														
WilLag7Nov	0.02	-0.18	-0.10	-0.11	0.06	0.00	-0.16	-0.03	1.00													
WilLag7Dec	-0.21	-0.10	-0.07	0.02	-0.02	0.23	-0.06	0.08	0.42	1.00												
WilLag7Jan	-0.47	-0.07	0.06	0.27	-0.12	0.24	0.11	0.16	0.23	0.54	1.00											
WilLag7Feb	-0.12	0.11	0.18	0.36	0.16	0.25	0.27	0.34	0.28	0.38	0.42	1.00										
WilLag7Mar	-0.20	-0.10	-0.06	0.06	-0.29	-0.10	-0.05	-0.14	0.18	0.03	0.31	0.26	1.00									
WilNOVJAN	-0.29	-0.14	-0.05	0.07	-0.04	0.21	-0.05	0.09	0.67	0.88	0.76	0.46	0.20	1.00								
WilJANMAR	-0.36	-0.01	0.10	0.33	-0.08	0.20	0.17	0.20	0.31	0.46	0.81	0.79	0.63	0.67	1.00							
WilLag8Nov	-0.06	0.08	-0.09	0.19	-0.20	0.02	0.05	0.00	-0.20	-0.12	-0.13	0.10	0.01	-0.18	-0.01	1.00						
WilLag8Dec	-0.19	0.07	0.04	0.22	-0.15	-0.12	0.13	0.00	-0.15	-0.12	-0.03	-0.01	0.21	-0.13	0.05	0.41	1.00					
WilLag8Jan	-0.46	0.14	0.02	0.23	-0.13	0.02	0.15	0.06	-0.10	0.04	0.25	-0.09	0.23	0.08	0.16	0.25	0.53	1.00				
WilLag8Feb	-0.02	0.11	0.04	0.05	-0.17	0.21	0.08	0.02	-0.07	-0.04	0.22	0.08	0.06	0.05	0.17	0.11	0.26	0.32	1.00			
WilLag8Mar	0.00	0.34	0.08	0.01	-0.08	-0.03	0.17	-0.04	-0.09	-0.06	0.06	-0.30	-0.11	-0.04	-0.16	0.14	0.03	0.28	0.41	1.00		
WilNOVJAN	-0.31	0.12	-0.01	0.27	-0.20	-0.05	0.14	0.03	-0.19	-0.09	0.04	0.00	0.20	-0.10	0.09	0.68	0.87	0.76	0.30	0.18	1.00	
WilJANMAR	-0.25	0.25	0.06	0.15	-0.17	0.09	0.18	0.03	-0.12	-0.02	0.25	-0.13	0.11	0.05	0.10	0.24	0.40	0.77	0.76	0.70	0.60	1.00

Variable shown in Table 7 and Figures 29-31 are the catches as expressed as Willamette catch, and flows November through March, with average flows with average flows on the Santiam from November to January, and January to March. Numbers indicate lags (for example, ‘6’ represents a 6-year lag). Correlations greater that 0.4 (pink) or -0.4 (light yellow) are highlighted showing some correlations across independent variables, though the main variable of interest in WILCatch and how that relates to each of these variables.

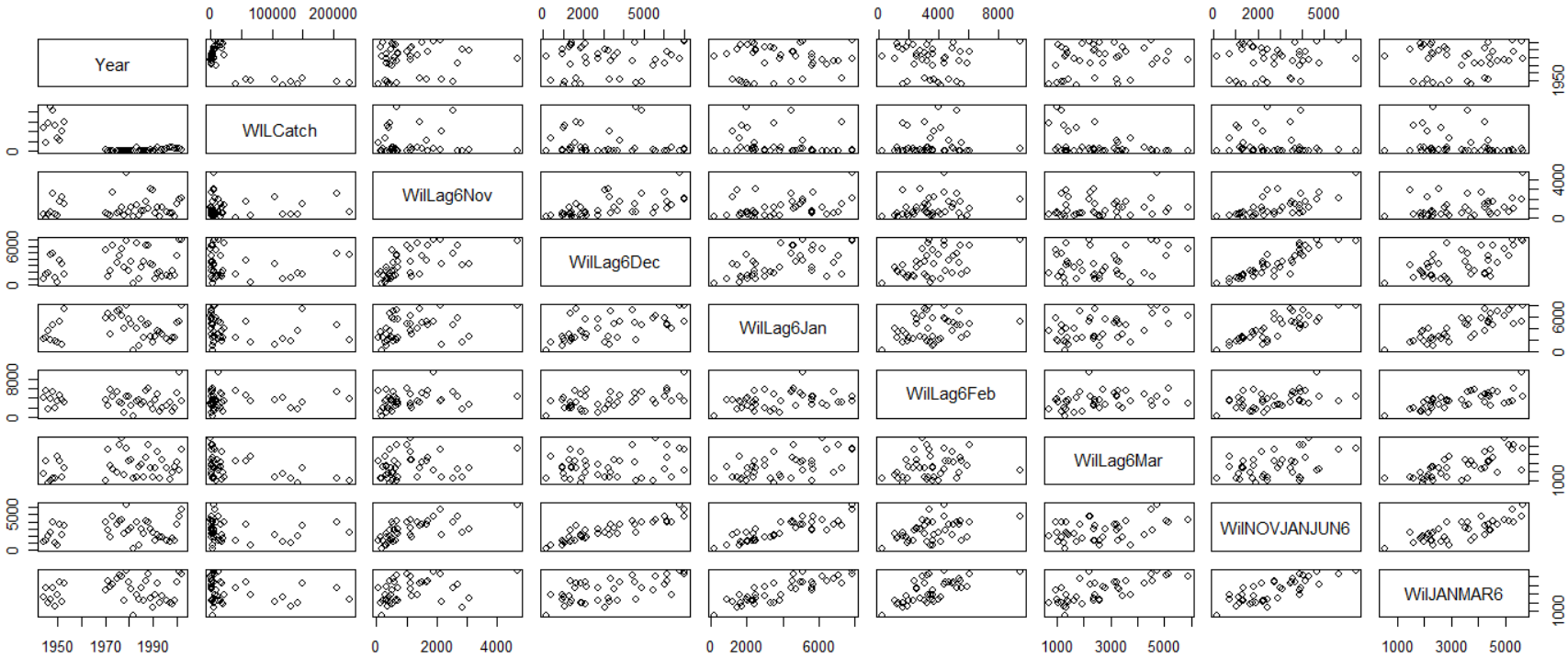

Figure 32: Lag 6 Plot of Monthly Tualatin River Flow Effects on Willamette Falls Lamprey Counts

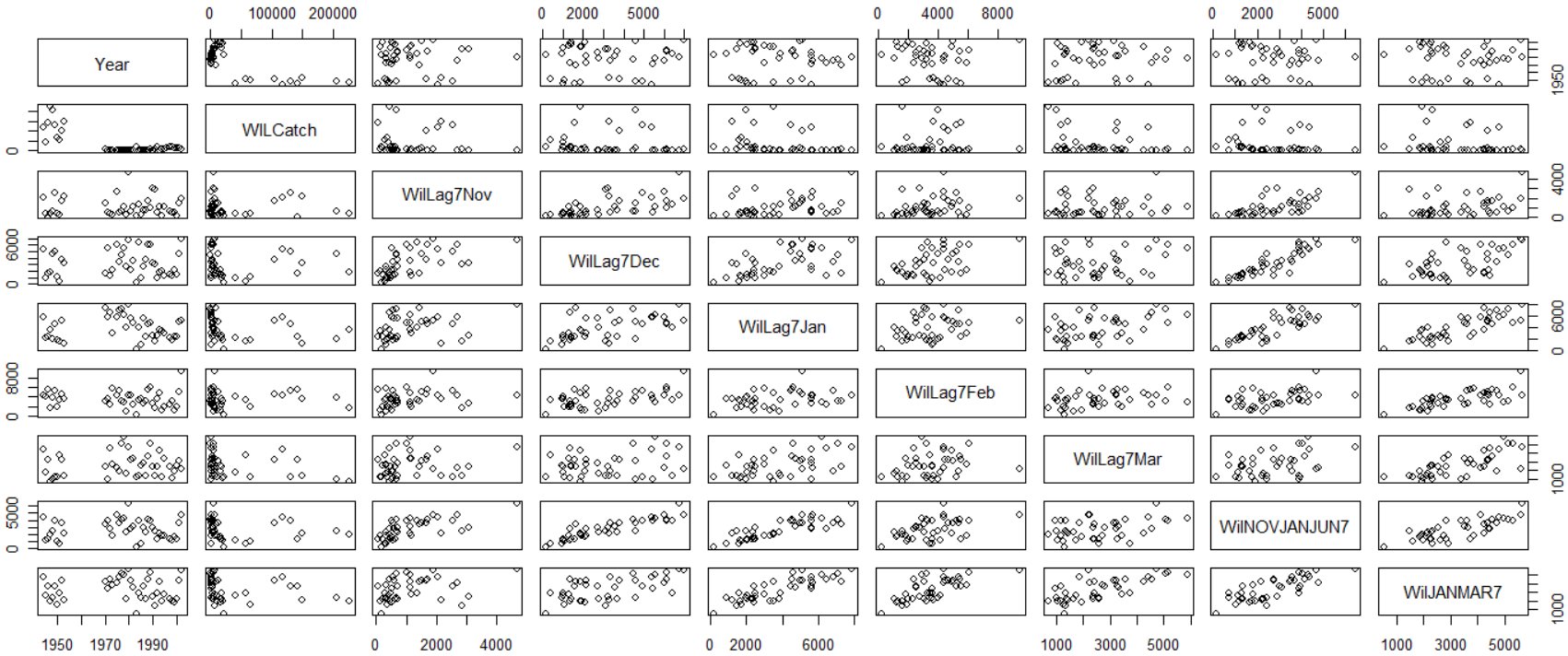

Figure 33: Lag 7 Plot of Monthly Tualatin River Flow Effects on Willamette Falls Lamprey Counts

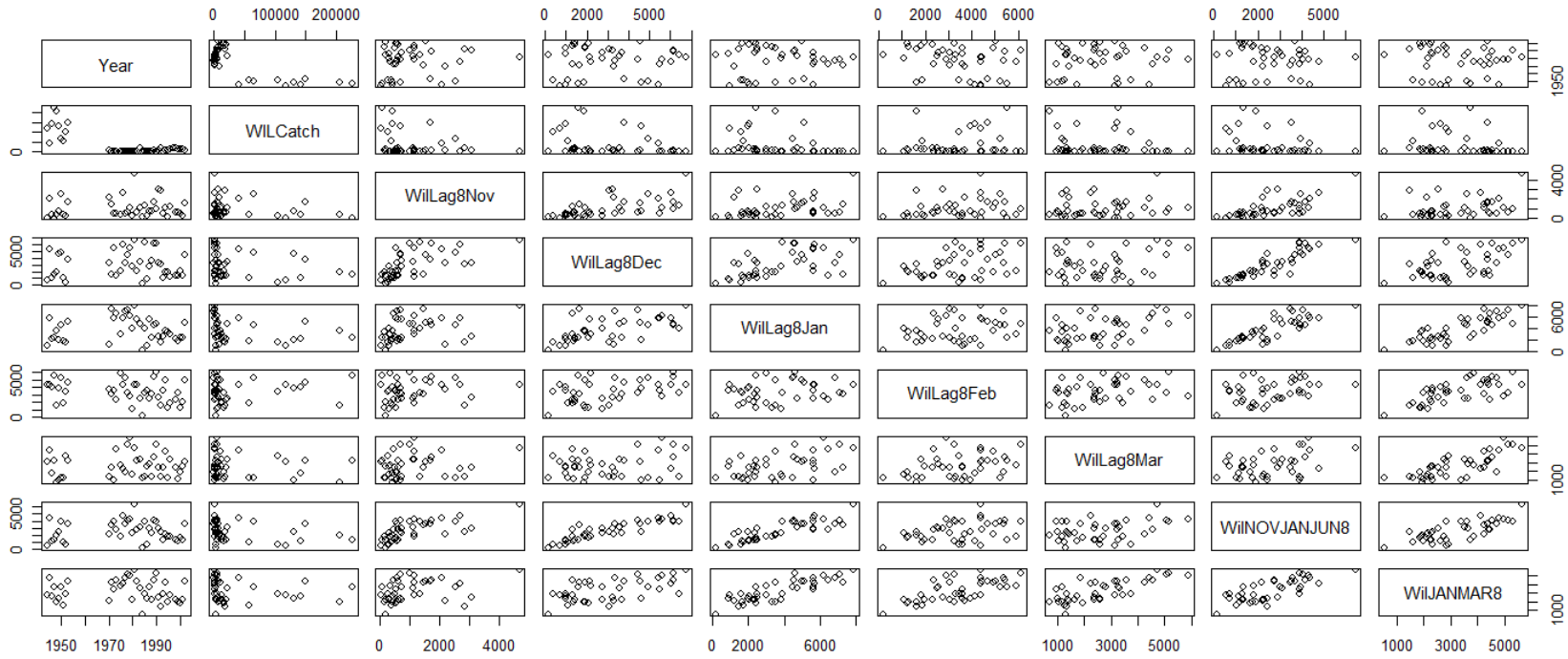

Figure 34: Lag 8 Plot of Monthly Tualatin River Flow Effects on Willamette Falls Lamprey Counts

Table 8: Covariance Matrix of Tualatin River Winter and Spring Flows with Willamette Falls Lamprey Count

	WILCatch	*ln(WILC)*	*WilLag6Nov*	*WilLag6Dec*	*WilLag6Jan*	*WilLag6Feb*	*WilLag6Mar*	*NOVJANJU*	*WilJANMAR*	*WilLag7Nov*	*WilLag7Dec*	*WilLag7Jan*	*WilLag7Feb*	*WilLag7Mar*	*NOVJANJU*	*WilJANMAR*	*WilLag8Nov*	*WilLag8Dec*	*WilLag8Jan*	*WilLag8Feb*	*WilLag8Mar*	*NOVJANJU*
WILCatch	1.00																					
ln(WILC)	0.85	1.00																				
WilLag6Nc	0.00	-0.01	1.00																			
WilLag6De	-0.12	-0.21	0.60	1.00																		
WilLag6Jar	-0.19	-0.29	0.34	0.58	1.00																	
WilLag6Fe	0.02	0.08	0.25	0.49	0.30	1.00																
WilLag6Ma	-0.42	-0.40	0.16	0.23	0.51	0.24	1.00															
WilNOVJA	-0.15	-0.24	0.69	0.90	0.84	0.43	0.40	1.00														
WilJANMA	-0.24	-0.26	0.34	0.61	0.84	0.69	0.72	0.78	1.00													
WilLag7Nc	-0.02	0.00	-0.05	-0.15	0.00	0.05	-0.15	-0.08	-0.03	1.00												
WilLag7De	-0.06	-0.23	0.09	0.07	0.15	0.09	0.15	0.13	0.17	0.61	1.00											
WilLag7Jar	-0.25	-0.44	-0.14	0.11	0.19	0.05	0.17	0.11	0.18	0.33	0.55	1.00										
WilLag7Fe	0.02	-0.05	0.11	0.20	0.29	0.11	0.12	0.26	0.24	0.27	0.51	0.32	1.00									
WilLag7Ma	-0.28	-0.36	-0.03	0.02	0.01	-0.02	0.01	0.01	0.00	0.17	0.25	0.52	0.28	1.00								
WilNOVJA	-0.16	-0.32	-0.03	0.05	0.17	0.08	0.12	0.10	0.16	0.70	0.90	0.83	0.46	0.41	1.00							
WilJANMA	-0.22	-0.37	-0.03	0.15	0.23	0.07	0.14	0.18	0.20	0.35	0.60	0.83	0.71	0.74	0.78	1.00						
WilLag8Nc	-0.75	-0.60	0.13	0.23	0.13	-0.04	0.25	0.20	0.14	0.04	0.09	0.03	-0.04	0.08	0.07	0.03	1.00					
WilLag8De	-0.22	-0.12	-0.03	-0.10	0.16	-0.11	0.34	0.02	0.15	-0.09	-0.24	-0.06	0.02	-0.19	-0.16	-0.09	0.09	1.00				
WilLag8Jar	-0.25	-0.27	0.20	0.10	0.23	-0.07	0.34	0.21	0.21	0.03	-0.05	0.05	0.07	0.07	0.01	0.08	0.07	0.62	1.00			
WilLag8Fe	-0.27	-0.49	0.23	0.18	0.40	-0.14	0.41	0.33	0.29	-0.17	0.05	0.15	0.03	0.12	0.06	0.13	0.02	0.35	0.58	1.00		
WilLag8Ma	0.13	0.02	-0.03	-0.10	-0.05	-0.34	-0.03	-0.08	-0.19	0.06	0.04	0.17	0.12	0.06	0.11	0.16	-0.21	0.19	0.39	0.29	1.00	
WilNOVJA	-0.15	-0.19	0.46	0.19	0.06	-0.17	-0.04	0.23	-0.06	-0.01	0.03	0.03	-0.04	0.06	0.02	0.02	0.08	0.14	0.25	0.50	0.34	1.00

Variable shown in Table 8 and Figures 32-34 are the catches expressed as Willamette catch, and flows November through March, with average flows with average flows on the Tualatin River from November to January, and January to March. Numbers indicate lags (for example, ‘6’ represents a 6-year lag). Correlations greater that 0.4 (pink) or -0.4 (light yellow) are highlighted showing some correlations across independent variables, though the main variable of interest in WILCatch and how that relates to each of these variables.

3.1.4.2 Average flow effects (lag 2, 3, 4 and 5)

Lag 2-5 effects were also examined for each of the systems (Willamette, Clackamas, Santiam and Tualatin). These also indicate that there is no strong relationship between flows and overall abundance a number of years later. The only strong relationship appears to be with the Clackamas River flows in February for some years (Table 12). In fact the lag 6-8 years are much stronger than the lag 2-5 years, as is apparent from Tables 9-12. This implies that (if catch were related to abundance), and accounting for fixed ocean effects and equilibrium conditions, the freshwater years closer to ocean outmigration for lamprey have lesser influence than the earlier years. Higher correlations imply that the earlier years in the lamprey freshwater life-cycle are of more importance than the later freshwater years, as was previously thought. However, given we have no age class information this is difficult to ascertain for sure, as each cohort is probably affected independently by particular freshwater and ocean effects, but without knowing what the age structure is, is impossible to examine in this report.

Table 9: Correlation between Willamette River Flow and Willamette Falls Lamprey Count using 2-lag 5 years

Willamette Lag 2-5 Relationships with flow and Abundance

	log(WILCa	*llag2N*	*llag3N*	*llag4N*	*llag5N*	*llag2D*	*llag3D*	*llag4D*	*llag5D*	*llag2J*	*llag3J*	*llag4J*	*llag5J*	*llag2F*	*llag3F*	*llag4F*	*llag5F*	*llag2M*	*llag3M*	*llag4M*	*llag5M*	*OVJAN.*	*OVJAN.*	*OVJAN.*	*OVJAN.*	*JANMA*	*JANMA*	*JANMA*	*JANMA*
log(WILCatch	1.00																												
Willag2Nov	-0.06	1.00																											
Willag3Nov	-0.14	-0.22	1.00																										
Willag4Nov	-0.16	0.14	-0.17	1.00																									
Willag5Nov	-0.06	-0.33	0.16	-0.13	1.00																								
Willag2Dec	-0.09	0.49	-0.19	-0.09	-0.26	1.00																							
Willag3Dec	-0.17	-0.01	0.50	-0.15	-0.07	-0.12	1.00																						
Willag4Dec	-0.08	0.09	0.02	0.52	-0.12	0.00	-0.09	1.00																					
Willag5Dec	-0.15	0.08	0.10	0.07	0.53	0.03	0.01	-0.05	1.00																				
Willag2Jan	-0.13	0.03	0.11	0.15	-0.12	0.09	0.13	-0.04	-0.11	1.00																			
Willag3Jan	-0.19	0.13	0.04	0.14	0.16	0.06	0.11	0.15	-0.02	-0.10	1.00																		
Willag4Jan	-0.28	-0.07	0.16	0.08	0.17	-0.26	0.08	0.12	0.19	0.08	-0.07	1.00																	
Willag5Jan	-0.23	0.02	-0.04	0.18	0.10	-0.14	-0.24	0.10	0.14	-0.04	0.10	-0.05	1.00																
Willag2Feb	0.01	0.14	0.02	0.33	-0.09	0.21	-0.10	0.19	0.08	0.20	-0.26	0.07	-0.03	1.00															
Willag3Feb	-0.11	-0.10	0.17	0.09	0.34	0.00	0.23	-0.05	0.20	0.03	0.22	-0.19	0.11	0.14	1.00														
Willag4Feb	-0.11	-0.30	-0.11	0.13	0.08	-0.27	-0.01	0.20	-0.05	-0.10	0.01	0.19	-0.21	0.19	0.12	1.00													
Willag5Feb	-0.09	-0.01	-0.31	-0.10	0.12	0.07	-0.27	0.00	0.18	0.03	-0.10	0.02	0.19	0.14	0.18	0.13	1.00												
Willag2Mar	0.03	0.19	-0.21	0.07	0.16	0.09	-0.08	-0.04	0.03	0.09	0.03	0.11	-0.01	0.36	0.18	0.11	0.25	1.00											
Willag3Mar	-0.08	-0.07	0.21	-0.13	0.10	-0.07	0.11	-0.02	-0.02	-0.07	0.12	0.08	0.14	0.18	0.39	0.16	0.10	0.22	1.00										
Willag4Mar	-0.21	-0.10	-0.08	0.18	-0.14	-0.18	-0.08	0.09	-0.03	-0.10	-0.08	0.10	0.06	0.03	0.16	0.39	0.16	-0.08	0.20	1.00									
Willag5Mar	-0.14	-0.23	-0.11	-0.09	0.17	-0.02	-0.19	-0.09	0.07	0.00	-0.11	-0.09	0.09	0.12	0.01	0.17	0.39	-0.03	-0.10	0.21	1.00								
WilNOVJANJ	-0.14	0.61	-0.12	0.07	-0.32	0.80	0.00	0.00	-0.02	0.61	0.02	-0.13	-0.10	0.28	-0.01	-0.31	0.05	0.16	-0.11	-0.19	-0.08	1.00							
WilNOVJANJ	-0.25	0.00	0.62	-0.07	0.09	-0.09	0.80	0.03	0.02	0.06	0.62	0.06	-0.10	-0.20	0.31	-0.03	-0.31	-0.09	0.19	-0.12	-0.20	-0.02	1.00						
WilNOVJANJ	-0.24	0.06	0.05	0.65	-0.02	-0.17	-0.06	0.80	0.09	0.07	0.09	0.63	0.09	0.25	-0.10	0.26	-0.02	0.06	-0.01	0.16	-0.13	-0.05	0.03	1.00					
WilNOVJANJ	-0.23	-0.04	0.08	0.10	0.65	-0.14	-0.14	-0.01	0.80	-0.12	0.09	0.13	0.65	0.00	0.28	-0.12	0.24	0.06	0.09	-0.03	0.14	-0.16	-0.01	0.09	1.00				
WilJANMAR2	-0.07	0.15	0.00	0.26	-0.05	0.18	0.01	0.04	-0.03	0.75	-0.16	0.13	-0.04	0.69	0.15	0.06	0.18	0.59	0.12	-0.08	0.04	0.57	-0.08	0.17	-0.05	1.00			
WilJANMAR3	-0.20	0.01	0.18	0.08	0.28	0.01	0.21	0.06	0.06	-0.07	0.76	-0.10	0.16	-0.03	0.71	0.12	0.05	0.18	0.61	0.09	-0.10	-0.03	0.59	0.01	0.21	0.01	1.00		
WilJANMAR4	-0.30	-0.21	0.02	0.17	0.09	-0.35	0.02	0.20	0.09	-0.03	-0.07	0.75	-0.10	0.14	-0.01	0.70	0.13	0.08	0.19	0.61	0.10	-0.29	-0.02	0.57	0.02	0.08	0.02	1.00	
WilJANMAR5	-0.24	-0.08	-0.20	0.04	0.18	-0.07	-0.34	0.03	0.20	-0.01	-0.02	-0.05	0.75	0.09	0.15	-0.01	0.70	0.09	0.09	0.19	0.60	-0.07	-0.27	0.00	0.57	0.06	0.09	0.03	1.00

Note, all variable names in Table 9 are the same as in previous figures and tables except that the lags are now 2, 3 4 and 5 rather than 6, 7 and 8. These relationships are with WilC, i.e. catches and November through March flows in 2-5 year lags. These relationships are for the mainstem Willamette gauge.

Table 10: Correlation between Tualatin River Flow and Willamette Falls Lamprey Count

Tulatin Lag 2-5 Relationships with flow and Abundance

	ln(WILC	Lag2N	Lag2D	Lag2J	Lag2F	Lag2M	OVJAN.	JANMA	Lag3N	Lag3D	Lag3J	Lag3F	Lag3M	OVJAN.	JANMA	Lag4N	Lag4D	Lag4J	Lag4F	Lag4M	OVJAN.	JANMA	Lag5N	Lag5D	Lag5J	Lag5F	Lag5M	OVJAN.	JANMA
ln(WILC)	1.00																												
WilLag2Nov	0.11	1.00																											
WilLag2Dec	0.03	0.60	1.00																										
WilLag2Jan	0.07	0.36	0.61	1.00																									
WilLag2Feb	0.26	0.36	0.58	0.44	1.00																								
WilLag2Mar	-0.13	0.21	0.33	0.56	0.38	1.00																							
WilNOVJANJ	0.07	0.69	0.91	0.86	0.57	0.47	1.00																						
WilJANMAR2	0.11	0.40	0.66	0.85	0.78	0.76	0.82	1.00																					
WilLag3Nov	-0.07	-0.02	-0.11	0.02	0.12	-0.12	-0.05	0.02	1.00																				
WilLag3Dec	-0.15	0.11	0.06	0.14	0.07	0.11	0.12	0.13	0.57	1.00																			
WilLag3Jan	-0.18	-0.07	0.13	0.22	0.11	0.21	0.15	0.22	0.34	0.56	1.00																		
WilLag3Feb	0.11	0.17	0.30	0.28	0.15	0.16	0.32	0.26	0.33	0.56	0.39	1.00																	
WilLag3Mar	-0.28	0.01	0.08	-0.01	-0.02	0.02	0.03	-0.01	0.19	0.26	0.55	0.33	1.00																
WilNOVJANJ	-0.17	0.01	0.07	0.18	0.11	0.12	0.12	0.18	0.68	0.89	0.84	0.54	0.44	1.00															
WilJANMAR3	-0.13	0.04	0.22	0.24	0.12	0.18	0.23	0.22	0.38	0.62	0.84	0.76	0.74	0.80	1.00														
WilLag4Nov	-0.19	-0.03	-0.11	0.10	-0.10	0.25	-0.01	0.08	-0.01	-0.11	0.05	0.12	-0.09	-0.03	0.05	1.00													
WilLag4Dec	-0.27	0.24	0.09	0.20	0.01	0.27	0.19	0.18	0.13	0.06	0.17	0.08	0.15	0.14	0.17	0.58	1.00												
WilLag4Jan	-0.15	0.21	0.15	0.32	-0.10	0.34	0.28	0.22	-0.07	0.11	0.22	0.10	0.21	0.15	0.22	0.35	0.57	1.00											
WilLag4Feb	-0.05	0.09	-0.14	-0.03	-0.27	-0.06	-0.06	-0.16	0.17	0.26	0.29	0.13	0.17	0.31	0.26	0.35	0.57	0.39	1.00										
WilLag4Mar	-0.27	0.41	0.15	0.01	-0.20	-0.06	0.17	-0.11	0.03	0.05	0.02	-0.03	0.06	0.04	0.02	0.22	0.28	0.54	0.36	1.00									
WilNOVJANJ	-0.24	0.21	0.09	0.28	-0.07	0.35	0.22	0.21	0.02	0.06	0.20	0.11	0.15	0.13	0.20	0.69	0.89	0.84	0.55	0.45	1.00								
WilJANMAR4	-0.18	0.28	0.06	0.15	-0.24	0.12	0.16	0.00	0.05	0.19	0.25	0.10	0.20	0.22	0.23	0.40	0.63	0.84	0.76	0.75	0.80	1.00							
WilLag5Nov	-0.15	-0.22	-0.29	-0.26	-0.21	-0.02	-0.31	-0.23	0.02	-0.09	0.17	-0.07	0.33	0.04	0.16	0.01	-0.09	0.06	0.16	-0.04	-0.01	0.09	1.00						
WilLag5Dec	-0.20	0.11	-0.02	-0.14	-0.02	0.10	-0.05	-0.05	0.29	0.12	0.30	0.06	0.36	0.28	0.29	0.15	0.07	0.19	0.12	0.18	0.16	0.21	0.57	1.00					
WilLag5Jan	-0.25	-0.01	0.07	-0.06	-0.01	-0.07	0.00	-0.05	0.25	0.18	0.41	-0.06	0.43	0.35	0.31	-0.06	0.13	0.24	0.14	0.24	0.16	0.26	0.35	0.56	1.00				
WilLag5Feb	0.07	0.14	0.08	0.06	0.11	0.14	0.10	0.12	0.16	-0.03	0.08	-0.18	0.03	0.07	-0.03	0.15	0.25	0.34	0.16	0.16	0.32	0.29	0.27	0.50	0.32	1.00			
WilLag5Mar	-0.30	0.07	-0.01	0.11	0.00	-0.04	0.07	0.04	0.49	0.24	0.10	-0.13	0.01	0.28	-0.01	0.01	0.03	0.03	-0.01	0.06	0.03	0.03	0.16	0.22	0.50	0.25	1.00		
WilNOVJANJ	-0.25	-0.01	-0.04	-0.16	-0.07	0.01	-0.10	-0.10	0.27	0.13	0.39	-0.02	0.46	0.31	0.33	0.04	0.07	0.23	0.16	0.20	0.16	0.25	0.69	0.89	0.84	0.46	0.39	1.00	
WilJANMAR5	-0.20	0.09	0.07	0.03	0.05	0.01	0.07	0.04	0.37	0.16	0.29	-0.16	0.24	0.31	0.14	0.04	0.19	0.29	0.14	0.22	0.24	0.28	0.36	0.59	0.84	0.70	0.72	0.78	1.00

Relationships in Table 10 are with WilC, i.e. catches and November through March flows in 2-5year lags. These relationships are for the Tualatin gauge.

Table 11: Correlation between Santiam River Flow and Willamette Falls Lamprey Count

Santiam Lag 2-5 Relationships with flow and Abundance

	ln(WILC	WilLag2N	WilLag2D	WilLag2J	WilLag2F	WilLag2N	WilNOVJAN	WilJANMAR2	WilLag3N	WilLag3D	WilLag3J	WilLag3F	WilLag3N	WilNOVJAN	WilJANMAR3	WilLag4N	WilLag4D	WilLag4J	WilLag4F	WilLa4Mar	WilNOVJAN	WilJANMAR4	WilLag5N	WilLag5D	WilLag5J	WilLag5F	WilLa5Mar	WilNOVJAN	WilJANMAR5
ln(WILC)	1.00																												
WilLag2Nov	0.06	1.00																											
WilLag2Dec	0.08	0.41	1.00																										
WilLag2Jan	0.12	0.25	0.55	1.00																									
WilLag2Feb	0.21	0.31	0.43	0.44	1.00																								
WilLag2Mar	-0.03	0.28	0.13	0.36	0.26	1.00																							
WilNOVJANJ	0.11	0.66	0.88	0.78	0.51	0.31	1.00																						
WilJANMAR2	0.15	0.37	0.52	0.83	0.78	0.65	0.73	1.00																					
WilLag3Nov	-0.07	-0.19	-0.12	-0.05	0.09	0.01	-0.15	0.02	1.00																				
WilLag3Dec	-0.12	-0.19	-0.17	-0.02	-0.05	0.19	-0.16	0.03	0.42	1.00																			
WilLag3Jan	-0.06	-0.08	0.05	0.30	-0.07	0.24	0.12	0.20	0.23	0.53	1.00																		
WilLag3Feb	0.01	0.10	0.18	0.35	0.18	0.25	0.27	0.34	0.23	0.34	0.38	1.00																	
WilLag3Mar	-0.16	-0.13	-0.11	0.03	-0.29	-0.13	-0.09	-0.16	0.23	0.08	0.31	0.24	1.00																
WilNOVJANJ	-0.11	-0.20	-0.11	0.08	-0.02	0.20	-0.09	0.10	0.66	0.89	0.76	0.41	0.24	1.00															
WilJANMAR3	-0.08	-0.04	0.07	0.33	-0.05	0.19	0.16	0.21	0.31	0.46	0.80	0.76	0.63	0.67	1.00														
WilLag4Nov	-0.20	0.16	-0.01	0.22	-0.30	-0.05	0.14	-0.05	-0.14	-0.07	-0.03	0.07	0.00	-0.09	0.02	1.00													
WilLag4Dec	-0.22	0.14	0.09	0.27	-0.19	-0.15	0.21	-0.01	-0.12	-0.09	0.03	-0.06	0.20	-0.08	0.06	0.45	1.00												
WilLag4Jan	-0.10	0.13	0.01	0.17	-0.20	-0.05	0.12	-0.02	-0.02	0.10	0.32	-0.11	0.21	0.17	0.18	0.26	0.56	1.00											
WilLag4Feb	-0.06	0.19	0.00	0.18	-0.22	0.17	0.14	0.05	0.13	0.21	0.37	0.17	0.24	0.30	0.36	0.24	0.36	0.39	1.00										
WilLa4Mar	-0.06	0.43	0.12	0.04	-0.04	-0.02	0.23	0.00	-0.11	-0.08	0.04	-0.31	-0.15	-0.06	-0.18	0.24	0.10	0.33	0.25	1.00									
WilNOVJANJ	-0.22	0.18	0.05	0.28	-0.28	-0.12	0.20	-0.03	-0.11	-0.03	0.13	-0.05	0.19	0.00	0.11	0.68	0.89	0.77	0.42	0.26	1.00								
WilJANMAR4	-0.10	0.31	0.05	0.19	-0.22	0.05	0.21	0.01	0.02	0.12	0.35	-0.09	0.17	0.21	0.20	0.33	0.49	0.81	0.76	0.64	0.69	1.00							
WilLag5Nov	-0.03	-0.33	-0.24	-0.21	-0.25	-0.12	-0.32	-0.26	0.09	-0.08	0.20	-0.23	-0.01	0.07	-0.01	-0.18	-0.13	-0.10	0.03	-0.03	-0.17	-0.05	1.00						
WilLag5Dec	-0.01	-0.05	0.02	-0.20	-0.01	-0.11	-0.09	-0.14	0.12	0.07	0.30	-0.14	-0.11	0.20	0.05	-0.15	-0.13	-0.01	-0.08	0.18	-0.12	0.02	0.46	1.00					
WilLag5Jan	-0.10	-0.03	0.02	-0.06	-0.14	-0.07	-0.02	-0.12	0.15	0.03	0.23	-0.15	-0.01	0.16	0.04	-0.03	0.07	0.30	-0.12	0.21	0.14	0.17	0.26	0.55	1.00				
WilLag5Feb	0.12	0.20	-0.08	0.06	-0.08	0.17	0.05	0.06	0.15	-0.04	0.17	-0.19	0.19	0.10	0.06	0.10	0.17	0.31	0.15	0.22	0.24	0.31	0.28	0.38	0.40	1.00			
WilLa5Mar	-0.05	0.04	0.08	0.13	0.17	-0.05	0.11	0.13	0.44	0.14	0.07	-0.03	-0.01	0.25	0.02	-0.10	-0.08	0.05	-0.31	-0.14	-0.06	-0.17	0.22	0.09	0.32	0.24	1.00		
WilNOVJANJ	-0.05	-0.15	-0.07	-0.20	-0.15	-0.13	-0.17	-0.21	0.15	0.02	0.31	-0.21	-0.07	0.19	0.04	-0.15	-0.09	0.08	-0.08	0.16	-0.07	0.06	0.69	0.89	0.76	0.45	0.25	1.00	
WilJANMAR5	-0.01	0.10	0.00	0.05	-0.05	0.03	0.05	0.01	0.30	0.04	0.22	-0.18	0.08	0.22	0.06	0.00	0.09	0.32	-0.10	0.16	0.17	0.17	0.34	0.49	0.81	0.77	0.63	0.69	1.00

Relationships in Table 11 are with WilC, i.e. catches and November through March flows in 2-5year lags. These relationships are for the Santiam gauge.

Table 12: Correlation between Clackamas River Flow and Willamette Falls Lamprey Count

Clackamas Lag 2-5 Relationships with flow and Abundance

	ln(WILC	*ILag2N*	*ILag2D*	*ILag2J*	*ILag2F*	*Lag2N*	*OVJAN.*	*JANMA*	*ILag3N*	*ILag3D*	*ILag3J*	*ILag3F*	*Lag3N*	*OVJAN.*	*JANMA*	*ILag4N*	*ILag4D*	*ILag4J*	*ILag4F*	*Lag4N*	*OVJAN.*	*JANMA*	*ILag5N*	*ILag5D*	*ILag5J*	*ILag5F*	*Lag5N*	*OVJAN.*	*JANMA*
ln(WILC)	1.00																												
WilLag2Nov	-0.10	1.00																											
WilLag2Dec	-0.03	0.60	1.00																										
WilLag2Jan	-0.01	0.21	0.36	1.00																									
WilLag2Feb	-0.33	0.20	0.22	0.41	1.00																								
WilLag2Mar	-0.17	0.19	0.27	0.39	0.35	1.00																							
WilNOVJANJ	-0.04	0.63	0.81	0.81	0.39	0.40	1.00																						
WilJANMAR2	-0.20	0.26	0.37	0.82	0.73	0.75	0.72	1.00																					
WilLag3Nov	-0.13	0.61	0.16	-0.01	0.11	0.08	0.20	0.07	1.00																				
WilLag3Dec	-0.13	0.47	0.00	-0.09	-0.04	0.03	0.05	-0.05	0.61	1.00																			
WilLag3Jan	-0.13	0.28	0.05	-0.03	0.00	0.02	0.07	-0.01	0.29	0.39	1.00																		
WilLag3Feb	-0.33	0.20	0.12	0.04	0.24	-0.03	0.13	0.10	0.22	0.22	0.43	1.00																	
WilLag3Mar	-0.18	0.42	0.36	0.15	0.06	0.26	0.35	0.20	0.23	0.28	0.40	0.37	1.00																
WilNOVJANJ	-0.16	0.51	0.06	-0.06	0.01	0.04	0.11	-0.01	0.66	0.81	0.83	0.40	0.42	1.00															
WilJANMAR3	-0.26	0.39	0.22	0.06	0.12	0.11	0.23	0.12	0.32	0.39	0.82	0.74	0.76	0.73	1.00														
WilLag4Nov	-0.21	0.57	0.41	0.15	0.20	-0.04	0.41	0.13	0.52	0.13	0.06	0.13	0.12	0.21	0.13	1.00													
WilLag4Dec	-0.12	0.30	0.14	-0.04	0.21	-0.10	0.11	0.02	0.40	-0.02	-0.02	-0.02	0.08	0.06	0.02	0.54	1.00												
WilLag4Jan	-0.05	0.29	0.06	0.12	0.29	-0.11	0.16	0.12	0.29	0.05	-0.01	0.02	0.04	0.08	0.02	0.30	0.40	1.00											
WilLag4Feb	-0.41	0.24	0.18	0.12	0.34	-0.01	0.21	0.19	0.20	0.13	0.08	0.26	0.01	0.15	0.14	0.22	0.24	0.44	1.00										
WilLag4Mar	-0.03	0.35	0.12	0.14	-0.02	-0.11	0.22	0.01	0.44	0.35	0.13	0.04	0.23	0.33	0.18	0.24	0.27	0.39	0.34	1.00									
WilNOVJANJ	-0.12	0.42	0.18	0.08	0.31	-0.12	0.23	0.11	0.45	0.05	0.00	0.02	0.08	0.12	0.04	0.62	0.80	0.86	0.42	0.40	1.00								
WilJANMAR4	-0.19	0.38	0.15	0.16	0.27	-0.10	0.25	0.14	0.41	0.22	0.08	0.13	0.12	0.23	0.14	0.34	0.40	0.82	0.74	0.74	0.75	1.00							
WilLag5Nov	-0.26	0.38	0.02	-0.15	0.03	-0.02	0.00	-0.07	0.50	0.40	0.22	0.21	-0.02	0.42	0.18	0.41	0.02	0.05	0.12	0.12	0.12	0.12	1.00						
WilLag5Dec	-0.02	0.16	-0.08	-0.14	-0.02	-0.12	-0.08	-0.13	0.36	0.16	-0.03	0.22	-0.08	0.13	0.04	0.50	0.03	0.00	0.01	0.06	0.11	0.03	0.62	1.00					
WilLag5Jan	-0.10	0.19	0.07	-0.05	-0.20	-0.17	0.04	-0.17	0.29	0.06	0.14	0.30	-0.09	0.17	0.14	0.30	0.05	0.00	0.03	0.03	0.08	0.02	0.31	0.42	1.00				
WilLag5Feb	-0.42	0.19	0.04	0.04	0.09	-0.24	0.08	-0.05	0.29	0.20	0.14	0.36	0.02	0.23	0.21	0.25	0.17	0.10	0.29	-0.01	0.18	0.15	0.26	0.26	0.45	1.00			
WilLag5Mar	-0.11	0.27	0.29	-0.10	-0.10	-0.15	0.13	-0.15	0.39	0.13	0.15	0.00	-0.09	0.23	0.03	0.52	0.39	0.15	0.06	0.22	0.36	0.19	0.28	0.28	0.40	0.35	1.00		
WilNOVJANJ	-0.11	0.26	0.01	-0.12	-0.12	-0.16	-0.01	-0.17	0.43	0.18	0.11	0.32	-0.09	0.24	0.14	0.48	0.05	0.01	0.04	0.07	0.12	0.05	0.64	0.81	0.86	0.44	0.42	1.00	
WilJANMAR5	-0.25	0.28	0.17	-0.05	-0.10	-0.23	0.11	-0.16	0.42	0.16	0.18	0.28	-0.08	0.27	0.16	0.46	0.26	0.10	0.15	0.10	0.26	0.15	0.37	0.42	0.82	0.75	0.75	0.76	1.00

Relationships in Table 12 are with WilC, i.e. catches and November through March flows in 2-5year lags. These relationships are for the Clackamas gauge.

3.1.5 Effects of Ocean Conditions on Willamette Catch Levels

Time series analysis indicates that the abundances are related to a lag one ARIMA model. Hence, conditions in the ocean for the year prior to the return were examined to see if this had any relationship with overall abundance. Simple correlational analysis was pursued as a first step to assess how the ocean variables may be affecting lamprey abundance.

Different correlational analysis was looked at with a one year lag (time series models indicated a one year lag using abundance data). SST from April through July were examined as they normally indicate a good upwelling condition (Bakun 1996) and food availability which coincides with higher than average survival for species on the west coast (e.g. salmon from Sharma, et al. 2013, and sardine, Bakun 1996). In addition, the upwelling index was used as direct measures for those months, as well as indicators of sea level pressure and long term oscillations in Pacific Ocean surface temperatures that drive regional climate (i.e. the El Nino Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO)).

Based on this analysis, only a few relationships appear to be biologically meaningful; the PDO conditions in May and June, and the negative relationship with abundance a year later, as well as the SST conditions in May. The other relationships are not biologically meaningful as positive upwelling and high Sea Level pressure should correspond to a larger abundance and not lower abundance as shown in Tables 13 & 14.

Table 13: Correlation Matrix of Sea Surface Temperature near the mouth of the Columbia River (from the previous year and months (Apr-Jul)) and Willamette Falls Lamprey Abundance

	SST1A	*SST2A*	*SSt3A*	*SST4A*	*SST1M*	*SST2M*	*SSt3M*	*SST4M*	*SST1J*	*SST2J*	*SSt3J*	*SST4J*	*SST1JU*	*SST2JU*	*SSt3JU*	*SST4JU*	*WILCatch*	*g(WILCatc*
SST1A	1.00																	
SST2A	0.99	1.00																
SSt3A	0.95	0.98	1.00															
SST4A	0.83	0.88	0.95	1.00														
SST1M	0.26	0.28	0.29	0.29	1.00													
SST2M	0.26	0.29	0.30	0.31	0.99	1.00												
SSt3M	0.27	0.30	0.33	0.34	0.95	0.98	1.00											
SST4M	0.30	0.33	0.36	0.41	0.85	0.91	0.96	1.00										
SST1J	0.21	0.23	0.25	0.27	0.70	0.70	0.69	0.67	1.00									
SST2J	0.24	0.26	0.29	0.31	0.68	0.68	0.70	0.69	0.99	1.00								
SSt3J	0.28	0.31	0.34	0.39	0.66	0.68	0.71	0.72	0.95	0.98	1.00							
SST4J	0.32	0.36	0.41	0.49	0.61	0.63	0.69	0.74	0.86	0.91	0.96	1.00						
SST1JU	0.22	0.24	0.26	0.29	0.50	0.51	0.52	0.52	0.64	0.65	0.65	0.61	1.00					
SST2JU	0.22	0.24	0.27	0.32	0.51	0.52	0.55	0.56	0.63	0.66	0.68	0.66	0.98	1.00				
SSt3JU	0.24	0.27	0.31	0.38	0.54	0.56	0.59	0.62	0.63	0.67	0.71	0.73	0.94	0.98	1.00			
SST4JU	0.24	0.28	0.34	0.44	0.53	0.55	0.59	0.63	0.57	0.61	0.68	0.75	0.83	0.89	0.95	1.00		
WILCatch	-0.14	-0.14	-0.18	-0.28	-0.06	-0.10	-0.17	-0.30	0.06	0.03	-0.05	-0.19	0.03	-0.02	-0.09	-0.19	1.00	
log(WILCatch)	0.01	0.01	-0.01	-0.10	0.08	0.05	-0.02	-0.14	0.13	0.11	0.07	-0.03	-0.04	-0.04	-0.05	-0.09	0.84	1.00

In Table 13, four Sea Surface Temperature (SST) stations near the Columbia were examined (see methods), with readings in April (A), May (M), June (J) and July (JU). These were all lag one relationships with Willamette Catch (WILCatch) numbers in subsequent years. As in previous tables only correlations greater than 0.4 or -0.4 are highlighted.

Table 14: Correlation matrix of Upwelling, UPI from the previous year and months (April through July, A, M, J, JU) and Willamette Abundance from stations (3 stations are from 42.5, 45 and 47.5 ºN. All stations are 125 ºW)

	UPIA1	*UPIA2*	*UPIA3*	*UPI1M*	*UPI2M*	*UPI3M*	*UPI1J*	*UPI2J*	*UPI3J*	*UPI1JU*	*UPI2JU*	*UPI3JU*	*WILCatch*	*log(WILCatch)*
UPIA1	1.00													
UPIA2	0.77	1.00												
UPIA3	0.60	0.86	1.00											
UPI1M	0.28	0.20	0.15	1.00										
UPI2M	0.03	0.09	0.08	0.83	1.00									
UPI3M	-0.02	0.12	0.19	0.61	0.84	1.00								
UPI1J	0.33	0.18	0.10	0.26	-0.03	-0.15	1.00							
UPI2J	0.14	0.20	0.12	0.18	0.06	0.00	0.72	1.00						
UPI3J	0.04	0.17	0.23	0.16	0.13	0.26	0.39	0.80	1.00					
UPI1JU	0.18	-0.14	-0.23	0.17	-0.11	-0.24	0.41	0.01	-0.08	1.00				
UPI2JU	0.12	-0.18	-0.32	0.11	-0.02	-0.13	0.16	-0.02	-0.10	0.75	1.00			
UPI3JU	0.12	-0.10	-0.08	-0.01	-0.09	0.00	-0.08	-0.14	0.05	0.51	0.81	1.00		
WILCatch	-0.18	-0.03	-0.14	-0.22	-0.05	-0.19	-0.34	-0.22	-0.31	-0.35	-0.38	-0.53	1.00	
log(WILCa	-0.20	-0.10	-0.24	-0.20	-0.02	-0.17	-0.27	-0.13	-0.25	-0.13	-0.15	-0.40	0.82	1

Table14 shows three upwelling (UPI) stations near the Columbia that were examined (see methods), with readings in April (A), May (M), June (J) and July (JU). These were all lag one relationships with Willamette Catch (WILCatch) numbers in subsequent years. As in previous tables only correlations greater than 0.4 or -0.4 are highlighted.

Table 15: Correlation Matrix of Sea Level Pressure from the Previous Year and Months (Apr-Jul) and Willamette Falls Lamprey Abundance

	SLP1A	*SLP2A*	*SLP3A*	*SLP1M*	*SLP2M*	*SLP3M*	*SLP1J*	*SLP2J*	*SLP3J*	*SLP1JU*	*SLP2JU*	*SLP3JU*	*WILCatch*	*g(WILCatch*
SLP1A	1.00													
SLP2A	0.94	1.00												
SLP3A	0.76	0.93	1.00											
SLP1M	0.12	0.14	0.14	1.00										
SLP2M	0.04	0.05	0.05	0.96	1.00									
SLP3M	-0.03	-0.02	-0.03	0.89	0.98	1.00								
SLP1J	0.16	0.10	0.02	0.13	0.04	-0.05	1.00							
SLP2J	0.21	0.16	0.10	0.11	0.03	-0.06	0.95	1.00						
SLP3J	0.20	0.16	0.11	0.10	0.03	-0.05	0.88	0.97	1.00					
SLP1JU	0.17	0.16	0.14	0.03	-0.10	-0.18	-0.07	-0.14	-0.17	1.00				
SLP2JU	0.22	0.17	0.09	0.01	-0.12	-0.20	-0.07	-0.14	-0.17	0.92	1.00			
SLP3JU	0.25	0.18	0.09	0.04	-0.10	-0.18	-0.02	-0.08	-0.11	0.79	0.95	1.00		
WILCatch	-0.29	-0.18	-0.02	0.09	0.13	0.17	-0.34	-0.31	-0.29	-0.21	-0.15	-0.08	1.00	
log(WILCa	-0.26	-0.19	-0.08	-0.02	0.05	0.10	-0.34	-0.35	-0.35	-0.12	-0.07	-0.04	0.77	1.00

Table 15 shows three Sea Level Pressure locations (SLP) stations near the Columbia that were examined, with readings in April (A), May (M), June (J) and July (JU). These were all lag one relationships with Willamette Catch (WILCatch) numbers in subsequent years. As in previous tables only correlations greater than 0.4 or -0.4 are highlighted.

Table 16: Correlation Matrix of Large Scale Indicators (ENSO and PDO) from the Previous Year and Months (May-Jun) and Willamette Falls Lamprey Abundance

	APRMAY (ENSO)	MAYJUN (ENSO)	APrilMayJuncomp (ENSO)	MAY (PDO)	JUN (PDO)	ay-junecomposite (PD	WILCatch	g(WILCatch
APRMAY (ENSO)	1.00							
MAYJUN (ENSO)	0.91	1.00						
APrilMayJuncomp (ENSO)	0.98	0.98	1.00					
MAY (PDO)	0.63	0.56	0.61	1.00				
JUN (PDO)	0.62	0.57	0.61	0.88	1.00			
May-junecomposite (PDO)	0.65	0.59	0.63	0.97	0.97	1.00		
WILCatch	-0.18	-0.17	-0.18	-0.30	-0.34	-0.33	1.00	
log(WILCatch)	-0.02	-0.01	-0.02	-0.07	-0.10	-0.09	0.77	1.00

Table 16 shows large-scale area (Pacific Ocean based) climate indices including the El Nino Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO). For ENSO, we examined the months of April and May and May and June, and April May and June composite from the previous year and its correlation with Willamette catch. For PDO we examined May, June and May-June composite and its correlation with Willamette Catch.

Relationships (Tables 13-16) were marginally significant, and only one variable, SST in May, and the PDO in May and June, showed a relationship that signified ocean conditions affected abundance, i.e. higher ocean temperatures and positive phases of the PDO in May and June of the year before had a negative effect on abundance (Figure 36). Likelihood profiles were examined for this and other variables that showed promise (Figure 35, namely Tualatin lag 8 February flow, main-stem Willamette Nov-Jan lag 8 flows, Clackamas February lag 7 flows, and Santiam Lag 8 January) in terms of relationship to abundance.

3.1.6 Likelihood Profile Analysis on the Main Variables

Freshwater Effects

Abundance changes were modelled as a function of absolute increase in flows (cfs) in certain months (February for the Tualatin and Clackamas Rivers, January for the Santiam River and November-January average for the mainstem Willamette River) at various river gauges and related to Willamette Falls estimates (assuming catches are representative of abundance). It appears that with an increase of 1000 cfs, a decline in abundance is predicted on each system, with a corresponding reduction of between 10 and 20 thousand lamprey from current conditions observed at Willamette falls. The magnitude is lesser (around 5000 fish) for the Santiam and mainstem Willamette, but this is largely a function of the size of the river. Hence a 1000 cfs increase in the streamflow of the Santiam or mainstem is about a 5% increase in flow in those rivers for the winter months versus a 1000 cfs increase in the Tualatin or Clackamas rivers would indicate a 30-40% increase in flows to those basins in the winter months. The possible biological mechanism is the washing out of ammocoetes due to large winter flow events that could decrease the juvenile stage survivals, and thereby abundance of the overall cohort. However, without any age structure information on the adults, actual yearly mechanisms could only be conjectured at this point.

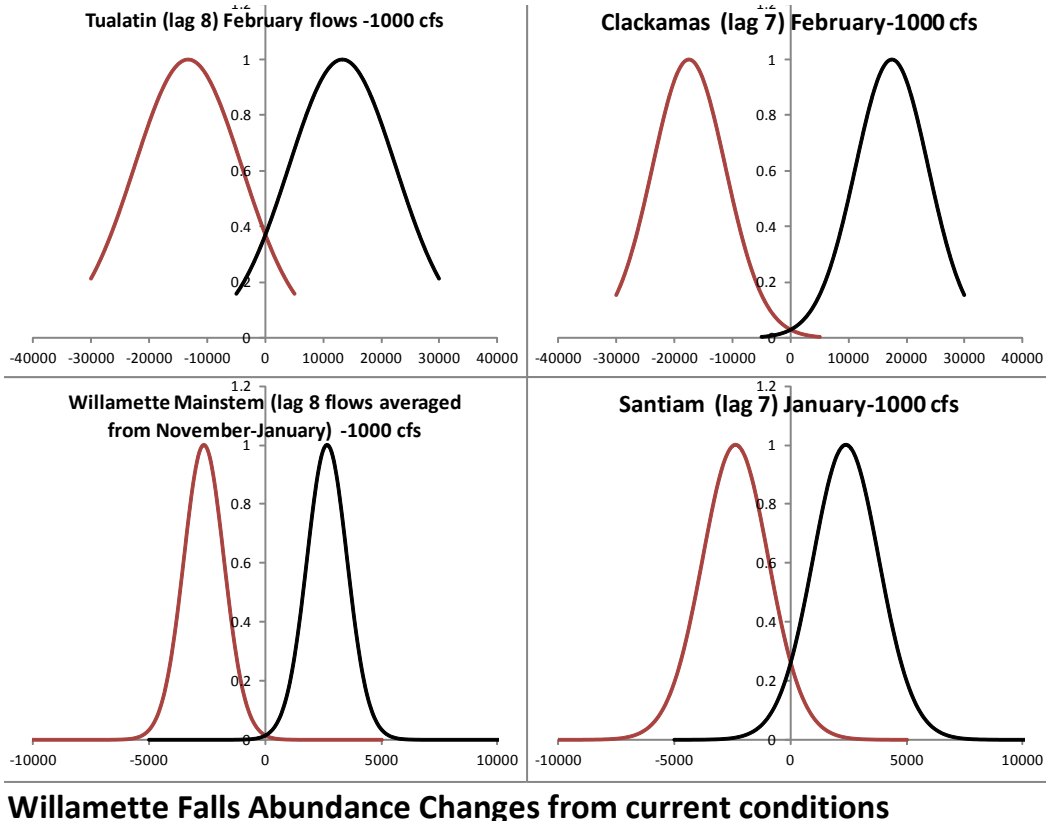

Figure 35: Hypothesized Effects on Willamette Falls Lamprey Abundance for 1000 CFS Increase or Decrease in Flows from Historic Conditions during Fall and Winter Months

Marine Effects

Colder water and wetter conditions in the oceans indicate a better survival, corresponding to an increase in abundance for the Willamette runs. A 1 degree change in SST in May and PDO conditions in May and June of the previous year (lag 1) indicate an increase in abundance on Willamette Falls by 25000 (in case of SST 1 degree change), or by 2000-4000 in case of a 0.2 change in PDO (an average increase in the NE Pacific) in May or June. These results are consistent with what is known about the life history of the species and how resilient they may be to changes in climate conditions. Actual projected changes to stream flows over the next 50 years could be used to understand these effects, though the general shape of these distributions will remain the same (however the mean effect would change as a function of the independent variable/predictor used).

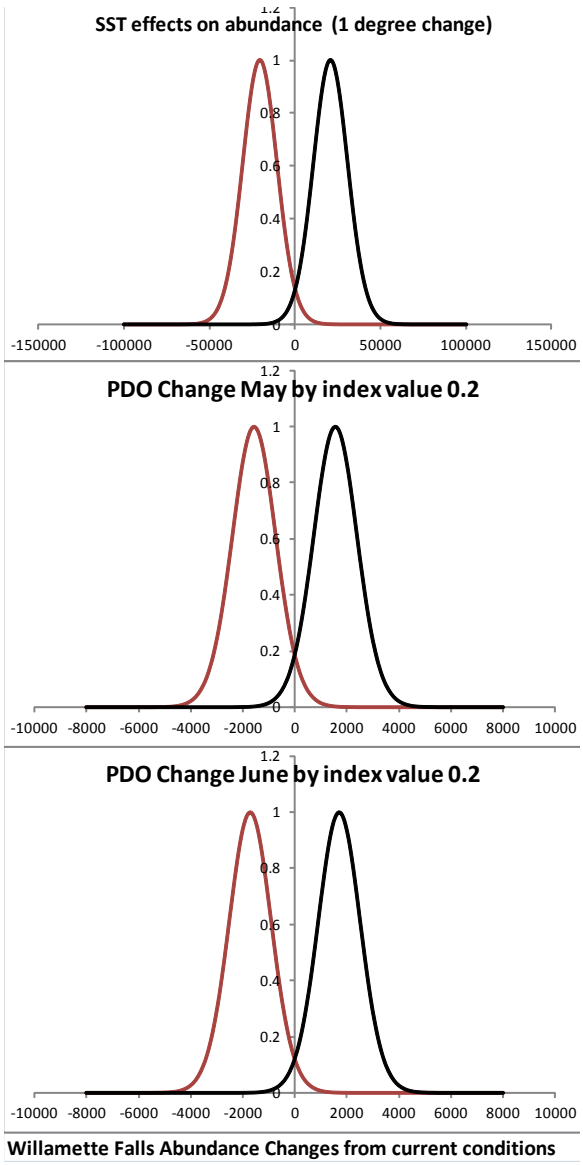

Figure 36: Hypothesized Effect on Willamette Falls Abundance from Ocean Condition Changes (SST, PDO) in the Year before Lamprey Adult Return

3.1.7 A Hypothetical Model of Climate Change Effects on Lamprey

Due to limitations in available data on lamprey, this aspect is currently not fully developed, though the methods and approaches have been outlined in the previous sections. A life-cycle model is presented in Appendix A, showing hypothetical results for lamprey survival and abundance in the Clackamas River.

3.1.8 Freshwater Climate Change Scenarios Results

The flow and temperature metrics presented in section 2.2.6 were analysed between the historic and 2040s climate change scenario for all streams with hypothetical lamprey distribution. The 2080s (2070-2099) scenario was not used for this analysis, both for simplicity and because the projections of this scenario are less certain due to unknown changes to greenhouse gas emissions that will occur during the

21st century. It is noteworthy, however, that the flow and temperature metrics we examined were progressively worse for coldwater fish under the 2080s scenario, meaning that relative changes to lamprey habitat will almost certainly be more severe by the latter 21st century under a "business as usual" A1B climate change emission scenario. Many tributaries that may hold suitable habitat for lamprey until mid-century may become uninhabitable by the end of the century solely because of climate-induced environmental change. For example, the mean August temperature of only 11.1% of stream segments are projected to increase by 1.8°C or more (from the historic period) in the 2040s scenario, but 99.9% of all stream segments are projected to increase over this threshold in the 2080s scenario. In the 2040s scenario, 14.6% of the hydrologic units are projected to experience decreases in late spring/early summer flow of 30% or greater (from the historical period), but in the 2080s scenario, 15.6% of the hydrologic units are projected to have decreases of 50% or greater. In the 2040s scenario, only 5.2% of hydrologic units are projected to have increases to winter flow of 75% or greater (from the historic period), but by the 2080s scenario, 21.9% of hydrologic units are projected to have increases of this magnitude.

Relative changes to the flow and temperature metrics were classified into ranks for the 2040s climate change scenario, as reported in Table 17. 37 of 96 (38.5%) hydrologic units projected flow increases during the winter months of greater than 25% from the historic period, and none showed flow decreases during this period. 58 of 96 (60.4%) hydrologic units projected flow decreases during late spring/summer months greater than 10% from the historic period, with only two showing a (slight) increase in flows. 61.1% of stream segments showed increases in August mean water temperature above 1.4°C from the historic period, and none showed increases lower than 0.9°C. Classifications were designed to group only the largest changes in the top rank (4) with an increasingly larger distribution in the lower classes. The summer flow decreases and summer water temperature increases were skewed to rank more units in the higher classes, reflecting the emphasis placed on these factors for lamprey in the literature.

Table 17: Lamprey Climate Change Impact Ranking Metrics (Historic Period to 2040s Scenario)

Metric	Rank 4 (Highest Impact)	Rank 3 (High - Moderate Impact)	Rank 2 (Moderate-Low Impact)	Rank 1 (Lowest Impact)
Winter (Dec-Feb) Flow Increase	> 75%	75 - 50%	50 - 25%	< 25%
Late Spring/Summer Flow Decrease (May-Jul)	> 30%	30 – 20%	20 – 10%	< 10%
Summer Water Temperature Increase (Mean August Value)	> 1.8°C	1.8°C – 1.6°C	1.6°C – 1.4°C	< 1.4°C

Stream segments from the hypothetical lamprey distribution were grouped by climate change impact rank and NatureServe status rank. The results are shown in Tables 18 through 20. The worst winter flow increases were particularly concentrated in areas where lamprey are most impacted already, with 22.5% of all lamprey distribution classified as “possibly extinct” and receiving a winter flow risk ranking of 3 or 4. Summer flow decreases are also concentrated in poorly performing areas, with 30.7% and 29.2% of all lamprey distribution classified respectively as “possibly extinct” or “critically imperilled” and having a summer flow risk ranking of 3 or 4. High summer temperature increase rankings (3 or 4) and “critically imperilled” status composes 19.7% of all distribution, but 16.3% of all distribution is classified as merely “imperilled” and ranked 1 or 2 for temperature increases, perhaps representing a habitat stronghold for lamprey.

Table 18: Total Distance (km) of Hypothetical Lamprey Distribution by Winter Flow Increase and NatureServe Status Ranks

NatureServe Rank	Winter Flow Rank	Km (%)
S1 - Critically Imperilled	1	1533 (10.7%)
S1 - Critically Imperilled	2	2134 (14.9%)
S1 - Critically Imperilled	3	1318 (9.2%)
S1 - Critically Imperilled	4	1124 (7.9%)
S1 - S2	1	550 (3.9%)
S2 – Imperilled	1	2174 (15.2%)
S2 – Imperilled	2	325 (2.3%)
SH - Possibly Extinct	1	266 (1.9%)
SH - Possibly Extinct	2	1641 (11.5%)
SH - Possibly Extinct	3	1172 (8.2%)
SH - Possibly Extinct	4	2046 (14.3%)

Table 19: Total Distance (km) of Hypothetical Lamprey Distribution by Late Spring/Summer Flow Decrease and NatureServe Status Ranks

NatureServe Rank	Sp/Sum Flow Rank	Km (%)
S1 - Critically Imperilled	1	1295 (9.1%)
S1 - Critically Imperilled	2	638 (4.5%)
S1 - Critically Imperilled	3	2490 (17.4%)
S1 - Critically Imperilled	4	1687 (11.8%)
S1 - S2	1	306 (2.1%)
S1 - S2	2	3 (<0.0%)
S1 - S2	3	240 (1.7%)
S1 - S2	4	1 (<0.0%)
S2 – Imperilled	1	1055 (7.4%)
S2 – Imperilled	2	305 (2.1%)

NatureServe Rank	Sp/Sum Flow Rank	Km (%)
S2 – Imperilled	3	628 (4.4%
S2 – Imperilled	4	511 (3.6%)
SH - Possibly Extinct	1	72 (0.1%)
SH - Possibly Extinct	2	662 (4.6%)
SH - Possibly Extinct	3	3216 (22.5%)
SH - Possibly Extinct	4	1176 (8.2%)

Table 20: Total Distance (km) of Hypothetical Lamprey Distribution by Summer Temperature Increase and NatureServe Status Ranks

NatureServe Rank	Summer Temp_Rank	Km (%)
S1 - Critically Imperilled	1	1242 (8.7%)
S1 - Critically Imperilled	2	2059 (14.4%)
S1 - Critically Imperilled	3	1559 (10.9%)
S1 - Critically Imperilled	4	1250 (8.8%)
S1 - S2	1	18 (0.1%)
S1 - S2	2	530 (3.7%)
S1 - S2	3	3 (>0.0%)
S2 – Imperilled	1	880 (6.2%)
S2 – Imperilled	2	1444 (10.1%)
S2 – Imperilled	3	175 (1.2%)
SH - Possibly Extinct	1	3731 (26.1%)
SH - Possibly Extinct	2	810 (5.7%
SH - Possibly Extinct	3	350 (2.5%)
SH - Possibly Extinct	4	233 (1.6%)

Figures 37 through 39 present maps of each climate change impact rank juxtaposed over the NatureServe status ranks. The worst increases to winter flow under future climate change scenarios are in hydrologic units with already poor lamprey status rankings including the Upper Salmon and Lochsa basins of Central Idaho and the Wenatchee basin. The least increases to winter flow are in hydrologic units with better status rankings including the Willamette, Lower Columbia, and Umatilla basins. The summer flow decrease rankings follow a similar geographic distribution as the winter increase rankings, although most of the other central Idaho fares poorly as do some snow-transitional basins of the Willamette and Lower Columbia (Clackamas, Middle Fork Willamette, Lewis, and Fifteenmile). The worst summer temperature increase rankings are found in the Yakima, Wenatchee, Okanogan, and Clearwater basins, while the Willamette, Lower Columbia, Deschutes, John Day, Umatilla, and Salmon basins fare relatively well. When considering these effects it should be noted that they do not portray existing

water flow or temperature conditions, but simply relative changes to these parameters in conjunction with existing lamprey status.

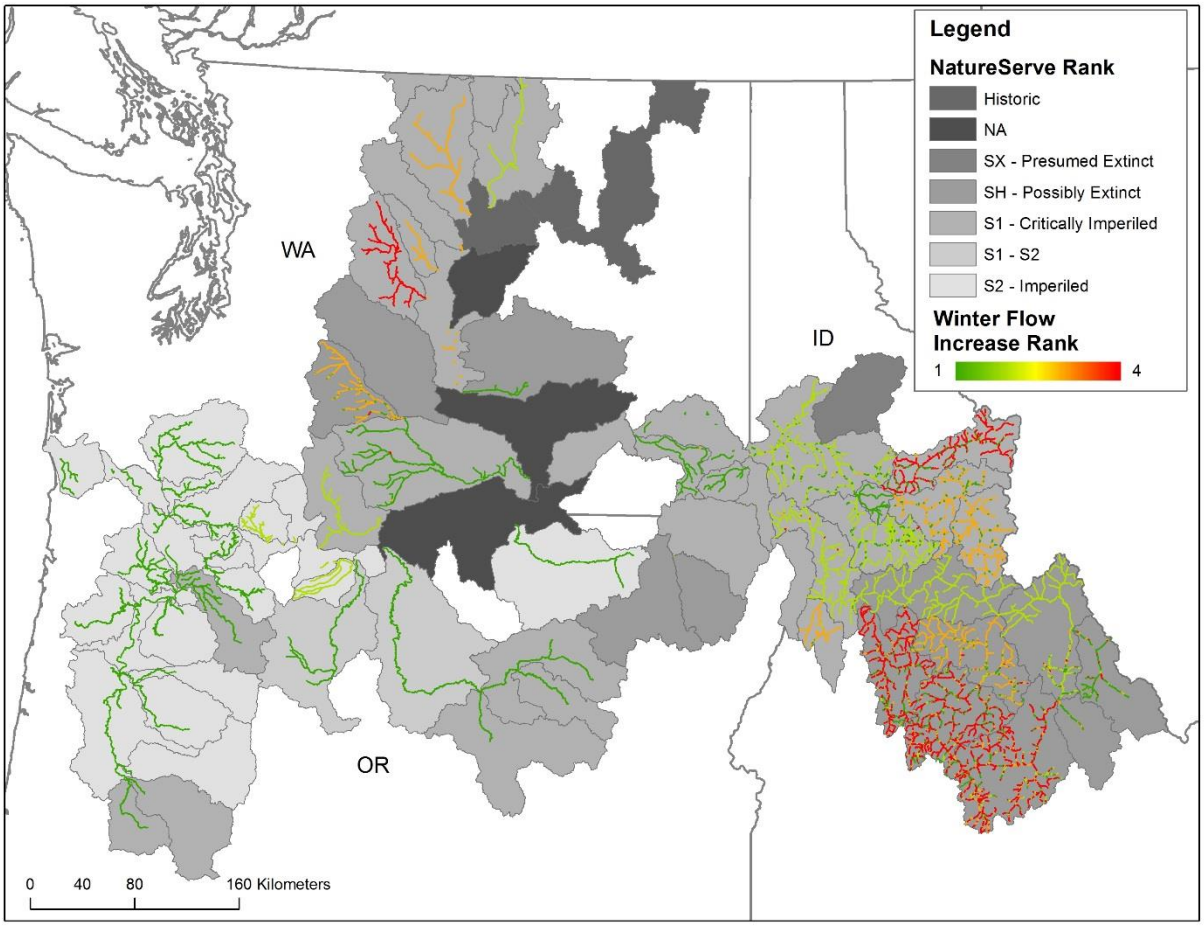

Figure 37: Map of Winter Flow Increase Impact Ranks on Hypothetical Lamprey Distribution

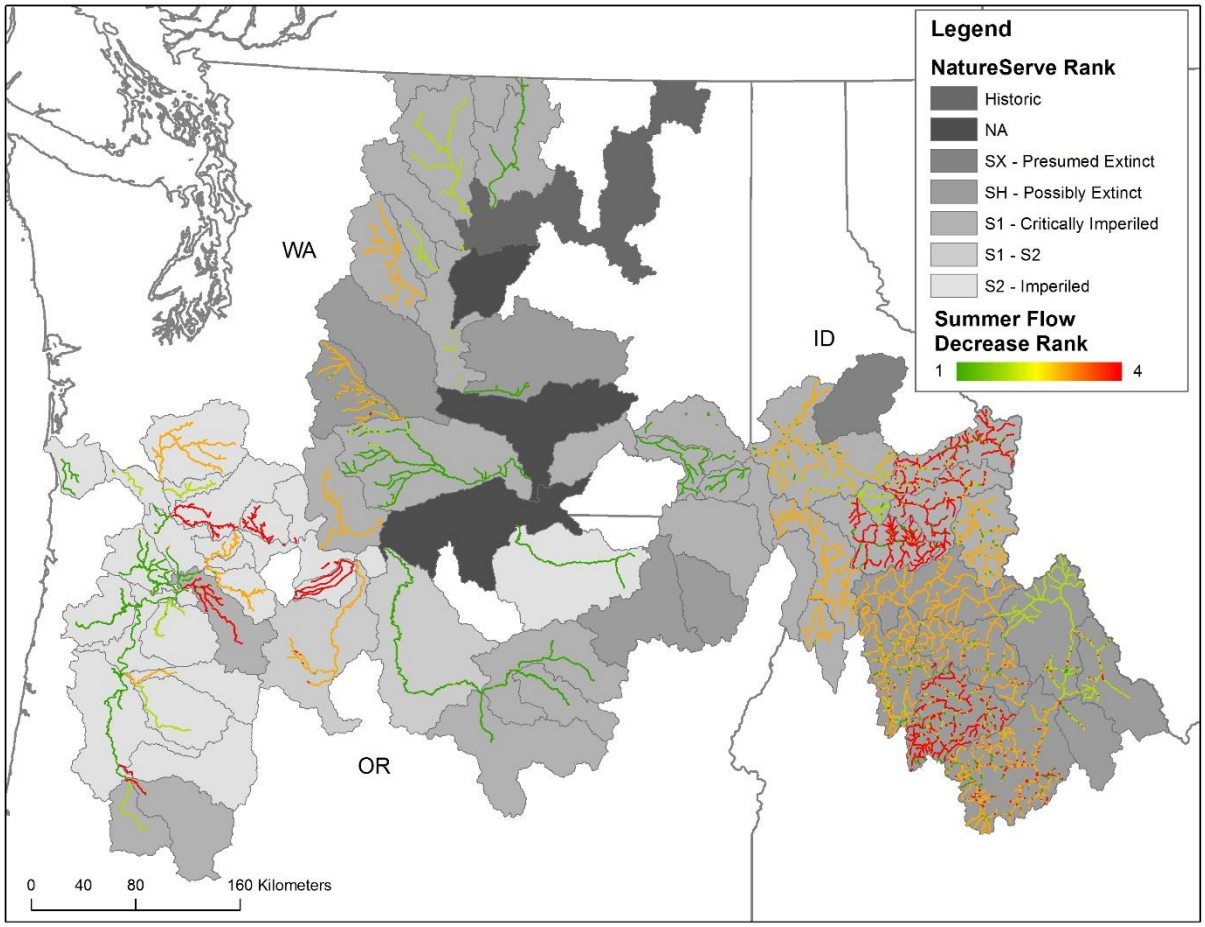

Figure 38: Map of Summer Flow Decrease Impact Ranks on Hypothetical Lamprey Distribution

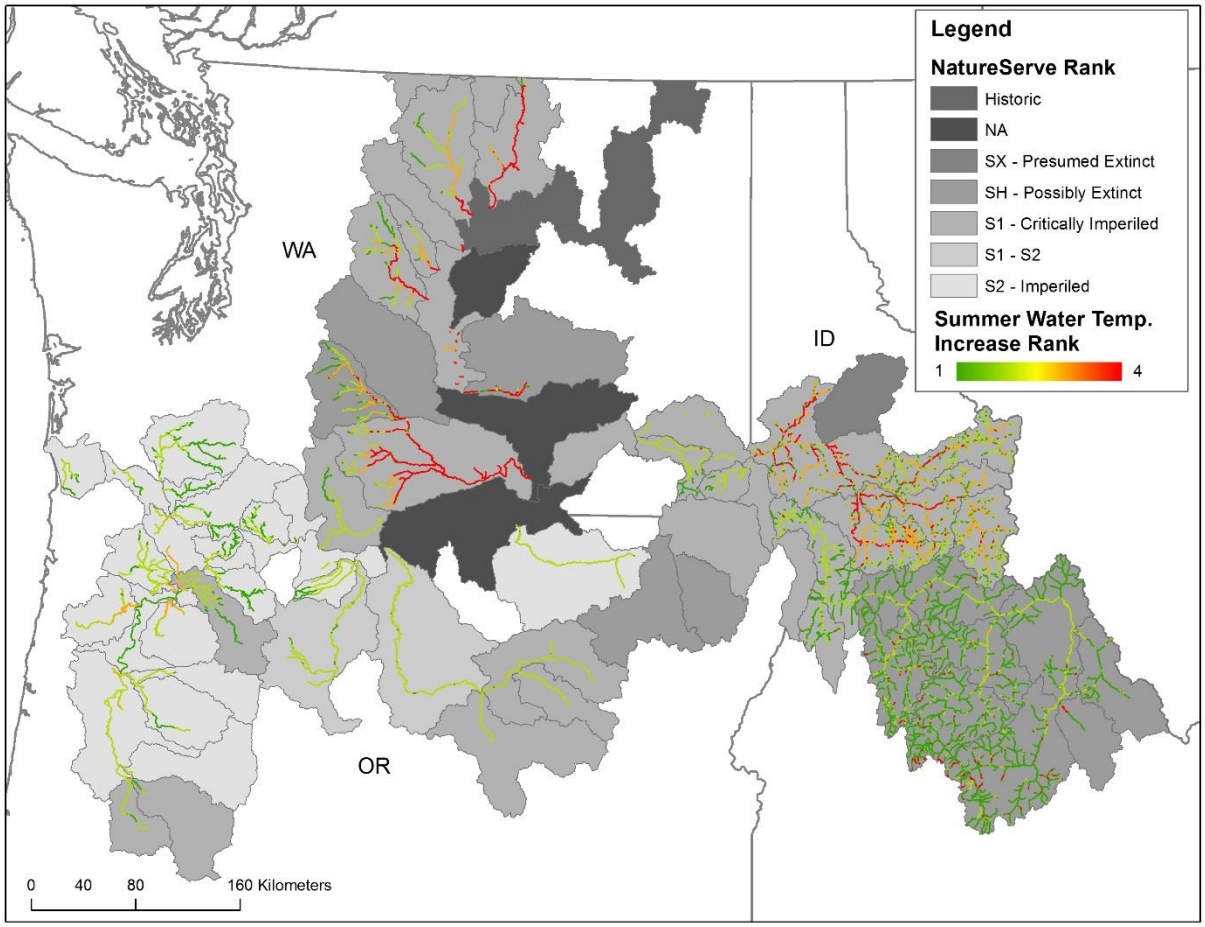

Figure 39: Map of Summer Water Temperature Increase Impact Ranks on Hypothetical Lamprey Distribution

The climate change impact rank values were summed for each segment to arrive at an overall combined ranking. This ranking is distributed from the highest possible climate change impact (12, reflecting rankings of 4 for all three metrics) to the lowest possible impact (3, reflecting rankings of 1 for all three metrics). Stream segments from the hypothetical lamprey distribution were grouped by the combined climate change impact rank and NatureServe status rank, as shown in Figure 40. In general, the stream distribution that was ranked worst for existing lamprey status also fare the most poorly with combined anticipated effects, while the stream distribution that was ranked with a relatively better status has lower combined climate change effects. Of the distribution ranked “Imperilled” or “S1-S2” 2,633 km (85.5%) received a combined climate change impact ranking of 3-6, while only 417 km (14.5%) received a ranking of 7-12. But for the distribution ranked “Critically Imperilled” or “Possibly Extinct”, 3,224 km (28.7%) received a ranking of 1-6, and 8,010 km (71.3%) received a ranking of 7-12. This analysis suggests that the areas with relatively stronger (but still imperilled) existing lamprey populations will be better insulated from near-term climate change impacts, while the areas where lamprey are currently struggling most (or already extinct) will experience the heaviest impacts.

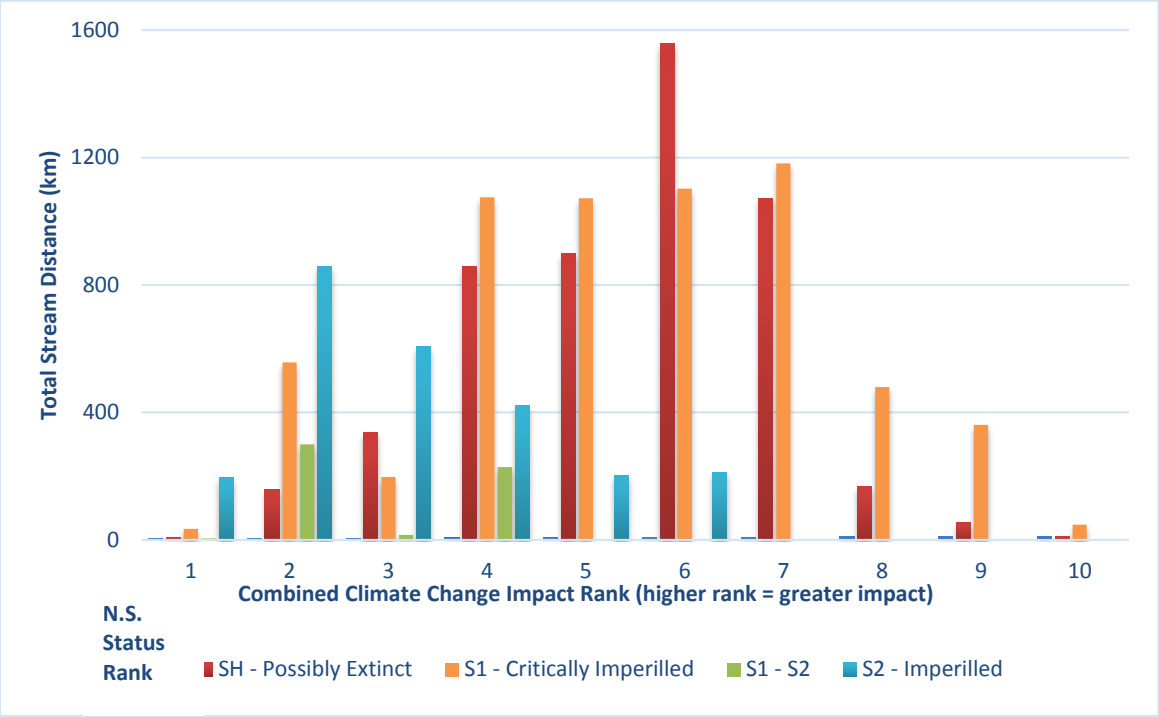

Figure 40: Total Stream Distance (km) of Hypothetical Lamprey Distribution by Combined Climate Change Impact and NatureServe Status Ranks

Combined climate change impact ranks for hypothetical lamprey distribution are mapped on the NatureServe status ranks in Figure 41. The Willamette Basin and Lower Columbia drainages have both lower combined lamprey status ranks and combined climate change effects. The middle Columbia basins do somewhat worse, with a mix of higher climate change impacts, particularly in the upper drainages. The Upper Columbia and Snake River basins fare the worst in combined climate change rankings, particularly in the Wenatchee (UC) and Clearwater (SR) drainages, and also have the lowest status rankings for lamprey. Generally, the climate change impacts are greatest in interior areas that rely on mid-elevation snowpack for sustained and cool summer stream flow. These basins will be most susceptible to a transition to rain-dominated patterns under climate change. In these areas, lamprey already are presented with long migrations through multiple hydropower dams, which have impacted their survival and presumed abundance. Tributaries of the lower Columbia River basin, where lamprey do not face as many migratory challenges, are historically rain-dominant to a larger degree with large inputs of groundwater to summer baseline flow in some tributaries (for example, the Willamette Basin), which makes them less susceptible (but not exempt) from the climate change impacts examined here.

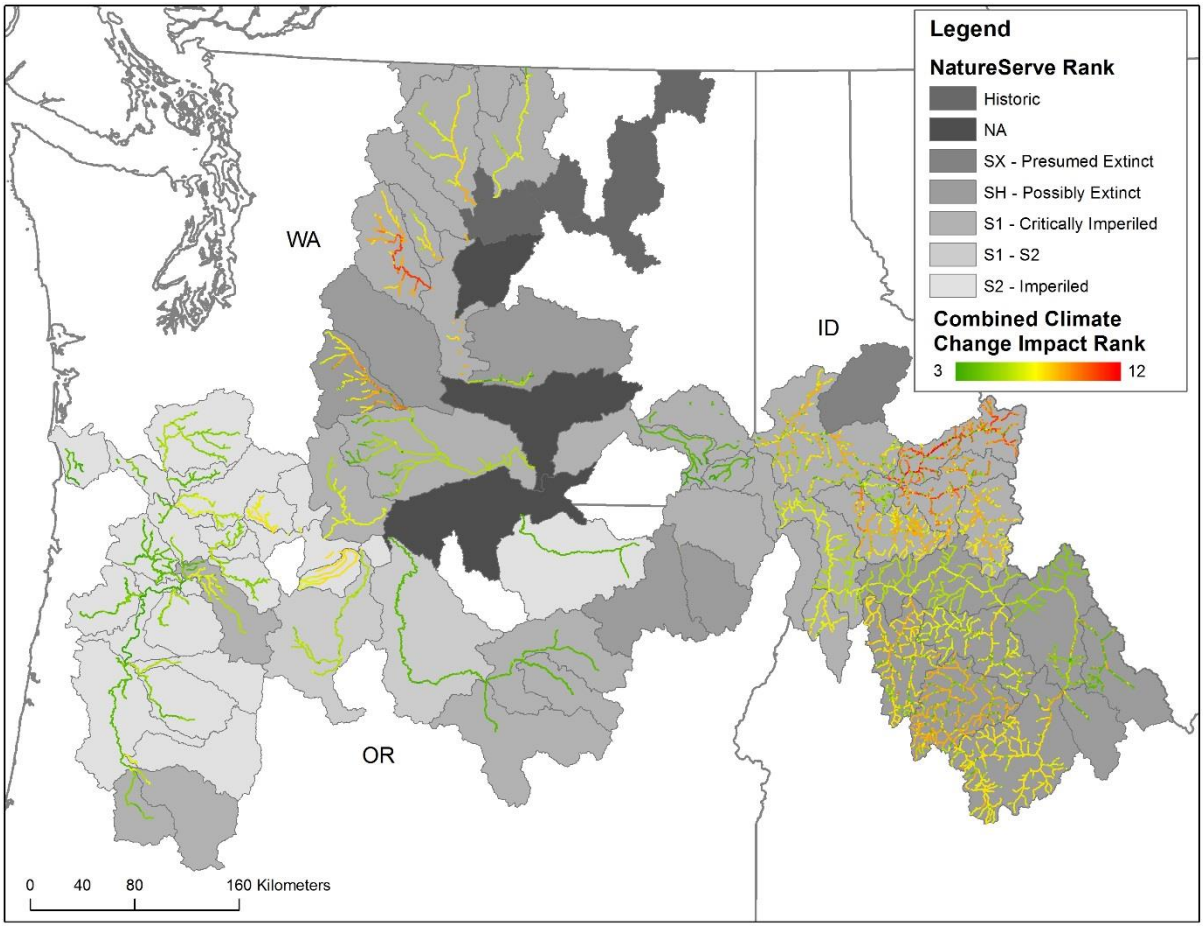

Figure 41: Map of Climate Change Impact Ranks on Hypothetical Lamprey Distribution

Overall, these results suggest that climate change impacts on the freshwater lifecycle stages of lamprey in Columbia River tributaries will be significant, but unevenly distributed. Areas where lamprey are believed to have a relatively stronger current status, such as the Willamette Basin, Lower Columbia tributaries, and parts of the Middle Columbia basin are projected to receive relatively smaller climate change impacts, and may present the best opportunities for restoration of lamprey runs. This analysis is not comprehensive, though, and the lack of available data suggests a need for much greater research on the distribution, abundance, and principal habitat factors affecting lamprey in the Columbia Basin. Additionally, there are several other factors that affect lamprey in the freshwater tributaries which also may be influenced by climate change (as well as other factors) including predation, sediment delivery, and habitat connectivity that were outside the scope of this analysis.

The passage of adult (upstream) and juvenile (downstream) lamprey through the mainstem reservoirs (Columbia and Snake rivers) is also very important to their abundance and distribution. This environment will also be affected by climate change, as warmer spring and summer water temperatures negatively affects both life cycles, and will likely benefit non-native predators of lamprey (Lawrence, et

al. 2014). Most future climate change scenarios also portend a diminished spring freshet available for mainstem flows, which may compromise the downstream migration of juveniles, which is believed to coincide with high periods of stream discharge, with increases in outmigrating juveniles at Bonneville Dam beginning around mid-April (Weitkamp, et al. 2015) An analysis of mainstem climate change impacts was also outside the scope of this paper because effects on flow will depend on how the hydropower system is operated under these changing conditions, as will effects on reservoir water temperatures.

3.2 Eulachon Empirical Analysis

The results presented here encompass five different analyses for eulachon: (i) A time series approach to assess whether there are any lag-based patterns in abundance (as related by catch numbers); (ii) A stochastic stock reduction analysis (SRA) of stock trajectories over time; (iii) A consideration of the effects of ocean conditions on catch levels and larval spawning biomass; (iv) An analysis of the trawl survey index in years prior to 2015; and (v) An examination of projected changes to future runoff and water temperature in eulachon spawning and migratory areas of the Lower Columbia Basin.

3.2.1 Time Series Analysis

Similar to the lamprey data and analysis, data were examined on the lower Columbia catches since 1938 (Figure 42) using times series approaches to assess the appropriate temporal scale to examine relationship with abundance as expressed as catch.

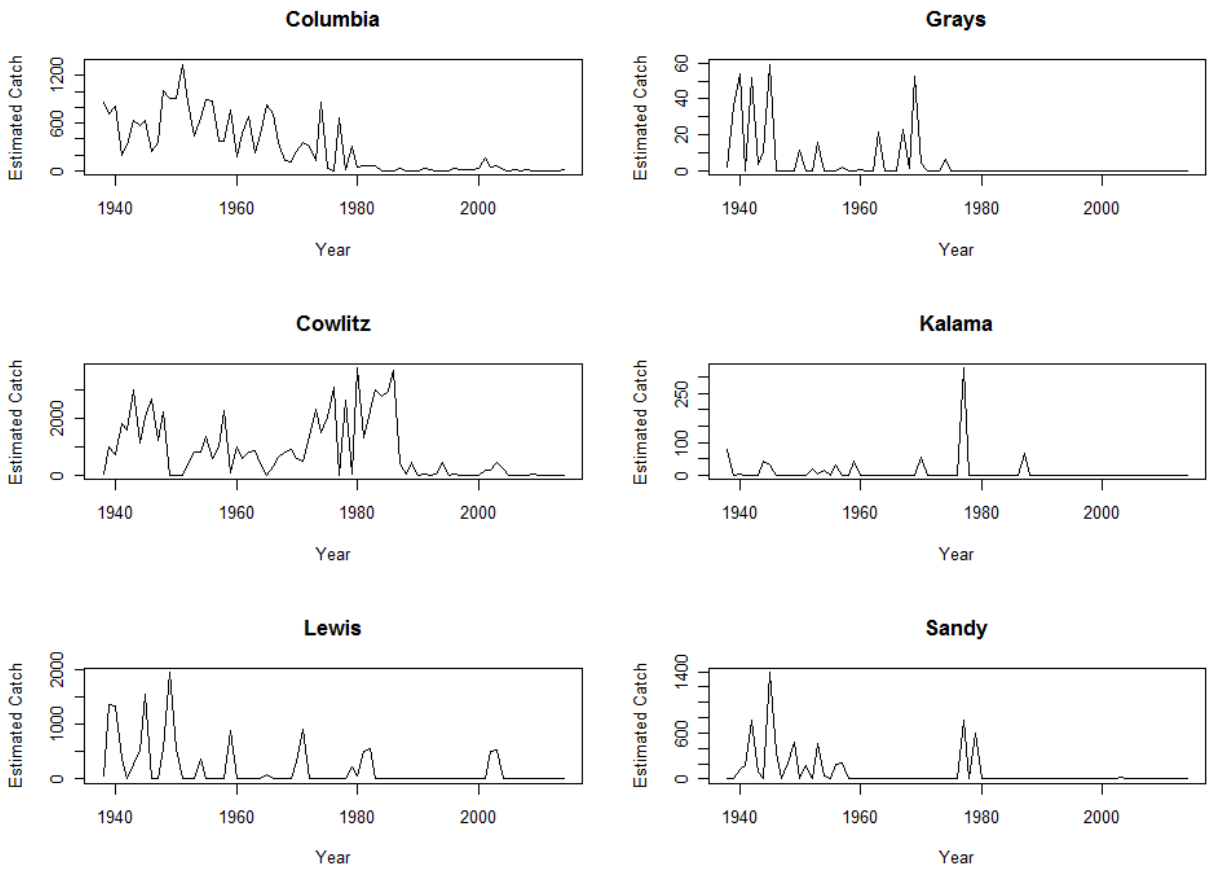

Figure 42: Eulachon Time Series Catch Data for Rivers in the Lower Columbia

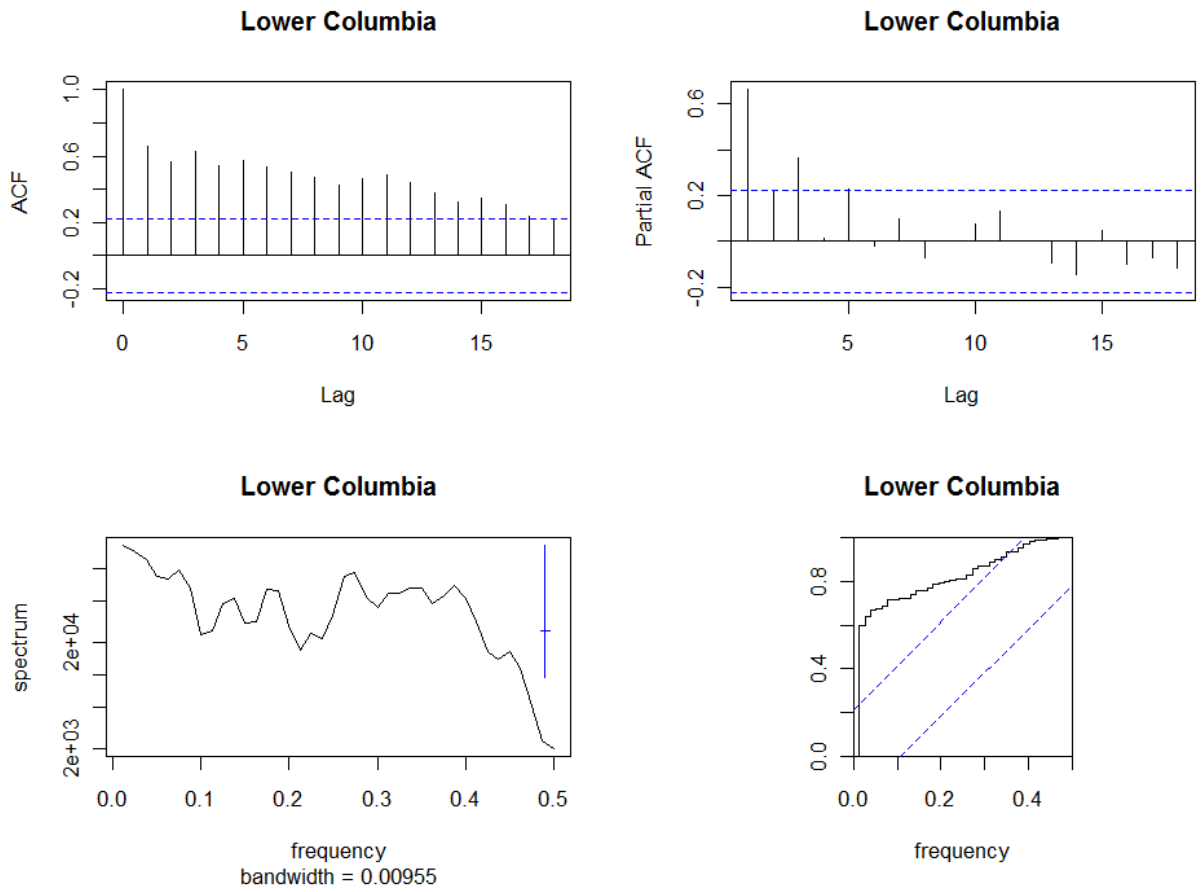

Figure 43: Autocorrelation (full and partial), Spectral Density, and CPgram Plots of the Eulachon Abundance (75-year) Series for the Lower Columbia River

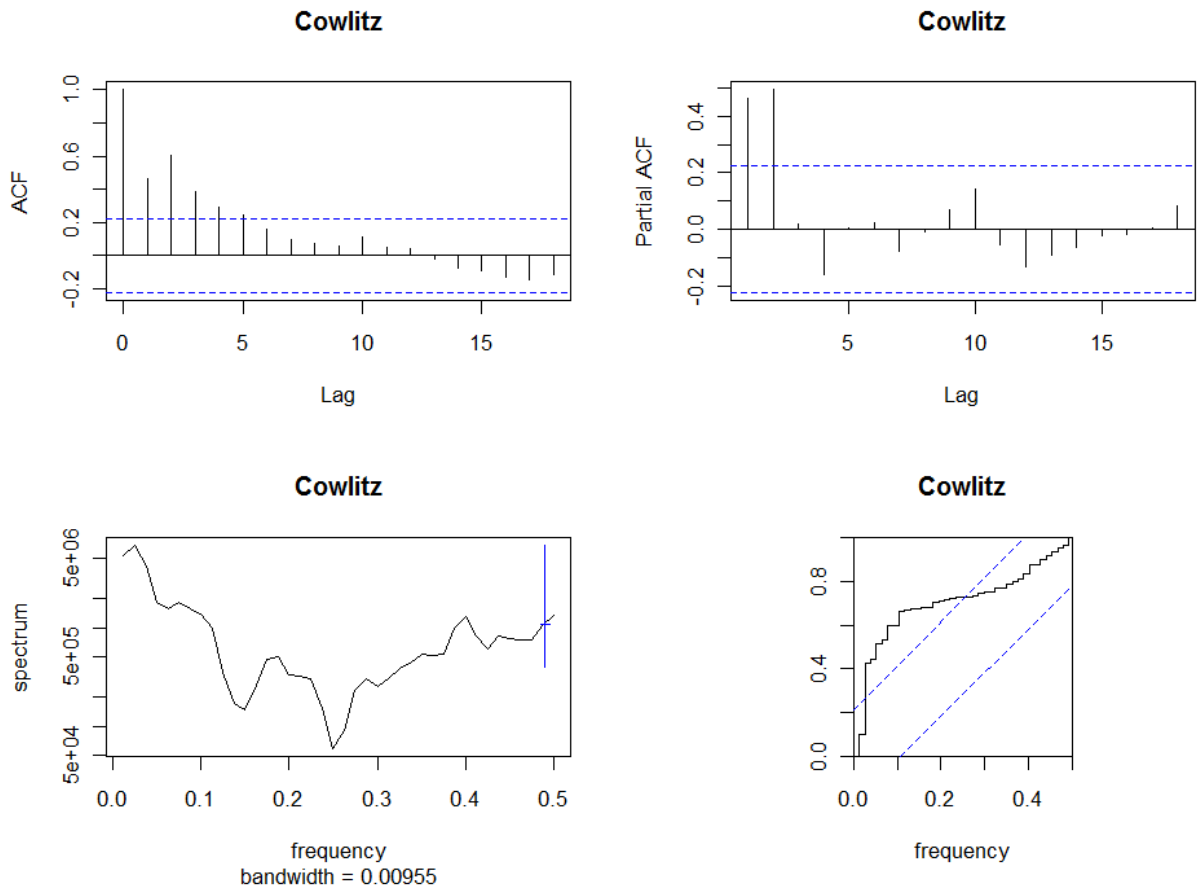

Figure 44: Autocorrelation (full and partial), Spectral Density, and CPgram Plots of the Eulachon Abundance (75-year) Series for the Cowlitz River

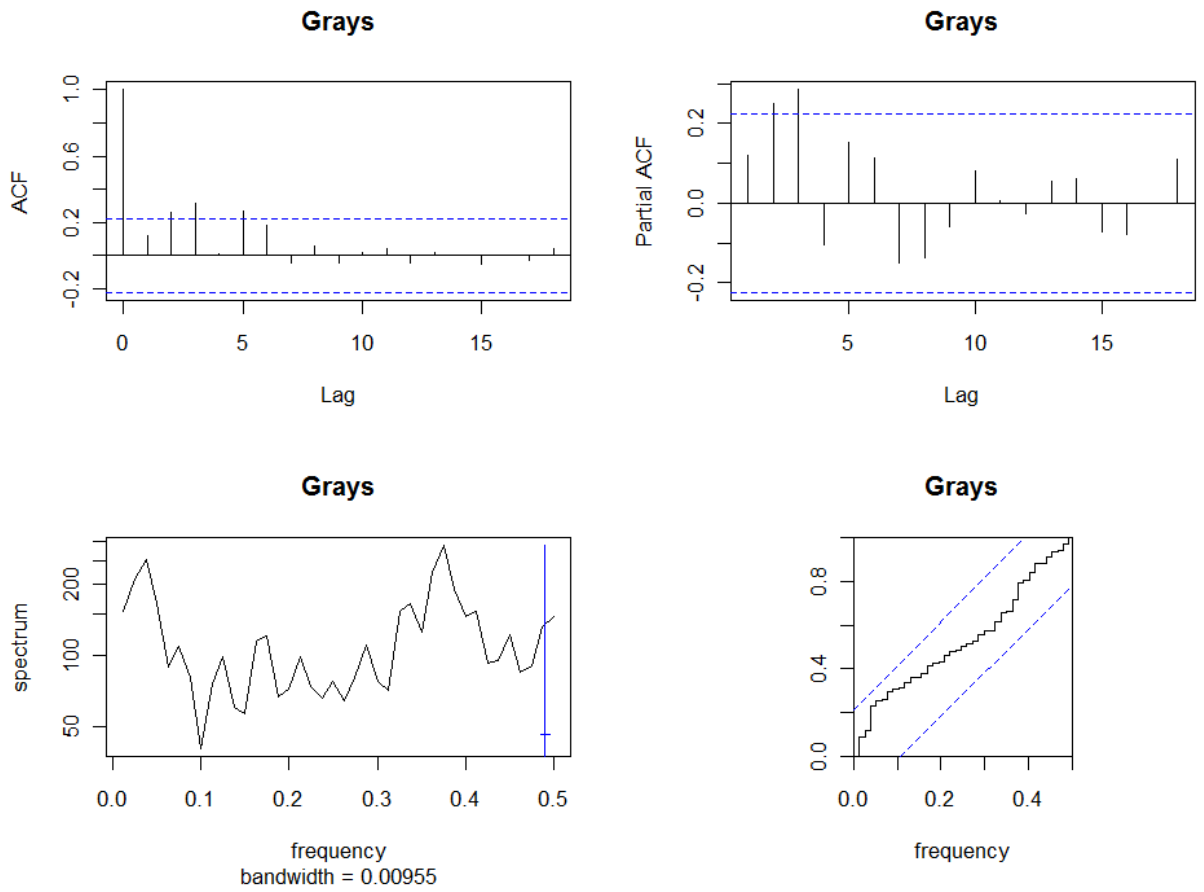

Figure 45: Autocorrelation (full and partial), Spectral Density, and CPgram Plots of the Eulachon Abundance (75-year) Series for the Grays River

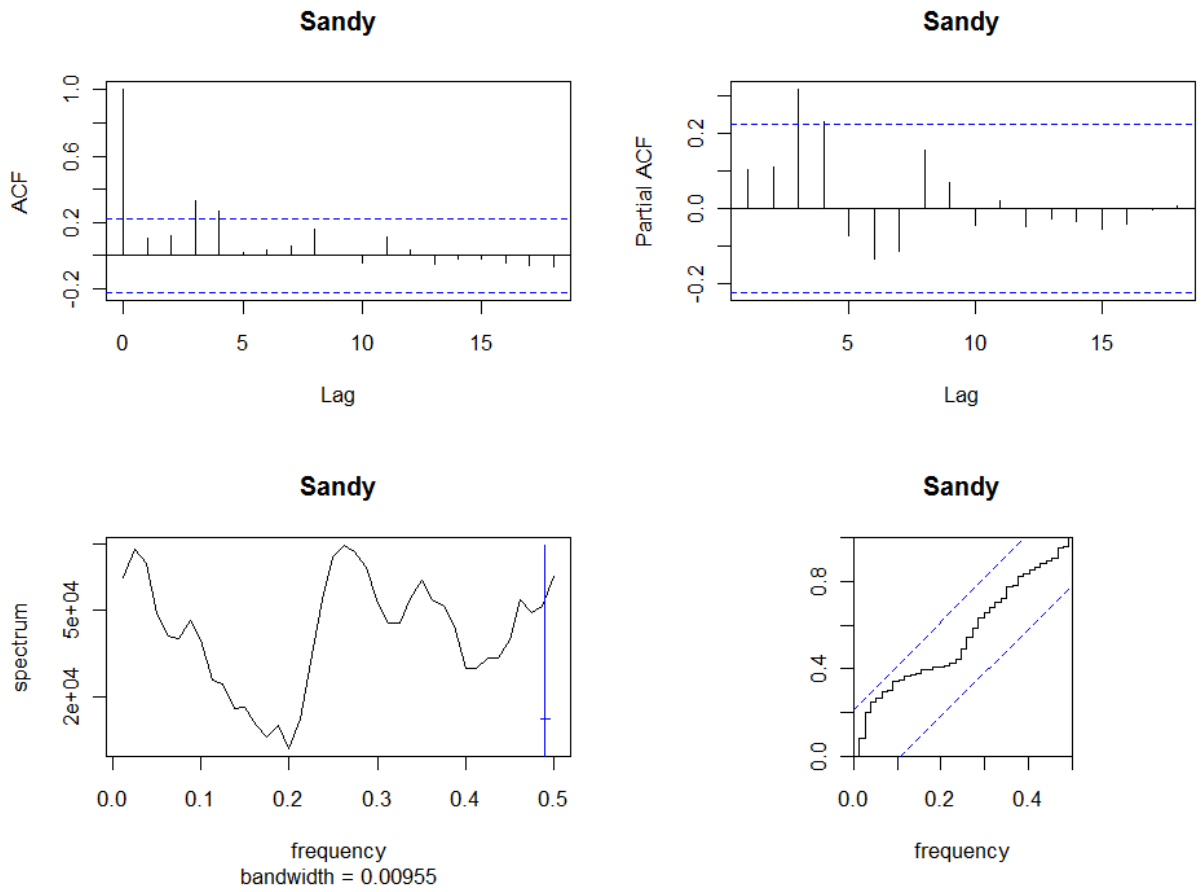

Figure 46: Autocorrelation (full and partial), Spectral Density, and CPgram Plots of the Eulachon Abundance (75-year) Series for the Sandy River

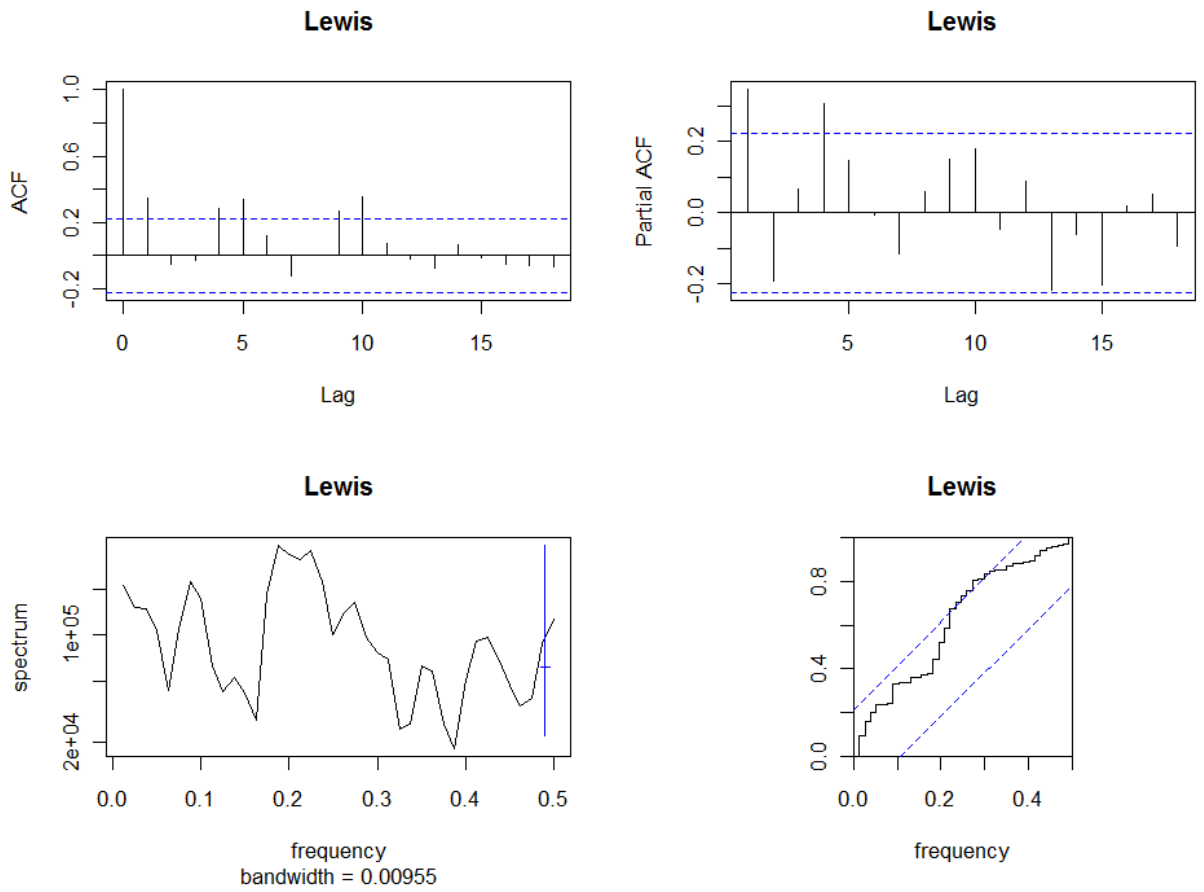

Figure 47: Autocorrelation (full and partial), Spectral Density, and CPgram Plots of the Eulachon Abundance (75-year) Series for the Lewis River

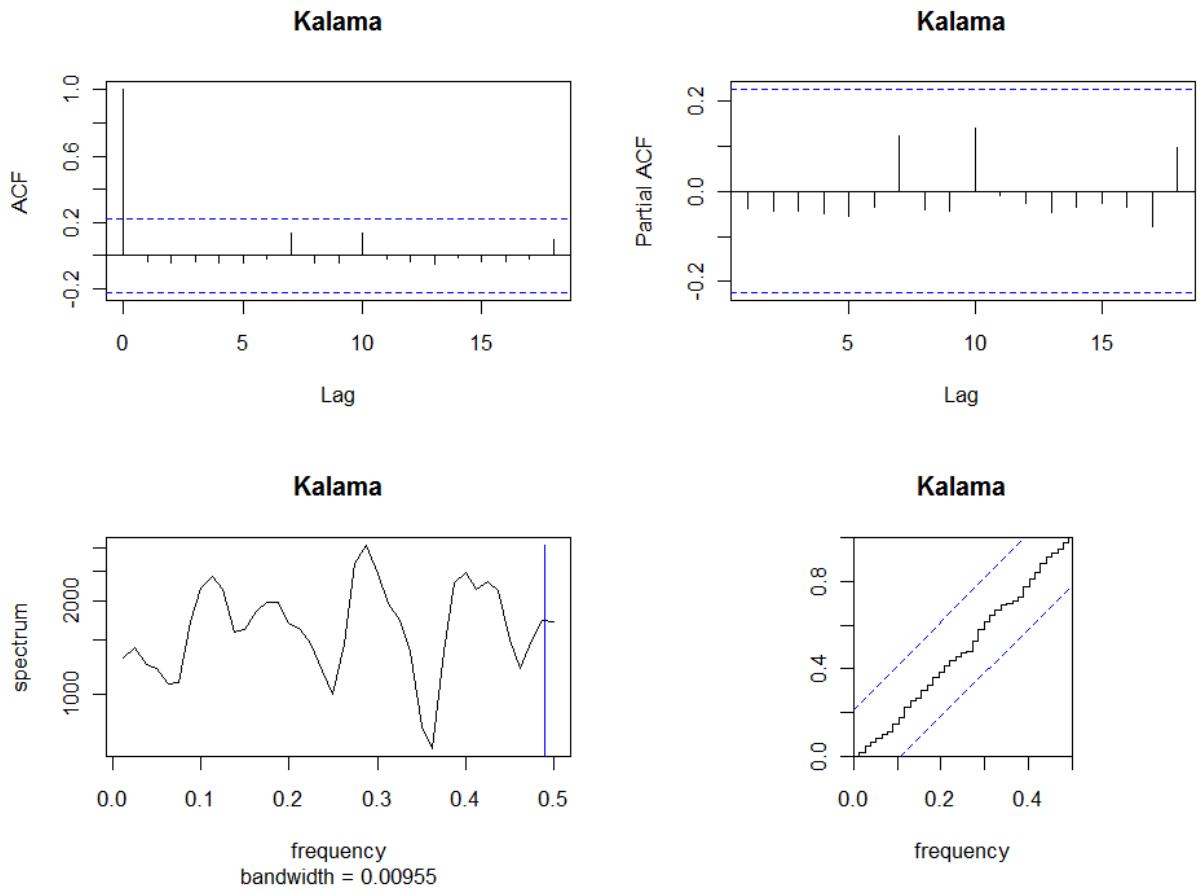

Figure 48: Autocorrelation (full and partial), Spectral Density, and CPgram Plots of the Eulachon Abundance (75-year) Series for the Kalama River

Figures 42-48 show Auto-correlation, partial autocorrelation plots, spectral density and CPgram of the 75 year eulachon abundance data series for the Lower Columbia, Grays, Cowlitz, Kalama, Lewis, and Sandy Rivers. Time series diagnostics used above on each of the rivers indicate that there are certain lag year effects noticeable on the catch from one to five years. However, with the Kalama River, lags were not as pronounced as with the other rivers (Figure 48). Most models examined above indicate a one – three year lag, but in some cases (lower Columbia, 2 or 3 year lags work as well). We examined 1, 2 or 3 year time series models based on these diagnostics in the next section on the Cowlitz and Lower Columbia Rivers.

3.2.1.1 Time Series Models Examined

Three models were examined (ARIMA 1, ARIMA 2, and ARIMA 3) for two populations, the lower Columbia and the Cowlitz, which account for the bulk of the returning eulachon (average of 97% from 1938-2014). The only models that were significant were the one year lag models (Table 21). Residual diagnostics for the ARIMA 1 to ARIMA 3 models are shown in Figures 49 and 50.

Table 21: Parameter Values of AR1-AR3 Models and AIC Values for the Lower Columbia and Cowlitz Rivers. The 1st block shows a lag 1 only model, the 2nd block shows a lag 2 model and the 3rd block a lag 3 model

Lower Columbia						Cowlitz				
Parameter values of the lag one ARIMA model:						Parameter values of the lag one ARIMA model:				
	AR 1 term	Intercept					AR 1 term	Intercept		
Estimate	0.68	303.81				Estimate	0.47	848.97		
SE	0.08	88.12				SE	0.10	192.42		
σ^2 estimated as 63021: log likelihood = -535.05, aic = 1076.09						σ^2estimated as 832001: log likelihood = -634.2, aic = 1274.39				
Parameter values of the lag two ARIMA model:						Parameter values of the lag two ARIMA model:				
	AR 1 term	AR 2 term	Intercept				AR 1 term	AR 2 term	Intercept	
Estimate	0.52	0.24	308.75			Estimate	0.23	0.50	798.88	
SE	0.11	0.11	111.93			SE	0.10	0.10	315.00	
σ^2 estimated as 59340: log likelihood = -532.8, aic = 1073.59						σ^2 estimated as 622152: log likelihood = -623.29, aic = 1254.57				
Parameter values of the lag three ARIMA model:						Parameter values of the lag three ARIMA model:				
	AR 1 term	AR 2 term	AR 3 term	Intercept			AR 1 term	AR 2 term	AR 3 term	Intercept
Estimate	0.43	0.03	0.42	327.28		Estimate	0.22	0.49	0.03	795.25
SE	0.10	0.11	0.10	173.86		SE	0.11	0.10	0.11	322.50
σ^2 estimated as 48776: log likelihood = -525.57, aic = 1061.15						σ^2estimated as 621689: log likelihood = -623.26, aic = 1256.52				

Table 21 indicates that AIC values are lowest for the AR-3 model with three terms for the lower Columbia stock, and 2 terms (AR-2) for the Cowlitz data. This is not surprising given that most eulachon complete their life-cycle in 3 years and hence are influenced on 2-3 year scales as the results suggest.

For the lower Columbia, some of the skew and residual diagnostics is reduced when we add the ARIMA3 model (Figure 49). This is not surprising given the life cycle of surf smelt occurs in 2-3 year intervals for the bulk of the run (an unknown proportion are repeat spawners, but likely quite low). In the case of the Cowlitz catch data, an AR2 model seems to perform best, based on the AIC values, and the residual diagnostics shown below (Figure 50)

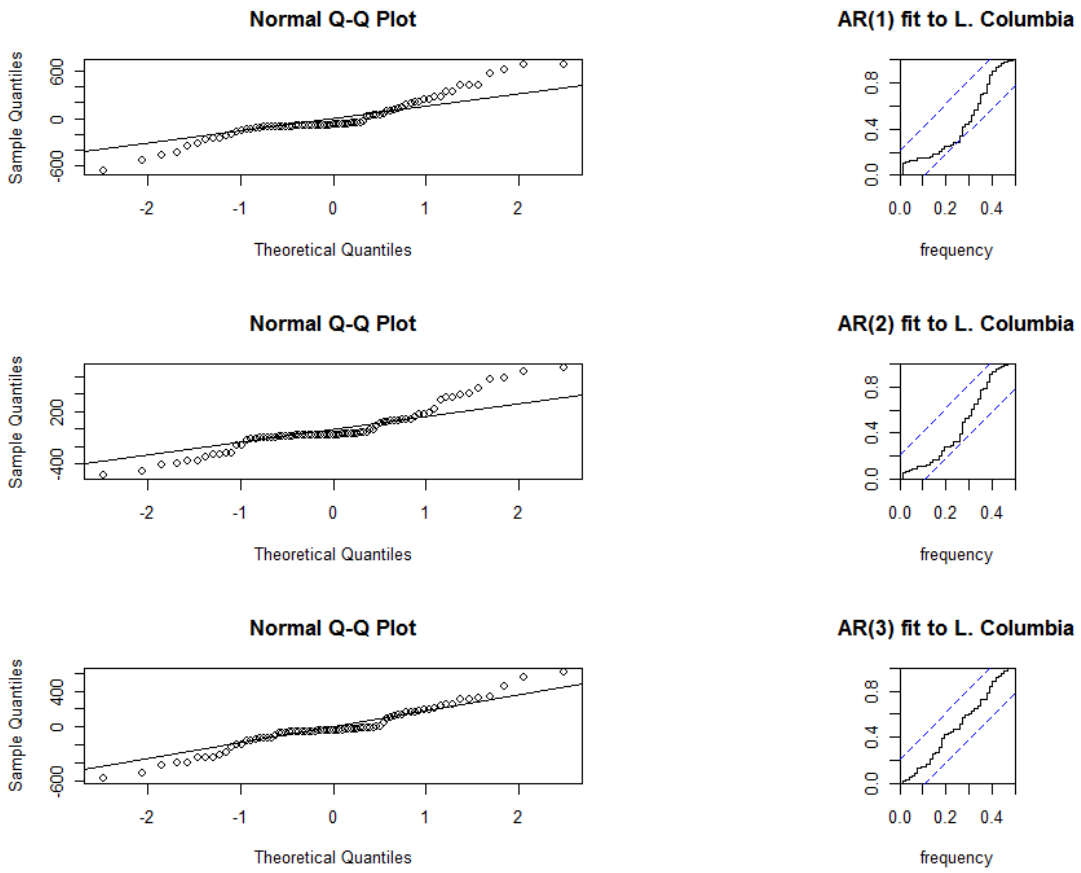

Figure 49: Residual Diagnostics of ARIMA Models on Lower Columbia Eulachon Data

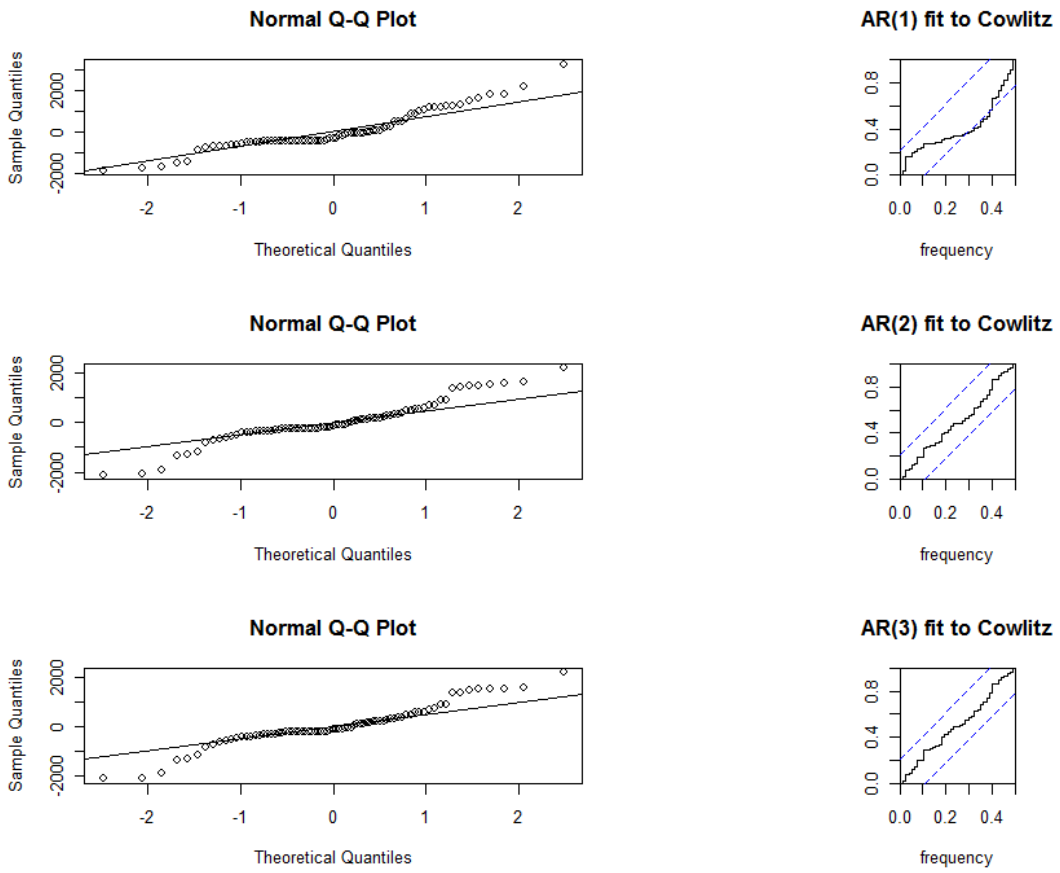

Figure 50: Residual Diagnostics of ARIMA Models on Cowlitz Eulachon Data

3.2.2 SRA Approach Results

The approaches developed by Martell and Froese (2012) are used in estimating likely parameters (Figure 51) that may explain the population trajectory till 1986, as fishery closures after 1986 makes it difficult to use this method.

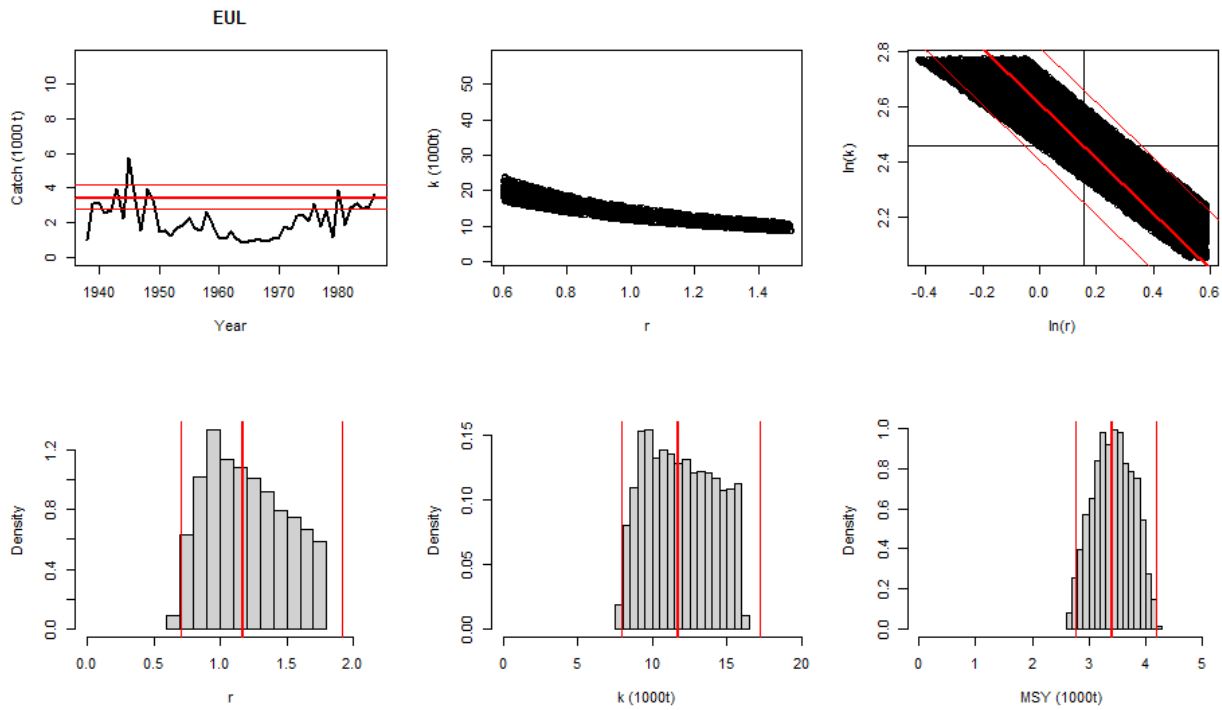

Figure 51: r () intrinsic growth rate), K (Carrying Capacity), Correlated r and K in Real and Log-Space and Distributions around r, K, and MSY (Maximum Sustainable Yield). See methods section for details of the parameter values and model used.

Results for optimal yield, r and K are shown below (Table 22):

Table 22: Catch-MSY based results for Eulachon catch data

Parameters	5%	50%	90%
S_{MSY} (M)	3.978	5.848	8.597
MSY (M)	2.775	3.411	4.192
R	0.71	1.17	1.92
K (M)	7.957	11.696	17.194

Data was used from 1938 to 1986 as catches declined severely after that due to management intervention. Stock trajectories based on simple biomass dynamic models are shown below (Figure 52). Based on the fact that the fishery was open in the earlier years, estimated target yields are between 2.8 million pounds and 4.2 million pounds. The Geometric mean is around 3.41 million pounds. It is likely the stock was severely affected by the poor ocean conditions between 1983 and 1997 (two El Nino's occurred during this period, severely affecting the areas off the Washington and Oregon coast (Hare and Francis 1995, Hare, et al. 1999)). After that point and probably due to better ocean conditions starting around 2002, with the exception of one poor ocean event in 2005 (warm ocean temperature in NE Pacific from April to June 2005), the stocks have had better than average conditions (from 2006 to 2012) and the spawning biomass appears to have increased dramatically (Figure 5b in data sections).

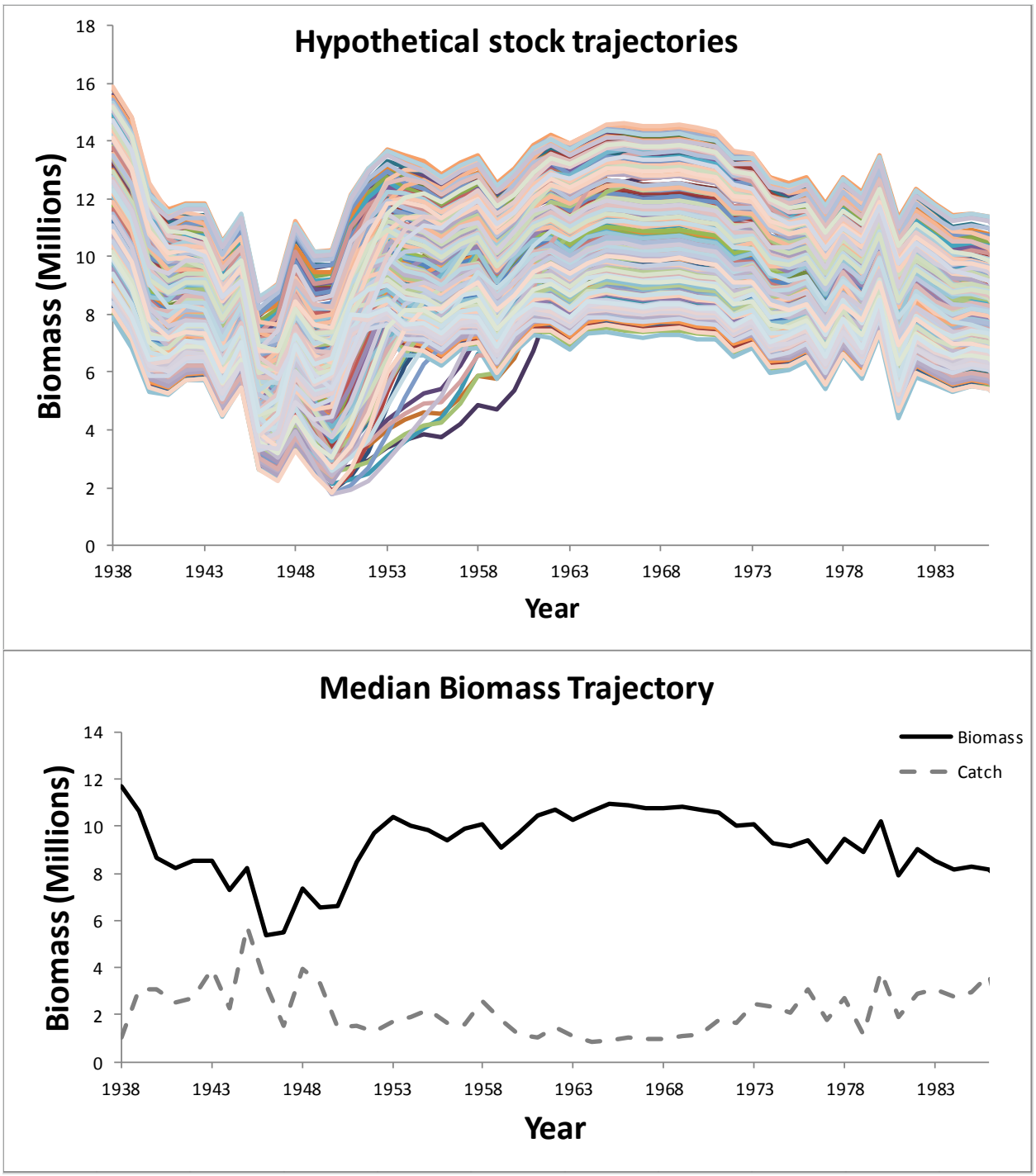

Figure 52: Population Trajectories of Columbia River eulachon (1938-2013) based on catch history.

Trajectories are relevant until drastic measures were taken to reduce catch in 1986 (Figure 52), and hence management affect regulated catch rather than the fishery itself. Drops in productivity subsequent to that created ESA listings for the stock, and hence trajectories after 1986 are overly optimistic.

Table 23: Correlation Analysis on 1, 2, and 3 Year Lags of Spring Outflow with Cowlitz River Catch. Spring outflow in the Cowlitz from April, May, June and July lagged by 1, 2 or 3 years and correlated to catch on the Cowlitz (catchCWF). Note: Positive and negative correlations greater than 0.4 are highlighted.

	catchCWF	*log(catch)*	*Aprillag3*	*Maylag3*	*Junelag3*	*Julylag3*	*AMJJUavglag3*	*Aprillag2*	*Maylag2*	*Junelag2*	*Julylag2*	*AMJJUavglag2*	*Aprillag1*	*Maylag1*	*Junelag1*	*Julylag1*	*AMJJUavglag1*
catchCWF	1.00																
log(catch)	0.55	1.00															
Aprillag3	-0.16	-0.14	1.00														
Maylag3	-0.11	0.00	0.30	1.00													
Junelag3	0.00	0.04	0.26	0.42	1.00												
Julylag3	-0.27	-0.16	0.00	0.19	0.48	1.00											
AMJJUavgl	-0.19	-0.09	0.69	0.74	0.75	0.48	1.00										
Aprillag2	0.16	0.15	0.05	0.19	0.07	-0.01	0.12	1.00									
Maylag2	-0.07	-0.03	0.04	0.01	-0.08	-0.04	-0.01	0.30	1.00								
Junelag2	-0.02	0.02	0.18	0.06	0.13	0.14	0.19	0.27	0.41	1.00							
Julylag2	-0.19	-0.05	-0.04	-0.02	-0.11	0.24	-0.01	0.00	0.19	0.48	1.00						
AMJJUavgl	0.00	0.05	0.09	0.11	0.01	0.08	0.11	0.69	0.74	0.75	0.48	1.00					
Aprillag1	-0.11	-0.06	0.14	0.10	0.11	0.04	0.16	0.04	0.20	0.08	0.00	0.13	1.00				
Maylag1	-0.10	-0.05	-0.09	-0.04	0.00	0.13	-0.03	0.05	0.01	-0.09	-0.05	-0.01	0.33	1.00			
Junelag1	0.03	-0.17	0.17	-0.09	-0.10	0.04	0.02	0.18	0.07	0.13	0.15	0.19	0.28	0.44	1.00		
Julylag1	-0.33	-0.12	-0.04	0.04	-0.02	0.16	0.03	-0.04	-0.01	-0.11	0.25	0.00	0.02	0.22	0.49	1.00	
AMJJUavgl	-0.17	-0.13	0.08	0.01	0.02	0.12	0.08	0.09	0.12	0.02	0.09	0.12	0.70	0.75	0.75	0.50	1

Table 24: Correlation Analysis on 1, 2, and 3 Year Lags of Spring Outflow with Lewis River Catch Spring outflow in the Lewis from April, May, June and July lagged by 1, 2 or 3 years and correlated to catch on the Cowlitz (catch Lewis). Note: Positive and negative correlations greater than 0.4 are highlighted.

	CatchLewis	*log(catch)*	*Aprillag3*	*Maylag3*	*Junelag3*	*Julylag3*	*AMJJUavglag3*	*Aprillag2*	*Maylag2*	*Junelag2*	*Julylag2*	*AMJJUavglag2*	*Aprillag1*	*Maylag1*	*Junelag1*	*Julylag1*	*AMJJUavglag1*
CatchLewi	1.00																
log(catch)	0.68	1.00															
Aprillag3	-0.20	-0.25	1.00														
Maylag3	-0.25	-0.22	0.45	1.00													
Junelag3	-0.17	-0.21	0.33	0.59	1.00												
Julylag3	0.04	-0.19	-0.10	0.12	0.34	1.00											
AMJJUavgl	-0.23	-0.31	0.68	0.82	0.82	0.40	1.00										
Aprillag2	-0.34	-0.34	0.14	0.20	0.14	-0.07	0.16	1.00									
Maylag2	-0.34	-0.40	0.01	0.08	0.02	0.11	0.08	0.44	1.00								
Junelag2	-0.20	-0.21	0.19	0.07	-0.03	0.17	0.14	0.32	0.57	1.00							
Julylag2	0.37	0.10	-0.16	-0.29	-0.23	0.21	-0.21	-0.10	0.12	0.34	1.00						
AMJJUavgl	-0.25	-0.35	0.09	0.06	-0.01	0.13	0.09	0.68	0.82	0.81	0.40	1.00					
Aprillag1	-0.11	-0.17	0.27	0.23	0.12	0.04	0.26	0.13	0.22	0.12	-0.06	0.17	1.00				
Maylag1	-0.13	-0.14	0.03	-0.05	-0.06	0.12	0.00	0.00	0.11	-0.01	0.11	0.07	0.49	1.00			
Junelag1	-0.16	-0.29	0.04	-0.07	-0.14	0.03	-0.05	0.18	0.09	-0.04	0.17	0.14	0.36	0.60	1.00		
Julylag1	0.09	-0.06	-0.19	-0.09	-0.13	0.05	-0.15	-0.16	-0.29	-0.24	0.21	-0.21	-0.09	0.12	0.33	1.00	
AMJJUavgl	-0.13	-0.24	0.09	0.03	-0.06	0.08	0.05	0.07	0.09	-0.03	0.13	0.09	0.70	0.83	0.82	0.39	1.00

Table 25: Correlation Analysis on 1, 2, and 3 Year Lags of Flow with Estimated Cowlitz River Eulachon Abundance (Langness, et al. 2015) Spring outflow in the Cowlitz from April, May, June and July lagged by 1, 2 or 3 years and correlated to abundance as estimate. Note: Positive and negative correlations greater than 0.4 are highlighted.

	ABDCWF	*log(catch)*	*Aprillag3*	*Maylag3*	*Junelag3*	*Julylag3*	*MJJUavglag*	*Aprillag2*	*Maylag2*	*Junelag2*	*Julylag2*	*MJJUavglag*	*Aprillag1*	*Maylag1*	*Junelag1*	*Julylag1*	*AMJJUavglag1*
ABDCWF	1.00																
log(catch)	0.88	1.00															
Aprillag3	0.20	0.23	1.00														
Maylag3	0.25	0.14	0.35	1.00													
Junelag3	0.26	0.03	-0.04	0.64	1.00												
Julylag3	0.58	0.29	0.14	0.50	0.86	1.00											
AMJJUavglag3	0.44	0.24	0.55	0.82	0.78	0.82	1.00										
Aprillag2	0.12	0.27	-0.34	-0.50	-0.54	-0.33	-0.58	1.00									
Maylag2	0.24	-0.03	-0.03	-0.29	0.03	0.34	0.02	0.40	1.00								
Junelag2	0.46	0.22	0.64	0.27	0.08	0.40	0.51	-0.03	0.64	1.00							
Julylag2	0.72	0.58	0.52	0.16	-0.04	0.29	0.35	0.11	0.48	0.85	1.00						
AMJJUavglag2	0.51	0.36	0.23	-0.15	-0.20	0.19	0.04	0.56	0.83	0.78	0.79	1.00					
Aprillag1	-0.26	-0.17	-0.12	-0.45	-0.34	-0.45	-0.45	-0.25	-0.47	-0.52	-0.34	-0.53	1.00				
Maylag1	0.18	0.29	0.31	-0.22	-0.37	-0.32	-0.16	-0.14	-0.32	0.00	0.35	-0.04	0.46	1.00			
Junelag1	0.48	0.57	-0.07	-0.35	-0.15	0.04	-0.17	0.42	0.14	0.01	0.39	0.35	-0.04	0.62	1.00		
Julylag1	0.52	0.67	-0.02	-0.49	-0.27	-0.02	-0.25	0.44	0.12	-0.06	0.29	0.30	0.10	0.49	0.83	1.00	
AMJJUavglag1	0.29	0.44	0.01	-0.53	-0.39	-0.26	-0.37	0.15	-0.19	-0.22	0.20	-0.01	0.55	0.85	0.78	0.80	1.00

We examined relationships of environmental variables to catch and abundance for the Cowlitz and Lewis River (assuming catches are a proxy for abundance, Tables 23 and 24). We did not examine the Grays, Kalama, and Sandy Rivers as they were a small proportion (less than 5% of the overall catch in the Columbia), and the lower Columbia catch as this is a function of all rivers but primarily the Cowlitz and Sandy rivers.

While the Lewis River catch shows a positive relationship with flow (Table 24), the Cowlitz River catch shows a declining relationship with flow (Table 23). However, on the Cowlitz River there is a strong relationship with flow on 1, 2 or 3 year lags, with the highest correlation on a 2 year lag in July (Table 25). To examine these relationships further we developed likelihood profile analysis as we had developed for lamprey earlier in this report.

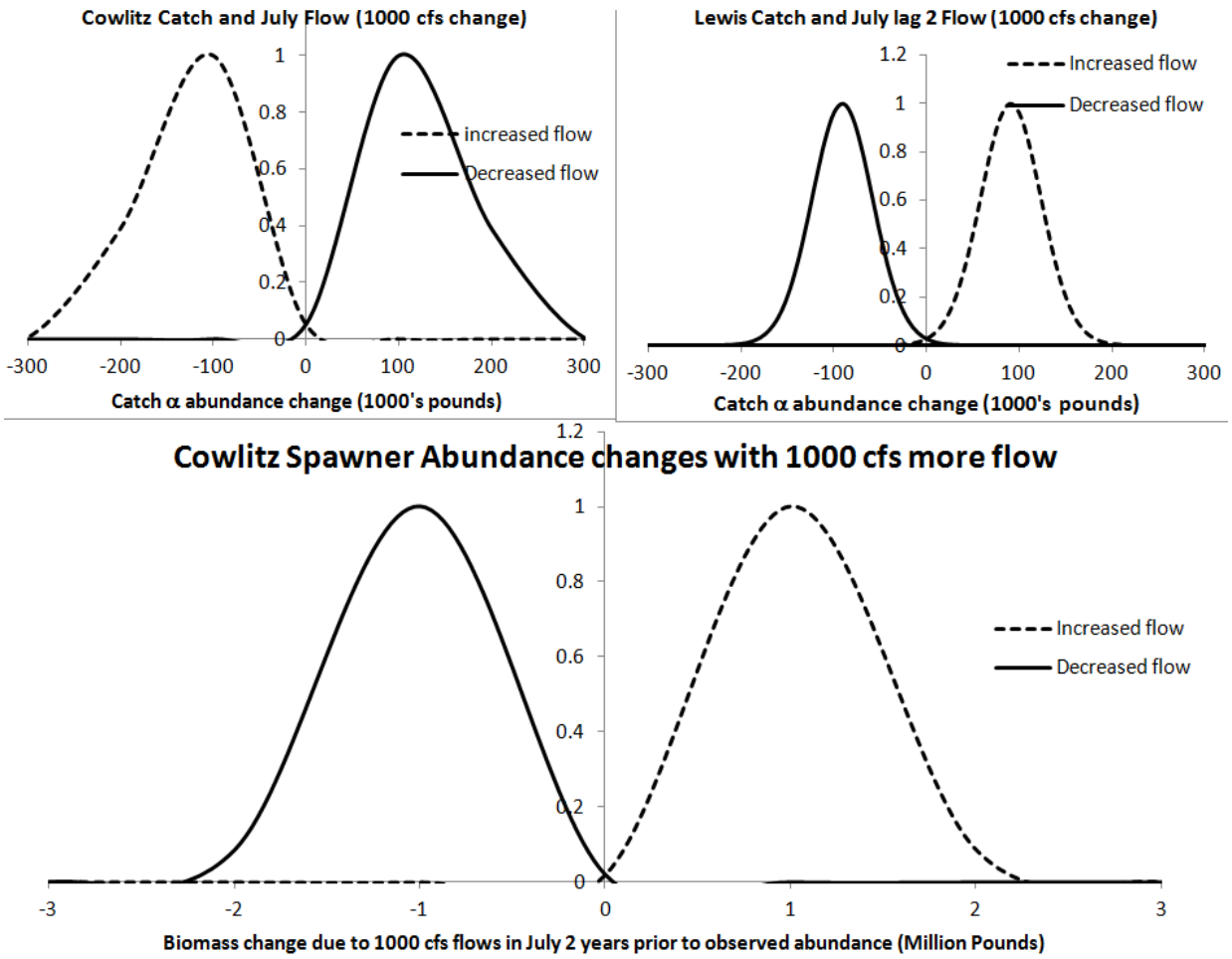

Figure 53: Uncertainty and Hypothesized Effect of Flow on Catch and Abundance Estimates of the Key Eulachon Variables

Two alternative relationships were examined, max flow and its effect on catch as a proxy for eulachon abundance, and max flow and its effect on actual abundance estimates, as estimated through larval surveys (Langness, et al. 2015).

While one hypothesis indicates that it would adversely affect abundance (Cowlitz catch), it is more likely that the latter hypothesis is more plausible, as the 2nd year lagged flow is in the Lewis River (July lag 2, Lewis catches) essentially showing the same positive effect on catch rates (Lewis River) as the abundance (Spawner) data does on the Cowlitz River (Figure 53) using a similar July lag 2 relationship.

As noted by Figure 53 above, a magnitude of 1000 cfs increase in July flows corresponds to more than 2 million more spawners in the Cowlitz River as estimated through the larval surveys, and thus more catch (possibly 100-200 K pounds as shown in the Lewis river). We, thus discounted the negative relationship shown on catch rates with abundance on the Cowlitz River, as it is not biologically feasible, and hypothesize that outmigrating flow for the juvenile larvae is key to overall survival and abundance a few years later. In addition, higher July flows may be correlated with better upwelling/high snowpack years (i.e. La Nina type years, Logerwell, et al. 2003, 2004) and will have a compounding effect on abundance as was noted with salmon runs in the years between 2009 and 2014.

3.2.3 Effects of Ocean Conditions on Catch Levels and Larval Spawning Biomass Estimates

Early marine survival is thought to be critical to survival of eulachon, and we examined the effects of average ocean conditions (Sea Surface Temperature (SST), Upwelling (UPI), and Sea Level Pressure (SLP) for the months of April, May, June, and July on one-year and three-year lagged abundance. Correlational analysis (Tables 26-32) was performed on the overall Columbia population catch and spawner estimates (obtained through larval surveys), and likelihood profile analysis was conducted on the main variables affecting abundance from the early marine survival aspects of this population. Since we are not sure how many juveniles were estimated for any given cohort, we examined 1, 2 and 3 year lags effects on the abundance and catches. In addition the time series analysis and ARIMA models suggested a 1-3 year lag model.

Table 26: Correlational Analysis on 1, 2, and 3 Year Lags of Sea Surface Temperature with Eulachon Columbia River Catch

	SST1A	*SST2A*	*SSt3A*	*SST4A*	*SST1M*	*SST2M*	*SSt3M*	*SST4M*	*SST1J*	*SST2J*	*SSt3J*	*SST4J*	*SST1JU*	*SST2JU*	*SSt3JU*	*SST4JU*	*COL catch*	*log(Catch)*	*COLclag2*	*log(Clag2)*	*ColClag3*	*log(Clag3)*
SST1A	1.00																					
SST2A	0.98	1.00																				
SSt3A	0.93	0.98	1.00																			
SST4A	0.76	0.83	0.93	1.00																		
SST1M	0.36	0.37	0.34	0.23	1.00																	
SST2M	0.34	0.36	0.34	0.24	0.99	1.00																
SSt3M	0.34	0.36	0.34	0.27	0.96	0.98	1.00															
SST4M	0.31	0.33	0.32	0.28	0.87	0.92	0.97	1.00														
SST1J	0.31	0.31	0.26	0.16	0.71	0.71	0.71	0.67	1.00													
SST2J	0.30	0.30	0.27	0.18	0.70	0.71	0.72	0.69	0.99	1.00												
SSt3J	0.33	0.32	0.30	0.23	0.69	0.71	0.74	0.73	0.96	0.99	1.00											
SST4J	0.34	0.33	0.32	0.30	0.66	0.69	0.74	0.76	0.87	0.91	0.97	1.00										
SST1JU	0.15	0.17	0.18	0.15	0.44	0.44	0.46	0.48	0.64	0.65	0.63	0.59	1.00									
SST2JU	0.08	0.10	0.13	0.14	0.41	0.42	0.45	0.49	0.58	0.61	0.62	0.60	0.97	1.00								
SSt3JU	0.09	0.11	0.15	0.18	0.42	0.44	0.48	0.53	0.56	0.59	0.63	0.65	0.92	0.98	1.00							
SST4JU	0.08	0.11	0.17	0.26	0.40	0.42	0.47	0.52	0.44	0.48	0.55	0.62	0.77	0.85	0.94	1.00						
COL catch	0.09	0.10	0.10	0.12	0.14	0.15	0.14	0.12	0.03	0.01	-0.02	-0.04	0.03	-0.01	-0.04	-0.02	1.00					
log(Catch)	0.08	0.10	0.11	0.14	0.12	0.13	0.13	0.11	0.04	0.01	-0.01	-0.03	0.04	0.00	-0.03	-0.03	0.96	1.00				
COLclag2	0.17	0.16	0.14	0.08	-0.01	-0.01	-0.01	-0.03	-0.11	-0.12	-0.12	-0.14	-0.08	-0.13	-0.14	-0.16	0.37	0.42	1.00			
log(Clag2)	0.08	0.08	0.08	0.06	-0.07	-0.06	-0.06	-0.08	-0.13	-0.14	-0.14	-0.15	-0.08	-0.12	-0.14	-0.13	0.45	0.52	0.96	1.00		
ColClag3	0.06	0.11	0.15	0.18	-0.11	-0.07	-0.04	-0.01	-0.26	-0.25	-0.25	-0.26	-0.08	-0.09	-0.13	-0.17	0.39	0.51	0.45	0.48	1.00	
log(Clag3)	-0.01	0.03	0.07	0.13	-0.17	-0.13	-0.09	-0.06	-0.30	-0.29	-0.28	-0.28	-0.13	-0.13	-0.15	-0.17	0.41	0.53	0.49	0.55	0.98	1.00

As with the previous analysis, Table 26 shows the sea-surface temperature at four stations near the Columbia (see methods) and recorded for the months of April (A). May (M), June (J) and July (JU), and

related to catches at 1, 2 or 3 year lags (Col catch is lag 1, ColClag2 is Columbia River catch at lag 2 and ColClag3 is Columbia River catch at lag 3).

Table 27: Correlational Analysis on 1, 2, and 3 Year Lags of Upwelling Indices with Eulachon Columbia River Catch

	UPI1A	UPI2A	UPI3A	UPI1M	UPI2M	UPI3M	UPI1J	UPI2J	UPI3J	UPI1JU	UPI2JU	UPI3JU	COLC	log(COLC)	lag2COLC	g(lag2COL(	lag3COLC	g(lag3LOG(
UPI1A	1.00																	
UPI2A	0.92	1.00																
UPI3A	0.79	0.87	1.00															
UPI1M	0.24	0.25	0.25	1.00														
UPI2M	0.22	0.31	0.30	0.88	1.00													
UPI3M	0.17	0.26	0.32	0.76	0.92	1.00												
UPI1J	0.16	0.12	0.10	0.27	0.07	0.02	1.00											
UPI2J	-0.01	0.01	0.02	0.24	0.14	0.13	0.84	1.00										
UPI3J	-0.11	-0.09	0.01	0.24	0.18	0.29	0.59	0.86	1.00									
UPI1JU	0.31	0.15	-0.02	0.21	0.17	0.11	0.29	0.21	0.13	1.00								
UPI2JU	0.20	0.12	-0.03	0.13	0.21	0.20	0.13	0.18	0.17	0.83	1.00							
UPI3JU	0.13	0.06	0.06	0.09	0.18	0.29	0.05	0.14	0.30	0.58	0.84	1.00						
COLC	-0.29	-0.19	-0.15	-0.18	-0.16	-0.11	-0.27	-0.11	0.01	-0.40	-0.35	-0.25	1.00					
log(COLC)	-0.30	-0.19	-0.17	-0.27	-0.27	-0.19	-0.25	-0.11	0.01	-0.41	-0.34	-0.25	0.96	1.00				
lag2COLC	-0.24	-0.20	-0.17	-0.29	-0.29	-0.24	-0.21	-0.26	-0.21	-0.27	-0.29	-0.19	0.37	0.42	1.00			
log(lag2CC	-0.26	-0.20	-0.16	-0.32	-0.35	-0.30	-0.17	-0.23	-0.17	-0.32	-0.33	-0.21	0.45	0.52	0.96	1.00		
lag3COLC	-0.34	-0.30	-0.19	-0.17	-0.22	-0.10	-0.30	-0.23	-0.08	-0.24	-0.17	0.00	0.39	0.51	0.45	0.48	1.00	
log(lag3LO	-0.36	-0.31	-0.21	-0.17	-0.24	-0.13	-0.29	-0.26	-0.12	-0.23	-0.17	-0.02	0.41	0.53	0.49	0.55	0.98	1.00

As with the previous analysis on lamprey, Table 27 shows upwelling at three stations near the Lower Columbia River (see methods) and recorded for the months of April (A). May (M), June (J) and July (JU), and related to catches at 1, 2 or 3 year lags (Col catch is lag 1, ColClag2 is Columbia River catch at lag 2 and ColClag3 is Columbia River catch at lag 3).

Table 28: Correlational Analysis on 1, 2, and 3 Year Lags of Sea Level Pressure with Eulachon Columbia River Catch

	SLP1	SLP2	SLP3	SLP1	SLP2	SLP3	SLP1	SLP2	SLP3	SLP1	SLP2	SLP3	COLC	log(COLC)	lag2COLC	g(lag2COL(	lag3COLC	g(lag3LOG(
SLP1	1.00																	
SLP2	0.96	1.00																
SLP3	0.85	0.96	1.00															
SLP1	-0.12	-0.16	-0.19	1.00														
SLP2	-0.11	-0.13	-0.15	0.96	1.00													
SLP3	-0.13	-0.13	-0.13	0.89	0.98	1.00												
SLP1	0.07	0.03	0.02	0.04	-0.05	-0.12	1.00											
SLP2	0.09	0.04	0.03	0.00	-0.11	-0.20	0.95	1.00										
SLP3	0.09	0.03	0.03	0.02	-0.09	-0.18	0.87	0.97	1.00									
SLP1	0.14	0.12	0.12	0.14	0.02	-0.05	0.20	0.15	0.12	1.00								
SLP2	0.16	0.14	0.14	0.04	-0.08	-0.15	0.13	0.09	0.07	0.95	1.00							
SLP3	0.14	0.14	0.14	0.02	-0.11	-0.18	0.11	0.10	0.09	0.88	0.97	1.00						
COLC	0.25	0.24	0.20	-0.22	-0.15	-0.12	0.27	0.29	0.28	0.11	0.03	-0.05	1.00					
log(COLC)	0.26	0.26	0.22	-0.25	-0.18	-0.15	0.22	0.23	0.23	0.11	0.05	-0.03	0.98	1.00				
lag2COLC	-0.15	-0.16	-0.15	0.07	0.09	0.12	0.25	0.16	0.11	0.21	0.14	0.07	0.43	0.48	1.00			
log(lag2CC	-0.12	-0.12	-0.11	0.02	0.05	0.08	0.23	0.15	0.12	0.17	0.12	0.06	0.50	0.57	0.98	1.00		
lag3COLC	0.16	0.17	0.19	0.07	0.07	0.07	0.28	0.24	0.23	0.30	0.20	0.12	0.70	0.71	0.47	0.52	1.00	
log(lag3LO	0.13	0.14	0.16	0.10	0.11	0.12	0.27	0.21	0.20	0.27	0.20	0.13	0.68	0.70	0.54	0.60	0.98	1.00

As with the previous analysis on lamprey, Table 28 shows Sea level pressure at three stations near the Lower Columbia River (see methods) and recorded for the months of April (A) in 1st 3 rows, in May (M) in 2nd 3 rows (i.e. rows 4-6), in June (J) in rows 6-9, and July (JU) in rows 9-12, and related to catches at 1, 2 or 3 year lags (Col catch is lag 1, ColClag2 is Columbia River catch at lag 2 and ColClag3 is Columbia River catch at lag 3).

Table 29: Correlational Analysis on 1, 2, and 3 Year Lags of Pacific Ocean Climate Variability (ENSO and PDO) with Eulachon Columbia River Catch

	APR May ENSO	May June Enso	APRMAY JUNE ENSO	MAY-PDO	JUN-PDO	May-june PDO	COLC	log(COLC)	lag2COLC	log(lag2COLC)	lag3COLC	log(lag3LOGC)
APR May ENSO	1.00											
May June Enso	0.93	1.00										
APR MAYJUNE ENSO	0.98	0.98	1.00									
MAY-PDO	0.66	0.56	0.62	1.00								
JUN-PDO	0.62	0.53	0.58	0.82	1.00							
May-june PDO	0.67	0.57	0.63	0.95	0.96	1.00						
COLC	0.35	0.26	0.31	0.35	0.26	0.32	1.00					
log(COLC)	0.33	0.23	0.28	0.34	0.24	0.30	0.98	1.00				
lag2COLC	0.21	0.16	0.19	0.33	0.15	0.25	0.43	0.48	1.00			
log(lag2COLC)	0.21	0.14	0.18	0.31	0.13	0.23	0.50	0.57	0.98	1.00		
lag3COLC	0.30	0.15	0.23	0.27	0.09	0.18	0.70	0.71	0.47	0.52	1.00	
log(lag3LOGC)	0.22	0.07	0.15	0.21	0.04	0.13	0.68	0.70	0.54	0.60	0.98	1.00

Table 29 shows large scale variables in the Pacific Ocean, including ENSO and PDO for April through June and their relationships to catches on the Columbia at different lags.

Table 30: Correlational Analysis on 1, 2, and 3 Year Lags of Sea Surface Temperature with Eulachon Estimated Abundance

	SST1A	SST2A	SSt3A	SST4A	SST1M	SST2M	SSt3M	SST4M	SST1J	SST2J	SSt3J	SST4J	SST1JU	SST2JU	SSt3JU	SST4JU	Biolag3
SST1A	1.00																
SST2A	0.99	1.00															
SSt3A	0.98	0.99	1.00														
SST4A	0.97	0.97	0.98	1.00													
SST1M	0.51	0.51	0.52	0.55	1.00												
SST2M	0.48	0.49	0.52	0.54	0.99	1.00											
SSt3M	0.55	0.56	0.58	0.59	0.98	0.99	1.00										
SST4M	0.71	0.71	0.72	0.72	0.93	0.93	0.96	1.00									
SST1J	0.16	0.15	0.14	0.16	0.65	0.65	0.65	0.62	1.00								
SST2J	0.20	0.21	0.21	0.21	0.73	0.75	0.75	0.71	0.96	1.00							
SSt3J	0.28	0.28	0.30	0.29	0.78	0.79	0.82	0.80	0.90	0.97	1.00						
SST4J	0.39	0.36	0.36	0.39	0.73	0.72	0.76	0.82	0.78	0.83	0.92	1.00					
SST1JU	-0.04	-0.06	-0.07	-0.13	0.39	0.41	0.41	0.38	0.37	0.50	0.52	0.42	1.00				
SST2JU	0.00	0.00	0.01	-0.09	0.38	0.41	0.42	0.38	0.26	0.44	0.48	0.36	0.97	1.00			
SSt3JU	0.09	0.09	0.11	0.01	0.46	0.50	0.51	0.49	0.31	0.50	0.56	0.46	0.94	0.99	1.00		
SST4JU	0.22	0.18	0.17	0.12	0.51	0.51	0.54	0.59	0.44	0.56	0.64	0.68	0.87	0.85	0.89	1.00	
Biolag3	-0.02	-0.11	-0.18	-0.14	-0.26	-0.33	-0.32	-0.16	-0.16	-0.29	-0.23	0.09	0.02	-0.12	-0.13	0.23	1.00
Biolag2	0.00	-0.08	-0.13	-0.03	-0.29	-0.35	-0.33	-0.16	0.08	-0.06	-0.08	0.15	0.20	0.03	0.01	0.34	1.00
BIOlag1	0.28	0.22	0.17	0.29	0.11	0.02	0.00	0.13	0.14	0.02	0.03	0.23	0.21	0.04	0.04	0.34	1.00

Table 30 shows a similar analysis to Table 27 but on estimated spawning abundance. Sea Surface Temperature (SST) is measured in April, May, June and July.

Table 31: Correlational Analysis on 1, 2, and 3 Year Lags of Upwelling Indices with Eulachon Estimated Abundance

	UPI1A	UPI2A	UPI3A	UPI1M	UPI2M	UPI3M	UPI1J	UPI2J	UPI3J	UPI1JU	UPI2JU	UPI3JU	Biolag3
UPI1A	1.00												
UPI2A	0.90	1.00											
UPI3A	0.78	0.96	1.00										
UPI1M	-0.03	-0.16	-0.22	1.00									
UPI2M	0.05	-0.06	-0.14	0.90	1.00								
UPI3M	0.18	0.17	0.11	0.72	0.88	1.00							
UPI1J	-0.03	-0.08	-0.01	0.43	0.17	-0.01	1.00						
UPI2J	-0.20	-0.06	0.04	0.22	0.10	-0.07	0.79	1.00					
UPI3J	0.01	0.15	0.26	0.05	0.01	-0.15	0.69	0.94	1.00				
UPI1JU	-0.40	-0.42	-0.32	0.08	-0.26	-0.44	0.62	0.43	0.32	1.00			
UPI2JU	-0.18	-0.06	0.04	-0.26	-0.50	-0.49	0.25	0.23	0.23	0.79	1.00		
UPI3JU	-0.07	0.11	0.19	-0.15	-0.29	-0.17	0.19	0.19	0.21	0.56	0.87	1.00	
Biolag3	-0.24	-0.17	-0.02	-0.32	-0.28	-0.23	-0.43	-0.45	-0.38	0.06	0.15	-0.05	1.00
Biolag2	0.03	-0.06	0.06	-0.09	-0.25	-0.30	-0.43	-0.61	-0.66	0.42	0.46	0.31	1.00
Biolag1	0.18	-0.01	0.04	-0.04	-0.32	-0.43	0.25	-0.24	-0.49	0.83	0.76	0.60	1.00

Table 31 shows a similar analysis to Table 28 but on estimated spawning abundance. Upwelling (UPI) is measured in April, May, June and July.

Table 32: Correlational Analysis on 1, 2, and 3 Year Lags of Pacific Ocean Climate Variability (ENSO and PDO) with Eulachon Estimated Spawning Abundance

	APRMAYE	*MAYJUNE*	*APrilMayJuncompE*	*MAYPDO*	*JUNPDO*	*May-june PDO*	*Biolag3*
APRMAYE	1.00						
MAYJUNE	0.45	1.00					
APrilMayJu	0.84	0.86	1.00				
MAYPDO	0.27	-0.30	-0.03	1.00			
JUNPDO	0.23	0.00	0.13	0.86	1.00		
May-june I	0.26	-0.17	0.04	0.97	0.95	1.00	
Biolag3	-0.18	-0.19	-0.22	-0.37	-0.55	-0.46	1.00
BIOlag2	0.12	0.16	0.17	-0.48	-0.57	-0.54	1.00
BIOlag1	0.24	0.06	0.17	0.05	-0.23	-0.07	1.00

Based on the above correlation plots (Table 26-32), we assessed that the relationship between marine indicators and catches is non-existent (or rather flawed, as they imply higher catches with higher SST or low UPI). The only relationships we found had an increase in catches as a function of the Upwelling and the ENSO/PDO indicators, , i.e. with warmer ocean phases, and low upwelling, we tend to get more catches observed on the Columbia River (shown in Tables 29 and 31). Higher abundances or catches in response to warmer oceans is not likely (Langness, et al. 2015, Hay, et al. 1997). We thus dismissed these as spurious relationships. We focussed only on the relationship with estimated spawning biomass, shown in Tables 30-32. Latter years of SLP data were not available, and hence no correlational analysis on abundance was conducted with SLP. However, SLP and UPI are highly correlated, so results from UPI could be informative for SLP as well.

In contrast when we examined the abundance data, we found the month of May (SST 2 and SST3) to be correlated with higher abundance when the SST is lower. In addition, in July, upwelling indices are positively correlated with abundance on either 1, or 2 year lags for the month of July. Finally, the large scale indicators are negatively correlated by a 2 to 3 year lag for PDO in May/June (see Table 32).

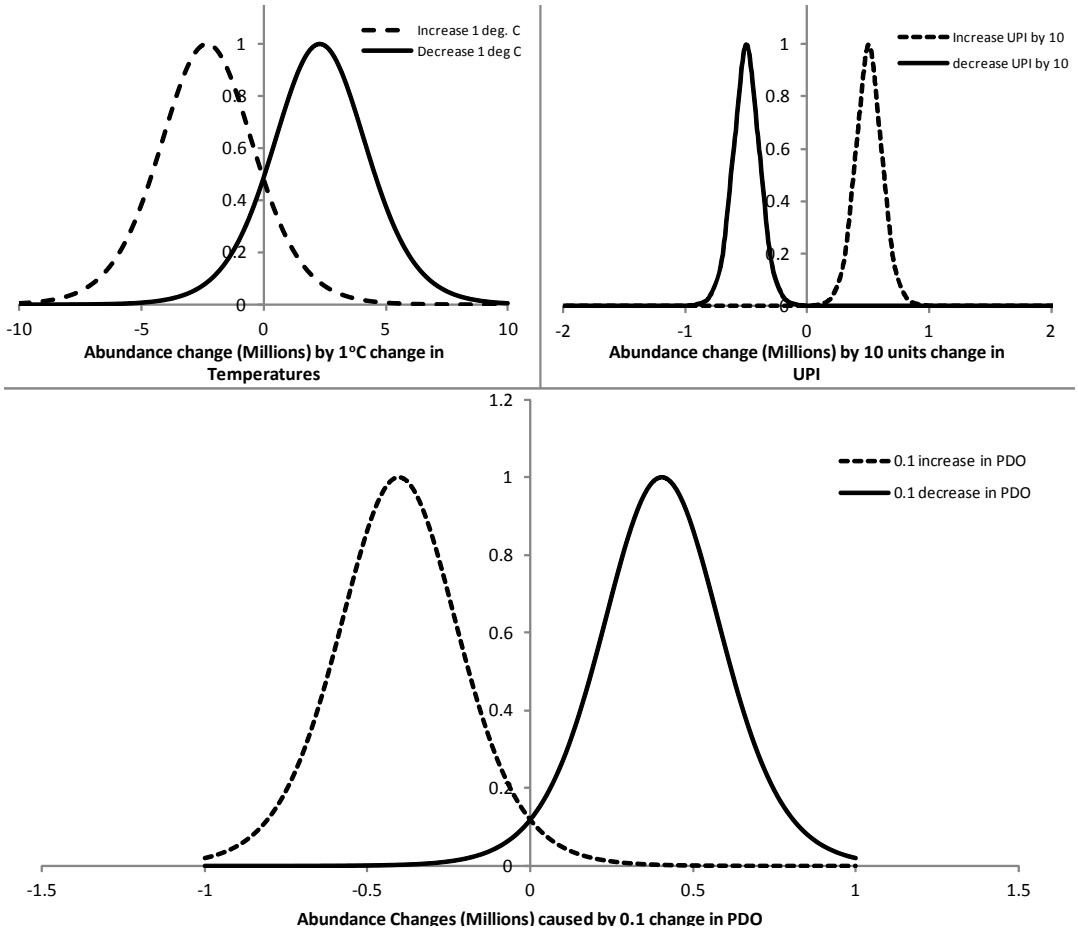

Figure 54: Likelihood profiles of abundance with changes in SST, UPI or PDO

Uncertainty and hypothesized effect of early marine survival indicators on eulachon abundance estimates as related to sea-surface temperature, upwelling, and the PDO is shown in Figure 54. A 1 degree increase in SST could reduce the abundance a few years later by as much as 2.5 million eulachon. In addition, UPI changes by 10 units could increase abundance by 0.5-1 Million. Finally, PDO signals (positive phase) from May using a 2 year lag can decrease abundance by 0.5 million as well. The examination of the relationship between biomass on the Cowlitz River and early marine survival indicators suggest that the year of outmigration (2 and perhaps 3 year lag) are important to survival (and abundance) of spawners two years later (Figure 54). Ocean residence may also be important as a one year residence lag is also influential on spawning abundance a year later.

Based on these findings the early life history is dependent on high flow events. This coupled with positive ocean conditions (as expressed through higher upwelling and lower SST) can provide a boost to survival and abundances as was seen in the last few years 2012-2015 (similar to Oregon coastal Coho, Logerwell et. al. 2003, 2004). These were a function of good ocean and freshwater conditions from 2009-2013, which were coincidentally also some of the best conditions for salmon survival, and returns on the Columbia.

3.2.4 Use of the Trawl Survey Index in Planning and Management

The index of abundance generated from the trawl survey index (Ward, et al. 2015) was examined with the spawning biomass estimated in the lower Columbia River based on larval surveys (Langness, et al. 2015). Data using the trawl index from the preceding year can be regressed with abundance data the following year. Based on this relationship, an extremely good estimate on what may be expected to return in the Columbia is possible using trawl survey data lagged by one year, as shown in Figure 55. This is an independent measure of abundance, and unfortunately with the bycatch mitigation measures implemented in 2015, this predictor is no longer available.

From a management view point, this would have enabled planning if no changes had been made to these indices, and catchability had remained constant, implying that a larger bycatch was implicitly highly correlated with a larger abundance (Figure 55). Results from this analysis are shown below (Table 33 and Figure 55). The results are significant at an $\alpha=0.01$ level of significance. The r^2 values are high (0.91) and the model appears to be unbiased but may tend to over-predict abundance (Figures 55 and 56). In essence, the shrimp trawl bycatch of eulachon was highly correlated with abundance, and if nothing changed in the fishery, this bycatch could have been a good predictor of the annual expected return of eulachon spawners to the Columbia River. However, the implementation of a rule by NOAA to use light sticks in the gear has drastically reduced the bycatch and thus it no longer can serve as a predictor anymore. NOAA could consider the utility of exempting a subset of this fleet from this rule in order to maintain a record of bycatch, which could be used to predict the abundance of spawners for the subsequent years, and to estimate changes in overall abundance of eulachon, but this would run the risk of an added exploitation of an endangered species (Wargo, et al. 2014).

Overall residual diagnostics and parameter values of the fit along with the anova are shown in Figure(s 56 and 57 and Table 33.

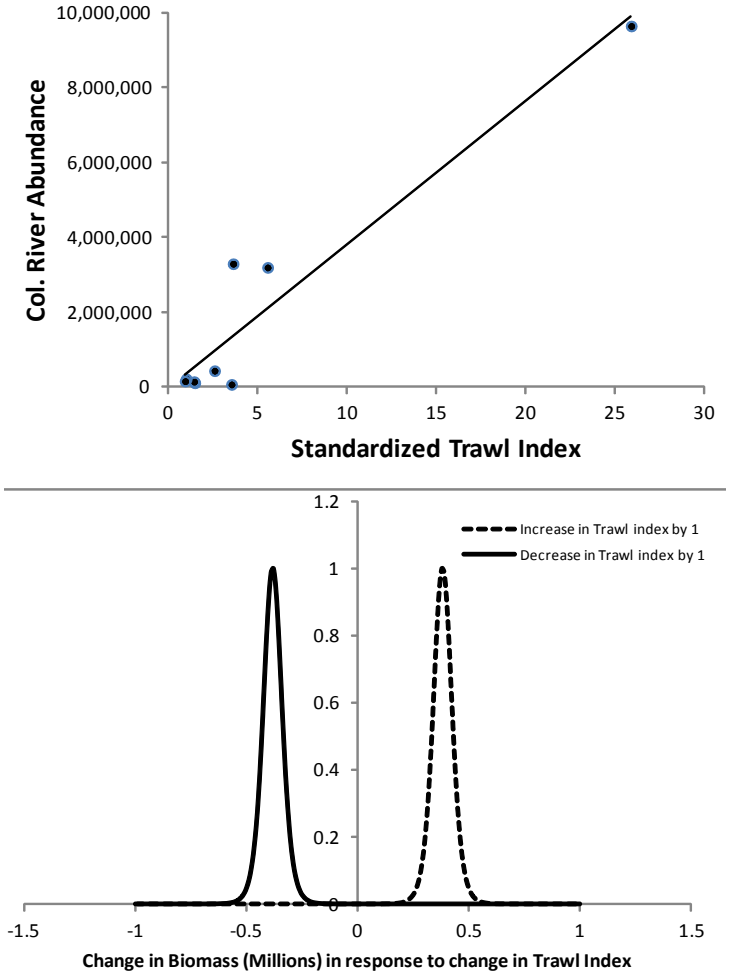

Figure 55: Relationship (fit to the index of abundance using the trawl index as estimated by Ward, et al. 2015) and Uncertainty estimated on changes in abundance as related to an increase/decrease in the bycatch survey by 1 unit

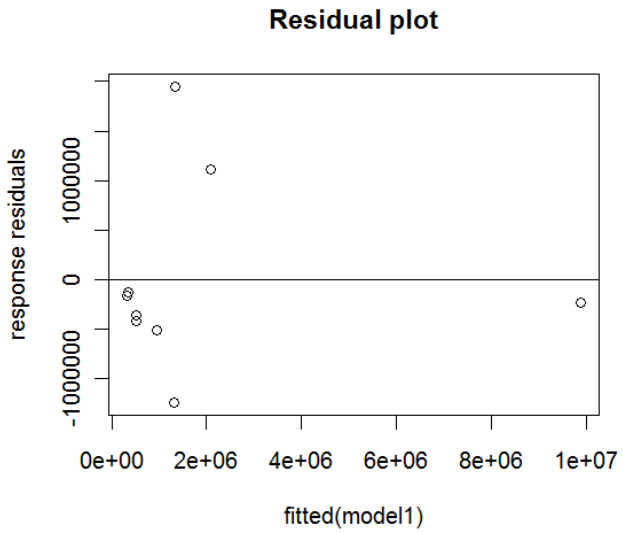

Figure 56: Plot of Fitted versus Residual over the Range of Observation for the model estimating abundance as a function of index estimated by Ward, et al. 2015.s

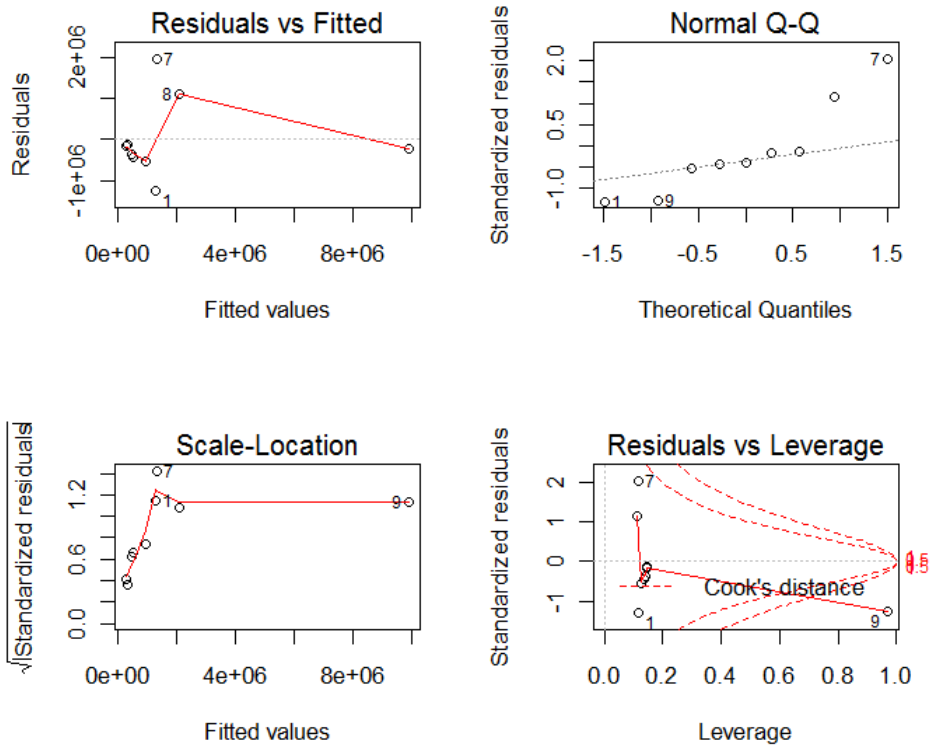

Figure 57: Other Residual Diagnostics of the model predicting abundance based on the trawl index estimated by Ward et al. 2015.

Table 33: ANOVA on Model and Parameter Values from the model predicting abundance (Langness, et al. 2015 as a function of the CPUE estimated from Ward, et al. 2015)

ANOVA

Response: Biomass

	Df	SSQ	MSE	F	Pr(>F)
Trawl	1	7.41E+13	7.41E+13	71.704	6.33E-05
Residuals	7	7.24E+12	1.03E+12		

α=0.01

Coefficients:

	Estimate	SE	t-value	Pr(>t)
(Intercept)	-40628	410522	-0.099	0.924
Trawl	383017	45232	8.468	6.33E-05

3.2.5 Freshwater Climate Change Scenarios Results

We examined modelled monthly runoff for historic and future climate change scenarios (described in section 2.3.4) in each hydrologic unit with eulachon spawning areas. Graphs of these data are shown in figures 57 through 61. The March freshet was projected to increase or remain steady in all hydrologic units, as overall increases in winter precipitation in future climate change scenarios compensates for a smaller snowpack. Notably, early and mid-winter flows are significantly higher for hydrologic units with headwaters in snow-dominant areas, presumably because more precipitation in future climate change scenarios falls as rain and less as snow, leading to earlier runoff. In the Cowlitz River Basin, the most prolific eulachon spawning tributary of the lower Columbia (Hinrichsen 1998), December-February combined runoff is projected to increase 26% from the baseline historic period to the 2040s, and 44% from the baseline historic period to the 2080s. Similar, but less dramatic increases are projected to occur in the Sandy and Lewis basins (Figure 58 and 59). The lower basins (Skamokawa, Elochoman, Kalama and Grays, shown in Figures 60-62) experience only small increases in early-mid winter runoff, because they are historically rain-dominant. These projections suggest that a reduction in the March freshet, which would likely be detrimental to the outmigration of future eulachon runs, may not be a concern in the lower Columbia tributaries, but a shift to earlier peak flows may change run timing (or protract the outmigration period).

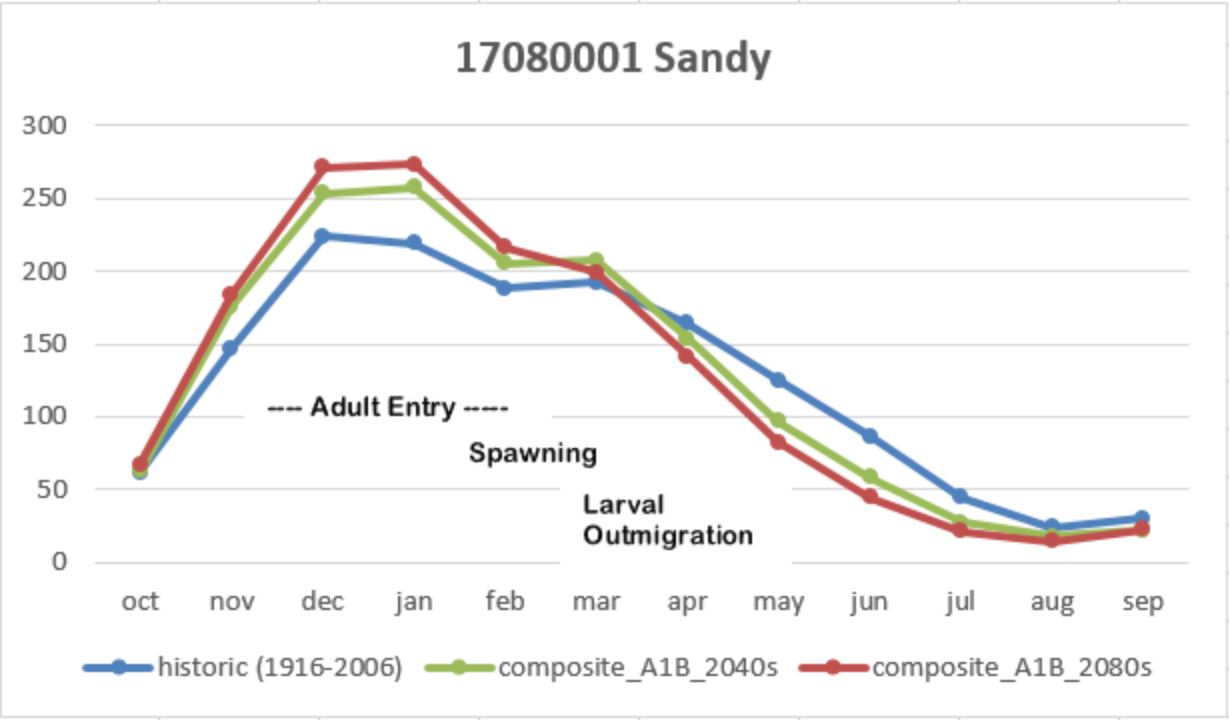

Figure 58: Relative Modelled Discharge of Historical and Climate Change Scenarios in HUC 17080001

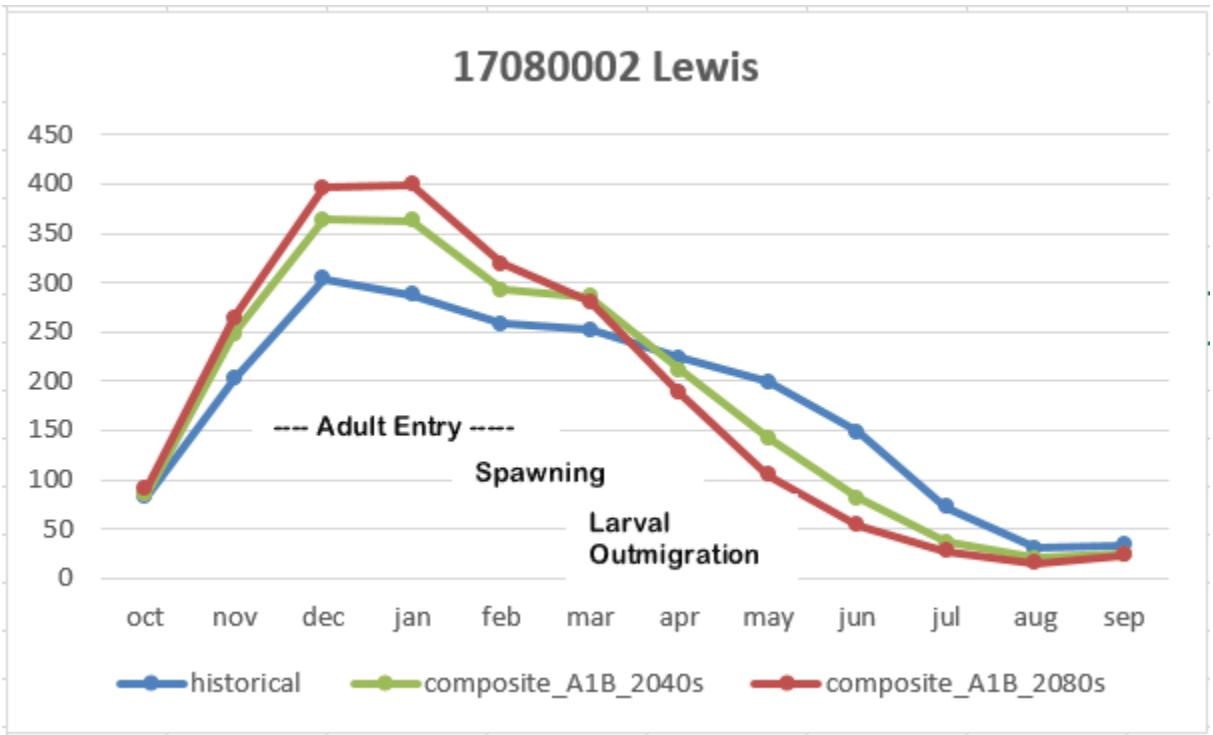

Figure 59: Relative Modelled Discharge of Historical and Climate Change Scenarios in HUC 17080002

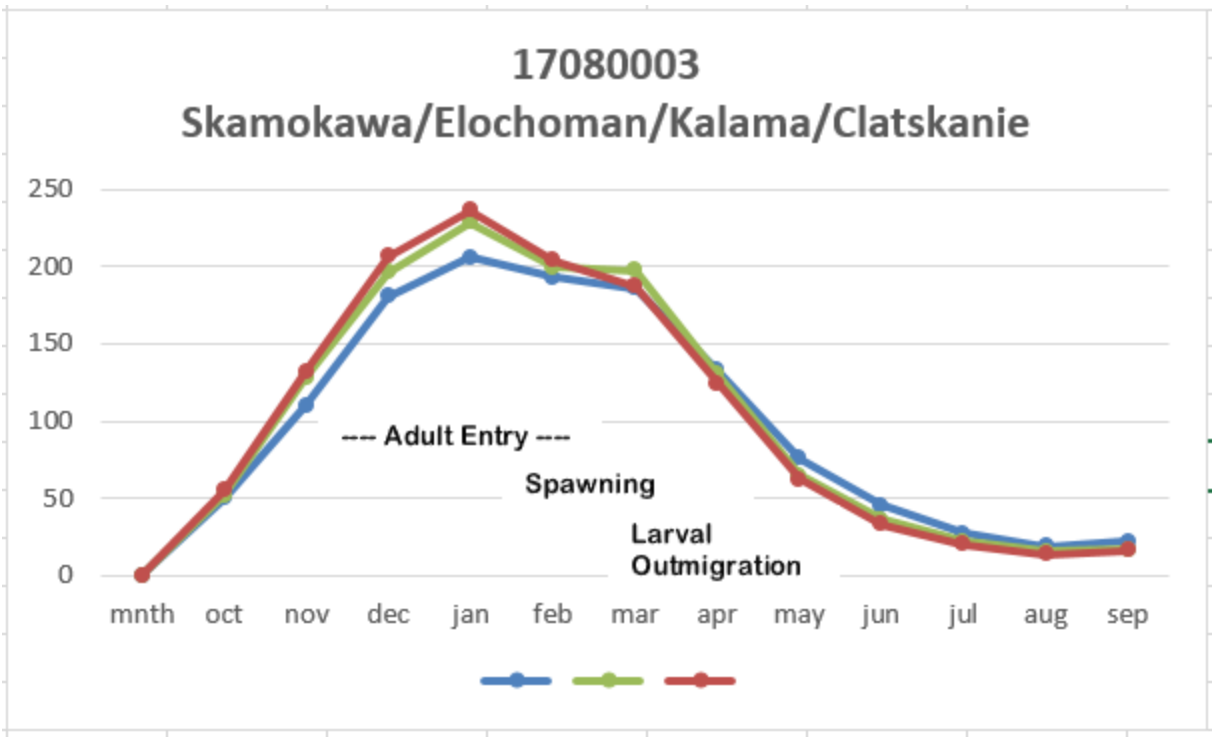

Figure 60: Relative Modelled Discharge of Historical and Climate Change Scenarios in HUC 17080003

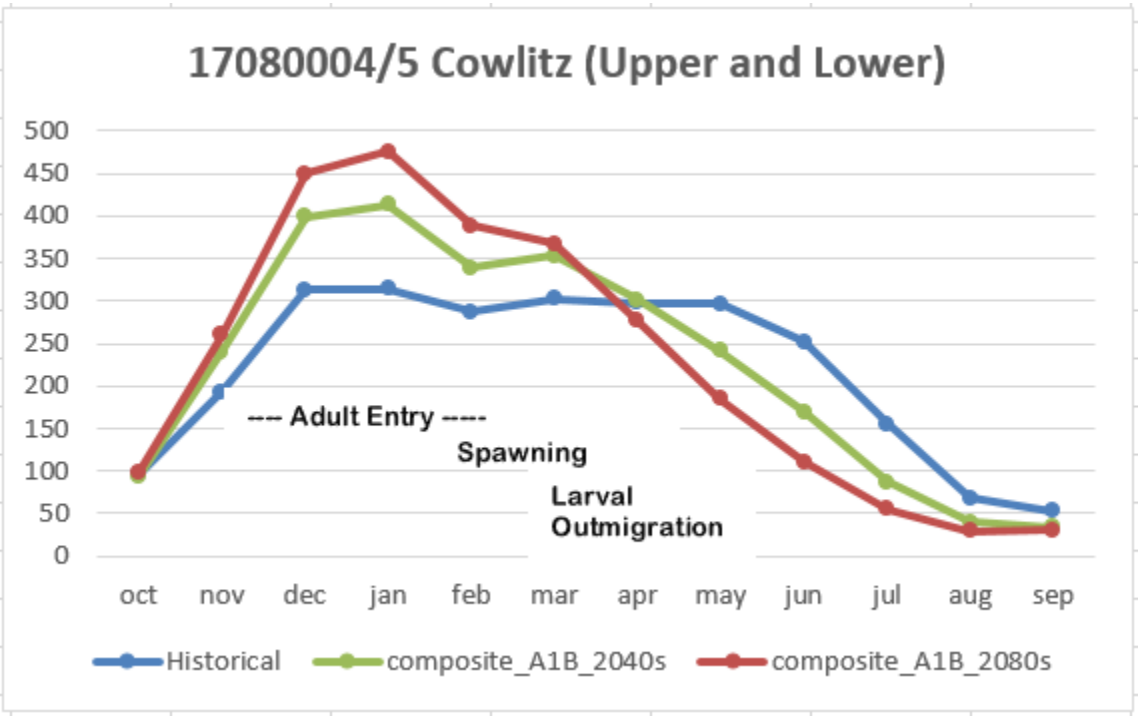

Figure 61: Relative Modelled Discharge of Historical and Climate Change Scenarios in HUC 17080004 and 5

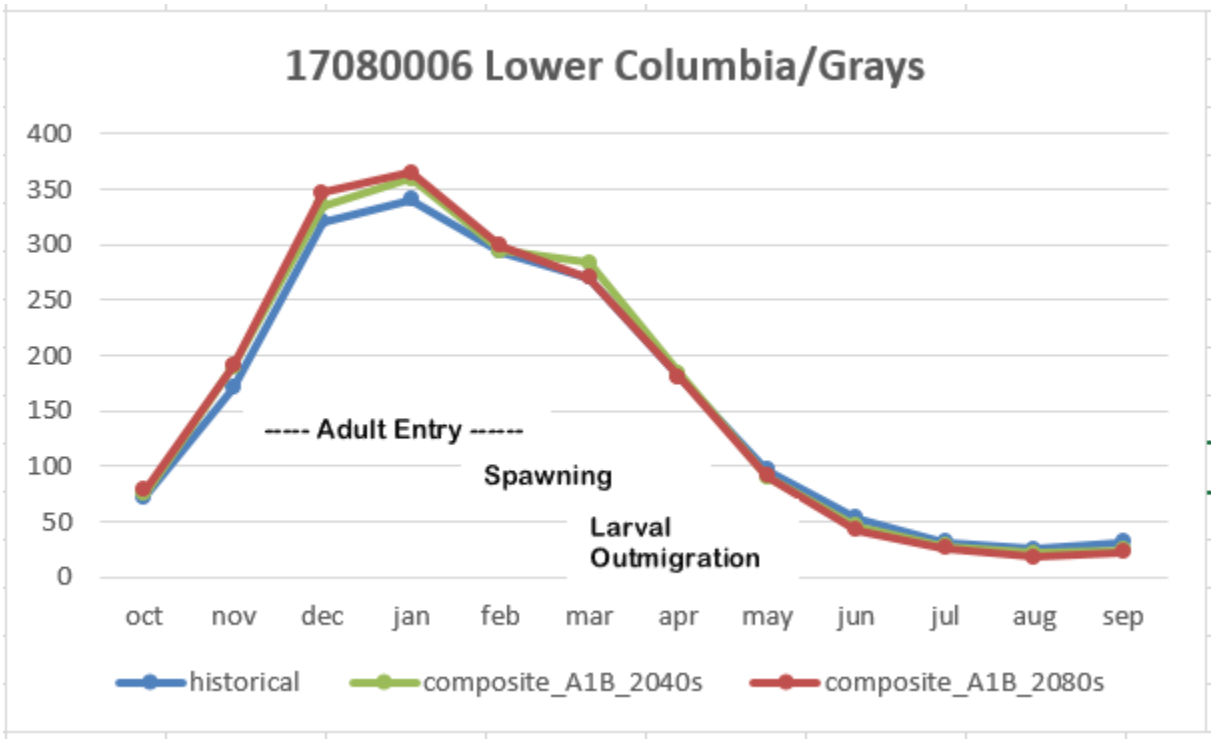

Figure 62: Relative Modelled Discharge of Historical and Climate Change Scenarios in HUC 17080006

In addition to tributary flows, outmigrating larvae are also aided by the spring freshet that occurs from the mainstem Columbia River. In general, the management of Columbia Basin dams and reservoirs have diminished this spring freshet from its natural peak, smoothing out flows to reduce flood risk and produce hydropower in the winter and summer months, when it is most in demand (Bottom, et al. 2005). Many provisions of this approach to river management are mandated by the Columbia River Treaty, signed in 1964 between the U.S. and Canada, which is currently under review and may be modified after 2024. It is believed that this reduction in the magnitude of the spring freshet may reduce the survival of larval eulachon in years that it doesn't facilitate their travel into the nutrient-rich waters of the coastal environment (Gustafson, et al. 2010) "Naturalized" flows are often modelled and examined in order to understand the discharge that would occur without the influence of dams and irrigation withdrawals. Figure 63 shows the projected change in unregulated flows for a range of future climate change scenarios and periods from UWCIG (2010). Increasing rainfall and less snowfall in the Upper Columbia River Basin is projected to cause the peak in available discharge to occur earlier in the spring, and likely increase the overall water supply during the winter months while decreasing it during the late spring and summer months. A consequent adjustment of dam operations to compensate for these changes may be a useful tool for aiding eulachon outmigration in the future and increasing their survival in the estuary-plume environment (Anderson 2015).

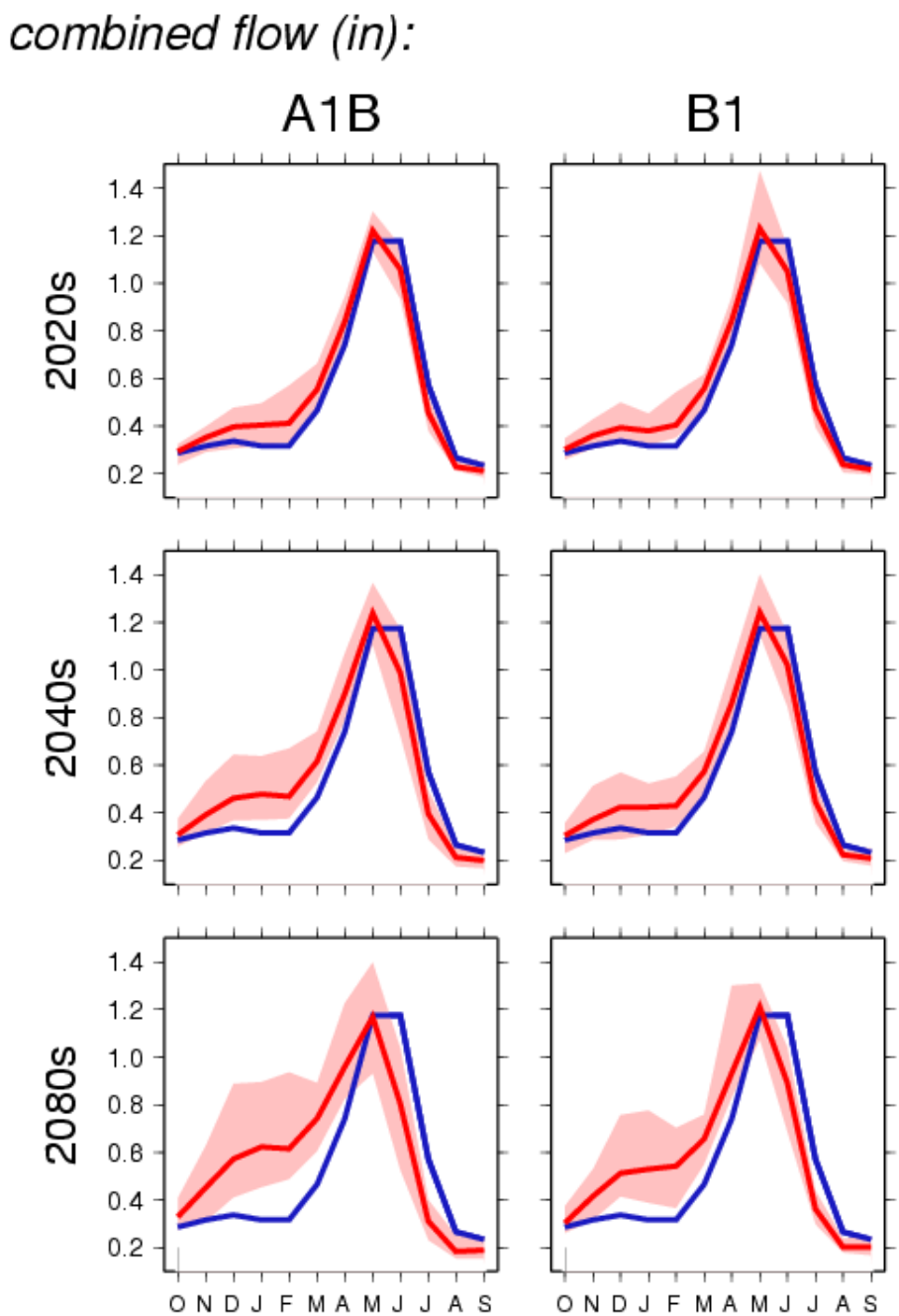

Figure 63: Projected Changes to the Naturalized Hydrograph of the Columbia River at Vancouver (blue = historic, red = range of projected flows from each future period and scenario ensemble) (from UWCIG 2010)

Because adult eulachon are adapted to begin their immigration to spawning tributaries after the coldest temperatures of winter have occurred, we also examined historic water temperatures in the Columbia River (DART 2015, see section 2.1.1.3 for a description of this data). Table 34 shows the mean date at which temperatures in the Lower Columbia River (at the Bonneville Dam forebay) first exceed 4.4° C

(this threshold was estimated to trigger eulachon inmigration (Bargmann 2000)) in each 10-year historic period.

Table 34: Mean Date that Lower Columbia River Temperature First Exceeded 4.4° C after the Mid-Winter Temperature in 7 Periods

Year Range	Date
2005-2014	27-Feb
1995-2004	14-Feb
1985-1994	3-Mar
1975-1984	21-Feb
1965-1974	7-Feb
1955-1964	27-Feb
1945-1954	25-Feb
Historic Range	7-Feb to 3-Mar

With warmer air temperatures and greater proportions of rain than snow, we can expect that winter river water temperatures will increase with climate change. An understanding of how this may occur would be aided by the application of water temperature models for the winter months, but this effort has not been undertaken yet to our knowledge in the lower Columbia River. For this analysis, we projected air temperature increases (January-March) from the ensemble climate change scenarios developed by WCIG 2010 onto the historical water temperature record of the Columbia River at Bonneville. In order to do this, it was necessary to convert air temperature increases to water temperature increases, because this generally doesn't occur in a 1:1 ratio, but rather as a diminished effect because of other controls on water temperature such as changes in discharge (Isaak, et al. 2012). Morrill, et al. (2005) examined the historic water temperature of a group of disparate streams and rivers, and found an average ratio of increase of +0.7°C water temperature for each increase of +1.0° C air temperature. We applied this 0.7:1.0 ratio increase to projected air temperature increases for future climate change scenarios to the historical water temperature record. As part of this process, it was also necessary to adjust for the difference between the climate change scenarios baseline period (1916-2006) and the period of the Columbia River temperature data (1965-2014). To do this, we used the Pacific Northwest Index, a climate index developed by Ebbesmeyer and Strickland (1995) and summarized online by the UWCIG (2012) to study climate effects on salmon productivity. We then summarized the mean water temperature in the Lower Columbia River by month for the historic and future scenarios. These results are presented in Table 35.

Table 35: Mean Monthly Water Temperature (°C) of the Columbia River below Bonneville Dam for Historic and Future Climate Change Scenarios

Scenario:	1916-2006	1965-2014	B1 2020s	A1B 2020s	B1 2040s	A1B 2040s	B1 2080s	A1B 2080s
January	4.47	4.55	5.02	5.32	5.42	5.80	6.00	6.99
February	4.09	4.18	4.91	4.97	5.04	5.35	5.79	6.51
March	6.10	6.18	6.83	6.84	6.83	8.03	7.56	8.43

According to this analysis, under all future climate change scenarios, a 4.4° C water temperature threshold appears irrelevant, as winter water temperatures will rarely dip below this mark, if at all. For in-migrating eulachon adults, it may mean that this will allow earlier migration into the system, as warmer water temperatures may be hospitable throughout the winter for spawning. This effect could potentially be beneficial to eulachon, in that it could allow for a longer spawning period, and different life cycle strategies to take advantage of this. However, higher water temperatures in coldwater fish during rearing causes a faster development but smaller size at hatch. Without adequate food sources, these fish are disadvantaged in their growth and development. There is also a potential for ill effects on out-migrating larvae, if they leave their natal rivers earlier in the winter, and their arrival in the ocean is mismatched with spring upwelling periods off of Oregon and Washington, which usually don't begin until April, and usually peaks in early summer (Schwing, et al. 2006). Further complicating matters, changes to the intensity and period of upwelling off the NE Pacific coast (i.e. the California Current) are uncertain under future climate conditions (Doney, et al. 2012).

4 Discussion

The findings of our varied analyses are summarized and discussed below in sections 4.1 through 4.3.

4.1 Effects and Threats on Lamprey

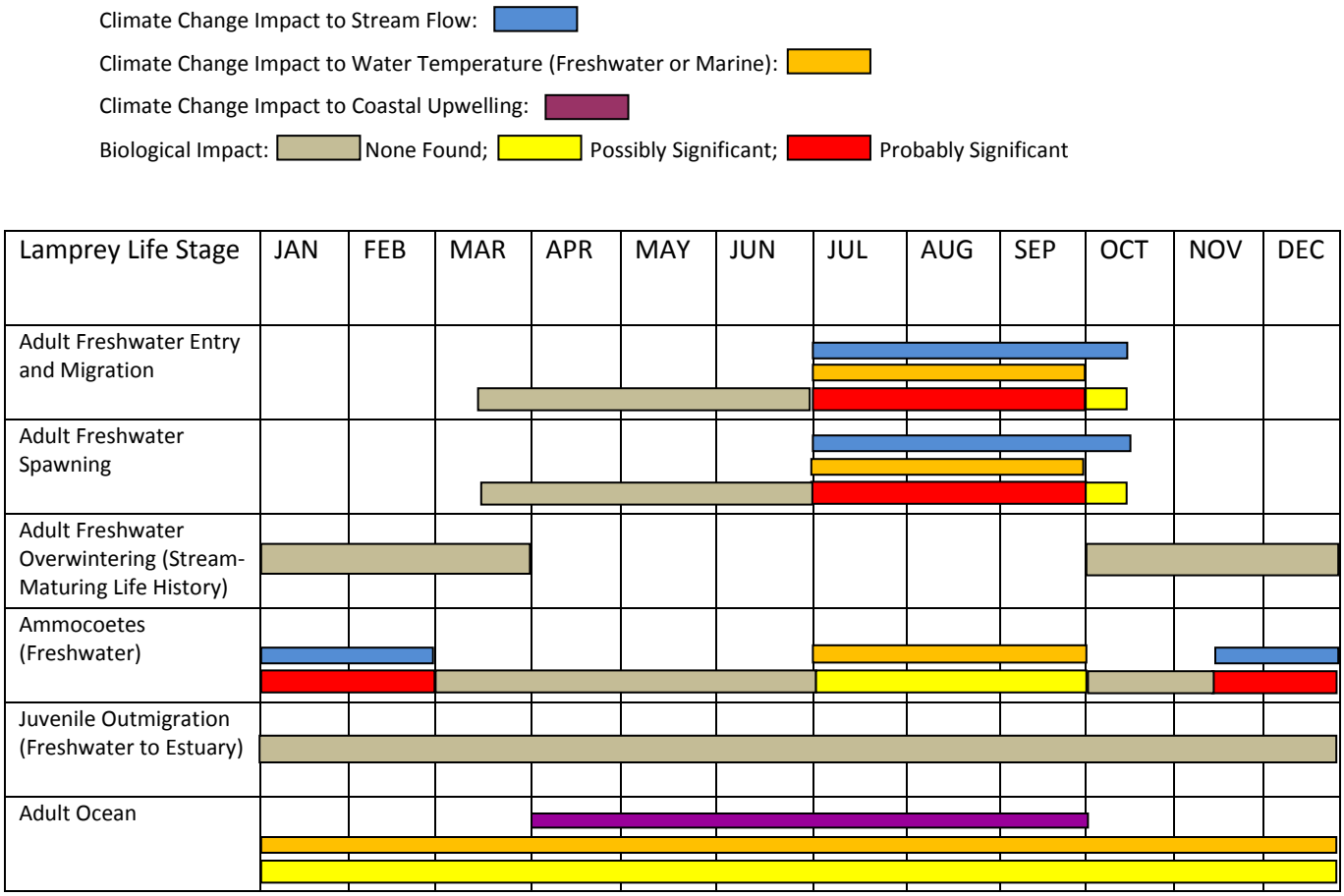

Figure 64: Lamprey Life History Stages and Assessed Potential Impacts of Climate Change

We developed a lamprey life cycle impacts graph (Figure 64) to summarize possible climate change effects to lamprey. Lamprey are known to adapt or vary their life history strategy to persist in various environments in the freshwater and ocean stages of their life-cycle, which may make them more resilient to climate change. However, serious impediments to passage and further degradations in freshwater and ocean conditions can further restrict their resilience. Areas of threat are evident in terms of habitat loss, spawning and rearing area reductions, and limitations in the near term presented by migratory challenges through a heavily managed river system.

Adult lamprey entry to freshwater covers a large number of months, and their spawning is thought to vary from one to two years of holding. Based on the freshwater life history of lamprey and current limitations to returning adults, it is likely that climate change will detrimentally affect the range and success of spawning and rearing through several mechanisms: (i) Because of diminished stream flows in the late spring and summer, lamprey migration will likely be hindered in affected tributaries; (ii) Higher water temperatures during the summer will likely decrease fitness for migrating adults; (iii) The combination of higher water temperatures and lower flows during the summer and early fall will likely negatively affect spawning and larval rearing; (iv) Higher water temperatures during the summer are likely to assist non-native predators of larval and juvenile lamprey; (v) Higher peak flows during the winter and consequently greater peak flows may push larvae or juveniles downriver before they are sufficiently developed. Our analysis suggests that these detrimental freshwater effects will be greatest in the interior watersheds of the Columbia Basin, with snow-dominant or transitional hydrological regimes, which will be most affected by air temperature increases, and also where lamprey are already most impacted by long migrations through several hydropower projects. Lower basins such as the Willamette River may offer a relative stronghold for lamprey spawning under a warming climate because their hydrologic regimes are more rain-dominant, and likely to experience relatively less disruption from climate change.

As juveniles, two pulses are evident on outmigration coinciding with peak flows, one in November and December and then another in April and May. Some evidence from our analysis suggests larger peak flows in November and December can adversely impact abundance (indirectly implying survival is lower when large flow events occur), though the mechanism for this is not entirely clear. A possible hypothesis is that ammocoetes or juveniles are forced out of the lower systems into the estuary/open waters where they suffer large predators, and hence survival declines. Global warming as expressed by increasing sea surface temperature are likely to reduce survival and abundance, but the magnitude of this effect is largely unknown as no measure of available ocean abundance is currently available.

As adults, in the ocean they are largely parasites, and can adapt to varying environments as a function of their host. As such, they are vulnerable to changes to ocean conditions that affect the abundance and composition of host species. Climate change ocean impacts that may directly affect host species and lamprey in the marine environment include higher water temperature and changes to offshore upwelling (studied here) and others such as ocean acidification (not studied here).

While climate change effects examined here are evident through impacts to freshwater migratory corridors and spawning habitat, and disruptions to the marine environment, a larger source of threat to their persistence is probably from human induced causes not examined in this report (e.g. both juvenile and adult passage through dams, as well as degradations to water quality) (CRITFC 2011). Effort is being made to develop better bypass systems and upriver translocation for these fish, which if successful, may assist in the recovery of some runs (CRITFC 2011). Fishery effects are minimal currently, and if they are kept to the levels currently observed, it is likely that rebuilding trajectories will occur if passage and bypass issues are fixed for these species.

4.2 Effects and Threats on Eulachon

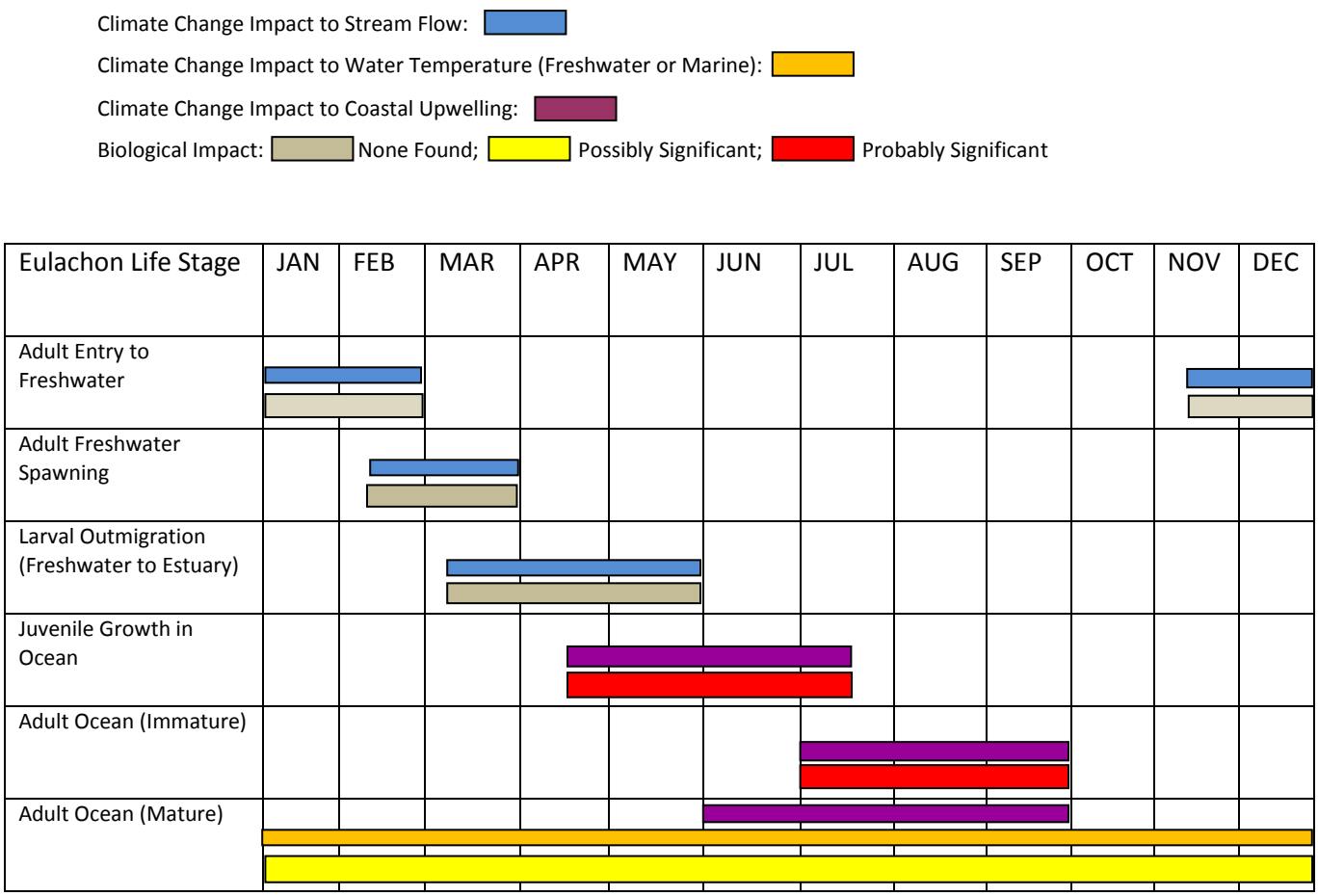

Figure 65: Eulachon Life History Stages and Assessed Potential Impacts of Climate Change

In Figure 65, we summarize the potential climate change impacts to eulachon life stages as hypothesized from our research and the existing literature. Eulachon enter the Columbia River and its lower tributaries between late fall and mid-winter, spawn in late winter, and then reside as larvae in the lower river until the freshet flushes them out in the early spring. Our examination of potential changes to flow and temperature in the freshwater environment suggest that eulachon spawning in the Lower Columbia River tributaries may not be adversely affected by climate change, and indeed it may extend the period

of suitable spawning. However, earlier spawning coupled with earlier and larger winter stream peak flows, which are forecast by climate models, may cause juvenile outmigration earlier in the year. This earlier outmigration could be detrimental to juvenile growth if it is mismatched with ocean upwelling conditions, which generally occur later in the spring. Modified dam operations on the mainstem Columbia and the Cowlitz River may be helpful in assisting the outmigration of juveniles to match optimum upwelling periods.

Maximum flow events in July, with a lag of two years before returning spawners appear to strongly influence survival and abundance as related to both catches and biomass. These are probably correlated with conditions in the June/July when the juveniles are transitioning from a freshwater to an ocean environment. Positive stream flow in July coincides with cooler PDO phases (primarily through higher snowpack), but also corresponds to good ocean conditions for these fish (Logerwell, et al. 2003). So, even though the mechanism for July flow may not make sense from a biological sense, the fact that abundance is also related to colder temperatures in the ocean in July and negative PDO conditions suggests that changes in both the timing and magnitude of spring transition and upwelling can have severe effects on eulachon abundance. This may be the reason for the decline in eulachon abundance during the 1980's and 1990's, as prolonged El-Nino events during this period may have amplified poor freshwater runoff along with poor ocean conditions for the larvae. Early life cycle survival as suggested by a lower spring run-off and warmer ocean conditions appears to be the limiting factor in these cases, and may be the primary reason for the declines observed in abundance over time. Such conditions are likely to increase in the future thereby affecting the long term persistence of eulachon in a greater manner unless they evolve to adapt to these changes.

Bycatch in shrimp trawl operations was determined to be a severe problem for the persistence of adults by Wargo, et al. (2014), but as demonstrated in our analysis, bycatch rates are highly correlated with abundance, and may be a useful planning tool for in-season fishery management. However, with the implementation of lights on shrimp trawl boats, these catches have declined substantially and can no longer be used as an indicator for abundance. We recommend a possible alternative to a complete ban on bycatch mitigation measures, by using an experimental set of boats that fish using the traditional method so that the trawl survey index could be generated and used in management as an early indicator for abundance.

4.3 Conclusion

The report we present here has taken varied approaches to examine the potential impacts of climate change on the life cycles of Pacific lamprey and Pacific eulachon. Implications for changes to freshwater distribution and survival are considered with the use of GIS, and empirical based approaches are used to examine correlations between abundance and both ocean and freshwater conditions. The two life history strategies incorporated by lamprey and eulachon are very different and these create different outcomes for the same environmental changes. While lamprey have a large array of life-history strategies that can adapt to climate change, they are still susceptible to several impacts including changes to tributary conditions (more winter flooding, reduced flows during the late spring and summer, and higher summer water temperatures) and changes to ocean conditions (higher sea surface temperature and reductions or changes in the composition of host species). Additionally, their current

persistence is imperilled by large hydropower dams on the Columbia and Snake Rivers that impede passage because adequate bypass mitigation measures are lacking. In contrast, eulachon are likely to be adversely affected by climate change from both changes to river and ocean conditions that may affect persistence (earlier run timing, early spawning, earlier freshets, missing spring transition and favourable upwelling conditions, affecting survival, and persistence). While Lower Columbia River eulachon are not affected by passage through the upstream dams, their outmigration is affected by the modified flows in the system from hydropower and flood control operations. Overall, the life cycle of Eulachon is thought to be not very adaptable, leaving populations susceptible to changes, especially in ocean conditions. A high variability in returns has occurred historically, however, with periodic declines followed by restored abundance, coinciding with improved ocean conditions.

Both lamprey and eulachon will likely be negatively affected by increases in Sea Surface Temperature and lower upwelling conditions the year before they show up to the river. In addition for eulachon, early life stage survivals are highly dependent on ocean conditions during their outmigration from the freshwater to the marine environment. In general, the timing of the spring transition and the magnitude of the upwelling and reductions in sea surface temperature that accompany it indicate larger survival and abundances for both species than contrary conditions of less upwelling and higher temperatures. The conditions prior to river entry as adults is also important as it indicates food availability to these species either directly (eulachon) or through their host (lamprey) which indirectly affects survival. With climate change effects that make these components less predictable, and more variable over time, this life-cycle phase has a large impact on the persistence of both species.

4.4 Future Work Planned

More work to collect finer scale data is important as both lamprey and eulachon have poor data availability on specific life stages, and larval, juvenile, and adult abundances information is incomplete in most areas. Additionally, biological data, including thermal preferences and lethal limits should be further developed, especially for lamprey. Once more data is collected, fine scale models on movement, distributional changes, and survival can be developed. Currently, only large scale dynamics can be hypothesized, but with better research and data, more refined knowledge can be inferred about the status and trends of these species in their respective habitats in the Columbia River Basin.

5 Acknowledgements

We thank the North Pacific Landscape Conservation Cooperative, the Northwest Climate Science Center, and the Bonneville Power Administration Fish and Wildlife Program for providing support and funding for this project.

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Appendix A: Hypothetical Lamprey Life Cycle Model Affected by Climate Change

Description of Hypothetical Model and Parameters

We present a hypothetical life cycle model here, created to simulate effects of climate and environmental change on the life history of Pacific lamprey. The model is applied here with data from the Clackamas River basin, a tributary of the Willamette River. The model was created for this application in a spreadsheet format, with parameters that may be easily modified, and life cycle trajectory results that may be viewed in tabular and graphic outputs. Because key data are missing on lamprey in this region, this model required many assumptions is only presented as an example and should not be considered an actual real world simulation

Land cover data along with stream area was obtained for the Clackamas basin for the years 1992 and 2011, using information from the USGS National Land Cover Data assessments (Vogelmann, et al. 1992, Homer, et al. 2011). The land cover composition and change between 1991 and 2011, and lamprey distribution (Oregon Department of Fish and Wildlife 2012) was summarized into major categories and is shown in Figure Ap1 and Table Ap1.

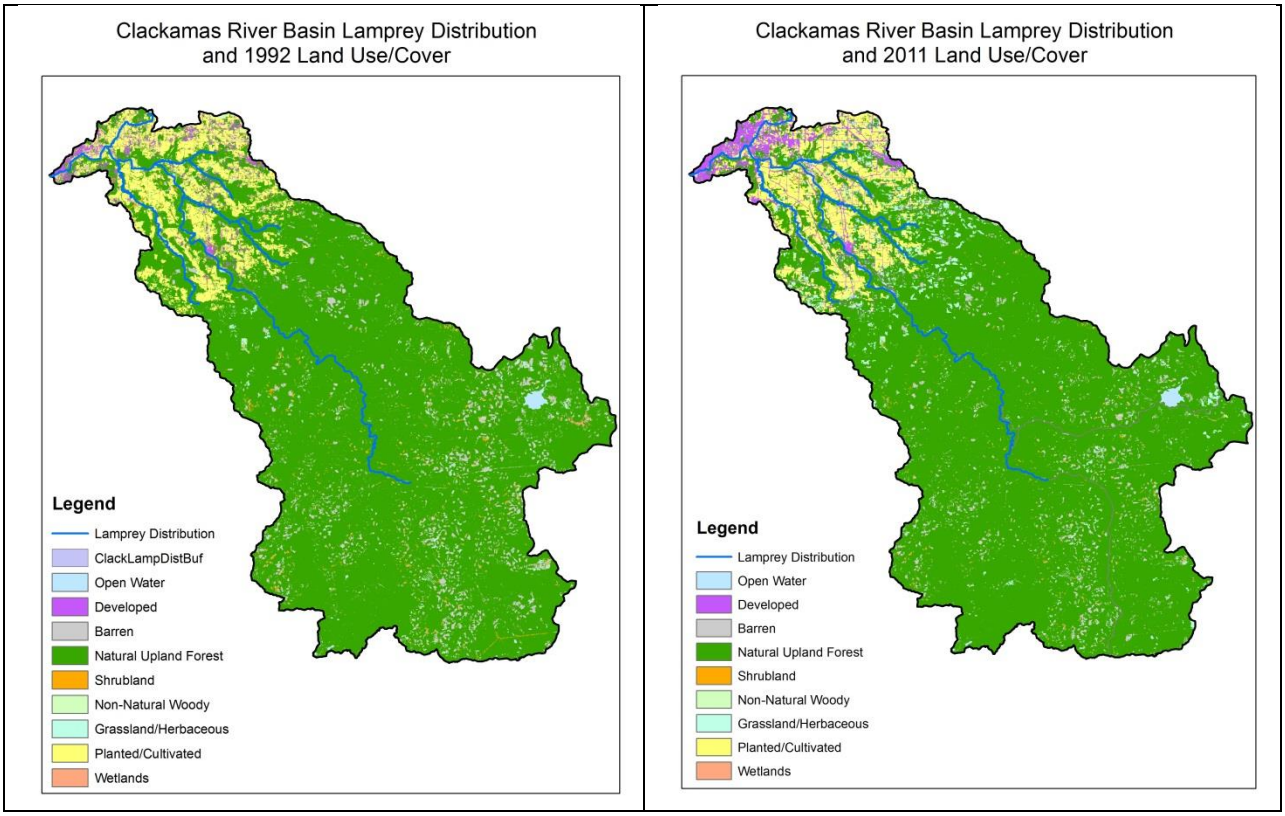

Figure Ap1: Clackamas land cover and stream area suitable for lamprey habitat between 1991 and 2011

Table Ap1: Areas by land cover type in the Clackamas Basin suitable for lamprey habitat

Year	1991 (Area Sq. kms)	2011 (Area sq. kms)	Productivity Scalar	Productivity Scalar (Sensitivity)
Natural Upland Forest	0.31416	0.28554	85%	100%
Shrubland	0.00488	0.04256	70%	85%
Barren	0.01604	0.00052	60%	60%
Grassland / Herbaceous/Planted/Cultivated	0.03576	0.03545	40%	50%
Wetlands/Open Water	0.00258	0.00331	40%	40%
Developed/Urban /Non Natural Woody	0.00654	0.01259	40%	30%

Using hypothetical capacity that can be derived by field studies, the amount of juvenile lamprey that can be estimated by life stage is shown below (Table Ap2).

Table Ap2: Hypothetical capacity for juvenile lamprey by stream attribute

Hypothetical Capacity juvenile lamprey/ m2				
Habitat type	egg-pre AM	pre-AM-Amm	Amm-prejuv	preju-juve
Pools	227.5	15.5	76.25	0
Cascades	0	20	0	0
Glides	180	8	10	0
Riffles	120	1	1	0
Rapids	60	1	1	0
other	180	105	50	0
sp gravel	0	0	0	1000

Based on how the stream area is distributed by habitat characteristics (Table Ap3), stage based Beverton-Holt life cycle models can be projected using life cycle stage based fecundities and survivals (Table Ap4).

Table Ap3: Distribution of stream habitat type by land use category

Year	Pools	Cascades	Glides	Riffles	runs	other
Natural Upland Forest	60%	0%	5%	30%	5%	0%
Shrubland	50%	0%	10%	30%	10%	0%
Non-Natural Woody/barren	40%	0%	10%	40%	10%	0%
Grassland / Herbaceous/Planted/Cultivated	20%	0%	20%	40%	20%	0%
Wetlands/Open Water	0%	0%	0%	0%	100%	0%
Developed/Urban/Non Natural Woody	10%	0%	20%	50%	20%	0%

Table Ap4: Stage based density independent survival and fecundity rates

Stage	Perfect conditions	productivity Scalar 1	Productivity Scalar 2
spawning-Egg (fecundity)	84100	64929	76329
egg-pre AM	10%	8%	9%
pre-AM-Amm	40%	31%	36%
Amm-prejuv	33%	26%	30%
preju-juve	75%	58%	68%

From these values, we projected and initial level of 300 annual spawning adult lamprey in the Clackamas basin, and the following dynamics for the productivity (scalar 1). We assumed returns to adults spawners occurring all within 5 years of moving out of the freshwater, with 15% coming back at age 3 ocean years, 40% at age 4 ocean years and 100% of the age 5 ocean years. Survival to the 1st ocean age was assumed to be 0.03 (this value is extremely sensitive and is assumed to be highly dependent on upwelling etc). Survival from one age to the next were assumed to be 0.7, 0.8 and 0.9 for years 2, 3, and 4, respectively. We modelled out to 84 generations, which translates out to between 800-1000 years into the future (assuming that each generation can live anywhere from 10 to 15 years).

Results and Model dynamics

Freshwater effects that could be modelled in response to climate

Two runs are presented here, examining freshwater effects on the species. These sensitivities could vary as a function of climate change, as well rather than land cover change, and we could simulate different productivity scalars for the same vegetation type over time. We examined the two sensitivities (Figure Ap2), the 1st having a slight decline and similar weights for the land classifications for grasslands,

wetlands and urban land cover classes, and the second one showing a decline in productivity by land class.

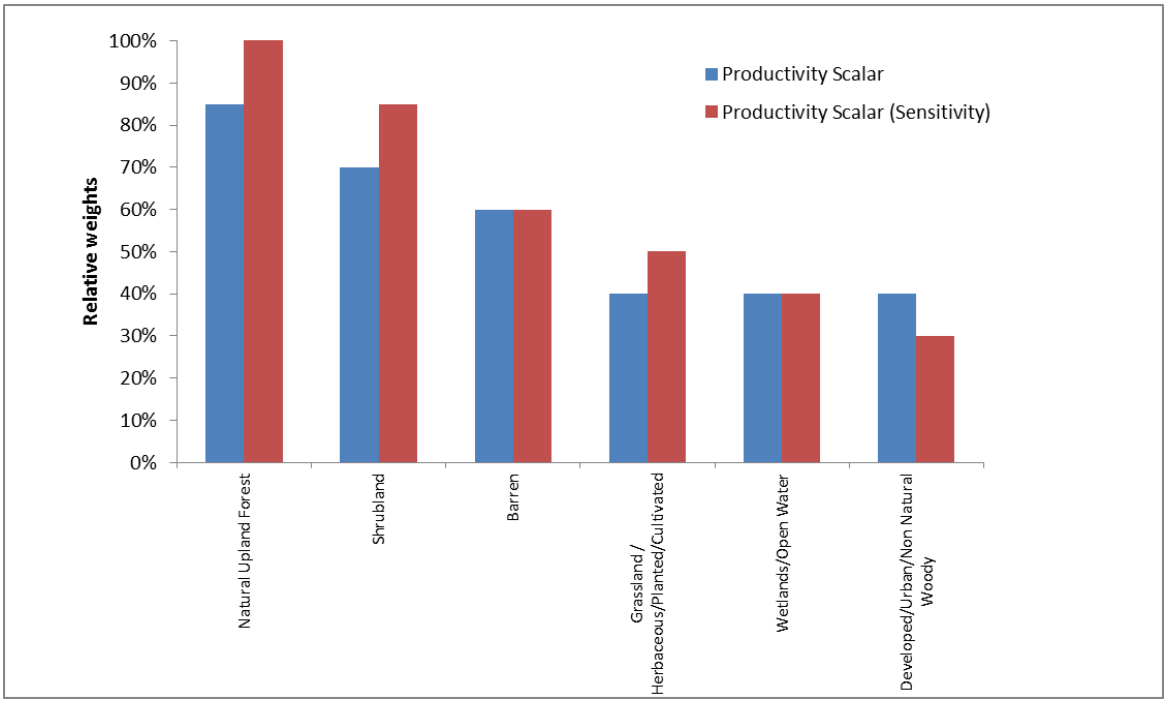

Figure Ap2: Sensitivities examined where different land-use types affect productivity by different weights

Another way to model the impact of climate would be to show the productivity change for the same land class type change every 5-10 years as function of changes to the freshwater environment, which could be done with slight modifications to the model presented here.

Dynamics by freshwater and ocean stage are shown below in Figure Ap3 (using the base case sensitivity shown in Figure Ap2), and a declining sensitivity (Figure Ap4).

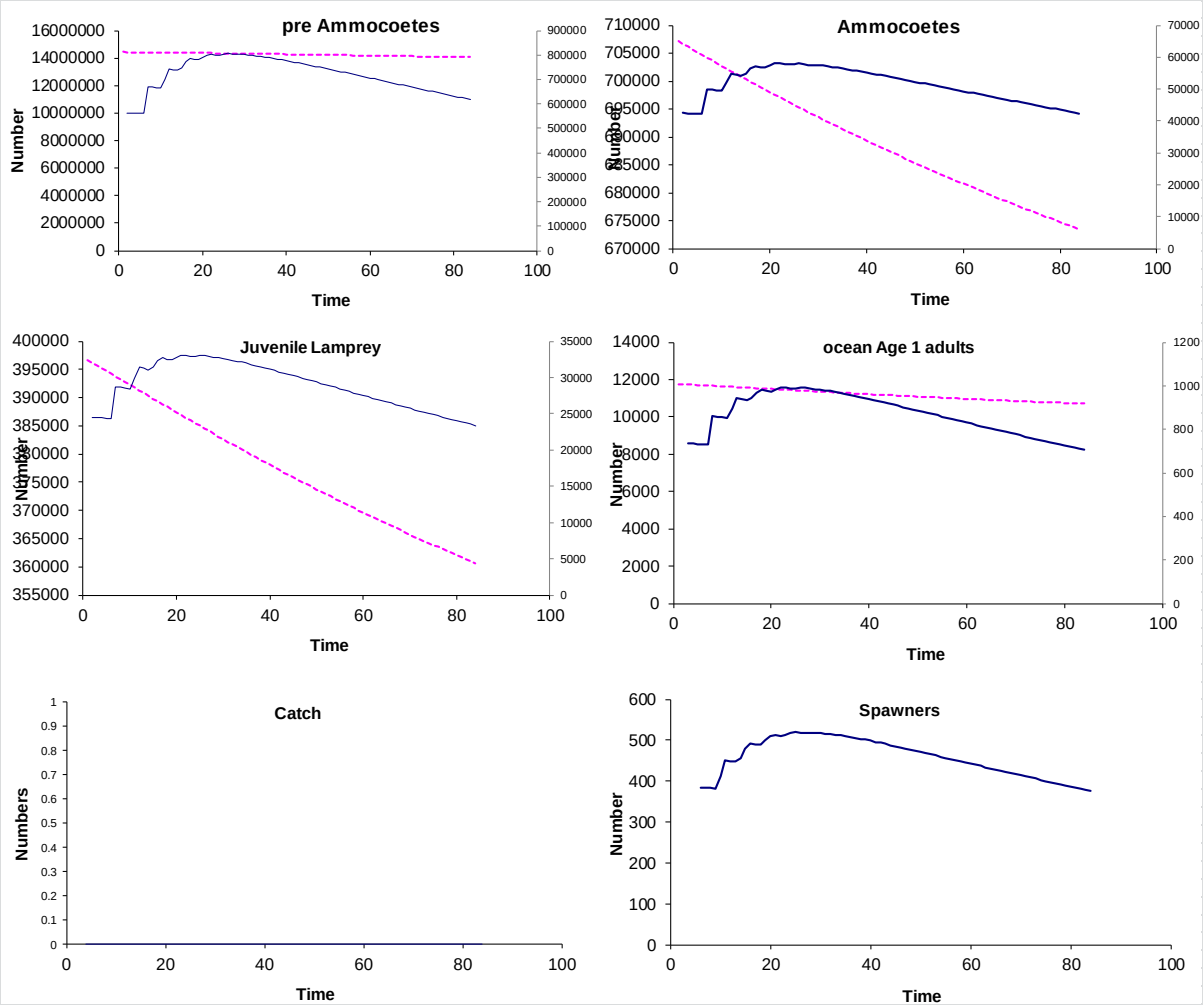

Figure Ap3: Population trajectories based on initial weights (marine survival is assumed to be 3% for the early life-cycle phase)

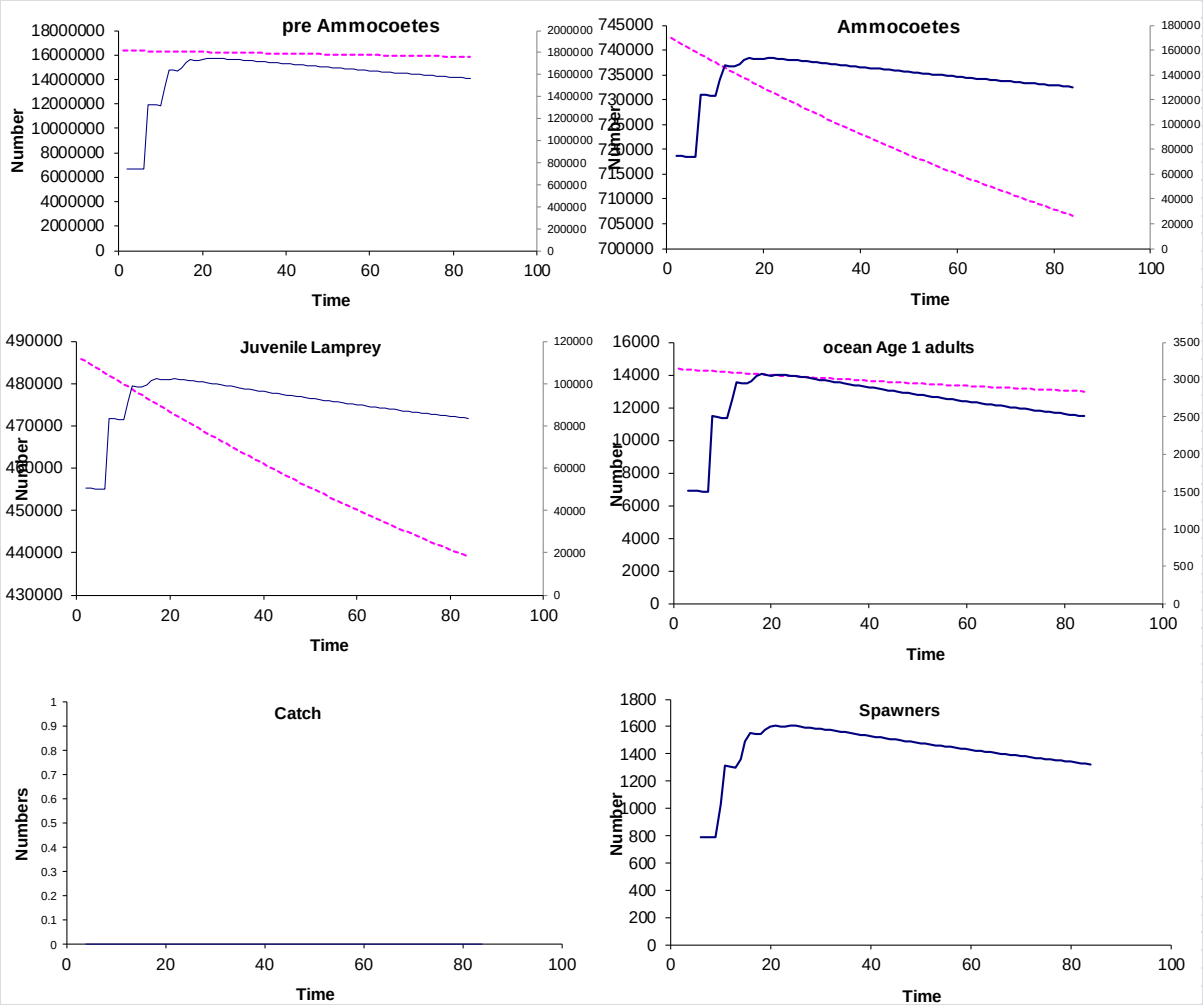

Figure Ap4: Population trajectory based on new weights from Table Ap1 (marine survival is assumed to be 3% for the early marine phase of the lamprey life history)

As forested areas are given higher weights here, it is apparent that the sensitivity two (Figure Ap4) is a more productive and optimistic scenario than the initial one (Figure Ap3). In both scenarios, it is assumed that there are is no harvest of lamprey.

Ocean effects modelled as influenced by climate change

Using the same scenario, but an assumption of lower survival from freshwater to ocean life history stages (the hypothesized limiting factor when lamprey transition from freshwater to a marine environment), the population declines precipitously when marine survival is reduced by half (Figure Ap5) to 1.5%, but shows higher abundances when it doubles from 3% (Figure Ap4) to 6% (Figure Ap6).

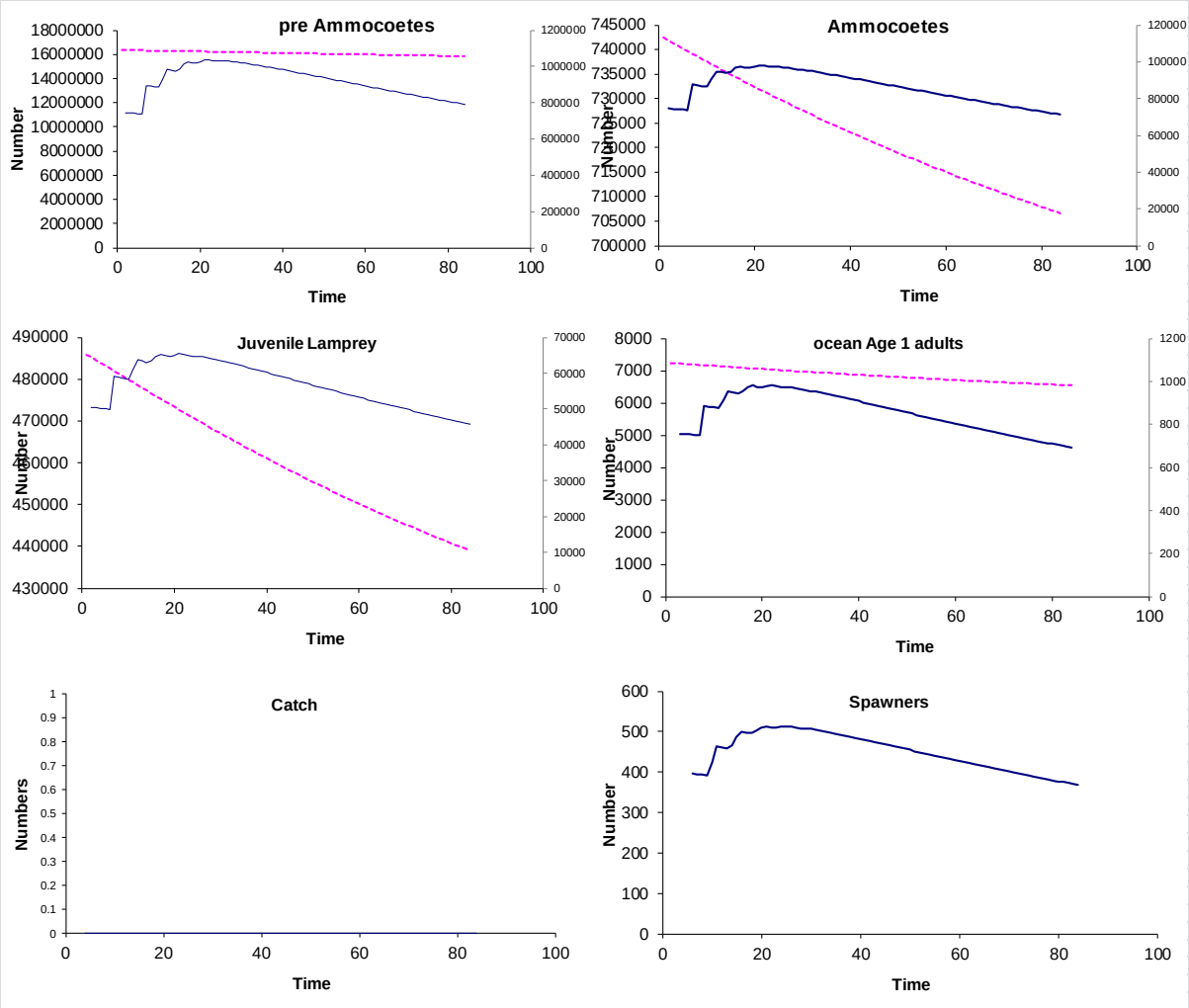

Figure Ap5: Population trajectory based on new weights from Table Ap1. Includes all constant parameters from Figure Ap4, except marine survival marine survival for the early marine phase is assumed to be 1.5%

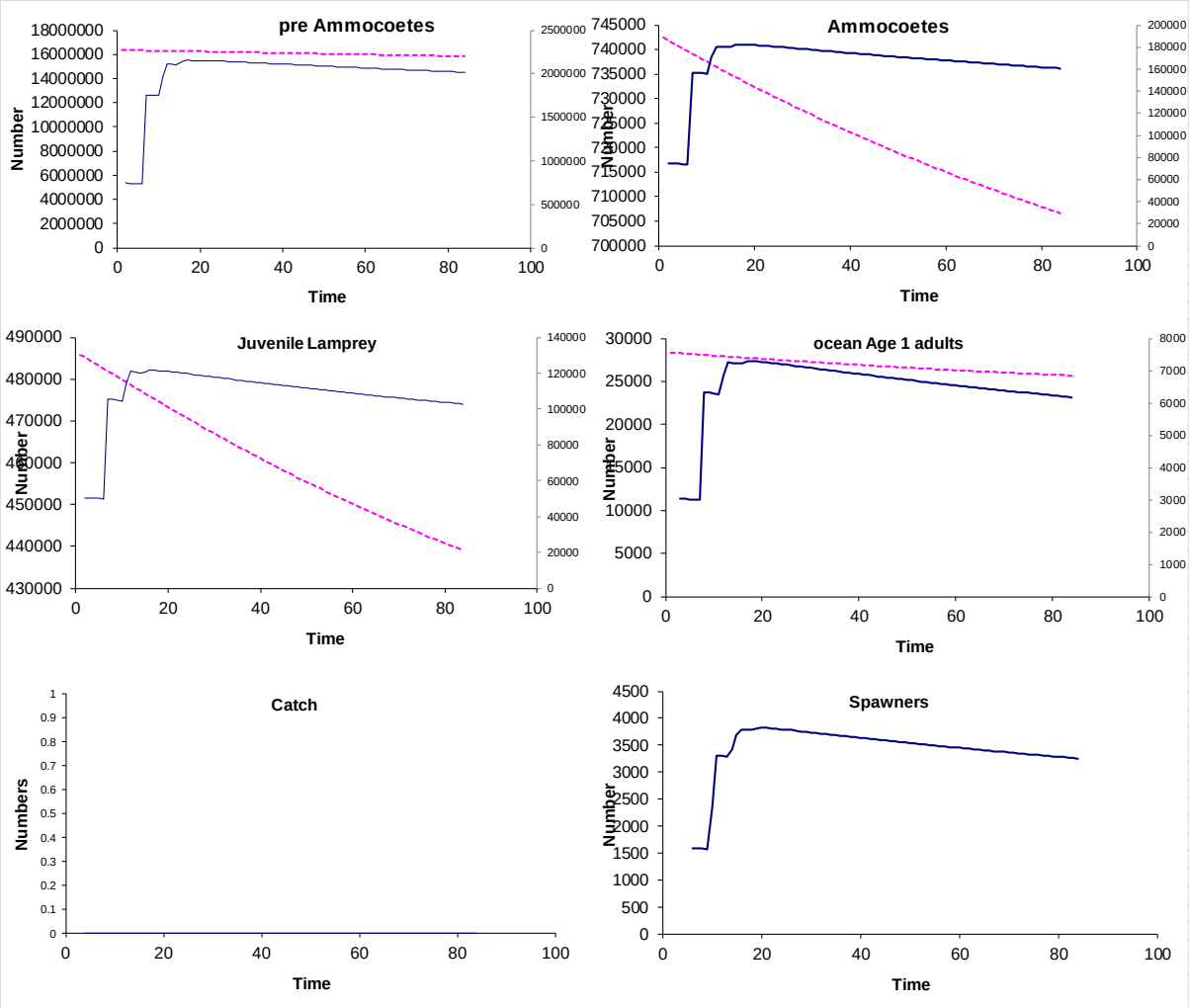

Figure Ap6: Population trajectory based on new weights from Table Ap1. Includes all constant parameters from Figure Ap4, except marine survival for the early marine phase is assumed to be 1.5%

Discussion

The rationale for the choice of these scenarios is primarily for illustrative purposes (i.e. to show what parameters would be influenced by climate change). While the model displayed here assumes these parameters are time invariant, these could vary by time and give interesting temporal trends/signals over time. In addition, in the case where the sensitivity was chosen, these could change over time for the same land classification indicating a trend in productivity driven by climatic changes. Because these sensitivities are not calibrated with empirical data, they solely demonstrate a potential application. With improved data, a model such as this could be employed to simulate lamprey life history in the context of changing climate and/or changing freshwater habitat conditions. Expanded life cycle monitoring and data collection, as recommended in the executive summary, could provide inputs for this conceptual model to provide a more accurate estimate of lamprey survival and consequent abundance and survival under hypothetical scenarios.