Hood Canal Intensively Monitored Watershed Study Plan

Submitted to:

Salmon Recovery Funding Board Monitoring Panel

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Summary

The Hood Canal Intensively Monitored Watershed complex encompasses Big Beef, Little Anderson, Seabeck and Stavis creeks in western Washington State. We have employed a Before-After-Control-Impact study design with Stavis Creek serving as the reference stream. The study focuses primarily on coho salmon and uses a life cycle monitoring approach, estimating the abundance of adults, parr and smolts. Adult abundance continues to be relatively low in these streams, particularly in Little Anderson and Seabeck creeks, where redd counts ≤ 30 are common across the time series. We observed evidence for density dependence productivity in Big Beef and Seabeck creeks based on a stock-recruit analysis. In most years, all four populations appear to be below carrying capacity. Parr to smolt survival (median = 15.6%, range = 0.9 - 32.5 %) showed a strong year effect, as trends within each of the four sites tended to track each other through time, suggesting a regional signal that was shared among the study populations. Habitat data are collected following the EMAP protocols supplemented by additional monitoring associated with restoration projects.

A variety of restoration project types have been implemented or are planned for the treatment watersheds including barrier removal, floodplain reconnection and enhancing in stream structure via placement of woody debris. In general, our approach to restoration aims to restore natural processes and patterns of habitat variability rather than engineer specific habitat types, and prioritizes restoring longitudinal and lateral connectivity first and foremost. To date, although relatively few restoration projects have been implemented, we have detected some fish and habitat responses to actions within Little Anderson Creek. Notably, we observed a large increase in smolt abundance following the replacement of a blocking culvert located near the creek mouth.

Introduction

Despite the considerable investment in stream restoration intended to improve habitat conditions for Pacific salmon and steelhead, the ultimate benefits of these efforts to fish populations are largely uncertain (Katz et al. 2007). Although reach-scale studies have demonstrated increased fish densities at restoration sites, examples of increases in population abundance due to restoration (e.g., Solazzi et al. 2000; Johnson et al. 2005) are much more rare, in part due to the resources required to effectively monitor at the population scale (Liermann and Roni 2008; Roni et al. 2008). The Intensively Monitored Watershed (IMW) program was initiated to fill this knowledge gap by determining whether restoration of freshwater habitat can increase population abundance of anadromous fish and identify mechanisms by which restoration increases fish abundance (Bilby et al. 2005).

Streams are dynamic ecosystems, and restoring habitats that foster resilience to natural variation and disturbance is a critical consideration for salmon recovery (Bisson et al. 2009). It is unlikely that a single factor consistently limits population abundance and productivity, as the physical and biological constraints on survival commonly vary from year to year. Diverse habitats promote diverse life histories and resilience to uncertain environmental conditions (Schindler et al. 2010), and so it is risky for recovery efforts to engineer "optimal" habitat features that focus on a single component of the salmon life cycle or a single habitat type (Bisson et al. 2009). Therefore, our approach to IMW treatments focuses on restoring processes needed to maximize habitat diversity (Beechie et al. 2010), increasing the number and complexity of ecological pathways by which individual fish can successfully grow, survive, and reproduce.

We have implemented this approach in four adjacent streams located on the eastern side of Hood Canal in Western Washington State: Little Anderson, Big Beef, Seabeck and Stavis creeks (Figure 1). These streams offer two major strengths as IMW study streams. First, smolt production has been monitored in all four watersheds since the mid-1990s (Table 1). In addition, Big Beef Creek is a long term coho index site, with high quality information on adult abundance, smolt abundance, and marine survival available since the late 1970s (Table 1). Second, the watersheds are small enough that it is feasible to implement restoration treatments (and monitoring) in a significant portion of them, providing a strong opportunity to produce a large-scale improvement in habitat conditions. Implementing restoration actions in a large fraction of treatment watersheds is an important element of an IMW study (Bennett et al. in review).

The Hood Canal IMW study focuses primarily on coho salmon. Several other salmonid species are present in one or more of the study watersheds, including steelhead trout, fall chum salmon, summer chum salmon and cutthroat trout (Table 1). However, only coho salmon are present in all four watersheds in measurable abundances at multiple life stages, permitting a BACI study design (see below for details) and life-stage specific assessment of survival. Coho salmon are the most abundant salmonid in all four watersheds. Furthermore, juvenile coho salmon from Washington populations typically spend one year rearing in streams and lakes prior to seaward migration (Sandercock 1991), thus their life history is strongly dependent on freshwater. Because coho salmon require a range of habitat types from spawning to smolt migration, the species represents an excellent study organism to evaluate the potential for restoration to improve habitat conditions. Although data are collected on all species encountered during sampling, in this study plan, we focus on coho salmon.

The Hood Canal IMW encompasses coordinated efforts from multiple entities (Table 2). Developing a restoration strategy and identifying specific restoration projects was a collaborative effort of the Hood Canal Salmon Enhancement Group (HCSEG) and IMW scientists. The restoration actions implemented and proposed for Hood Canal IMW streams are varied, as the watersheds suffer from several sources of degradation, and there is no single project type that we expect to ameliorate these issues. Following Beechie et al. (2010) and Bisson et al. (2009), our general approach aims to promote natural patterns of habitat variation by restoring watershed processes rather than symptoms of poor habitat quality. As advocated by Roni et al. (2002), our restoration strategy is to:

A) First, restore longitudinal and lateral connectivity for sediment delivery, woody debris and fish
B) Subsequently, enhance stream complexity via placement of in-stream structures such as large woody debris.

The specific projects we propose are guided by more than ten years of intensive habitat and fish monitoring from the IMW team, discussions with the HCSEG and the Hood Canal Coordinating Council (HCCC), and commissioned reports (Stillwater Sciences 2008a; 2008b).

The specific hypotheses that the Hood Canal IMW program addresses are:

1. Treated streams experience an increase in summer parr abundance and body size relative to the reference watershed and/or period prior to restoration
2. Treated streams experience an increase in smolt outmigrant abundance and body size relative to the reference watershed and/or period prior to restoration
3. Treated streams experience an increase in egg to parr survival relative to the reference watershed and/or period prior to restoration
4. Treated streams experience an increase in parr to smolt survival relative to the reference watershed and/or period prior to restoration
5. Treated streams experience a measurable increase in habitat complexity relative to the reference watershed and/or period prior to restoration
6. Fish abundance and survival metrics are correlated with changes in habitat complexity

In addition, we advance the following hypotheses regarding mechanisms governing fish abundance.

7. Greater stream flows during fall spawning permit greater adult dispersal, and hence promote greater egg to parr survival
8. Summer low flows restrict the quantity and quality of available rearing habitat and are correlated with parr to smolt survival

Study design

The IMW program uses a Before-After-Control-Impact (BACI) study design to maximize our ability to detect changes in salmon production that result from habitat restoration actions while minimizing the probability of detecting spurious treatment effects (Underwood 1994; Smith

2002). A BACI study uses one or more non-manipulated sites or watersheds (i.e., references) as an experimental control to account for variation not due to treatments (Stewart-Oaten and Bence 2001). In the Hood Canal IMW, Stavis Creek serves as the reference watershed, whereas Little Anderson, Big Beef and Seabeck creeks serve as the treatment watersheds.

The BACI design assumes that the treatment and reference conditions are dynamic, but correlated (Parker and Wiens 2005). That is, conditions are similar among watersheds and change at similar rates before treatments. While perfect replicates are not possible in field studies, we use the fact that salmon population changes in spatially proximate watersheds are often similar (Bradford 1999) to provide reasonable replicate treatment and reference watersheds. If the assumption of correlation between treatment and reference watersheds is violated, we will use a Before-After (BA) study design. The BA analysis simply compares the response variable within the treatment watershed before and after restoration. In comparison to the BACI design, the BA analysis will have less statistical power, and therefore more years of data will be required to detect a change of similar magnitude (see *Power analysis* below).

We also use measurements of environmental conditions to account for failures to meet the assumptions of the experimental design (Benedetti-Cecchi 2001; Steinbeck et al. 2005) and to strengthen our analyses by using environmental covariates to reduce unexplained variability in salmon production. By establishing relationships between salmon production and environmental variables, we can elucidate mechanisms by which restoration might affect salmon production. A range of habitat data is collected annually to assess these assumptions, to be used as covariates in analyses of treatment effects, and to identify treatment effects on habitat.

Power analysis

The purpose of these power analyses is to quantify our ability to detect a change in coho smolt abundance (e.g. magnitude of change and number of sampling events and years needed to detect that change). The detectable change in smolt abundance should create clear expectations for the IMW program when viewed in the context of the anticipated effects of habitat restoration.
A major advantage of the BACI design is that the effect of external drivers of productivity (e.g. heavy precipitation events and related high stream flow or marine survival) that affect all study streams can be statistically removed, thereby making changes due to habitat restoration easier to detect. The degree to which the ability to detect a treatment effect is improved is a function of the strength of the correlation between the treatment and control basins.

The lower regression line in Figure 1 shows the pre-restoration relationship between coho smolt production in Seabeck Creek and Stavis Creek, the reference stream. This power analysis assumes that after restoration smolt production will increase, i.e. the regression line will be displaced upward so that for a given level of production in Stavis Creek, production in Seabeck Creek will be higher than it was pre-restoration.

The minimum detectable change (assuming a one-tailed, two-sample t-test) is a function of the confidence level (α), power ($1-\beta$), the variance of the data, and the sample size (Equation 1). We have set $\alpha=\beta=0.10$ for all analyses.

$$\Delta P = \sqrt{\frac{2s^2(t_{1-\alpha} + t_{1-\beta})^2}{n}}$$ **Equation 1**

where ΔP = the detectable change in smolt production,
s^2 = variance of the pre-restoration data (for the Before-After case) or the residuals of the treatment vs. reference stream regression (for the BACI design),
$t_{1-\alpha} = t_{(0.90,\, n)}$ ($\alpha = 0.10$, one-tailed test)
$t_{1-\beta} = t_{(0.90,\, n)}$ ($\beta = 0.10$)
n= number of years of pre and post-restoration monitoring (sample size).

The power analyses conducted assumed:

1) a Before-After design, applicable if the pre-restoration relationship between reference and treatment was not significant (Big Beef Creek);
2) a BACI design, applicable where there is a statistically significant relationship between the reference and treatment basins (Seabeck Creek and Little Anderson Creek).

The variance of annual, pre-restoration smolt production (Figure 12) in the treatment stream was used in Equation 1 for the Before-After comparison. A simple linear regression model of treatment stream vs. Stavis Creek, the reference stream, was used for the second analysis. The relationship between Big Beef Creek and Stavis creeks was not significant (r^2=0.0) so only Before-After comparison was done. In 2002, a culvert on Little Anderson Creek was replaced with a channel spanning bridge. After this, the relationship between Little Anderson and Stavis Creek changed dramatically. Prior to the bridge there was no significant relationship between the two streams, but a strong linear relationship was observed afterward. For this reason, the Little Anderson vs. Stavis Creek regression used only data collected after 2004. The results of the analyses are shown in Table 3 and in Figures 2 - 4.

Assuming an equal number of years of monitoring pre and post-restoration, the analysis shows that we could detect an increase in smolt production on Big Beef Creek equal to 68% and 45% of mean production after six years (two coho salmon generations) and 12 years (four generations) of post-restoration monitoring, respectively, using a Before-After design.

The results using Seabeck Creek data were similar. Detectable changes of 62% and 41% at six and 12 years, respectively, were calculated using a Before-After design. Use of the BACI design reduced this to 44% and 29% at six and 12 years, respectively.

In Little Anderson Creek detectable changes calculated using the Before-After analysis were 74% and 49% at six and 12 years, respectively. Use of the BACI design reduced the detectable change to 50% and 40% at six and 12 years, respectively.

These results indicate there is a high probability that the ongoing IMW monitoring will be able to detect a response in coho smolt production to restoration in the Hood Canal complex streams of 30-50% after 12 years or four coho salmon generations (Table 3). Larger responses could be detected sooner.

Study site description

Little Anderson, Big Beef, Seabeck and Stavis (reference) creeks (Figure 1) are located in Kitsap County, Water Resource Inventory Area (WRIA) 15 and each flows north into Hood Canal. The watersheds are relatively small and have relatively low maximum elevation (Table 3) and topographic relief (Figure 1). As a result of glaciations that covered the area about 13,000 years ago, glacial (Vashon) till and alluvium are the dominant geology of these watersheds. Glacial till and alluvium are fairly resistant to erosion, but subsurface flows across less-permeable clay layers create locations of erosion, especially where crossed by stream channels and roads (Booth and Jackson 1997). Average annual rainfall is about 105 cm/y. Substantial flooding occurred in 2004 and 2007 that caused road crossing failures and changes to channel morphology.

The watersheds of the Hood Canal IMW complex were some of the first to be commercially logged in Washington, with logging underway by 1870. Extensive logging of the uplands was conducted in the 1920s through the 1940s. Most of these watersheds have likely been logged more than once. Some evidence for the use of splash dams has been noted in Seabeck Creek and instream large wood was removed through the 1970s. The majority of each of these watersheds is forested and ownership is a patchwork of public and private land (Table 4). Importantly, rural residential development is continuing in all watersheds and urban development is occurring in the Little Anderson Creek watershed. Most but not all paved road crossing tend to occur near creek mouths.

Also as a result of glaciations, the Hood Canal IMW streams initiate in a relatively flat upland plateau with associated wetlands and have relatively steep mid-reaches that decline in gradient near the mouth (Booth et al. 2003). The few relatively high gradient stream reaches are likely sources of bedload that is deposited in lower gradient reaches (Figure 1). The relatively low drainage density (i.e., total length of stream divided by watershed area) of Big Beef and Stavis creeks suggest that they might have higher base flows and slower hydrographic responses to rainfall than Little Anderson or Seabeck creeks (Table 4). Stream flow data are collected near the outlet of each creek and at other locations in the watersheds as part of this study, though the data collection methods have changed over the years (see *Discharge* section).

Naturally produced salmonids from the Hood Canal Complex include coho salmon, fall chum salmon, cutthroat trout, and a small population of steelhead (Table 1). Big Beef Creek also has a small return of summer chum salmon. In the past, the University of Washington operated a small scale artificial production facility on Big Beef Creek, where summer chum and Chinook salmon were reared. All hatchery origin Chinook salmon returning to the creek were sorted at a weir located at the mouth and precluded from migrating upstream to spawn in the wild. All of the releases from this facility occurred downstream of the weir and therefore did not affect the wild juvenile downstream migrant counts at Big Beef Creek.

Hood Canal coho salmon are harvested in regional fisheries. Historically, a substantial portion of the harvest occurred in outside fisheries (i.e., Vancouver Island Troll Fishery, Washington Troll and Sport Fisheries). As these mixed stock fisheries became increasingly constrained by management of weaker populations, terminal harvests in the Hood Canal net fishery have made up the majority of the fishing impact on this stock.

Methods

Fish sampling

The fish monitoring methods summarized here have been consistently employed over the duration of the IMW study. Additional methodological details can be found in Kinsel and Zimmerman (2011) and Kinsel et al. (2009).

On Big Beef Creek, adult coho salmon are sampled upon entry into freshwater via a full capture weir. All salmon are identified by species and sex, and adipose-clipped coho salmon are excluded from the area upstream from the weir. The trap is generally installed in late August and operated continuously until late January. At the time of weir removal, counts of adult coho are typically zero for weeks, providing strong evidence that the majority of the run was counted. During recent years (2003-present), the trap has only been inundated and prevented from fishing twice. In both instances, redd surveys (2007) and weir catches following re-installation (2009) indicated that missed catch was minimal.

In all four creeks, redd surveys count the number of salmon nests approximately every other week. These spawning surveys cover the known spawning distribution to the extent possible, although there are some areas in Big Beef Creek (approximately 10%) that are not logistically feasible to survey. These surveys are spatially explicit, as each watershed is broken into 100 m reaches, and counts are made within each reach during each survey. In terms of numerical abundance, redd counts are conservative, minimum estimates because in some cases, high flows and turbid conditions reduce visibility or even preclude surveys.

Annual abundance of coho parr is estimated using a mark-recapture study design. Juvenile coho salmon are collected via electrofishing and seine net in late July and early August. Within each creek, ten index sites approximately 50 m in length were randomly selected using a spatially balanced design (Stevens Jr. and Olsen 2004); these same sites are visited each year (Figures 5-9). Lengths are recorded on all fish encountered within the study reaches. In order to increase the abundance of the coho salmon mark group, we also collect salmon outside, but immediately adjacent to, these reaches. All juvenile coho encountered are marked via adipose fin clip and released back to the stream.

Each spring, we install fan traps (Big Beef Creek) or fence weirs (Little Anderson, Seabeck, and Stavis creeks) to capture downstream migrating smolts of all species. Both trap types capture 100% of downstream migrating fish. In some cases, high flows caused trap outages. During these periods, we estimated missed catch using the average daily catch rate before and after the outage. The vast majority of smolts were directly enumerated rather than estimated during trap outages (cf. smolts sampled and estimated smolt abundance in Table 9). All captured coho salmon are examined for adipose fin clip and then released back to the stream. A subset are also measured for length. Despite common use of adipose fin clip to mark hatchery fish in the region, the selection of this mark had minimal effect on our results. The adipose fin clip was only used to estimate parr abundance via recapture at the smolt stage, a period when our study populations were obviously not vulnerable to mark-selective fisheries.

We use coded wire tags (CWT) to estimate the marine survival and harvest rate of coho salmon in Big Beef Creek. Smolts are tagged daily, throughout the migration, upon entry into marine waters. We do not tag any smolts that have been adipose clipped as parr in order to avoid exposure to mark selective fisheries and to ensure that a clipped adipose fin could be used to identify adults at the full capture weir originating from locations other than Big Beef Creek (i.e., "strays"). Adults are sampled from fisheries that typically encounter Big Beef Creek coho salmon. All adult salmon returning to the weir are scanned for CWT, and a sub-sample of CWT-positive fish (typically < 10%) are sacrificed to determine their population of origin. CWTs are also recovered from carcasses encountered during spawning surveys within Big Beef Creek.

Fish analysis

Below, we describe our statistical approaches to estimating numerical population abundance for analysis of patterns of productivity and survival. To estimate the population abundance of parr at the time of sampling ($\widehat{N}$), we used a Petersen estimator with a Chapman modification (Seber 1982):

Equation 2

$$\widehat{N} = \frac{(m+1)(s+1)}{r+1}$$

where *m* is the number of marked parr, *s* is the number of smolts examined for marks, *r* is the number of marked smolts. Variance of this estimate is

Equation 3

$$Var(\widehat{N}) = \frac{(m+1)(s+1)(m-r)(s-r)}{(r+1)^2(r+2)}$$

We estimated parr to smolt survival as the estimated number of smolts divided by the estimated parr abundance the previous summer.

Marine survival was calculated as

Equation 4

$$Marine\ survival = \frac{E+H}{T}$$

where *E* is the escapement (number of CWT counted at the Big Beef Creek weir), *H* is the number of tags estimated from all fisheries, and *T* is the total number of smolts tagged from a given cohort. We did not adjust for mortality associated with implanting of CWT, so we have likely underestimated true marine survival. Harvest rate was calculated as

Equation 5

$$Harvest\ rate = \frac{H}{E+H}$$

We fit a series of Ricker and Beverton-Holt stock-recruit models (Hilborn and Walters 1992) to test for density dependent productivity of coho salmon inhabiting each watershed. The models explored two life-stage transitions, adult to parr and parr to smolt. The form of the simple Ricker density-dependent model was:

Equation 6

$$ln\left(\frac{R}{S}\right) = a + bS + \varepsilon$$

where *S* represents the abundance at life stage 1 ("stock") and *R* represents abundance at life stage 2 ("recruit"), *a* is a density independent intercept, and *b* is a density dependent slope. We fit model using standard ordinary least squares regression, thereby assuming log-normally distributed residual error ε. We also fit a Beverton-Holt model of the form:

Equation 7

$$ln(R) = ln\left(\frac{aS}{1+bS}\right)$$

The density-dependent models were compared to a simple linear or null model of density independent productivity:

Equation 8

$$ln\left(\frac{R}{S}\right) = a + \varepsilon$$

For each combination of watershed and life stage transition (adult to parr or parr to smolt), we compared the Ricker, Beverton-Holt and null models using Akaike's Information Criterion adjusted for small sample sizes (Burnham and Anderson 2002). A value of ΔAICc ≥ 2 was interpreted as support for one model over another.

Discharge

As part of the Hood Canal IMW project, we are quantifying relations between stream flow statistics during specific life stages of coho and the geographic distribution of spawning coho, and their subsequent survival and production. Stream flow (i.e., discharge; Q) estimates were procured from the Washington Department of Ecology (ECY; https://fortress.wa.gov/ecy/wrx/wrx/flows/regions/state.asp) at the outlet of Little Anderson and Seabeck creeks and below Lake Symington on Big Beef Creek. In 2010 and 2011 ECY stopped stream flow monitoring on these streams and WDFW initiated similar monitoring using water level loggers and standard stream flow measurement methods. Stream flow data from near the outlet of Big Beef Creek were also procured from the US Geological Survey (http://wa.water.usgs.gov/cgi/adr.cgi?12069550) and from Kitsap County. Data that were classified by the source agencies as unreliable were removed from the respective dataset. Mean daily flow estimates that were missing or removed were estimated via non-linear relation to flow estimates made for the same day from the stream gauge that had the strongest correlation after empirically correcting for temporal lags in flow among watersheds. Missing mean daily flow estimates, usually associated with high flow events, were iteratively estimated until very few missing statistics remained.

We calculated several flow statistics hypothesized to influence coho salmon productivity (Table 5). The frequency of high flows was calculated as the number of days during each spawning season when the mean daily flow was greater than the median of the mean daily flow during the spawning season during all study years (e.g., brood years 2004 through 2009). We conjecture that years with high spawning flows permit greater adult dispersal and access to spawning areas. High flows during incubation may destroy embryos via redd scour, and so we calculated the number of days discharge exceeded bankfull widths during this period (Table 5). A similar statistic was developed for winter parr under the hypothesis that high flows may cause direct mortality and displace juveniles from preferred rearing habitats (Table 5). Because daily variability in summer base flows is usually within the measurement error of the gauges, we use wetted stream length measured during an annual census as a more direct measure of summer habitat quantity (Table 5).

Habitat – watershed scale

The IMW habitat sampling plan and field methods are adapted from the US EPA, Environmental Monitoring and Assessment Program (EMAP, http://www.epa.gov/emap) as described in Peck et al. (draft, http://www.epa.gov/emap/html/pubs/docs/groupdocs/surfwatr/field/ewwsm01.html) and Crawford (Crawford 2008c; 2008a; 2008b) for the Washington Salmon Recovery Funding Board (SRFB). These methods are recommended in the Washington Comprehensive Monitoring Strategy and Action Plan for Watershed Health and Salmon Recovery (Crawford et al. 2008) and meet the preliminary criteria of the Pacific Northwest Aquatic Monitoring Partnership (PNAMP; http://www.pnamp.org/). Samples consist of several measures and counts made at and between 21 equally spaced cross-sections. Cross-sections are positioned along a length of stream that is the longer of either 40 bankfull widths or 300 m. Note that these methods often do not include common fish habitat measurements, such as pool area, but they are designed and selected to have very low measurement error among surveyors. Low and consistent measurement error is especially important for long-term projects in which many different surveyors are expected to participate.

Sampling locations were identified using a random, spatially balanced design (Stevens Jr. and Olsen 2004) that was stratified by stream order (Strahler 1957). This allows statistically valid descriptions and comparisons of watersheds. Some sampling locations were changed in 2006 to include a greater number of locations where fish presence is likely. That is, we redefined the sampling frame to exclude some very small reaches that are distant from the outlet, but retained random site selection within the new sampling frame. Preliminary analysis in 2006 suggested that repeated measures sampling, rather than a rotating panel, would allow the collection of more samples in each year and likely provide better change detection via repeated measures analysis. This is especially useful in the Hood Canal IMW watersheds in which a relatively large proportion of total stream length is sampled in each watershed in every year (> 10% in Big Beef Creek to > 21% in Little Anderson Creek), because habitat samples are long (i.e., 300 m) and total stream length is relatively short (~ 28 to 58 km). Since 2007, about 20 locations have been sampled every year in each watershed in each complex. In each year as logistically feasible, additional random locations are sampled to increase spatial coverage of samples within watersheds. Sampling rotates among watersheds approximately weekly to minimize seasonal bias (e.g., stream drying as summer progresses). This sampling plan provides an accurate description of habitat conditions in each watershed in every year. Additionally, because sample locations are randomly selected, it is possible to parse and stratify samples to address specific questions. For example, one can select sites within and downstream of restored reaches (and similar locations within reference reaches and reference watersheds) to more certainly detect downstream effects of restoration actions.

Habitat – project effectiveness

Project effectiveness monitoring is also conducted as part of this work. When possible, we use a similar protocol as described above to collect data pertinent to detecting site-scale changes to habitat conditions at and near the locations of restoration actions. Where appropriate, additional information is collected in order to more precisely measure changes. For example, laser levels were used to measure channel shape at the locations of Large Wood Debris (LWD) restoration actions in Little Anderson Creek in 2009 and 2010. Although not always optimal for measuring expected changes at a restoration site due to the treatment, using the same basic sampling methods for project effectiveness monitoring has several important advantages. First, surveyors are already trained and experienced using the methods which reduces sampling error. Second, our habitat database is already designed to store and manage those data. Thus, all habitat data are reliably stored and readily available for analysis. Third and perhaps most importantly, because standard monitoring data and project effectiveness monitoring data are commensurate, novel analyses, such as comparisons of project effectiveness and standard annual habitat sampling data using a BACI design, are possible.

Environmental covariates

We expect that habitat data will be extremely beneficial in developing environmental covariates for use as predictors in the stock-recruit analysis of coho salmon productivity. This approach would help identify mechanisms by which habitat affects productivity and reduce variability in the response variable (productivity), thereby providing greater power to detect a trend due to restoration effects. Table 5 provides some example covariates based on discharge statistics and EMAP data; we expect to identify additional covariates as our work proceeds. Habitat complexity might be described by a variety of metrics based on the EMAP data, but all will generally calculate patterns of data dispersion (e.g., variance) rather than central tendency (e.g., mean). In addition to productivity and survival, the covariates might be used to describe patterns in fish body size and growth.

Data quality and data management

Fish and habitat monitoring program does not have a formal quality assurance / quality control procedure. Fish monitoring data collected by WDFW have employed consistent methodology and largely the same personnel (biologists and technicians) throughout the duration of the IMW project. The methods are consistent with guidelines published by the American Fisheries Society (Crawford et al. 2007; Gallagher et al. 2007; Temple and Pearsons 2007; Zimmerman and Zabkar 2007). Data are entered by technicians and error checked by supervisory biologists.

In terms of data management, WDFW maintains standardized agency databases that contain smolt abundance data with associated protocols (JMX – Juvenile Migrant Exchange) and adult abundance and distribution data (SaSI – Salmon Stock Inventory database, SGS – Spawning Ground Survey database). Summer parr data are stored in standardized electronic format developed by Weyerhaeuser and WDFW. WDFW maintains a geo-spatial database to house EMAP habitat data.

Restoration treatments

Overarching strategy

Our restoration strategy is founded on the concept that reestablishing the fundamental processes that create and maintain dynamic stream habitat conditions are most likely to improve salmon survival (Bisson et al. 2009). Increasing system resiliency (Landres et al. 1999; Waples et al. 2009) and increasing both habitat quantity and quality have the greatest potential to affect large, detectable increases in salmon survival (Beechie et al. 2014). In order to develop our restoration strategy, we linked these themes to our preliminary analyses comparing the survival of coho salmon at various life stages and observations of environmental attributes likely to affect fish productivity (e.g., seasonal flows). Information from supplemental studies (e.g., Stillwater Sciences 2008b) have also contributed to our approach.

With these overarching principles in mind, our restoration strategy is to:

1) First, restore patterns of connectivity for water, sediment, wood and fish

2) Subsequently, enhance stream complexity

In sequencing restoration actions, we prioritize connectivity projects over complexity projects because improve connectivity should benefit the hydrologic processes that create and maintain complex habitats (Roni et al. 2008). In addressing connectivity, we aim to enhance both longitudinal (e.g., replace culverts) and lateral (e.g., reconnect floodplain) connectivity. Regarding complexity, stream roughness elements (e.g., large wood) are generally lacking in these systems and their absence contributes to high bedload transport rates. Thus, roughness elements, especially large wood, will be returned to the system. We acknowledge woody debris placement is a short-term fix that presumably will not be needed as long-term processes are restored in the future (i.e., recruitment from riparian stands following recovery from history of logging). Large wood placement projects are often associated with barrier projects as an efficiency and value-added measure. Specific projects are prioritized to facilitate synergistic effects of restored flows of water, sediment and wood with increased roughness. Because the Hood Canal IMW watersheds are relatively small and because some restoration opportunities (problems) appear to be acute, (e.g., the near absence of off-channel habitats and wetlands in lower Big Beef Creek, where they were once abundant), we speculate that our relatively short list of projects might have a large effect on the function of the watersheds and subsequently on salmon survival.

It is important to note that Puget Sound coho salmon are not listed under the Endangered Species Act (ESA), so these restoration actions are not a specific component of a formal recovery plan. Puget Sound steelhead are ESA-listed as threatened, but a recovery plan has not yet been developed.

Completed to date

To date, the Hood Canal Salmon Enhancement Group and Hood Canal Coordinating Council have primarily been responsible for securing funding for project development, design, and implementation. IMW researchers have provided advice and guidance regarding the identification and selection of restoration treatments.

At this point in time, Little Anderson Creek has received the most significant restoration treatment (Table 6, Figure 5). A culvert where Anderson Hill Rd crosses the stream near its mouth was replaced with a channel spanning bridge in summer of 2002 (Table 6). In addition, LWD has been added to the creek in two phases: approximately 750 m of stream near the creek mouth received wood in 2007. In 2009, a mainstem reach roughly 1.75 km further upstream was treated with more than 200 pieces of LWD. These placements included some very large pieces of wood (~ > 15 m length, with root wads intact) that in some cases are currently perched above the creek, isolated from the hydrology of stream.

In Seabeck Creek, restoration treatments have focused on culvert replacements (Table 6, Figure 8). Seabeck-Holly Rd crosses Seabeck Creek at multiple points; an upper culvert was replaced in 2010 but a lower culvert persists as a partial barrier to fish and sediment. Culverts were also replaced on Hite Center Rd and Dragonfly Rd, but both of these crossing are in the upper reaches of the watershed, upstream of typical coho salmon distribution.

Overall, relatively little restoration has occurred in Big Beef (Table 6), although a floodplain restoration project is currently underway (Table 7).

Although Stavis was designed as the reference stream without treatments, it has received some projects (Table 6). This includes one culvert replacement and one bridge replacement, both located near the creek mouth (Figure 9). These activities, sponsored by Kitsap County Public works, demonstrate that restoration actions are not under the control of IMW researchers, and projects are often implemented outside the bounds of our study design. We have not yet seen a significant before-after increase of our response variables in Stavis Creek.

Planned and proposed

For this study plan, the IMW monitoring team collaborated with the Hood Canal Salmon Enhancement Group to create a list of projects that we think, in total, are likely to sufficiently restore system function to affect an observable positive benefit to fish populations (Table 7). A need common to all IMWs are large contrast treatments (Bennett et al. in review), thus we aimed to identify projects of sufficiently large magnitude and spatial extent to have a significant impact on habitat and subsequently fish.

In terms of the restoration funding process, the Hood Canal Salmon Enhancement Group serves as the project sponsor, and submits proposals to the Hood Canal Coordinating Council (lead entity). Following the SRFB's recent commitment to fund restoration projects in IMW watersheds, IMW scientists took a more active role in identifying and prioritizing projects than we have in the past. Several of the projects listed in Table 7 have already been funded or proposed under the current SRFB funding cycle.

In Little Anderson Creek, we aim to address the limited channel complexity with wood placement throughout the watershed, including augmenting previous projects. In some cases, smaller pieces of wood are needed to connect large pieces that were added but are not currently influencing channel dynamics. An additional identified problem was a lack of connectivity to wetlands upstream of Newberry Hill Rd that might serve as high quality winter coho salmon habitat.

In Seabeck Creek, restricted sediment transport at road crossing culverts is a significant issue, perhaps more so than fish passage at these same structures. Indeed, large stretches of fish bearing middle reaches of Seabeck Creek are intermittent during the summer low flow period due, in part, to excessive sediment accumulation. Following the general strategy laid out above, replacing culverts is the top priority, as there is a need to restore transport processes before increasing channel complexity. We anticipate that replacing culverts in the middle reaches would restore sediment delivery to the estuary rather than retaining this material within the creek. Woody debris placement projects would start in the headwaters, the source of much of the sediment, in order to restore more normative (slower) sediment delivery to the lower reaches used by fish.

Big Beef Creek suffers from a lack of off channel habitat in the lower reaches where there is a floodplain but it often disconnected from main channel. A major floodplain reconnection project is currently underway in two phases. We identified additional reaches upstream that may benefit from increased channel complexity and connection to off channel habitat via wood placement. Finally, a causeway across the mouth of Big Beef Creek restricts fish and sediment movement through a narrow passageway. A larger span would improve sediment delivery to Hood Canal, and create a more natural estuary. Although this is an expensive project, it could reduce predation by allowing fish that are currently concentrated during migration to disperse as well as provide rearing habitat for species not natal to Big Beef Creek (e.g., Skokomish Chinook salmon).

Results

Fish

Adult abundance has not shown any significant trend during the IMW study. In all four streams, the maximum adult abundance observed during the study period occurred during the first year of the IMW program (2004, Figure 10). The large adult abundances observed in 2004 coincided with the highest marine survival and lowest harvest rate measured in the Big Beef Creek population (Table 8). Adult abundances from the four study streams generally tend to track each other (Figure 10). In both Seabeck and Little Anderson creeks, < 50 redds have been observed annually since 2005 (Figure 10). Little Anderson Creek has a particularly small population, with ≤ 10 redds observed in more than half of the study years.

The estimated number of coho salmon parr observed during late July and early August is generally synchronous across the four study watersheds (Figure 11, Table 9). The exception is Big Beef Creek, which has shown strong oscillations during the period from 2009 to 2013 when abundances in the other three creeks were more stable. Parr abundances in Little Anderson and Seabeck creeks match each other very closely; Stavis shows the same general trend in parr abundance, but has a tendency to have a larger difference between strong and weak years. In general, the mark-recapture approach gave relatively precise estimates of parr abundance (Table 9).

Coho salmon smolt abundance is the longest continuously monitored fish metric across all four watersheds because these creeks were sampled for more than a decade prior to the IMW program. Similar to parr abundances, smolt abundance from Stavis, Seabeck and Little Anderson creeks track each other during the IMW study period (2004 – 2014), but Big Beef Creek shows strong oscillations in recent years that are not present in the other three systems (Figure 12). Smolt abundance in all four systems has increased over the last three years (Figure 12)

Smolt data from Little Anderson Creek, owing to the length of the time series, show the strongest response to restoration treatment. Following the replacement of a partial barrier culvert near the mouth of Little Anderson Creek in 2002, smolt production increased considerably from 2004 to 2005 (Figure 12). Over the last ten years, smolt production in Little Anderson has exceeded the maximum value observed prior to the culvert replacement on several occasions (2005-2007, 2009, 2011, 2013-2014). We have also observed low abundances during this period (e.g., 2008 and 2010), but smolt abundance was likely constrained, at least to some degree, by extremely low adult abundances. These years coincided with low smolt abundances in the reference stream Stavis Creek (Figure 12).

A comparison of parr per adult (Figure 13) and parr to smolt survival (Figure 14), both metrics of relative survival from one life stage to the next, show some interesting patterns. For both metrics, the study watersheds tended to track each other through time; years of high vs. low productivity tended to be experienced by all (or at least multiple) creeks. Trends in parr to smolt survival appeared to track between watersheds tighter than parr per adult, perhaps due to the larger error associated with adult redds counts compared to the parr and smolt estimates. One might expect the parr per redd values to be lowest in Big Beef Creek due to the full census count of adults, whereas any missed or unobserved redds in Little Anderson, Seabeck and Stavis creeks would tend to inflate parr per redd values. However, Big Beef Creek did not consistently yield the lowest parr per redd values (Figure 13), supporting the use of redd counts as an index of adult abundance.

Parr to smolt survival appeared to show a strong year effect and greater interannual variation than parr per adult (Figures 13 and 14). Parr to smolt survival trends within each of the four sites tended to track each other through time, suggesting a regional signal that was shared among the study populations (Figure 14). Interestingly, the cohort that experienced the greatest parr per adult (brood year 2006) also yielded some of the lowest values for parr to smolt survival, at least in Little Anderson, Seabeck and Stavis creeks. Parr to smolt survival has shown an increasing trend over the last four brood cycles (Figure 14).

We observed evidence for density dependent freshwater productivity in Big Beef and Seabeck creeks (Figure 15, Table 10). In both cases, the adult to parr relationship was heavily leveraged by the large adult abundance year of 2004 (Figure 15, Figure 10). Beverton-Holt models tended to fit the data better than Ricker models of density dependence (Table 10). In Big Beef Creek, density dependence was observed at the adult to parr but not parr to adult life stages (Figure 15). There was no statistical evidence for density dependence at either the adult to parr or parr to smolt stage within Little Anderson or Stavis creeks (Figure 15). There was some evidence for density dependent growth, as parr tended to be smaller in years of greater parr abundance, particularly in Little Anderson, Big Beef, and Stavis creeks (Figure 16). In general, the relationship between body size and abundance appeared to be weaker for smolts than parr (Figure 17), suggesting that density dependent growth may be strongest at younger life stages.

Marine survival of Big Beef Creek coho salmon has shown substantial variation during the IMW study period, ranging from 1.6 – 18.6 % (Table 8). The two years of greatest marine survival were observed at the outset of the IMW program, in smolt migration years 2003 and 2004. Harvest rates have ranged from 42.9 – 84.0 % with a median of 72.4 % (Table 8).

Habitat

Habitat data have been collected using a standardized protocol since 2004 and the same 20 locations in each watershed have been sampled each year (with few exceptions) since 2006. The primary intended use of the habitat data is to assess continued adherence to the principal assumption of our study design – no dominant, divergent trend in habitat conditions among study watersheds. Although variability within each watershed is generally high for most measured attributes, we observe similar interannual patterns across the four watersheds and no divergent trends have been detected. For example, annual counts of all large wood (24 size classes based on length and diameters) within the bankfull channel (i.e., excluding bridging wood) have very similar temporal patterns: higher abundance from 2011 through 2013 than in preceding years, followed by declines in 2014 (Figure 18). Similarly, annual estimates of the percent of cross-sections that bisect a pool in each watershed follow similar temporal patterns, although the watersheds show different levels of interannual variation (Figure 19).

An additional intended use of the habitat data is to measure watershed-scale changes to instream habitat that might be expected following restoration treatments. This supports stronger inferences regarding the effects of restoration treatments. For example, if restoration increases habitat complexity, we would expect to observe increased variance in metrics such as width-to-depth ratios. Similar to our monitoring results for large wood and pools, width-to-depth ratio is variable among locations, years and watersheds, but interannual patterns show some concordance between watersheds (Figure 20), suggesting that such statistics might be useful for detecting increased habitat heterogeneity. Annual habitat attribute statistics that are correlated with coho survival and production statistics might prove useful as covariates, allowing us to more readily detect fish responses to treatment effects (Table 5).

Finally, because 1) we use identical sampling methods for our annual sampling and for project monitoring whenever possible, and 2) annual habitat data are collected from randomly selected locations, novel analyses are possible. For example, as part of the large wood addition restoration project completed in 2010 by the HCCC and HCSEG, we collected our standard suite of habitat data (and some additional data) in 2009 (pre-project), in 2010 (post-winter flows) and in 2011. Analyses of data collected within the treatment reach suggested only moderate effects of the restoration project on channel profiles, pool frequency, and measures of channel widths and depths (Pittman and Krueger 2012). Without references, attribution of the changes to the restoration treatments was unreliable. At the watershed scale, we did not detect an effect of the large wood restoration project: pool frequency in Little Anderson Creek did not increase in absolute terms or relative to Stavis Creek (reference stream). However, downstream of the LWD treatment reach in Little Anderson Creek, pool frequency increased from 2006 to 2011 but not in similarly positioned control sites in Stavis Creek during this same time period (Figure 21). Pool frequency in these Little Anderson sites has not remained elevated at the peak value observed in 2010 (Figure 21), suggesting that we may have observed a temporary increase as the restoration treatments stored mobile sediment, but the supply of sediment available for transport remains greater than the storage capacity. Such inferences are possible only when sufficient long term monitoring data from multiple sites are available. These and similar analyses are available for the Hood Canal, Lower Columbia, and Strait of Juan de Fuca IMWs in Krueger et al. (2012).

Discussion

Increased coho salmon smolt abundance in Little Anderson following replacement of a culvert with a channel spanning bridge was the only significant response we observed to restoration actions. This observation was an encouraging result that demonstrates the potential of stream restoration. However, the increase in smolt abundance was not accompanied by a before-after perspective from the detailed monitoring data offered by the IMW study (e.g., parr abundance, spatial distribution of redds) because the culvert was replaced prior to initiation of the IMW program.

Our ability to detect a significant response to restoration in the other treatment watersheds, as well a response in Little Anderson Creek to actions other than the culvert replacement, is limited by the scale, magnitude and extent of restoration projects implemented to date. Quite simply, more restoration is needed before we would expect to see a significant response from coho salmon populations in the IMW watersheds. Hood Canal streams were selected for an IMW study in part because it the watersheds are small enough that is it feasible to treat a significant proportion of the habitat. In this study plan, we have identified a series of projects that would make major progress towards this goal (Table 7), actions that would provide a realistic opportunity to increase both the quality of salmon habitat and our knowledge of how salmonid populations respond to such actions. The duration of the IMW study will largely be dictated by the implementation schedule of the projects described in Table 7. Two generations (six years) following the final restoration project would be the absolute minimum required to have a reasonable opportunity to detect a population response, with four generations (12 years) of post-project monitoring enhancing statistical power (Table 3, Figures 2 – 4).

The low adult coho salmon abundances observed in Hood Canal IMW streams have important implications for the biological processes by which restoration might benefit freshwater survival. Specifically, in all four watersheds, adult abundances were typically well below carrying capacity (Figure 15). Even where density dependent productivity was observed (Big Beef and Seabeck creeks), in most years, adult abundances were in the linear portion of the stock-recruit curve near the origin (Figure 15).

Some benefits of restoration may depend on populations that regularly exceed carrying capacity. For example, if new habitat is created via restoration, it would provide the greatest benefit to abundance if the population is currently limited by habitat quantity. Such is the case of the Skagit IMW, where strong density dependence governs rearing capacity in the estuary, and benefits are hypothesized to be mediated by adding space for fry migrant Chinook salmon (Greene et al. 2015). The Hood Canal IMW will provide an interesting contrast to the Skagit IMW, and it will be important to consider the quality of restored habitat and not just the quantity of habitat added to the system via treatments. Ecological processes such as connectivity and habitat that offers resiliency to extreme events (e.g., winter peak flow and summer low flow) are likely to be a critical component of restoration responses when simply creating more space is unlikely to benefit the population. Furthermore, it is unlikely that a single limiting factor governs productivity in all years, and diverse habitats may buffer populations against unpredictable density independent constraints.

Body size and growth are additional response variables that may highlight linkages between habitat changes due to restoration and fish populations. We have seen some preliminary evidence for density dependent growth in IMW watersheds based on a negative relationship between parr abundance and parr body size (Figure 16). Thus, habitat quantity and quality likely play a role in growth patterns. To the extent that larger coho salmon have higher marine survival (Holtby et al. 1990; Irvine et al. 2013; Bennett et al. 2015), any benefits to growth afforded by restoration may ultimately increase population abundance. As the study proceeds, we plan to pursue analysis of growth, its role in survival, and its relationship to habitat attributes that can be affected by restoration.

Our habitat monitoring data are serving several important functions. First, they are providing reasonable evidence that habitat attributes commonly correlated with coho abundance and survival, such as pool frequency, are on similar trajectories in treatment and reference watersheds prior to restoration (Figures 18-20). Therefore, we have not observed any major habitat divergence between watersheds that could confound the study. Second, because we are using highly repeatable sampling methods, consistent training, sound quality assurance and data management methods and standardized analyses, we are very likely to identify changes in habitat conditions that are due to restoration treatments and other processes (e.g., large floods). Such information will help better substantiate the effects of restoration treatments or explain the absence of detectable effects. Third, because our sampling plan allows for spatial and temporal partitioning of data, we can conduct novel analyses, as we did to detect effects of the Little Anderson Creek large wood addition downstream of the treatment reach. Our monitoring suggests that the treated systems are not in a state of dynamic equilibrium and that the supplies of sediment, wood and water are not balanced. Therefore, detecting system level responses resulting from altered transport of these materials requires watershed scale rather than restoration project scale monitoring.

Perhaps most importantly given the objective of this plan, our extensive and long-term fish and habitat monitoring data are proving invaluable for identifying restoration needs and planning restoration actions. Our restoration plan is founded on our understanding of the structure and function of these watersheds, especially the flows of water, sediment and large wood. We aim to restore the dynamic processes that create and maintain productive fish habitat. We acknowledge that restoration to historic conditions (e.g., old growth cedar swamp) is unlikely and not a restoration objective for these systems, but altering the sediment and wood budgets to allow for the reestablishment side channels and increased system complexity is possible.

What lessons from the Hood Canal IMW could be transferred to salmon recovery efforts in other basins? First, in order to make apply specific results about fish-habitat relationships, one might develop a landscape classification scheme to identify similar watersheds (or other units) based on proximity, climate, geology, topography, land use, salmonids species present, or other characteristics. Such landscape metrics could be used to draw parallel inferences regarding the quantitative relationships between habitat and fish productivity, and subsequently the role of restoration in improving survival.

More broadly, the IMW program is providing fundamental, yet rare, information on the biological and physical habitat processes that govern salmon productivity and survival, knowledge that is directly applicable to salmon recovery efforts elsewhere. By understanding the various mechanisms by which physical habitat influences survival at multiple points during the salmonid life cycle, the study can help identify population bottlenecks, and how these bottlenecks might be addressed by restoration. The unique advantage of the IMW approach is the spatial and temporal scale of the study. By measuring population parameters at the watershed scale, we will gain an understanding of whether the magnitude of a given restoration action was a large enough to promote a response in the fish population. Similarly, streams are highly dynamic environments, and the long term nature of the study allows us to gauge the extent to which population bottlenecks change based on environmental conditions. We have already witnessed this lesson in the Hood Canal IMW, as the relative influence of density-dependence (Figure 15) and over-winter survival (Figure 14) varied substantially from year to year. Understanding the nature of constraints on survival, which life stages are frequently affected and how these constraints respond to different flow conditions, are lessons that can be applied to salmon recovery efforts throughout the region.

The IMW program presents a tremendous opportunity to advance our understanding of how salmonid populations respond to restoration. The study design is unique in its ability to identify causal mechanisms and quantify the benefits of restoration at the watershed and population scale. However, the lack of funded restoration projects to date in the Hood Canal IMWs has significantly limited the impact of the study. Future funding of restoration projects in these watersheds will be critical to the success of the program in terms of generating new information and providing guidance for future restoration activities in similar systems.

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Tables

Table 1. Summary of historical and contemporary fish monitoring data by species, life stage, metric and watershed (BB = Big Beef, LA = Little Anderson, SE = Seabeck, ST = Stavis).

Lifestage	Watershed	Metric	Species	Time frame
Adult	BB	Weir counts	Coho, summer chum, fall chum	1976 - present
Adults	BB, LA, SE, ST	Redd surveys	Coho and fall chum salmon	2004 - present
Adults	BB	Redd surveys	steelhead	2007 - present
Parr	BB, LA, SE, ST	Parr sampling	Coho salmon, cutthroat trout, steelhead[1]	2004 – present
Smolts	LA, SE, ST	Weir counts	Coho salmon, cutthroat trout, steelhead[1]	1992 - present
Smolts	BB	Weir counts	Coho salmon, cutthroat trout, steelhead[1]	1977 - present
Smolts	BB	Marine survival and harvest	Coho salmon	1977 - present

[1] Steelhead only present in appreciable numbers in Big Beef Creek

Table 2. Contributions of the Salmon Recovery Funding Board (SRFB), the Hood Canal Salmon Enhancement Group (HCSEG), and IMW Scientists toward the Hood Canal IMW.

	SRFB	HCSEG	IMW Scientists
Develop restoration strategy		X	X
Design, propose and sponsor projects		X	
Fund projects	X		
Implement projects		X	
Baseline monitoring			X
Evaluate response			X

Table 3. Comparison of estimated detectable change with six and 12 years of post-restoration monitoring based on long-term smolt monitoring data collected in Hood Canal IMW complex. Data indicate that if restoration yields an increases in production of approximately 30% and 50% of the mean, the change would be detectable with 12 of post-restoration monitoring at $\alpha = 0.10$ and $\beta = 0.10$.

Design	**R^2**	**Detectable change (% mean)**	
		6 years	**12 years**
Big Beef Creek			
Before-After	NA	68%	45%
Seabeck Creek			
Before-After	NA	62%	41%
BACI	0.47	44%	29%
Little Anderson Creek			
Before-After	NA	74%	49%
BACI	0.59	50%	40%

Table 4. General characteristics of Hood Canal IMW watersheds.

Attribute	Little Anderson	Big Beef	Seabeck	Stavis
Area (ha)	12.9	36.6	13.3	17.4
Max. Elevation (m)	117	151	113	126
Land Cover (%)				
Forested	67	74	80	76
Developed	11	5	7	3
Ownership	72.9 % Private, 27.1 % Public			
Est. N Road Crossings	58	41	40	8

Table 5. Examples of potential covariates for analysis of coho salmon productivity in the Hood Canal IMW.

Metric	Life-stage	Hypothesis	
		Effect on productivity	Mechanism
Spatial distribution of spawning adults	Spawning	Positive	Greater dispersal alleviates density dependence
Number of days flow > median during incubation period Sept 1 – Jan 15	Egg deposition	Positive	Higher flows permit adult dispersal
Number of days flow > bankfull during incubation period Nov 1 – Feb 28	Egg to parr	Negative	High flows scour redds
Geographic extent of wetted habitat (km) during summer (July – Aug)	Parr to smolt	Positive	Subsurface flow restricts connectivity, limits habitat availability and magnifies density dependence
Number of days flow > bankfull during overwinter period Oct 15 – Feb 28	Parr to smolt overwinter	Negative	High flows during winter reduce juvenile overwinter survival and flush fish out of system
Pool frequency	Parr to smolt overwinter	Positive	Pools provide refuge from high flows
Habitat complexity: variance in stream width to depth ratio	Egg to smolt	Positive	Complex habitats promote productive populations

Table 6. Completed restoration projects in Hood Canal IMW stream.

Watershed	Type	Description	Date complete
Little Anderson	Passage	Partial barrier culvert replaced with channel spanning bridge at Anderson Hill Rd crossing, near mouth of creek	2002
Little Anderson	LWD	Phase I: LWD added to approximately 1.6 km of creek upstream from Anderson Hill Rd	2007
Little Anderson	LWD	Phase II: LWD added to approximately 2.4 km of creek upstream from Phase I project	2009
Seabeck	Passage	Replaced culvert and acquired adjacent property at Dragonfly Rd	2003
Seabeck	Passage	Replaced bridge on private drive with one of greater span. Located near mouth of creek, just upstream from Miami Beach Rd NW crossing.	NA
Seabeck	Passage	Replaced culvert and roughened channel at upper Seabeck-Holly Rd crossing	2010
Seabeck	Passage	Replaced culvert at NW Hite Center Rd and associated riparian planting	2012
Big Beef	Passage	Replaced culvert at Kid Haven Rd	2008
Stavis	Passage	Replaced culvert at West Fork Stavis Creek crosses Seabeck-Holly Rd	2010
Stavis	Passage	Replaced Stavis Bay Rd bridge with one of greater span	2011

Table 7. Proposed, planned and desired restoration projects in Hood Canal IMW streams.

Watershed	Type	Description	Priority	Current status
Little Anderson	LWD	Supplement existing log jams in middle reaches of main creek to increase channel complexity. Both adding small pieces to existing structures and creating new jams.	1	Funded
Little Anderson	Passage & LWD	Replace barrier culvert on tributary at Newberry Hill Rd to increase connectivity to upstream wetland and place wood in channel to control sediment movement	2	Design funded
Little Anderson	Passage & LWD	Replace partial barrier culvert on tributary at Anderson Hill Rd and place wood in channel to control sediment movement. Also remove fill associated with eroding road.	3	None
Little Anderson	Passage & LWD	Replace barrier culvert on main creek at Newberry Hill Rd and place wood in channel to control sediment movement	4	None
Little Anderson	LWD	Wood placement to increase channel complexity in fish bearing tributaries	5	None
Little Anderson	Passage	Replace barrier culvert on private drive in tributary than enters main creek near its mouth	6	None
Big Beef	Floodplain reconnection	Remove fill, buildings and diked road from mouth upstream ~ 1.6 km. Add LWD structures to enhance complexity.	1	Phase I funded, Phase II proposed
Big Beef	LWD	Wood placement in lower ~ 8 km of mainstem to enhance winter habitat conditions, especially off channel areas.	2	None
Big Beef	LWD	Wood placement to increase channel complexity within mainstem immediately below dam and in important tributaries.	3	None
Big Beef	Riparian	Riparian planting and fencing to protect lower reaches of productivity tributary Vine Maple Creek.	4	None

Big Beef	Estuarine	Replace causeway and narrow bridge at creek mouth with bridge of larger span to increase sediment delivery and reduce predation.	NA	Designed but not funded. Cost ~ $10M.
Seabeck	Property	Acquire three adjacent parcels at creek mouth. Remove bridge limiting sediment delivery. Proposal includes some restoration actions but more may be necessary.	1	Proposed
Seabeck	Passage & LWD	Replace undersized culvert near mouth with failing fish ladder, grade channel, and place wood up and downstream to control sediment movement.	2	Proposed
Seabeck	LWD	Wood placement in upper reaches to retain sediment	3	Proposed
Seabeck	LWD	Wood placement in middle and lower reaches lacking channel complexity, where intermittent summer flow creates isolated pools.	4	None
Seabeck	Dike removal	Remove old railroad grade where it crosses the channel to allow proper floodplain function and control erosion.	5	None
Seabeck	Passage & LWD	Replace three partial barrier culverts and place wood in the channel to control sediment movement in a small tributary that enters main creek near its mouth.	6	None

Table 8. Estimated marine survival and harvest of coho salmon smolts coded wire tagged from Big Beef Creek during IMW study.

Smolt Year	Return Year	Smolts tagged	Tags recovered			Harvest rate	Marine survival
			Fishery observed	Fishery estimated	Escapement		
2003	2004	30,449	1,263	2,436	3,237	42.9 %	18.6 %
2004	2005	22,086	1,006	2,070	776	72.7 %	12.9 %
2005	2006	29,343	320	1,057	201	84.0 %	4.3 %
2006	2007	33,329	1,423	2,283	719	76.0 %	9.0 %
2007	2008	26,789	408	536	321	62.5 %	3.2 %
2008	2009	24,709	838	2,012	778	72.1 %	11.3 %
2009	2010	38,547	234	438	183	70.5 %	1.6 %
2010	2011	21,278	366	964	307	75.8 %	6.0 %
2011	2012	51,932	894	3,097	1,507	67.3%	8.9 %
2012	2013	18,732	574	1,264	360	77.8%	8.7%

Table 9. Mark-recapture data from coho salmon parr and smolt sampling.

		Parr		Smolts		
Brood Year	Site	Marked	Estimated abundance[1]	Sampled	Marks recovered	Estimated abundance
2003	Little Anderson	336	18,014 ± 5,519	1,870	34	1,969
	Big Beef	961	244,516 ± 39,747	31,1771	124	32,950
	Seabeck	1601	40,276 ± 7,493	2,488	98	2,725
	Stavis	978	102,487 ± 20,867	8,688	82	9,667
2004	Little Anderson	351	21,927 ± 7,742	1,681	26	1,743
	Big Beef	1,754	247,920 ± 27,914	36,163	255	38,579
	Seabeck	960	16,619 ± 2,946	1,763	101	1,829
	Stavis	878	60,870 ± 10,408	7,755	111	8,043
2005	Little Anderson	265	4,517 ± 958	1,035	60	1,075
	Big Beef	1,314	141,546 ± 15,165	28,416	263	29,911
	Seabeck	440	4,492 ± 881	753	73	787
	Stavis	834	26,420 ± 3,064	6,549	206	6,749
2006	Little Anderson	476	11,209 ± 9,574	93	3	96
	Big Beef	1,050	171,430 ± 24,307	26,097	159	27,416
	Seabeck	994	10,319 ± 2,077	808	77	828
	Stavis	1,515	59,664 ± 13,381	2,754	69	2,850
2007	Little Anderson	501	9,123 ± 2,149	1,035	56	1,101
	Big Beef	1,506	224,097 ± 23,012	43,272	290	45,398
	Seabeck	951	7,541 ± 1,500	609	76	626
	Stavis	847	29,727 ± 5,727	3,119	88	3,474
2008	Little Anderson	0	NA	207	NA	214
	Big Beef	1,028	83,499 ± 8,158	23,207	285	23,396
	Seabeck	158	1,525 ± 328	479	49	496
	Stavis	479	10,414 ± 2,134	1,583	72	1,663
2009	Little Anderson	203	3,921 ± 988	845	43	917
	Big Beef	979	290,089 ± 37,117	979	187	57,271
	Seabeck	744	8,891 ± 1,610	744	92	1,154
	Stavis	510	12,674 ± 3,042	1,388	55	1,550
2010	Little Anderson	147	2,610 ± 781	546	30	566
	Big Beef	1,031	92,379 ± 10,414	20,677	230	20,815
	Seabeck	619	5,193 ± 784	996	118	1,030
	Stavis	213	7,453 ± 1,564	2,089	59	2,168
2011	Little Anderson	292	7,041 ± 1,527	1,465	60	1,507
	Big Beef	1,405	174,474 ± 21,387	26,555	213	27,246
	Seabeck	1,145	8,816 ± 1,126	1,330	172	1,368
	Stavis	603	13,565 ± 1,575	4,199	186	4,327
2012	Little Anderson	354	8,974 ± 1,817	1,794	70	1,857
	Big Beef	1,431	312,169 ± 34,264	56,460	258	58,136
	Seabeck	1,042	12,795 ± 2,180	1,324	107	1,509
	Stavis	794	37,248 ± 6,363	5,153	109	6,076

[1] Abundance estimate ± 95% confidence interval

Table 10. Tests for density dependent in coho salmon adult to parr and parr to smolt stages within Hood Canal IMW streams. Null model assumes density independent productivity, whereas the Ricker and Beverton-Holt models assume density-dependent productivity. For each combination of watershed, predictor and response, a ΔAICc value ≥ 2 for the density dependent models relative to the null model (highlighted in bold) provides evidence for density dependence.

Watershed	Predictor	Response	Model	AICc
Little Anderson	Redds	Parr	Null	29.37
	Redds	Parr	Ricker	32.95
	Redds	Parr	Beverton-Holt	NA[1]
	Parr	Smolts	Null	31.58
	Parr	Smolts	Ricker	34.63
	Parr	Smolts	Beverton-Holt	33.97
Big Beef	Females	Parr	Null	20.55
	Females	**Parr**	**Ricker**	**12.44**
	Females	**Parr**	**Beverton-Holt**	**12.31**
	Parr	Smolts	Null	3.98
	Parr	Smolts	Ricker	3.39
	Parr	Smolts	Beverton-Holt	3.37
Seabeck	Redds	Parr	Null	23.16
	Redds	**Parr**	**Ricker**	**17.37**
	Redds	**Parr**	**Beverton-Holt**	**16.53**
	Parr	Smolts	Null	18.18
	Parr	Smolts	Ricker	16.28
	Parr	**Smolts**	**Beverton-Holt**	**13.26**
Stavis	Redds	Parr	Null	22.62
	Redds	Parr	Ricker	22.72
	Redds	Parr	Beverton-Holt	22.38
	Parr	Smolts	Null	21.87
	Parr	Smolts	Ricker	21.23
	Parr	Smolts	Beverton-Holt	20.59

[1] Model would not converge, perhaps due to missing data points

Figures

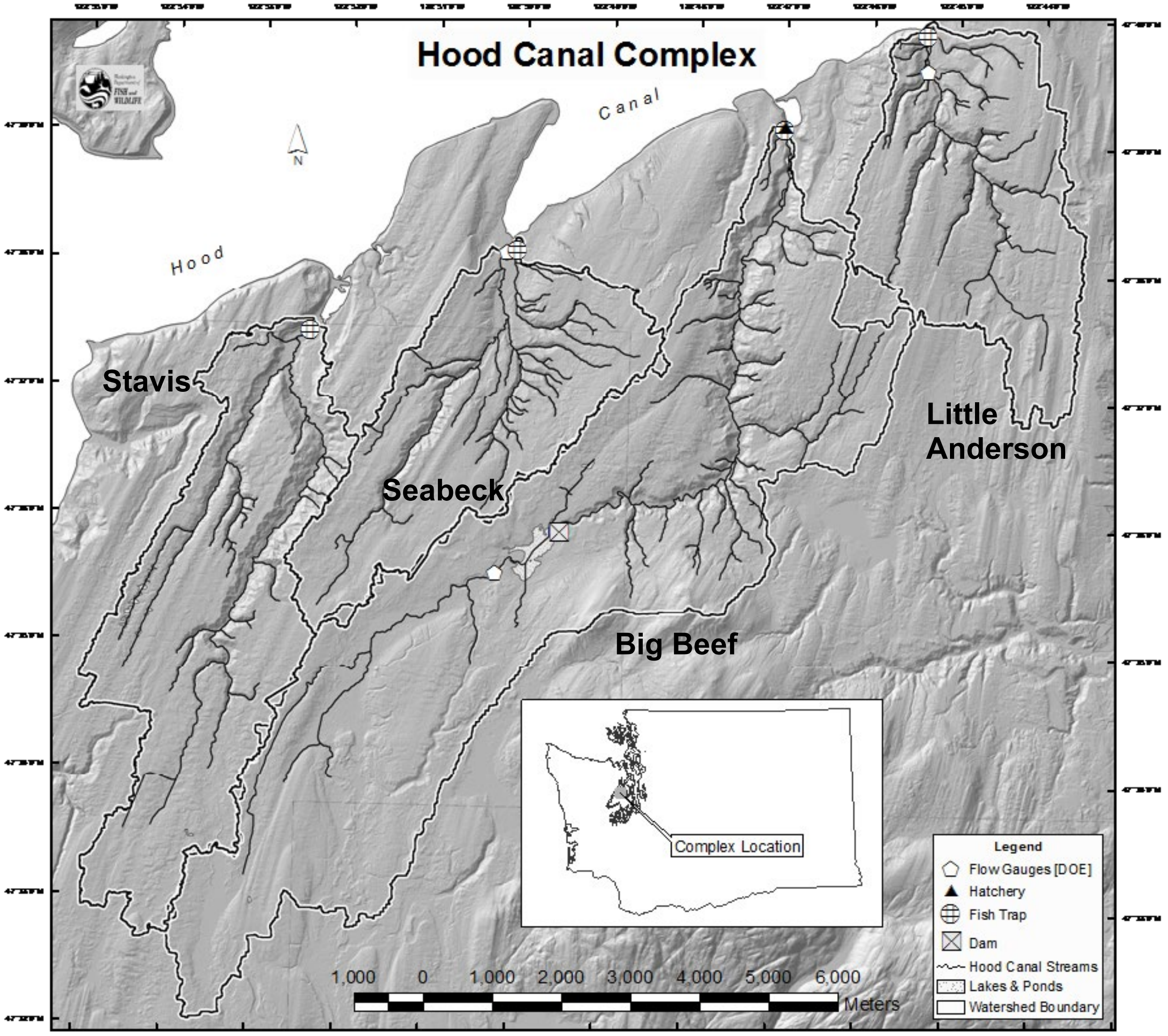

Figure 1. Location of the Hood Canal IMW Complex (Little Anderson, Big Beef, Seabeck, and Stavis creeks) in Washington and the location of flow gauges, the Big Beef Research Station hatchery, spawner weirs, and Lake Symington Dam. Topography is depicted using LiDAR data collected in 2001 by the Puget Sound LiDAR Consortium.

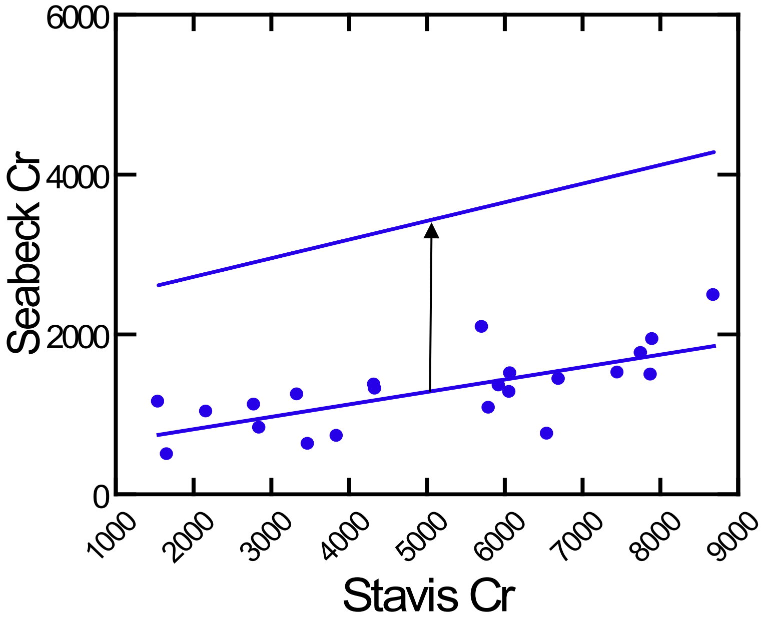

Figure 2. Assumed increase in smolt production is shown as a translation of the regression line upward (*i.e.* higher production in Seabeck Creek post-restoration for any given level of production in Stavis Creek).

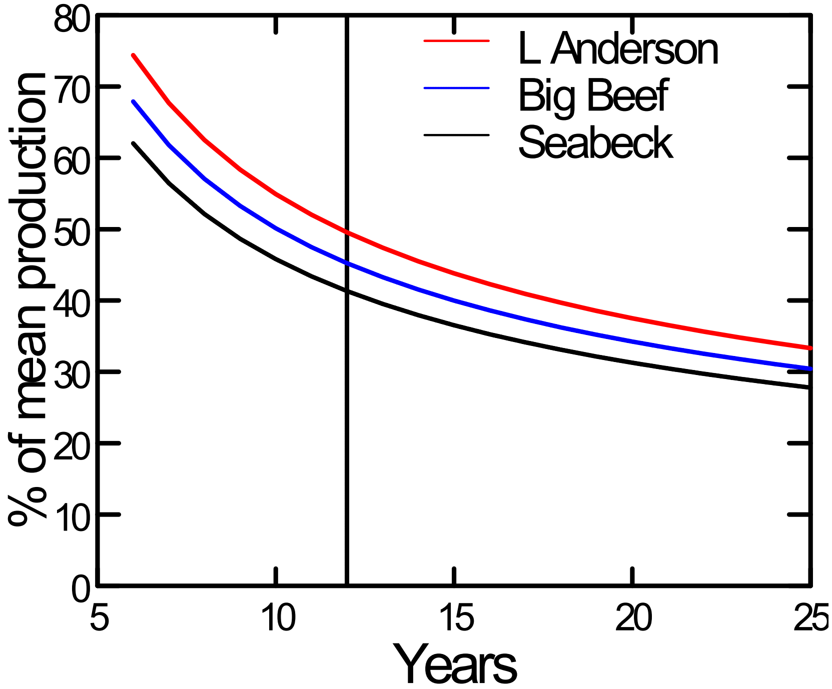

Figure 3. Detectable change in smolt production, presented as a percentage of the mean production, vs. number of years needed to monitor post-restoration for all three treatment streams using a Before/After analysis.

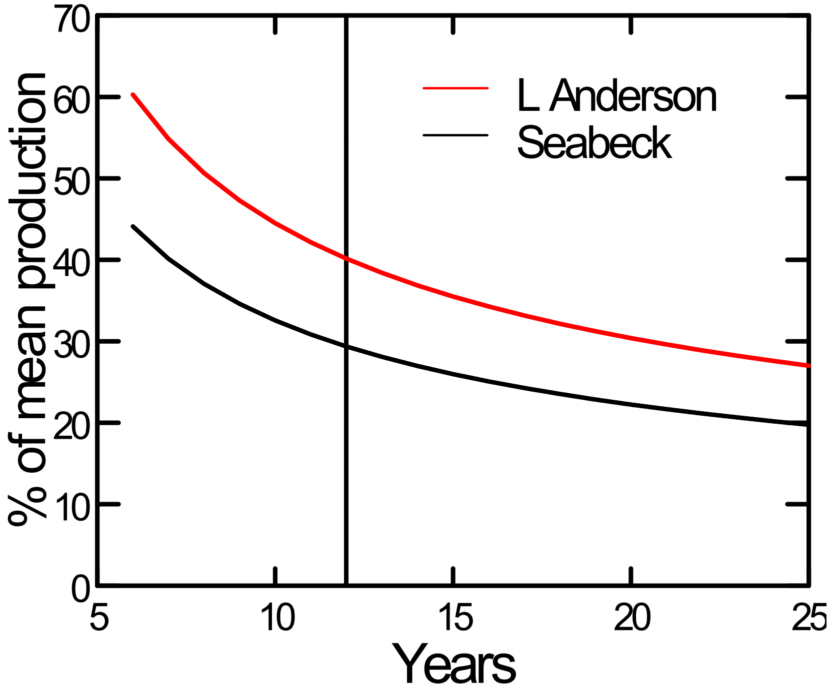

Figure 4. Detectable change in smolt production, presented as a percentage of the mean production, vs. number of years needed to monitor post-restoration for Seabeck Creek and Little Anderson Creek using a BACI analysis.

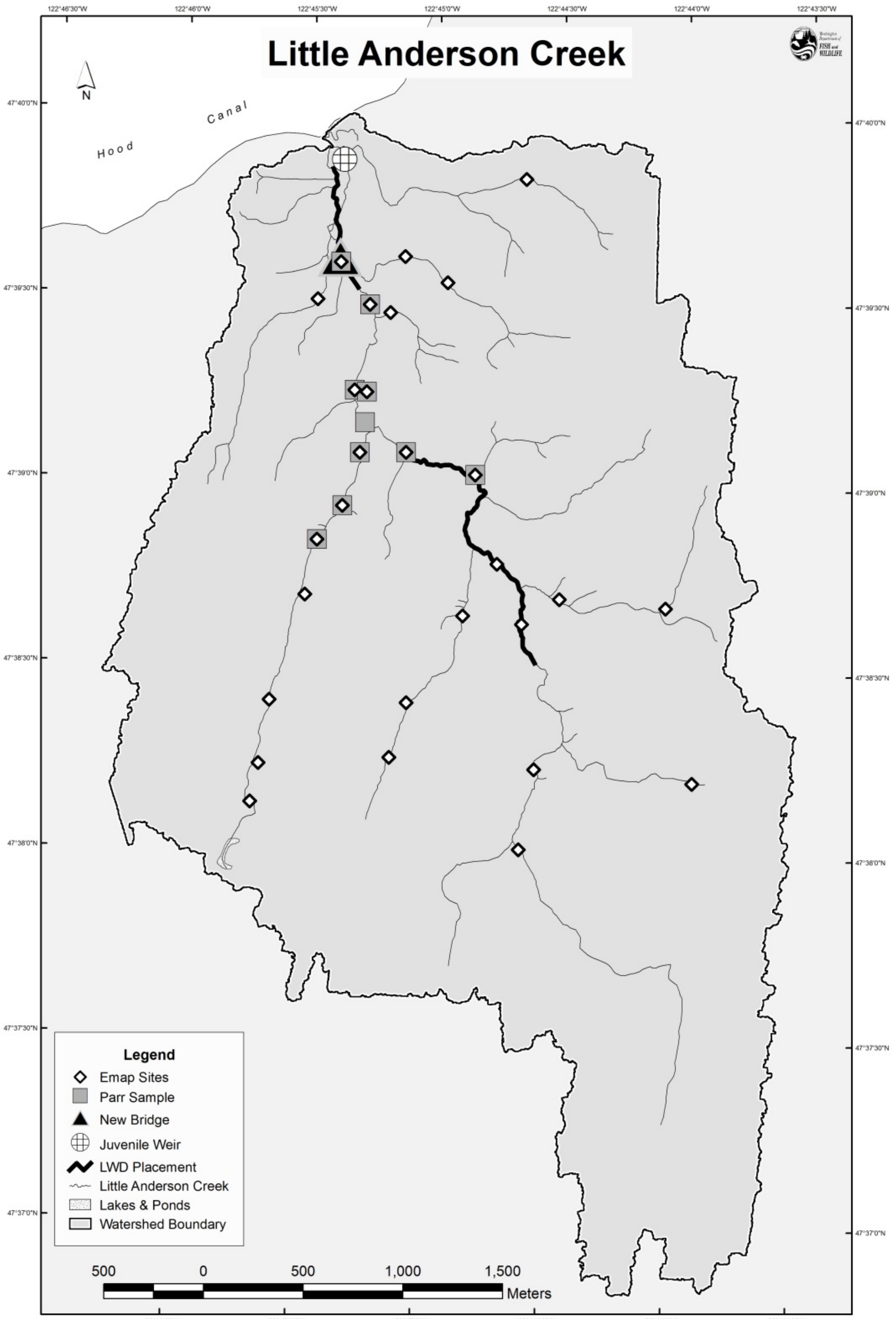

Figure 5. Map of Little Anderson Creek showing sampling sites and completed culvert and LWD restoration projects.

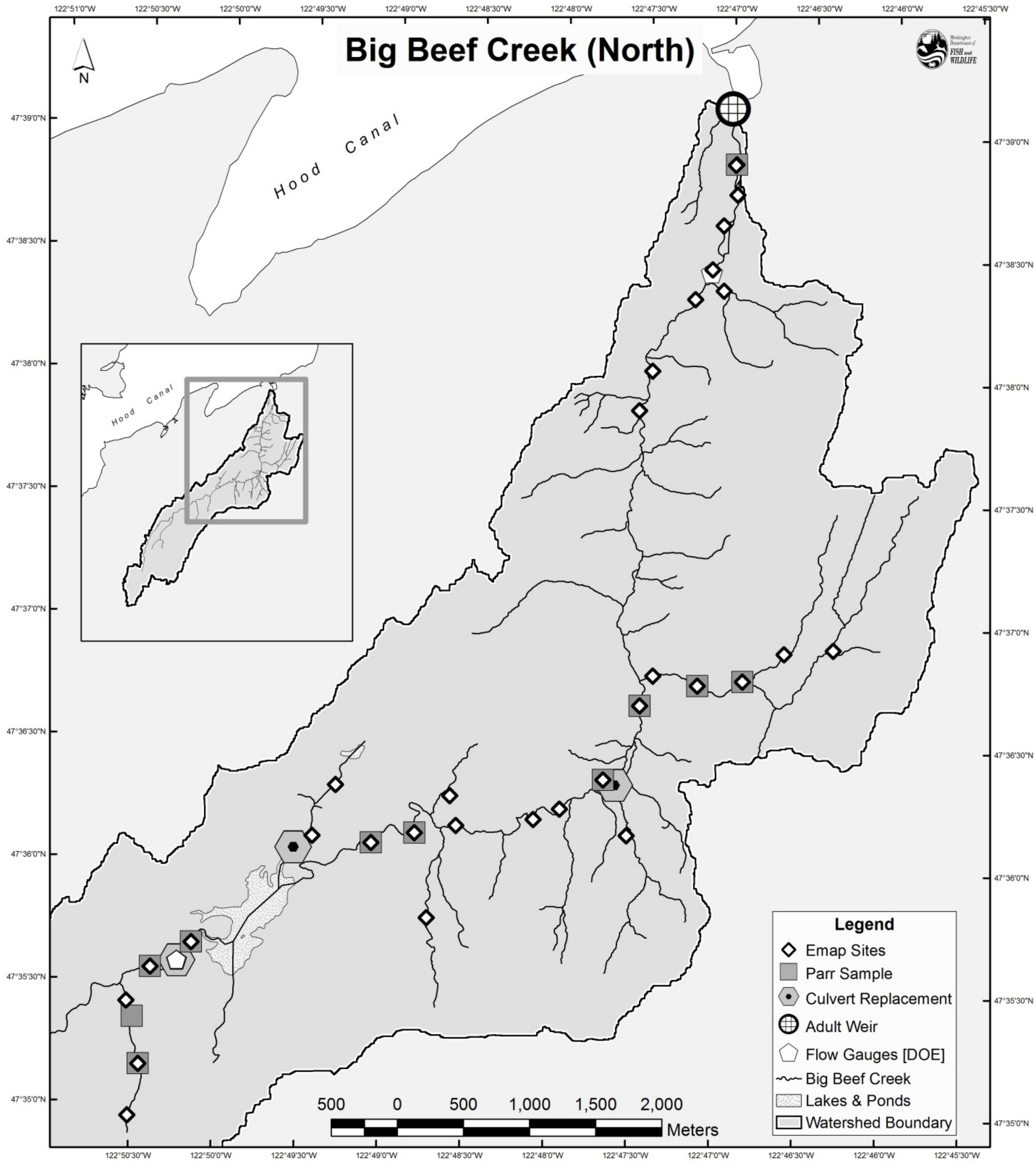

Figure 6. Map of northern half of Big Beef Creek showing sampling sites and completed culvert restoration projects.

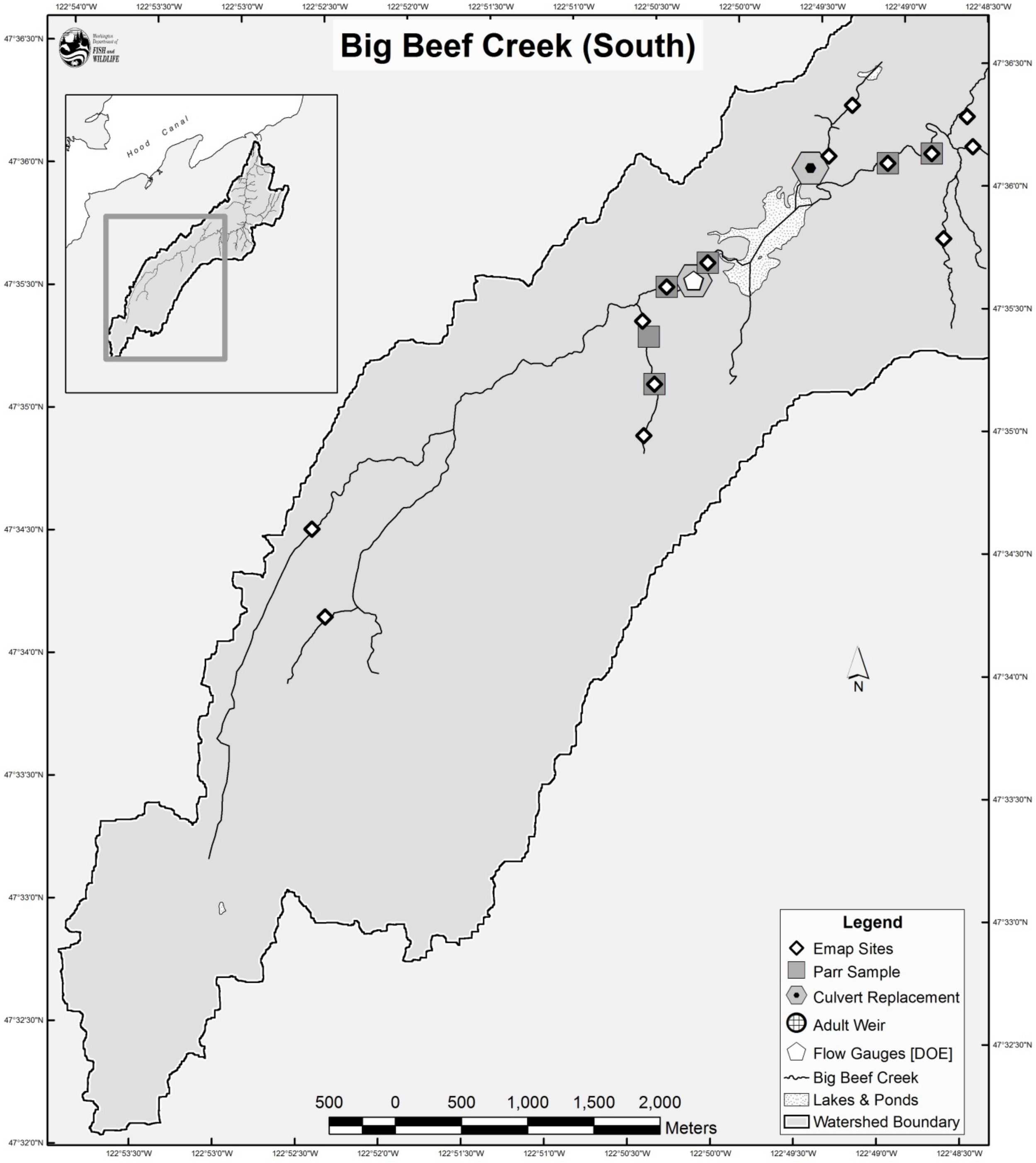

Figure 7. Map of southern half of Big Beef Creek showing sampling sites and completed culvert restoration projects.

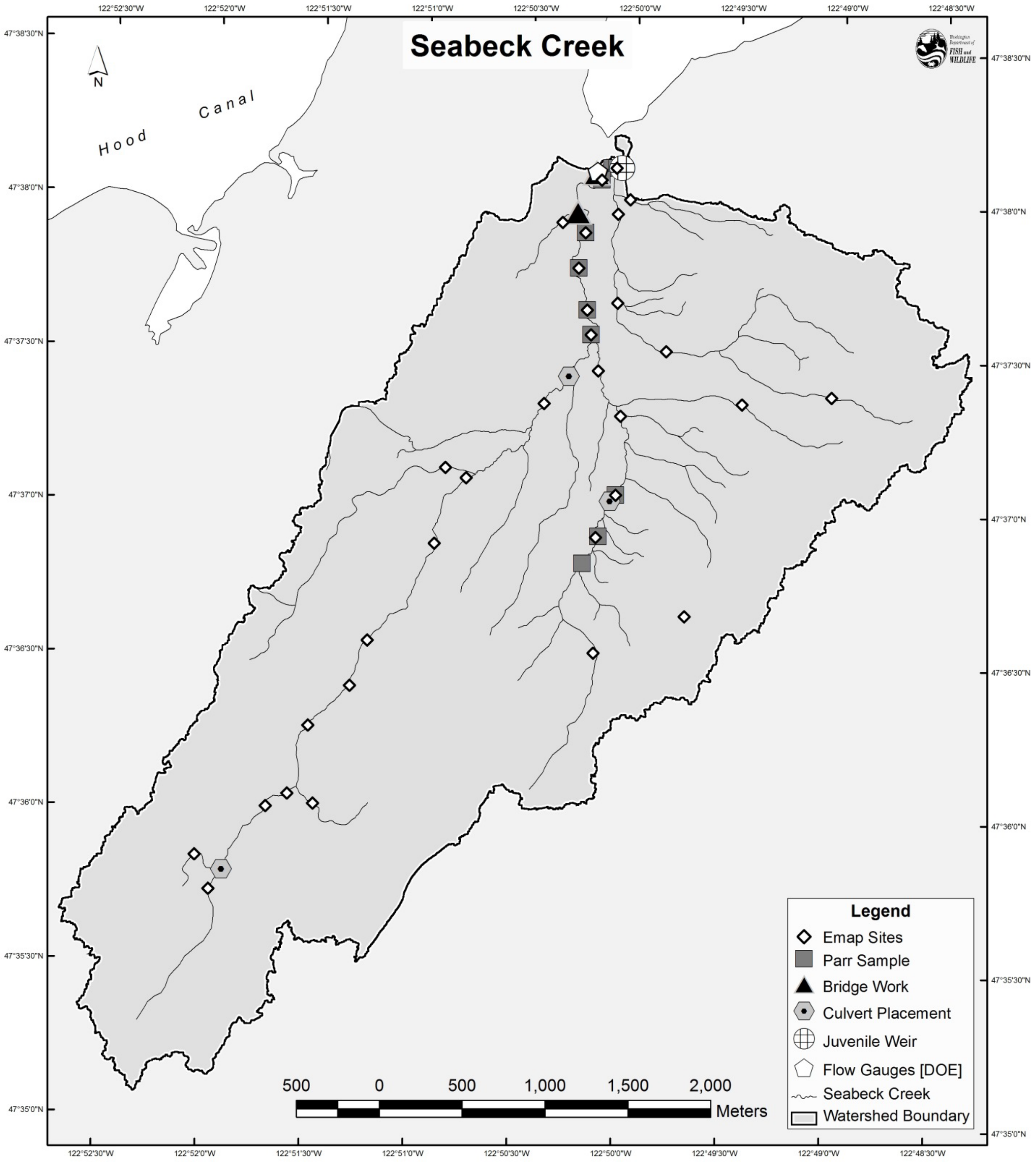

Figure 8. Map of Seabeck Creek showing sampling sites and completed culvert restoration projects.

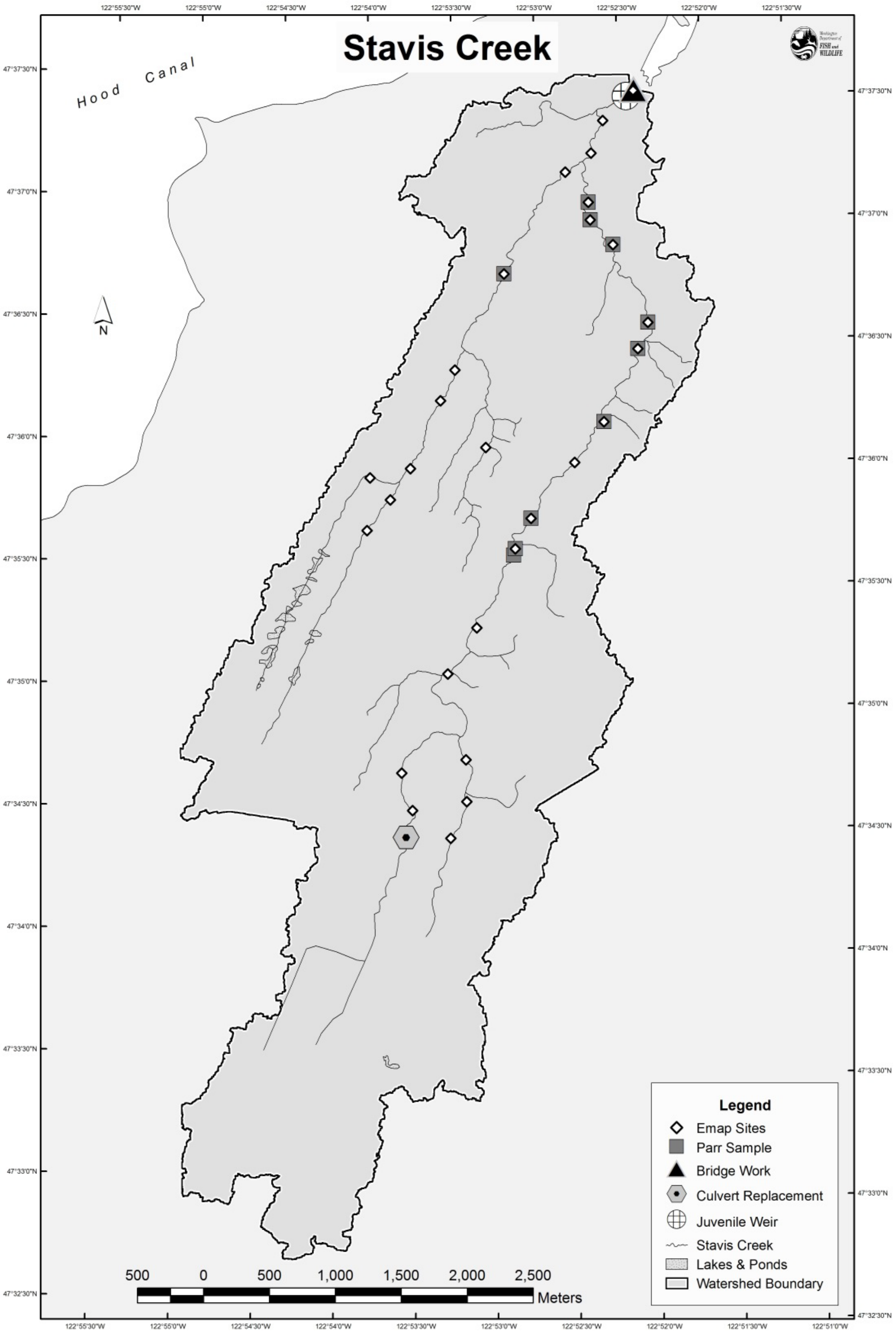

Figure 9. Map of Stavis Creek showing sampling sites and completed bridge and culvert replacement projects.

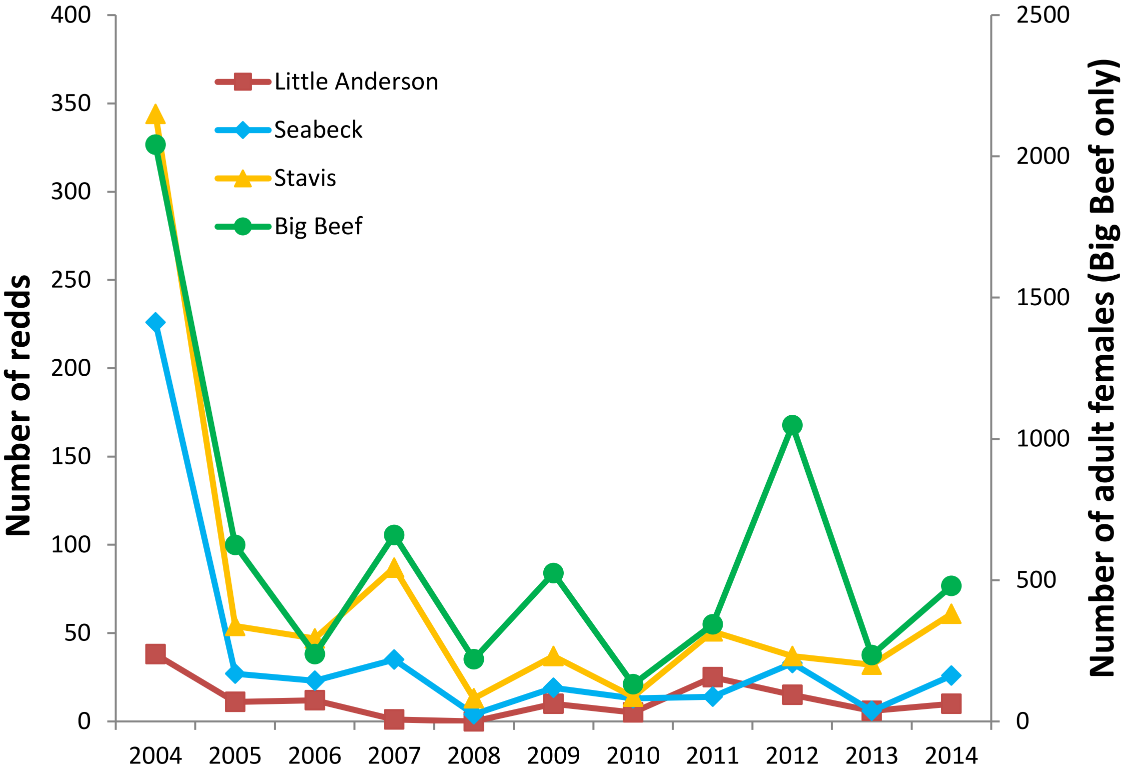

Figure 10. Trends in adult coho salmon for Hood Canal IMW stream. Values represent the number of observed redds in Seabeck, Stavis, and Little Anderson (left axis) and number of adult females counted at the Big Beef Creek weir (right axis).

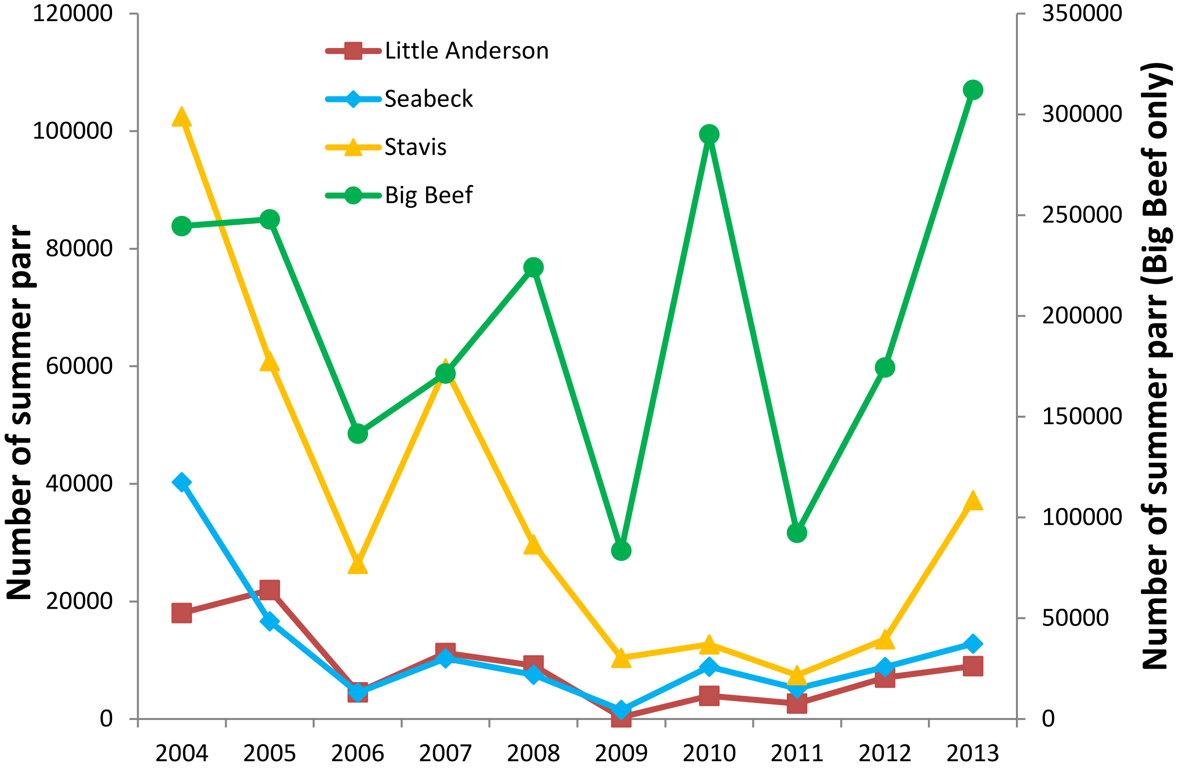

Figure 11. Estimated number of coho salmon parr rearing in Hood Canal IMW streams during the summer. Little Anderson, Seabeck and Stavis creeks are plotted on the left axis; Big Beef Creek is plotted on the right axis. Estimates obtained via mark-recapture techniques. Coefficient of variation for abundance estimates (not shown for sake of figure clarity) generally range from 5 – 15%.

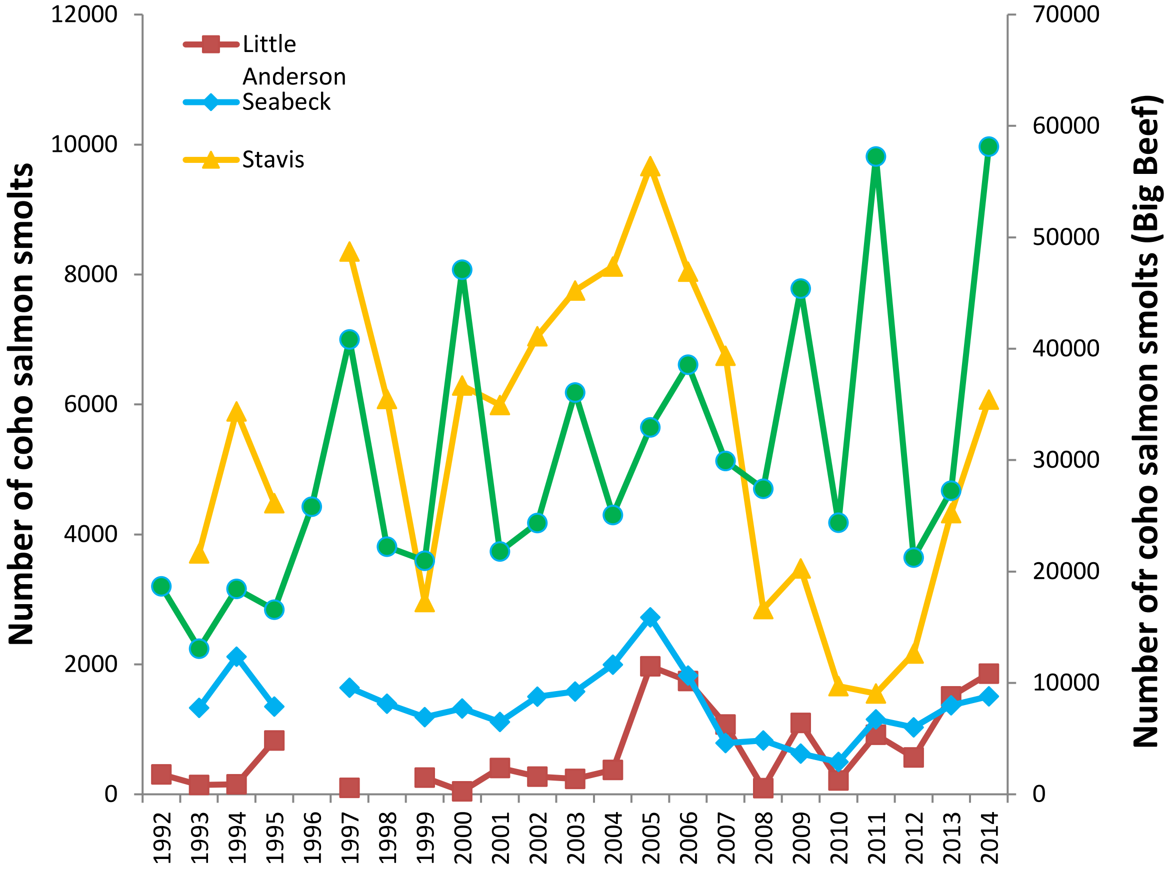

Figure 12. Coho salmon smolt abundance within Hood Canal IMW. Little Anderson, Seabeck, Stavis plotted on left axis, Big Beef on the right axis.

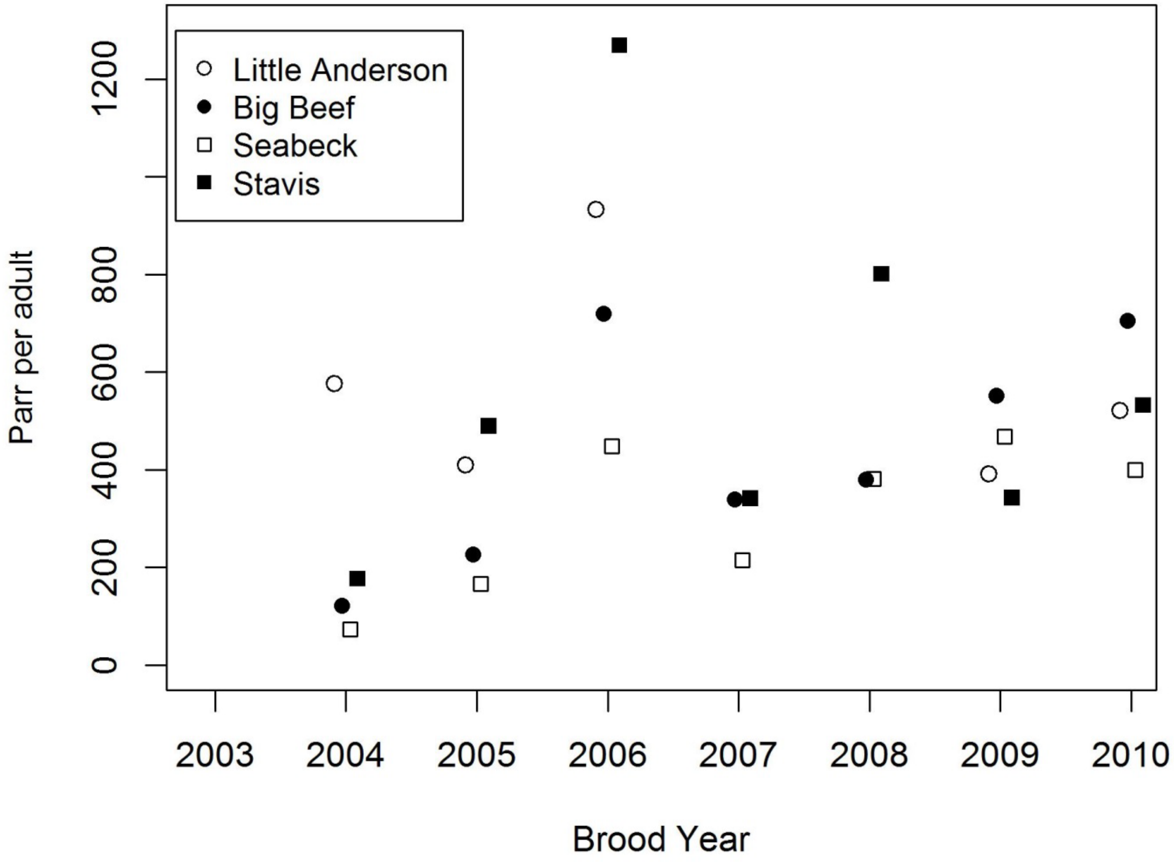

Figure 13. Estimated number of coho salmon parr per adult within cohorts. Estimates for Big Beef Creek are based on number of adults passed upstream of the weir, all other watersheds based on total redd counts. Total redd counts are likely underestimates of number of spawning females but data are collected consistently across years within each watershed.

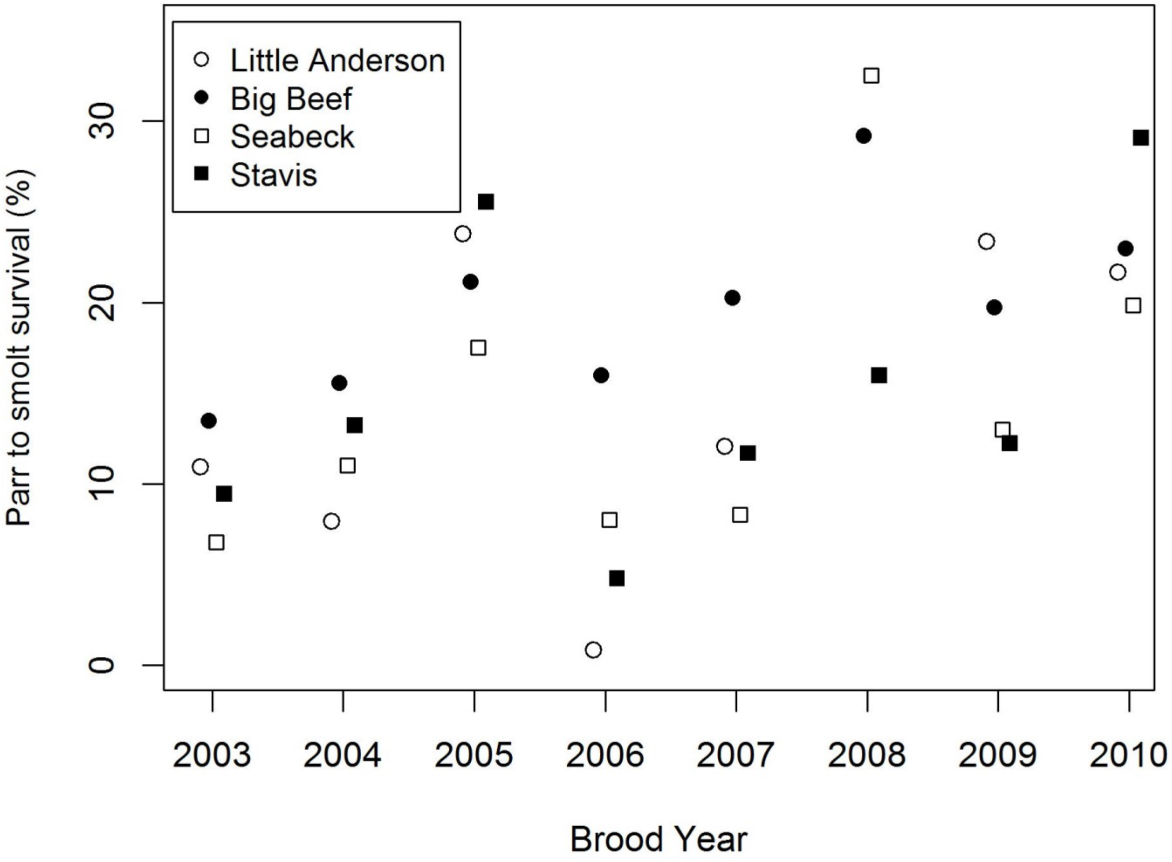

Figure 14. Parr to smolt survival of coho salmon in Hood Canal IMW streams.

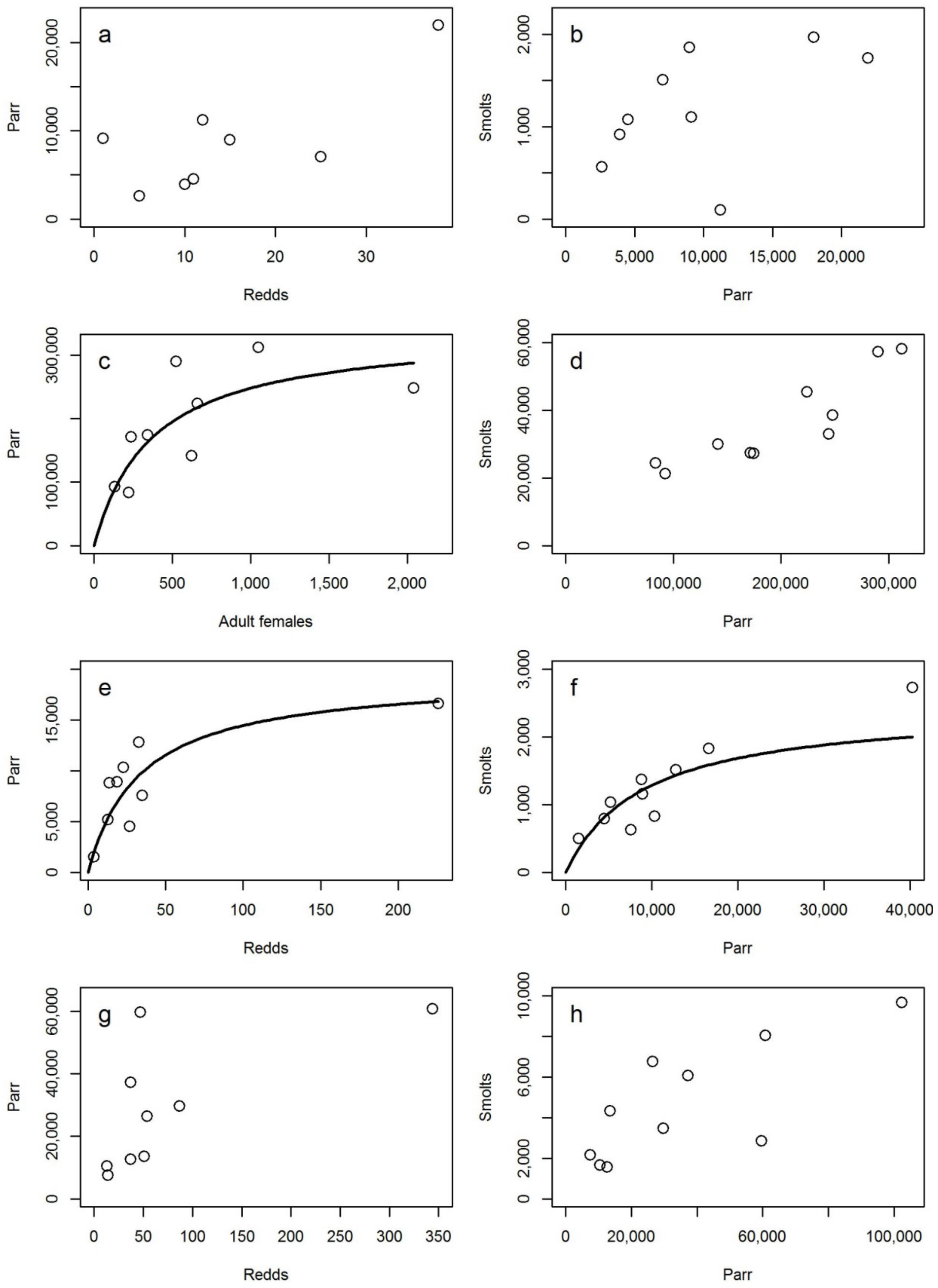

Figure 15. Coho salmon stock-recruit relationships for Little Anderson (panel a and b), Big Beef (c and d), Seabeck (e and f), and Stavis (g and h) creeks. Left column compares parr to adults; right column compares parr to smolts. Lines are shown for data sets where a simple Beverton-Holt density dependent model fit the data better than a linear density independent model (ΔAICc ≥ 2).

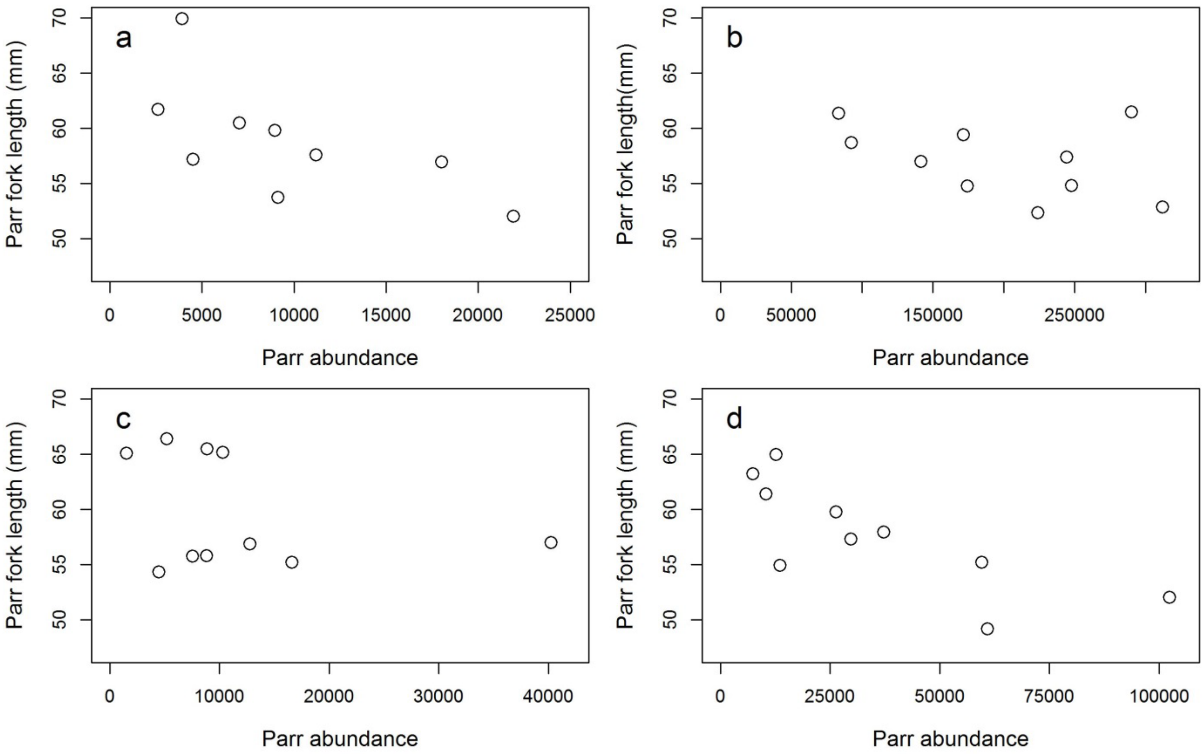

Figure 16. Relationship between coho salmon parr abundance and annual average parr fork length for coho salmon sampled Little Anderson (a), Big Beef (b), Seabeck (c), and Stavis (d) creeks.

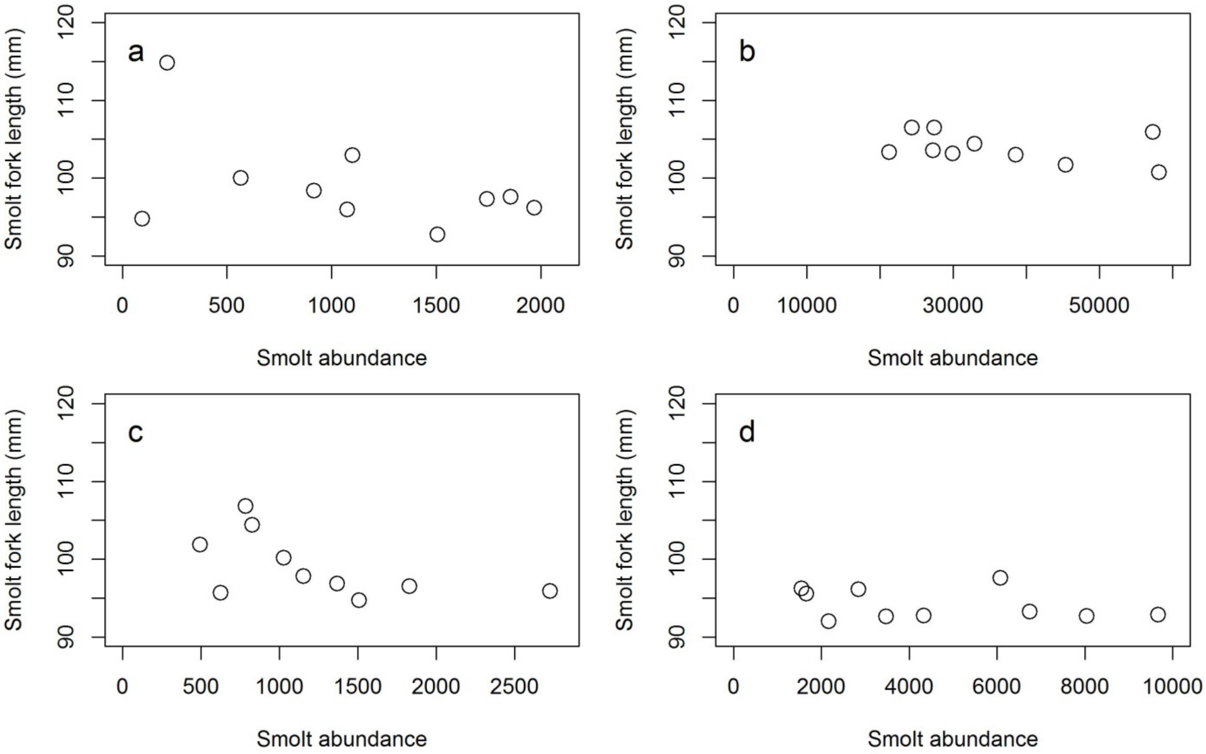

Figure 17. Relationship between coho salmon smolt abundance and annual average smolt fork length for Little Anderson (a), Big Beef (b), Seabeck (c), and Stavis (d) creeks.

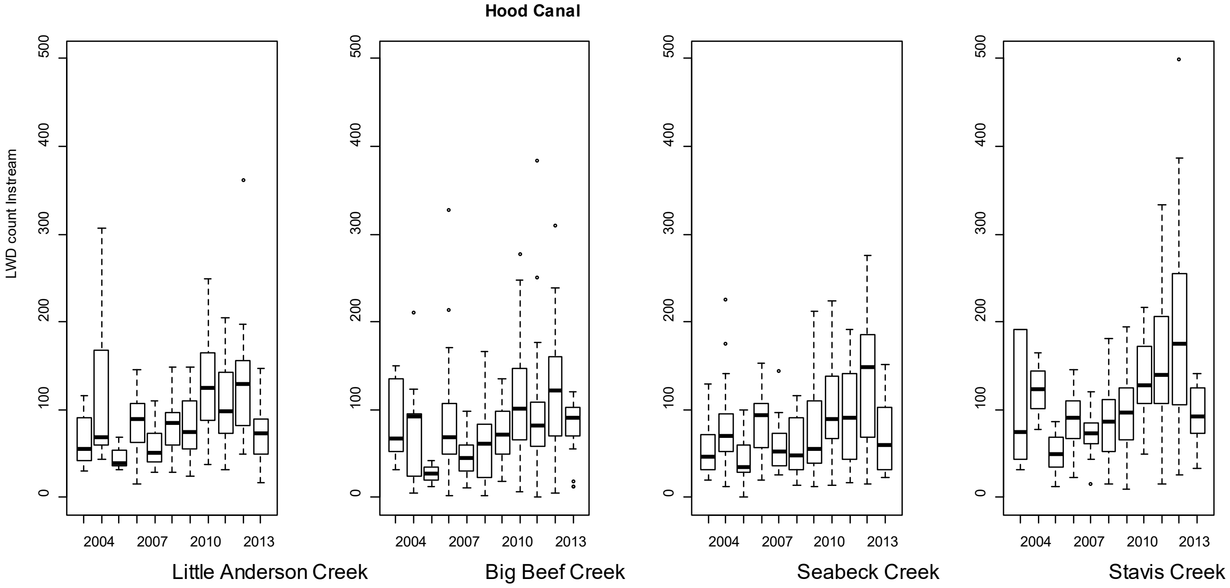

Figure 18. Boxplots of counts of large wood that is within the bankfull channel in Little Anderson, Big Beef, Seabeck and Stavis (reference) creeks from 2004 through 2014. Note that some sample locations were changed in 2006, so sample sizes are smaller for years 2004 and 2005.

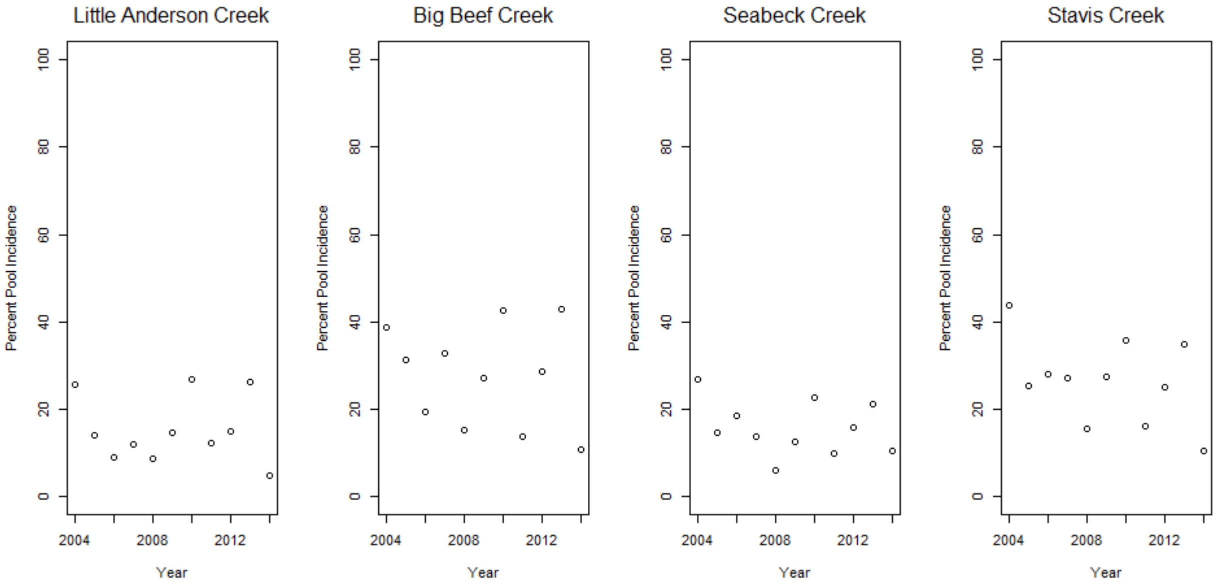

Figure 19. Percent of all cross-sections (n = 21 per site per year) that intersect a pool in annually repeated sample locations (n ~ 20 per watershed per year) in Little Anderson, Big Beef, Seabeck and Stavis (reference) creeks from 2004 through 2014. Note that some sample locations were changed in 2006, so sample sizes are smaller for years 2004 and 2005.

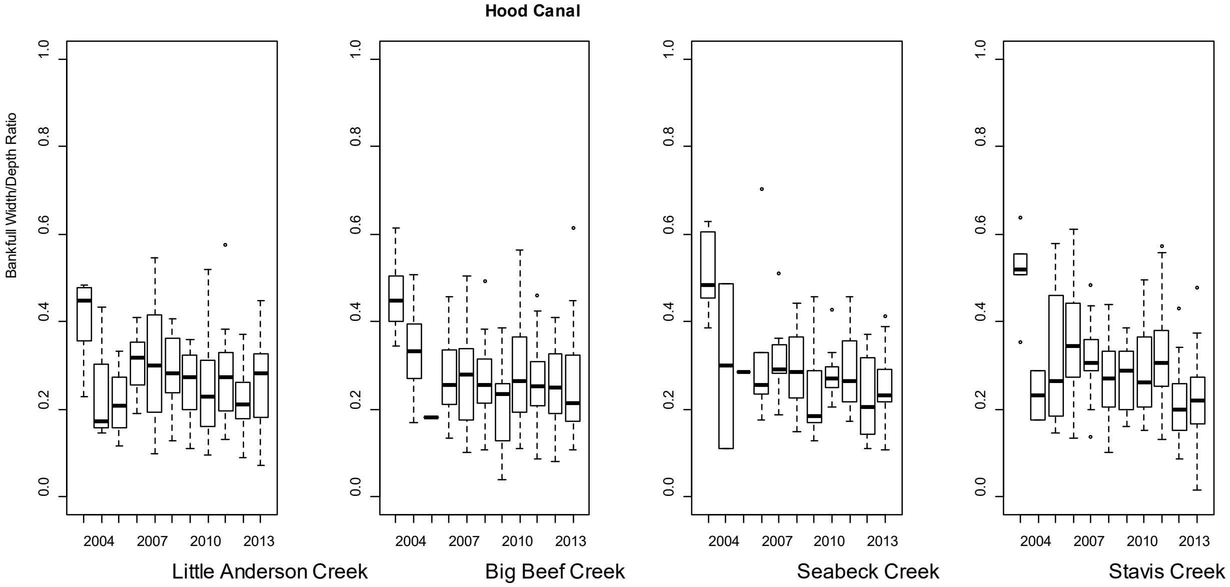

Figure 20. Bankfull-width to thalweg depth ratios for all cross-sections (n = 21 per site per year) from annually repeated sample locations (n ~ 20 per watershed per year) in Little Anderson, Big Beef, Seabeck and Stavis (reference) creeks from 2004 through 2014. Note that some sample locations were changed in 2006, so sample sizes are smaller for years 2004 and 2005.

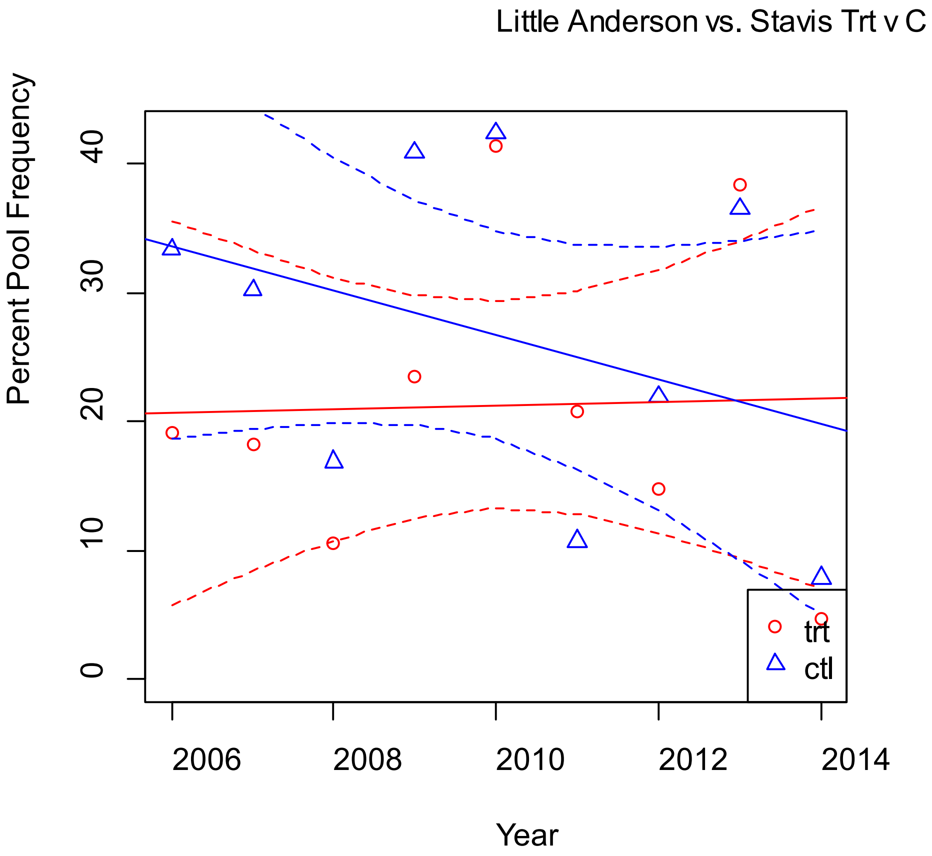

Figure 21. Linear models and confidence bounds describing changes in pool frequency in sample sited downstream of restoration in Little Anderson Creek (n = 8, treatment) and at sample sites in similar locations in Stavis Creek (reference). Note that pool frequency increase is minor in Little Anderson Creek and that low pool incidence in 2014 affected model fit. Restricting the data to 2006 through 2011 yields a significant ($p < 0.05$) positive model for Little Anderson, but not for Stavis Creek. Analyzing the complete time series 2006 to 2014 data (lines shown in figure) provides a similar pattern of moderate increase in Little Anderson and decline in Stavis creeks, but the models are not significant.